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International Institute
for
Applied Systems Analysis

PROCEEDINGS
OF
IIASA PLANNING CONFERENCE
ON
ENERGY SYSTEMS

July 17-20, 1973

Schloss Laxenburg
2361 Laxenburg
Austria

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INTERNATIONAL INSTITUTE FOR APPLIED SYSTEMS ANALYSIS

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July 17-20, 1973 - Baden, Austria

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Introductory Remarks by the Institute Director

H. Raiffa

On behalf of the Institute, I would like to welcome you to this Planning Conference on Energy Systems. This is part of a series of meetings which the Institute is holding to seek expert opinion in better defining the most promising directions for Institute research. The Institute hopes these conferences will provide a frank, open airing of viewpoints, opinions, and controversies. To encourage such exchange, the minutes of the conference will reflect the varying sentiments of the participants but will avoid attribution of positions without prior approval of the speaker; however, remarks by the Chairman and by discussion leaders will be attributed. Any written statements from the participants will be welcome and shall be included in the final proceedings. The minutes of the conference will be distributed among the participants and the Council members.

Before outlining for you the Institute research plans, I would like briefly to sketch the history of IIASA. Early in 1967, Mr. McGeorge Bundy, representing the President of the United States, met in Moscow with Dr. Jerman Gvishiani, Deputy Chairman of the State Committee of the U.S.S.R. for Science and Technology. Their discussions dealt with a proposal of the President "to explore the possibility of establishing an international center for studies of the common problems of advanced societies." That meeting opened a five-year period of planning conferences and multi-national negotiations held under the Chairmanship of Lord Solly Zuckerman of the United Kingdom and convoked with the goal of establishing such a center.

At the risk of slighting many people who contributed greatly to the planning for the Institute, it is only just to mention that major roles were played by Monsieur Pierre Aigrain of the French government, Prof. Philip Handler of the U.S. National Academy of Sciences, Dr. O. Leupold of the German Democratic Republic, Signor Aurelio Peccei of Italy, Dr. Friedrich Schneider of the Max Planck Gesellschaft, Prof. D. Smolenski of the Polish Academy of Sciences, as well as by Messrs. Bundy, Gvishiani, and Zuckerman. A representative national scientific institution from each of their countries and, in early 1972, from Bulgaria, Canada, Czechoslovakia, and Japan were invited to join the Institute, bringing the founding membership to twelve.

On 4 October 1972, these founding members signed the Charter creating IIASA as a non-governmental international institute; at the same time, they selected Laxenburg, Austria, to be the site of the Institute headquarters. The Austrian government had proposed to renovate the former Habsburg palace there, and the first set of offices was completed on schedule in June, 1973. Work on another wing of Schloss Laxenburg is in progress and should be finished by the end of 1973. We expect completion of the first major phase of renovations by the end of 1974, with a second phase to begin in 1975.

The timetable for development of the Institute has three overlapping phases: organization of the Institute administration (October, 1972 through June, 1973); research planning conferences, of which this is one (July through October, 1973); and expansion of the research program (already begun and continuing in the future at an accelerated pace).

The number of scientists in residence will treble between now and September, 1975, when approximately ninety scholars will be working in Laxenburg. These scientists will be chosen with consideration of geographical distribution among the member nations. They will be invited to work at the Institute for short terms or for periods up to three years, with most coming for one year.

In addition to normal administrative support for the scholars, the Institute is developing scientific support to include three essential services: an in-house library connected with libraries in Vienna and abroad, an information distribution system, and computer facilities. The Institute currently has time-sharing arrangements with the Honeywell-Bull Mark I and Mark III systems, using terminals already installed in the castle. The computer section is presently selecting an appropriate mini-computer, and investigating the possibility of eventually purchasing a large, primary machine.

This gives you an overview of the background and phsyical structure of the Institute. I would now like to describe the Institute plans for its research program, and then finally, to express our goals for this conference.

The Institute has two branches: the Council, which is responsible for broad policy, and the Directorate, which implements, directs, and administers the research program. Planning for this program has gone through various stages of refinement. The Council has determined what the broad areas of Institute research are to be, and now, using ideas and suggestions gleaned from the research planning conferences, the Director, Deputy Director, and other IIASA research leaders will propose for approval by the Council a more formal research strategy. In the interim, the Directorate has had a partial mandate to invite scholars to begin work this year.

The Council outlined ten broad research areas with overlapping boundaries. To overcome problems which the breadth of these areas could create, the Institute chose two approaches. Its scholars will work on topics with obvious interrelations, and, in addition to this in-house research, will exploit the infrastructures of other groups such as the national member organizations, United Nations groups, and other national and international institutions engaged in projects related to IIASA interests.

However, the Institute will be neither a project-oriented consulting group, nor merely a data-collecting institution. Rather, it will attempt to strike a balance between methodological and applied studies in seeking solutions for real world problems.

It is further essential that we maintain a healthy geographic balance across the research team structure. The teams must be so designed that scientists of different nationalities supplement each other, communicate, and learn from each other. The structure should be such that this occurs naturally, with guidance from the leadership, but without constant interference.

As important, and perhaps as difficult as the balance of nationalities, is the balance of disciplines. Applied and methodological researchers, applied mathematicians and engineers, statisticians and organizational theorists, social scientists and operations researchers, economists and decision analysts have much to contribute to one another. IIASA projects should be structured so that each group feels vitally a need for the others. We feel that perhaps the best way to achieve this is through concentration upon applied projects, as the project in Energy Systems, in which the disparate disciplines must interact with each other in order to produce concrete results.

During the course of this conference, the Institute expects you to voice your opinions, to map out alternate designs for approaching the research, to isolate theoretical research topics within the energy area, to suggest ways to collaborate with other groups, and to discuss possibilities for choosing a concrete problem for analysis if this course appears fruitful. We further hope that the conference will produce preliminary suggestions for a basic library in the energy area, and guidelines for necessary computer support.

The conference participants should explore the value of reanalyses by IIASA scientists of current outside projects, or the desirability of retrospective critiques of past projects. Here IIASA could bring to bear its wealth of cross-cultural and cross-disciplinary viewpoints in seeking out lessons from other projects which could improve its own research efforts in energy systems.

We should also discuss what types of experts could usefully complement and support the Energy project. For example, how might the energy project benefit from the contributions of economists, physicists, biologists, meteorologists, engineers, lawyers, organizational experts, or geographers?

Finally, the conference participants should identify points of natural contact between the energy project and other Institute projects. The question of nuclear plants and the effects of thermal pollution upon water systems could involve researchers from the energy, water, and environmental projects in a joint study.

Valuable suggestions have emerged from our previous conferences. We feel that the discussions in this planning conference will further identify what we might term "the distinctive competence" of IIASA. Only then can we shape a research program for the Institute which will make a unique contribution to research in the area of Energy Systems.

August 1973

Energy Systems

by
Wolf Häfele

1.) Introduction

Up to the present the production, transmission and distribution of energy has been considered mostly as a fragmented problem, at best only subsystems had been considered. Today the scale of energy utilization is increasing rapidly, and corresponding by, the reliance of societies on energy. Such strong quantitative increases influence the qualitative nature of energy utilization in most of its aspects. Resources, reserves, reliability and environment are among the key words that may characterize the change of the nature of the problem of energy utilization. Energy can no longer be considered an isolated technical and economical problem. Instead, it is embedded in the ecosphere and the society-technology complex. Restraints and boundary conditions have to be taken into account with the same degree of attention as in traditional technical problems, for example a steam turbine. This results in a strong degree of interweaving. Further, the purpose of providing energy becomes more visible, that is, to make survival possible in a civilized and highly populated world on a finite globe. Because of such interweaving and finiteness it is felt that energy should be considered as a system and the term "energy systems" is used therefore. The production of energy is only one component of such a system, the handling of energy and the embedding of energy in the global and social complex in terms of ecology, economy, risks and resources are of similar importance.

The systems approach to the energy problem needs more explanation. This paper is meant to give an outline on the underlying problems and it is hoped that by doing so the wide range of sometimes confusing voices or statements about energy can be better understood. Such confusion starts already with the term "energy crisis". Is there an energy crisis or not?

Much future work is required to tackle the problems of energy systems. This paper can only marginally help in that respect. But it is hoped that this paper helps to understand what the scope of the problem is.

2.) The Phasing of the Energy Problem.

It is vital to realize that the problem of energy seems to appear in phases. During these phases the detailed features of the energy problem will be quite different, sometimes even of an opposite nature.

One should distinguish the following three phases:

the short range phase,	1970 - 1985
the medium range phase,	1980 - 1995
the long range phase,	1990 - 2050 (?)

The years given above shall be only indicative, the phases are overlapping and not so clearly defined. In the following a few explanations are given that may characterize these three phases and can perhaps make their introduction plausible, see also for this purpose figure 1.

2 a.) The Short Range Phase (1970 - 1985)

In the short range phase of the energy problem there will be certain shortages and changes in the fuel market, particularly in the market for oil and gas. Technological developments can help to adjust for this situation. However, this requires time, probably ten to fifteen years. Therefore it is just this lead time that determines the time range of the first phase of the energy problem as during this first phase only existing technological and economical tools can be expected to be of help.

The most obvious problem of this first phase is the supply of oil and gas, particularly in the United States. Consider for instance the problem of oil prospecting. According to M.K. Hubbert /1/ the amount of oil discovered per foot of drilling in the U.S. has strongly declined since 1938 and is now only

35 barrels/foot. Further, Hubbert assumes that the discoveries up to 1965 represent about 82 % of the prospective ultimate total. The situation for gas is qualitatively similiar, but this is not the case for coal. Other factors inhibit the easy use of coal /2/. There is not much hope that new resources for oil and gas can be discovered easily. An uncommonly large amount of capital would be required for such discoveries.

Energy conservation will be therefore a prevailing theme in the years to come. Increased efficiencies of energy conversion, the reduction of wasteful uses, better heat insulation of offices and homes and other measures will have continued attention. The existing forecasts for the demand of energy must then be reexamined considering such energy conservation. This will be especially so in the U.S. /3/ where a change from affluence to conservation of energy will be experienced. In other countries such change will be less drastic but it will exist.

Conservation can merely reduce but not eliminate the problem of oil and gas shortage. During the short range phase of the energy problem the U.S. has no choice but to import the necessary amounts of oil from the Middle East which has about 50 % of all oil resources outside the USSR and China. One has to realize however that Japan gets ~ 80 % and Western Europe ~ 60 % of its oil supply from the Middle East. The implications of these facts are outlined in detail for instance by Walter Levy /4, 5/.

Nuclear Power will increase its share in the production of electrical power but this share will be limited because the lead time for the construction of a nuclear power plant is steadily increasing. In the U.S. eight to nine years for such lead time are not unusual. Further, one has to realize that all electrical power makes up only 25 % of the primary energy demand and only as little as 10 % of the secondary energy demand. Nuclear power will therefore have a smaller but nevertheless important impact on the overall energy problem in the short range phase than was expected previously.

There are many existing regulations for the use of energy, import, taxes, rates. Quite often these regulations have been arrived at from a fragmented point of view. Suboptimizations have taken place when energy was not yet a comprehensive problem. An example is the import quotas for oil in the U.S.

But also in the Federal Republic of Germany for instance it is only now that a comprehensive plan for dealing with energy as a whole is being worked at. Additionally, regulations for the protection of the environment are now being added at an increasing rate. To some extent it was nuclear power that initiated an awareness for environmental problems. Of course one realizes that nuclear power fulfilled only a pilot function there, the environmental problems are much more general. Nevertheless, the complication that the licensing of nuclear power plants experiences due to actions of environmental groups worsens the problem of sufficient supply of electrical power. Similarly, rigorous regulations for the emissions of pollutants of combustion engines tend to increase the consumption of gasoline. Therefore regulations probably have to be reconsidered from a comprehensive, systems point of view.

Some observers feel that at present there is overreaction to the environmental challenges. A particularly sensitive point is the siting of large industrial installations such as power plants, deep water terminals, refineries, high voltage transmission lines and others. It is expected that the next ten years will bring a certain equilibrium between environmental and economical requirements. Such establishment of a reasonable equilibrium is probably characteristic for the short range phase of the energy problem.

Also energy prices will be put in equilibrium with the general economy of the next decade. The installation of new facilities like refineries, enhanced exploration of fossil fuel resources meeting environmental standards, research and development for energy technologies, and other requirements will all tend to increase the energy prices. It remains to be seen where this equilibrium will occur.

Much has been published on these questions in the recent past. In particular an article of St. D. Bechtel /6/ helps make necessary distinctions and which therefore shall be mentioned here.

2 b.) The Medium Range Phase (1980 - 1995)

As mentioned before technology can help society adjust mainly to new conditions and constraints in the problem of energy. The necessary lead time for the implementation of such measures determines the beginning of the medium range phase of the energy problem. This is the phase where technological adjustments can be felt. In order to see roughly where such adjustments have to be made it is important to realize that as a rule of thumb the energy consumption splits in the rations 1:1:1:1. 25 % of the primary energy demand goes into households and commercial buildings, 25 % is for industrial purposes, 25 % is for transportation and 25 % is the primary energy demand for the generation of electricity. Because of conversion inefficiencies this last 25 % constitutes only 10 % of the secondary form of overall energy demands. Nuclear energy has been developed almost exclusively with a view to produce electrical power. Even if nuclear power takes over the majority of electrical power plants (and it probably will) the problem of providing sufficient energy will prevail in that period, because it is not readily clear that an all electric economy is a feasible solution. At least it seems obvious that airplanes cannot fly on an electrical basis. Fossil fuel will continue to play an important role and fortunately there is much fossil fuel in the form of coal. The exploitation of coal has been constant or decreasing in the past. This is largely due to the present practices of mining but also improved standards and safety regulations and a lack of research and development contributed to the difficulties that the coal industries have experiened in the past decade /2/. The technologies that have been mentioned above will therefore probably attack the problem of making use of coal by other means than conventional mining, the most obvious schemes being coal liquification and gasification and the transport of such fuel through pipe lines /7/. Such a scheme allows for a smooth transition from the use of natural gas to the substitute of natural gas (SNG). Gasification of coal requires process heat. It is therefore interesting to evaluate the potential of nuclear power for the provision of such process heat. This could lead to an enhanced development of the High Temperature Gas Cooled Reactor (HTGR).

Probably, also the problem of siting could be the subject for significant technological advancements. The scheme of having a serial production of nuclear power stations that are placed on floating platforms has to be mentioned here. This allows for cheaper fabrication under strict quality control provisions and it helps to ease the ever increasing difficulties of choosing sites for power plants and other technical installations in crowded areas. But other developments on the general problem of siting have to be envisaged too.

Another goal for technological research and development could be abatement measures for the use of fossil fuels. Also special uses of solar power have to be mentioned. For instance, local space heatings in warmer climates fall under this category. Such special use of solar energy is taking place already today.

More important however will be the major adjustment of the economy and infrastructures of modern societies to the third phase, the long range phase of the energy problem. As we will see in the next chapter, fossil fuel resources are limited and in the long run one or two of the few existing options for the practically infinite supply of energy has to be prepared for. This probably requires adjustments. For instance, it might be necessary to change the boundary between the electrical and the non electrical form of energy uses or to consider more explicitly the relations between the availability of energy and the availability of water. Adjustments of that kind will have very significant consequences.

2 c.) The Long Range Phase (1990 - 2050 (?))

The main characteristics of the long range phase of the energy problem could be the following ones:

- One or two of the few existing options to have a practically infinite supply of energy have been identified and fully investigated for large scale implementation.

- The size of the global energy demand has been increased by at least a factor of ten. The developing nations are among those with the highest increase of energy consumption.

- Boundary and constraints for the global use of energy have been identified and modes for the production and use of energy that are consistent with such boundaries and constraints have been developed.

- The medium range phase of the energy problem has been used for a smooth transition into this long range phase of the energy problem.

The emphasis is more on these characteristics than on the particular date of 1995. Predictions of dates come out to be wrong more easily than predictions of the characteristics as such.

In the following chapters more will be said about the above mentioned few options for the practically infinite supply of energy and equally on the boundary and constraints for the global use of such amounts of energy. Such a more detailed consideration for the long range phase is important because the medium range phase is expected to provide a smooth transition from the short range into the long range phase. We will therefore elaborate now in greater detail on more specific aspects of energy systems and on the existing options, boundaries and constraints for the large scale use of energy and will thereafter come back to considerations of the long range phase.

3.) Modelling of Demand and Supply of Energy Systems.

In the past it was largely the demand of energy that was the driving force for the development of energy technology and the evolution of an energy economy. Other considerations were secondary and it was therefore possible to consider highly aggregated forms of parameters in the energy field such as the increase of the demand for electrical energy. Best known is perhaps the observation that this demand for electrical energy doubled every ten years. Such considerations were also very useful because these high aggregations led to fairly accurate results. Fluctuations in the components of such aggregation seemed to cancel out each other.

Now one faces a situation that changes. In the short range phase of the energy problem the supply of certain kinds of fuels cannot meet the demands so easily any more. Ecological and other constraints as outlined above come into the picture too and can no longer be considered to be of secondary importance. It is therefore mandatory to come to more detailed evaluations of less aggregated parameters. This leads into the mathematical modelling of demand and supply of energy.

It seems possible to observe three aspects of such modelling:

sensing, optimization and forecast

There are several things that must be sensed by modelling. It has been mentioned earlier that regulations in the energy field have been sometimes arrived at from a fragmented view point, subsystems have been considered. Modelling now should lead to a more comprehensive point of view: What happens, if ..... It should be possible to evaluate certain policies and regulations by such procedures. This may be particularly true for the establishment of environmental and economical considerations, as has been mentioned earlier. But also, and in relation to that, the complex problem of technology assessment can probably be brought in. This way it might be possible to evaluate priorities for research and development. Undoubtedly there is a preoccupation in the community of science and technology for the production of energy while probably the handling and embedding of energy is more urgent in the long run. This could be more clearly assessed by modelling. Further, the impact of energy conservation could be better evaluated up to the problem of limited economical growth or no growth.

Optimization is an obvious objective for mathematical modelling. The best and timely distribution of fuel supply, optimal inter fuel substitution and the optimal provision of capital come into the picture. Up to now the objective function was simply arrived at by economical considerations of monetary prices and costs. It will be important by now to incorporate multiple objectives in the objective function that account for economical values as well as for environmental and social values. This leads into the much more general problem of comparing such values. Sometimes this problem is referred to as comparing "apples and oranges". More methodological work is obviously required here.

Forecast is the third aspect of modelling. The problem of forecast shall not be explained in greater detail. It is a widely recognized problem. Later in this paper we will elaborate on "system problems". Therefore the observation shall be made that the forecast of such system problems will be of special interest if one wants to understand energy systems. A typical example for the modelling of energy demand and supply has been presented at a recent MIT Conference on energy modelling by Schweizer, Love and Chiles of the Westinghouse Corporation /8/. These authors consider a fuel allocation model as described in figure 2. A model for demand of energy and its growth for various types of fuel in various regions and market sectors is used. The energy demand model is combined with a model on the various partial elasticities to serve as an input for a linear programming allocation algorithm. The same is done for a model of the supply, its growth and the elasticities involved. The linear programming algorithm then allocates demand growths to supply growths for a given objective function. The result is an energy strategy of meeting the demand growth with the connected price changes. Such an approach implies certain fuel interchangebilities. This leads to the field of energy conversion and the related models for that. New technologies have to be considered here, but equally, also models for energy policies that are under consideration. The over all model as described in figure 3 can help to assess priorities for technological R + D work, for evaluating the consequences of considering other objective functions than just minimum price and they can help to evaluate the impact of certain policies.

A brief outline of the mathematics that is involved in that model is given in table 1.

The process of designing such a model and the numerical playing with such a model can help to understand better the inherent features of the reality to which that model is applied. Of particular importance may be the identification of possibly existing various levels of the considered system and the degree of coupling between these levels. For instance, the construction of a new power plant is a part of the electricity supply system of a considered region. Such an electricity supply system in turn is part of the general supply system for all forms of energy and so on. Now it may be interesting to consider for instance the problem as to whether a change in the boundaries of the system in question influences the various conclusions that can be made, or in other words: the degree of coupling of a considered system with systems of higher levels /9/.

A remark must be made on data input. Mathematical models are of value only if the necessary input data are available. Evaluations for the asymptotic solution of the energy problem require global considerations. The type of data that are required for this must be identified. It is then the problem to make the degree of aggregation of raw data compatible. Furthermore the required data may be available for the domain of economy, but of equal importance are data for pollution, thermal waste heat, sociological data or in other words data that allow for the more general objective functions that have been mentioned earlier.

4.) Long Range Energy Demands.

In the following we will deal with large amounts of energy. It is therefore useful to introduce the unit of $Q = 10^{18}$ BTU. In table 2 the equivalent of Q in several units is given.

In table 3 a few figures are given that characterize the consumption of energy. It should be noted that the world consumption of energy in 1970 is roughly 1/4 Q/year whereas the consumption for the year 2050 could be 6 Q/year. This is a factor of 25 larger than the value for 1970. The figure of 10^{10} for the population is an unsophisticated straight forward guess and can be heavily debated. It should be realized however that this figure does not imply exponential growth. A key figure, on the other hand, is the value of 20 kW/capita. This figure has been introduced by Weinberg and Hammond /10/ after having studied in somewhat greater detail future conditions of a civilized society. A break down of that figure is given in table 4. Again it should be noted that also in the KW/capita figures no exponential growth of any kind has been assumed. The point that has to be made here is that we have to consider the life conditions of future decades when the population is high and recycling of resources and in particular water is probably necessary. In order to better understand such future life conditions sophisticate scenario writings and life style descriptions are required. But the argument goes further. Figure 4 /11/ demonstrates the fact that at present the use of energy is very non uniformly distributed over the globe. Contrary to that any consideration of asymptotic solutions of the energy problem must start from the assumptions that the provision of power per capita will be equal for all of the world population and further, the actual value of that figure will correspond to the highest figure in question, for instance the figure for the U.S. It is impossible that a non-proliferation of high power installations per capita can ever come into effect. Eventually the same comfort for all of the world population must be feasible and accessible, at least potentially, and that means that any asymptotic solution of the energy problem must be based on that assumption of equality. On the basis of these few conceptual considerations alone one can see that the demand of energy as compared with today's values will be significantly larger, at least 10 times but probably more.

In a previous chapter a time scale for the three phases of the energy problem has been given. The third phase, the long range phase, has been characterized by the fact that one or two of the few options for practically unlimited fuel supply was chosen for implementation, fossil fuel cannot be employed in a large scale any more. As we will see in the next chapter this happens when the energy consumption reaches a few Q/year. This in turn depends largely on the size of the world population and the rate at which the developing nations are keeping up in their standard of civilization. This may happen sooner or later than 1995 and the long range phase of the energy problem will then appear sooner or later accordingly. The date of 1995 is therefore only indicative as has been mentioned above.

The relevance of such considerations can be felt if figure 5 is considered. It demonstrates the linearity between the energy use/capita and the gross national product/capita and the continued linearity if the recent increases in these figures are evaluated. There is debate today as to what extent this linearity is a necessity and this in turn leads again to mathematical modelling. Much work has to be done there.

One more observation must be made. The linear relationship of figure 5 seems to underline a simple scheme that is given in figure 6. The circle of fuel supply and its price levels shall indicate a constraint but otherwise there appears only energy and the gross national product. This was a reasonable scheme as long as the previously mentioned restraints and boundary conditions were of secondary importance. But this changes now.

5.) Energy Resources.

The fuel that has been exclusivly used up to now is fossil fuel. In view of future phases we have to compare fossil fuel resources with those from other sources.

5 a.) Fossil Fuel.

Widely different figures for fossil fuel resources are being reported and discussed today. The reason for these discrepancies is the simple fact that it is difficult to clearly define an obvious upper limit for declaring deposits as resources. Earl Cook /12/ makes the observation that there are three methods of forecasting the availability of resources. One is the economic method that simply projects historic trends and demand elasticities together with technological trends and simply concludes that if under such conditions one would look for fuel: it will be there. This was perhaps a reasonable approach in the past when the scale of energy production was small if compared with global yardsticks. Here we are concerned with a different order of magnitude of the energy problem. The next method is the geologic-analogy method which is supply oriented and not demand oriented as is the economic method. Extrapolations are made on the basis of geological considerations. The third method is the exploitation-history method of M.K. Hubbert /13/ that takes into account the history of the production curve, the proved - reserve curve and the curve of discovery per foot of exploratory drilling. The last two methods seem applicable for our considerations here.

In table 5 we present information that was given by V.E. Mc Kelvey and D.C. Duncan /14/ and M.K. Hubbert /13/. The large difference between the lower and the upper limit in the case of the McKelvey-Duncan data and the data of M.K. Hubbert that are in between illustrate the above given remarks. It should again be noted that the upper values are no limit in a physical sense. In the case of coal, for instance, the figure refers only to resources above a depth of 1800 m.

Oil resources are somewhere between 2 Q and 20 Q. It was outlined in the last chapter that consumption rates of a few Q/year must be anticipated in the not so distant future. The figures in table 5 therefore indicate that such consumptions cannot be based on oil, it must be coal instead. There the resources are larger by a factor of ten or so. It is therefore indeed reasonable to possibly make coal a corner stone for the medium range phase of the energy problem. It could last for a few decades if simple minded straight forward algebra would be applied. One has to think however on the conditions that would characterize such harvesting of coal at a large scale. It requires world wide major operations. As we will see in the next chapter this leads into system problems, that is, side effects that were secondary when the harvesting of resources were modest will become first order effects. For illustration the problems of surface mining could be mentioned. Similar remarks should be made also for the case of shale oil.

Much effort is required to identify such system problems. It is not sufficient to simply point to a single and yet not so large resource figure. The time period during which one can rely on coal might be therefore more limited. This underlines the explanations of the chapter on the phases of the energy problems saying that the medium range phase should be primarly a phase for smooth transition.

5 b.) Uranium and Thorium Resources

The remarks on the difficulties of having meaningful estimates of fossil fuel resources apply equally also to resources for nuclear fission reactors, that is uranium and thorium. There are many publications on this question. In the middle sixties the question of uranium reserves was heavily debated /16/. It should be realized however that all the figures on that time referred to known deposits or deposits that could be discovered with a high degree of certainty. Further, only uranium prices of up to 30 $/pound of U_3O_8 were considered. In order to appreciate this one has to realize what the ore costs per KWh relative to the busbar costs are for the various types of power plants. They are given in table 6. An increase of ore prices from 10 $/pound to 30 $/pound would increase in case of a light water reactor the busbar costs by about 1 mill/KWh. Such consideration were setting the limits in the discussions of the sixties. However, in that time the main consideration was the commercial competition between nuclear and fossil power. In the context of todays energy considerations in general and this paper in particular this is not the only valid view point now. Therefore in table 7 we have also given estimates for higher uranium prices. At 100 $/pound the cost increase for electrical power from LWR would be at

5 mill/KWh and the resources would still be only a few hundred Q. These are quantities that are comparable to fossil resources. Nuclear power on the basis of present nuclear power plants does not differ from fossil fuel plants so far as fuel resources are concerned. The picture is qualitatively different for the breeder reactor. Its near term importance is the fact that increases in prices for uranium ores are practically not felt in the busbar costs of a breeder power station. Prices of beyond 500 $/pound of U_3O_8 can be afforded. Therefore vast amounts of resources become accessible and those resources are better converted to energy by about a factor of 100. Table 7 therefore indicates that the energy resources that are accessible through the nuclear breeder reactor are practically unlimited and this is the long term importance of the breeder. M.K. Hubbert /13/ gives the example for uranium deposits that become meaningfully accessible by the breeder technology: In the U.S., the Chattanooga shale spreads out along the Western boarder of the Appalachian Mountains. This shale has a uranium rich stratum, which is 5 m thick and contains 60 g per ton. This is a value far below what is considered interesting under todays circumstances. The energy content of this shale per square meter would be equivalent to that of 2000 metric tons of coal or the energy content of an area of 13 kilometer square would be equivalent to that of the world resources of crude oil ($2 \cdot 10^{12}$ barrel)!

The distribution of thorium on the various parts of the globe is different from that of uranium and this will have regional consequences. For instance India has not much uranium but vast amounts of thorium. India therefore must look for special ways and means for the use of these resources. Altogether however the energy equivalent of the thorium resources only slighly exceeds that of the uranium resources. One is essentially correct if one assumes that these equivalents are equal. For further details we refer to McKelvey and Duncan /14/. Energy through the fission of the uranium and of the thorium atom by the use of the breeder reactor provides therefore the first option for a practically unlimited supply of energy.

One has to realize that the development of the breeder reactor is far advanced. The most advanced version of the breeder reactor is the liquid metal fast breeder reactor. It is developed by the USSR, France, the UK, Germany together with Belgium and the Netherlands, the USA and Japan. Large scale developments like that of the fast breeder reactor have to pass three thresholds:

the threshold of scientific feasibility
the threshold of industrial feasibility
and the threshold of commercial feasibility.

A present large industrial prototype reactors in the 300 MWe class are being built or put into operation by the USSR, France, the UK and Germany together with Belgium and the Netherlands. In the USA and Japan such construction is expected to come soon. That means that the second threshold, that of industrial feasibility is being passed now. The commercial feasibility is expected for the middle eighties /17/. Further, the liquid metal cooled fast breeder reactor has back-ups. The helium cooled fast breeder provides such a back-up solution. Certain key problems of this reactor type are being investigated. But also the thermal breeder /18/ and especially the molten salt breeder as pursued by Oak Ridge Nat. Lab. in the U.S. backs up the development of the liquid metal fast breeder reactor. The point that must be made here is this: already with the technology of the seventies and the eighties we have by the fast breeder reactor one industrially feasible option for practically unlimited supply of energy, even if in the not so far future energy consumption of a few Q/year have to be envisaged. Figure 7 summarizes the situation for fossile fuel and nuclear fission reactors /11/ and illustrates how one cannot have one single figure for energy resources.

5 c.) Lithium and Deuterium Resources.

Besides fission there is fusion as another form of nuclear power. It is known that fusion reactors have not yet passed the threshold of scientific feasibility, but it is not unlikely that this will happen in the next ten or fifteen years. Whatever the answer to the scientific and the other feasibilities might be, it is worthwhile to have a look on the fuel resources. By far the most probable scheme for fusion is the D-T reaction. This requires lithium as a fuel in addition to deuterium. It turns out that lithium is the limiting factor for the fuel supply. In fact such a reactor is fairly precisely a fusion breeder /19/ as lithium is bred into tritium similarly to the breeding of U-238 into Pu-239. If a technical fusion reactor is envisaged then it has been found that 1 MWd/gram of natural Li (7.4 % Li-6 and 92.6 % Li-7) can be produced /20/. That is the same amount as for uranium or thorium in fission reactors.

Also here low figures for Li have been reported /14/. This is obviously the case because formerly there was no incentive for adequate prospecting. But the amount of the lithium in the oceans alone is indicative: $2.7 \cdot 10^{11}$ which corresponds to $2.2 \cdot 10^{7}$ Q if all lithium could be extracted. If we again assume a factor of $\sim 3 \cdot 10^{-2}$ for extraction we obtain $\sim 7 \cdot 10^{5}$ Q.

A fusion reactor on the basis of the D-D reaction would be still another thing, no lithium is required in that case. One should realize however that this is significantly more difficult than a D-T fusion reactor and as pointed out earlier even its feasibility remains to be proven. In any event, the deuterium content of the ocean is equivalent to $\sim 10^{10}$ Q, or if again a factor of $3 \cdot 10^{-2}$ for extraction is applied we end up with the equivalent of $3 \cdot 10^{8}$ Q.

It is obvious that fusion would be a second option for the practically unlimited supply of energy if it eventually can be made a technically feasible scheme.

5 d.) Geothermal Sources.

The use of geothermal sources for the supply of energy at a large scale is a comparatively new aspect. In the past only in Italy, New Zealand and the U.S. geothermal power stations have been operated. The scale was modest, a few hundred MW at best. The expected lifetime of these stations is in the order of a few decades /13/. It was on this basis that this source had not attracted much attention when question for energy at a large scale were under debate. More recently the question has been reexamined however. Donald E. White /21/ has estimated that the world's ultimate geothermal capacity down to a depth of 10 km is roughly $4 \cdot 10^{20}$ Wsec. Not counting any conversion factors etc. this equals 0.4 Q. It is obvious that this is a negligible amount of energy in the context considered here.

However, there are also other voices. Recently R.W. Dose /22/ has made the statement that by making more rigorous use of the existing geothermal sources in the U.S., sources with a lifetime of more than 1000 years and with 10^{5} MW could possibly be explored. This would correspond to 3 Q in the U.S. and could therefore be crudely compared to the U.S. oil resources. Details for such estimates were not given.

A different order of magnitude comes into the picture when the heat content of the earth's crust is considered. The temperature gradient is on the order of a few tens of degrees C per km depth. If the earth's crust underneath the continents is considered down to a depth of 10 km then the heat content is in the order of $5 \cdot 10^5$ Q. Conversion losses have to be taken into account and only a fraction of the crust underneath the continents can possibly be exploited. A few thousand Q may be in principle available that way. But this is not more than a quick and unsophisticated estimate.

The argument about geothermal power goes further. Besides the continents there is the ocean. The upper 200 m of the ocean is warmer by ten degrees C or so. Again taking all of the surface of the oceans one arrives at a figure of 3000 Q or so. Here the conversion losses will be considerable because the temperature difference is only 10^{0}C and only a fraction of the oceans can possibly be exploited. A few dozen Q may be in principle available that way.

The question whether geothermal energy is exploitable at a large scale is a very open question. No real conclusion can be drawn here. It is not really clear whether geothermal power can be considered an option for large scale energy supply.

5 e.) Water and Tidal Power

Water and Tidal power resources of the world are in the order of few tenths of a Q /13/. Those power sources may be of regional interest but are definitly not an option for the large scale supply of energy.

5 f.) Solar Power

The supply of solar power as such is infinite. It is rather a problem of power density. The solar input above the atmosphere averaged over day and night and all zones of the globe is 340 W/m^2. Roughly 47 % reach the surface of the globe, that is 160 W/m^2. The net value of the outgoing infrared radiation is $\sim$ 70 W/m^2. We therefore have

$$\underset{\text{visible light}}{160\ W/m^2} = \underset{\text{infrared radiation}}{70\ W/m^2} + \underset{\text{heat balance.}}{90\ W/m^2}$$

Figure 8 gives the energy balance in somewhat greater detail. The heat balance is used in turn to drive the water cycle in the atmosphere by evaporization of rain water, to heat the ground and the lower part of the atmosphere and to provide the power for biological processes.

The determining consideration for the harvesting of solar power on the surface of the globe is then obviously the question to what extent this energy balance may be distorted. This is of course an extremly complex problem of a systems nature and more will be said about it in the next chapter. A straight forward estimate for the global average value for harvesting solar power may be 20 W/m^2. It should be noted however that regionally considerably higher values could be acceptable. This will then be of regional significance accordingly. Here in this context we are interested in the question of global large scale energy supply. A value of 20 W/m^2 makes it obvious as we will see later that not the supply of power but land use is the determining factor for the collection of solar power on the surface of the globe.

But it is not necessarily so that solar power must be harvested on the surface of the globe, it could be harvested in outer space. A recent proposal of P.E. Glaser elaborates on that /23, 24/.

It becomes clear that solar power is in principle an option for the large scale supply of energy.

We can summarize this chapter by concluding that at least in principle there are three (four) options for the large scale supply of energy. Large scale means a few Q/year for thousand years or much more. These options are the followings:

1.) Energy by nuclear fission
2.) Energy by nuclear fusion
3.) Solar power
4.) Energy from geothermal sources (?)

It should be clearly noted that the one option that is feasible with certainty is energy from fission. Other sources of energy like fossil fuel, water, tidal etc. do not fit in that category. Their local importance may be nevertheless significant.

6. System Problems

If there is more than one option for having eventually large scale supply of energy: What is the problem? According to figure 6 there should be none.

Fission energy is the one option that is feasible already today. More than that, it is being installed now at such a rate that the impact of nuclear energy begins to be felt even in the over all picture of energy. By the end of this decade a number of countries expect to have nuclear power produce about 30 % of all their electricity. In the U.S. more than 150 GWe are today in operation, under construction or firmly ordered. In the FRG the figure is 13 GWe, in Japan 15 GWe, that for the whole world 254 GWe. But even so it is not pure pleasure to be a promotor for nuclear energy today. There is much objection against nuclear power. The arguments that can be heard are about the following:

a) The operation of nuclear power plants imply a certain radiological burden
b) Nuclear power plants could lead to major radiological burdens in case of a major accident. Especially in the focus is the problem of emergency core cooling systems (ECCS).
c) The operation of nuclear power plants necessitates the long term disposal of radioactive waste.
d) The large scale handling of Plutonium in the fuel cycle will unavoidably lead to losses of such Plutonium into the biosphere.
e) Fissionable material is potentially dangerous as it can be used for military purposes and the illegal diversion of such material by thefts or groups must be taken into account.
f) Large nuclear power plants release large amounts of waste heat and lead to a distortion of the biosphere by the warming of rivers and lakes.
g) Nuclear power plants require large amounts of land.

h) We do not need the power from nuclear power plants.

A few years ago the objection concentrated on single nuclear power plants. Today the trend is more toward the installation and operation of a large nuclear fuel cycle. How many transports of irradiated fuel elements are required? What about the superposition of the various releases? And what about plutonium in principle?

To a certain extent the above given questions are legimate. They were originally contemplated and answered when nuclear energy was in its infancy. Now that nuclear power is becoming mature the questions come up again for reconsideration. This statement however shall not be interpreted to the end that all objections to nuclear power that are heard are considered legitimate /25/.

Let us now take as an example the question of the radiological burden that is due to the operation of nuclear power plants. The Gofman-Templin debate in the U.S. is deeply interwoven to that problem. Together with other influences it led to a standard for acceptable radiological burden that is as low as 5 mrem/year (light water reactor).
The central question now is this: What are the alternatives? In a recent publication of the nuclear research centers of Karlsruhe und Jülich in the Federal Republic of Germany a comparison of alternatives was attempted /26/. It was assumed that all the electrical power of the FRG would be produced alternatively by coal, lignite, gas, by pressurized water reactors or by boiling water reactors. It is of course a problem to compare a burden that is due to SO_2 with a burden that is due to radioactivity. To that end the existing standards for each of the relevant pollutants were taken and the values of ambient dose rates (obtained from an admittedly crude meteorological model) were normalized by these standards and the normalized values were then added (see Table 8).

The methodological problems of such a comparison are obvious. For instance, no synergistic effects are taken into account nor is it clear that the various standards were derived by similarly rigorous procedures. We touched earlier on the problem of comparing "apples and oranges". This is one of the key problems of systems analysis.

Even with these reservations in mind it seems fairly obvious that each of the alternatives has a higher pollution load than nuclear energy. So the problem of pollution burdens is much more general. It is not a specific nuclear problem but it became visible and known to the public with the advent of nuclear power. The real problem is: The size of energy production. It is an unprecedented dimension of experience and together with it, concern.

Let us move to the second example. The risk of nuclear accidents is exceedingly small but it exists. In the past such extremely low risks were not explicitly considered but after having gone through the exercise of nuclear power also other risks are being evaluated. Recently Ch. Starr, M.A. Greenfield and D.F. Hausknecht compared the risks of a nuclear power plant to that of an oil fired plant /27/. Figure 9 gives one of the results of this comparison. Again there are methodological questions because qualitatively different things are being compared. The argument here is not so much the details of this comparison. They may change back and forth when the comparison becomes more sophisticated. But the argument is that such a comparison is now imminent. Again, the question of risk is not a special one for nuclear energy, it is a general problem that comes now to the forefront because of the mere size of energy production.

A further example is the waste during power production. The data given in table 9 shall point to that. In case of fossil fuel ordinary pollution will not be considered. Ideally abatement measures may have taken care of that problem. But the production of CO_2 is an inherent characteristic of that type of production of energy and the amounts of CO_2 are so large that it has to be released to the atmosphere. At the present rate of world energy production this leads to an increase of 5 ppm by weight/year. An energy production that is 25 times higher leads to accordingly higher values. The short remark "unrecycled" in table 9 refers to the fact that atmospheric CO_2 is in a dynamic equilibrium to the CO_2 content of the oceans and the biosphere and the actual values are therefore smaller by a factor that is somewhere near 2. Such values for the increase of the CO_2 content have to be weighted against the natural CO_2 content of the atmosphere. In 1950 this was 450 ppm by weight. There is considerable concern that the infrared radiation from the earth back to outer space is upheld by an increased CO_2 content due to the so-called green house effect /28/. At present the effect is definitly small but it is not clear today how large an increase of CO_2 in the atmosphere can be accepted. Much more work is required here.

But also nuclear power produces waste. Due to the famous factor of $2.5 \cdot 10^6$ (energy output per gram fuel in the case of nuclear power as compared with fossil power) this waste is small in volume and can, contrary to the case of CO_2, be contained. This of course establishes the task to do this reliably and for very long times and this is a large problem. But the right question is not: Do we want to have this problem or not? Rather it is the question: What is more acceptable, to have an impact on the climate (which at present is still to be better understood) or to have a long term waste problem of small volumes? Again completely different categories have to be compared, a typical systems task that is oriented toward the understanding of interweaving.

In the case of waste heat disposal it became obvious even in the public debate that this is a general problem of the production of energy. It is two-fold: In the conversion of energy there are sometimes very large losses and further, all useful energy finally ends up as waste heat (except the tiny fraction that goes into binding energies). We will devote a whole chapter on this problem. There in particular we will see that this was a secondary question so far but because of the mere size of the production of energy it now becomes a primary question, probably even the limiting one. Once energy is produced from binding energies it remains and does not disappear (except for the tiny fraction that goes back to binding energies). The stream of energy eventually goes to outer space by infrared radiation and this stream of energy must be embedded therefore in such a way that the deterioration of the natural conditions of the globe remains within acceptable limits. It is obvious that the investigation on the problem of acceptability is an integral part of the systems problems.

It is not the purpose of this chapter to deal with all system problems of all forms of energy productions. Nor is it intended to indicate that only fission has system problems. Fusion for instance has system problems too /19/. The same is to be expected for solar power or energy from geothermal sources. Geothermal sources may for instance require considerations on potential earthquakes. The study of system problems is a tremendous task that requires many, many years and remains to be done in the next years. The point here is rather this: We more and more realize that nuclear power took on a pilot function for all energy production schemes in detecting the fact that there are system problems if the mere size of energy production becomes large. The yardsticks for evaluating such sizes are still to be better elaborated but it is clear that nature itself and the conditions of the finite globe do implicitly provide these yardsticks. These yardsticks that must be made explicit refer more to the handling of energy, to the embedding of energy and to the problem of acceptability than the problem of energy production as such, contrary to the situation of the past.

7.) The Task of Systems Analysis in the Case of Energy Systems.

It is now more easily possible to spell out what the task of systems analysis is in the case of energy systems. It is probable that a proper generalization could lead to an understanding of the nature of system problems beyond that of energy systems. The task has the following subtasks:

a) It is necessary to identify and understand all system problems that are inherent in the various options for large scale energy supply. This will be a perpetuating task and will probably never be completed as energy systems expand further and further. This task is not a matter of algorithm. It is rather a matter of technological and sociological substance. Scenario writings and life style descriptions will probably be among the tools for accomplishing this task. It will be in particular important to identify the various interweavings that become important with the increasing size of energy production. This requires to some extent disciplinary oriented work but only to the extent that is necessary for the identification of the discipline oriented questions. From then on it is the task for the various scientific disciplines to pursue the so identified questions in connection with the systems analysis.

b) In the case of energy systems the predominant system problem seems to be that of embedding, not the production of energy. Such embedding is required in view of the function of the globe. There must be embedding of energy into:

- the atmosphere

- the hydrosphere
- the ecosphere
- the sociosphere

c) It is then necessary to identify and evaluate alternatives, options for large scale implementation. There seem to be the following options for large scale energy supply:
    - energy by nuclear fission
    - energy by nuclear fusion
    - solar power
    - energy from geothermal sources.

   While system problems of energy from nuclear fission have been identified to some extent in the past it will be necessary to do the same for the other options. For the task of comparing the various options it will be necessary to have not only cost/benefit procedures but cost/benefit/risk procedures in a special and a general sense.

d) Finally it will be necessary to minimize the system problems. This leads into severe methodological problems. We mentioned the comparison of apples and oranges several times. More scholarly expressed, it leads into the methodology problem of multiple objectives and decision under uncertainty.

Such systems analysis work has to permanently accompany the technological and sociological evolution of energy systems.

8.) Embedding of Energy into the Atmosphere.

Much emphasis has been given above on what may be called embedding. It seems to be necessary therefore to give more substance to that. As a first step let us consider the embedding of the stream of energy into the atmosphere. For that it is helpful to consider the distribution of the solar power input as given in figure 8.

The solar input is 340 Watt per square meter of the spherical upper surface of the atmosphere averaged over day and night and all zones of the globe. Roughly 34 % of that value is reflected immediatly, 19 % is absorbed and transformed into heat already in the atmosphere and 47 %, that is then 160 W/m^2, reach the surface of the earth. Out of this 20 % of 340 W/m^2 make up for the difference between outgoing infrared radiation and the infrared radiation that is back scattered from the atmosphere down to the surface of the earth. 22 % is used to drive the rain cycle. This amount of power evaporizes the water of the rain cycle. By this evaporation the water is lifted to the middle parts of the atmosphere, condensation takes place there, and the condensation heat goes to outer space. 5 % is used to heat the lower part of the atmosphere. All heat given to the atmosphere is eventually radiated away to outer space and therefore a balance is maintained between solar power input and heat power output. The temperature of the earth and the atmosphere is such that it permits this balance exactly. We therefore have a yardstick of power densities on the surface of the globe. Table 10 gives a number of such natural power densities in a convenient form. It should be noted that the figure of 55 W/m^2 is not the global average, it refers to wetter parts of the continents.

A few observations must be made:

- the energy balance is a delicate one, it results from a difference between large quantities (in the visible spectrum and in the infrared spectrum). One must therefore carefully evaluate the various influences on the energy exchange mechanisms, for instance the effect of an increased CO_2 concentration in the atmosphere or changes in the various albedos involved.
- the recycling of water in the mechanism of vaporization and condensation is intimately coupled to the energy balance
- the yardstick of these natural mechanisms is given in terms of power density.

For reasons of comparison we now consider man-made power densities. Orientation figures for that are given in table 11. Today the global average of man-made power density is certainly too small to create a problem but the previously considered 20 kW/capita at a level of 10^{10} people gives a completely different picture. A value of 1.35 W/m^2 on the continents compares already with the global average of the power density for wind, waves, convections and currents.

But it is certainly insufficient to consider only global averages. Man's activity is not equally distributed on the globe. Already today, in the case of the Federal Republic of Germany, we have roughly 1 W/m^2. In the more distant future one has to consider highly industrialized areas that give values between 17 W/m^2 and several hundred W/m^2. The question whether such values lead to adverse effects to the atmosphere and the climate is essentially open today. It is obvious that one has to approach this problem in steps.

The first level of an impact of such man-made power densities could be on the pattern of the rain cycle. Already today there is indication that the number of heavy rainfalls changes over industrialized areas. Industrial areas however do not only produce waste heat but also particulates and pollutants and one has to consider the whole impact. This is complex. If the industrial areas become larger such change of the pattern of the rain cycle could be more than just of local significance.

A second level of an impact of man made power densities would be one on climatic patterns over larger areas while changing only slightly certain climatic averages. One has to bear in mind that there may well be instabilities in the atmospheric equilibrium. The question therefore comes up whether there are areas on the globe that are sensitive (or insensitive) to the production of waste heat.

A still more rigorous level of impact of man made power densities would be on the global climate as a whole. It would lead also to an increase of the average temperature. One should bear in mind that climatic temperature changes of 1-2 ^{o}C are already very significant.

These questions are very difficult ones. They lead into the area of methodological and climatological modelling. This requires very large computer facilities. Of equal importance are the input data. But also adequate understanding of the physics of the highly nonlinear equations that govern the atmosphere still require much work. In the past years these problems have attracted more and more attention /28/. Names like Budyko, Smagorinski, Manabe, Washington, Lamb, Fortak, Bryson, Kellogg and others characterize such work. For 1977 the world meteorological organization and the international council of scientific unions plan "The First Garp Global Experiment" of a Global Atmosphere Research Programe (GARP) /29/. But also the observational branch of climatic sciences must be employed and promoted. There the CLIMAP program maps the climat of earlier ages and provides therefore the opportunity to test the capability of large climatic computer programs.

Earlier in this paper reference was made to possible system problems if solar power would be harvested at a large scale. From tables 10 and 11 we realize that the required power densities for purposes of civilization in certain industrialized areas will be similar to or larger then nature's power densities. The industrially significant employment of solar power involves therefore large areas on the globe. So the involved changes of albedo and the redistribution of energy lead into the same questions that have been mentioned above in the context of waste heat.

One has to put forward the question whether it will be necessary to bring into phase the relevant research and development work in the field of atmospheric sciences and in the energy field.

9.) Embedding of Energy into the Hydrosphere.

We now will investigate the embedding of energy into the hydrosphere. Figure 10 provides the necessary background for that. The average rainfall on the earth is 101 cm/year totalling in an amount of $513 \cdot 10^3$ km^3/year. The same amount necessarily evaporizes. But the ratio of evaporization and rainfall is not the same in the case of the oceans and the continents. Rain water is transported from the oceans to the continents. This feeds the run-offs, that is, rivers and creeks. The total run-off is $35 \cdot 10^3$ km^3/year. Table 12 characterizes water consumption. Contrary to a wide spread belief,it is irrigation that makes up most of the water consumption today. But for the year 2000 this is expected to change. Lvovich /30/ has estimated the consumption in the year 2000 to be roughly 13 000 km^3/year or roughly 1/3 of all the run off's. It should be noted however that global averages are in most cases not adequate. The regional picture may differ drastically. In the case of the Ruhr area, already today 0.63 km^3/year of industrially used water is lost through vaporization or an equivalent of 14 cm/year or roughly 1/3 of the local run-offs. These considerations do not relate yet to energy but give a yardstick for evaluating relevant relations.

A first relation is desalination. It has been estimated that $32\cdot10^6$ km^2 of land could be cultivated. (The total area of the continents is $148\cdot10^6$ km^2.) Roughly $20\cdot10^6$ km^2 are arid and sufficient amounts of water must be provided for. In table 13 it is indicated that an amount of water equivalent to 200 cm/year of rainfall is required because that makes up for the difference between arid areas and cultivated land in areas that were originally arid. 200 cm/year for $20\cdot10^6$ km^2 gives 40 000 km^3/year. From figure 10 it is obvious that such an amount of water can be provided for only by desalination. Today this requires roughly 50 KWh/m^3 thus leading to 7 Q/year. This more or less doubles the previously considered energy consumption of 20 kw/capita and 10^{10} men, thus leading to a total of 7 + 6 = 13 Q/year. These are of course considerations of orders of magnitude only.

It is obvious that land use by cultivating arid areas, water use and energy use go together here.

But there are more connections between energy and water. In fact, the density of rainfall limits the production of electricity: The difference between the rainfall and evaporization which is on the average at 40 cm/year feeds the run-offs and the amount of run-offs is therefore proportional to the rainfall if properly averaged over sufficiently large areas. One can now ask for the amount of waste heat that can be taken away by all the run off's either for the case of once through cooling or by wet cooling towers. Table 14 gives information on that. Due to the connection between rainfall and run-offs also here the limits are in terms of power densities. This refers inherently to land use. If all the run-offs are heated by 5^oC, only 0.25 W/m^2 can be dumped. This admittedly crude consideration leads sometimes to surprisingly good results. In the Federal Republic of Germany for instance roughly 30 GW of electricly production rely on once through cooling. This leads to roughly 60 GW waste heat or 0.24 W/m^2 and this then indeed leads to a situation where the heating of rivers and lakes becomes a legitimate concern.

That is what happens today in the FRG.

Wet cooling towers help for some time, but one must realize that only a

fraction of the run offs can be used for consumption in wet cooling towers. If one compares then the densities with those of man-made densities of tomorrow one realizes that again there should be a problem. This is indeed the case. More detailed investigations in the Federal Republic of Germany come to the conclusion that wet cooling towers probably help only for the next fifteen years or so /31/.
A third connection between water and energy has been mentioned previously. It is the feedback of waste heat to the pattern and the amount of rainfall.

Figure 11 tries to make these interweavings between water, energy and weather more obvious. It is kind of a summary of chapters 8 and 9.

Most of what has been said before refers to water on the continents. But there is also the vast reservoir of water in the oceans. Heat dumping there is feasible so far as the heat capacity is concerned but leads to questions of ecology and the dynamics of ocean currents. It might be necessary to identify areas in the oceans that are stable and insensitive to the discharge of large amounts of waste heat. This then would lead to a decoupling of the heavy interweaving of water, energy and weather as outlined in figure 11. Installing (nuclear) power parks by the ocean or in the ocean then leads to the problem of energy transport over larger distances. In order to fully appreciate this problem one should realize that today there is no transport of electrical energy over really large distances. In the case of the Federal Republic of Germany large amounts of electricity are transported not more than 150 km (average) or so. Most of the high voltage lines essentially only stabilize area oriented distributions of electrical energy. There are a number of technological options for energy transportation at a large scale: Ultra high voltage lines, superconductive cables, hydrogen pipe lines and others. In the past most of the large scale technological R+D effort has gone into the problem of energy production, for instance the development of nuclear power. However, under the scope of considering energy use, land use and water use as one comprehensive problem it appears that the technological problem of energy transport may be more important than the development of another energy source.

10.) The Embedding of Energy to the Ecosphere.

Embedding the use of energy into the ecosphere leads among others to certain environmental problems. Not all of the environmental problems come into the picture this way, of course. A reasonable first step is probably the study of accountability systems. Power plants, urban areas, vehicles are emitters of pollutants. Such emissions lead to ambient concentrations. Simple or sophisticated meteorological and hydrological models could establish the relation of the emissions with the ambient concentrations. The design of monitoring systems could help to establish an experimental background for such relations and thus verify the validity of such models. Parallel to that it might be possible to establish the relation between the production of industrial goods and certain emissions thus leading to the relation: goods - emissions - concentrations of pollutants. Eventually it will be possible this way to establish an overall accountability for the flow of pollutants. This would give inherently the possibility of managing such pollutions. In order to fully appreciate this one should realize that the establishment of a truly global accountability system for nuclear materials that is now implemented by the International Atomic Energy Agency /32/ comes out to be the key for the secure handling of nuclear materials. The universality of the approach poses also certain managerial problems. It is proposed to study this aspect of universality. In so doing it should be recognized that systems analysis did play a major role in the design of the present IAEA safeguard system /33/.

To draw certain conclusions from the results obtained by accountability systems standards are required. The establishment of standards may allow for instance for the design of certain levels of actions. Incomplete knowledge in the field of toxicology, decisions under uncertainty, public acceptance, the legislative process and other aspects come into the picture there. The debate on appropriate standards for radiotoxic dose rates that took place in the U.S. and elsewhere in the recent years may be an example for that. The phenomenon of the Gofman-Templing affair, the rule making process for "as low as practicable" doses rates, the function of public hearings in the decision making process and other events of the recent years should be more thoroughly understood from this point of view.

Figure 12 briefly illustrates this problem of environmental accountability as discussed above.

11.) Embedding of Energy into the Sociosphere, Risk and Reliability.

A thorough reflection on the problem of pollution leads also into the domain of reliability control and risk evaluation. For that it is useful to study table 9 again. Besides of embedding energy into the atmosphere one is led to the problem of risk.

Such risk has two components: The risk component that is due to the lack of knowledge that in principle is obtainable and the risk component that even in principle cannot be determined /34/. This second component is due to the fact that the strict application of deterministic scientific models requires complete knowledge of initial and boundary conditions even if the laws of nature are fully known. In many cases it is impossible to acquire such complete knowledge, it would require a "Laplacean Demon". Then a risk of the second kind evolves.

The relase of CO_2 into the atmosphere together with that of other pollutants establishes a risk of the first kind. In principle it should be possible to understand whether an increased CO_2 content will affect the climate or not, but at present this is not possible.

Nuclear energy leads to a risk of the second kind: It is possible to produce energy without touching the environment at all, at least in principle. The reactions in the domain of the atomic nucleus result however in the production of radioactive elements. (This is also true for power from technical fusion reactors that use the D-T process /19/). Due to the factor $2.5 \cdot 10^6$ between nuclear and fossil power the radioactive elements are so small in volume and weight that they can be contained, contrary to the problem of the release to the environment of reaction products in the case of fossile power as has been pointed out above. Containment, now, is an example for a technological measure. All technological measures can fail and this constitutes the risk.

While the risk of the first kind can be eliminated in principle the risk of the second kind remains in principle. But the risk of a technological measure can be made smaller than any given small number, the residual risk limit. This leads into the domain of reliability control. Space research, electronics and more recently nuclear energy have been the areas where methods of reliability control were developed and applied. The principal tool of reliability control is the establishment of a failure tree. The top of a failure tree represents the undesired accidental event. The use of logical symbols helps to represent the logical structure of the reliability of a given technological device. Figure 13 shows an emergency power supply system for the German-Belgian-Dutch fast breeder prototype reactor SNR 300 and figure 14 shows the failure tree that was used for the evaluation of reliability of that supply system. Having established the failure tree in question, it is then possible to evaluate the failure rate of the considered technological system by computer simulation using among others, Monto Carlo techniques.

However, a number of methodological problems remain: In most cases there is a lack of input data (the failure rates of the various components of the technological systems), it is difficult to make sure that the considered failure tree is sufficient for the purpose in question, confidence levels must be evaluated, etc. On the other hand it is necessary to have reliability control procedures in most of the technological projects to come because society has to rely on technology to an ever increasing extent.

Even if the methods of reliability control are fully mastered it will not be possible to make the reliability of a given technological device exactly one. The limit for the residual risk will always be different from zero, albeit very small. So it will be necessary to establish design limits for such residual risks in the same sense as it was necessary to establish standards for the evaluation of accountability systems for pollutants. Such establishment of design limits can only come from the evaluation of existing risks. Risk evaluation as a scientific disciplin is only in its beginnings and it is in particular the work of Ch. Starr and Erdmann at the University of California, Los Angeles and H. Otway (Los Alamos, University of California, Los Angeles and IAEA) that must be mentioned here explicitly. In table 15 a spectrum of existing risks is given. Ch. Starr /35/ was able to evaluate a number of quasi laws. For instance there seems to be a difference between voluntary risks and involuntary risks, that differ by a factor of 10^3. Further, for voluntary risks there seems to be a relationship between expected benefits and risks. That is illustrated in figure 15. Figure 16 indicates an approach to rationally answering the question: How safe is safe enough? It is obvious that the general problem of systems analysis, the problem of quantification, becomes particularly virulent in the case of risk evaluation. More work is obviously necessary in this field. This could result in more established procedures for the assessment of risks.

12.) Energy Systems

It should now be possible to give a first order approach on the meaning of the term energy systems.

Already before we made it obvious that the simple relationship of figure 6 is insufficient. As we have seen, in the more distant future the production of large amounts of energy is not a constraint. There is sufficient energy. But there are other probably severe constraints. One such constraint is the amount of cooling water if power plants are to be built on the continents. As we have seen, it is the power density that is limited. Also the acceptable heat load to the atmosphere is a limit that is given in terms of a density. In the case of pollution load this is also true at least for a long time to come, although there may also eventually be absolute limits. The case of CO_2 could be a tentative example for that. Having focused the attention on the term density one realizes that probably also risk puts its limit as a density. The whole discussion on reactor siting points to that. For instance an airport, a chemical factory and two nuclear power plants all in one place are sometimes considered too much of an aggregation. A spread out is then required.

Figure 17 is an attempt to illustrate what the term energy systems could mean. In dashed lines we have the traditional understanding of figure 6. The circles indicate constraints. Each constraint refers also to acceptability and therefore to the sociological part of the constraints. Within these constraints energy can be produced. An optimization process now should lead to an adjustment of densities for risk, power and pollution. The means that allow for that are technological development, the spread out of all relevant installations and the transportation of energy and water over larger distances. A generalized objective function as discussed in chapter 3 will be employed in such an optimization. Econometry becomes thereby a more general discipline than previously. It is obvious that other factors have to be taken into account on that level of an approach for long range policies. For example communication, data processing, general transport requirements and other things come equally into the picture. But the scope is now broad enough to describe the impact so far as energy is concerned and to provide for a proper integration of energy systems into a supersystem. The result of such an optimization is a scheme for land use. Only through the use of land can energy result in a gross national product. Land use then is one of the major interweavings between energy systems and other large systems of an infrastructure of a modern civilization.

13.) More Remarks on the Long Range Phase of the Energy Problem.

Earlier in this paper the observation was made that a smooth transition through the medium range phase into the long range phase of the energy problem should be achieved. For that it is necessary to have a conceptual understanding of asymptotic solutions of the energy problem. After the remarks on embedding it is now more easily possible to elaborate a little bit further on one example for an asymptotic solution of the energy problem.

We have seen that the concept of having large nuclear parks could lead to a certain decoupling of the interweaving between water, energy and the weather. To that extent it might be necessary to identify certain areas in the oceans that are particularly insensitive against the release of large amounts of waste heat in terms of meteorology as well as in terms of ecology. Large meterological and ecological modelling is probably required for that. Such nuclear parks should be large enough to incorporate the whole nuclear fuel cycle. This means that a minimum size of 30 GW thermal or so is required. A concentration of the nuclear fuel cycle would eliminate a number of concerns about nuclear power. For instance all the plutonium would remain in one place and the operators could be highly trained and highly effective due to the concentration of facilities. An upper limit of such nuclear parks is probably given by considerations of the security of energy supply. As we have seen earlier the production of electricity is only one aspect. It is not necessarily so that an all electric economy is an optimal solution. We therefore envisage the production of hydrogen in high temperature reactors. Conversion efficiencies of 75 % can be expected there. In a more or less stable future economy the breeding gain of large fast breeder reactors must not necessarily be obtained as plutonium, also U-233 could be produced and this U-233 could be used to allow for the operation of high temperature gas cooled reactors. The transportation of electricity and hydrogen should be not too large a problem. We have mentioned earlier new technological aspects for that. Hydrogen could be pumped into the pipeline system of the medium range energy phase when gaseous hydrocarbons were the secondary fuel. A very smooth transition could then take place.

Electricity and hydrogen are both very clean secondary fuels and hydrogen is feasible also for all forms of transportations and the use in industry. Probably only very minor pollution impacts are to be expected.

Much work is required to study in detail all aspects and in particular the systems problems of such a scheme of an asymptotic solution of the energy problem. The remarks that are made here should only give an example for what could be an asymptotic solution. Other options have to be studied too. For instance the Peter Glaser scheme to harvest solar power in outer space /23/ should be pursued and its systems problems better understood.

This paper is not meant to accomplish already a certain part of that task. It shall only help to understand what the scope for the problem of energy systems could be.

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Table 1 Dynamical Energy Allocation Model

$$\delta P = \sum_{ik} \delta P_{ik}$$

$\delta P_{ik} \equiv$ Growth of prices of K-TH fuel to be paid by I-TH industry

$$\delta D_i \leq \sum_k d_{ik} \cdot \delta P_{ik} = \sum_k \beta_{ik} \cdot \frac{D_{ik}}{P_{ik}} \cdot \delta P_{ik}$$

$\delta D_i \equiv$ Growth of minimum of total fuel consumption of I-TH industry

$$\beta_{ik} = \frac{\delta D_{ik}}{D_{ik}} \Big/ \frac{\delta P_{ik}}{P_{ik}}$$ $\equiv$ Partial elasticity (known from elasticity models)

$$\delta S_k \geq \sum_i s_{ik} \cdot \delta P'_{ik} = \sum_i \gamma_{ik} \cdot \frac{S_{ik}}{P_{ik}} \cdot \delta P_{ik}$$

$\delta S_k \equiv$ Growth of maximum of total supply of K-TH fuel available

$$\gamma_{ik} = \frac{\delta S_{ik}}{S_{ik}} \Big/ \frac{\delta P'_{ik}}{P'_{ik}}$$ $\equiv$ Partial elasticity (known from elasticity models)

$P'_{ik} = P_{ik} - g_{ik} \cdot P'_{ik}$ $\equiv$ Supply costs of K-TH fuel to I-TH industry

LP - Problem : Minimize growth of total prices δP with respect to variables δP_{ik} and constraints D_i and S_k.

Note : Criterion of optimiziation could be different (E.G. Growth of pollution) ;
Additional constraints could be considered (E.G. Resources)

Table 2 Energy Equivalence

$$1\ Q \equiv 10^{18}\ \text{BTU} = 2.52 \times 10^{17}\ \text{kcal}$$
$$= 1.05 \times 10^{21}\ \text{joule}$$
$$= 2.93 \times 10^{14}\ \text{kWh (th)}$$
$$= 1.22 \times 10^{10}\ \text{MWd (th)}$$
$$= 3.35 \times 10^{7}\ \text{MW year (th)}$$

Table 3 Energy Consumption

USA	1970	0.07 Q/a	
USA	2000	0.16 Q/a	
World	1970	0.24 Q/a	(4×10^9 people, 2 kW (th)/capita)
World	2000	2.1 Q/a	(7×10^9 people, 10 kW (th)/capita)
World	2050	6 Q/a	(10×10^9 people, 20 kW (th)/capita)

Table 4 Energy Budget for a Steady - State Civilization *

		kW (th) / capita
Present U.S. level		10.0
Adjustment for the future		
Steel, Aluminium and Magnesium production	0.1	
Recovery and recycle of scarce elements	2.0	
Electrolytic hydrogen	2.5	
Water by desalting (100 gal/day)	0.3	
Water transport to cities	0.1	
Air conditioning to cities	0.3	
Intensive food production	0.2	
Sewage and waste treatment	0.5	
Total adjustments		6.0
Contingency		4.0
		20.0

* (Weinberg, Hammond, Global Effects of Increased Use of Energy, Geneva, September 1971)

Table 5 Energy Content of the Worlds Supply of Fossil Fuel

in units of Q $\equiv 10^{18}$ BTU

	According to V.E. Mc Kelvey and D.C. Duncan [12]		According to M.K. Hubbert [13]	
	Known recoverable	undiscovered and for marginal	eventually recoverable	%
Coal	17.3	320	192	88.8
Crude oil	1.73	23	11.1	5.2
Nat. gas	1.95	20	10.1	4.7
Nat. gas liquids	0.21	3.2		
Tar - sand oil	0.23	6.3	1.7	0.8
Shale oil	0.87	77	1.1	0.5
Total	22.5 Q	450 Q	216 Q	

Table 6 Busbar Cost Sensitivity to Ore / Fuel Costs

Fossil fuel	0.5	(at $\approx \frac{\text{50 cent}}{\text{million BTU}}$)
Light water reactor	0.1	(at $\approx$ 10 \$ / pound of U_3O_8)
Breeder reactor	0.001	

Table 7 Uranium Resources

in units of $Q \equiv 10^{18}$ BTU

(Figures are taken from or are consistent with V.E. Mc Kelvey and D.C. Duncan [12] , exept if otherwise indicated)

	Known deposits		Unappraised and undiscovered resources	
	Light water reactor b.)	Breeder reactor c.)	Light water reactor b.)	Breeder reactor c.)
up to 10 \$ / pound of U_3O_8 a.)	0.7	70	≈30 d.)	≈3000 d.)
up to 100 \$ / pound of U_3O_8 a.)	—	—	$(2-10)\times10^2$ e.)	$(2-10)\times10^4$ e.)
up to 500 \$ / pound of U_3O_8 a.)	—	—	5×10^4 d.)	5×10^6 d.)
Ocean g.)	1×10^2 f.)	1×10^4 f.)	3×10^3	3×10^5

a.) US \$ values of the late sixtees

b.) assuming a conversion factor of 1 short ton of $U_3O_8 = 7\times10^{11}$ BTU

c.) assuming a conversion factor of 1 short ton of $U_3O_8 = 7\times10^{13}$ BTU (1 short ton = 907 kg)

d.) making reference to note d.) of table 4 in [14]

e.) not necessarily consistent with [14]

f.) assuming a technical extraction factor of 3×10^{-2}

g.) it has been estimated that the extraction of uranium from the sea could be done at 25 \$ /pound of U_3O_8 [15]

Table 8 Relative Pollutions in case of FRG Using Different Electric Power Sources (1970) after Ref. [26]

	SO_2	Dust	NO_x	Fluorine	Xe	Kr	Total*
Anthracite	0.94	0.45	0.17	0.75	—	—	2.31
Brown coal	1.20	0.86	0.28	1.65	—	—	3.99
Oil	1.16	0.22	0.20	0.06	—	—	1.64
Nat. gas	3.1×10^{-4}	—	0.16	—	—	—	0.16
BWR	—	—	—	—	1×10^{-3}	1×10^{-3}	2×10^{-3}
PWR	—	—	—	—	3×10^{-4}	1.4×10^{-3}	1.7×10^{-3}

* This means only pollution caused by electrical energy production is included

Table 9

Fossil Energy

$$C + O_2 \longrightarrow CO_2 + 97\ \text{Kcal}$$

$$\Downarrow$$

$$1g\ C \longrightarrow 3.4 \times 10^4\ \text{Wsec}$$

Nuclear Energy

$$\text{Fission of 1 atom U} \longrightarrow 200\ \text{MeV}$$

$$\Downarrow$$

$$1g\ U \longrightarrow 1\ \text{MWd} = 8.6 \times 10^{10}\ \text{Wsec}$$

$$(1g\ Li \longrightarrow 1\ \text{MWd})$$

$$\boxed{\frac{1g\ U\ (Li)}{1g\ C} \longrightarrow \frac{8.6 \times 10^{10}\ \text{Wsec}}{3.4 \times 10^4\ \text{Wsec}} = 2.5 \times 10^6}$$

Fossil :

$$0.24\ Q/\text{year} \longrightarrow 2.5 \times 10^{20}\ \text{Wsec/year}$$

$$\Longrightarrow 5\ \text{ppm}\ CO_2/\text{year, by weight}$$

(unrecycled)

Nuclear :

$$0.24\ Q/\text{year} \longrightarrow 8 \times 10^6\ \text{MW}$$

$$\Longrightarrow 8 \times 10^6 \cdot f\ \text{Curies/year}$$

	10^8 sec	10^{10} sec	10^{11} sec
f =	10^4	10	1

Table 10 Nature's Power Densities

Heat balance on the surface of earth (Average)	100 W/m^2
Latent heat density of rainfall on the continents	55 W/m^2
Sensible heat density for 1°C of rainfall water on the continents	0.1 W/m^2
Winds, waves, convections and currents (All globe)	0.7 W/m^2
Photosynthesis	0.075 W/m^2

Table 11 Man Made Power Densities

Consumption

	Today	Tomorrow
Global average	$\frac{1.5\ KW/cap \cdot 3.3 \times 10^9\ cap}{1.48 \times 10^{14}\ m^2} = 0.033\ W/m^2$	$\frac{20\ KW/cap \cdot 10^{10}\ cap}{1.48 \times 10^{14}\ m^2} = 1.35\ W/m^2$
F. R. Germany	$\frac{4\ KW/cap \cdot 6 \times 10^7\ cap}{2.5 \times 10^{11}\ m^2} = 1\ W/m^2$	$\frac{20\ KW/cap \cdot 6 \times 10^7\ cap}{2.5 \times 10^{11}\ m^2} = 5\ W/m^2$
Industrial area	$\frac{18\ KW/cap \cdot 6 \times 10^6\ cap}{6.5 \times 10^9\ m^2} = 17\ W/m^2$ (Ruhr area)	$\frac{100\ KW/cap \cdot 10^8\ cap}{10^{10}\ m^2} = 1000\ W/m^2$

Production

Large nuclear power parks $30\,000\ MW_e \longrightarrow 100\,000\ MW_{th}$

$$\frac{7 \times 10^{10}\ W_{th}\ (\text{waste})}{3.5 \times 10^6\ m^2} = 20\,000\ W/m^2$$

Table 12 Water Consumption (after Lvovich 1969) and Water Resources

	1965			2000		
Water consumption	Consumption	Wastes	Evaporation	Consumption	Wastes	Evaporation
Urban supply	98	56	42 km^3/a	950	760	190 km^3/a
Irrigation	2 300	600	1700 "	4 250	400	3 850 "
Industry	200	160	40 "	3 000	2 400	600 "
Power plants	250	235	15 "	4 500	4 230	230 "
Total	2 848	1 051	1797 "	12 700	7 790	4 910 "

Table 13 Representative Values for the Heat Balance in Egypt

(after Flohn 1971)

	Arid	Cultivated land
Global radiation input	280 W/m^2	280 W/m^2
Albedo	25 %	10 %
Black body radiation, net value	32.5 W/m^2	38 W/m^2
Net balance Q	170 W/m^2	205 W/m^2
a) Evaporization	2 cm / a	220 cm / a
b) Vaporization heat	1.7 W/m^2 ≙ 1 % of Q	176 W/m^2 ≙ 86 % of Q
c) Sensible heat + remainder	99 % of Q	14 % of Q

Bowen ratio :	$\frac{\text{Sensible heat}}{\text{Latent heat}}$	104	0.16

Table 14 Limits for the Production of Electricity due to Waste Heat Disposal

Total water run off o——o 40 cm / a

A) All run offs heated by ΔT :

$$\frac{N_{th}}{F} = 0.054 \cdot \Delta T \quad W/m^2$$

(for instance $\Delta T = 2°C \longrightarrow \frac{N_{th}}{F} = 0.1\, W/m^2$)

B) All run offs evaporized (wet cooling towers)

$$\frac{N_{th}}{F} = 40\ W/m^2$$

Table 15 Fatal Accidents USA 1967

Type of accident	Total deaths	Probability of death per person per year
Motor vehicle (M.V.)	52. 924	2.7×10^{-4}
Falls	20.120	1.0×10^{-4}
Fire and explosion	7.423	3.7×10^{-5}
Firearms	2.896	1.5×10^{-5}
Aircraft	1.799	9.0×10^{-6}
Railway accident (exept M.V.)	997	5.0×10^{-6}
Electric current	376	1.9×10^{-6}
Lightning	88	4.4×10^{-7}
Explosion of pressure vessel	42	2.1×10^{-7}
Streetcar (exept M.V. and train collision)	5	2.5×10^{-8}

(National Safety Council , Chicago 1970)

Fig. 1 The Phasing of the Energy Problem

Short range 1970 - 1985	Medium range 1980 - 1995	Long range 1990 - 2050(?)	Thereafter
Energy prices	New technologies for the use of coal	Fast breeder	In addition
Oil import	LWR at a large scale	Hydrogen	Large scale uses of solar power ??
Security of supply	HTGR	Energy transportation at a large scale	
Conservation	Pipe lines	HTGR	
Capital funds	Floating islands	Nuclear complexes	
Siting	Local space heating by solar power	Optimization for embedding	
	Prospecting	Global monitoring	
	Pollution control at a large scale		

Fig. 2 Energy Allocation Model

(after Schweizer, Love, Chiles, Westinghouse Electric Corporation)

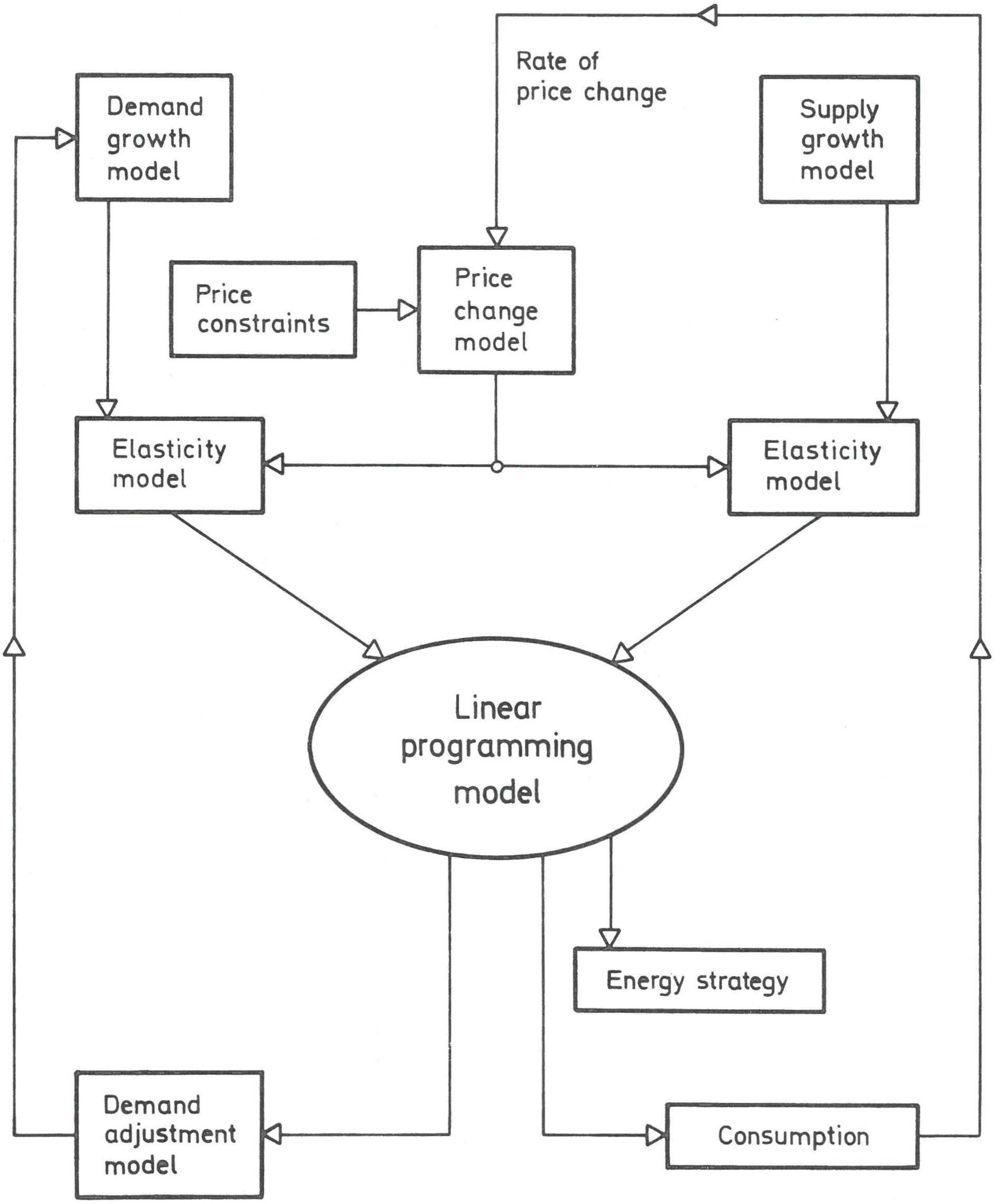


Fig.3 Computer Energy Model

(after Schweizer, Love, Chiles, Westinghouse Electric Corporation)

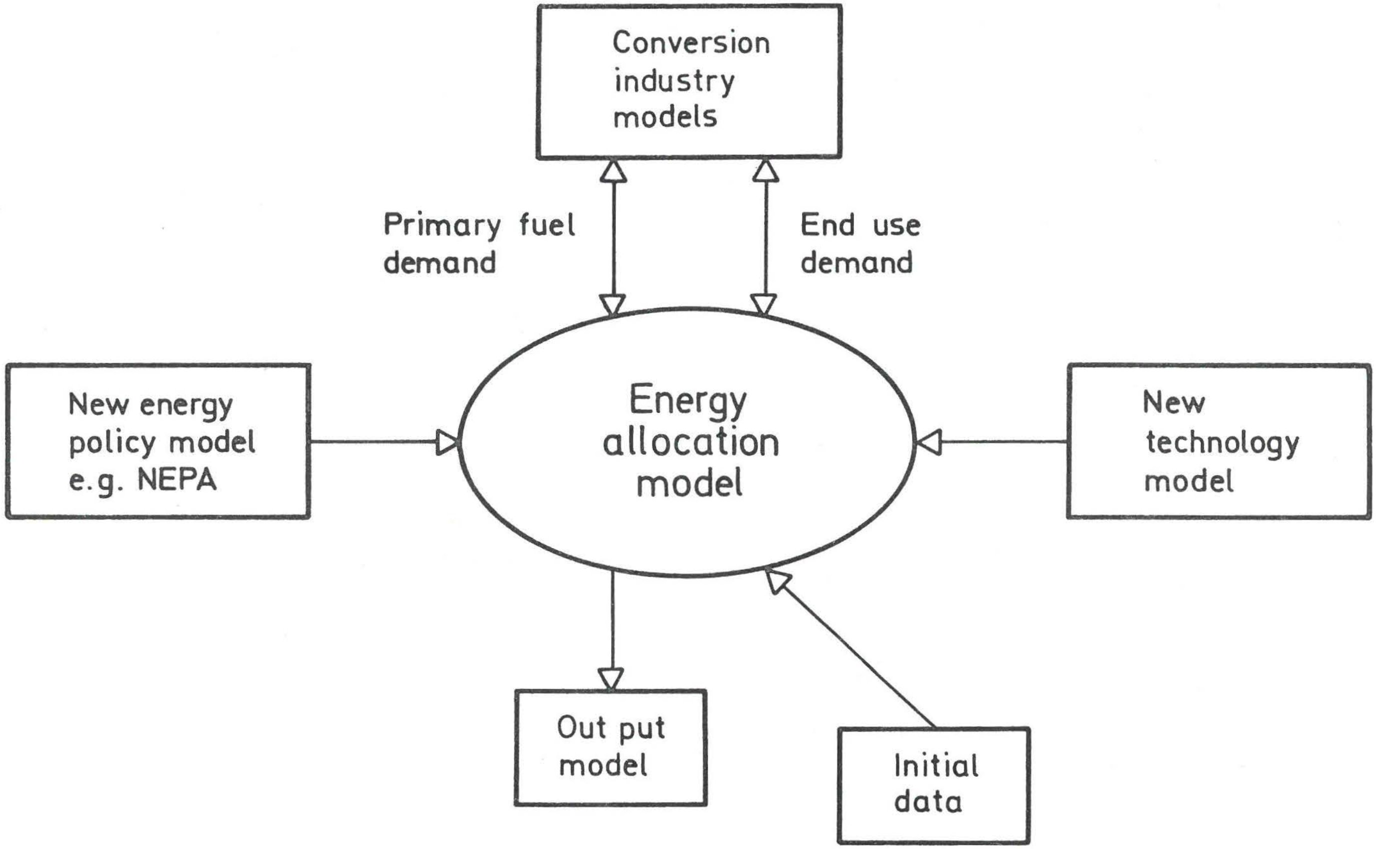


Fig. 4 Growth in Energy Demand

Source : Ch. Starr [11]

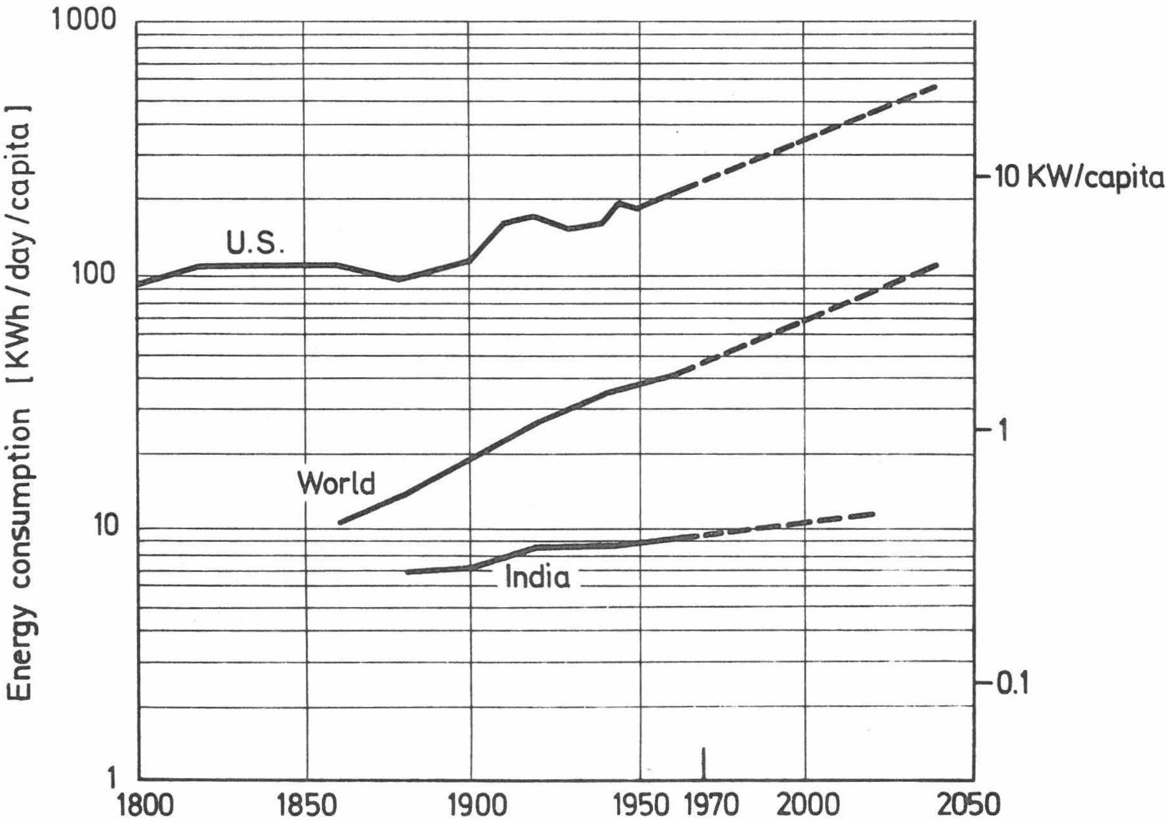


Fig. 5 Commercial Energy use and Gross National Product

● 1968 after Stat. Yearbook of UN (1970)

○ (1961 /1962) after Ch. Starr
Energy and Power , 1971 S. 4

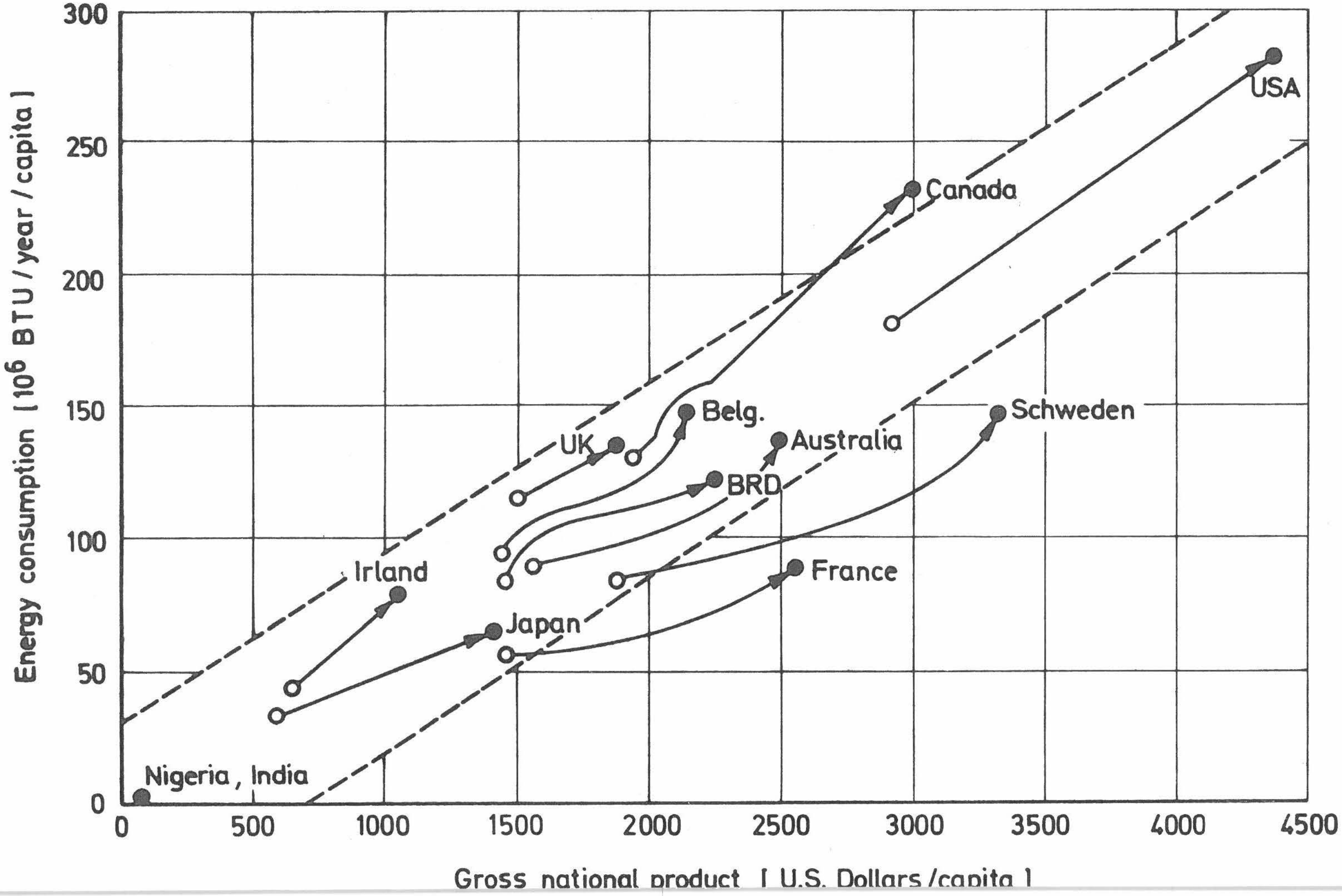


Fig. 6 A Relationship between Fuel, Energy and Gross National Product

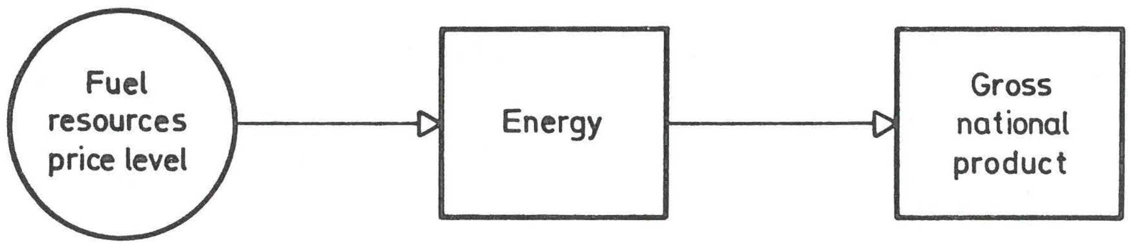


Fig. 7 Comparative Fuel Costs

Source : Ch. Starr [11]

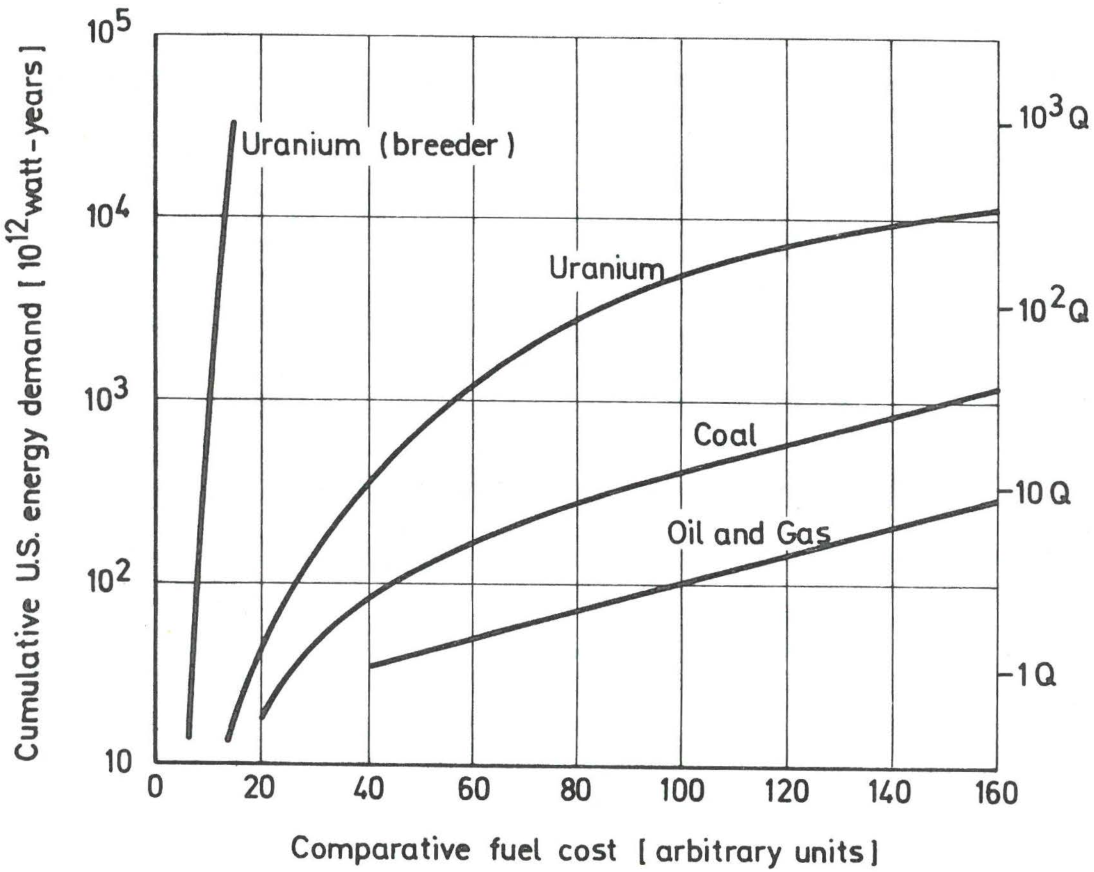


Fig. 8 Distribution of Solar Power Input

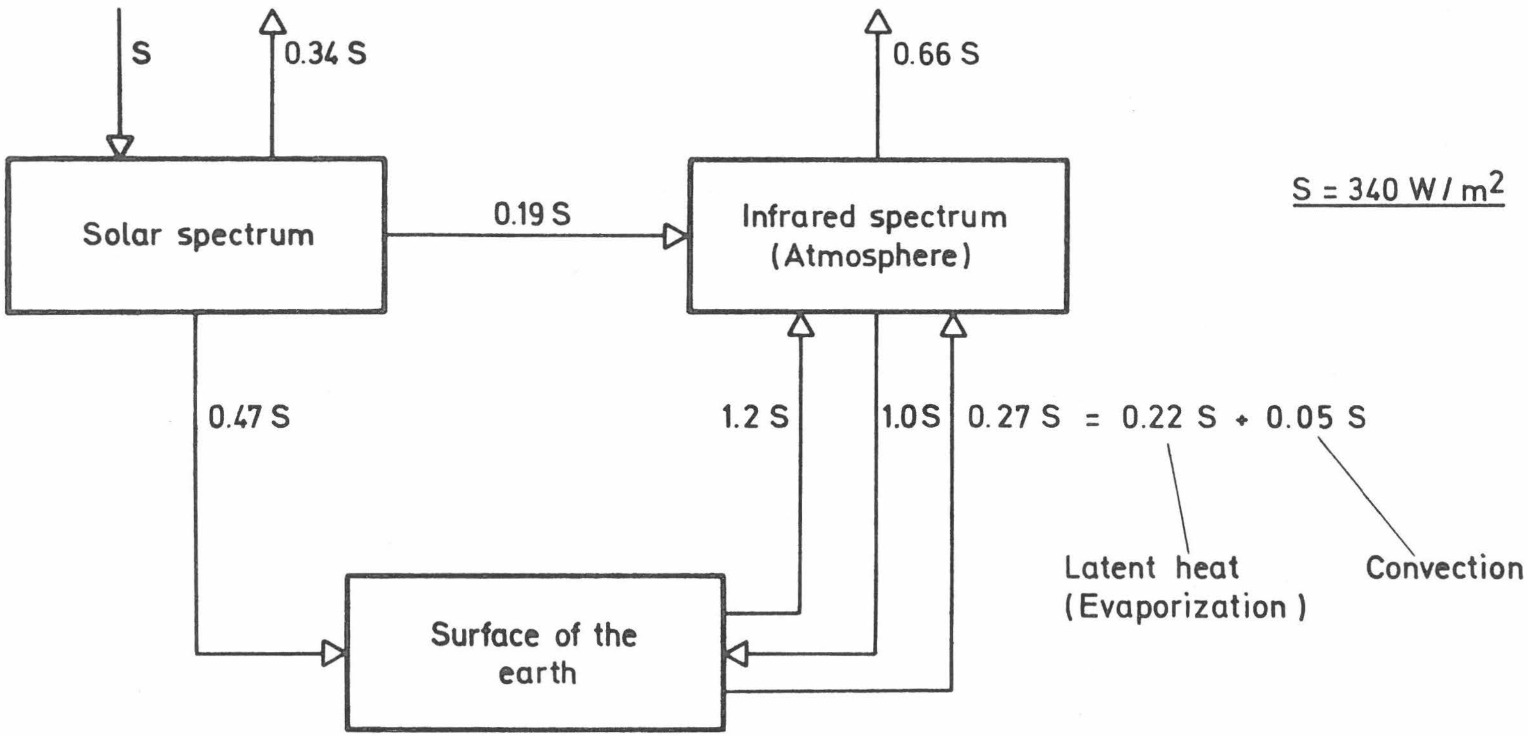


Fig. 9 Nuclear vs. Oil Fired Power Plant

(after Ch. Starr et al.)

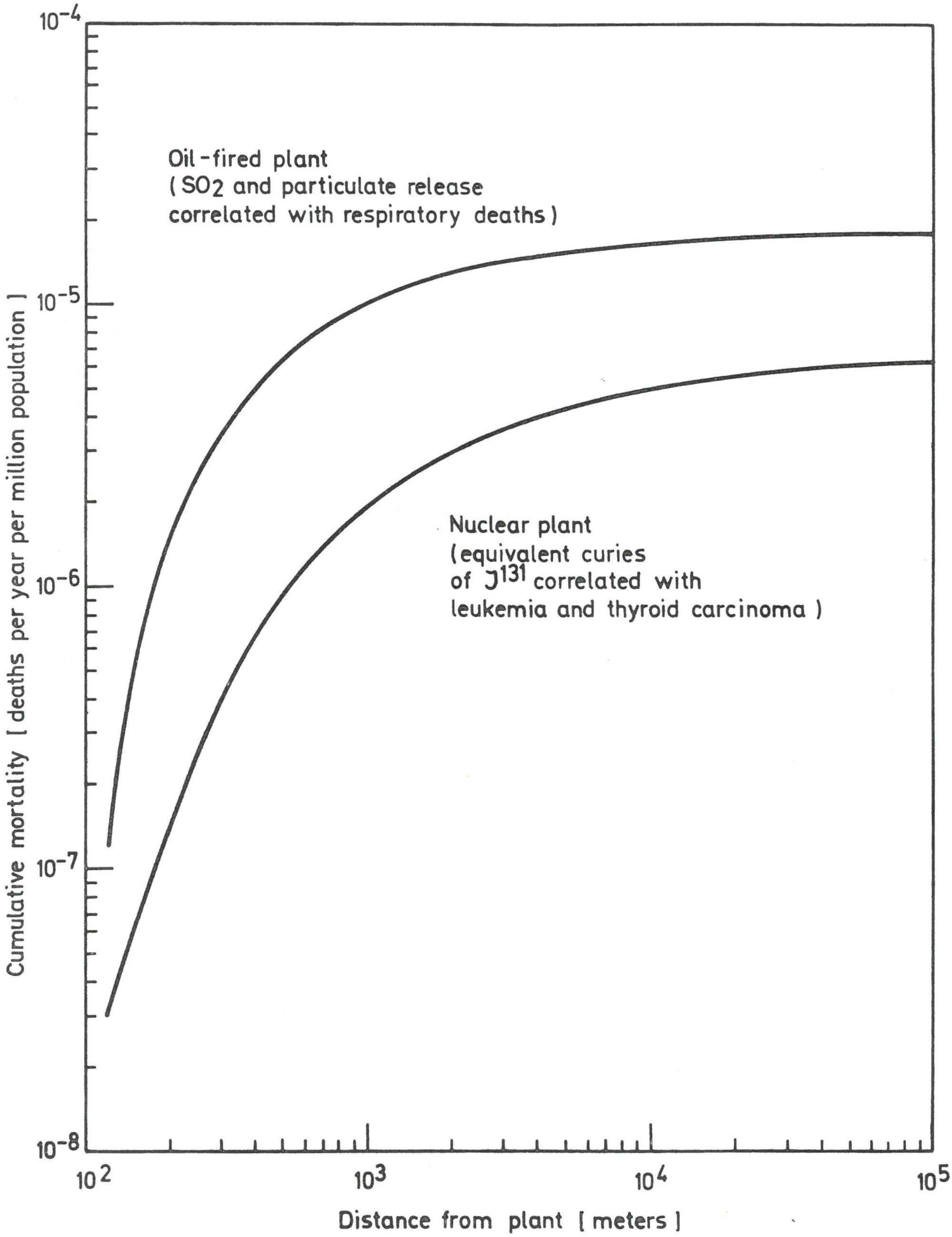
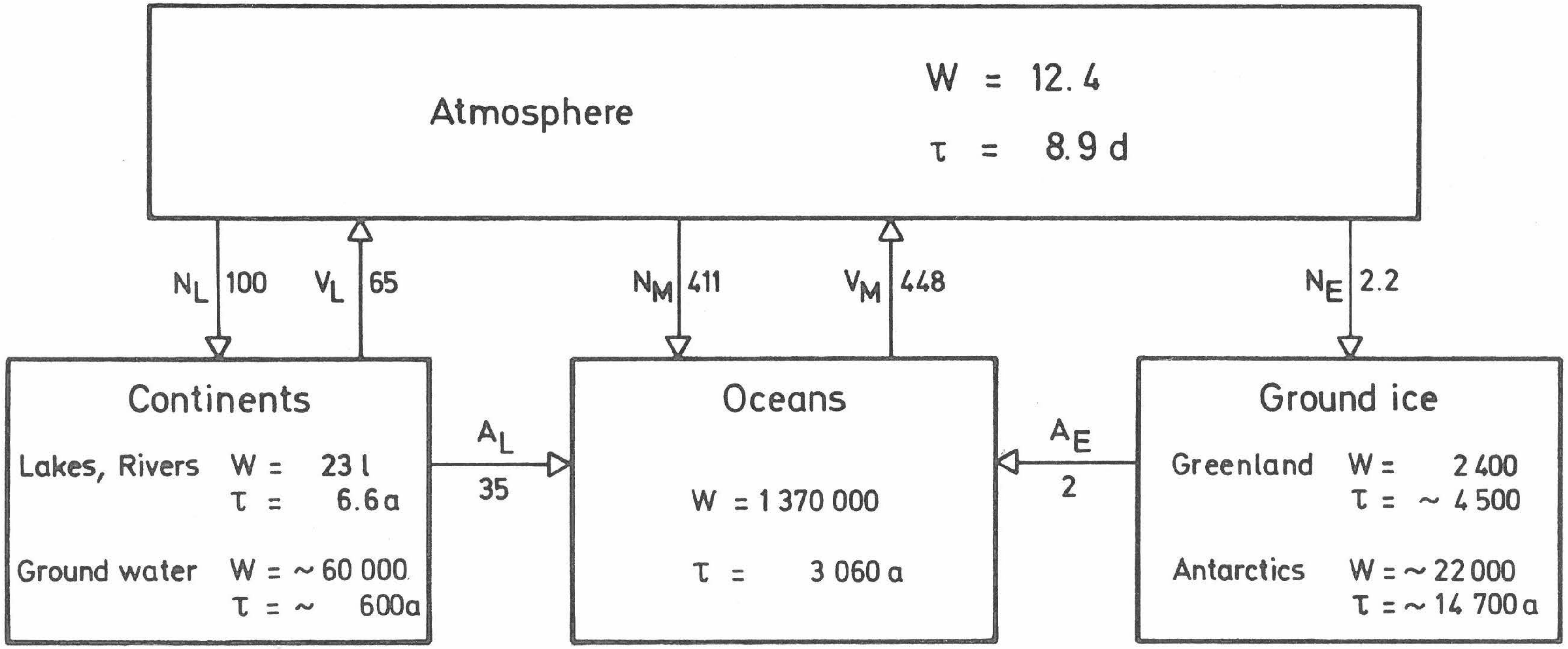


Fig. 10 Water Cycle of the Earth

(after Lvovich 1970)



Water content : W in 10^3 km^3

Transports : F in 10^3 km^3/a

Residence time : $\tau = W/F$

Earth : $V_E = N_E = 513 \times 10^3$ km^3/a
$= 101$ cm/a

Fig. 11 Interweaving between Water, Weather and Energy

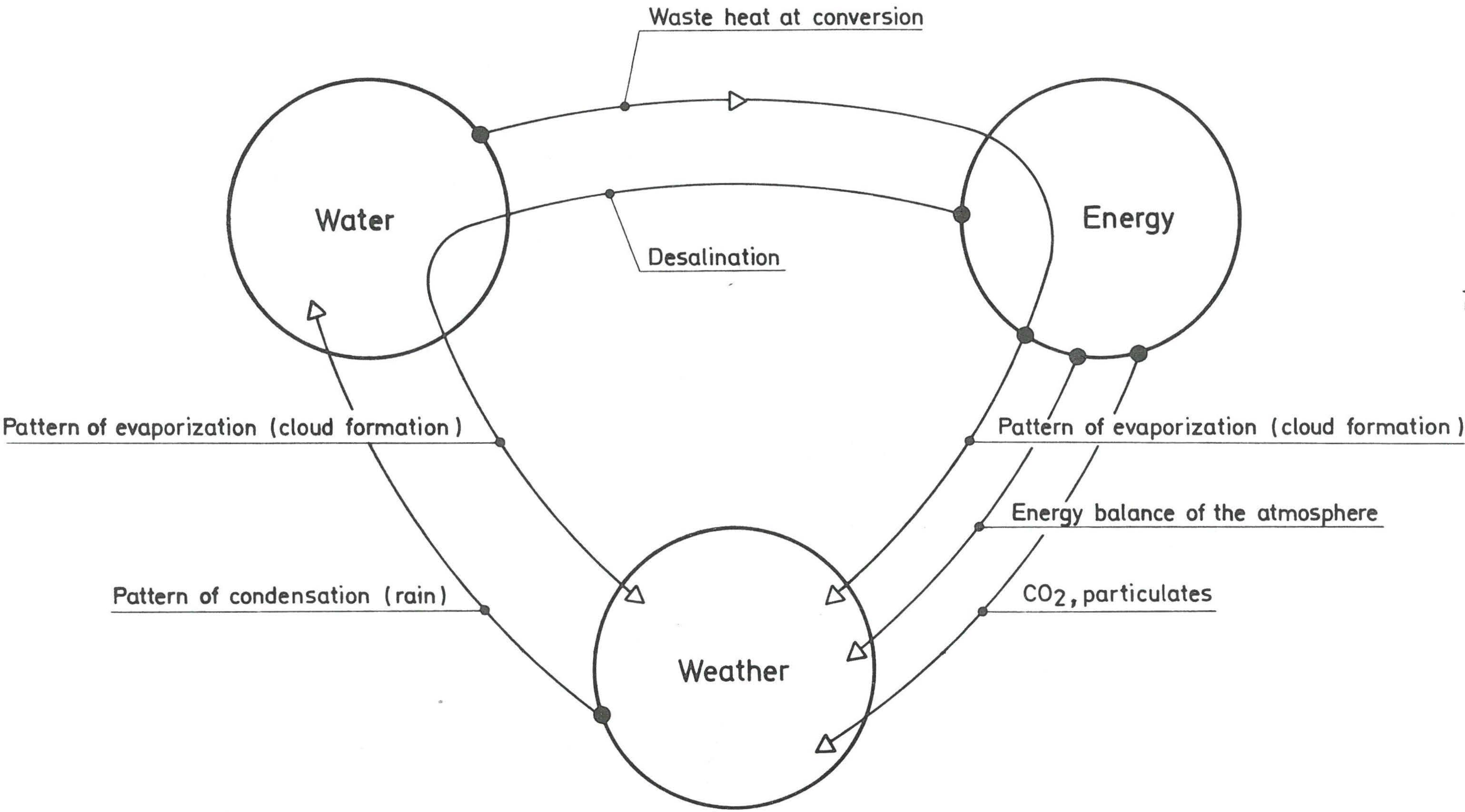
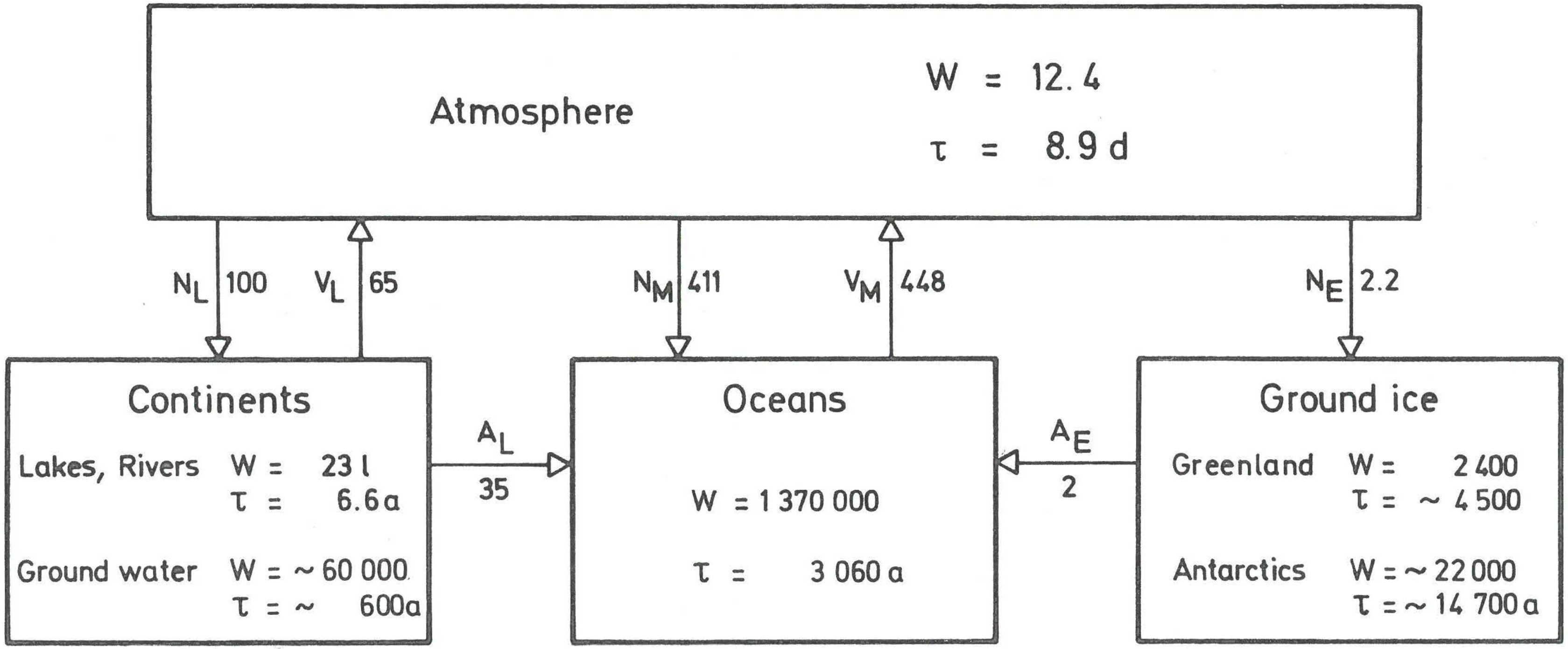


Fig. 10 Water Cycle of the Earth

(after Lvovich 1970)



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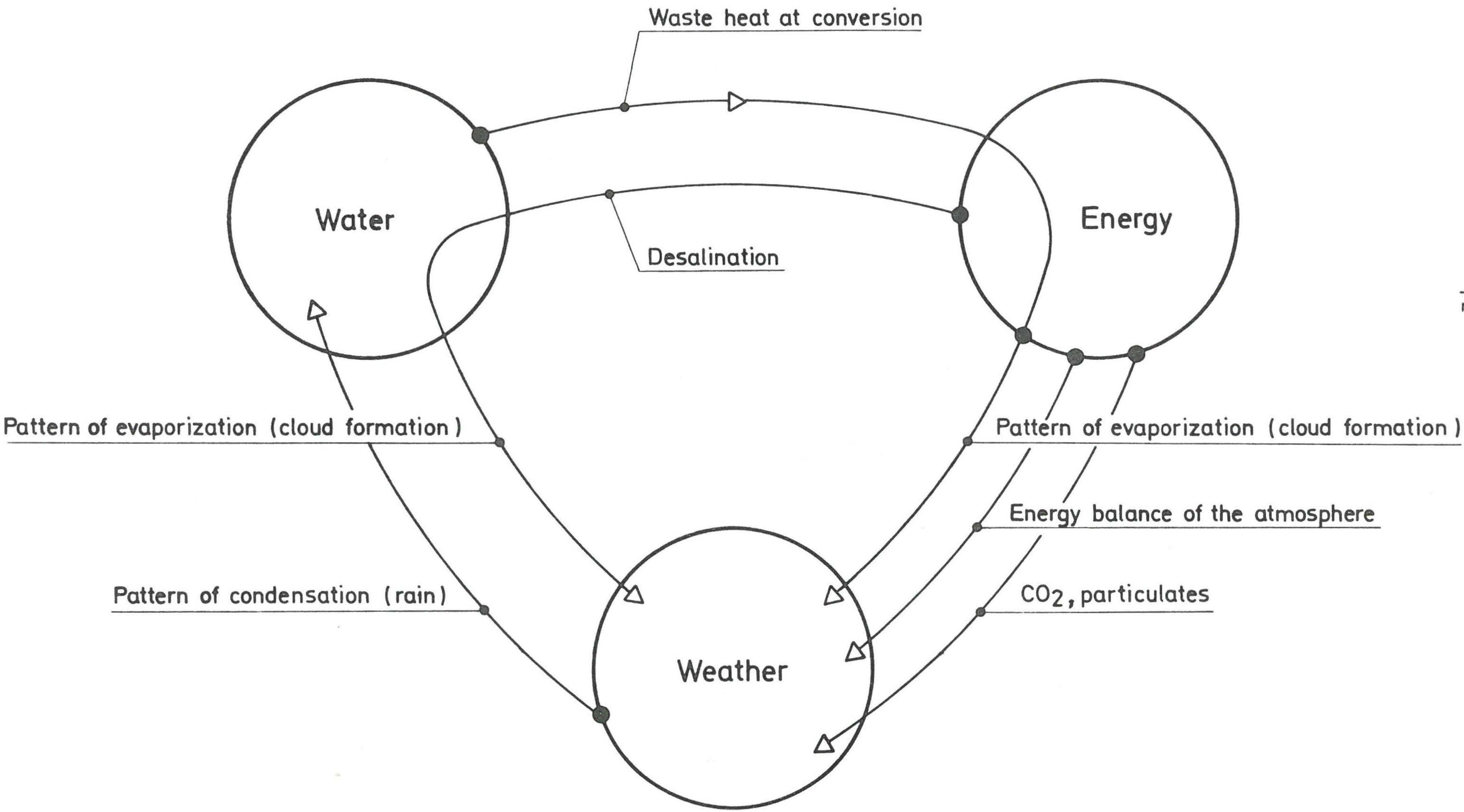


Fig. 12 Environmental Accountability

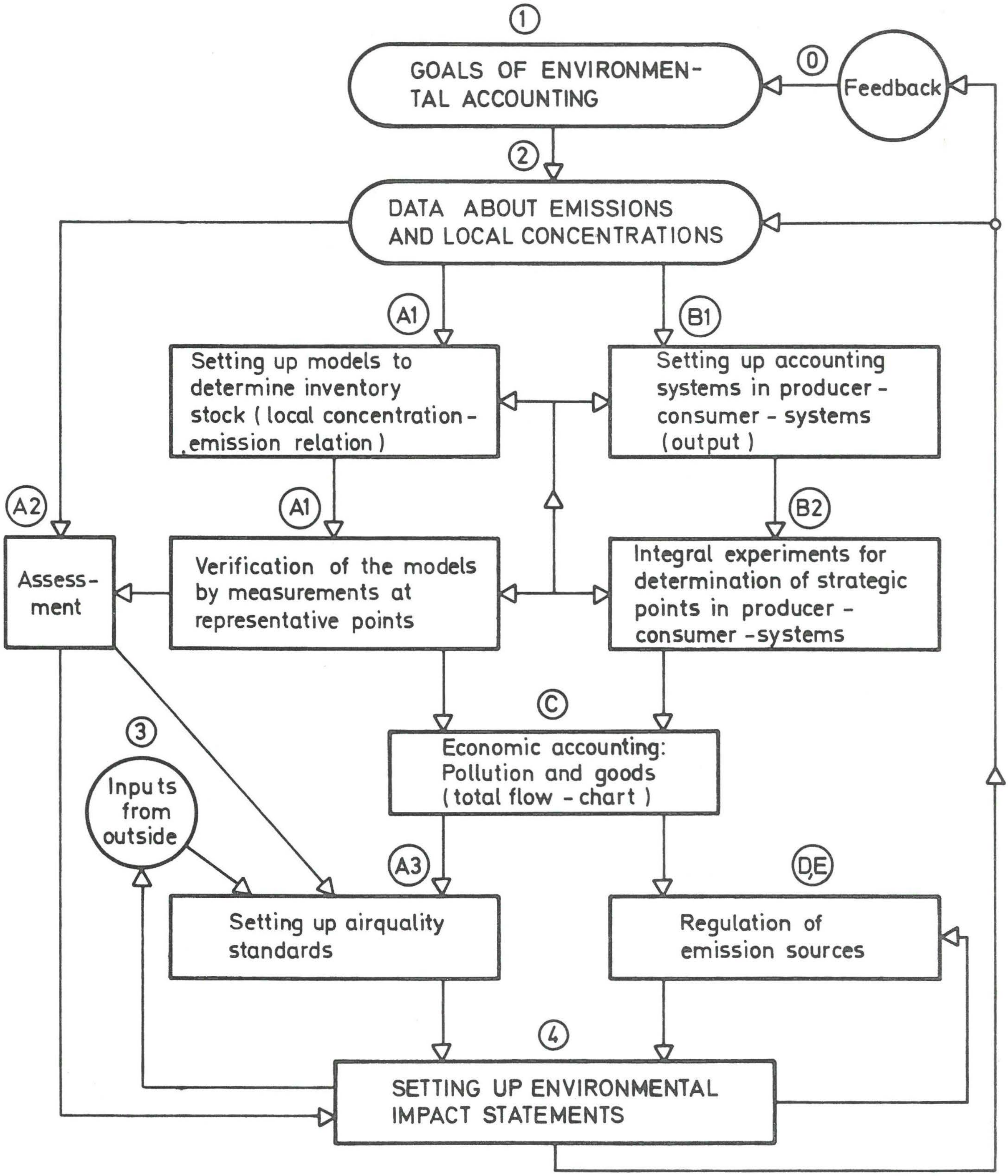
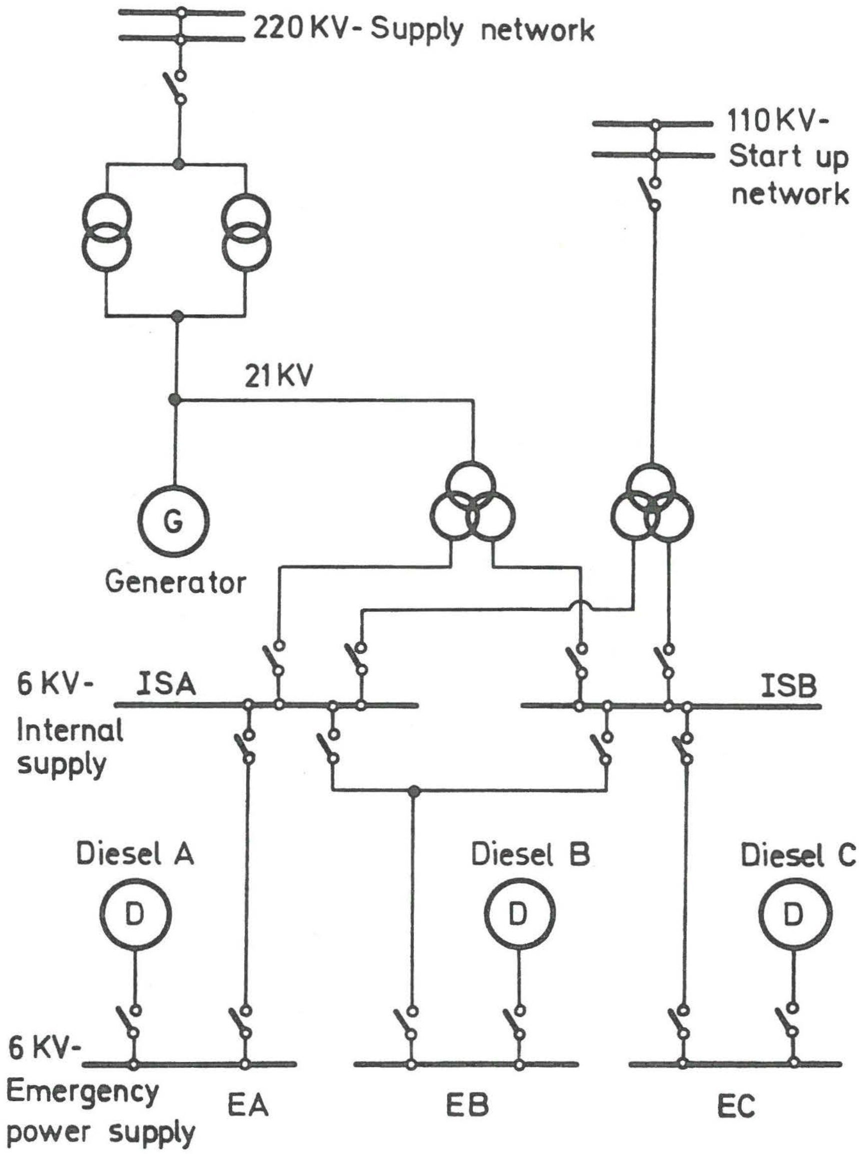


Fig. 13 Power Supply System of SNR 300



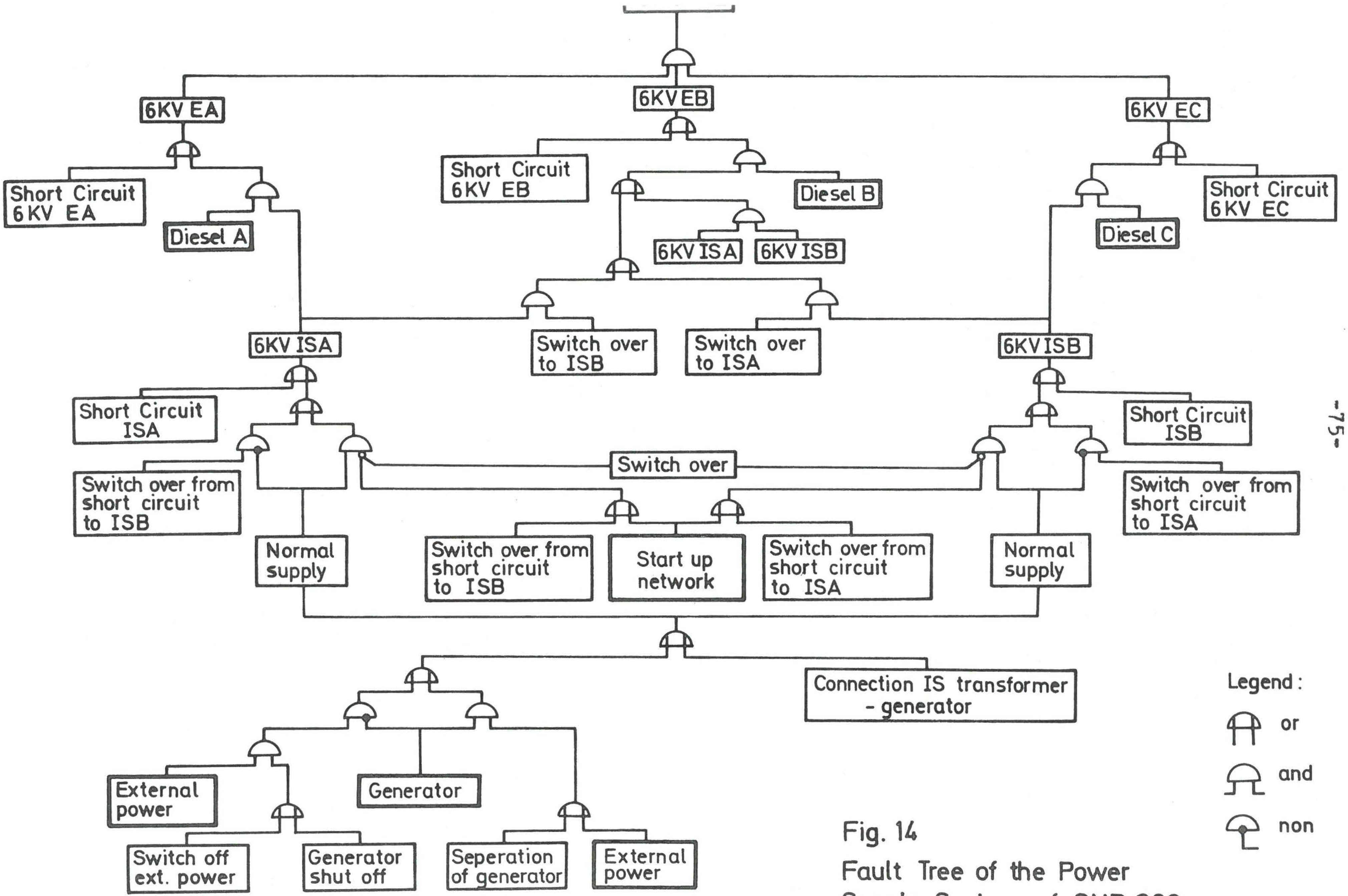


Fig. 14

Fault Tree of the Power Supply System of SNR 300

Fig. 15 Mining Accident Rates vs. Incentive

(Ch. Starr, Benefit - Cost Studies in Socio - Technical Systems, April 1971)

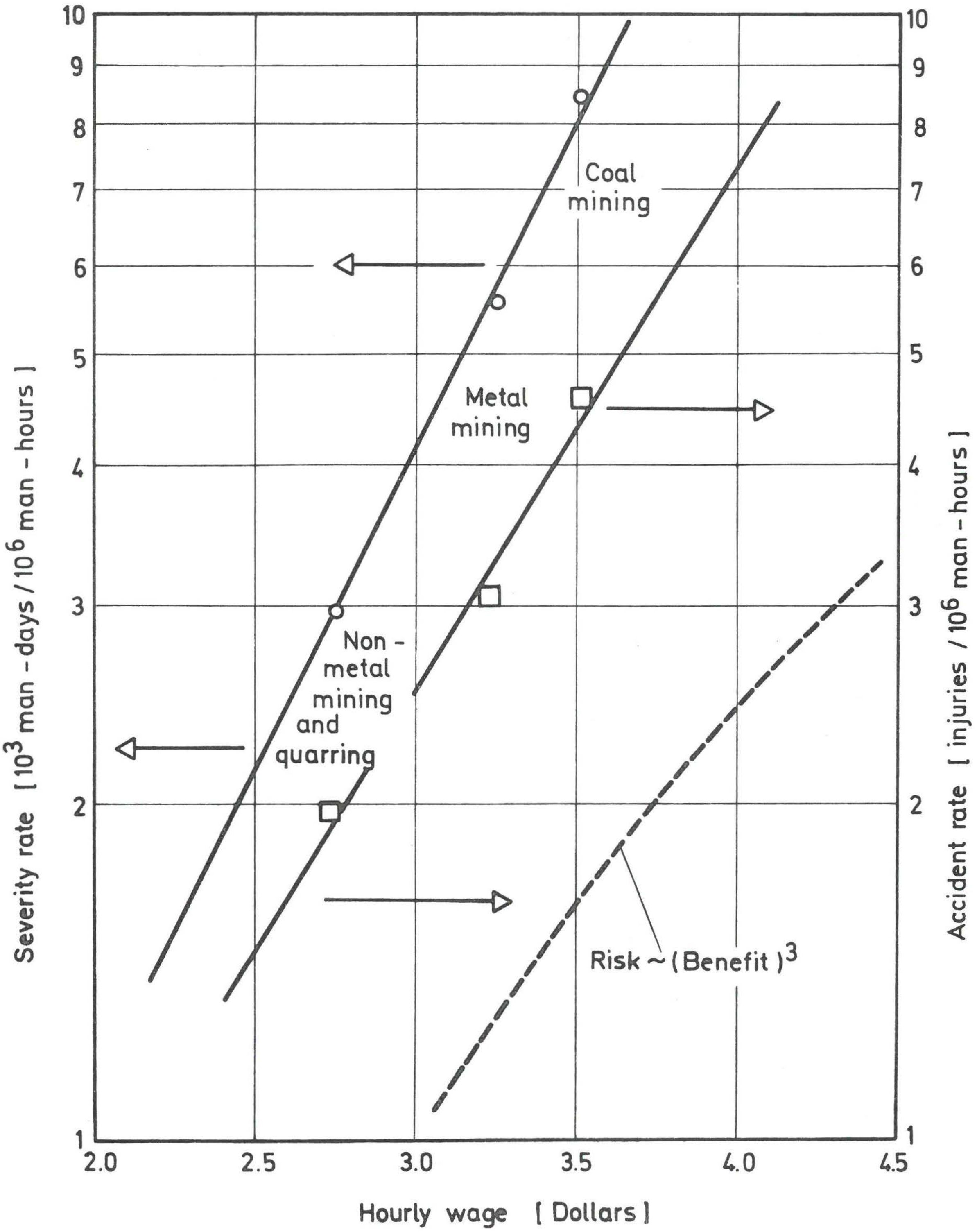


Fig. 16 Risk vs. Benefit
Voluntary and Involuntary Exposure

(Ch. Starr, Benefit-Cost Studies in Socio-Technical Systems, April 1971)

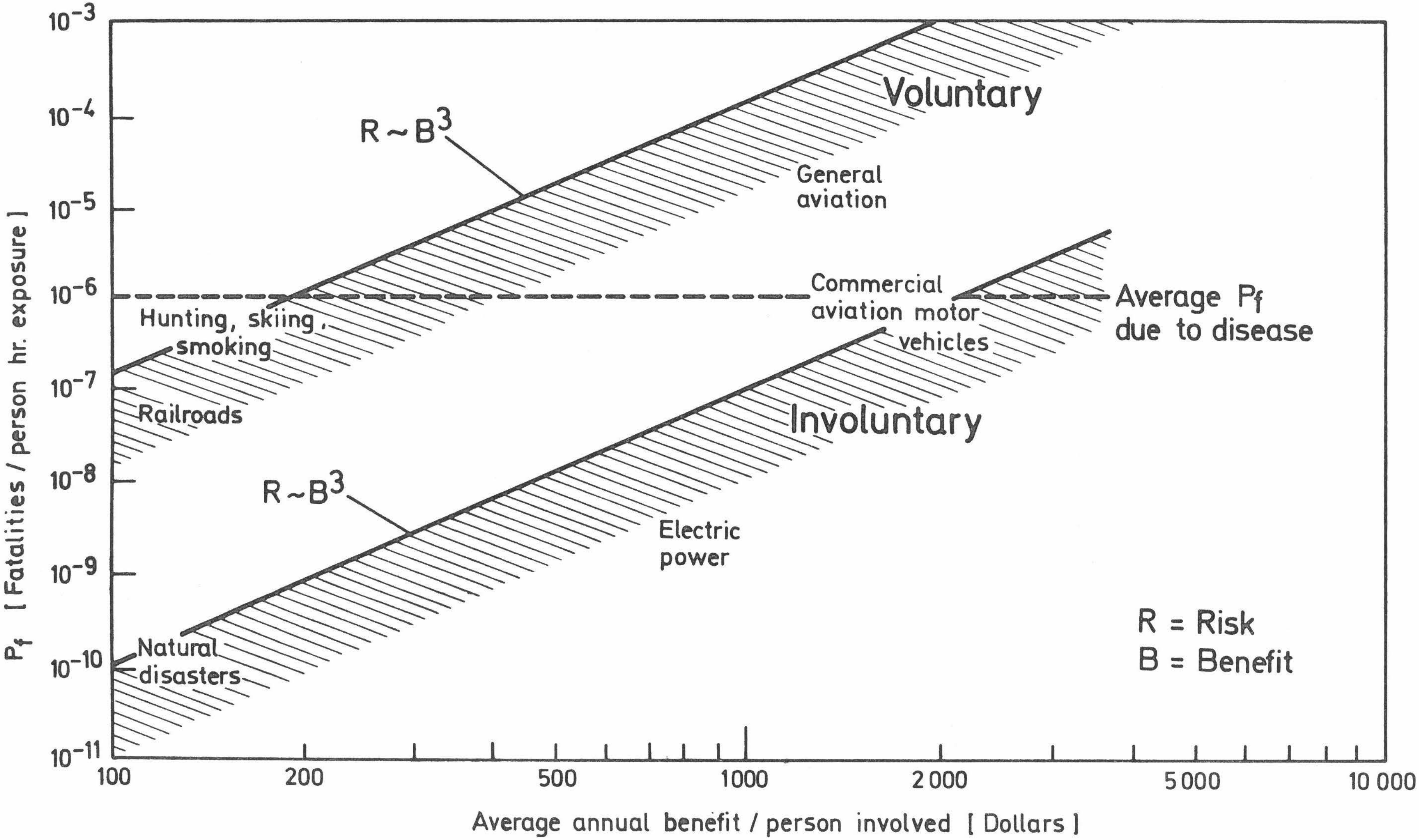
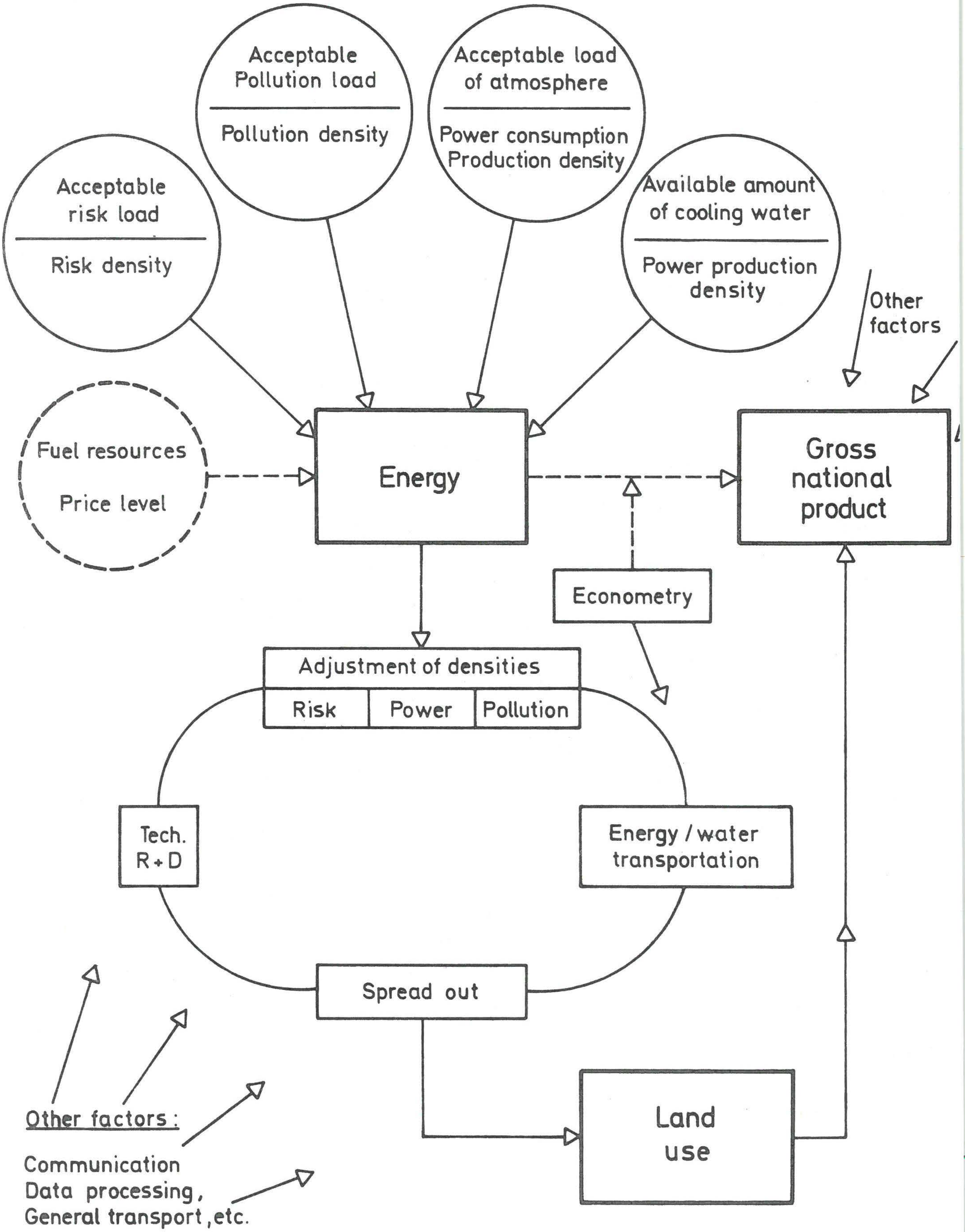


Fig. 17 Energy - Land Use - Gross National Product



Discussion

One of the participants asked for a definition of systems problems. Mr. Haefele responded that, in this context, systems problems mean those problems that arise from placing many different pieces in one large picture. Some problems are not taken into account when each piece is looked at separately.

Another delegate asked what is done with errors arising from GNP. Mr. Haefele replied that this topic would be covered in his afternoon presentation. The delegate asked whether the first slide referred to a research and development effort. Mr. Haefele replied that that was only partly true; administrative and legal elements were also involved. The delegate questioned the inclusion of coal and the HTGR in the medium range category. In the first case, we could do the necessary research and development, but probably could not modify the supply system in less than twelve years. In the second case, we could perhaps get a working machine, but it was unclear that we should move so quickly. Mr. Haefele agreed with these comments, remarking that the divisions into short, medium, and long range were not meant to advise to decision makers but only to identify the problems and their phasing. One could envision decisions not to put technologies into effect as soon as they are available. The same questioner commented on the magnitude of Q. He agreed with the desirability of having a common unit, but felt that one with higher resolution would be more useful. He also thought that the factor for increase in heat extraction when going from the LWR to the FBR was 40, rather than 130, and noted that thorium is another potential large source of energy. Finally, he cautioned against the misconception that countries near the top of the band in a graph of energy versus GNP per capita are using energy inefficiently. Rather, efficiency seems to remain constant across countries; the distribution in the band is a function of sociological and natural conditions. Mr. Haefele agreed.

Another participant then made several remarks. First, he noted that the 10^5 Q figure for the uranium content of the earth represented a cutoff price of perhaps $200 per lb. for the price of uranium. If one made a similar calculation with a figure of $5000 per lb., which would represent mining to a depth of several kilometers, one would get 6×10^{15} tons of uranium, resulting in close to 10^{10} or 10^{11} Q. Mr. Haefele responded that he was trying to be conservative in his talk. The participant next commented on the Starr computation, noting that one must be cautious in quantifying relative risks. At a recent American Medical Association meeting, some evidence was presented that SO_2 has no medical effect unless it is already mixed with particulates. One man there claimed that fossil fuel could be made medically innocuous with little effort. Finally, the speaker remarked that

Messieurs Raiffa and Haefele were making the basic assumption that the methcds of systems analysis were equal to this task. Only nine years ago these techniques would probably not have been sufficient to foresee the environmental concerns of today. He asked for comments on the fact that "we are not smart enough to see the future."

Mr. Haefele agreed with the point. Not all developments are foreseeable. Systems analysis must be a permanent and constant effort with continual readjustments. Mr. Raiffa concurred. Optimization is easy when everything is given and you are sure that nothing has been excluded, but we have seen cases where assumptions have changed, yet master plans have remained rigid. It is vital to build flexibility and feedback into analyses.

Another participant seconded this point. He mentioned that in his country there is a large and unanticipated public resistance to nuclear energy which must be taken into account. One cannot make a complete model including value systems as these cannot be quantified. Thus, one should make an objective model and use practical, applied feedback for its implementation.

One delegate had two questions. First, he asked whether the Westinghouse group's model discussed by Mr. Haefele applied to the long or to the medium term. Secondly, he repeated the earlier question on what constitutes a system. As a first step, one could accept Forrester's definition. One of the aims of IIASA would be to define "energy systems." Mr. Haefele responded that he gave the example of the Westinghouse group's work not because he necessarily believes in it but to indicate the general nature of such models. He had understood this model as referring to the near term. Secondly, he thought that economic modelling would be enlarged to include ecological objectives.

A delegate inquired how generally accepted- for example, in the U.S. - is the idea that the FBR would provide unlimited energy. Mr. Haefele said his impression is that the vision of an unlimited source is not very clear, in large part precisely because there is no feasible upper limit yet discovered for the FBR. There are a number of different guesses; perhaps one of IIASA's tasks should be to evaluate these.

Another participant returned to the role of modelling and systems analysis. He said that the purpose of systems analysis is not to say that "if we do this, then that happens," but rather to indicate what will happen if we do nothin. "No decision is also a decision." Systems analysis sketches the consequences of present policies and strategies continued into the future. Secondly, one can identify pockets of our current society already experiencing the life of the future. Identification of these pockets helps us see where problems will arise and decide how to deal with them. Such identification would be an important job for IIASA.

Yet another delegate agreed and added that IIASA should identify subsystems in the environment appropirate for discussion. For each subsystem, it should identify important variables, develop sensors to measure them, and report the results to social planners and policy makers. Economics has progressed precisely because it has done this.

It was urged that history be used as the laboratory to check systems analysis models. Someone else noted that predated forecasts usually compare poorly with what actually happens. However, we are not trying to determine the consequences of today's decisions in the sense of really expecting those consequences. Instead, we are trying to see the effect of our decisions upon our options in the future. We do not determine our future but only to change our options. Mr. Haefele added that this is especially true in a finite environment.

Another speaker brought up the question of disposal of nuclear power plants. Mr. Haefele noted that this is a very important sub-aspect of the waste disposal problem.

Mr. Raiffa commented that he had not spoken enough about the methodological research of the Institute in his opening comments. The Institute had already decided to study optimization of very large systems. The problems of multiple objectives and trade-offs and of technological forecasting seem to arise frequently and may be studied. These areas interact with the energy problem, and such interplay will be continuous in IIASA's work. He asked the conference participants to consider which methodological problems in this field IIASA might tackle.

The third questioner returned to his original query, noting that a concern for the environment has only explicitly entered energy discussions within the last ten years. He asked IIASA to examine the process by which this happened in order to learn what types of people, contacts, and frameworks encourage the identification of such problems.

The discussion continued after presentation of the second half of Mr. Haefele's paper.

The first speaker pointed out the importance of considering the distribution of risks among people rather than just the overall level of risk.

Another participant remarked that inclusion of environmental concerns in an objective function, especially if health is used as an indicator, requires medical specialists. The data has been paid to the low level effects of radiation than to those of fossil fuels. Secondly, the reliability problem intensifies as components are linked. This raises questions about the desirable level of diversity in the agricultural, ecological, and energy systems. Interdependencies present methodological problems. Mr. Raiffa replied that IIASA would have research in the bio-medical area; those scientists will interact with the energy project scholars.

Mr. Raiffa replied to the second point to say that the problem of probabilistic dependencies (e.g. common failure modes) plagues all of technological forecasting. In this case, there is an additional problem. If, after performing a fault tree analysis, people are asked to estimate the probability that an accident occurring during an absence of theirs had appeared on the tree, they tend to choose a low probability. This phenomenon seems to be a function of probabilistic maturity; insurance people are better at such exercises. Someone else presented an example to illustrate this point. Several months ago at the Millstone Point reactor in the United States, sea water accidentally entered the main circulating system and corroded most of the monitor thermocouples. The control experts said that they would not have included corrosion in a fault tree analysis. The moral is that these analyses require a wide variety of knowledgable inputs. A second example is that the 7Q figure assumes that 200 cm are required to take care of evaporation--2000 gallons per person per day for 25 gallons of fuel. Agricultural experts would say that one could do 20 times better, thus implying a much less important feedback.

One participant asked how many cubic meters of air are required per kilowatt hour (kwh) in a dry cooling tower. In other words, how many cubic meters of air would stream into a power park two kilometers in diameter. Mr. Haefele said he was not sure, but he did not think this factor would be a constraint. The questioner also asked whether the project would be regionalized because of the great differences in problems, options, time scales, and technological means from place to place. Dr. Haefele agreed with the point but was uncertain whether the separation of time and space domains should be done in the first step of the research.

After a coffee break, Mr. Letov urged exploiting the close overlaps between the IIASA projects. In particular, he suggested imaginatively using the waste heat put into water used for cooling. For example, the warm water could be used for agriculture in cold regions and seasons.

One scientist suggested using solar power for production of hydrogen via microbial photosynthesis. Mr. Haefele asked an expert in the use of hydrogen as an energy source to respond. He said that one can do the same thing without algae. Chlorophyll decomposes water with two photons; one could also use titanium dioxide for this process. The questioner also asked where the production of methane from organic gas materials by the use of solar energy fits into the time scheme. Mr. Haefele said that this was an additional subject. The schema was not meant to be complete but merely to show the scope of the problem.

One scientist asked about energy storage. Mr. Haefele responded that this is critical and is reflected in the importance placed on the hydrogen economy. It is very difficult to store electricity and much easier to store gases. The hydrogen expert added that it is easy to store hydrogen under pressure. It can be kept for a few days in aquifers as natural gas is now. Dr. Haefele added that, although the superconductivity people speak of storage of electricity, they can only store up to 1000 mega watt sec, and that this is very expensive.

Another scientist mentioned the potential climatic effects of using solar energy. Blackening the Sahara might change both climate and the heat balance of the earth. There might be regional and distributional effects as well. Mr. Haefele agreed that although solar energy seems to be clean, this is only true when it is used on a small and local scale. It is a widely distributed thin form of energy. Thus, to get significant amounts of it, a large area is required, creating changes in the heat balance and in the climate. We therefore need climatological research and systems evaluations.

One participant returned to the social question, calling the risk approach objective and interesting. He pointed out that some fears are social phenomenon which must be understood by means of social psychology. For example, some of the fear of radiation is due to the fact that it is unknown compared, for example, to SO_2. One can compare nuclear and conventional power stations, but public acceptance is a different phenomenon requiring use of social science to understand it. Mr. Haefele said that risk is multiplied by a profile of acceptance. It is unclear whether we understand the link between objective risk and subjective acceptance. It is also unclear whether the public understands 10^{-5} or can compare it to 10^{-6}. Moreover, it is questionable whether the numeric approach is the most reasonable. Someone commented that research is being done on the difference between risk as quantified and as perceived. In one case, people were compensated for their perceived, rather than real, risk, and this solved the acceptance problem. Someone else noted that one problem with the "public" is that "the public" does not exist. Instead, there are many groups of people, none of which wants a nuclear plant in its own backyard, while the rest of the public wants the energy.

One participant made two comments. First, discussions of time scale depend sensitively on the energy production assumptions made. The estimates cary widely and are often taken more seriously than they deserve to be. He feels it is more probable that we have over-estimated rather than under-estimated energy demand. Secondly, qualitative factors may cast the entire quantitative analysis in a different light. In particular, the siting of nuclear plants is proceeding as though reactors were merely replacements for boilers. The current policy of putting plants everywhere is irrational and may lead to a catastrophe. He mentioned the exceptional case of Sweden where reactors are now restricted to only four sites. The siting problem is an important task for IIASA to consider undertaking.

The next speaker made numerous comments. He agreed with Dr. Haefele that the development of nuclear energy is the main path to be followed. He also underscored the vital role of technology in energy systems and their importance in energy modelling. Thirdly, he stated that the rate of energy transfer or conversion is as important as the density of energy. For example, in the case of geo-thermal energy, it might take millions of years to restore the heat balance of the earth once it is tampered with. Photosynthesis and the diesel engine both operate on the principle of oxidation, but they proceed at very different rates. Fourthly, there are two different types of energy accessible to us. The first comes from the fact that the planet is moving; it is analogous to the electricity generated in a railway coach by a train's movement. Geo-thermal and solar energy and photosynthesis belong to this group. The second type is the limited resources analogous to the stores on an ocean liner - including fossil and nuclear fuels.

The speaker went on to note that energy problems must be studied in environmental, economic, and technological contexts. Thus, a program oriented and systematic approach is required. Second, the energy problem does have the characteristics of a systems analysis problem. It can be divided into a number of subsystems, including energy from gravity, fossil fuels, electromagnetism, and photosynthesis. Each of these should be examined from the same angles: availability, accumulation possibilities, and transportability. Third, the possibility of realizing the potential of one or another energy system or subsystem is a function of social norms, legislation, and non-technical decisions. Fourth, ecological requirements imply a need to produce and to consume clean energy. In this, thermal pollution seems especially dangerous; it is a global problem which can effect climatic changes and may require alteration in the pattern of using energy resources. Preserving the cold points on the planet is a near term problem. These ecological requirements imply that a systems analysis view of the energy problem is necessary. The speaker noted parenthetically that the amount of energy we consume as food equals half of the amount we produce in power stations. Fifth, water is an important element. We should think of all water in terms of its energy producing capacity, both directly with gravitational forces and indirectly as a medium for energy or heat transfer. Sixth, the success of technological processes affects the system. Seventh, there already exists an extensive literature on some energy systems. It is time to examine it to determine the state of our knowledge. IIASA should look at one, two, or three systems (work is particularly required on atomic and geo-thermal energy, and less on fossil fuels) to determine what we know. Finally, we know how to produce energy far better than we know how to use it. There will be a gap at the end of the century before breeder reactors are widely used. It is important to learn how to use energy most efficiently and to pride ourselves on using less.

Oil and the Energy Crisis

W. E. Barratt

I do not know who coined the term "Energy Crisis." It has had such widespread and common usage in recent months, however, to assure its continuation as a catchy phrase in discussion on almost any incident involving energy use or production that comes to public attention.

If you regard a crisis as a simple turning point, in which conditions which have prevailed for some time are undergoing significant change, then you could say that the whole world is currently in the stages of an energy crisis. A description of these changes, which are fundamental and long range in both cause and effect, and some analysis of the worldwide challenges arising from these changes, will, in fact, be the main theme in my comments to you.

If you take the view, however, that a crisis is more than just any ordinary turning point, but reflects, in a sense, a condition in which the patient will either live or die, then it would be incorrect, in my view, to use the term energy crisis to describe what is going on today. This is the case whether we are looking at the world situation, the Canadian situation, or even that in the United States. It is true that the United States is in the midst of a special short-term energy problem--one of their own making and one which has significant implications and messages for other countries. I am referring to highly publicized events in that country over the past few months, which have included gas curtailments and heating oil shortages closing schools and factories for short intervals in some cities, and more recently, some curtailments in motor gasoline shipments to service stations, serious enough to cause the periodic shutdown of hundreds of these outlets.

Of these two situations, that is, first the fundamental, long-range, worldwide transition in energy conditions, and second, the shorter range U. S. energy supply situation, I have no difficulty in selecting the first of these as the most important in terms of eventual significance. In other words, if energy crisis is an appropriate term to use at all, which I personally doubt, then it applied to the longer range challenges facing all of us, and not the highly visible, highly publicized short-term position that the U. S. has gotten itself into. Later on, I will talk in more detail about this short-term position. This is mainly because I think we all can learn from the many mistakes that the U. S. has made in managing its energy affairs in recent years.

One thing that Canada can be thankful for to the U. S. is that they, and not us, were first to stub their toe badly in not fully recognizing the importance of the underlying changes taking place in the worldwide energy scene. This is because even in retrospect it is difficult, as well as debatable, to try and pick out any starting point for this transition. For this reason, some of my first slides go back in time for twenty years or more in order to understand some of the reasons for the changes that are taking place. We will be looking first at some supply/demand data for Canada, which is typical of the pattern for "market economy" countries of the world.

Slide 1

This shows comparative data for 1952 and 1972. The amount of primary energy used, that is before production, conversion, transmission, and distribution losses is shown on the top line of the table in terms of BTU's times 10^{15}. The increase, 1972 versus 1952, is 140%, or equivalent to a compound annual average growth of 4½%. This, in turn, is representative of the kind of growth experienced in other developed countries in the world over this period. About half of this change is due to Canadian population growth which went up by around 50% over the period, the other half due to more intensive energy use per capita.

Slide 1. Changing Canadian Energy Pattern

	1952	1972
Energy Use BTU's x 10^{15}	2.4	5.8
% from Oil	38	54
Gas	3	25
Coal/Wood	50	10
Hydro (output)	9	10
Nuclear	-	1
Electricity Production BTU's x 10^{15}	.22	.77

The second feature that you will note is the dramatic shift over time in supply contribution with oil and gas shares growing at the expense of coal, even though oil and gas prices, per BTU, in major markets, were well above those for coal. This shift to higher priced energy by the consumer is shown also in the bottom line of the table, by the fact that electricity production was higher, 1972 versus 1952, by a factor of 3½.

Slide 2

This shows more historical data for Canada in total for the years 1952 and 1972. Because of the distorting effect of inflation, the dollar numbers for 1952 have been recalculated to put them in terms of 1972 currency value. The top line is an estimate based on average prices paid by final consumers in all market sectors. These cost estimates include all forms of taxes that are built into consumer prices.

Slide 2. Energy Costs Historically
(Low & Stable - '72 Dollars)

	1952	1972
Energy Costs - $ Billion	4.2	8.8
Per Million BTU's - $	1.80	1.51
% of GNP	10.5	8.5
$/Capita	293	400

You will note that when we divide these total costs into the primary supply numbers which I showed on an earlier slide, the cost per million BTU's, in 1972 dollar terms, declined from $1.80 in 1952 to $1.51 in 1972. You will note also that when we express these overall energy costs as a percent of GNP, we get 10.5% of GNP in 1952, declining to 8.5% in 1972. These features are remarkable in view of the shift over this period by energy users to higher price energy fuels. On average, individual energy fuel prices went down significantly relative to prices on other goods and services in the economy.

One of the consequences of energy price stability in the 1950's and 1960's is that there was little opportunity to test demand elasticity (that is the variation in total energy use to changes in price) for any specific use at any location over any suitable time frame. With the outlook now for rising energy prices, we have no historical experience therefore to call on that tells us what to expect to happen to market volumes in circumstances of changing prices.

One thing that we know for sure is that, in relation to value, energy has been and continues to be a tremendous bargain for Canadians. The last line of the table shown here expresses energy costs on a per capita basis. This is higher in 1972 versus 1952 simply because of the much higher per capita use; in other words, Canadians have become very adept at finding more and more ways of exploiting this wonderful energy bargain.

Let's take a closer look at this 1972 figure of $400 per capita to elaborate on this last point. This works out to $1.10 per day per person. This $1.10 a day bought everything that commercial energy did for Canada in 1972, everything that lit up for us, everything that got hot or cold for us, and everything that moved for us--that is, payments for all the energy in 1972 for our homes, cars, trains, ships and airplanes, all the factory used energy for our clothes, buildings, furniture, and other material possessions--all this, including gasoline and all other taxes, for $1.10 per day per person.

Slide 3

This is the first of a series of slides that places the energy scene in Canada within the broader context of world patterns. As you would expect, there is a very high correlation between economic well being and energy consumption. This lies in the fact that energy can be economically substituted for human effort.

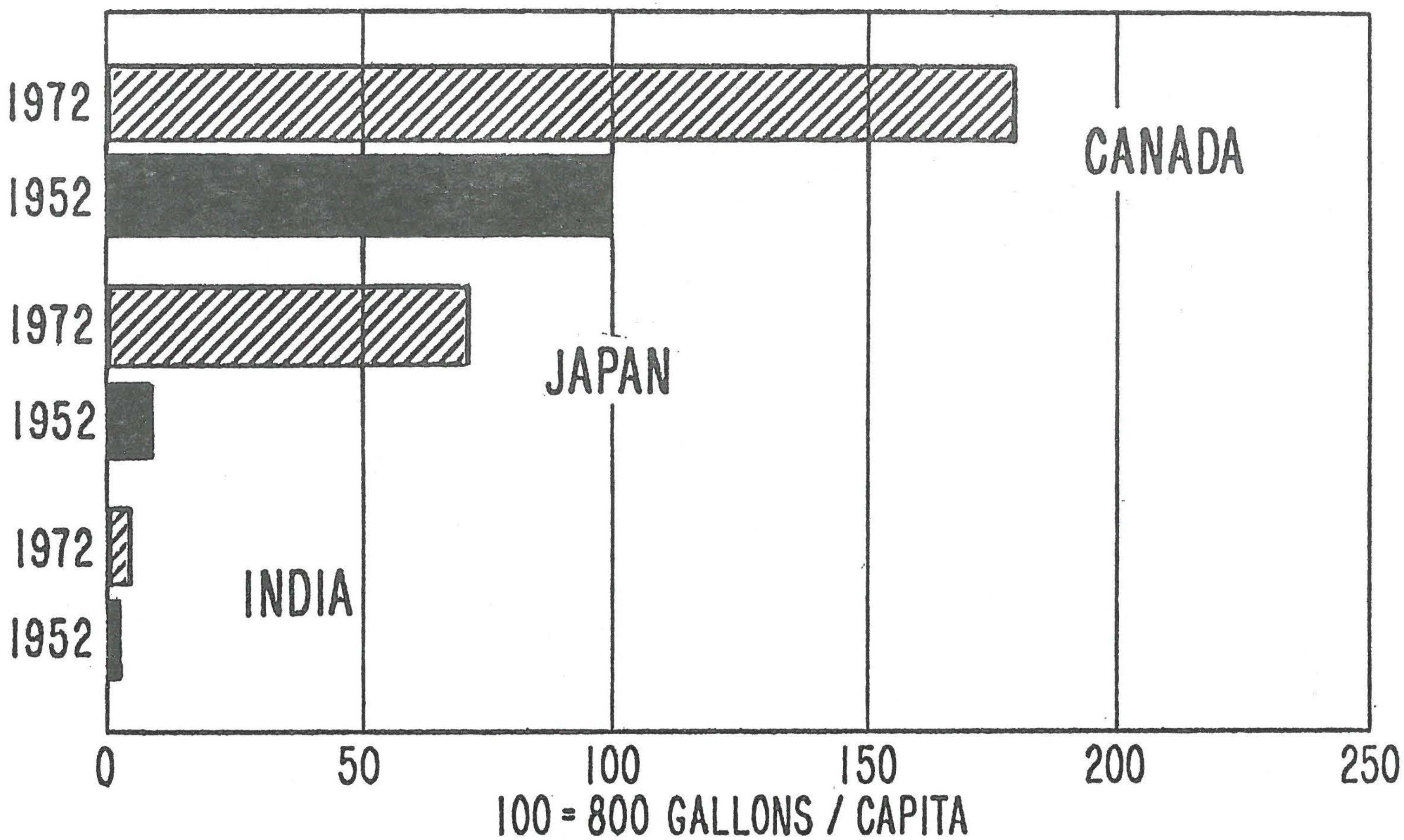
This slide compares three countries in terms of changes in per capita energy use over the past twenty years, using the Canadian 1952 experience at 100 units as an index.

Canada (typical also of the United States) even by 1952, relative to other countries, had developed skills, technologies, and attitudes that permitted sophisticated energy usage. Note, however, that even at this stage in our development, we still continued to expand per capita usage, in effect, using more intensive energy use as a springboard to maintain economic growth.

Japan is a unique case. Per capita energy use in 1952 was one-eighth of the level in Canada. But look at the remarkable change in twenty years. Here is a country that has emerged from out of nowhere to become a major economic and strategic world force. And this graph would suggest that the way in which Japan exploited the energy bargains that have

Slide 3

COMPARISONS IN PER CAPITA ENERGY USE



prevailed in the past twenty years, has provided the fundamental basis for this phenomenal economic growth.

Even in 1972 Japan's per capita consumption was below that of our own in 1952, and is about half of Canada's current level. There will be a tendency for per capita energy use in Japan to continue to expand therefore, tempered by the feature that energy costs will likely be relatively higher for Japan over the next twenty years than they were for Canada at a comparable stage of per capita energy usage.

The example of India further demonstrates the close linkage between economic well being and the ability to take advantage of energy usage opportunities. In a more general sense, nations develop beyond the subsistence level only when individual effort can be supplemented by inanimate sources of energy.

Slide 4

This is a long-range historical plot of energy use in "market economy" countries of the world. Japan makes up much of this line labelled "other," accounting for 35% of the total in 1972. Note the flatness of the curve until 1940; that cost of the total increase from 1940 to 1950 occurred in North America, that is, in the United States and Canada; that all developed regions experienced an upsurge of demand between 1950 and 1960; and that this demand growth pace was stepped up even more between 1960 and 1970. One of the basic foundations for the tremendous growth in wealth of developed countries in the postwar period has been the availability of very low cost energy coupled with the social, political, cultural, and economic capabilities to exploit this wonderful bargain.

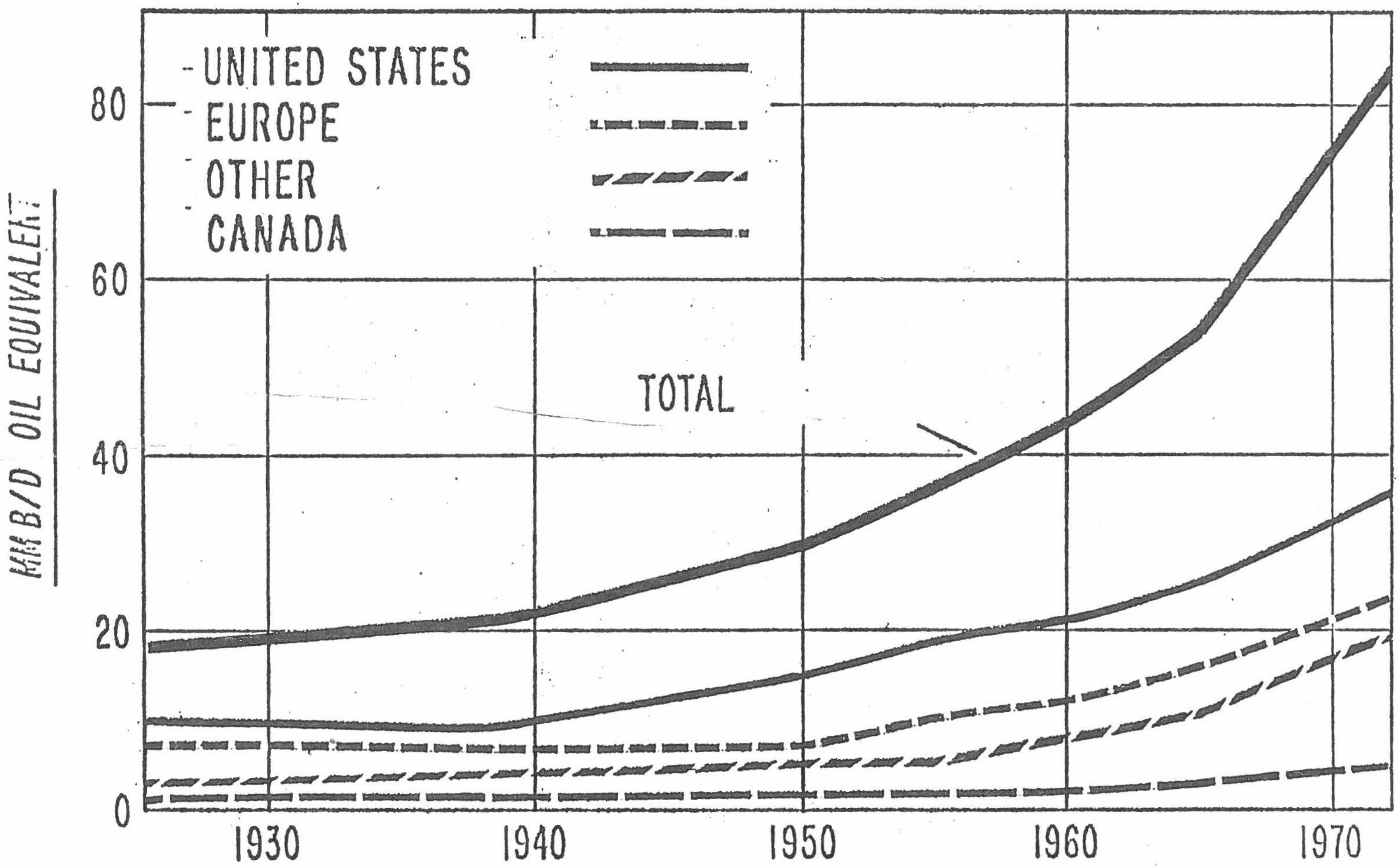
Up to now, this all sounds a bit like a fairy story. And while fairy stories may not always have a happy ending, at least, they have a predictable one. This is where the resemblance ends then between the energy scene and a fairy story, as we will see in the next few slides.

Slide 5

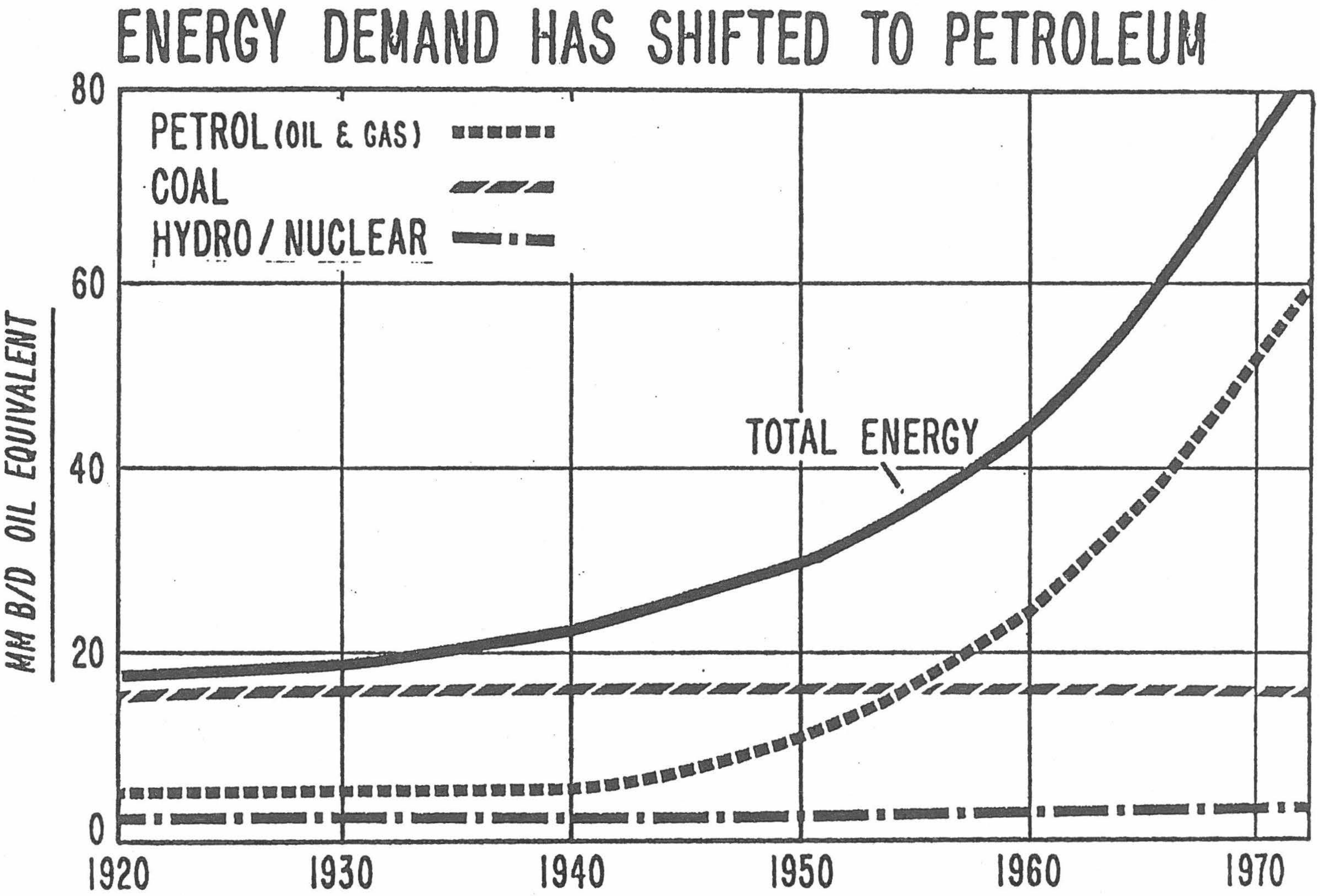
Here we show the same historical portrayal of total energy usage (in black) in "market economy" countries as was shown in the previous slide. In this slide, however, we have plotted the contributions to energy usage by primary source.

Slide 4

ENERGY DEMAND



Slide 5



ENERGY DEMAND HAS SHIFTED TO PETROLEUM
PETROL (OIL & GAS)
COAL
HYDRO / NUCLEAR
TOTAL ENERGY
MM B/D OIL EQUIVALENT
80
60
40
20
0
1920
1930
1940
1950
1960
1970

The outstanding feature that this slide demonstrates is that most of the growth in world energy over the past 30 years has been supplied by oil and gas production from conventional reservoir deposits, with the rate of growth accelerating in recent years. The oil and gas contribution is combined in the dotted line on this slide. This recent burgeoning in oil and gas production is a function both of inherent desirable qualities in the market place (cheapness, convenience, cleanliness, etc.) and of restraints placed on the contribution from other energy alternatives: with hydro limited by economic site availability; coal primarily by more strict sulfur emission standards; and nuclear power by a combination of public concern over plant design, location, and operational and technical problems in plant fabrication and construction.

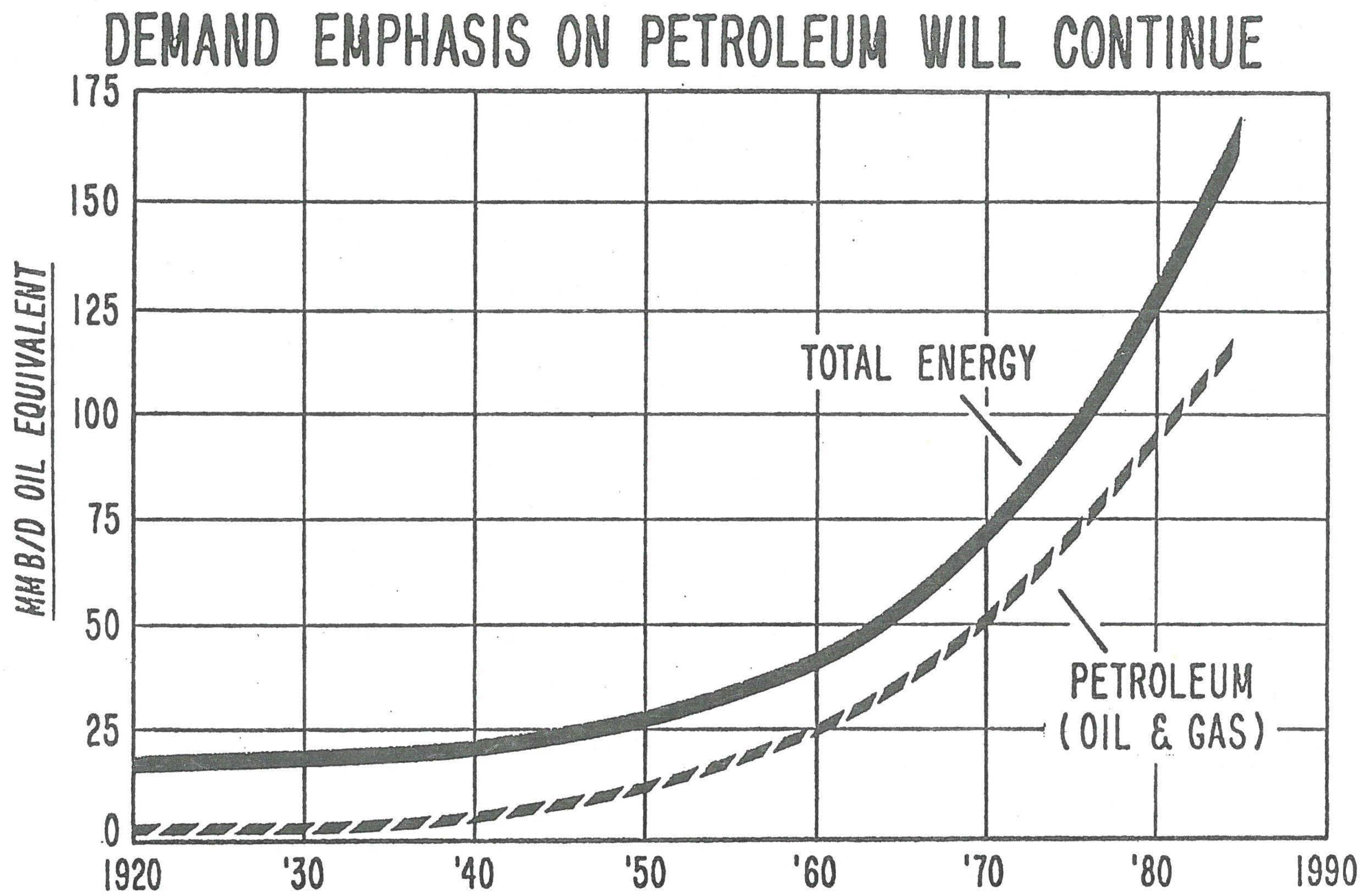
Keep in mind also that within this total for oil and gas, the share contribution from natural gas has been recently declining, because of the topping out in gas production in the U. S., which is the largest producing country for that commodity. Over the ten-year period from 1962 to 1972, world production of oil (from market economy countries) by itself grew at an annual compound growth rate of 8%. In other words, oil consumption in 1972 was more than double what it had been just nine years earlier. Even to an old-timer like myself in the oil business, this is an amazing phenomenon--to have demand for something as vital as oil doubling in size in this recent nine-year period. The absolute volume dimensions are enormous. The total oil production rate in 1972, 45 MM barrels per day, equates to an annual consumption of over 16 billion barrels. This annual amount is greater than all discoveries to date in Canada of conventional reservoir crude oil.

Slide 6

This slide shows an extension into the future assuming total energy demand continues to expand at recent growth rates and that world oil and gas production continue to pick up most of the burden for satisfying this growth. At the pace implied in this projection, oil production by itself will double again from the 1972 figure in another eight to nine years, in the "market economy" regions of the world.

But will energy demand continue to grow at recent rates? Keep in mind that tremendous bargain prices have prevailed for energy during the 1950's and 1960's. But most energy prices since 1970 have been rising much more rapidly than in earlier years. In addition, there is much greater public awareness of the changing energy supply/demand outlook and much more concern in terms of efficient energy usage. So, any projection for total energy demand is subject to some new

Slide 6


DEMAND EMPHASIS ON PETROLEUM WILL CONTINUE
MM B/D OIL EQUIVALENT
175
150
125
100
75
50
25
0
1920
'30
'40
'50
'60
'70
'80
1990
TOTAL ENERGY
PETROLEUM
(OIL & GAS)

variables that we forecasters have not had to contend with in the past. Another key feature to keep in mind is that oil and gas from conventional reservoir deposits just cannot keep expanding indefinitely to meet added energy growth. The next four slides deal with this feature with respect to oil.

Slide 7

This slide shows the dominance by a handful of countries of the remaining proven reserves of conventional reservoir crude oil. Almost two-thirds of "market economy" reserves are in Middle East countries, bordering the Persian Gulf, about one-quarter in Saudi Arabia alone. Another one-fifth is in Africa.

Slide 8

Here we have plotted the crude oil production rate for three of the major producing regions from the period beginning with 1965. Despite apprehensions expressed earlier about forecast variability, the plotting has been extended out to 1975 since we are pretty well buffered from the influence of any significant changes to supply or demand patterns in this short time frame.

The burden of filling the growing demand for oil will continue to be borne, in large part, by Middle East countries. Note that their combined production approximately matched the U. S. in 1965 and is now growing at a rate that almost equals a "new Venezuela" every year. This is truly a phenomenal response to the world's need for oil.

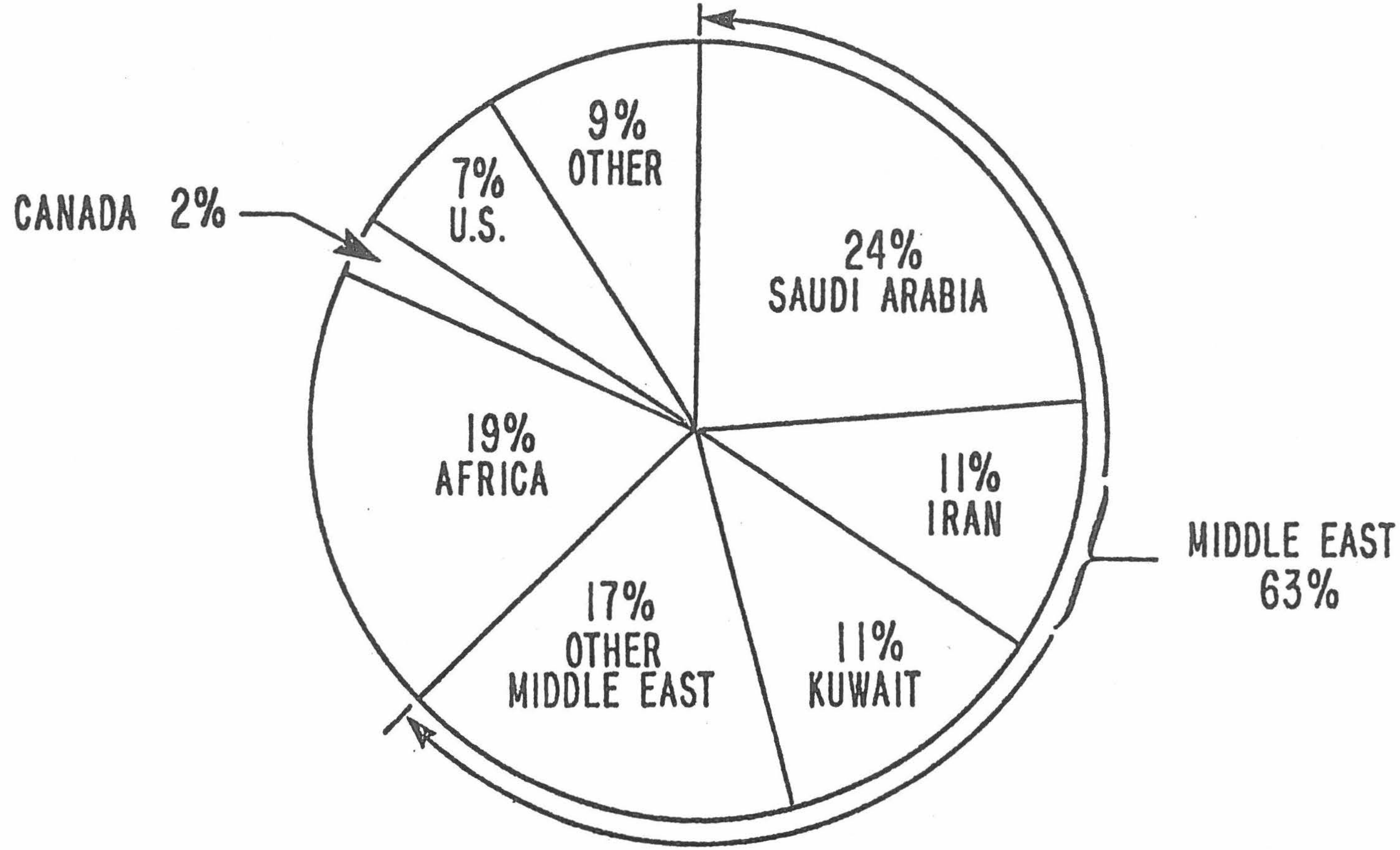
Slide 9

This slide shows what has been happening generally to world oil prices by plotting the F.O.B. price of a representative Persian Gulf crude oil up until January--i.e., more recent changes have been made, but are not included in the plot. The important features of this graph are that prices have been rising sharply since 1970, and are continuing to rise, but are still well below those prices necessary to make it attractive, on a large scale, to invest in oil substitutes.

Let me draw your attention to another feature of the oil marketing scene that is behind the numbers from which this graph was developed. In the Persian Gulf and in other overseas countries, oil is produced as a result of arrangements

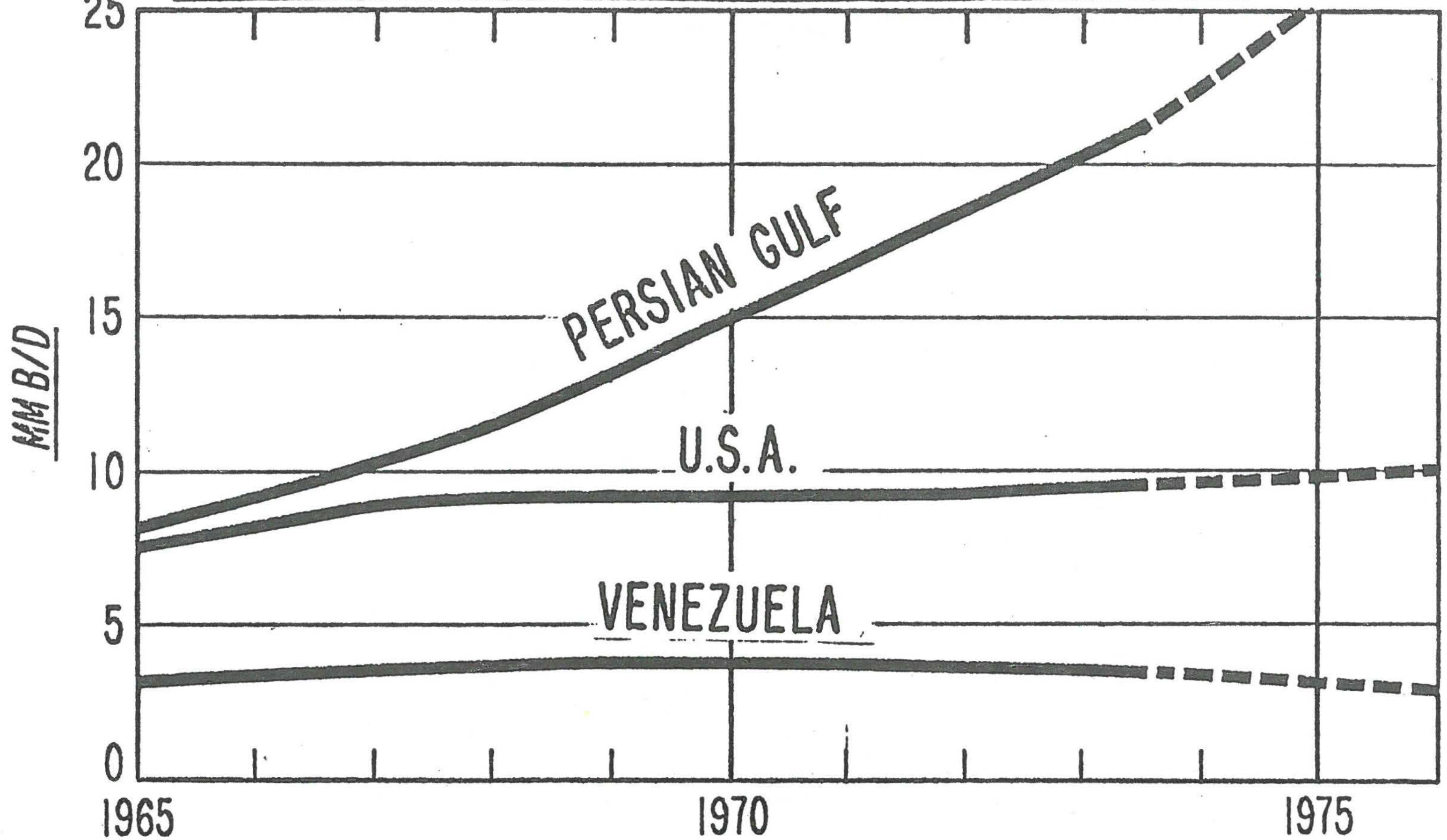
Slide 7

PROVEN OIL RESERVES ARE DOMINATED BY A FEW COUNTRIES

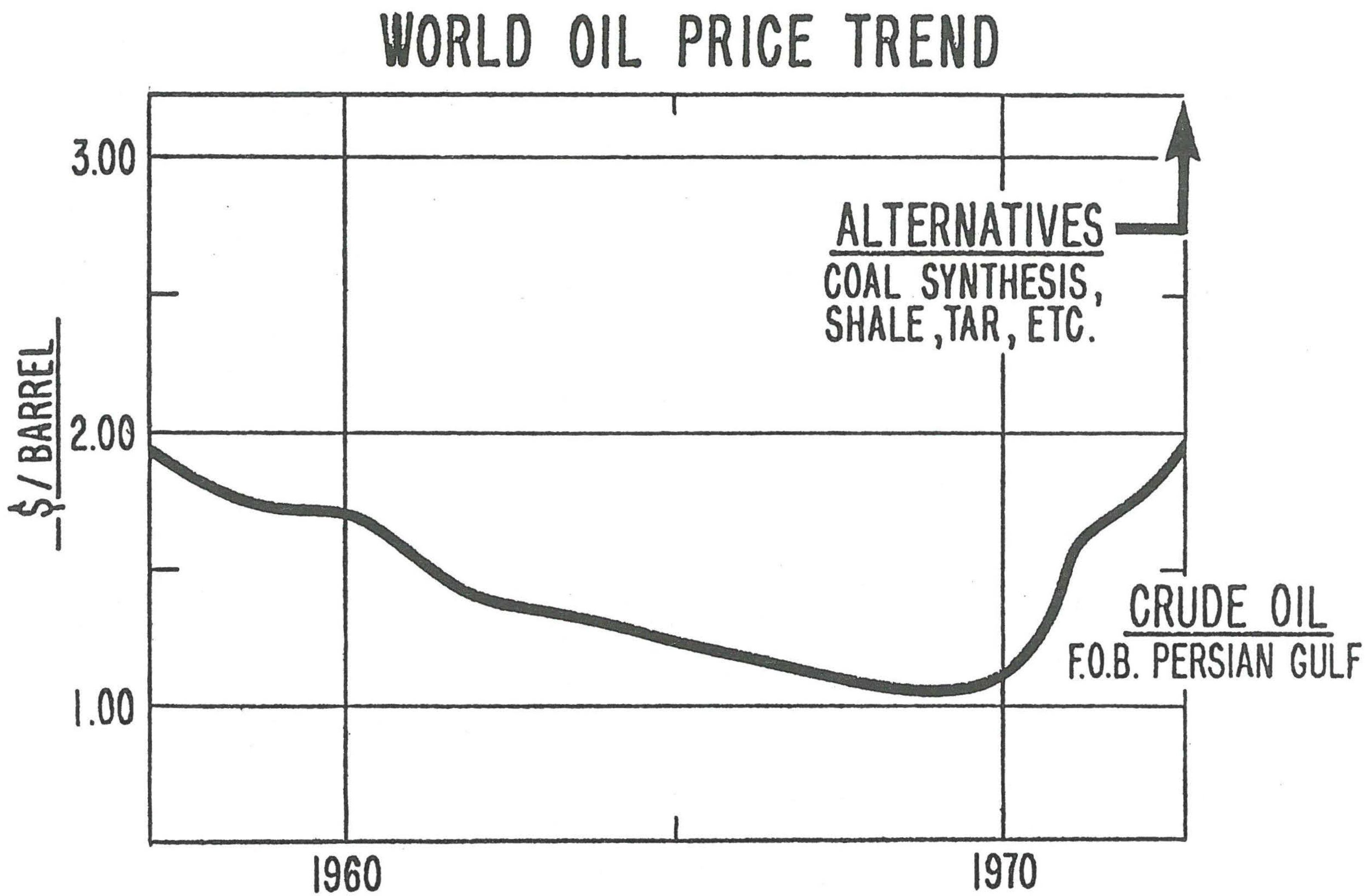


Slide 8

RAPID EXPANSION IN PERSIAN GULF PRODUCTION TO KEEP PACE WITH WORLDWIDE DEMAND GROWTH



Slide 9


WORLD OIL PRICE TREND
$/BARREL
3.00
2.00
1.00
1960
1970
ALTERNATIVES
COAL SYNTHESIS,
SHALE, TAR, ETC.
CRUDE OIL
F.O.B. PERSIAN GULF

on concessions negotiated between private companies, mainly major international oil companies, and the government leaders of each country. Since 1960 when it was first formed, the Organization of Petroleum Exporting Countries, or OPEC for short, has attracted most of the overseas country governments into its organization. OPEC has proven to be an effective coordination, communication, research, and, most important, common front mechanism for actions by individual producing country governments in their negotiations with concession holders. Over the ten-year period from 1960 to 1970, the unit selling price for oil by the producing companies declined significantly, as shown in the slide here. However, average government take per barrel actually increased. For Middle East countries, their average increase was eight cents per barrel, which represented a 10% improvement.

If individual countries could pack this kind of wallop in negotiating better concession terms during a period of declining world prices, it is no wonder that they have been so effective in these same kinds of negotiations in recent years, as the burden for meeting growing world energy needs has fallen for the most part on oil reserves underlying these concessions. Not only has most of the increase shown here since 1970 in F.O.B. price gone to the producing countries; many of these countries have negotiated substantial direct ownership participating in the oil reserves within their boundaries.

Slide 10

This is a listing of major challenges, worldwide in nature, arising from the transition period, in energy matters, which we are going through, and which I have tried to portray to you in previous slides.

Slide 10. Challenges in Meeting Growing Energy Requirements (Worldwide in Nature)

1. Appropriate priority on energy supply continuity
2. Better understanding of energy use/cost characteristics
3. Accept inevitability of higher energy costs
4. Avoid inhibitions to development of higher cost sources
5. Develop substitutes to conventional reservoir petroleum
6. Find necessary mechanisms for orderly development
7. Capitalize on opportunities as changes occur

The first item on our list of challenges is to place appropriate priority on energy supply continuity. This is because of the essential link between energy usage and economic well being and all the options that are opened up as wealth increases. In my opinion, failure in the U. S. to place an appropriate priority on energy supply continuity, reflected in the attitude that they could continue to enjoy an infinite fingertip supply of dirt-cheap energy, is directly behind the short-term energy mess in which that country is now involved.

The second challenge is another way of saying that we have to stop taking energy for granted and must learn more about how and why it is used. I am not talking here just about feel conservation departments that many companies have formed already in order to help combat higher costs. I am talking about the advantage of having all users better informed on how to use energy more efficiently. As prices rise, there are things we will all be able to do to conserve energy, that will make economic sense, without involving governments in onerous control or allocation decisions.

The next item on the list is directed to those who are not aware of the transition zone we are in with respect to energy and who may be mixing up recent price increases for energy with price increases on almost all other commodities. The key factors that will set energy prices in the future are not inflationary cost pressures, although the latter pressures will also have to accommodated. In the short-term future, that is over the next two to five years, the major factor in oil price setting will be whether the strength of the governments of oil producing countries can be maintained in negotiations on government take on oil production. In the longer term, energy prices will tend to be set by the cost of marginal supplies of alternative energy forms. In this respect, there are all kinds of energy supply substitutes to conventionally produced oil and gas with the caveats that they are more expensive, long lead times are required, and, in some cases, acceptable technology has not been developed.

The fourth and fifth items on the list relate to the positive side of energy price increases, that is that higher prices do call forth new supplies. I have already stressed the importance that I think we should place on energy supply continuity. Also, we would recognize that there is a limit to our very low cost energy resources. For that reason, it is prudent not to let the fear of higher prices stand in the way of extending our resource base in higher cost regions, such as the Arctic, or for higher cost energy sources such as those derived from our coal and oil sand deposits.

The development of substitutes to conventional reservoir petroleum, point five on the list, is of critical importance for two reasons. First of all, even the vast oil and gas reservoirs in OPEC countries will someday be physically incapable of matching ever-growing demands. Secondly, the demonstration to OPEC countries that oil buyers are rapidly developing legitimate alternatives to oil produced in their regions is the best protection, in fact, may be the only protection, against escalating prices for this oil, as well as the best insurance for oil supply continuity.

The sixth point on the list is perhaps the most difficult of the challenges facing many countries in the world--that is, to find the necessary mechanisms between the different institutions involved, i.e., government, the private sector, etc., in bringing about an orderly development of new patterns in both energy supply and demand.

The seventh point is particularly appropriate to countries like Canada, who, as a result of extensive fossil fuel occurrences, are in a position to capitalize on energy opportunities arising as a result of changing world circumstances.

Slide 11

As promised at the outset of my presentation, or perhaps threatened would be a better word, I have some comments to offer on the current U. S. energy scene. This is because of the public attention that this situation is attracting and the natural tendency for people to attach the handy catch phrase "energy crisis" to popularized current issues. As I have stressed earlier, the significant energy challenges facing us and the rest of the world need to be cast in the longer-range context.

This is why I have titled this slide "Special U. S. Short-Term Problem" and the material shown here is the first of a three-part analysis of that problem, which will be covered in this and the next two slides. The first part, covered here, lists four background factors contributing to the current U. S. situation.

The first point on this slide relates to natural gas pricing. Natural gas, in many ways, is the key to the U. S. energy problem. This is because it is so easy to convert to gas for almost all energy uses, except transportation. Its rapid market growth in the U. S. over the past twenty years has been stimulated by artificially low prices, controlled by the Federal Power Commission on behalf of Congress. Between 1955 and 1970, the share of the U. S. energy market

Slide 11. Special U. S. Short-term Problem

These factors

1. Gas price controls
2. Overly ambitious environmental protection program
3. Uncertainties on - oil import policies
   - trade policy changes
   - price freedom for energy suppliers
4. Production shortfalls by nuclear plants

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going to gas went from 23% to 33%, largely a result of prices lower than those for competing fuels. This occurred at a time when energy prices around the world were at the kind of bargain levels which I described earlier.

A by-product of the low regulated prices for gas in the U. S. was to discourage exploration for new reserves. By early 1972, gas production had peaked in the United States with two concurrent consequences--first, a denial to some traditional buyers of the gas they wanted, and secondly, a scramble for substitutes such as imported liquefied gas at several times the wellhead price of flowing gas.

The second factor on the list refers to various U. S. actions in environmental protection programs. The key words here are "overly ambitious." No one would deny the need for more precise and stringent standards than those in effect ten years ago for clean air, water, and land, related both to new plant design and siting, and to existing manufacturing plant operations. There has just not been an appropriate balance between the introduction of these standards in recent years in the U. S. and to other important goals of that country such as energy supply continuity and orderly pricing. Here are just a few examples of how energy supply/demand balances have been adversely affected. One effect has been to impede the use of coal to help meet energy growth; another to frustrate location decisions with respect to nuclear and fossil fuel power plants and petroleum refining capacity; another to severely limit the use of high sulfur fuel oils; and still another to reduce gasoline engine efficiencies. With respect to this last mentioned feature, those of you fortunate enough to own a standard-sized 1973 North American produced automobile will experience an 11 to 24% increase in gasoline consumption per mile, according to a recent DuPont estimate, compared with pre-emission control cars. This penalty is predicted to double if controls meeting the 1976 standards mandated by the Clean Air Act are used.

The third item on this list of factors refers to the negative effect on investor confidence of government policy uncertainties, particularly related to the location of new petroleum refining capacity. The effects can be illustrated by comparing recent growth in demand for the refined petroleum products with changes in plant capacity. To start with, we must recognize that U. S. demand for petroleum products in the last few years has been inflated by the inability of other energy forms such as gas, coal, and nuclear power to take up an appropriate share of total energy growth, and also by lower conversion efficiencies, stemming from new emission control and other environmental protection standards. In fact, the 1973 demand for oil and oil products in the U. S. will be greater than that estimated for the year 1975 by a Cabinet Task Force, who prepared their estimates just three years ago.

The rapid growth in U. S. oil demand, from 1970 to 1973, had added nearly 2½ MM barrels a day to their requirements. This oil growth increment over three years is around half as much again as consumed in total in Canada. Compared with a growth in demand of 2½ MM barrels a day, refining capacity in the U. S. has grown by only 1 MM barrels a day, or only 40% of the demand growth. I attribute this feature to factors (2) and (3) listed on this slide.

The fourth factor on the slide relates to production shortfalls by U. S. nuclear plants, which tend to add to oil's burden in meeting energy growth. Part of this shortfall I have already referred to, in terms of licensing delays and other legal impediments to new capacity additions imposed by eager environmentalists, and by other forms of delays in actual constructions time versus forecast. Another significant contribution, however, has been the lower than expected performance of completed U. S. nuclear plants.

Most economic studies that led U. S. utility companies to go to nuclear plants assumed reliable delivery of 80% or more of a plant's potential power. A few projected 90%. In contrast, the President of Consolidated Edison was recently quoted in the Wall Street Journal as follows:

> The eighteen longest running U. S. nuclear plants averaged only 61.9% of their potential output through last September 30th.

As noted earlier, any nuclear plant shortfall means either more use of oil or less production of electricity. The U. S. has experienced both.

Slide 12

This is the second part of the analysis of the current U. S. situation. Because of the four factors, previously discussed and listed again at the top of this slide, the U. S. is experiencing a variety of disconcerting pressures. These are listed here and I will comment on them one at a time.

Slide 12 . Special U. S. Short-term Problem

These Factors ...

* Gas Pricing
* Environmental Program
* Policy Uncertainties
* Nuclear Shortfalls

Have Produced These Results

1. Burgeoning demand for certain types of oil
2. Heavy drawdown of finished product inventories
3. No short-term solution in sight for needed U. S. port/refining facilities
4. Recurring & growing shortages of gasoline/heating oil to at least 1975
5. Similar shortages/curtailments for gas & electricity

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1. One effect is the burgeoning oil demand, particularly for certain oil types--more specifically, for finished products of all kinds and for tanker delivered oil of low sulfur content.

2. Another effect is the heavy drawdown in finished oil product inventories. Normally, as demand grows, so does inventory. In contrast, in 1972, stocks of gasoline, heating oils, and other finished products in the United States declined by around 70 million barrels.

3. There is no short-term solution in sight for the needed U. S. port and refining facilities. While one of the features of the recent energy message by President Nixon was to provide incentives for domestic refinery construction, it takes time to construct such facilities and perhaps five to ten years for the U. S. to catch up for the construction shortfall in recent years--all assuming that the essential resources such as capital, engineering manpower, skilled

construction craftsmen, and equipment fabrication capacity can all be effectively marshalled for the task.

4. We can expect, therefore, recurring and growing shortages of gasolines, heating oils, turbo fuels, etc., in the United States through to at least 1975.

5. We can also expect similar shortages and curtailments in parts of the country and to certain classes of customer for other energy supplies such as gas and electricity.

Slide 13

This slide rounds out the analysis of the U. S. short-term energy problem by citing the consequences of what is taking place there. This listing is in the bottom part of the slide.

Slide 13. Special U. S. Short-term Problem

These Factors ...

* Gas Pricing
* Environmental Program
* Policy Uncertainties
* Nuclear Shortfalls

These Results ...

* Recurring Shortages of Gasoline/Heating Oil
* Continuing Curtailments for Gas & Electricity

With These Consequences

1. Contingency planning with emergency overtones
2. Growing pressure for quick solutions
3. Mounting concern in other countries
4. Confusion between short and longer-range energy situation

The first item notes the rush to contingency planning with emergency overtones. Since their price control program has limited their options on how to cope with scarce petroleum supplies, the U. S. is very busy now considering other allocation mechanisms.

Also, almost all energy issues have become newsworthy these days. We can expect, therefore, as noted in the second point, pressures for government action, with good media coverage, in almost all instances of customer dissatisfaction in price or supply terms on his energy transactions.

The third point extends the notion that continuing and highly visible breakdown in normal energy supplies in the U. S. will cause people in other countries to ask with repeated frequency--can it happen to us?

Finally, there is bound to be confusion between what's happening today in the U. S., which is really a product of their own making, and the longer term fundamental transition in energy that is taking place, that is a worldwide and not just a U. S. phenomenon.

Let me go on now to talk about the effect of these events on the outlook for oil and oil prices. A good starting point is to keep in mind that up until a few months ago, in Canada and the United States and in most other countries, many people believed that there would be a continuing, unending supply of energy at the low prices to which they had become accustomed. This is at least six years after the first evidences of fundamental changes occurring with respect to energy costs, prices, and availability. As we have come to learn, the policy makers in the OPEC countries were alert to these evidences.

There is another marketing feature of petroleum to which OPEC countries had also become very sensitive. This is that the total demand for motor gasoline, which is the principal finished product of raw petroleum which, in turn, has become the principal energy fuel, does not vary appreciably with changes in price. Here the reasons have been very low costs in relation to value for the product, combined with the absence of any competitive substitute. This explains why very high road taxes prevail on motor gasoline around the world.

Very substantial tax sums on petroleum are collected, therefore, by governments in the oil consuming countries. On average around the world, they have amounted to around five dollars per barrel of total raw petroleum. To oil-producing countries, who had struggled very hard to get their tax take-up to one dollar per barrel, this five dollar tax collected by far-away governments became a very sore point.

As soon as their bargaining power permitted them to do so, OPEC countries were bound to go after more of the prize, feeling that consuming countries had already put a much higher value on the refined petroleum product.

Well, as I have said, OPEC bargaining power has shifted in their favour in recent years. And this relates to two features: changes in the supply pattern to meet the rapidly growing demands, which I have outlined earlier to you; and secondly, the ability of oil-producing countries to pack a wallop in negotiating new terms with oil concession holders.

You will recall my earlier reference to the increases in average per barrel tax take during the 1960's in Venezuela and the Middle East countries despite the significant reduction in selling prices realized by the oil companies. The extent of the ability of producing countries to command a much bigger share of the pie became first evident in 1970.

I am referring to Libya's actions in the spring of that year, just eight months after a revolution in that country had converted them from a monarchy to an Arab republic, and just two weeks after a Syrian bulldozer had ruptured one of the principal overland pipelines to loading ports on the Eastern Mediterranean. In this instance, Libya imposed production limits on some of the concession holders. The long tanker hauls around Africa to replace the pipeline movement caused tanker rates to soar and Libyan crude oil became much more valuable, because of its closer location to key markets. But instead of allowing the valves to open, Libya called on concession holders one by one for higher taxes and royalty rates, threatening production shutdown as an alternative. Something had to give and it was the oil companies, beginning interestingly with an independent newcomer and not one of the majors.

It was this particular showdown in 1970 that, in my opinion, heralded that we were really in a new era in the relationships between the oil countries and concession holders. For this event led to a succession of negotiations, involving all OPEC countries, in the latter part of 1970, with ever-escalating demands on the oil companies, that culminated in the Tehran and Tripoli agreements in 1971. Subsequent tax changes in Venezuela and in direct ownership participation steps by some Mid-East countries are a continuation in these escalating demands by these oil-producing countries.

Analysts, journalists, civil servants, and others around the world are still attempting to total the financial consequences of the new deals that have been made over the past 2½ years, which have so dramatically increased the OPEC countries' take. If the bargaining position of the oil-producing countries is not impaired, the higher per barrel figures on oil company production will be only part of the story. Total government take will be further increased from the greater production expected in some countries, notably Arabia, and by some direct government ownership of concession crude oil. One leading bank economist has noted that the predicted flood of dollars into the oil-producing nations will represent the number one problem of the world monetary system during the next decade. From their oil trade with the United States alone, the State Department estimates that Eastern Hemisphere governments will be gaining 12 billion dollars annually by 1980, or over ten times the rate in 1970.

That is where we stand today then in terms of changes in the oil trade outlook and the financial consequences. The implications of the current setting, however, go well beyond that of the effects of the accrual of large dollar amounts to oil-exporting nations.

I am going to spend the balance of my presentation in exploring some of these implications. While there are a very large number of important implications for the major actors in this scene, I will be presenting only the top three, or main points, as I see them with respect to each of these three major parties of interest--the oil companies, the overseas producing countries, and the oil importing countries. Also, to provide a reasonable basis for subsequent discussion, I will present these implications in the form of challenges facing the major parties.

Slide 14

Starting first with the oil companies, I see three major challenges.

Slide 14. Major Challenges - Oil Companies

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1. Adapting to shift in bargaining power
2. Adjusting to new business role
3. Explaining changes to public

The first is how to cope with the recent dramatic shift in bargaining power vis-à-vis host governments in the OPEC countries. This challenge has two dimensions. The first is to optimally preserve the companies' stake in the oil reserve assets in OPEC countries in which they continue to have a large financial interest. The second is to provide continuity in supply of essential petroleum products to consumers around the world on terms that are demonstrably better than alternative institutional arrangements, such as those that might stem from direct dealings between governments of consuming countries and those of the producing countries.

A second challenge to the oil industry is to satisfactorily carry out its intermediary role between the governments of oil-exporting nations on the one hand and oil-importing nations on the other, and still generate sufficient cash outflows from their operations to help underwrite the exploration, development, refining, marketing, and other capacity additions required to meet expanding product demand.

The third challenge, and perhaps the most important, is to communicate better to appropriate consumers and producers the essential role played by oil companies in meeting world energy needs.

Slide 15

The next main group that I will pose challenges for are the host governments in OPEC countries.

Slide 15. Major Challenges - OPEC Countries

1. Maintaining bargaining strengths
2. Managing curreny inflows
3. Coping politically with new economic powers

The basis for my selection of three major challenges for this group all relate to the question of how they will cope with the dramatic shift in bargaining power, which has occurred in their favour over the past few years. One challenge will be to maintain this effective bargaining strength vis-à-vis oil companies with one of the threats of dilution coming from pressures generated within the group itself. In this respect, a number of OPEC countries are coming into possession of some of their own crude oil for sale as a result of recent participation settlements. Will this feature create new competitive pressures between countries and, if so, how will individual countries respond? A good question.

A second challenge will be how OPEC countries manage the expected buildup in their dollar inflows. Without speculating in numbers, you can see that these amounts will be vast by any sort of measure.

The Saudi Arabian Oil Minister has recently proposed investment by his own country in U. S. refining and marketing oil operations. His proposal is being seriously considered in the context that the oil industry by itself may not be capable of providing the needed funds for such facilities. If enough promising investment ventures outside their own countries cannot be found to absorb these funds, then one or more may decide to limit their income and keep their oil underground.

A third challenge to OPEC countries is how they will cope politically with the changes in the power base that will accompany both their wealth accrual and the growing dependence by consuming countries on their oil resources. There are many dimensions to this challenge because of the many differences that exist between OPEC countries: in terms of internal political stability of the group in power in each country; in terms of each country's relationships with other OPEC countries; in terms of their relations with other developing nations who will not have the wealth buildup of OPEC countries, but rather will be underwriting part of this buildup; and in terms of relations with major consuming countries, some of whom are continuing to extend financial and other support to Israel.

Slide 16

Now let's take a look at the challenges facing the major oil-importing countries around the world. Here also there are many economic, political, social, and other differences that will provide different overtones to the three challenges that I have selected to present to you.

One challenge is to cope with the outlook for increased costs of energy in all forms. Here the main difficulty seems to be one of abandoning out-of-date attitudes with respect to energy costs and availability. By that I mean that there must be clear recognition that higher prices will bring out new alternative supplies of clean energy and that even at the required price levels energy will still be a bargain. It is

Slide 16. Major Challenges - Importing Countries

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1. Facing up to higher energy costs
2. Developing alternatives to OPEC oil
3. Coping with new political pressures

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resistance to higher prices which, in my opinion, has been chief contributor to the so-called energy crisis in the United States--which is not really an energy crisis as much as it is a crisis in contradictory policies. As a result of these contradictions, the continuity of energy supply in the United States has been seriously jeopardized. The same thing can happen in other countries, if a new set of attitudes, consistent with recent fundamental changes in energy outlook, are not adopted.

A second challenge to oil-consuming countries is to develop, more rapidly than they have, alternative energy supplies. This is really an outgrowth of the more general challenge of out-of-date attitudes which has just been discussed. Alternatives to purchases of oil produced in OPEC countries are obviously the best protection against escalating prices for this oil, as well as the best insurance for energy supply continuity. Even the vast oil reservoirs in OPEC countries will someday be physically incapable of matching ever-growing demands. It is this feature that helps provide the impetus for development of new Canadian energy resources.

The third challenge on my list for oil-consuming countries is to cope with the new political pressures arising from recent fundamental changes in energy outlook. Some of these, such as Mid-East policy and the problem to low income nations of higher energy costs, will be similar to the political challenges faced by OPEC countries. There will be many others that will be distinct to consuming countries, such as the attitude to possible major trade dealings in energy with the Soviet Union and even perhaps China, and the repercussions from possible introduction of new trade barriers by individual countries in order for them to cope with the negative balance of payments implications of higher prices and larger volumes of imported crude oil.

That completes a quick coverage of the implications of the current world oil and energy outlook as seen in the form of challenges to the major parties of interest. The overriding conclusion that emerges is that the recent changes in the oil setting, which have been reviewed with you today, do fit into an energy situation that has some very significant global economic and political implications. It will take considerable skill, wisdom, and some luck on the part of the world political leaders to reorient their policies to accommodate the new energy situation.

The Near Term Energy Situation
Supply of Oil, Gas, and Coal

R. Janin

My talk this evening is directly related to that of Mr. Barratt. Moreover, I will be obliged to deal with a certain number of remarks previously made today, but I will try to present them in a different form by showing in passing where systems analysis could be useful.

My goal is to emphasize above all the most important factors which will help shape the energy situation around 1985 and during the decade now ahead of us. In this period, only techniques now known will have a tangible effect upon the energy picture. This is, furthermore, a feature of the period as defined for us by Professor Haefele.

I will adopt from the outset Professor Haefele's conclusion of this afternoon: "We have sufficient energy." This is completely valid until 1985 if we consider the potential resources. A world-wide energy shortage, if one eventually appears, will not come until far beyond the period I will portray tonight. However, this does not mean that we will not have to be concerned with the problem of resources, particularly at the end of the period. I will return to this point.

I must begin by reminding you that the world consumption of energy in 1970 was about five billion equivalent tons of oil. (E.T.O.) For the past few years, the growth of total energy demand has been on the order of five per cent annually, which, with the population increase of about two per cent annually, brings the annual increase in per capita consumption to three percent. This progression is likely to continue up to 1985, and everyone--with only minor differences among the experts--appears to agree that the rate of five per cent will continue up to that date. With this five percent annual growth, which corresponds appreciably to a doubling in fifteen years, we arrive at a forecast on the order of 10 billion equivalent tons of oil by 1985. This consumption will not pose problems in quantative terms if we are content to compare it with the substantial potential reserves which we listed with Professor Haefele today.

But let us examine the breakdown of primary forms of energy at the 1970 consumption rate and for a reasonable forecast for 1985.

	1970 Billions E.T.O.	%	1985 Billions E.T.O.	%	Increase Billions E.T.O.
Oil	2.2	44	5.1	51	2.9
Coal	1.6	32	2.2	22	0.6
Gas	1.0	20	1.7	17	0.7
Hydro-electric	0.2	4	0.3	3	0.1
Nuclear	-	-	0.7	7	0.7
	5.0		10.0		5.0

These figures immediately suggest a few remarks:

1. By a large margin, oil will remain in first place for the world supply; its percentage will even tend to increase during the next fifteen years, assuring by itself about half of the world energy consumption. Furthermore, consumption will have more than doubled between 1970 and 1985, which represents an annual increase of seven to eight percent.

2. Hydroelectric power will increase slightly in absolute terms, but its weight--although important for some countries--is minor in the overall picture. I will not speak further about this form of energy whose resources are, for all practical purposes, "exhausted" in the industrialized countries. We can count only upon the progressive development of these resources to the extent that the need grows in countries with large potential resources far from the consumption centers.

3. We notice for the rest that each of the other forms of primary energy (coal, gas, nuclear) will grow in terms substantially equal in absolute value (twelve to fourteen percent of the global increase).

4. This is insufficient for maintaining the current position of coal and gas in the overall balance. In particular, we will see the continued decrease of the role of coal, which

assured ninety percent of our needs at the start of this century but only twenty-two percent by 1985.

5. It follows that nuclear energy deserves particular notice. As we said this morning, it will assume a progressively larger role in the energy picture, but, from now until 1985, it will still occupy only a limited place. We should note further that practically all the production will come from thermal neutron reactors. Even if we think the preceding forecast is pessimistic for this energy form, it remains clear that nuclear energy can by this date satisfy no more than ten percent of world needs. Its influence will be greater by the dynamism of its growth than by its absolute value during this period. We have seen in reverse the role it will come to play afterwards. I will thus not dwell further upon nuclear energy in describing its impact upon the world energy outlook.

I would like to examine in more detail a few problems posed by coal, oil, and gas which are not directly apparent in the global balance.

Coal, despite its continuing decline, will still play an important role. But we should note that its market tends to become "regional," not global, in spite of the enormous world reserves available. Thus, while there are forecasts for increases in consumption in the U.S. and in the U.S.S.R., there will still be a reduction in absolute consumption in Western Europe. Without a doubt, coal is easily transported and often over long distances; but intercontinental transport is basically weak for transfer of energy.

This holds essentially for long distance transport costs, and perhaps even more for distribution costs to the end user, so much so that the increase in consumption of this primary energy contributes to a great extent to the development of large coal-using industries which by their nature escape the high costs of distribution. It follows that, as in the past, these large user industries will in general have an advantage in being located near the mines.

Gasification processes envisaged at this time--in the U.S. as much as in Europe--aim to overcome the handicap of transport and distribution costs. But, in the period from now until 1985, we do not foresee that these will become widespread. We notice, moreover, that following the depletion of the European mines, gasification processes can at most only slow down the decrease in coal consumption; this excludes the development of mines whose extraction costs will, in any case, be high.

Contrarily, oil forms a genuine, largely open world market; a glance at the map illustrating the oil transportation network verifies this. This is even more true as the Middle East role in oil production has grown considerably, with that region supplying nearly all areas of the world.

The global aspect in the oil market comes from the considerable progress achieved in transport, as much from pipeline technology permitting exploitation of wells far from the coast as from sea transport. Mr. Barratt already mentioned the strong decrease in oil costs over the last twenty years. We see therein the results due as much to technical progress in prospecting and exploitation of the oil beds as to technical progress in transport.

The whole "oil system" has thus been able to offer lower prices because it has available all at the same time larger reserves, better tools, wider markets, and, as a corollary, a more efficient organization as a result of the increased competition in the world market.

During the period up to 1985, the problem of exhausted reserves should still not overly influence the market, even toward the end of the period, as this perspective indicates.

Given the progression in the demand for oil, we will have to discover between now and 1985 oil reserves equivalent to the entire present Middle East reserves. This necessitates, of course, important explorations, but little compared with the efforts which will be necessary afterwards to find the equivalent of two Middle Easts between 1985 and 1995, and four between 1995 and 2005.

Thus in the world oil market we cannot totally exclude that the prospect of exhausted reserves will begin to play a role towards 1985. This might be expressed by noticeable price increases, if only to ensure financing of the investments necessary to double production, investments representing in the order of 1,000 billion dollars from now until 1985.

We must also emphasize the great disparity between the allocation of reserves and the allocation of needs. The table below shows this eloquently:

	Consumption	Reserves
North America-Western Europe-Japan	70%	9%
Eastern Countries	16%	12%
Rest of the World	14%	79%*
	100%	100%

*of which 58% are reserves in the Middle East

Here the deficiency of oil reserves in the western industrialized countries appears clearly while, as we have seen, it is essentially towards oil that energy needs will develop from now through 1985.

Natural gas--in common with oil--has also become a world market. And, as for oil, progress gained in transport has completely altered the market to give it a worldwide character. Movement of energy by sea transport of liquified natural gas is becoming significant on a world scale. We should, however, point out that the reserves of gas appear better divided among the consumer nations, and that the three groups of countries seen above (western industrial countries and Japan, socialist countries, and the rest of the world) have essentially the same quantities of reserves at their disposal--one third for each group of countries. It follows, however, that the "rest of the world" has relatively low energy consumption, and will export largely to the most industrialized countries.

This brief sketch of the energy situation for the next ten years shows that, in the end, there are fairly numerous problems which the world balance does not reveal. It is at this level where we see the appeal of decomposing the energy sector into systems, each having some constraints. I would now like to emphasize specific points which could prove particularly important for the future.

1. First, we are struck by the importance which energy exchanges will have in the exterior trade of the Western industrial countries and of Japan. The disequilibrium which in all certainty will appear in the trade balance of certain countries seems grave; it will certainly have serious consequences for the international monetary systems.

We can calculate, for example, that toward 1980, the income of the oil producing countries will amount to 55 billion dollars annually. Thus, a country like Saudi Arabia will have at its disposal considerable foreign currency reserves, estimated to be twice the current monetary reserves of the United States. This situation permits us to foresee changes in the balance of political power by the possibilities it could create for pressure or for blackmail.

2. Under these conditions, we can see the difficulty of elaborating sure hypotheses for the evolution of the world markets and even of their structures. This is a subject in which systems analysis could be helpful. In effect, when we are content to perform optimizations calculations upon *a priori* hypotheses, we assume that a certain number of relationships will be maintained--for example, there will be no break in contractual agreements. In fact, if we examine certain energy systems--and notably those of Western Europe during

this period--the weakness in the security of supply could bring about either behavior or limitations which an optimization model could not reproduce. Another approach must be found.

3. Nevertheless, it would not be appropriate for IIASA to deal with this burning question, the political nature of which is evident. However, this problem merits analysis from the methodological aspect of the contribution which systems analysis can make in dealing with a complex problem. In this respect, we should mention that the usual methods of forecasting can generally be criticized when we apply them to periods longer than ten years. It would thus be appropriate to make not "forecasts" but "prospective inquiries." The essential difference is that the prospective method obliges judgment of the future in coherence with itself, not with today. Rather than follow out, by inertia, current tendencies, we seek to learn how a given scenario is compatible with what a given year will be. We then look for the means of passing from the future scenario to the current situation. In the energy area--whether for 1985 or for 2000--it is important to have this "prospective" attitude to read in the facts of today what could be the evolution of tomorrow.

In this context, the recent past and the immediate future clearly point out the roles played by a certain number of actors. We can list those who appear to be the most important at present:

a) Consumers, who seek the greatest possible supply of energy at the least cost:

b) Oil Producing Countries, whose game in principle is to profit maximally from the revenues of the situation available to them; if the needs of the "poor" countries are immediate, those of the "rich" countries can be longer term, which can cause them to behave differently;

c) Transporters and Equippers, on one hand, and

d) Oil Companies, on the other, who are the real actors in the international market;

e) "Citizens," meaning social groups which express choices--notably about the environment--and thereby create constraints which occasionally ignore the consumer role of members of their group. Fundamental incoherences clearly could--and do in fact--exist between the two viewpoints, i.e. that of "consumer" and that of "citizen" for single individual; a fortiori the same situation obtains when we think of social groups;

f) States, whose mission is to support the social groups and thus constitute a reality, if only by the collection of taxes;

g) Public Services, which by nature are more or less linked to the actions of the State; and

h) Industries, whether they manufacture the material for energy production and transport, or whether they produce the material for utilizing this energy.

This is not a classical game, and is, moreover, non-zero sum. My goal is not to describe it is detail but to show how the complex relationships between the actors are born and, from there, to create constraints.

A first grouping of relationships occurs at the level of the consumers: competition among the different forms of energy. This competition is indispensable for the proper functioning of the group. It is essential that the consumers be brought by the play of the price structure to choose the most efficient--and thus least costly--energy sources. Here, I would like to point out that in Professor Haefele's presentation, the part of electricity remained only 25% in the final consumption. I think that we could go even further: electricity has no specific application and is perhaps the sole form of energy amenable to assuring directly any type of use (heat, motive force, electrolysis, etc.). Use of electric power certainly creates efficiency losses, according to the second law of thermodynamics, but this handicap is compensated on the economic level by the low distribution costs. Thus in France today we see a rapid development of "all-electric" housing units. This leads us to think that by the end of the century, electricity will account for about forty percent of the total end uses.

Another case of competition merits mention: the competition between fuel oil and nuclear power. Over the past ten years we have noticed a simultaneous decrease in the drop of prices for fuel oil and atomic power. It is well known that the drop in oil prices delayed until recently the start of the first nuclear projects. What is less brought to light is that the recent upswing in the price of oil seems brutal, as though oil, spent from efforts to remain competitive, has finally abandoned the game now to seek only to benefit from the revenues of its position.

In this description, we are far from the classical competition among products with similar prices. This can no doubt be explained by the relationships among the different actors of the systems involved.

Another set of relationships among the actors is formed by the price system. I have already underlined the role played by the drop in transport costs. Inversely, a rise in prices of primary energy (conceivable outside of nuclear energy) would act to modify energy needs and would perhaps influence the price system as a whole. At the extreme, this could affect the very rhythm of economic growth.

At the level of the <u>citizens</u>, the "quality of life" plays an important role. If, on one hand, the quality of life seems to base itself more and more upon energy norms (one is poor if he does not have at his disposal a certain quantity of energy), it appears, on the other hand, increasingly necessary to take care that energy consumption and, moreover, all human activity, do not diminish what we can call the quality of life. Many factors intervene to define it--not only temperature, air quality, and noise, but also the esthetic environment. It is not impossible that, between now and 1985, factors secondary today will come to play an important role, at very least in the most industrialized countries: for example, will we accept noise as we do today?

Social behaviors constitute a group of relationships among the actors defined above. These behaviors concern widely diverse problems. Here we find, for example, the sensitivity which changes in the price structure can have (expressed in economics by demand elasticity), but we know how much an idea which the consumers form collectively can act upon the very price mechanism itself. We also find, as previously mentioned, the public reaction to certain attacks upon the environment (e.g. construction of new factories, no matter what their nature). We must further add the acceptance of a certain from of distribution of income and, in a general manner, the sharing of revenues, without overlooking the burden of taxes. Finally, we must not forget the increasingly large role played by the "mass media" in the reactions of public opinion; here we could speak of social embedding.

We have shown above how the political and economic organization can come into play in a particular case. In a general manner, economic theory shows poorly--and this is not its role--the consequences of situations in disequilibrium.

But, it is clear that, if the scarcity of products brings in revenue for their owner, this scarcity can also give him a type of power. Conversely, a stubborn will can prolong the life of solutions of debatable profitability. It would seem that systems analysis could permit analysis of the current constraints of this type which can exist in the energy sector. Might systems analysis not also show future constraints which will subsequently appear?

Conclusions

1. We should first inquire about the interest in developing the above ideas. How can they help us in our daily actions? A reply is evident: we have the duty of preparing the future, the duty to promote the technical progress which will make available cheaper, more abundant energy. We must also be able to choose what efforts to undertake as it is clear that humanity cannot allow itself to make enormous R and D expenditures for all potential energy sources at once (fusion, solar, geothermal). Before starting out, it is appropriate in particular to assure that none of the conditions of some type of energy is inacceptable for whatever reason. For example, if we expect to economize by increasing the size of machines, we must ask if this size increase is compatible with the quality of life desired elsewhere (will we continue to tolerate cities congested by large trucks?).

2. Among the actors we have listed (without seeking to be exhaustive), quantitative relationships exist, but also, we have seen, non-quantifiable relationships playing upon the structures of the problems. These relationships are, finally, numerous, and as in any complex system, the degrees of freedom are ultimately limited. We must be aware that we are moving towards a progressive reduction in these degrees of freedom because the progress of knowledge reveals the existence of "laws" which, even if they existed, were not previously perceived. The day Einstein pronounced the famous equivalence between mass and energy, with the same blow he put a ceiling upon the world energy supply.

An incompatibility between the "desired" and the "possible" may one day appear in our economic analyses, and this could be particularly true in the energy area. Systems analysis permits us to envisage other outcomes, to change the conditions linking a given system to others, in sum, to show at once the need and the possibility of innovations and mutations. The oil-nuclear competition seems a good example to examine from this angle.

3. Before we can arrive at that point, it would seem particularly helpful to be able to employ the matrix of reciprocal influences of a certain number of characteristic

events. This examination--at which, to my knowledge today, we have had only timid attempts--would permit more precise definition of homogeneous systems upon which we could base a precise analysis.

IIASA could play a large role in facilitating the development of all the studies I have mentioned, studies which appear necessary to assure the harmonious increase of world energy consumption. Even more, IIASA could help prepare the long term future of this sector so important for the future of mankind.

Discussion

The participant who opened the discussion observed that Mr. Barratt had spoken about the challenges of the short term energy crisis. He commented that it would be useful for the group to discuss to cope with these challenges and to decide which options should be kept open for the medium and long terms. Second, there is a dilemma in deciding whether to treat short or long range problems with systems analysis. With short term problems one cannot globalize but must disaggregate to capture the players, options, and frames of mind. However, there are no technological surprises, although one must build up the technical capacity to have options open for the long term. In long term analyses one can aggregate and still get meaningful results, but in this case one must take account of surprises. The challenge is to do both forms of analysis. If one starts with long term problems, short term problems require beginning the research effort completely anew. Moreover, IIASA will be measured in its first decade by its successes in short term problems. Thus, IIASA should start with the short term and go to middle and long term analyses with the accumulated knowledge of available options.

Another participant commented on Mr. Janin's discussion of the oil market to say that the distinction between light and heavy fuel oil is important. In Great Britain, oil companies use their monopoly position to price heavy fuel oil below the coal price in order to influence the installation of new plants. As oil prices rise, coal will have a temporary advantage because of the low elasticity between coal and nuclear energy. The transfer to nuclear energy will be slow and will probably last until 1985 or 1990. Coal might be the controlling factor in the intermediate period.

Mr. Janin mentioned that some Belgians have suggested opening new coal mines. Nuclear energy seems to him a better and cheaper solution for most of Europe because the coal industry is declining. His questioner agreed that the coal solution is probably possible only for the U.K. and Germany.

Mr. Janin made a final point on the value of systems analysis in this context. The investment required for extension of petroleum production is very large. Systems analysis can show constraints that we could not see if we only made forecasts and did not divide the problem into subsystems.

Mr. Haefele opened the Wednesday morning session by inviting written comments from the conference participants. One of them asked that more time be allowed for discussion to formulate what IIASA should do. Rather than just "ventilating" viewpoints, the group should make concrete recommendations and thus facilitate the director's task of choosing a research program. Energy is already being studied by several institutions. The conference should select aspects that have global significance and should consider in what form they could be studied, that is, what form the IIASA research should take. Two criteria should govern these choices:

a) absence of duplication of ongoing national activities and

b) an appropirate organizational form.

Modelling of Energy Supply and Demand

F. W. Hutber

Outline

Appendices

: INTRODUCTION

.. The Energy Model Group was formed in 1967 by the Ministry of Power (now part of ;he Department of Trade and Industry). It now constitutes a branch of one of the ;ix Economics and Statistics divisions of the Department of Trade and Industry and /hich is concerned with Energy and Steel statistics. On energy matters the division ;ervices the four main policy divisions concerned with coal, oil, gas and electricity ıs well as advising the Atomic Energy division and the Fuel and Nationalised Industry 'olicy division. With the addition of one further division, Energy Technology division, .t can be seen that a total of eight full divisions are responsible in various ways :or advising the Minister for Industry on energy policy decisions.

. The problem of co-ordinating the work of such a large group poses problems, not east of which is that of ensuring that the effect of decisions in one sector on the ther sectors is realised and accounted for. It was in this climate of interacting ectors that the idea of the Energy Model was conceived. The scale of the area being odelled is large, covering 13% of the total domestic expenditure and 8% of the ross domestic fixed capital formation, and is second only in size to the modelling f the national economy by the Treasury. Further, since the model is expected to ontribute to individual decisions in each sector, the modelling system has to perate at the micro as well as the macro level of analysis. Whether this can be chieved within a unified system of modelling must be judged from the results reported elow.

[OBJECTIVES

. The long term aim of the Model Group is to produce a computable model of the UK nergy economy that balances supply and demand by fuel in each market in time. By ime we mean future time and we expect the model to resolve the system for current · single year ahead problems, in the medium term (from now to 5 or 10 years ahead) s well as the long term (from now to 30 years ahead). A single modelling system may ot be found to perform all these functions efficiently so that if different structures e specified for the different timescales then the results from them must be compatole in the broad sense that one result may be interpreted in terms of others.

4. A statement of the objectives should not be passed without identifying the nee that they are intended to satisfy. One of these has already been mentioned - co-ordination of fuel industry policy. Another is the reconciliation of the invest proposals of the energy industries - making sure that the sum of the parts does not exceed the anticipated total investment in energy and determining where any adjustm is needed. The re-alignment of national and corporate interest is required from ti to time when perhaps some national economic or social development makes it necessar to modify the commercial judgement of one particular industry. This can sometimes achieved indirectly by the manipulation of some regulator such as a tax, thus conse ing the freedom of commercial judgment of the industries concerned. At other times due to the lack of a suitable regulator, direct intervention can be justified in th national interest. The effect of such variation may be demonstrated with a suitabl model structure by modifying the basis of the data set used and /or objective funct to suit the specific need and then evaluating an optimal solution obtained by the us of one data set in terms of another data set.

III STRUCTURE OF THE MODEL

5. For the purposes of the supply side of the energy sector is regarded as compris ing four main industries - coal, petroleum, electricity and gas - which either individually or in combination take primary energy in the form of coal, oil, natural gas, nuclear fuel, hydro power, etc and sell it to final consumers in the form of the fuel products that they require. The flow of fuels from their primary sourc direct or through the secondary processing industries to the final consumers is illustrated in Figure 1. There the outer ring represents the primary fuels, the ne ring the conversion to products in the required form and the inner circle the final consumers. Costs can be regarded as building up in the same directions as fuel prod move, whilst expenditures flow in the opposite direction.

6. The current experimental version of the integrated model of the energy economy consists basically of five sub-models, that is a demand sub-model and four supply models, one for each of the main fuel industries. Demand for energy depends mainly on relationships outside the energy sector such as growth of the national economy, industrial production and consumer expenditure. The share for each fuel depends

principally on the price asked, and this in turn depends on the cost of supply and is affected by the scale of protection for indigenous fuels in the form of taxes, subsidies and import controls.

7. The supply sub-models calculate the unit costs of meeting the demand in terms of the capital expenditure, operating costs and manpower required. To do this, they are provided with general information as to the prices of materials, the level of wage rates and the costs and performance of various factors of production that might be used to meet the demand. It will be seen that the operation of the energy model is in the form of the closed loop illustrated in Figure 2 and the interchange of information between the demand and supply sub-models is the essential feature of the balancing process so that either the sub-models have to be used simultaneously or sequentially in iterative fashion to obtain a solution.

8. Our approach has been to build the model in sections (the sub-models) each with its own project group enabling the work to proceed on a broad front and using a sixth project group to develop the control and integration side of the model work as a whole. The gas, electricity and coal supply models have been developed in considerable detail. The oil model is still in a rudimentary state and is used with simplified models of the other industries in the integration experiments. The form of development adopted has a number of advantages:-

(i) it enables the overall timescale for construction to be shortened;

(ii) it induces expertise in the project group in one of the fuel industries as well as in the modelling techniques used;

(iii) whatever the outcome of the integrated energy model research we have created with the detailed sub-models a worthwhile analytical capacity for the individual industries concerned.

III A THE DEMAND SUB-MODEL

9. The demand sub-model is the main link with the national economic variables which are exogenous to the energy model. It is a regression type model and a technical description is given in Appendix 1. The original concept of the demand model was one in which an assumed growth in the national economy as a whole could be interpreted by means of a set of activity indicators into total energy demands in each sector of the economy. This unified approach has not proved satisfactory and currently total energy demand in each sector is projected individually by the method found to be best suited

to the historic behaviour and the data available which is not consistently good. This 'bottom up' approach is then checked against forecasts using the macro indicators such as GDP for consistency before arriving at the final values to be used. The second and third parts of the model are the determination of desired market shares and the lagged relationship between desired and actual market shares.

III B THE GAS SUPPLY SUB-MODEL

10. The gas supply industry consists oftwelve virtually autonomous Area Boards.* In 1971 nearly 90% of the gas sold was natural gas, mainly from the North Sea, entering the country through only a few terminals. The production side of the industry is represented by a single geographical area or point model.

11. The modelling technique used is linear programming.

The model considers mainly the activities of the Gas Council such as the purchase, transmission and storage of gas and goes as far as the bulk supply points to Area Boards. The distribution costs are taken into account by adding a cost per therm to the other supply costs. The industry has major choices that it can make, for instance in building more pipeline, storage facilities or capital-intens gas plant to meet the winter peak. The cost of each individual activity (such as building a plant, running it, buying gas from the North Sea producers or elsewhere) is known or assumed, as are the quantitative relationships between the constraints on these activities.

12. More detailed local distribution and service activities of the Area Boards are represented by a separate regression type model. These activities are characterised by a large number of individual investment decisions, each one leading to an expenditure on a much smaller scale than any in the production model described above, althoug they add up in total to $\frac{2}{3}$ of the total cost of supply. The local distribution expenditures are related to appropriate levels of activity in the industry (such as annual demand, peak demand and the number of consumers) as well as the available data will allow. These costs are not as clearly defined or as easily estimated as those in the bulk production model.

*From the end of 1972, the Area Boards' responsibilities have been combined in the Gas Corporation.

III C THE ELECTRICITY SUPPLY SUB-MODEL

13. The Electricity Supply Industry consists of twelve Area Boards which supply consumer service and distribute electricity purchased in bulk from the Central Electricity Generating Board (CEGB). Our model represents the CEGB and covers the generating of electricity in England and Wales. It is basically a linear programming model and there are two versions of it, one modelling investment decisions, the other modelling the detailed operation of the system in a single year. The essential difference is to be found in the type of problem it is intended to resolve. Investment decisions are essentially long timescale decisions involving plant lives of 30 years or more so that some detail on the system definition can be sacrificed for detail in the time dimension. Thus the investment model is a single geographical area or point model seeing in the time dimension one coal supply area and a crude grouping of power stations by fuel type, efficiency, etc whereas the operations model (called the Electricity, Coal, Transport or ECT model) sees 15 coal supply areas, a larger number of power station groups which allows for grouping by geographical location, and a transportation matrix to connect them. A technical description of the investment model is given in Appendix 2. The two models interact in such a way that a system description has to be determined before the ECT model can be used and this may be generated by the investment model. Conversely, the ECT model can be thought of as producing cross-section data for the investment model provided that they work in dimensions essentially orthogonal to one other.

III D THE COAL SUPPLY SUB-MODEL

14. The coal supply model is a straightforward data processing program which unbundles the latest available cost structure of the National Coal Board (NCB) and then reassembles the data for a future year with new projected productivity values obtained exogenously. This type of programme is conditioned by the contraction of the industry in that the dependant parameters are the productivity and the latest tranche of output due for closure. This type of analysis is done for each area, 15 in all, to produce supply tranches for the ECT model. The electricity generating industry currently accounts for over 50% of the total consumption of coal so that the view is taken that electricity generation takes all marginal coal. Other markets of domestic and coking

coals are taken as prior demands on the industry to be met first before general purpose coal is made available to the electricity industry.

III E THE OIL SUPPLY SUB-MODEL

15. The oil model has not yet been developed to the same extent as the sub-models previously described for the following reasons. The previous three sections describ supply models for fuels which are indigenous to the UK and as such national fuel pol determines the framework within which the industries operate. For oil, the supply is determined by international markets and the price of crude oil ruling in them at the time. Until recently, the combination of crude oil price and charter rates kept the landed price of crude oil steady enough for us to employ a simple 'tap' supply model in which it is assumed that unlimited quantities of oil are available at the ruling market price. Changes in the international oil scene although controlled by re-negotiable agreements between participants at regular five-year intervals make longer term estimates of oil prices more uncertain and the tap model less credible so that an improved representation of oil supply is now necessary. Until the new model is available, the results from our energy sub-models are therefore very dependent on the quality of the advice on the oil price and quantity available fed to it exogenously.

IV INTEGRATION

16. Given the sectoral basis of the models, our first approach to integration was a modular one. A system was designed to run the various sub-models in turn start with the demand module and transferring information on prices and quantities between them after each sub-model had been executed. At the end of a complete pass through a the sub-models, the price generated by the gas model, for example, will be different from the price assumed by the demand model, when it was executed. An additional contr module was devised to chose a new price which would try to reconcile the difference o the next pass. Similarly, the other supply sub-models have generated prices which wi need to be reconciled with the Demand model. The combined effect of these will requir an alteration to the market shares in the Demand model. A complex multidimensional search problem is thus created.

17. There are two major problems with this method of integration:

(a) will it converge?

(b) the expense of running it to convergence.

No guarantee can be given that the technique described will reach a solution which will satisfy the demand and supply models jointly. It would appear plausible given the inbuilt sluggishness in the reponse of demand to price changes that such a solution would exist but this is not certain. On cost, a large number of what may be very expensive iterations could be required before a satisfactory solution is obtained.

18. A pilot study of this area was undertaken with very simplified supply models which shed light on both these problems. The main objective of the study was to examine properties of various convergence strategies which attempted to select improved values for the prices. Even with simplified supply models, the system took over ten iterations to converge to anything approaching a compatible set of quantities and prices and was found to be an expensive system to run. With more representative supply models, the system may take even longer to settle down.

19. At about this time, a new system for building LP models (the matrix generator/ generator became available which encouraged the team involved to look at the possibility of producing an integrated fuel sector model within the framework of a single LP. The difficulty in achieving this centred mainly on the problem of formulating the demand model in LP terms. The first approach was to tranche the demand curves and give each tranche a fixed preference for the four fuels. This approach has many difficulties, not least the problem of developing a price difference tranche structure for a price ratio model. Attempts to resolve this problem led to a parametrised separable program in which a parameter in the model is adjusted until an equilibrium is reached. However, if the demand model could be expressed in price difference terms as opposed to price ratio terms, the parameterisation would be unnecessary. The full development of this latter model is still not yet complete.

20. Linear programming has the disadvantage that the models are relatively complex, they are expensive to run and the results can be difficult to explain. A simpler approach is the econometric or projective type of model in which the optimising power of LP is abandoned during the course of the interactive run.

21. The supply equations used must reflect the resource allocations that are to be made but these may be computed externally to the integrated run by means of a survey of the possibilities so that the cost, quantity, time space can be represented by a small number of parameters. This approach would be valid for problems that involved the normal market price mechanism, even with regulators provided they operated across the board as is usually the case, but clearly distortions caused by differential subsidies on tranches of supply could not be represented without carrying out a speci survey. It seems likely that such a macro econometric model would require a special set of 'interpretive' runs on an LP model to generate the precise implications of the macro-model solution.

22. There is little doubt that the construction of an integrated model of the energy economy is feasible. The component sub-models have been developed to the point of being used separately by policy makers on analytical work in aid of policy decisions. Our experiments on modular integration though successful in achieving convergence lead us to believe that at the level of complexity of the developed sub-models the cost of execution is too high for it to be used widely. The integrate LP has emerged as a result of finding this out but further work is required before we will know whether the resolution of the simplified structure is adequate for policy determination. We propose to press on with the development of an econometric type macro-model as this holds out the hope of dealing with the major technical obstacle-size and therefore the cost of operation.

V A WORLD ENERGY MODEL

23. The balance of the world supply and demand for different fuels forms an essential background of the consideration of national energy policies. It is the purpose of the model which is being constructed to pull together the various estimate which are made from time to time about the availability of fuel supplies and the demands likely to be placed on them. The model is a means of setting out in a formal and systematic way the inter-relationships which exist in the world energy economy, and of illustrating the effects of particular trends and changing assumptions.

24. Although the structure of the model has been kept as simple as possible it contains a very large mass of data much of which is based on assumptions and knowledge which are inevitably speculative. Some of the types of problem that can usefully be examined using the model are changes in the world pattern of consumption caused by:-

(a) changes in the proved reserves of fuels;

(b) changes in producer take (OPEC cartel effects);

(c) changes in import/export restrictions, taxes and political constraints;

(d) the impact of investment in nuclear power;

(e) changes in cost relativities.

25. For the purposes of the model the world has been divided into fifteen regions as shown in Figure 3. The countries have been grouped on the basis of geography, energy significance and with due regard also to political considerations. The model concerned with the supply and demand for five primary fuels: coal, oil, gas, nuclear and hydro power. The standard unit measurement used throughout is 10^9 therms per annum.*

26. Within each region estimates are made of the availability of each fuel in terms of extraction costs and quantities. These estimates are based on the best information which is to hand, but of course the numbers may be changed in the light of new discoveries or technological knowledge. There are thus 75 region and fuel combinations each of which is represented by a "supply curve" which shows the amount of the particular fuel available in that region at ten specified levels of cost in pence per therm. Intermediate costs and quantities are read by interpolation. A typical availability curve for oil in the North America region is given in Figure 4. Similar schedules showing the costs of various tranches of the reserves exist for the other four fuels in North America and for each of the fuels in each of the other fourteen regions.

NOTE: * 1 million tons of coal = 0.23×10^9 therms
1 million tons of oil = 0.42×10^9 therms
1 terawatt hour = 0.034×10^9 therms

27. The next major element in the data input consists of the patterns of actual production and consumption of the fuels in each region. The starting point for these is taken as 1970, the latest year for which fully comprehensive international data is available, and this therefore forms the base line for the model. It is assumed that regional consumption of energy will grow from year to year in line with the growth of GDP which is projected forward on the basis of past trends. This increasing demand can be met by increased production of particular fuels or by substitution between them. In each case there are technological limits to the extent to which such expansion or substitution can take place and these constraints have to be applied to the model. For initial working purposes upper limits have been imposed of 10% per annum as an expansion rate for production and 15% per annum as an upper limit for substitution between fuels. Lower figures than these can, of course, arise within the model as a means of matching supply and demand but if the upper limits are reached, then a deficiency may arise which would have to be met (as in the real world) in other ways.

28. There are a number of other characteristics of the world energy economy which are included in the model. First of all, since the method of the model is to meet demands in each region at the lowest possible cost, it is necessary to include transport costs between particular regions and not merely the extraction costs in the country of origin. This is achieved by a cost of transportation matrix which comes into operation when fuels are assumed to be transported from one region to another and which affects their comparative costs. Second, in the real world there are supply constraints between particular areas which may arise for political or other regions. These can be simulated by a supply constraint matrix which can be adapted to permit or forbid transfers between particular regions. For example, an oil surplus arising in Eastern Europe might or might not be available to meet a deficiency in the West. Thirdly, on similar lines, constraints imposed by contract quantities can be added. Fourth, cost levels are also affected by consumer taxes and these too are identified and taken into account within the model.

29. Having assembled all the data on the lines set out above, the first therm costs of each of the 75 combinations of regions and fuels are sorted and arranged in ascending order of cost and the fuels are allocated to particular regions, working down the list, according to certain decision rules described below.

30. The model begins to work by selecting a tranche of supply from the supply curve containing the lowest cost level out of the 75 assorted combinations. This is represented as a certain quantity of therms from the availability curve. The model attempts to allocate this fuel indigenously first, and then, having satisfied home consumption, if there is any output remaining, attempts to export it. This process goes on through all the tranches of supply until all consumption demands which can be met are satisfied. At this point a report is produced which shows the way in which the allocations of fuel have been made and where any deficiencies exist. This pattern of allocations becomes the data base for meeting the demands arising in the following year. The model moves forward year by year with demand growing according to the earlier growth assumptions, and the supply being provided from the situation depicted by the availability curves.

31. It is necessary to return, however, to explain the rules governing the allocation process in some greater detail. The tranche of supply of the particular fuel (i.e. so many therms of it at a certain cost), is "offered" to the producing region's home market by the posing of three questions:-

1. Can this amount of the fuel be produced? This is answered by reference to the maximum produc ion potential in the region, i.e. production in the base year increased by a growth factor with an upper limit (we have assumed 10%;

2. Does the market need this quantity? This is tested by reference to total energy requirements i.e. consumption in the base year increased by a growth factor with a limit related to the growth of GDP;

3. Can the market consume this quantity of this fuel? This is established by reference to the substitution limits.

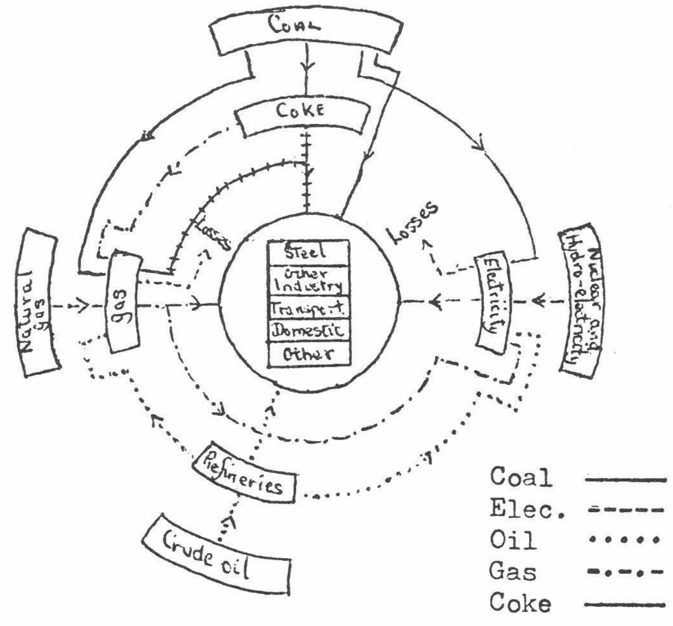
The replies to these questions may set a limit to the quantity allocated, but if the replies to questions 2 and 3 suggest that needs and consumption are less than production the surplus is offered for export.

32. When such a quantity of fuel production is in surplus and available as export potential, preference is given for contracted quantities before offering the quantity for sale. Assuming this point is reached, the model simulates the operation of an auction in order to allocate the exportable surplus. Some bidders may be excluded by the supply constraint matrix which represents political as well as commercial vetoes. For each accepted bidder, the one for which the cost of the auctioned fuel offers the greatest margin over the cost of the highest cost tranche of fuel available to them is judged successful and gets the supply. This is logically consistent with the buyer deriving the maximum utility from the purchase and thus being able to outbid the other competitors. Having identified the purchasing region, the same set of questions (para 31) is asked and an allocation made. If there is still residual output from the producing region the auction is repeated on the remaining tranche of production.

33. The various constraints in the system, e.g. on costs and supplies, are dynamically updated as the calculation proceeds so that eventually so far as possible each region's consumption and production targets are satisfied within the limits of the assumptions made. The calculation ends for the year with a few regions with surplus capacity for export. The lowest marginal cost for these supplies is given in the world summary table at the end of the report generated - these are equivalent to a world 'spot' cost for each fuel.

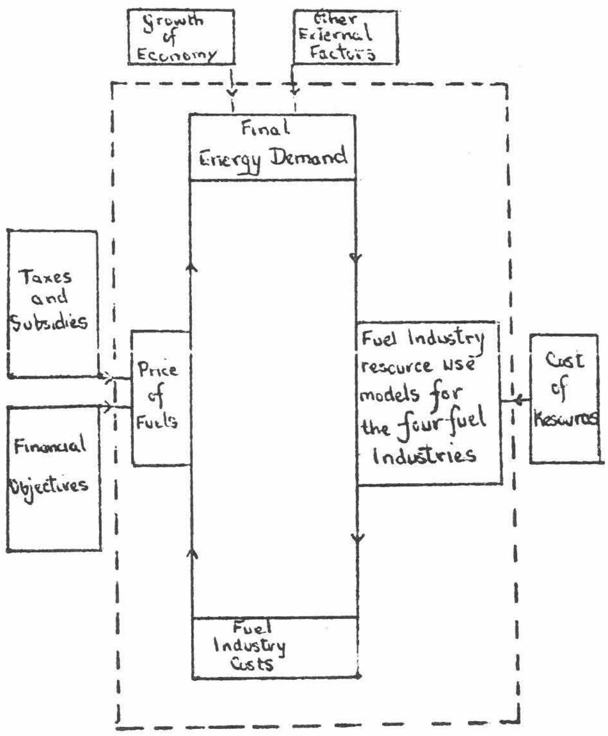
34. The model is dynamic and can be run up to the year 2000 as it is at present set up. So far the allocation logic and theability to set up and execute the next year's allocations correctly has been tested.

Fig 1



Structure of the energy sector

Fig 2



Flow diagram of the energy sector model

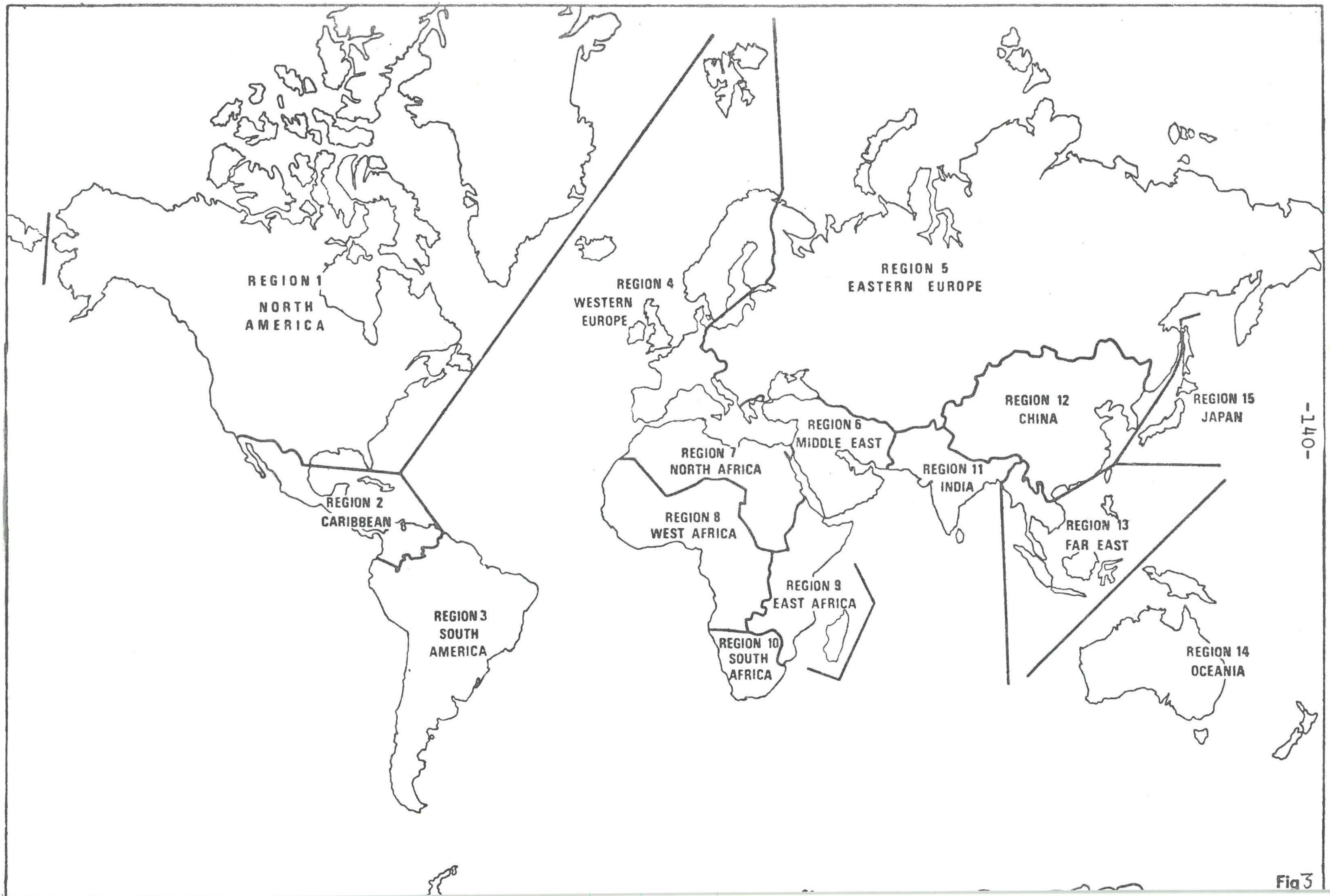

REGION 1
NORTH AMERICA
REGION 2
CARIBBEAN
REGION 3
SOUTH AMERICA
REGION 4
WESTERN EUROPE
REGION 5
EASTERN EUROPE
REGION 6
MIDDLE EAST
REGION 7
NORTH AFRICA
REGION 8
WEST AFRICA
REGION 9
EAST AFRICA
REGION 10
SOUTH AFRICA
REGION 11
INDIA
REGION 12
CHINA
REGION 13
FAR EAST
REGION 14
OCEANIA
REGION 15
JAPAN

Fig 3

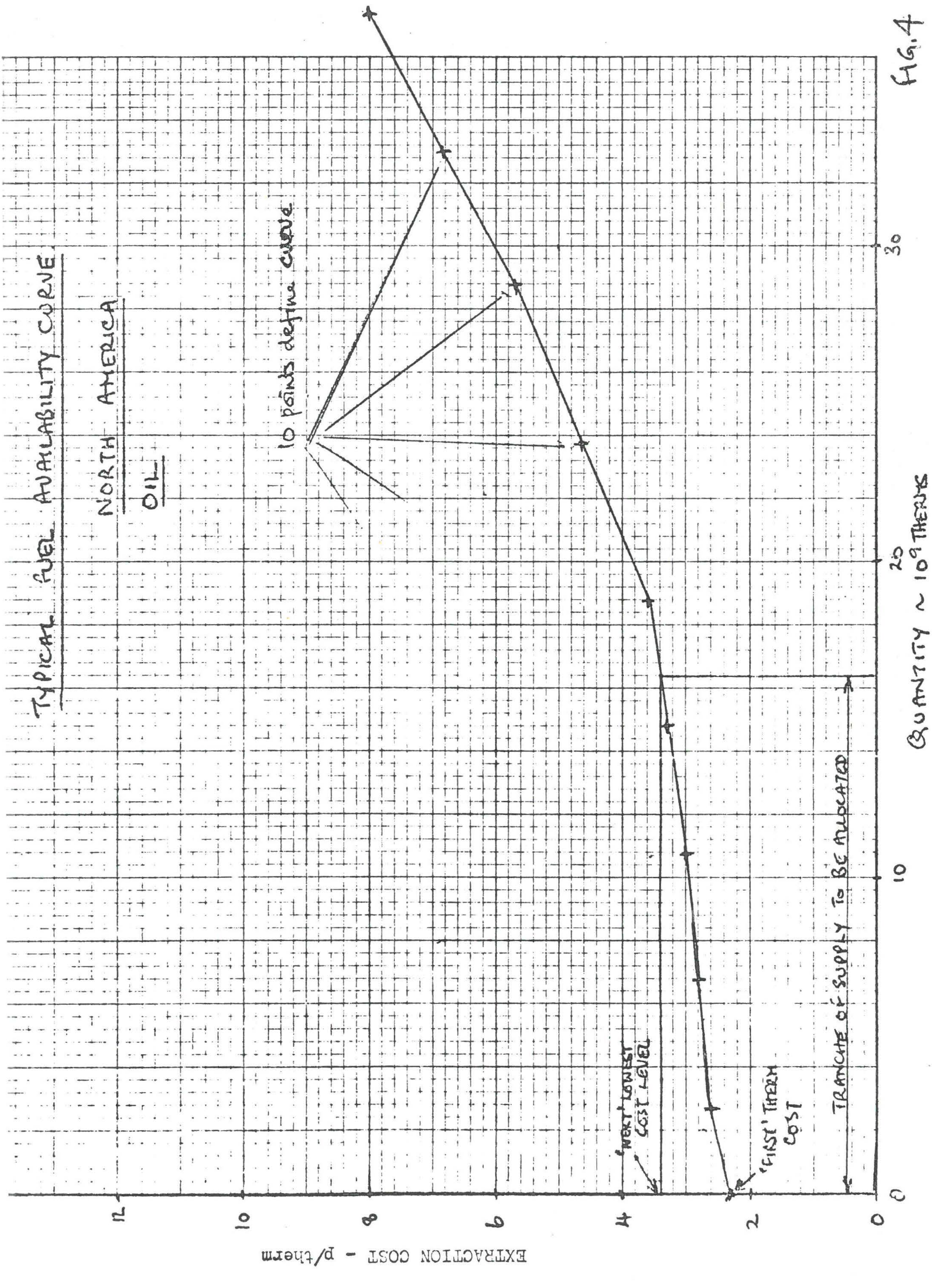

TYPICAL FUEL AVAILABILITY CURVE
NORTH AMERICA
OIL
10 points define curve
'NEXT' LOWEST COST LEVEL
'FIRST' THERM COST
TRANCHE OF SUPPLY TO BE ALLOCATED
EXTRACTION COST - p/therm
QUANTITY ~ 10^9 THERMS
0
2
4
6
8
10
12
10
20
30

FIG. 4

Appendix 1

Technical Description of the Demand Sub-Model

The total final demand for energy to final users is broken down into nine sectors:-

Domestic
Iron and Steel
Other Industry
Public Administration
Miscellaneous and Agriculture
Transport - Rail
Transport - Road
Transport - Water
Transport - Air

Demands for primary fuels to be converted to secondary forms of energy are not considered.

Choice of Model. The form of model used has been largely dictated by the following considerations about the nature of the problem:

1 The determinants of the behaviour of fuel consumers are not known. The method used to investigate them is basically an empirical one. It is assumed that at least part of this behaviour of consumers will give some useful information about the nature of the processes involved and that this information can be applied directly or extrapolated for useful application in the future.

2 It is further assumed that the systematic aspects of consumer behaviour can be described by a mathematical model and that this model can be chosen on the basis of its capacity to represent those features believed to be important in the field.

The form adopted for the model has been further influenced by the nature of available data. All relevant historical data available on a consistent basis is highly aggregated although it is disaggregated as far as the principal sectors of the fuel economy - Domestic, Industry, Commercial, Public Administration, Transport. Differences between these markets as regards fuel purchasing behaviour are expected but they are thought to be differences of degree rather than in the underlying mechanism. To represent this, the structure consists of models of identical form for each sector but with parameters varying between sectors. For technical reasons the Transport sector and the Iron and Steel industry cannot be represented satisfactorily by the selected model form.

Although the estimation of models of the type used is based on consistent time series data, reliable estimation of any parameters by alternative means will tend to improve the remaining estimates (1). The possibility of such alternative estimation using census data such as that obtained by the Family Expenditure Survey has been examined and the initial indications are promising although results from this approach have not yet been adopted.

The Model. The model is in three parts.

Initially, the total energy demand within a sector, E, is expressed as a function of an activity indicator, A, for the sector, the average price of fuel, P, calculated as a weighted average and the temperature, T. In addition, any time trend in the total energy series is estimated by the use of a trend variable, t, whose value increases by 1 in each successive time period. t is also used as a suffix to indicate the time period to which any particular observation on any variable relates. The form used for the total energy demand equation is then

$$E_t = a_0 A_t^{a_1} P_t^{a_2} T_t^{a_3} e^{a_4 t} \qquad (1)$$

which is preferred to the linear alternative

$$E_t = b_0 + b_1 A_t + b_2 P_t + b_3 T_t + b_4 t \qquad (2)$$

partly on intuitive grounds and partly because empirical investigation suggests that it tends to perform better. (The a_i and b_i are constants varying only between the sectors. e is a known constant = 2.7183)

The second part of the model examines the unrestrained or ideal choice of fuel for given total energy. This is distinguished from the actual choice of fuel and represents the choice which consumers would make if they were able to adjust their purchasing behaviour immediately, without the lag imposed in practice by considerations of buying and installing equipment. The model form suggests that the quantity of any fuel, q_i^*, which would be purchased is determined essentially by the price of the fuel, p_i, with reference to a price response factor, θ, which is assumed the same for all fuels.

$$q_{it}^* = A_i \, p_{it}^{-\theta} \qquad (3)$$

The constant A_i represents the effect of non-price factors. The importance of certain of these to the work done with the model and the possible opportunity for improving explanation in terms of measurable variables has suggested removal from this term of economic activity for the sector measured by a suitable indicator, I_t, and any time trend present in q_i^*. The A_i continues to represent the effects of advertising, taste, convenience and other factors and equation (3) becomes

$$q_{it}^* = A_i \, P_{it}^{-\theta} \, I_t^{b_i} \, c_i^{t} \qquad (4)$$

with the responses to activity and time assumed to be fuel specific.

Changes in q_{it}^* will be constrained by changes both in total energy demand and in demands for other fuels. These effects are incorporated by transforming the relationship (4) to that determining the corresponding market share.

If total ideal demand is Q_t, then

$$Q_t = \sum_{\text{all } i} q_{it}^*$$

and $r^*_{it} = \dfrac{q_{it}^*}{Q_t}$ where r_{it}^* is the ideal share of fuel i at time t.

Equation (4) then becomes

$$r_{it}^* = \frac{A_i \, p_{it}^{-\theta} \, I_t^{b_i} \, c_i^{t}}{\sum\limits_{\text{all } j} A_j \, p_{jt}^{-\theta} \, I_t^{b_j} \, c_j^{t}} \qquad (5)$$

Ideal shares are not observable and their behaviour must be deduced from that of actual shares. To do this the third part of the model is brought into use with actual shares, r_i, in time periods t and t-1 assumed related by

$$r_{it} = (r_{it-1})^{\phi} (r_{it}^{*})^{1-\phi} \qquad (6)$$

which implies that purchasing behaviour is adjusted towards the ideal share but at a rate determined by the parameter ϕ which allows for the fact that only a certain proportion of consumers will change their fuel-using equipment in any one year. An alternative mechanism which has been experimented with is

$$r_{it} = \phi\, r_{it-1} + (1-\phi)\, r_{it}^{*} \qquad (7)$$

but this has been found generally less useful than (6). In the remainder of the discussion (6) and (7) are referred to as Model 2 and Model 1 respectively.

ϕ is assumed to be the same for each fuel and

$$\sum_{\text{all } i} r_{it}^{*} = \sum_{\text{all } i} r_{it-1} = \sum_{\text{all } i} r_{it} = 1$$

Units. Use of market shares means that fuel demand data must be prepared in terms of common units and those used are useful therms, calculated from consumptions measured in original units by use of thermal contents and efficiencies. The thermal contents are physical constants but efficiency factors depend upon assumptions about the population of fuel-using appliances in each sector and the conditions under which they work. A future application of the model will be improvement of the approximate efficiencies used at present.

Regression. The technique used for the analyses is multiple linear regression. This is described extensively in numerous sources, e.g. (2), (3), and is not explained here.

Linearisation. The use of multiple regression requires linearisation of the model functions and addition of a stochastic term to the specified relationship to allow for non-systematic variations in the dependent variables. In the case of relation (1) this can be done directly by assuming a multiplicative stochastic effect and expressing the relation as a linear structure in logarithms. If the stochastic term is represented by u, then (1) becomes

$$E_t = a_0 A_t^{a_1} P_t^{a_2} T_t^{a_3} e^{a_4 t} u_t \qquad (8)$$

and in logarithms this becomes

$$\log E_t = \log a_0 + a_1 \log A_t + a_2 \log P_t + a_3 \log T_t$$
$$+ a_4 t + \log u_t \qquad (9)$$

in following the same procedure for equation (6), r_{it}^* must be removed since it is not measurable. This is done by substituting equation (5), giving

$$\log r_{it} = \phi \log r_{it-1} + (1-\phi) \log \left[\frac{A_i \, p_{it}^{-\theta} \, I_t^{b_i} \, c_i^t}{\sum\limits_{\text{all } j} A_j \, p_{jt}^{-\theta} \, I_t^{b_j} \, c_j^t} \right] \qquad (10)$$

which is not linear in the logarithms of the observed variables. To overcome this relation (11) is constructed as a log ratio of the shares of any two fuels in the form

$$\log \left[\frac{r_{it}}{r_{kt}}\right] = \phi \log \left[\frac{r_{it-1}}{r_{kt-1}}\right] + (1-\phi) \log \left[\frac{A_i}{A_k}\right] - \theta (1-\phi) \log \left[\frac{p_{it}}{p_{kt}}\right]$$
$$+ (b_i - b_k)(1-\phi) \log I_t + (1-\phi) \log \left[\frac{c_i}{c_k}\right] t \qquad (11)$$

and a stochastic term added to this.

Such a transformation cannot be made directly in the case of relation (7) and the equivalent reformulation of this used is

$$\log \left[\frac{r_{it} - \phi \, r_{it-1}}{r_{kt} - \phi \, r_{kt-1}}\right] = \log \left[\frac{A_i}{A_k}\right] - \theta \log \left[\frac{p_{it}}{p_{kt}}\right]$$
$$+ (b_i - b_k) \log I_t + \log \left[\frac{c_i}{c_k}\right] t \qquad (12)$$

in which one unknown parameter (ϕ) appears on the left-hand side. In estimating this relation regressions are carried out for each of a number of ϕ values and the "best" value of ϕ and the other coefficients deduced from a consideration of the various statistical measures.

Estimation. Consideration of relations (11) and (12) shows that for any number of fuels there will be only a limited number of ratios from which valid information can be derived. For the 4 fuels examined in our studies, only 3 ratios will yield independent results. Further, if as assumed, the parameters ϕ and θ are the same for all fuels, their values should be obtained more efficiently by pooling the data for all 3 ratios in the estimation of these quantities. For estimation by regression special variables must be constructed to allow for the fuel-specific responses to the other variables.

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Appendix 3

Technical Description of the Electricity Investment Sub-Model

INTRODUCTION

1 The Electricity Generating System exists to meet the demand for electricity. This demand varies in time, fluctuating from hour to hour, and growing over the years. The short-term variations in demand are met by having sufficient capacity in the system to meet the peak demand. To meet increases in demand for electricity in the longer term, additional power station capacity must be built. There is a choice of types of station which can be built at any point in time, and a choice of the type of fuel used.

2 The Investment Model of the electricity generating industry represents the principle investment decisions that have to be taken by the industry, namely the choice of plant mix to be built, to meet growing demands for electricity. For each type of new station, there are variables in the model representing

a the capacity of the station; (MW so)

b the use made of the stations over their lifetime;

and c the fuel used by the station

Given data about the capital cost of the capacity, the running cost of the station in generating electricity, and the cost of the fuel used, the total cost of adding any new capacity to the system is evaluated. From among all the possible combinations of plant which could be used, the model chooses that plant mix which minimises the total cost of meeting the demands made on the system.

3 The mathematical form of the model is a mixed-integer programme which minimises the total discounted system cost over the period studied. Certain approximations are made in representing the system. It is a "point" model, in that no representation is made of the geographical distribution of energy and fuel supply. The power stations are combined into groups on the basis of thermal efficiency and broad geographical location. These groups of plants

are associated into fuel groups. The supply curves representing the cost of each fuel can be approximated by up to five price levels. The transport and handling costs are included in the running costs for each plant group. The representation of the system through time is approximated by modelling the system operation in "snapshot" years, and interpolating the variables and costs for the intervening years.

4 In order to define the characteristics of the system within which the minimum cost program is found, the following main assumptions and data must be specified :-

a The future load and pattern of demand to be supplied by the generating system.

b The existing and contracted capacities of all types of plant.

c For each plant type to be considered the following physical characteristics are required:

Fuel used - coal, oil, gas, nuclear;

Thermal efficiency

Maximum and mean availability (within a year)

Development pattern of availability (of a new set)

Physical and accounting life

Any limitations on capacities which can be built

Earliest commissioning date of each type of plant

Any predetermined order in which plants must be built eg the early development versions must be built before the later versions

d The cost information required by the model consists of

Capital cost of new capacity (either varying in time or on capacity constructed)

Running costs of each plant group

Fixed costs of each plant group

Fuel costs

e Additional data required are

Discount rate to be used

Depreciation pattern to be used for valuing plant at the end of the study

Planning margin on SMD

Any minimum or maximum constraints on the quantity of fuel used.

f For plant types producing and using plutonium, the production and refuelling rates are needed, together with the initial fuel requirement.

Different types of plant are distinguished by different combinations of these characteristics.

5 In choosing the minimum cost plant mix, the model ensures that various physical constraints and relationships are satisfied. These constraints are as follows:

a The demand for electricity must be met at all times and for all years.

b The use made of any plant must be less than or equal to the stated available capacity of that plant.

c The total capacity in any year must be greater than the ACS peak demand in that year, by the margin deemed necessary to ensure the desired level of risk of plant outage.

d Some plant types are inflexible, in that they are unable to follow rapid changes in load, and are therefore restricted to base load operation.

e The amount of fuel taken at a given price may be restricted.

f The total amount of any fuel may be restricted either to a minimum or a maximum level.

g The total stock of plutonium must be in positive balance at all times; ie before fast reactors are introduced to the system, there must be sufficient plutonium available to fuel them, produced from thermal reactors.

h Whenever conventional and nuclear main sets are built, auxiliary gas turbines are also brought into the system to a stated level.

i If required, prespecified plant programs can be introduced into the system. In this case the remaining plant program is chosen and operated to minimise costs.

j Any order imposed on the introduction of plants is satisfied.

6 The results produced by the model:

a the new plant built in each year studied

b the electricity generated by each plant type in each year

c the quantities of fuel used in each year

d the capital and operating costs in each year

e the production and consumption of plutonium between each snapshot year

f estimates of the marginal costs of different patterns of load increment

g the availability of the system in each year

VARIABLES USED IN THE MODEL

7 The values of the variables represent the operation of the different plants in each year, the amount of new plant commissioned in each year, and the quantities of each type of fuel used in each year. The degree of detail used in the model is defined by the following quantities.

NPLANT : the number of plant groups represented, indexed by p.

NYR : the number of snapshot years considered, indexed by i.

NINST : the number of snapshot instants used within each year, indexed by l.

NFTYP : the number of fuel types used, indexed by k.

NFTNCH : the number of tranches of each fuel represented, indexed by t.

NSTAP : number of types with several development stages, indexed by q.

NSTAGE : maximum number of development stages, indexed by s.

The variables used in the model can now be written down as follows.

n_{pi} : defined for $p = 1, 2, \ldots, \text{NPLANT},$

$i = 1, 2, \ldots, \text{NYR},$

representing the capacity of new plant of type p commissioned between snapshot years y_{i-1} and y_i.

z_{pli} : defined for $p = 1, 2, \ldots, \text{NPLANT},$

$i = 1, 2, \ldots, \text{NYR},$

$l = 1, 2, \ldots, \text{NINST},$

representing the increase in use of plant p, between snapshot instants l and l + 1, in year y_i.

f_{kti} : defined for $k = 1, 2, \ldots, \text{NFTYP},$

$t = 1, 2, \ldots, \text{NFTNCH},$

$i = 1, 2, \ldots, \text{NYR},$

representing the quantity of fuel type k taken from tranche t in snapshot year y_i.

p_i : defined for $i = 1, 2, \ldots, \text{NYR},$

representing the stock of plutonium at the start of snapshot year y_i.

a_{qis} : variables used in arranging the different development stages of new types of plant into order. These variables are formed into Special Ordered Sets within the UMPIRE system, and are used to introduce the necessary integer programming in a compact manner into the model.

The interpolation of these variables between snapshot years is illustrated in Figures 1 and 2.

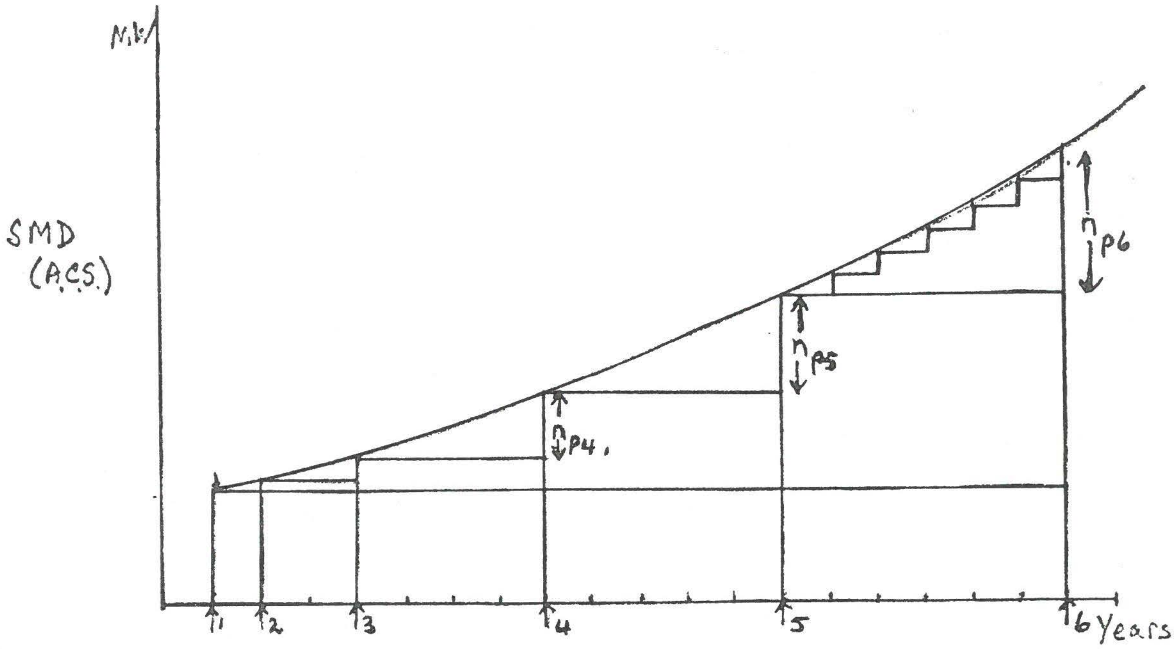

Figure 1

The new plant variables n_{pi} represent the increase in the total plant capacity between snapshot years. This increase is assumed to be distributed over the intervening years as indicated, and is costed and discounted accordingly.

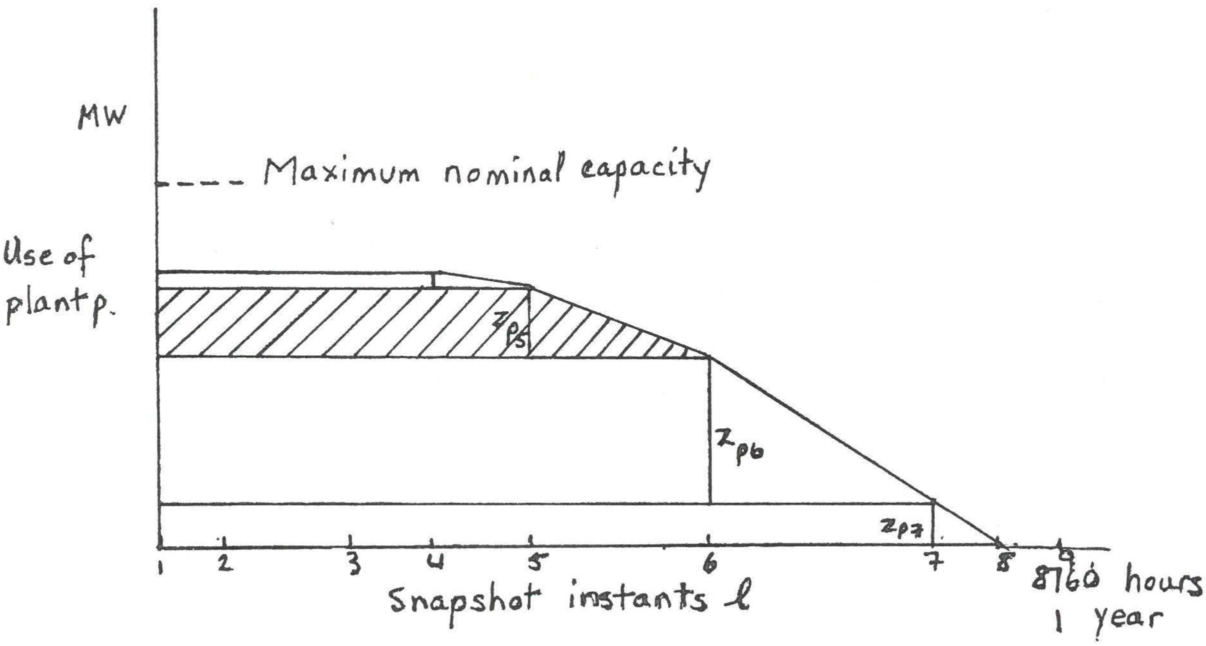

Figure 2

The use of the increments of use, z_{pli} is primarily for reasons of efficiency in the linear program. A consequence of this representation is that the duratic curve of each plant is taken to be monotonic. This means that the representatic of plants with an interruptible supply of fuel will require some modification.

8 The energy sent out by the station is represented by the area under the curve, which can be divided into sections associated with each increment z_{pli} as indicated by the shaded area in Figure 2. Given the location of the snapshot instants l, the evaluation of these areas, and thus the energy sent out by the plant, is very straightforward. Similarly, the quantity of fuel used by the plant is directly related to the energy sent out, and thus the total quantities of each type of fuel used. The purpose of the variables f_{kti} is to represent the possible variation in the price of fuel with the quantities taken, as shown in Figure 3.

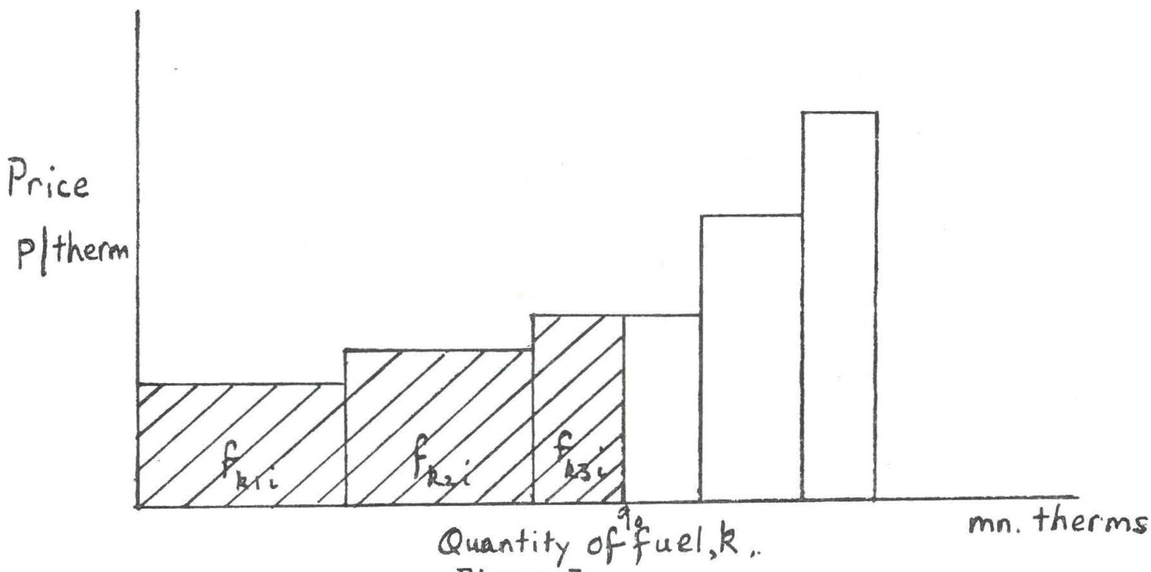

Figure 3

The shaded area indicates the cost of a quantity of fuel q_o, represented by the three variables f_{k1i}, f_{k2i} and f_{k3i}, these variables essentially define quantities of fuel type k distinguished only by differences in cost to the industry.

DATA AND ASSUMPTIONS REQUIRED BY THE MODEL

9 The environment within which the industry will have to operate is defined by the demands for electricity to be met by the industry, the physical and cost characteristics of the generating plants available for meeting the demands, and the thermal and cost characteristics of the fuels available to the industry. This section describes the elements of data required as input to the model in order to define this environment of the industry.

DEMAND DATA

10	$NYRNO_i$	:	The snapshot years to be used by the model. $NYRNO_1$ is the first year of the study, $NYRNO_{NYR}$ the last.
	HR_l	:	The hours from peak, defining the snapshot instants at which demand is represented within each year.
	DEM_{li}	:	The demand rate relative to peak demand in year $NYRNO_i$ at duration HR_l. This pattern defines the load duration curve in each year, and implies the load factor of demand assumed in that year.
	$PKFAC_i$	:	The planning margin to be applied in year $NYRO_i$.
	SMDALL(j)	:	The peak demands to be met in <u>all</u> years of the study, the index j running from $NYRNO_1$ to $NYRNO_{NYR}$.
	SMDi	:	The peak demand in year NYRNO;

The pattern of peak demands is used to interpolate activities between the snapshot years used.

The interpolation of variables between snapshot years is defined in terms of weights to be applied to the model variables associated with the snapshot years. Denoting values in all year by capitals, and values of snapshot variables by lower case, we define:

$$X_j = \sum_{L=1}^{NYR} W_{ji}\, x_i$$

where j is an index running over all years.

The weights W_{ji} are such that

$$\sum_{L=1}^{NYR} W_{ji} = 1$$

In the implementation used in this model the weights are defined as

$$W_{ji} = \frac{SMDALL(j) - SMDALL(NYRNO_{i=1})}{SMDALL(NYRNO_i) - SMDALL(NYRNO_{i-1})} ,$$

$$W_{ji-1} = 1 - W_{ji} ,$$

$$\text{for } NYRNO_{i-1} < j \leqslant NYRNO_i ;$$

$$W_{ji} = o \quad \text{otherwise.}$$

In matrix notation, these interpolation formulae can be written as

$$\underline{X} = W\, \underline{x}$$

and are applicable to variablesrepresentive cumulative, or total activities in each year.

For variables, such as the new plant building variables, which represent the increment in a total quantity between years, a different, but related, set of weights are used. These weights are denoted by V_{ji}, and in matrix notation we have

$$\underline{N} = V\underline{n},$$

the elements V_{ji} being defined as

$$V_{ji} = \frac{SMDALL(j) - SMDALL(j-1)}{SMDALL(NYRNO_i) - SMDALL(NYRNO_{i-1})}.$$

$$\text{for } NYRNO_{i-1} < j \leqslant NYRNO_i$$

$$V_{ji} = o \quad \text{otherwise.}$$

In the formulation of the model, the general form of these interpolation formulae is used, so that any change in the particular weights required will be straightforward, and will not affect the constraints or objective function of the linear program. Interpolating between values of variables within the year is different in kind, since it is continuous rather than discrete. The principle is however the same, in that the shape of the load duration curve is used for interpolating between variables representing activities at snapshot instants. In this present formulation, the load duration curve is approximated by a polygon between the demand levels at the snapshot instants; that is the interpolation shape between each pair of snapshots is a straight line. Given this fact, any required interpolation can be easily worked out. In particular, to evaluate the total energy supplied by plant p in year i, we have to evaluate the areas shown in Figure 2. The data values HR_l denote the distance of the instants l from the peak. It is then obvious that the shaded area is given by

$$\tfrac{1}{2}(HR_4 + HR_5)\ z_{p5i}$$

and the total energy produced is given by

$$\sum_{l=1}^{NINST} HRS_l\ z_{pil}$$

where

$$HRS_l = \tfrac{1}{2}(HR_l + HR_{l+1}) \text{ for } l = 1, 2, \ldots, NINST$$

with $$HR_{NINST+1} = HR_{NINST}$$

These weights HRS_l are used for all plants.

PLANT DATA

11 $ACAP_{pi}$: The existing and contracted capacity of plant p in year $NYRNO_i$. Included in this figure are the existing capacity at the start of the study, the additions to capacity by new building during the study period already contracted for at the start of the study, less the capacity scrapped by year $NYRNO_i$.

$GNUMB_p$	:	The fuel used by plant p, identified by a fuel group number.
$AVPEAK_{pi}$	:	Availability of plant p in year $NYRNO_i$, on-peak and off-
$AVOFF_{pi}$		peak respectively.
NFFINS	:	An index defining the first off-peak instant.
$COMP_p(t)$	:	Development pattern of availability for plant p, defining the availability of new capacity relative to the final availability after t years of operation.
$LPHYS_{pi}$	:	Physical life of capacity of plant type p built between years $NYRNO_{i-1}$ and $NYRNO_i$.
$LACCNT_{pi}$	:	Accounting life of capacity of plant type p built between years $NYRNO_{i-1}$ and $NYRNO_i$.
$IPINS1_p$	:	First year in which new capacity can be commissioned.
$IPINS2_p$	:	Last year in which new capacity can be commissioned.
$HRMIN_{pi}$	:	The minimum number of hours which plant p must be operated in year $NYRNO_i$. This is used to constrain plants to operate above a required load factor, ie restricting their ability to follow rapid changes in load.
EFF_p	:	Thermal efficiency of plant p.
$GTPER_p$	:	Proportion of auxiliary gas turbine capacity associated with new capacity of plant p.
$BMIN_{pi}$	:	Lower and upper limits on the new capacity of plant p
$BMAX_{pi}$		that can be built between years $NYRNO_{i-1}$ and $NYRNO_i$.
$NOST_q$	:	The number of development stages for new type q.
$NSETQ_{qt}$	:	Plant number corresponding to stage t of type q.
$QCAP_{qt}$	:	Capacity of stage s to type q which must be built before stage t + 1 is built.
$FULRAT_p$	:	Initial plutonium requirement for new capacity of plant p, associated with fast reactor stations.

$PRDRAT_p$: Plutonium production rate for plant p, associated with thermal and fast reactors.

$REFRAT_p$: Plutonium refuelling rate for plant p, associated with fast reactors.

$REFRAT_p$: Plutonium refuelling rate for plant p, associated with fast reactors.

These items of data define the characteristics of the plant type made available to the model. An important characteristic is the fuel group number, identifying the fuel burnt by the plant type. As currently implemented, the existing stations are represented by two nuclear, four oil, 12 coal, two gas and one gas turbine group. Within these fuel groups, the main difference is in thermal efficiency, and the associated difference in operating costs.

FUEL DATA

12 $FTMAX_{kti}$: The maximum quantity of fuel k available in year $NYRNO_i$ at price $COSTF_{kti}$.

$FMAX_{ki}$: Upper and lower limits on the quantity of fuel k taken in

$FMIN_{ki}$ year i.

PSTOCK : Initial stock of plutonium at the start of the study.

Using the tranches of fuel $FTMAX_{kti}$ with the associated prices, supply curves for each fuel can be represented, together with changes in fuel prices over time. A modification is being considered which will enable any shape of supply curve to be approximated. The present formulation will only represent curves in which the cost of the fuel increases with quantity.

COST DATA

13 $COSTZ_p$: The operating cost for plant p, in units p/kWh, the components being the fuel handling costs, fuel handling repair and maintenance, and $\frac{1}{3}$ of the other R & M costs, together with delivery costs.

$COSTC_{pi}$: Capital cost of new plant type p built in year $NYRNO_i$. This cost includes the construction cost, the interest during construction, and the initial fuel charges in the case of nuclear plant. The interest during construction represents the compounding forward to the time of commissioning of the stream of cash spent during construction. Units are £/kW.

$COSTF_{kti}$: The cost of fuel type k, from tranche t in year $NYRNO_i$ The units used are p/therm, and these costs are taken to be the fuel costs at pit-head, or ex-refinery.

FC_p : Fixed costs for plant p, and the pattern of fixed costs
$FC_p(t)$ over the lifetime of plant p, are part of the avoidable costs of any new capacity built.

These four items are used to cover all items of avoidable cost. Modifications are being considered for the representation of fuel costs, to cover the possibility of a fuel supply curve which falls with quantity. In the representation of capital costs, the representation of the necessity of building high cost stations of a new type before constructing later stations at lower cost, is included in the facility for ordering stations, using the variables quoted by a_{qis}.

RELATIONSHIPS AND CONSTRAINTS

14 Before the values of the variables described in paragraph 4 can be considered to be representing the generating system, they must satisfy various constraints and relationships which define essential characteristics of the system. In this section the relationships in the model are listed, together with their mathematical forms which have been included in the model.

14.1 Demand Constraint

The demand for electricity must be met at each instant, in each year. This is expressed in the model in the form that the increase in the total load supplied from one instant to the next must be greater than the increment in the demand between these instants.

$$\sum_p z_{pli} \geq (DEM_{li} - DEM_{ltli})*SMD_i$$

for $l = 1, 2, \ldots, NINST$

and $i = 1, 2, \ldots, NYR$

14.2 Capacity Constraint

The use made of any plant at any instant must be less than the available capacity at that instant. These constraints are defined for each plant in each year at two levels, an on-peak and an off-peak level ov availability. The mathematical forms defined below are modified in the programme its f for technical reasons which improve the efficiency of the linear program.

On-peak:

$$\sum_{l=1}^{NINST} z_{pli} \leq AVPEAK_{pi} \left[ACAP_{pi} + \sum_{j=1}^{i} \alpha_{pji} \; n_{pj} \right]$$

for $p = 1, 2, \ldots, NPLANT$,

and $i = 1, 2, \ldots, NYR$,

$$\text{where } \alpha_{pji} = \sum_{k = NYRNO_{j-1} + 1}^{NYRNO_j} V_{kj} * COMP_p(i - k + 1) * TRFOI_{pki}$$

= the proportion of plant built between years y_{j-1} and y_j which is available in year i, taking account of the build-up of availability of new capacity

and $TRFOI_{pki} = 1$ if $i < k + LPHYS_{pj}$

$= 0$ otherwise,

thus scrapping new capacity after the physical life.

Off-peak

$$\sum_{l=NFINS}^{NINST} z_{pli} \leq AVOFF_{pi} \left[ACAP_{pi} + \sum_{j=1}^{i} \alpha_{pji} \; n_{pj} \right]$$

for p = 1, 2, ..., NPLANT,

for i = 1, 2, ..., NYR.

14.3 Inflexibility of Operation

Plants may be restricted to operate above some minimum load factor. The purpose of these constraints is to model the inflexibility of some types of plant, particularly early nuclear stations, which cannot be switched on and off within short periods of time.

$$\sum_{l=1}^{NINST} HRS_l \, z_{pli} \geq HRMIN_{pi} \left[ACAP_{pi} + \sum_{j=1}^{i} \beta_{pji} \; n_{pj} \right]$$

for p = 1, 2, ..., NPLANT

and i = 1, 2, ..., NYR

$$\text{where } \beta_{pji} = \sum_{k = NYRNO_{j-1}+1}^{NYRNO_j} V_{kj} \, TRFOI_{pki}$$

$$\text{and } TRFOI_{pki} = 1 \quad \text{if } i < k + LPHYS_{pj}$$

$$= o \quad \text{otherwise.}$$

At present care is necessary in setting the data for this constraint since it may conflict with the availability constraints 14.2

14.4 Security of Supply

Sufficient total capacity must be planned to ensure that the peak demand can be met with the desired level of risk. This requirement may be expressed in several ways eg

a Total nominal capacity must be equal to a fixed margin above expected peak demand. When system availability is changing systematically, this constraint will result in a changing security level.

b Total available capacity must be equal to a fixed margin above expected peak demand, resulting in a fixed security level of supply.

c Total available capacity must be greater than a given margin above expected peak demand. In this situation, the security will be at least as high as a specified level, but if economically beneficial, more capacity can be built resulting in a higher level of security than necessary.

d Total available capacity must be equal to a given margin over peak demand, unless other constraints on the capacity which can be built conflict with this requirement, in which case the margin must move to accommodate them.

These various alternatives are built into the constraint used in the model, the particular constraint used being selected by the data supplied at execution stage. The two major alternatives (nominal and available capacity) are shown separately.

Nominal Capacity

$$\sum_{p} \left[ACAP_{pi} + \sum_{j=1}^{i} \beta_{pji}\, n_{pj} \right] + sl_i - sh_i = PKFAC_i * SMD_i$$

Available capacity

$$\sum_{p} AVPEAK_{pi} \left[ACAP_{pi} + \sum_{j=1}^{i} \alpha_{pji}\, n_{pj} \right] + sl_i - sh_i = PKFAC_i * SMD_i$$

for $i = 1, 2, \ldots, NYR$

where α_{pji}, β_{pji} are defined in 14.2 and 14.3 above.

The "slack variables", sl_i and sh_i, allow the equality to be broken in either direction, the preferred direction being controlled by the costs associated with these variables in the objective function.

14.5 Fuel Balance

The amount of each fuel supplied to the system must be equal to the amount of that fuel burnt by the system. At present this constraint is a simple balance, but it can be modified to take account of stocks of fuel held within the system. It should also be possible to take account of lighting up oil used by coal fired stations by modifying the conversion factors K_p.

$$\sum_{p \in FG_k} K_p \sum_{l=1}^{NINST} HRS_l \, z_{pli} = \sum_{t=1}^{NFTNCH} f_{kti}$$

for i = 1, 2, ..., NYR, and k = 1, 2, ..., NFTYP,

where $K_p = \dfrac{1}{EFF_p * 29300}$

a conversion factor from MWh to million therms and FG_k is the group of plants using fuel k.

14.6 Fuel Supply Limitations

The amount of fuel taken from each tranche (ie at each price) must be less than the quantity of fuel available in that tranche.

$$f_{kti} \leq FTMAX_{kti}$$

for k = 1, 2, ..., NFTYP,

t = 1, 2, ..., NFTNCH;

and i = 1, 2, ..., NYR.

14.7 There may be minimum and maximum limits on the total quantity of each fuel which can be supplied, in each year

$$FMIN_{ki} \leq \sum_{t=1}^{NFTNCH} f_{kti} \leq FMAX_{ki}$$

for k = 1, 2, ..., NFTYP

and i = 1, 2, ..., NYR.

14.8 Building Constraints

Limitations on the amount of new plant built between snapshot years can be introduced, either in the form of equality constraints, to fix a particular plant program, or as minimum or maximum constraints, representing respectively a minimum level of orders to maintain a manufacturing capability, and a maximum possible construction capacity for any type of plant.

$$BMIN_{pi} \leqslant n_{pi} \leqslant BMAX_{pi}$$

for $p = 1, 2, \ldots, NPLANT$,

and $i = 1, 2, \ldots, NYR$.

14.9 Auxiliary Gas Turbines

With any modern large set there is associated an auxiliary gas turbine, which is used in starting up the station, and in emergencies. Under normal operation, these auxiliary gas turbine plants are available for meeting peak demands. The proportion of capacity which forms the auxiliary gas turbine is supplied for each fuel group, and the constraint is applied to all plants within the gas turbine group, FGT.

$$\sum_{p \varepsilon FGT} n_{pi} \geqslant \sum_{p} GTPER_{p} \, n_{pi}$$

for $i = 1, 2, \ldots, NYR$.

14.10 Plutonium Balance

For a system which includes thermal and fast reactors, there may be a constraint imposed on the operation of the system because of the need to have sufficient plutonium available to fuel the initial programme of fast reactors. After some time enough plutonium will be produced by the fast reactor program to be self-sustaining. This restriction is modelled by requiring the stock of useful plutonium to be positive. It is expressed in the form:-

Decrease in stock between two years

= plutonium used for initial fuelling of new plant commissioned at start of second year

+ plutonium used for refuelling fast reactors during the year

- usable plutonium produced from thermal and fast reactors

The last term covers the fact that, after being produced in a reactor, the plutonium must be cooled and refabricated before it can be supplied to the system, a process which takes about 9 months. The mathematical form given below expressed the constraint between snapshot years $NYRNO_i$. It may be necessary to introduce the constraint for all years.

$$p_i = p_{i-1} - \sum_p FULRAT_p \, n_{pi} \quad + \quad .... \, ($$

$$+ \sum_p \sum_l \sum_{j=1} \Big[\tfrac{3}{4} PRDRAT_p \, HRS_l \sum_{k=NYRNO_{i-1}-1}^{NYRNO_i-2} W_{kj}$$

$$+ (\tfrac{1}{4} (PDRAT_p - REFRAT_p) \, HRS_l \sum_{k\,=\,NYRNO_{i-1}}^{NYRNO_i} W_{kj} \Big] z_{plj}$$

for $i = 1, 2, ..., NYR$

(When the stock at the start of every year is modelled, the stock variables (p_k are indexed by k which will run over all years. The constraint is then of the form

$$p_k = p_{k-1} - \sum_p \sum_i FULRAT_p \, V_{ki} \, n_{pi}$$

$$+ \sum_p \sum_l \sum_i HRS_l \Big[(0.75 W_{k-2i} + 0.25 W_{k-1i}) \, PRDRAT_p - W_{k-il} \, REFRAT_p \Big] z_{pli}$$

The form of the matrices W and V will in practice reduce the number of variables appearing in these constraints))

14.11 Launching costs of New Types

A group of different plants may be constrained to be built in a given order in time. In particular, if the plants represent development stages of a new type of plant, each stage may not be built unless a given capacity of the previous stage has been built. Such a situation can arise when the developed forms of the type may be economically attractive, although the early versions are not. The questions then arise as to whether the combined programme is viable, and, if so, in the context of the complete system, when it should be built. The following constraints impose the required arrangement on the group of plants denoted by $NSETQ_{qt}$, $t = 1, 2, \ldots, NOST_q$.

The variables a_{qis} are constrained by the equation

$$\sum_{s=1}^{NS_q} a_{qis} = 1$$

where $NS_q = NOST_q + 1$

These variables are related to the new plant building variables n_{pi} by the equalities

$$n_{p_{qt}i} = QCAP_{qt} \sum_{s=t+1}^{NSq} (a_{qis} - a_{qi-is})$$

for $t = 1, 2, \ldots, NOST_q$, and where $p_{gt} = NSETQ_{qt}$.

When an additional condition is imposed on each set of the variables $(a_{qis}, s = 1, 2, \ldots, NS_q)$ that at most two may be non-zero, and these two must be neighbouring elements of the set, the above constraints result in the required arrangement of the plants into order.

14.12 Smoothing of Plant Building

In some studies, it may be desirable to restrict the pattern of building of some types of capacity over the period of the study to follow a smooth path. That is, from one period to another the rate of addition of capacity should not oscillate too violently. To enable such restraints to be imposed, constraints can be added to the model which limit the building on one year to within specified ranges of the amount built in the previous year.

14.13 The basic form of the constraint is

$$\sum_{p \in x} n_{p\ i+1} \lessgtr \beta \sum_{p \in x} n_{pi} \pm \alpha$$

where α and β are set to give the required growth or decay rates from one year to the next and X is the group of plants being restricted. To cater for the situation where the snapshot years are distributed in time, the constraints take the form

$$\sum_{p\varepsilon x} n_{pi+1} \lessgtr \beta^{l} \left(\frac{\beta^{k} - 1}{\beta^{l} - 1} \right) \sum_{p\varepsilon x} n_{pi} \pm \frac{\alpha}{\beta - 1} \left[l \beta^{l} \left(\frac{\beta^{k} - 1}{\beta^{l} - 1} \right) - k \right]$$

where $l = (NYRNO_{i} - NYRNO_{i-1})$

and $k = (NYRNO_{i+1} - NYRNO_{i})$

When $\beta = 1$, this reduces to

$$\sum_{p\varepsilon x} n_{pi+1} \gtrless \frac{k}{l} \sum_{p\varepsilon x} n_{pi} \pm \frac{\alpha}{2} k(k+1)$$

Varying the values of α, β enables more of less restrictive limits to be applied as desired.

THE OBJECTIVE FUNCTION

15 Any set of values of the variables which satisfy the relationships and constraints defined in paragraph 14 represents a feasible method of operating the generating system over the period considered. The model is completed by specifying an objective function. By choosing that set of values of the variables which satisfies the constraints, and which "extremises" the objective, we determine the method of operating the system which the industry will use to meet its objective. In the present formulation, the objective function used in the model is the total discounted system cost of operating the system over the period studied.

The total system cost, present-valued to the start of the study is composed of three components as at present implemented. These components are the capital and fixed capacity related costs, the operating costs, including transport and handling, and the fuel costs. The mathematical form is

$$\sum_p \sum_i CON_{pi}\, n_{pi} + \sum_p \sum_l \sum_i COZ_{pli}\, z_{pli} + \sum_k \sum_t \sum_i COF_{kti}\, f_{kti}$$

The coefficient of n_{pi}, representing capital and fixed costs, is given by

$$CON_{pi} = COSTC_{pi} \sum_{j = NYRNO_{i-1}+1}^{NYRNO_i} V_{ji}\, \delta^{j-1}\, DEPREC_{pj}$$

$$+ FC_p \sum_{j = NYRNO_{i-1}+1}^{NRYNO} V_{ji} \sum_{k=j}^{kmax} \delta^{k-1}\, FCP\,(k - j + 1)$$

where $\delta = \dfrac{1}{1 + DISC}$, gives present value effect,

$DEPREC_{pj} = \dfrac{1 - \delta^{K+1}}{1 - \delta^{L+1}}$, gives fraction of capital depreciated in period of study,

$K = \min\,(LACCNT_{pi},\ NYRNO_{NYR} - j + 1)$,

$L = LACCNT_{pi}$,

and $kmax = \min\,(j + LPHYS_{pi} - 1,\ NYRND_{NYR})$.

The operating cost coefficient is given by

$$COZ_{pli} = COSTZ_p\, HRS_l\, CSTRUN_i\, CONVZ$$

where $CSTRUN_i = \sum_{j=1}^{NYRNO_{NYR}} W_{ji}\, \delta^{j-1}$

and $CONVZ = 0.01$

= conversion factor to give £'000 in the objective function.

The fuel cost coefficient is

$$COF_{kti} = COSTF_{kti}\, CSTRUN_i\, CONVF$$

where $CONVF = 10$

= conversion factor to £'000.

Additional terms are added to the objective function to deal with the slack variables introduced in the constraints in section 14.4. These terms are

$$\sum_{L=1}^{NYR} \prod \left(\sum_{j = NYRNO_{i-1} + 1}^{NYRNO_i} V_{ji} * \delta^{j-1} \right) \left(CSL_i * sl_i + CSH_i * sh_i \right)$$

Setting different values for the "costs" CSL_i and CSH_i has the effect of modifying the type of inequality appearing in the peak demand constraint 14.4.

OUTPUT OF RESULTS

16 The values of all the variables are available on the completion of any computer run. However, to obtain useful results, a certain amount of processing is required after the linear programming. A brief description of the present output analyser is given below. As use of the model develops, it will be straightforward to add further analyses to this program.

17 The Output Analyser is a program that analyses and prints the results from the solution file output by the linear programming investment model of the electricity industry.

The MGG created routines of the output analyser read the solution file, called the unravl file, from unit 8 and either re-read the MG data from unit 5 or read a dump of common (unit optional) taken at the end of the MG and then call subroutine REPORT, the user-written Fortran routine that controls the analysis.

18 REPORT

This routine organises the calling of other routines that:

1 Read the data required by the output analyser only, from unit 5.

2 Perform basic calculations to obtain values which are required by more than one routine.

3 Perform calculations on the matrix generator data and optionally print out the data and calculated values in tabular form.

4 Perform calculations on the solution results and optionally print out the calculation and solution results in tabular form.

19 CONTENTS OF DATA TABLES

I Demand Data Table - Option 11

The maximum demand for each year and the load factor, energy supplied, planning margin and demands at snapshot instants for each snapshot year.

II Plant Data Tables - Option 12

1 Capital cost table

The cost of installation of each plant in each snapshot year.

2 Existing capacity table

The existing and contracted capacity of each plant in each snapshot year.

3 Plant life table

The physical and accounting life of each plant built in each snapshot year.

4 Minimum running time table

The minimum running time of each plant in each snapshot year.

5 Peak availability table

The peak availability of each plant in each snapshot year.

6 Off-peak availability table

The off-peak availability of each plant in each snapshot year.

7 Plant installation and running table

The first and last snapshot year for installation, cost of running and thermal efficiency of each plant.

III Fuel Data Table - Option 13

The minimum and maximum quantities of fuel for each snapshot year and the tranche size and fuel price for each tranche for each snapshot year. A block for each fuel group.

20 CONTENTS OF RESULT TABLES

I Plant operation and installation table - Option 1.

The existing, new and total capacity, generation, load factor,marginal running cost, fuel savings and system saving for each plant for each snapshot year.

II Plant usage at different load levels table - Option 2

The total capacity and plant usage at different percentages of peak demand for each plant for each snapshot year.

III Plant building and capital cost table - Option 3

The amount of each plant type being built in each actual year and the capital cost for that year.

IV Fuel consumption and costs table - Option 4

The capacity, generation, load factor, fuel used, fuel cost and other costs for each fuel group in each snapshot year.

V Simple summary table - Option 5

The existing and contracted capacity, plant building and generation at each load level, for each plant for each snapshot year.

VI Marginal cost table - Option 6

Prints out the array of weights applied to the shadow prices and the load factor and load pattern of the increase in demand for each consumer type. This is followed by the actual table of the marginal cost of meeting a unit increase in demand for each consumer type for each year.

VII Plutonium table - Option 7

Prints initial fuelling, production and refuelling rates and the initial stock of plutonium and initial fuelling. This is followed by the opening stock for each snapshot year and the initial fuelling, production and replacement fuelling between snapshot years.

VIII Availability Table - Option 8

Prints out annual figures of nominal and available system capacity, together with the margins of spare capacity over system maximum demand.

IX Analysis of Objective Function - Option 9

Prints annual breakdown of future avoidable costs, giving capital costs, fixed costs, fuel costs, andother variable costs.

Discussion

The question session began with comments on the electrical model. Linear programming models have been used by EdF for the last twenty years. Over time, the models have been getting larger and more complex as they become more realistic. The questioner agreed with Hutber upon the necessity to consider a long time scale, such as thirty years. As the problem grows, non-linear programs apparently allow for cheaper and more realistic representations. (Hydro-stations and load curves can be included with fewer variables.) Two years ago, however, they found that they could not deal with storage stations in the same way. Cost of energy and order of operations were unknown. A new approach is needed. Perhaps sub-optimizing by use of control theory inside a non-linear program will work. Large models are required to represent the electrical system realistically. Plutonium, for example, will require a separate model.

Mr. Hutber agreed that it is difficult to represent pump storage. His model only considers the number of power stations rather than named ones, although this suppresses site differences. Pump storage is grafted onto the model through the gas turbine component. The plutonium question is built into the model by requiring the fast thermal reactor to balance with respect to plutonium.

His questioner agreed that specification of pump storage is not so important for a general model, but felt it could become important if nuclear energy is used for more than just a base. He added that at EdF linear and non-linear programs generate economic values for the engineers who must make the choices. Mr. Hutber responded that his group does the same thing.

The question arose whether the basic assumption of the model is that all oil and gas will be burned, and that therefore the only question is how quickly this happens, or whether instead the underlying idea is that we must find new technical processes which conserve petroleum, in which case these should be integrated into the model. He urged IIASA to focus on conservation and on means for better using oil and gas.

Mr. Haefele responded that first we must know the present state of the art used by current energy managers before we can increase the level of sophistication and incorporate long-range technical concerns. He asked Hubter whether he had described what he can do today.

Mr. Hutber said yes. He added that, although the model is based on a market economy, one could distort prices, the producer take, the tax structure, or other features to see the effects of policy changes. He went on to describe the kind of model he hopes to achieve. Econometric models provide a convenient way of simplifying the world with explanatory variables. The aim is to build a model with a non-linear top line describing the macro situation and a linear programming base to produce supply curves to feed the econometric model. This will avoid the problem that a linear program tends to re-estimate an entire system even if you only alter a relatively isolated portion of it. Thus, it will allow you to design only that portion which you want redone.

Someone else commented that he understood the model as an allocation model of primary energy that would be useful on the strategy level. Once a policy had been chosen, this linear program would help in formulation of a strategy to implement it. Thus, the job is enormous. This program is already large and complicated, but it is just a subroutine. Heuristics and satisficing are other possible ways of choosing strategies. He went on to say that therefore he disagreed with a previous speaker; this type of model is relevant to IIASA as a very important subroutine. The basic point is the fashioning of systemic tools to deal with the broader questions of policy and then to determine strategy.

Mr. Raiffa commented that two econometricians with interest in the energy problem, Tjalling Koopmans and Allen Manne, will be coming to IIASA. They will bring with them knowledge of the work being done in the United States. The methodological problems with the extensions of linear programming is one of the areas already picked as an IIASA project. He agreed with a previous speaker that long range models become increasingly sensitive to uncertainty. These models are primarily designed for short range phenomena. He agreed with another speaker that IIASA must stress its "peculiar role as an international organization." It would be lovely to find problems where IIASA could make a significant contribution on the global level. Secondly, IIASA definitely should be a conduit for exchange of ideas on handling problems replicated in all of the countries, such as siting. One possibility would be for IIASA to sponsor conferences in such areas as short run modelling.

Mr. Hutber endorsed Mr. Raiffa's remarks. He noted that good links between the scientific work in different countries do not yet exist, although the U.N., for example, is trying to foster such ties in Geneva. However, these are governmental links one thus gets national stances which inhibit scientific exchanges. True technical exchanges are easier to get in small groups like this conference.

One of the participants thanked Mr. Hutber for mentioning the U.N., noting that the U.N. has never discussed the oil problem. He objected to the context in which the OPEC countries had been discussed in the proceedings up to then and urged that

IIASA not forecast prices or the political behavior of OPEC countries. It would be wiser not to study the energy problem from the point of view of prognoses, forecasting, price changes or political and economic influences. If these factors were discussed, one must also try to understand the point of view of the exporting countries, and IIASA is not the proper place for this. Rather, it should base its modelling on conservation and the substitution problem and focus on technological rather than political forecasting.

Comments upon the Discussion of F. Hutber

R. Janin

For the past twenty years, Electricité de France has been using optimization models to define its production investment programs. We have gone through different and progressively more complicated stages.

In the beginning, we used a very simple linear program which finally proved rather unrealistic in its results. The production function was, in effect, poorly represented by linear functions.

We then sought to make these functions more complex to make them closer to actual management. But in reality, the French system of production is very complex, and we soon realized that it was preferable to represent operating costs by non-linear functions. We thus developed a group of programs widely used at this time to define the marginal costs upon which the value estimates for production equipment are based.

However, pump storage stations are not easily represented by the technique which has been used up to now. We have been working for some time on a final stage which consists of using control theory to represent satisfactorily the management of a production plant including pump storage stations. Moreover, control theory makes it possible to use powerful optimization algorithms developed to economize on the volume of calculations.

A Unified Framework for Energy System Planning*

Kenneth C. Hoffman

ABSTRACT

A linear programming model of the nation's energy system was developed to provide a framework for planning and technology assessment. The model encompasses the entire energy system and reflects the full feasible range of interfuel substitutability. It includes both electric and non-electric energy forms and focuses on the technical, economic, and environmental characteristics of the energy conversion, delivery, and utilization devices that make up the energy system. The analytical approach, in its general form, considers n alternate supply categories and a set of m demand categories, providing n x m possible supply-demand combinations or paths. The solutions obtained indicate the optimal supply-demand configuration of the energy system within the constraints on resources, demands, and environmental impacts that are specified exogenously. The model may be formulated on a regional or national level for some future planning year by specifying, along with the appropriate constraints, a cost coefficient, supply efficiency, utilization efficiency, and set of environmental impacts for each feasible supply-demand combination. The load-duration characteristics of electrical demands are also incorporated in the model. The optimization may be performed with respect to cost, or alternatively, with respect to an environmental effect or some arbitrary combination of such effects.

The model, in its current form, has 13 supply categories and 15 demand categories, and the impact of several new technologies has been evaluated using a set

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*Taken from the dissertation submitted to the Faculty of the Polytechnic Institute of Brooklyn in partial fulfillment of the requirements for the degree of Doctor of Philosophy (System Engineering).

of supply and demand constraints estimated for the year 2000. The technologies that were evaluated are a high-performance, non-electric air conditioner, an electric automobile, and fuel cells.

Possible extensions of the model and the input data requirements for this planning technique are outlined. The current availability of data in the required format is reviewed.

INTRODUCTION

The nation's energy system may be usefully though of as consisting of an integrated set of technical activities operating within a complex private and governmental institutional framework. The technical activities involve the exploitation of a wide range of energy resources to provide various energy forms to all sectors of the U. S. economy. This system strongly interacts with the social and physical environment. It is a vital element of the nation's economy while, at the same time, it produces environmental effects that adversely affect the quality of life. Serious analysis of the nation's energy system and the development of short- and long-range strategies for its future development requires a comprehensive framework within which technical, environmental, economic, and policy constraints may be expressed and alternate strategies evaluated. The linear programming model described here was specifically designed to contribute to such a framework.

Much of the energy system analysis and modelling effort presently under way is devoted to specific sectors of the energy system for special-purpose studies such as the determination of the mix of generating facilities employed to satisfy a specified level of electrical demand,[1] estimation of the demand for and/or the production of oil or gas,[2] and the evaluation of nuclear reactor concepts and fuel cycles.[3] Such activities treat these individual sectors in much more detail than is feasible in a more inclusive energy system model and provide essential input data to such a model.

The linear programming model presented here is directed at the evaluation of technologies and policies and includes the full range of interfuel substitutability, including substitution between electric and non-electric energy forms. It encompasses the entire energy system including all resources and demand sectors. Since the range of interfuel substitutability that is feasible depends on the supply and utilization technologies that are available, the model is constructed around these technologies. The technology related parameters which appear explicitly in the model are the efficiencies of energy conversion, delivery, and utilization devices; the emissions or environmental effects produced by the devices; and their cost.

The important characteristics of the linear programming model may be summarized as follows:

1. The model encompasses the entire energy system including all alternate resources and both electric and non-electric demands.
2. The full feasible range of interfuel substitutability is reflected.
3. Technical, economic, and environmental characteristics of energy conversion devices (both supply and utilization) are incorporated.
4. The load-duration characteristics of electrical demands are included. (This is a very important element that is frequently ignored in energy system modelling.)
5. Supply, demand, and environmental constraints are specified exogenously.
6. Optimal supply-demand configurations are indicated by the model. The optimization may be performed with respect to cost, resource consumption, or environmental effects in a given planning year, or with respect to some arbitrary combination of these factors. It should be noted that the optimization is performed on the

basis of annual cost in the planning year rather than a minimum present worth over some number of years or over a planning increment. The two objectives do, however, correspond under certain restrictive assumptions. Inclusion of the optimization over a planning increment feature is feasible but would enlarge the size of the linear program and would complicate the interpretation of results and sensitivity analyses.

7. The model may be applied to regional energy planning or at the national level using national average parameters. The physical siting of power plants is not considered in the model, although population density in the vicinity of a class of power plants may be reflected by appropriate weighting of the environmental effects.

The intent in establishing the scope of the model has been to include the technical elements that are felt to be of major importance in a framework that is as simple as possible. Simplicity is felt to be a requirement if all assumptions are to be evident and the results easily interpreted. The decision concerning which features should be included and which should not is, of course, a matter of personal judgment and some rationale should be given for excluding specific elements.

Certain elements have been excluded from the model simply because they are not compatible with the analytical approach while, in other instances, they have been left out only because they are not sufficiently quantifiable or are of limited interest except for special purpose studies.

The more significant elements that are not included explicitly in the current version of the model are dynamic features of the energy system and energy demand elasticities. Dynamic characteristics of the energy system may be introduced by applying the model sequentially to a series of incremental development periods, with growth of demand and equipment turnover specified exogenously. Demand elasticities have not been included in the model as the basic energy demands are specified exogenously. It should be noted, however, that the demand constraints are not expressed in terms of the quantity of fuel used but are based on, for example, the number of households to be heated, the number of passenger miles of automotive travel required, and the tons of iron to be produced. Alternate systems, with different efficiencies and, most probably, different costs may compete in the optimization process to serve that demand. The allowance of such substitution of fuel demands does account for part of the demand elasticity. Production functions for various energy sources also have not been represented, but may easily be included as alternate supply categories representing a step-like function.

DESCRIPTION OF THE ANALYTICAL MODEL

The energy system, on a regional or national level, may be represented in a network format as shown in Figure 1. The network in this case is quantified with the energy flows for the year 1969 from alternate resources through the various energy conversion and delivery activities to specific end uses. Each link in the network represents a process or mix of processes used for a given activity such as the refining of crude oil. Costs and environmental effects may be assigned to each link. Similar energy system diagrams have been developed for the purpose of technology assessment for selected future years.[4] Examination of the energy demand sectors at the right-hand side of the diagram indicates the degree of disaggregation that is required in the demand sectors. To evaluate the potential benefits of a high-efficiency air-conditioner, for example, it is necessary to define the demand level for this specific end use and to estimate the degree of implementation of the improved system whether such implementation comes about purely from competitive market forces or from a policy or regulatory decision. It is also necessary, particularly in the example of the air-conditioner, to establish the electrical load-duration characteristics of the demand sectors, as the type of generating equipment installed to serve that demand depends strongly on the load factor.

It is possible to develop energy system diagrams by specifying the fuel mix and technology mix at some future point in time on the basis of available forecasts and trend analysis. In view of changing prices, demand levels, and fuel supplies it is desirable to have at hand an analytical model that will indicate optimal fuel mix configurations within the resource, environmental, and demand constraints that operate on the energy system. The linear programming model provides this function. Rather than using a network algorithm for further analysis and optimization, the energy system diagram may be transformed to a simpler structure. Figure 1 indicates that a given resource may be converted to electricity and one, or in some instances several, general-purpose fuels. Rather than to reflect these in a network structure it is convenient in the linear program to consider them as alternate supply categories subject, when appropriate, to a single resource constraint.

THE ANALYTICAL MODEL

The linear programming model is formulated about the classical transportation problem of determining the optimal routing of a product, in this case an intermediate energy form, from a set of n supply nodes to m demand modes where a cost and set of environmental impacts are identified for a unit of energy passing over each of the n x m possible paths. The typical linear programming representation of the transportation problem is modified by the inclusion of efficiency coefficients in the supply and demand constraints and is augmented by additional constraint equations reflecting the environmental factors as well as certain technical features of the energy system. A graphical representation of the basic model and a definition of terms is given in Figure 2.

The n supply nodes and m demand nodes can include all supply and demand categories. To provide a feasible path between a supply and demand category, both a supply and utilizing technology must be identified. For a given path, j, a resource S_u is converted to intermediate energy form, x_j, at an efficiency, e_{uj}. In turn, the intermediate energy form is used to satisfy demand D_v at an efficiency d_{vj}. A cost c_j and set of environmental effects, included in $\overline{f}_j$, are also defined per unit of intermediate energy form.

The mathematical formulation of the model is as follows:

Minimize

$$\sum_{j=1}^{p} c_j x_j,$$

subject to

$$\sum_j \frac{1}{e_{uj}} x_j \le S_u \qquad u = 1,n ,$$

$$\sum_j d_{vj} x_j = D_v \qquad v = 1,m ,$$

$$\sum_j f_{wj} x_j \le B_w \qquad w = 1,\ell$$

and

$$x_j \ge 0. \tag{1}$$

The summation in each constraint equation is over only those indices j that represent admissible intermediate energy forms for the supply category, demand category, or other constraint. The full linear program array thus has $k = n+m+\ell$ constraints and these may be represented as:

$$\sum_{j=1}^{p} a_{ij} x_j \le b_i \qquad i = 1,k, \tag{2}$$

where the a_{ij} include e_{uj}, d_{vj}, and f_{wj} in the previous formulation and the b_i correspond to the S_u, D_v, and B_w. This problem may be solved by the application of any of several algorithms. For a complete discussion of these techniques see Dantzig(5) and Wagner.(6)

The ℓ equations that augment the supply and demand constraints include the environmental constraints and equations that constrain certain energy flows to reflect technical features of the energy system. The latter group of equations include:

1. <u>Off-peak constraints</u> that specify the maximum amount of energy available from each central station electric source to serve off-peak electric or thermal demands;
2. <u>energy balance constraints</u> that specify the amount of by-product energy available from specific sources to serve other demands;
3. <u>storage balance equations</u> that ensure equality between the amount of energy supplied to storage and that delivered from storage including losses;
4. <u>endogenous demand constraints</u> by which portions of central station electric demands can be reassigned internally to categories with different load factors; and
5. special constraints on individual intermediate energy forms.

To illustrate an off-peak constraint equation consider a central station supply category, such as a gas-turbine generator operating on fuel oil, which can furnish electrical energy to two demand categories, a peak electrical demand with a load factor of 0.5 and an off-peak electrical demand that can use energy at any time that it is available. If these demands were the only ones that could be served by this supply category, a peaking constraint equation would be required to ensure that the installed power capacity to deliver an amount of energy x_1 to the peak demand was not exceeded by the power involved in supplying amounts of energy x_2 to the off-peak demand. For every unit of energy x_1, up to that same amount can be supplied in the ideal case as x_2 and the off-peak constraint equation would be of the form

$$-x_1 + x_2 \leq 0. \qquad (3)$$

If in a solution, x_1 were equal to x_2, the installed power generating capacity would be base-loaded.

The general expression for an <u>off-peak constraint</u> equation for electric supply category S_u where the off-peak demands have no time restriction and the supply plant can operate with a plant factor PF for the annual period is:

$$\sum_j a_{ij} x_j \leq 0, \qquad (4)$$

where

$a_{ij} = \dfrac{LF_j - PF}{LF_j}$ for electric energy delivered to peak demands with a load factor $LF_j \leq PF$,

$a_{ij} = 1$ for electric energy delivered to off-peak demands,

$a_{ij} = e_{uj}$ for thermal energy delivered to off-peak demands.

Additional correction factors may be applied to the coefficients to reflect other time restrictions on the use of off-peak power. If both seasonal and weekly peak and off-peak demands can be satisfied by an electric supply category, then an off-peak constraint equation is required for each period.

An <u>energy balance constraint</u> is required when by-product heat is available from an electric generating device to serve other demands for thermal energy. If the conversion efficiency of such a device is e, the load factor of the thermal energy demand LF, and a fraction α of the waste power can be used effectively, then the constraint is given by

$$\frac{\alpha(e-1)\ LF}{e} x_1 + x_2 \leq 0 \qquad (5)$$

where x_1 is the amount of electric energy produced and x_2 is the intermediate energy form, heat, supplied to another demand sector.

When provision is made for the storage of by-product or off-peak energy for use in other demand categories, the storage medium is defined as both a demand category that can accept that energy and a supply category that can, in turn, deliver the energy to other demand categories. A <u>storage balance equation</u> is required to ensure the proper balance, allowing for any inefficiencies that may be involved, between the energy supplied to storage and that supplied from it.

The <u>endogenous demand constraints</u> are developed in the following manner. Let demand category v, with a demand constraint D_v, be served by two alternative central station electric supply categories, which deliver intermediate energy forms x_1 and x_2, and by a decentralized supply category delivering energy form x_3. Further assume that the primary load factor for D_v is 0.5 but a fraction g of the intermediate energy form used at the primary load factor is used at a load factor of 0.1. Also, let x_4 and x_5 represent intermediate energy forms delivered at a load factor of 0.1 from two sources that could even be the same type of plant that delivers energy forms x_1 and x_2. Clearly,

$$E_v = \frac{D_v}{1+g} ,$$

where E_v is the amount of energy required by demand category v at the primary load factor of 0.5. The <u>exogenous</u> demand constraint in this case, for $d_{v1} = d_{v2}$, is

$$d_{v1} \ (1+g) \ x_1 + d_{v2} \ (1+g) \ x_2 + d_{v3} \ x_3 = D_v \qquad (7)$$

and the <u>endogenous</u> demand constraint is

$$gx_1 + gx_2 - x_4 - x_5 = 0. \qquad (8)$$

Any portion of the demand D_v that is satisfied by the intermediate energy form x_3 does not involve any reassignment of energy to the endogenous demand category. This is because, unlike the case with central station electric sources, no other equipment can be used to furnish the low load factor portion of the demand. The cost coefficients for variable x_3 in this instance must be based on the composite load factor.

Only one endogenous demand constraint is required for a given load factor category and portions of any other demands that have a component with that load factor may be assigned to this category in the same equation.

The following example will illustrate the complete formulation of the model in a simple case.

Illustrative example: Consider three supply categories (S_1, S_2, and S_3), the first two of which are central station electric sources, and two demand categories (D_1 and D_2). Let D_1 be a peak demand with a primary load factor of 0.5 but with a fraction g of that primary component required at a load factor of 0.1. Further, let D_2 be an off-peak demand with no time restriction and assume that all e_{vj} and d_{vj} are unity. Finally, let c_j be the cost and a_j the air pollutant emission coefficients for variables x_j. Formulate the linear programming model for this problem.

Solution: The problem may be put in supply-demand matrix form as:

		Demands		
		D_1 (primary LF = 0.5)	Endogenous demand (LF = 0.1)	D_2 off-peak
Supply:	central station, S_1	x_1	x_2	x_3
	central station, S_2	x_4	x_5	x_6
	decentralized, S_3	x_7		x_8

(The subscripts of variables in this example bear no relationship to those used in previous illustrations of constraint equations.)

The solution to this problem is given by:

$$x_1 + x_2 + x_3 \leq S_1 \qquad (9)$$

$$x_4 + x_5 + x_6 \leq S_2 \qquad (10)$$

$$x_7 + x_8 \leq S_3 \qquad (11)$$

$$(1+g)x_1 + (1+g)x_4 + x_7 = D_1 \qquad (12)$$

$$x_3 + x_6 + x_8 = D_2 \qquad (13)$$

$$-gx_1 + x_2 - gx_4 + x_5 = 0 \qquad (14)$$

$$-x_1 - 9x_2 + x_3 \leq 0 \qquad (15)$$

$$-x_4 - 9x_5 + x_6 \leq 0 \qquad (16)$$

$$-(1+9g)/(1+g)x_7 + x_8 \leq 0 \qquad (17)$$

$$a_1x_1 + a_2x_2 + a_3x_3 + a_4x_4 + a_5x_5 + a_6x_6 + a_7x_7 + a_8x_8 \leq B_5 \qquad (18)$$

$$c_1x_1 + c_2x_2 + c_3x_3 + c_4x_4 + c_5x_5 + c_6x_6 + c_7x_7 + c_8x_8 = \min z \qquad (19)$$

This example illustrates the supply and demand constraints (eqs. 9 through 13), the endogenous demand constraint (eq. 14), the off-peak constraint (eqs. 15 through 17), the environmental constraint (eq. 18), and the objective function (eq. 19). Note that variables x_2 and x_5 represent energy delivered to D_1 at the low load factor. In a larger problem, each of these variables could represent energy delivered to a number of demand sectors. Any electric generating capacity installed to handle this load is also available for off-peak demands and this is reflected in the off-peak constraints for each central station supply category.

If the value of B_5, the environmental constraint, is set high, then eq. 18 will merely serve to sum up the emissions. The value may be set lower, however, to constrain the solution within some total emission level.

The coefficients in the objective function (eq. 19) would reflect the capital cost of the facilities used in the energy supply system as well as fuel and other operating costs. Social costs, or externalities, may also be included if these can be quantified. The capital and operating cost of utilizing devices such as home furnaces, air-conditioners, automotive engines, and blast furnaces may also be included. The typical cost coefficient is therefore made of the sum of at least two cost elements; a capital recovery cost, c_c, and an operating cost, c_f.

The capital recovery cost, when the intermediate energy form is electricity, is calculated using the following relationship:

$$c_c = \frac{Y \cdot (CRF) \cdot 10^6}{3413 \cdot 8760 \cdot (PF)} \qquad (20)$$

where

c_c = capital recovery cost, $\$/10^6$ Btu (electric),

Y = capital cost of supply and/or utilizing facility, \$/kW (electric),

CRF = capital recovery factor, and

PF = plant factor.

The plant factor will generally be taken to be equal to the load factor so long as that provides for any plant shutdown period that may be required. However, if the load factor is 1.0 or even near that value, the plant factor may be reduced below the load factor by whatever margin is desired.

The operating cost includes the annual cost of fuels and resources comsumed as well as the cost of other operations such as fuel transport and distribution. In general, the fuel cost will include the capital recovery cost of any fuel extraction and treatment facilities that are required.

It is important that the cost coefficients be defined in terms of the intermediate energy form represented by the variable that they operate on. When the intermediate energy form is electricity, for example, the capital recovery cost of central station electric plants will be defined properly using eq. 20, but the fuel costs must be multiplied by the inverse of the supply efficiency so that they refer to the electrical output rather than to the energy input to the plant.

The capital recovery cost for an electric supply category is a function of the plant factor which, in turn, depends on the load factor of the demands that are served. When energy is delivered to a peaking or base-load demand category, the full capital cost of the generating capacity required to produce that energy is recovered and some additional capacity margin may even be included to account for plant shutdown periods that may be required. Thus, within the off-peak constraint that is specified for this generating capacity, off-peak energy may be delivered to other demand sectors that can utilize this energy form, with no capital recovery charge. The appropriate fuel cost is recovered, however, in both peak and off-peak demands. The allocation of costs in this manner does not imply any rate structure but merely ensures that the full costs of the energy system are recovered. Thus, in the illustrative example, the cost coefficients c_1, c_2, and c_3 would all include fuel costs. The coefficient c_3 would include no capital recovery cost element. Coefficients c_1 and c_2 would include the capital recovery cost, calculated for each case using the appropriate plant factor.

In an optimal solution to the linear programming problem, each central station electric supply category is assigned to serve a specific demand or combination of demands. The electrical energy supplied from these sources, however, is a common product and the only significance to be attached to a specific assignment is the combined load factor of the demands that are served. Examination of the optimal solution will indicate which central station categories are base-loaded and which are employed for intermediate and peaking service.

It is clear that there are no implicit assumptions built into the model regarding objectives or continued growth of energy demands. The analysis simply indicates the optimal configuration of the energy system within the constraints that are defined for a particular analysis. The annual cost of the overall energy system is minimized in each analysis. There will be cases where some individual demand sectors may bear a higher cost for service in an optimal solution than they would in some non-optimal assignment. The overall optimality condition, however, ensures the existence of an internal rate structure that can redistribute costs such that some or all parties will be better off, and none worse off, than they would be with some non-optimal allocation.

The linear programming model has the capability of very high accuracy in determining an optimal solution; higher, perhaps, than is justified by the accuracy of the parameters that are defined. In particular, if the planning horizon exceeds 15 years or so, the constraints and technological coefficients will be speculative. This indicates the need to recognize possible solutions that may be near optimal and to perform extensive sensitivity analysis in the planning process. In any event, the value of the particular analytical technique selected for this framework is not in its capability for high accuracy; but is in its ability to capture the essential structure of a complex system, such as that involved in the supply and utilization of energy, in a simple format where the assumptions and constraints are quite accessible. The admission of an objective function for optimization is another important factor in the selection of this approach.

The detailed quantification and formulation of the model for a given planning task depends, of course, on the specific objectives of that task. It is important in any case to include all alternative energy resources and all demand sectors that compete for scarce resources at a reasonable level of detail; however, individual sectors, such as transportation or industry, can be included at a greater level of detail for studies directed specifically at these sectors.

The level of disaggregation of supply and demand categories is optional and will, of course, determine the size of the linear programming problem. Table I outlines a set of supply and demand categories that were defined for a general study[7] of alternative supply-demand configurations of the energy system in the year 2000. Note that only one endogenous demand category, with a load factor of 0.1, and one storage concept, pumped storage, have been included in this formulation. The environmental factors included in that study were CO_2, CO, SO_2, NO_x, particulates, long-lived radioactive waste, and waste heat. The supply and demand constraints used in this sample analysis are given in Table I along with the numerical values representing the optimal intermediate energy form flows, in units of 10^{15} Btu, from supply categories to demand categories. The other output information on cost and environmental effects for this sample case are given in Table II.

The linear program for this year 2000 study had 58 rows excluding the objective function, and 165 variables excluding slack variables. This is a relatively small linear program by any standards and further disaggregation of supply and demand categories may easily be accommodated.

APPLICATIONS

The model is sufficiently general, that it may be applied to regional energy planning with imports and exports of fuels fixed as exogenous supply and demand categories, or to energy system planning at the national level. In some respects the analytical model can be quantified with more precise costs and environmental constraints at the regional level, although resource constraints are more easily defined at the national level. The appropriate area to be addressed in a regional study depends on the planning objective. For air pollution studies the air quality region will be the area of interest while for other purposes a river basin, megalopolis, or city might be the preferable region.

Both near- and long-term planning horizons may be addressed. In the near term, the model would be applied to indicate the optimal configuration of the new supply and utilization systems installed over, say, a 5-year period. The optimization would be performed with respect to either total cost or annual cost in any given year. The growth of demands and the turnover of existing equipment would be considered in developing the supply and demand constraints that would operate in the planning year. For long-range strategic planning, the model may be applied to analyze optimal configurations of the energy system in say, the year 2010, where it may be assumed that all existing systems will be obsolete.

The model has been developed in its current format at a level of detail appropriate for the evaluation of new energy technologies. A base case is first established in which the introduction of new resources or technologies is limited. Alternative resources, energy conversion systems, utilization devices, and environmental controls may be introduced into the model and the cost level at which they will be competitive determined by sensitivity analysis. The benefits of full implementation of a technology, regardless of cost, may be determined by assigning a low cost coefficient to the system that is to be introduced so that it will show up in the optimal solution to the extent permitted by other constraints. The resource consumption and environmental effects in this perturbed solution may then be compared with the base case indicating the effect of the new technology.

For other evaluations or planning applications additional detail may be required in specific categories. Imported oil or gas could be distinguished from domestic resources by cost or sulfur content, for example. The analysis of alternate energy policies may be performed through their impact on demand, supply, environmental effects, or cost.

A general series of economic studies may be addressed by progressively constraining resources and/or environmental effects and determining the shadow prices of the constrained elements. In such an analysis it is important to ensure that all of the feasible technological alternatives are included in the model. To determine the shadow price of SO_2 emissions from central station power plants, for instance, all alternative SO_2 control schemes should be included along with the option of low sulfur fuel.

EXTENSIONS OF THE MODEL AND DATA REQUIREMENTS

The most straightforward extension of the model that can be accomplished is an enlargement to include additional supply and demand categories. Supply categories may be usefully expanded to include imported products, additional storage techniques, and perhaps several regional coal resources so that some distinction may be maintained on ash and sulfur content. In the demand categories, the miscellaneous electric and thermal categories may be further disaggregated. It would be particularly desirable to disaggregate the thermal category by temperature at which the energy is required. This is an important consideration in evaluating dual purpose power generating facilities where the waste heat or low temperature steam is utilized along with the electricity. The inclusion of additional endogenous electrical demand categories with different load factors would allow more flexibility in the assignment of load-duration structures to specific demand categories. Additional environmental impacts such as solid waste, land use, and fatalities may also be added so long as they can be related to energy flows through the causative activity.

A substantial amount of detail can be added to the model by the aforementioned steps without excessive complication of the analysis. Some other extensions may be feasible, but would dictate a more complex analytical procedure.

An extension that would couple the energy system model to a more general model of the U.S. economy involves the use of input-output techniques to develop the demand constraints for the energy model. To accomplish this it would be necessary to express the energy requirements for various sectors of the economy in general terms in the input-output matrix and leave the assignment of energy technologies and fuels to be determined by solution of the linear programming energy model. This implies the extraction from the input-output matrix of the technological coefficients associated with energy conversion and utilization.

Another useful extension of the model might involve the inclusion of pricing strategies once a cost optimal solution is determined. The demand constraints could be modified to reflect price elasticity effects and the revised problem solved again for the cost optimal solution. The process could be repeated until satisfactory convergence is achieved.

The information needed to evaluate a new technology consists of the energy forms that may be utilized and delivered by that technology, as well as its efficiency, environmental effects, and cost. Much of this data can be provided by those responsible for the development of the new system, however, independent economic analyses are generally needed. Policies to be evaluated must be expressed in terms of their impact on supplies of specific resources, demands, and environmental or economic constraints. Here, some of the more specific econometric models that are under development will provide useful inputs. For either technology or policy analyses, likely ranges of variations of the parameters of interest should be specified and sensitivity analyses performed with the linear programming model.

Other input data required for the linear programming model is not readily available in the required form. The need to address specific end-use categories, the technologies employed in them, and the possibility of substituting other energy forms required detailed definition on the load-duration structure and the demand in each category. Most energy demand forecasts and utility load studies deal with aggregated demand sectors such as residential, commercial, industrial, and transportation. Thus, the required data are not directly available, although reasonable approximations may be made in most cases. There are some sources of data in the detailed and disaggregated form required here. Among these are the studies by Schurr and Netschert[8] and Stanford Research Institute.[9] Apparently this type of data format is not as useful for demand forecasting as are the more aggregated formats, however, some research should go into reconciling aggregated forecasts with the more detailed view of the end-use activities.

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TABLE I OPTIMAL SOLUTION FOR BASE CASE (T-1), 10^{15} Btu

DEMAND / SUPPLY	SPACE HEAT	AIR CONDITIONING	INTERMED ELEC L.F. 0.5	BASE LOAD ELEC L.F. 1.0	PEAK ELECTRIC L.F. 0.1	WATER DESALINATION	PUMP STGE & SYNTH FUEL	WATER HEATING	MISC THERMAL USES	AIR TRANSPORT	GROUND TRANS PUB & COML	GROUND TRANS PRIVATE	IRON PRODUCTION	CEMENT PRODUCTION	PETROCHEM & SYNTH MATL	SUPPLY SLACK	SUPPLY CONSTRAINT	MARGINAL VALUE, $/10^6 Btu
HYDROELECTRIC			*	1.09			*	0.58		--	0.73				--		3.0	0.21
GEOTHERMAL ELEC					0.20					--					--		1.0	0.40
COAL STEAM ELEC	1.25	1.00	*	2.72		*	*	*		--	0.41				--	77.1	90.0	
LWR ELECTRIC	*	*	1.13	8.57		3.00	*	*		--	*				--		35.0	0.05
LMFBR ELECTRIC			1.20	*		*	1.00	1.78		--	2.27				--		15.0	0.09
GAS TURB ELEC					0.48					--					--	47.6	50.0	
PUMPED STORAGE	--	--		--	0.71	--	--	--		--			--		--		1.0	1.32
OIL PRODUCTS										8.50		30.17			6.79		50.0	0.05
NATURAL GAS	*								18.18	*							20.0	0.18
SYNTHETIC FUEL																50.0	50.0	
COAL GAS & COAL	13.38					*			29.07	*			5.00	1.75	4.28	14.2	90.0	
SOLAR						2.30		0.34							2.00	50.0	54.6	
TOT ENERGY SYST	0.25	0.20	0.14			--	--	--	--	--	--	0.11	--	--	--		1.0	1.19
DEMAND SLACK							49.1											
DEMAND CONSTRAINT	12.2	3.9	2.7	13.0		2.6	50.0	2.7	37.8	1.7	3.0	6.1	2.0	1.4	10.5			

*- Indicates that variable would enter the optimal base with a cost reduction of less than 0.10 $/$10^6$ Btu.

TABLE II. COST AND EMISSIONS SUMMARY FOR SAMPLE ANALYSIS

	Base case
Objective, minimized	cost
Annual cost, $\$10^9$	213.1
Efficiency,[a] %	43.5
CO_2, 10^{11} lb	305.0
CO, 10^9 lb	37.0
NO_x, 10^9 lb	25.9
SO_2, 10^9 lb	27.3
Particulates, 10^9 lb	9.6
Hydrocarbons, 10^8 lb	50.9
Radioactive waste, 10^8 curies	65.0
Thermal energy,[b] 10^{15} Btu	213.1

[a]Hydropower and solar energy are excluded from this calculated efficiency.

[b]May also be interpreted as consumption of exhaustible resources.

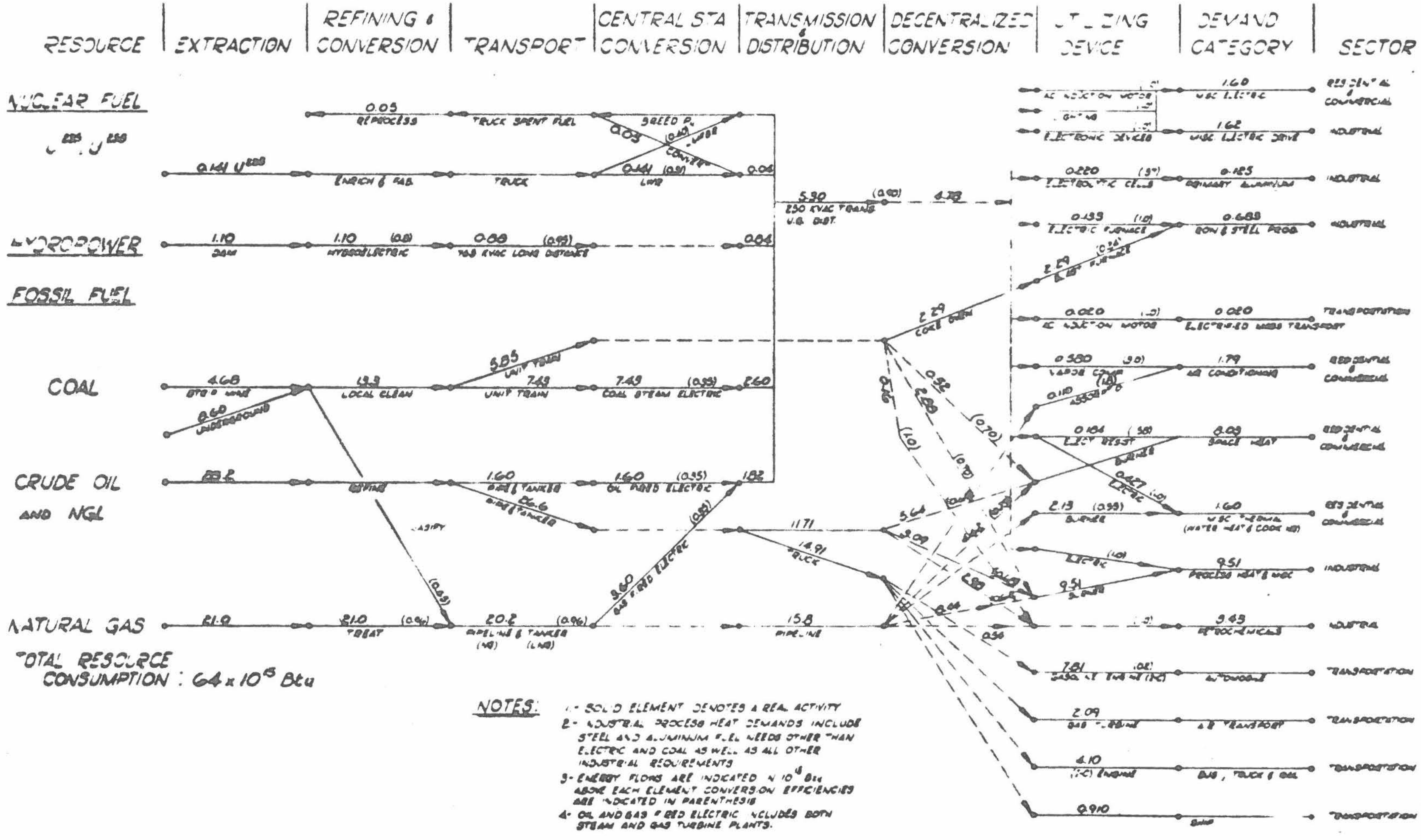
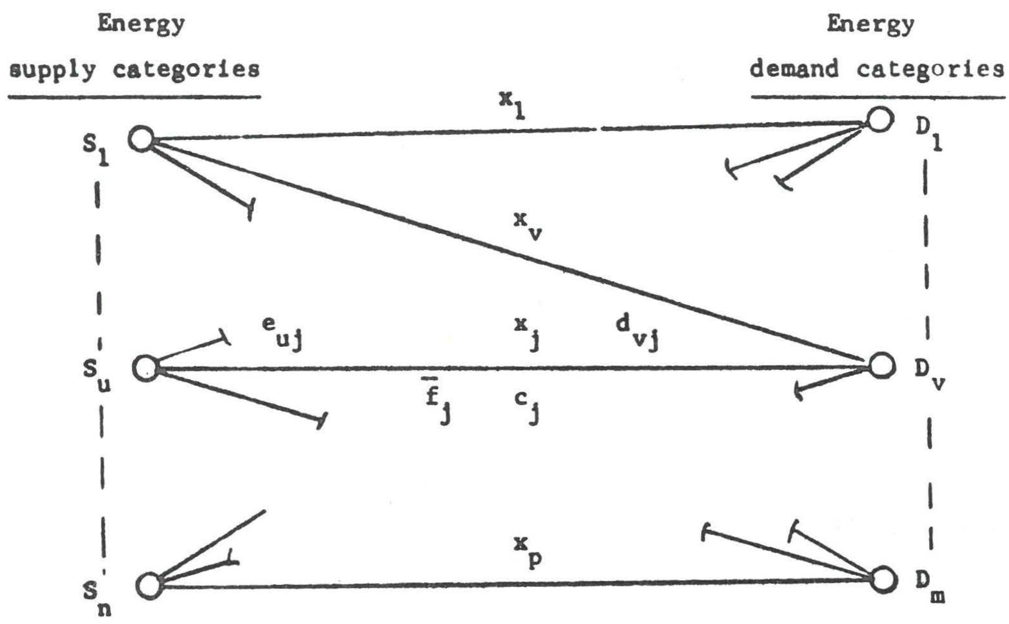


Figure 1 Energy System Network, U.S., 1969



Definition of terms:

S_u Supply constraints, $u = 1,n$

D_v Demand constraints, $v = 1,m$

x_j Quantity of intermediate energy form j delivered from S_u to D_v; $j=1,p$ where $p=n \cdot m$

e_{uj} Supply efficiency for energy x_j

d_{vj} Utilization efficiency for energy x_j

$\bar{f}_j$ Other constraint equation coefficients for variables x_j, constrained by $\bar{B}$. Both $\bar{f}_j$ and $\bar{B}$ are column vectors of dimension ℓ

c_j Cost per unit quantity of energy x_j

Figure 2 Graphical representation of linear programming model

Discussion

The discussion began with a question about the basis for Mr. Hoffman's assumption of a U.S. demand of .2Q (20 KW per person in a population of 300 million). Mr. Hoffman responded that the demand constraints were developed for each identified demand sector on the assumption that people will live much like they do today except for saturation effects, for example, from everyone having an air conditioner. Problems arose in the industrial estimations where some data were unavailable. The questioner then asked who would be involved in the generation of more refined estimates. Mr. Hoffman said that various social scientists and futurologists would attend a summer session for refinement of the model.

Another participant asked about the sector division chosen. Mr. Hoffman said that the traditional economic sectors had been disaggregated into end-use categories. His questioner remarked that every specialist would come up with a different set of categories, depending upon his field. He suggested developing standard sets of categories at each level of disaggregation to facilitate inter-disciplinary studies, and asked Mr. Hoffman if he would be willing to re-interpret his data into such categories. Mr. Hoffman agreed and added that the data base itself contains many discrepancies. He suggested that IIASA might concern itself with recommending common terminologies for data.

Someone seconded Mr. Hoffman on this point, noting that the methodology for assessment of resources varies across countries. It would be important for IIASA to generate common terminology not only for resources but also for needs and demands. Moreover, it is important to distinguish real demands from invented ones. For example, we wear clothing made from artificial substances. These require energy to produce, and, the more profound the chemical conversions are, the more energy they require. Will we have such conversions in the future, or rely on what is produced by nature? Another example is the automobile, which is a metal monster from an energy point of view. It is one and a half tons used to carry a load of seventy kilograms; its thermal efficiency is two or three percent. Thus, we must look at the demands of the future. Urbanization and globality can also change the pattern of energy consumption. We will require different things from energy, for example, elevators instead of cars. These developments will disturb our impressions and prognoses. Regional developments will also change the demand pattern. For example, there will be more movement of software and less of hardware. Such changes in energy demand should be studied at IIASA. Finally, it is unclear in what context the medical aspects will be studied. In the past, it has been for economic assessments, such as number of lost working days, rather than for biological or medical reasons.

It was mentioned that the new auto-emission control standards in the United States reduce gas mileage by three miles per gallon. They were imposed because of air pollution which, even in the most affected areas, has not demonstrably caused a significant number of illnesses or deaths. The reaction is psychological rather than physical. There is clearly enough energy for basic needs in any country, as seen by the fact that people still live. The question is whether the rapid acceleration of an automobile is worth a certain amount of fuel consumption. Psychological experiments have indicated that if consumption is limited people will adjust. When controls are imposed the level of expectation is higher than reality. However, the level falls to meet reality, and eventually people are just as happy as they were before controls. There is great psychological flexibility.

Mr. Hoffman said that the case he presented corresponds to one particular life style being taken as the upper bound. He would like to develop alternative demand constraints and to see what they imply for energy. This would require an interdisciplinary group. More research is needed on health effects, especially on the low level effects of such fossil fuel pollutants as SO_2. These may be carcinogenic, perhaps even more so than radiation. Blocking nuclear plants would mean the construction of more conventional fuel ones. Thus, research is needed for the incorporation of morbidity and mortality into the model.

Mr. Raiffa commented that IIASA could help facilitate exchange of information about the relationship between pollutants and morbidity. His own bias is that the physical effects will probably prove minor relative to such psychological effects as a desire for clear skies. These are hard to incorporate in a model but are important. He asked whether there are aspects of the modelling, such as data collection techniques, which could be transferred to an international setting, in particular, to IIASA. If so, how could it be done and by whom? Would it be worthwhile to maintain copies of all publications and software?

Mr. Hoffman said that the general modelling techniques are appropriate for different countries. Another modeller noted that it takes a great deal of money to do this type of work. Groups would like to build on experience obtained elsewhere. For example, people have come to look at his models (although none have yet requested the programs). The data are clearly peculiar to each country, but exchanges like the present one permit learning about what others are doing. If there is interest, bilateral contacts can follow. Mr. Raiffa suggested that IIASA might work on the methodological problems of data collection, i.e. how is the data collected and verified. The modeller doubted that this could be standardized. Even within a group as relatively homogeneous as the EEC it has been difficult to standardize the data.

Mr. Raiffa went on to pose two technical questions to Mr. Hoffman. First, how does the model, designed to optimize in a single year, relate to the orthogonal model representing the time flow of money, the stream of investments? Second, how does Mr. Hoffman deal with the time distribution of capital investments? Mr. Hoffman responded that the model he presented dealt with the year 2000. Presumably, all of the current capacity would be obsolete then, and thus he was freely able to reconfigure the power system as though it were all built in the year 2000. In the dynamic model with yearly optimizations, facilities are assumed to retire at the end of 25 years. Some utilizing devices, such as transformers, could have a shorter time scale, but the frame for basic structural changes is 25 years. The model starts with the current configuration and adds new and replacement installations each year. Capital costs are included in the cost elements as annual capital charges at a 10 percent fixed charge rate. Optimization in the dynamic model will be based on estimated fuel costs.

Someone else agreed with an earlier point on the distinction between apparent and true needs. However, he noted, if one wants to determine what must be done most urgently, it is important to know what would happen if things continue as they are. Thus, a model based on projections of current per capita energy use is valuable. He asked whether the distribution of demand is available in addition to the mean demands. It was said that regionalized demand data is available for the United States. Mr. Hoffman said there is also data broken down by income group. The speaker explained that this is important because the international argument that other countries will want to catch up to the U.S. consumption level applies within the industrialized countries as well. Those at lower consumption levels will want to rise. Mr. Hoffman agreed that it is important to know whether the seven percent growth in demand for electricity in the U.S. is caused by people with low standards of living catching up or by those with a higher standard raising it even more.

Another participant remarked that, in his country, interest focuses mainly on short term studies, especially those relating the increase in energy prices to the national economy. This, however, is not something IIASA could undertake as it is very country-specific. However, there is also great interest in his country in methodology and in how well different models work. IIASA could serve as a clearing house for comparing methodologies. Workshops, perhaps a few months in duration, on the level of the actual functions and software would facilitate the exchange. Secondly, IIASA should not serve as a data base, but could ease the data problem by determining what data is needed and trying to promote provision of it. Thirdly, in the long term, all of the national decisions will influence all of the actors. IIASA is a good place to do the work of logically and non-ideologically considering the relationships of long term technological changes, changes in the world energy situation, and changes in life style. This would be a very long term continuous analysis.

Someone agreed with these comments and then made several points with respect to price and the market system. First, he said that prices are essential for making comparisons both within the energy system and between it and the rest of society. Moreover, in order to determine asymptotic energy consumption per capita, it is important to know energy costs relative to other economic activities. This is lacking in Meadows's study. Second, the rate structure can completely alter the shape of the load curve. Third, there are great gaps in the data on costs of new techniques. The figures assigned to these costs are in some sense random. Fourth, these models generally assume a perfect market, that is, that the user will choose the cheapest source of energy. In practice, this is not true. For example, few people choose the form of space heating they live with. It is important to recognize that the system of decisions is not formed by users but is an industrial system. In this respect, there is not so much difference between the socialist and non-socialist countries.

One participant made several proposals for IIASA research topics. First, he proposed working on global models. He noted that two models developed in his country, $E = f(t)$ and $E = f(t,D,J)$ where

E = global demand for energy ,

t = time ,

D = GDP , and

J = industrial production ,

produced fits of five percent and three percent, respectively, to the actual 1970 figures. Thus, one can get very good results from very simple models. Secondly, he proposed investigating the asymptotic limit to the growth of electric energy consumption. He had co-authored a model which produced a 50 percent error in 1970: $E = e^{a+bt}$ where bt was taken as constant. However, we now know that it is not constant. (Fig. 1)

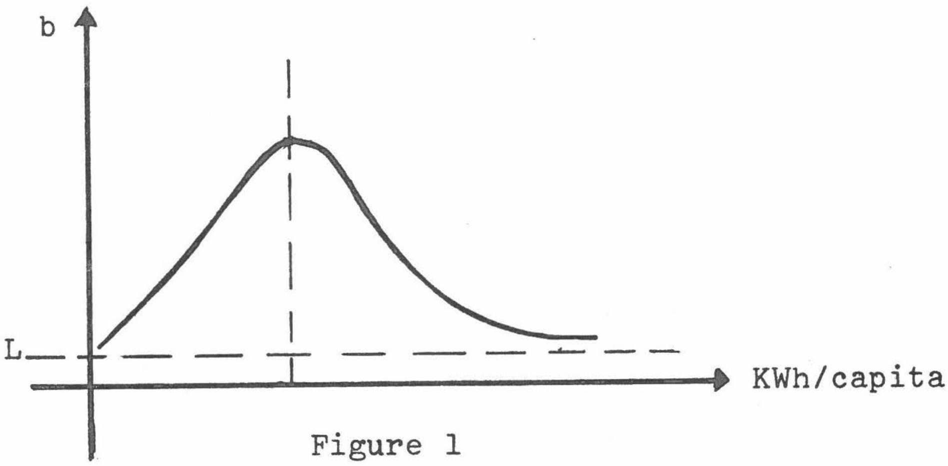


Figure 1

Hence, we have the question; what is the value of the limit L, or, what is the limit to the growth of electric energy consumption? There is an estimate in his country of C_∞ as 55,000 KWh per capita, C_{2000} as 10,000 KWh per capita, and C_{2000} in the U.S. as 30,000 KWh per capita. In his latest book Mr. Felix estimates a U.S. demand of 150,000 KWh per capita in the year 2150. One could study where the limit really is. The third investigation in whether or not there actually is a linear relationship between energy and GNP. Perhaps we are only looking at countries on a linear portion of the curve shown in Figure 2, i.e., at points where the abscissa is greater than C. Finally, there is the problem

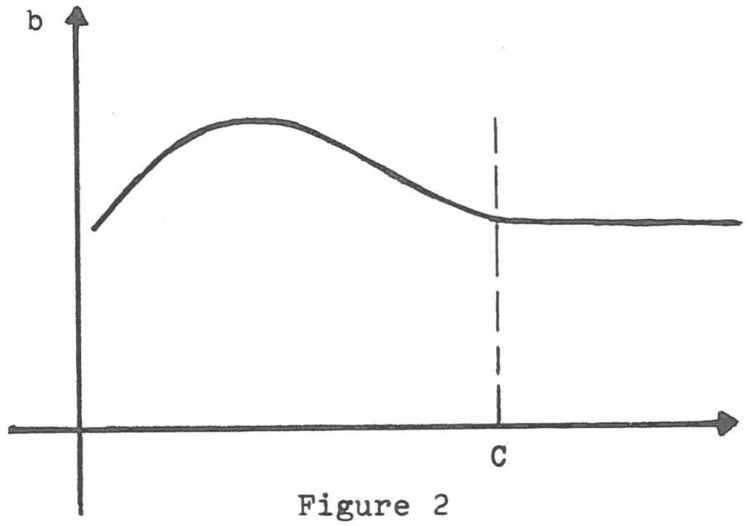


Figure 2

of prices and the elasticity of demand. Elasticity is defined by

$$\lim_{\Delta p \to 0} \frac{\Delta E}{E} \div \frac{\Delta p}{p} = \eta \quad .$$

He used the regression function in the form

$$Y = \alpha_0 x_1^{\alpha_1} x_2^{\alpha_2} \cdots \quad ,$$

which is particularly useful for considering connections to other systems. It is unclear that it is possible to calculate elasticities based on the data. When the change in price is great, estimation of elasticity is theoretically impossible. When price changes considerably, there are new demand curves and one cannot estimate elasticity.

Energy System
Econometric Modelling, Demand and Supply: An Opinion of the Program of the International Institute for Applied Systems Analysis

P. Zvetanov

In his paper, Prof. Haefele outlines the basic problems before the International Institute of Applied System Analysis in dealing with such a complex problem as energy systems. Also formulated are the tasks of econometrics which must optimize not only the complicated process of energy supply and demand but also pollution and the risks taken. The range of these problems is enormous. The question arises how IIASA will develop its detailed program for the project on Energy Systems. Undoubtedly, the complex should be developed according to the meaning of the term, "Energy System," introduced in Fig. 13 of Prof. Haefele's paper. Furthermore, in the long run it should have a global character, i.e. be valid for the whole planet. Obviously, development will proceed in this order: national models, international models grouping together certain countries, continental models, global model.

For energy we may assume that currently the majority of the nations have their own national models for development. In our opinion, development of the international models should be the first stage in IIASA work on the project in Energy Systems. I will present below some considerations in the development of such models.

Conditions for Developing the International Models

The conditions for developing the international models are:

1) the increasing interrelation among the national power systems and the necessity to analyse and forecast the repercussions of the evolution of the European and the world fuel market on the energy policy of the nations;

2) the existence of national models in a significant number of countries; and

3) the development of international cooperation in setting up international statistical records of the various energy carriers and the energy sector as a whole, thus

permitting coordinated energy and fuel balances to be made. For example, UN General Statistical Bulletin on Energy for 1967 contains information according to energy carriers and sectors as stated in Appendix 1.

Functions of the International Models

The national models should be integrated on an international basis. To this end, all export- and import-determining factors of the countries should be defined, quantitatively assessed and integrated as internal factors into the national models jointly with the planners of these models.

Certain difficulties should be overcome in connection with the eventual conclusion that the hypotheses adopted thus far in the various national models are incomparable. It will be necessary to construct hypotheses or exemplary models for countries lacking them but, despite this, influence energy supply and demand.

When developing the international models, the decisions based on the national models may have a combined (total or compensating) effect on the estimate of world resources and prices. At present this effect is rather obscure.

The governments need analyses and forecasts more accurate than those available now about the state of energy generation in the various regions. The need arises to explain more precisely in terms of quantity the internal mechanism and the eventual structures. To this end, the problems of more general character should be stressed to clarify in terms of quantity the components of energy supply and demand according to groups of consumers and energy-generating regions. Thus the international models could build up a system with a rather original concept based on a selection of parameters and directed toward an analysis of forecasts of the links between these models. The international models thus developed will serve as basis for setting up the global model of energy systems.

Criteria for Grouping Together the Countries Within the Framework of the International Models

In our opinion it would be unrealistic to begin with the development of econometric models covering vast regions-- e.g. Europe-- containing all energy carriers, the large number of consumers, the short-term, the medium-term and the long-term perspective plans, and the basic elements of the energy balance (generation, exports and imports, internal reserves, transformation, total demand). Now the problem arises for rational grouping of the various countries.

Grouping of countries in sub-regions might follow these criteria:

- Close features of general structure of economy (planned economy, market economy, mixed economy)

- Uniformity of prime resources of energy (countries highly dependent on coal or on water power)

- Uniformity of energy consumers (highly industrialized nations, developing nations)

- Countries with highly developed fuel trade

- Countries with comparatively similar geographic and weather conditions

- Countries whose statistical records are standardized from the viewpoint of energy state analysis.

However, none of these criteria is fully satisfactory. Thus the group of nations with a planned economy includes countries with enormous differences in their sizes. Uniformity of prime energy resources and the active trade links in the field of fuel are suitable for models of the energy resources but in no case can be applied to models of the entire energy sector. Climatic characteristics do not play a determining role.

A suitable solution might be perhaps the combination of these criteria. In the case of Europe the following division may be made:

- Highly industrialized countries in Western Europe (Austria, the Common Market nations, the United Kingdom, Switzerland)

- The countries of Eastern Europe (Bulgaria, Hungary, the German Democratic Republic, Rumania, Czechoslovakia, Poland)

- Scandinavian countries (Denmark, Finland, Norway, Sweden)

- Countries around the Mediterranean Sea (Spain, Greece, Italy -- also included in the West European Countries -- Portugal, Yugoslavia, Albania, Turkey)

- USSR

Results of Aggregation and Disaggregation When Developing the International Models

In principle, thwo methods of constructing the international model are possible: indirect connection between the national models, or direct calculation of regional coefficients, choice depending on statistical and economic considerations. We might suppose that at the present stage of international cooperation in statistics, when, with some exceptions, no global data about the various energy-consuming industries are available, the direct method will face considerable difficulties. A comparable compilation of international statistics on cost and price of the various fuels is also lacking. Price formation is purely national in character, and the establishment of regional price indexes would only encumber studies. This gives us enough grounds to resort to the indirect method of disaggregation where data coming from the separate countries will be summed up (coefficient of growth, expenditures for each kind of fuel, etc.), and the national model will be connected through the exports and the imports. The adoption of the disaggregation method would not only avoid excessive simplifications but would also allow the consideration of a number of national features whose significance in both the national and the international aspect cannot be ignored.

Degree of Specification of the International Models. Choice of Determining Factors.

The international models should describe energy supply and demand as well as the mechanism of balance established between supply and demand by means of prices or plan targets. The degree of specification of the international models according to energy carriers, regions and demand branches can differ. In our opinion, the breakdown used in the UN statistics given as appendix to this paper can be successfully applied.

The basic illustration factors used in the national models are:

1) In models of the demand: price of energy carriers, figures giving the growth of the consumption branches and in particular the basic energy-consuming industries, consumption expenditures, installed equipment, input/output relations, time.

2) In models of the supply: composition of the national energy products, production costs, equipment costs, time.

3) In models of the balance of supply and demand: stores, prices, decisions on planning and orientation.

However, these factors are subject to certain limitations, e.g. production capacity, available manpower, commercial and financial constraints.

Experimental Model

In our opinion IIASA should develop from the very beginning an experimental model simultaneously with methodological study of the general problems of creating an international model. The model should cover a group of relatively homogenous countries for which relatively full statistical data on international level are available. The model will permit a more detailed specification of the requirements toward the basic data, and, for international models, will define the general trends in establishing their form, content, methods used, and limits, as well as requirements they should meet.

Conclusion

Proceeding from the exceptionally complete account by Prof. Haefele of complex Energy Systems I have attempted within the framework of the section on Econometric Modelling - Demand and Supply, to put forward an opinion about establishing a preliminary program for IIASA work on this problem. Such a program-- which includes a study of the national models, treatment of the general problems of setting up international models and treatment of an experimental model for a group of countries combined with the work on the remaining parts of the complex-- could serve as basis of IIASA's project in Energy Systems.

Annex:

Information Contained in UN Annual Bulletin of Energy Statistics

I. Production of Energy by Form

1. Solid Fuels

Primary energy	hard coal, brown coal(including pech coal and lignite), fuel peat and other primary solid fuels
Derivate energy	coke-oven coke, gas coke, brown coal coke, patent fuel, brown coal briquettes, dried brown coal, peat briquettes

2. Liquid Fuels

Primary energy	crude petroleum, natural gasoline produced at crude petroleum and natural gas sources
Derivative energy	aviation and motor gasoline, jet fuel, kerosene, naphthas, gas (diesel) oil, residual fuel oil from distillation or reconstruction, refinery fuel

3. Gaseous Fuels

Primary energy	natural gas, liquefied petroleum gas produced at crude petroleum and natural gas sources
Derivative energy	gasworks gas, coke-oven gas, blast furnace gas, liquefied petroleum gas (excluding that produced at crude petroleum and natural gas sources), refinery gas

4. Electric Energy

Primary energy	geothermal electric energy, hydro-electric energy (excluding that resulting from pumping), nuclear electric energy
Derivate energy	thermo-electric energy, hydro-electric energy resulting from pumping, energy produced by self-producers

5. Steam and Hot Water	steam and hot water from geothermal sources, steam and hot water from public thermal power plants for combined generation of electric energy and heat

II. Breakdown of Consumption by Energy Producing Industries

1. Primary Energy Industries	coal and brown coal mines, crude petroleum and natural gas wells (including separation installations), hydro-electric, geothermal and nuclear power plants, excluding pumping stations
2. Energy Conversion Industries	patent fuel plants, brown coal briquettes and brown coal coke plants, coke-oven plants, blast furnaces, gas works, petroleum refineries, thermal power plants for production of electric energy only, thermal power plants for combined generation of electric energy and heat
3. Final Consumption	industry and construction (excluding energy producing industries), iron and steel basic industry, chemical industry, transport, household and other consumers.

Application of Economic-Mathematical Methods for Optimization of the Power Industry of the GDR

H. Knop

In the German Democratic Republic, economic-mathematical methods have for a long time been successfully used for optimizing the economic partial systems of the power industry. We start from the knowledge that, on the one hand, the power industry belongs to the economic spheres which essentially influence the development of the national economy and the growth of revenue of the country. On the other hand, the power industry itself consists of elements which are closely interconnected with each other by object and time, and are influenced by a multitude of economic, technical-technological, and especially politico-economic and political factors.

This variety of relationships can no longer satisfactorily be mastered by traditional methods. By applying economic-mathematical methods and by consistently using the systems approach in a close relationship to actual practice, it becomes possible to analyze and to understand the essential factors of influence as well as the marginal conditions specified for the particular case. For this reason, economic-mathematical models and systems of models are increasingly being used in the power industry of the GDR.

Main Model

The central model of the power industry is representative of all models used in the GDR for optimizing the structure of plants and energy carriers. In this model, power industry is not shown as an administrative unit. But instead, all the important plants for energy demand and energy transformation and the import and export of energy carriers over a longer period are considered independently from their administrative incorporation. The minimal social expenditure is used as economic aim function. It comprises all substantial components of investments and current expenditures according to their different temporary evaluation (actualization for a specific moment). Societal demand for a surplus of products is taken into consideration by an accumulation factor for investments as well as by a consumption factor for the earned income. The actualization is realized by using the accumulation factor.

Thus,

$$AW_0 = \sum_{j=-1}^{-d} I_j q^{-j} + \sum_{j=1}^{n} I_j q^{-j+1} + \sum_{j=1}^{n} U_j q^{-j+1}$$

$$-q^{-n} \sum_{j=1}^{n} U_j + \sum_{j=1}^{n} (l_j q_k + m_j)\, q^{-j} \quad ,$$

where

AW_0 = Cash value of social expenditure ,

I_j = Investments in the year j ,

l_j = Wages in the year j ,

m_j = Expenditures on material andother costs without wages and amortization, in years j ,

q = Accumulation factor ,

q_k = Consumption factor ,

n = Time of utilization (Time of amortization) ,

d = Time of construction up to the beginning or production .

We use the linear optimization method. With a concrete model of the system, it is possible to achieve a temporarily and partially mathematically dynamic behavior. In the model the following aspects can simultaneously be considered over a longer period:

1. Development of demand through time

2. Sequence of investments

3. Varying configurations of investments and operating costs

4. The different use of plants in successive periods according to needs

5. Economically necessary early shutdown of existing plants

6. Change of economic-technical characteristics over time.

7. Development of techniques in successive periods; continuous simple and expanded production according to the recent level of modern techniques

8. The mutual influence of plants and processes existing at any given moment or of plants and processes chosen from a finite number of variants. Thus, the plants and processes existing at the beginning of the time period considered influence projected future plants and processes, and the plants and processes being planned for an earlier period in turn influence those being planned for a later time. We thus observe a temporary economic-dynamic choice of plants and processes, i.e., the system itself accomplishes a forward and backward account in a cybernetically simultaneous way.

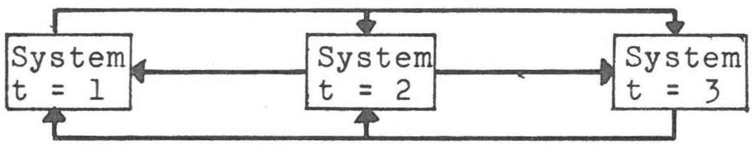


Figure 1. Principal scheme of a system orientated towards a corresponding period of time

(t = time)

9. An appropriate concentrated representation and formation of groups of plants for receiving and for transforming raw energy as well as existing sources of energy in the country.

10. Interconnection between the plants of the whole power industry

11. The main restricting conditions by the national economy including the possible imports of energy carriers.

In this connection, it is of great importance that the whole power industry be considered as a uniform operating system also in an economic aspect. This is done by neglecting the direct evaluation of intermediate and final products exchanged between the partial plants, as well as the method of distribution of costs.

The expenditures for invested products, for labor and for materials directly taken over from other systems are completely comprised under the consideration of interconnection. For an energy model, expenditures on fuels appear only in connection with the import of energy carriers, while the receiving and distributing costs of the raw energy carriers from their own resources are proved directly by the necessary investments, by the materials and capacities accepted from other systems as well as by the demand for manpower, and indirectly by necessary expenditures of other partial plants of the system. Thus "optimal prices" are practically formed continuously for any plant, and, upon reaching a barrier, more unfavorable conditions automatically arise for the process which already shows the greatest ineffectiveness before reaching the barriers. The selected model does all this based upon using existing variants and conditions independently, without any necessity to formulate separately the single relationships. This type of model is designated as optimization model for several years, characterized by a real optimization of spaces of time.

Model System

As already mentioned, the principal ideas described for the optimization model have already been used in power industry of the GDR for some years. On this basis, in addition to the model of the whole power industry, a number of economic-mathematical models for the several partial spheres were created. At present, the following optimization models are used for elaborating middle-term and long-term plans:

- a central model which represents the power industry in a highly aggregated form;
- optimization models for the spheres of extracting and processing of coal, generation of electric energy, generation and transmission of gas, primary refining of crude oil;
- a model for optimizing the demand of large industrial energy consumers which is to be substituted.

On the same basis, two other types of models were elaborated. These permit a long-term balancing of energy demand of macro- and microterritories as well as an optimization of the structural development of the territorial power industry after a corresponding economic evaluation. All these economic-mathematical models are, of course, primarily concentrated upon the conditions and interests of a corresponding production process which is taken into consideration. Thus a mutual influence and coordination of the single structural variants is not possible or can only be realized by a temporarily expensive balancing or additional accounts. That is why the single models of the power industry of the

GDR are being connected with each other. As it is practically impossible to construct and to use a supermodel, the connection of the single models in the GDR is realized by an economic-mathematical system of models. In this model system, all the single models mentioned above are directly coupled with each other without resulting in a "super-model."

The structure of the system of models is shown on Figure 2. The aim of applying such a system of models is to determine a structure of development for the power industry which will require the minimum social expenditure. We should note that the users of energy do not by any means have at hand such energy carriers which produce the most economical results. Only such a structure of energy carriers is considered to be an optimal one which is equally effective for both generation and use of energy. This aim can only be reached if the individual results of optimization are coordinated with each other. This demands a direct coupling of all single models. For this purpose the following conditions must be fulfilled:

- Complete analysis of all the essential processes of generation and utilization of energy.

- Clear delimination of the single spheres of power industry.

- Application of the same method of optimization, including the method for calculating the goal criterion.

- Consideration of the same space of time with uniform division into sections for several years.

In order to master the system of models, this task has been and will be solved gradually.

Stage 0 of construction:	Application of the central model and coupling with the model for optimization of large industrial energy consumers.
Stage 1 of construction:	Coupling of the central model with models of the spheres of electric energy, extraction and processing of coal, generation and transmission of gas, primary refining of crude oil and with the model of power demand of large consumers which is to be substituted.
Stage 2 of construction:	Integration of territorial energy models into the model system.

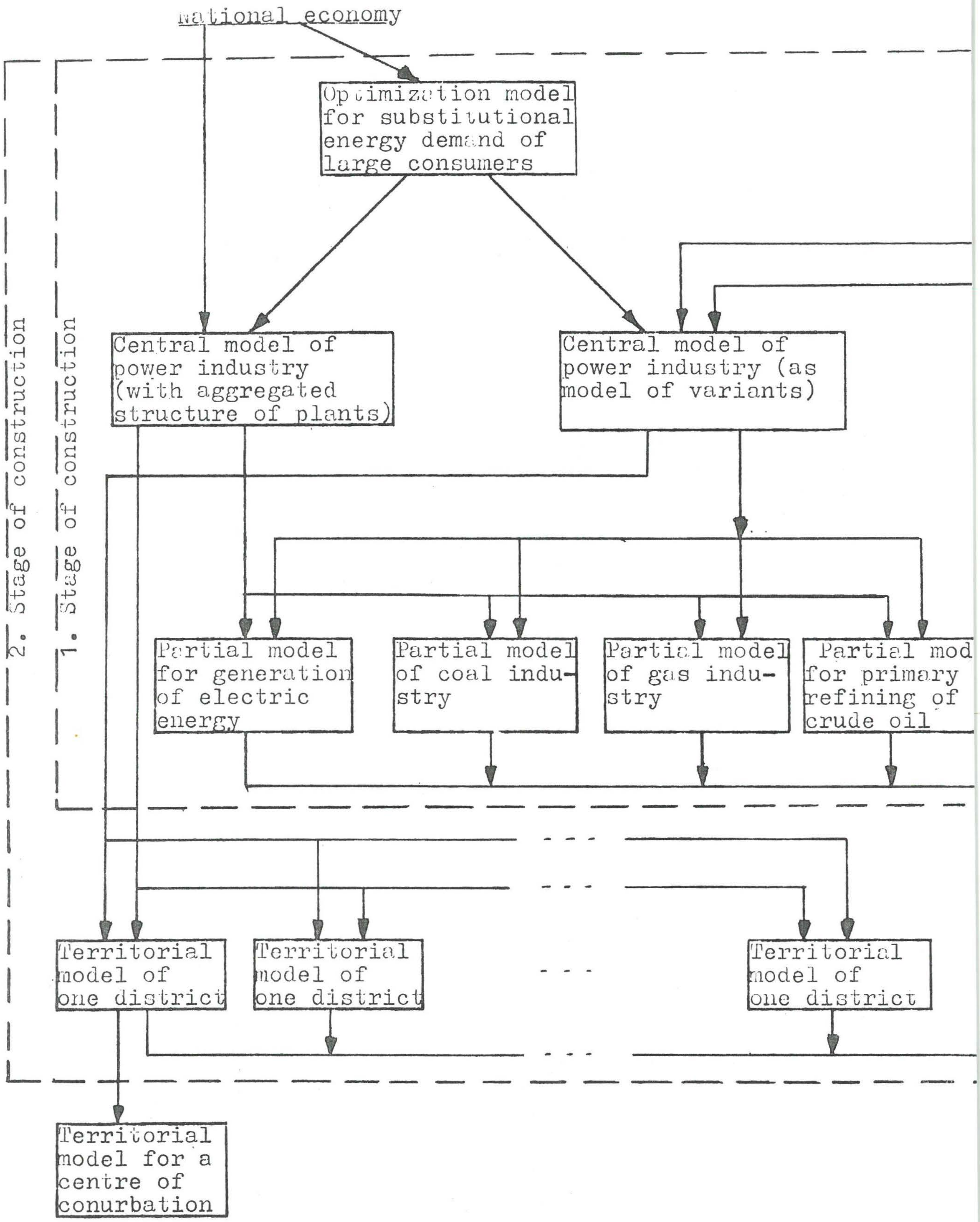


Fig. 2: Principal scheme of the model system of power industry of the GDR

In the first stage of construction, territorial aspects are essentially not taken into consideration. The territorial demand is given as a restriction which is to be fulfilled.

The selected procedure of gradually building up the model system has the following advantages:

1. The expenditure of work can be mastered by the available manpower.

2. Accelerated integration of scientific results into practice.

3. Practical proof of theoretical results of research. Thus it is possible to build up the following stage of construction in a shorter time and to avoid possible errors.

A further important task of the first stage of construction consists of elaborating an appropriate economic-mathematical coupling algorithm. This coupling algorithm must correspond to the following conditions:

a) It must reflect the demands of the planning system of practice without contradictions and guarantee a complete interconnection of all spheres generating and using energy.

b) It must be possible to introduce it into practice and to reach the result without many iterations.

c) It must make possible, both economically and technologically, the realization of all the intermediate and final solutions.

d It must permit a variable use of single models. Each model must be applicable, without any additional expenditure of work, both as a separate individual model and as a component of the model system.

e) It must correspond completely to the cybernetic relationship, "man-made-machine."

The basic idea of the coupling algorithm developed in the GDR consists of using the substitute optimization model for large energy consumers to calculate demand variants for a bindingly accepted structure of the non-energy production.

$$Z_{\upsilon}^{B} = \sum_{j,l,t} c_{jlt}\, y_{jlt\upsilon} \rightarrow \text{Min}$$

$$\sum_{j,l} a_{ijlt}\, y_{jlt\upsilon} \leq g_{it\upsilon}$$

$$\sum_{j} y_{jlt\upsilon} = Y_{lt}$$

$$y_{jlt\upsilon} \lessgtr \omega_{jlt} \geq 0 \quad .$$

This gives

$$b_{it\upsilon} = \sum_{j} a_{ijlt}\, y_{jlt\upsilon}, Z_{\upsilon} \quad .$$

These economically evaluated demand structures will be integrated into a central model. The central model comprises the plan for energy generation in a highly aggregated form. According to its structure, it is a model of coefficients.

$$Z = \sum_{k,t} c_{kt}\, x_{kt} + \sum_{i,t} c_{it}\, i_{it} + \sum_{\upsilon} Z_{\upsilon}^{B}\, p_{\upsilon} \rightarrow \text{Min}$$

$$\sum_{k} a_{ikt}\, x_{kt} \qquad i_{it} + \sum_{\upsilon} b_{it\upsilon}\, p_{\upsilon} \geq \hat{b}_{it}$$

$$x_{kt} \lessgtr X_{kt}$$

$$i_{it} \lessgtr I_{it}$$

$$\sum_{\upsilon} p_{\upsilon} = 1 \quad .$$

Considering certain central restrictions, i.e., possibilities of import, etc., as well as the demand which is not subject to optimization research, we first determine an optimal structure of energy demand and provision. Because of the high degree of aggregation of the central model, detailed calculations of the partial models will be necessary. The application of these models is based on calculations of the central model. Furthermore, it is possible to calculate additional variants by using the partial models derived from the research and conceptions of the several spheres of the power industry. The range of decision in which the optimal solution will be accepted is delimited by these calculating operations. To coordinate all calculated variants a central model is again used. In comparison with the above-mentioned model, this central model is a vector model.

$$Z = \sum_{\upsilon} z_{\upsilon}^{B} p_{\upsilon} + \sum_{s\lambda} z_{s\lambda} \psi_{s\lambda} + \sum_{i,t} c_{it} i_{it} \rightarrow \text{Min}$$

$$\sum_{\upsilon} b_{it\upsilon} p_{\upsilon} + \sum_{s\lambda} f_{ist\lambda} \psi_{s\lambda} + i_{it} \geq \hat{b}_{it}$$

$$\sum_{\upsilon} q_{rt\upsilon} p_{\upsilon} + \sum_{s\lambda} q_{rst\lambda} \psi_{s\lambda} \lesseqgtr Q_{rt}$$

$$\sum_{\upsilon} p_{\upsilon} = 1$$

$$\sum_{\lambda} \psi_{s\lambda} \leq 1 \quad \text{(for each s)}$$

With this model, an optimized variant is being calculated for each sphere, including the consumers of energy. These variants are exactly defined or reified in the partial models. For this aim all variants already calculated are incorporated into the decision range of the optimization model. The variants are estimated according to their economic valency in the total system. For this purpose, the "reduced costs" of the central model are used.

$$Z^B = \sum_{j,l,t} c_{jlt}\, y_{jlt} + \sum_{\upsilon} r_{\upsilon}\, \psi_{\upsilon} \rightarrow \text{Min}$$

$$\sum_{j,l} a_{ijlt} - y_{jlt} + \sum_{\upsilon} b_{it}\, \psi_{\upsilon} \geq 0$$

$$\sum_{j} y_{jlt} = Y_{lt}$$

$$y_{jlt} \lesseqgtr \omega_{jlt} \geq 0$$

$$\sum_{\upsilon} \psi_{\upsilon} \leq 1 \quad .$$

These calculations can help improve structure in a considered sphere. Simultaneously, it may occur that the optimal solution determined by the central model cannot be realized in a technological or in an economical respect. This may be observed when two (or more) variants are mixed.

If the calculations of partial models show results other than those of the central model, the process of iteration is continued by repeating the calculation of the central model until the central and decentral solutions correspond to each other. Calculations already completed have shown that this process of iteration is characterized by a quick convergence which can further be increased by preliminarily balancing possible ranges of variation of the structure of energy demand.

The above model system in its first stage of construction, including the described coupling algorithm, has already been used successfully for practical calculations of optimized structural variants. Thereby it became evident that the model system is of great practical importance for planning purposes, if the calculations of optimization are accompanied by operations of evaluation and stability research done on computers. Simultaneously, valuable results have been obtained for further improving the efficiency and conclusiveness of the model system in doing the first calculations. This especially concerns the necessary information flow between the single models. At present the model system of the power industry has reached a level of development in its first stage of construction where it can be used directly and immediately for calculations of structure. It is, however, necessary that the inputs be very up-to-date in any case.

The present and future work being connected with the model system consists of the successive incorporation of territorial energy models into the model system. The conception for completion of the model systems first provides for the analysis of the most important energy territories by models. The territorial models which may be coupled are incorporated by the same coupling algorithm already used in the first stage of construction.

The construction of the model system and the algorithm used for the coupling of models are characterized by a further essential feature: The principal solution represented is not restricted to the power industry. It may be used in a similar form for other spheres of the national economy if the models of these systems are designed correspondingly. It must be guaranteed, however, that the goods produced in the corresponding branches, are not characterized by an excessively large variety. The branches of engine-building are probably unsuitable for an application of such a model system. More concrete results, however, must still be obtained by further detailed investigations.

On the mathematical-methodological side, it is quite possible to combine homogeneous systems of some countries to a model system in this way. For example, we could imagine applying a model system which couples the power industries of some countries with the aim of using effectively the existing resources of energy carriers. The difficulties of realizing such a plan are above all to be considered with regard to content, i.e., they are to be attributed to the existing economic conditions in the different countries.

With the progress of socialistic economic integration, there will arise more favorable conditions for such couplings in the frame of the Council of Mutual Economical Aid.

Explanations of formulas

a_{ijlt}	Specific consumption of energy carrier i of technology j for fulfilling the task of generation and supply in the year t
a_{ikt}	Specific consumption or generation of energy carrier in the plant of energy transformation k in the year t
$b_{it\upsilon}$	Demand of energy users for energy carrier i in the year t, variant υ
$\hat{b}_{it}$	Demand for energy carrier i in the year t which is not subject to optimization
c_{jlt}	Specific social expenditure of technology j concerning the task of generation and supply l in the year t
c_{kt}	Specific social expenditure of the plant of energy transformation k in the year t
c_{it}	Specific expenditure on the import of energy carrier in the year t
$f_{ist\lambda}$	Delivery or receipt of energy carrier i in the year t by the energy partial system s, variant λ
$g_{it\upsilon}$	Resources of energy carrier i in the year t, variant υ
i_{it}	Import of energy carrier i in the year t
I_{it}	Restriction of import of energy carriers
$p_{\upsilon}, \psi_{s}, \psi_{\upsilon}$	Factors of valuation ($0 \leq p, \psi \leq 1$)
$q_{rt\upsilon}, q_{rst\lambda}$	Use of the central restriction r in the year t by the energy users ($q_{rt\upsilon}$) or by the energy partial system s; variants υ or λ
Q_{rt}	Restriction of the central condition in the year t
r_{υ}	"Reduced costs" of the central model; variant υ
x_{kt}	Throughput of the plant of energy transformation k in the year t
X_{jt}	Limitation of throughput of the plant of energy transformation

$Y_{jlt\upsilon}$	Throughput in connection with the utilization of the technology j of the task of generation and supply l in the year t; variant υ
Y_{lt}	Rate of the task of generation and supply l in the year t
$Z^B, Z, Z_{s\lambda}$	Total social expenditure of the optimized variants
ω_{jlt}	Limitation of the technology j of the task of generation and supply l in the year t

Discussion

The discussion began with an example of the importance of social and psychological factors in determining energy needs. Altering the normal living space temperature greatly alters energy demand. The speaker also indicated a social problem related to education. People are becoming more and more educated, but our requirements for workers have not changed comparably. We have established a division between education and work. An important question for the future, and perhaps for IIASA, is what to do with well-educated people.

The speaker also stated that prices can be treated either as data or as results. If one develops a linear programming model, duality provides prices as a result. In this case, hypotheses are the data. When a decision maker is introduced, prices are not just taken from the linear program. A good systems analysis subject is the interface between decision maker, price system, and user or supplier subsystem.

Discussion

The representative of WMO emphasized the importance of determining who should pay for energy. He suggested that IIASA establish the potential of different sources of energy and urged that someone study how energy uses affect the climate. He noted that man changes the climate both unintentionally, as by-product of his other activities, and deliberately, to create "artificial" conditions. Finally, he suggested cooperation between IIASA and WMO.

Translated from Russian

ENERGY PROBLEMS AND THE UTILIZATION OF POWER SOURCES

K.V. Ananichev

Energy is one of mankind's principal necessities. Without the expenditure of energy and the utilization of power sources no economic, technical or environmental question can conceivably be resolved. Moreover, the availability and exploitation of power sources are essential to coping with the problems arising out of the relationship between man and nature.

In recent years, questions associated with energy and the utilization of power sources have been considered increasingly both in the context of environmental protection and in that of the predicted development of mankind over the next 50-100 years. It is quite obvious that, if mankind does not ensure itself an adequate supply of energy, all development forecasts and all plans for overcoming the ecological crisis will be pointless.

Almost all the forms of energy on our planet have, as we know, a single primary source - the energy radiated by stars, and in particular by the sun, our closest star. Our planet receives from the sun 40 000 000 million kilocalories of energy per second; of this about half is dispersed and absorbed in the earth's atmosphere, while clouds, dust and other solid particles reduce the fraction of solar energy reaching the earth's surface to approximately 40%. Thus, the surface of our planet receives 16 000 000 million kilocalories of solar radiation per second.

Part of the solar energy reaching the earth is reflected and escapes into space in the form of short-wave radiation. A further part is absorbed by the earth's atmosphere, hydrosphere, lithosphere and biosphere. The absorption of energy by the atmosphere and the hydrosphere gives rise to evaporation, atmospheric precipitation, winds, waves and - to some extent - ocean currents and other phenomena. Through photosynthesis, the energy absorbed by the biosphere becomes incorporated in the biomass of plants and animals on land and in the sea. The energy absorbed by the lithosphere re-emerges as thermal, chemical and nuclear energy - including hydrocarbon fuels, which result from the decomposition of living matter.

As a result of evaporation, atmospheric precipitation, the movement of ocean waters, the respiration of plants and animals, and the combustion of hydrocarbon fuels, part of the solar energy accumulated by the earth is also returned to space in the form of long-wave radiation.

These processes - the radiation of solar energy to the earth, its absorption by the atmosphere, the hydrosphere, the lithosphere and the biosphere, and its subsequent escape into space - occur steadily and without interruption.

There are also power sources, however, which are not directly linked with solar radiation - they include the earth's internal heat and tidal movements. These forms of accumulated energy result from gravitational forces, the earth's rotation, electromagnetism and various other phenomena.

Man has four forms of energy at his disposal: solar energy; the kinetic and potential energy of the earth's gravitational system; the earth's internal heat; the energy resulting from the earth's rotation and the circulation of the earth's atmosphere.

Although there are many forms of energy associated with the earth's gravitational system, for simplicity of analysis it is best to confine oneself to the energy of rivers and tides. On the other hand, besides the energy contained in organic matter (accumulated solar energy), an enormous amount of solar energy is locked up in the myriad chemical compounds which were formed during different geological periods in the course of the earth's formation.

Power sources can be divided into two major categories: non-renewable and renewable. Non-renewable power sources include hydrocarbon fuels (coal, oil, natural gas, bituminous shales, peat, etc.) and nuclear fuels (i.e. materials which can release energy through nuclear disintegration and thermonuclear fusion). Renewable power sources include photosynthetic energy, directly utilized solar radiation, water power, the energy of tides and waves, the energy of evaporation and precipitation processes, wind energy, energy based on the temperature difference between the atmosphere and land and water surfaces, and geothermal energy.

In general, man uses only a few of these many energy forms, preferring above all hydrocarbon fuels. Until quite recently (120-150 years ago) human and animal muscle and wood fuels were the main sources of power. They were then supplemented by coal and later by oil and gas, which in recent years have also been followed by nuclear fuel. Although there has been widespread use of water power, its role in the world's energy balance is only a minor one. The use of the energy of hot underground waters (geothermal energy) and of waters under great pressure is still in an early stage, as is the use of solar radiation, tidal energy and wind energy.

Power generation is at present based mainly on hydrocarbon fuels (coal, oil and gas), about 6000 million tons coal equivalent (heat value 7000 kcal/kg) being extracted each year. This is equivalent to an average of two tons coal equivalent per human being. However, there are considerable differences between countries; for example, the figure for the United States is 10 tons and for India 0.2 tons (50 times less). Upon being burned, each ton coal equivalent releases 7 million kilocalories of energy, so that the energy derived from the hydrocarbon fuel extracted each year amounts to 42×10^{15} kilocalories.

There is a great deal of contradictory information about how this energy is used. In some publications, for example, it is stated that 25-30% of the fuel in question is used for transport, 30-35% is burned at thermal electric power stations, 30% is used in industry and 5-10% goes to domestic users. According to other authors, however, 23.9% is used for transport, 24.7% is burned at thermal power stations, 30.7% is used in industry and 20.5% goes for everyday domestic uses. Despite such discrepancies, there is clearly a steady increase in the power demands of industry and transport.

It is very important to know both how much of each form of fuel is consumed in a year and for what purpose. The figures in the following table relate to the world consumption in 1964.

Power source (Type of fuel)	Amount (in millions of tons coal equivalent)	Fraction of total (%)
Coal	2241	36.57
Oil and derivatives	1867	30.46
Wood	974	15.90
Natural gas	880	14.36
Hydroelectric and nuclear energy	105	1.71
Fuel of animal origin	61	1.00
	6128	100.00

Almost two thirds of the power from these sources is lost, only about 35% being used in the form of heat, mechanical power and electricity.

Let us now consider how power consumption is spread over different sectors of the economy, taking by way of example the world's most highly developed capitalist country - the United States of America. The following table (based on United States statistics) shows the share of five basic sectors of the country's economy in power consumption.

Sector of the economy	Fraction (%)
Industry	32
Electricity utilities	25
Transport	24
Communal and domestic users	14
Commerce	5
	100

In this table, the figure for "Electricity utilities" indicates not power consumption but the conversion of primary energy into electricity which is then supplied to the consumer; 68% of the electricity produced by the utilities is used in industry and commerce, the remaining 32% being used by the population at large for domestic purposes. Thus, the final distribution among users is as follows: industry and commerce - 54%; transport - 24%; communal and domestic users - 22%.

"Transport" breaks down into two roughly equal parts. Private automobiles and other private means of transport account for slightly more than half of the figure given in the table. The other half is accounted for by the air, rail and road transport of freight and by passenger transport services. Thus, private means of transport and communal and domestic users account for one third of the total power consumption, while business activities (industry and commerce) account for two thirds. The relationship between business and the private sector as regards power consumption is important for planning and predicting the development of power sources.

Let us consider power consumption in different sectors of the economy, comparing figures for 1970 with predictions for 1985 (the figures are based on computations performed by the Chase Manhattan Bank).

In the "transport" sector a 71.2% increase in power consumption is expected during the period 1970-85. However, the fraction of total power consumption accounted for by transport is expected to fall from 24% in 1970 to 21% in 1985.

Form of transport	Fraction of total power consumption in the "transport" sector (in %)	Increase in power consumption by 1985 (in %)
Private automobiles	53	72.7
Trucks and buses	22	53.1
Passenger aircraft	13	137.0
Agricultural and other machines	5	35.7
Ships and boats	4	25.0
Railways	3	19.0
Total	100	71.2

All means of transport in the United States will burn liquid fuel, with the exception of a very small number of coal-burning ships.

In "industry", power consumption is expected to increase by 57.7% during the same period, the fraction of total power consumption accounted for by industry also declining (from 32% in 1970 to 26% in 1985). As can be seen from the following tables, there will in addition be a change in the power supply structure.

Type of fuel	Fraction of total (%)	
	1970	1985
Coal	22	18
Oil	29	46
Natural gas	49	36
Totals	100	100

Fuels used	Fraction of total (%) 1970	1985
- for combustion	67	61
- as raw materials	33	39
Totals	100	100

It should be noted that more than half of the oil and coal consumed at present is used as raw materials (i.e. not for combustion). As regards natural gas, a little over 10% is used as raw materials, the remaining 90% being burned in industry.

In "commerce", fuel consumption is expected to increase by 73% during the period 1970-85, the fraction of total power consumption accounted for by commerce remaining the same. The power supply structure will also remain virtually unchanged, the share of natural gas increasing from 60% in 1970 to 62% in 1985 (the rest of the demand for fuel is covered by oil derivatives).

In the "communal and domestic" sector, a 50% increase is expected, the fraction of total power consumption accounted for by this sector declining from 14% in 1970 to 11% in 1985. The power supply structure will change only slightly; for example, the share of natural gas will increase from 52% to 56%, while that of oil will decline from 45% to 43%. There will also be a decline in the share of coal - from 3% in 1970 to 1% in 1985.

In the field of electricity generation, great changes are expected in the United States during the period 1970-85. For example, the per capita consumption of electricity is expected to more than double. The use of electricity is increasing faster than that of primary power sources, and there is a growing trend to use electricity instead of other forms of power. The consumption of primary power in the generation of electricity is expected to increase from 25% in 1970 to 37% in 1985.

In the field of electricity generation there are also expected to be pronounced changes with regard to primary sources of power, as can be seen from the following table.

Power source	Fraction of total (%)	
	1970	1985
Coal	49	29
Natural gas	24	11
Hydraulic power stations	15	8
Oil and oil derivatives	11	17
Nuclear fuel	1	35
Totals	100	100

During the period 1970-85, electricity consumption will increase by 189%, the annual rate of increase being 7.3%. It has been estimated that electricity consumption will be almost three times higher during 1970-85 than during the 15 preceding years. There is a striking increase in the figure for electricity generation by nuclear power stations, which by 1985 will account for more than a third of the electricity generated in the United States.

The figures in the following table indicate, as a percentage of the figures for 1970, the increase in power derived from different sources by 1985.

Power source	Increase by 1985 (%)
Oil and oil derivatives	105.1
Natural gas	23.2
Coal	62.4
Hydroelectric power stations	44.7
Nuclear fuel	659.5
All power sources	93.2

As can be seen from this table, oil and nuclear fuel consumption will have increased most by 1985. The reason for the substantial increase in oil consumption lies in the fact that oil is such a universal fuel and raw material and that the development of transport has resulted in a higher demand for oil. The relatively small increase in natural gas consumption is due not to reduced demand but to the shortage which is expected to make itself felt during the next few years. Without this shortage the increase in gas consumption would be much greater. The relatively large increase in coal consumption has two causes: the shortage of natural gas and a possible increase in oil prices; increased processing of coal both in metallurgy and in the production of liquid and gaseous fuels.

As regards the expected increase in the consumption of hydroelectric power, this is a natural reaction to the growing "power famine", it may also be attributed to the trend in the United States towards "clean" energy which does not affect the environment. The very large increase in electricity generation by nuclear power stations is attributable not only to the future shortage of hydrocarbon fuels but also to the energy strategy of the United States.

World power generation is increasing steadily. During the period 1860-1956, the average annual growth rate was 3.75% - with occasional annual growth rates of 5-7%. The growth rate increased considerably during the period 1958-61, reaching 19% per annum between 1961 and 1964. This continued during subsequent years. In the United States, for example, a sharp increase in power generation began in 1967. Among the reasons for the increased growth of world power generation are the development of power-intensive industries, the further electrification of production processes, in the service industries and in the home, and accelerated industrialization in many countries - including developing countries.

The rapid growth of power generation in recent years on the basis mainly of coal, oil and gas has led in turn to a rapid increase in the extraction of these hydrocarbon fuels, the reserves of which - considered inexhaustible not long ago - are now increasingly attracting attention by virtue of their "finiteness" and the possibility of their being exhausted in the relatively near future. Moreover, the proven reserves are increasing more slowly than power consumption. In view of these facts, estimates have recently been made of the world's power sources - and especially of the reserves of hydrocarbon fuels.

Many different - but on the whole fairly similar - estimates of the world's economic reserves of coal, oil and natural gas have been made on the basis of known deposits and geological predictions. One such estimate is presented below.

Type of fuel	World reserves		Extractable reserves	
	Amount in 1000 million tons coal equivalent	Fraction (%)	Amount in 1000 million tons coal equivalent	Fraction (%)
Coal	11 240	90.44	2880	82.66
Oil	743	6.00	372	10.68
Gas	229	1.85	178	5.11
Total	12 394		3484	

If it is assumed that 6000 million tons coal equivalent of these three types of fuel were extracted in 1970, then 0.15% of the world's economic reserves were extracted in that year. If one goes on to assume that the rate of extraction doubles every 20 years, one can estimate when all the economically extractable reserves will be exhausted; on the basis of the above figures this point will have been reached by the year 2050 - i.e. in 80 years' time. Lastly, if one assumes that further geological exploration and a higher extraction factor will lead to an increase in reserves by a factor of - say - eight, then the world's hydrocarbon fuel reserves will be exhausted by the year 2110 rather than 2050 - in 140 rather than 80 years' time.

According to American data, the economic fuel reserves of the United States will be exhausted in 75-100 years' time and its total potential reserves in 150-200 years' time.

Thus, in the foreseeable future mankind will be faced with catastrophe - the exhaustion of the world's hydrocarbon fuels, which also constitute chemical raw materials of great value. The situation is particularly acute with regard to oil and gas, which are representing a larger and larger fraction of the fuel burned in the course of power generation and now accounting for at least 70% of the total.

With hydrocarbon fuels constituting the basis of mankind's power supply, the situation which is developing as regards gas, oil and coal can only be regarded as an approaching power famine; this is the essence of mankind's energy problem.

To this one must add that the burning of hydrocarbon fuels is accompanied by serious atmospheric pollution and by the release into the atmosphere of enormous quantities of carbon dioxide which give rise to a "hothouse" effect.

Mankind must therefore switch to new power sources for the following reasons:

(a) The possible exhaustion of reserves of hydrocarbon fuel (especially gas and oil) in a few decades;

(b) The need to use oil, gas and coal as raw materials in the chemical industry;

(c) The danger of atmospheric pollution owing to the release of enormous quantities of carbon dioxide and other compounds resulting from the combustion of hydrocarbon fuels;

(d) The increasing demand for power and the growing social costs of power generation.

These conclusions are probably valid even if fuel consumption increases at a somewhat different rate and the power consumption pattern is different. For example, according to data presented at the 8th World Power Conference, the gross world production of economic power increased from 6140 million tons coal equivalent in 1968 to 6650 million tons coal equivalent in 1970, which means an average annual increase of 4.9%. In 1970, the share of oil in total world power consumption reached 46% and that of gas 20%, while the share of coal had fallen from 51% to 31% in the course of ten years.

It was estimated at the World Power Conference that, if the average annual increase during the decade 1970-80 was 4.5%, total annual power generation would be about 10 000 million tons coal equivalent by 1980, approximately two thirds being attributable to oil and gas and the share of nuclear fuel remaining at 4-7%. Total world power generation in the year 2000 may, according to the data presented at the World Power Conference, exceed 20 000 million tons coal equivalent, oil and gas accounting for slightly over three fifths of the total and nuclear fuel for up to one fifth; the remainder will be attributable to solid fuels - mainly coal.

Whereas, for example, Academician N.N. Semenov assumes doubling of power consumption every ten years (which is supported by, in particular, United Nations data for 1958-68), a much longer doubling time is used in the calculations of the World Power Conference. The marked discrepancy in assessments of how power generation will develop during the period up to the year 2000 are quite understandable if one thinks of the large discrepancies in many national assessments. In the United States, for example, the Battelle Memorial Institute estimates that mean annual power consumption will increase at a rate of 3.2% during the period 1970-2000, whereas other experts assume a growth rate of 4.35% during the period 1970-80 followed by a reduction in growth rate to 3.5% during the period 1980-90; the demand for power will increase during the period 1970-2000 by a factor of 2.56% according to some estimates and by a factor of three according to others.

Despite their diversity, the various quantitative estimates all indicate rising world power consumption and declining fuel resources - especially hydrocarbon fuel resources. The American experts Hottel and Howard have correctly pointed out that, over and above all accepted quantitative predictions, there is a commonly held view that by the end of this century the demand for power will be enormously large by current standards. This confirms what has already been stated regarding the need to find reliable new forms and sources of power.

Let us look at the energy systems (or power sources) which are being or could be used by man, considering separately the group of systems based on renewable power sources and the group based on non-renewable power sources.

As the first energy system within the first group we take the action of gravitational forces, the earth's rotation, molecular motion (the temperature difference between atmosphere, lithosphere and hydrosphere), tides and waves, air movement (winds); geothermal energy also belongs to this system. Man has been making use of these power sources for a very long time, converting energy from one form to another. For example, the energy of the winds has been used to propel sailing ships and turn windmills and mills linked up with electric generators and pumps; the gravitational forces represented by the water masses in rivers regulated by dams are used to drive hydraulic turbines connected with electric generators; gravitational forces are also the basis of tidal power stations.

A major advantage of these power sources is that they operate continuously and are virtually inexhaustible over time. Moreover, their exploitation by man does not have any serious ecological consequences - with the exception of hydroelectric projects, which can give rise to environmental disturbances (the flooding of land, changes in the hydro-meteorological conditions, etc.).

Their main disadvantages are that they are not distributed uniformly over the earth's surface and that they cannot be relied upon to be available whenever and to the extent required. Moreover, although the world's hydraulic, tidal, wave and wind energy resources are substantial by present standards, they are totally inadequate for meeting the demand for power in, say, the year 2000. It has been estimated that all these power sources together could meet only 6-10% of mankind's demand for power at the end of this century, so that there is little hope of using them as the basis for solving the future world energy problem. Nevertheless, one should not ignore the possibility of using these power sources in specific regions and under specific conditions.

A subject which deserves special attention is geothermal energy, the possibilities of which were either played down, or even totally ignored, until quite recently. We know that the predicted reserves of geothermal energy are tremendous, but for a long time the chances of using them appeared to be very limited. The literature contains frequent references to the fact that geothermal energy can be used only in certain parts of the globe, mainly in areas of volcanic activity. Yet recent studies in a variety of countries, and in particular exploration sponsored by the United Nations, have shown that geothermal energy can be utilized virtually everywhere, the only difference being that in some regions of the globe the geothermal waters and high-pressure cavities are close to the surface while in other parts they are a long way below it.

Current opinion with regard to the possibility of utilizing geothermal energy to produce heat and electricity is based on a more exhaustive study of such resources and on the progress achieved in deep boring techniques, including the sinking of bore-holes in the lithosphere by means of directed atomic explosions. There can be no doubt, of course, that the drilling of geothermal bore-holes, particularly under high-temperature conditions, is still an extremely difficult matter, but the latest achievements in metallurgy, production of special materials and cooling systems warrant greater optimism in assessing the prospects of using geothermal waters and geothermal superheated steam for power production purposes. Scientific theories developed over the last few years indicate the theoretical possibility of using volcanic activity as a source of heat energy. Pumping water into hot magmatic layers of the lithosph could in principle provide a tremendous amount of boiling water or steam for subsequent use in heat engines.

On this account there has been renewed activity over the last few years in the area of heat engines working with low-temperature gradients. This normally refers to two-circuit engines in which the geothermal water is used as the workir fluid in the first circuit, and the vapour of low-boiling specially-prepared liquid mixtures is used for the second circuit.

According to calculations made by American research workers, the developmen of geothermal energy in the United States is highly promising. For example, it is reckoned that the potential output of American geothermal power stations will be 750 MW by 1975, 132 000 MW by 1985, and 395 000 MW by the year 2000. As will be clear from these estimates, by the end of the present century geothermal power may account for a substantial proportion of the United States energy balan Right now, of course, it is difficult to say for certain exactly how realistic the prospects of geothermal power are, but studies conducted over the last few years suggest that within the context of the first energy system which we discus geothermal power is the one solution to the energy and power resource problem offering the greatest promise. It should be stressed in this connection that practical harnessing of this form of energy is not far off.

The second energy system in the first group involves the vital activity of living organisms. It includes the utilization of solar energy in the process of photosynthesis by vegetation and the vital energy of micro-organisms. Sunlight, solar heat and, possibly, cosmic radiation are the prime sources of the energy processes taking place in living matter. Utilization of this energy system take the form of nourishment, application of muscular strength in man and animals, fermentation and microbiological action in industrial and agricultural processes and also the production of heat when fuel of vegetable or animal origin is burne

Like the first energy system, this one is virtually inexhaustible, self-restoring and renewable. This is its main advantage. The muscular strength of a living organism has a fairly high degree of efficiency. Food energy is converted into muscular energy by slow, flameless oxidation within the organism. A living organism can in theory carry out a momentary transformation of one form of energy into another with a relatively high degree of efficiency. In actual systems, however, living organisms, like energy sources, are characterized by a number of shortcomings. These include, first and foremost, high heat energy losses during metabolism.

The second energy system, just like the first, involves indirect rather than direct utilization of solar energy. In the first case the energy is utilized and transformed via non-living matter, whereas in the second instance the process takes place via living organisms, i.e. the biomass, in which the chemical transformation of solar energy into the energy of growth, movement and muscular activity takes place.

Until quite recently living matter was not taken very seriously by scientists as a means of conversion of one form of energy into another, or as a source of energy on the earth. This was simply because of the presence of a large quantity of residual living matter that had not gone through the oxidation stage, in the form of oil, gas and coal. Today, however, increasing numbers of investigators are looking more and more persistently at living matter as a converter of energy which may hold promise for the long term and as a storer of energy that might once and for all solve the problem of the world's energy and power resources.

It is estimated that the overall productive capacity of photosynthesis throughout the world per year - in extremely approximate terms - is 80 000 million tons, or some 14 times more than the amount of fuel recovered every year. The question is, can we induce photosynthesis outside of living organisms and is it possible to find an artificial way of transforming solar into chemical energy with a fairly high degree of efficiency? Over the last few years many prominent scientists have come to the conclusion that this way of producing energy is theoretically possible. Among others, Academician N.N. Semenov has suggested that it might be possible, by some such mechanism, to increase the efficiency with which solar energy is used to 20% i.e. to double the "biological" efficiency of photosynthesis in plants. It is interesting to note that towards the end of his life, Jean-Frédéric Joliot-Curie, who played a leading part in laying the scientific foundations for the utilization of nuclear energy, attached major importance to the idea of harnessing the energy of the sun.

The third energy system is taken to mean the direct utilization of solar energy in photochemical, photoelectric and thermoelectric processes. By means of this system, man can produce thermal or electric power based on electrochemical reactions and on the focusing of the sun's light rays by optical means.

The advantage of the third energy system is that it can be used for direct transformation of solar energy into thermal or electric power. Its more positive aspects include the possibility of storing the energy (on a comparatively small scale) by biochemical or electrochemical means. The impossibility of utilizing the system on a large scale is its main disadvantage.

This energy system has long been a subject of interest to investigators because of its apparent simplicity, yet all attempts, even the latest and most serious efforts, to construct efficient solar batteries have run into insuperable difficulties associated with the very large size of such batteries or the high cost of the transforming elements in them. It must be assumed that even in the future, direct conversion of solar energy can only be of a limited nature. It is true, of course, that solar cookers, small boilers, pumping units and other such devices have already been constructed and operate efficiently, but there can hardly be any serious grounds for expecting a major breakthrough in the direct conversion of solar energy either in the foreseeable or even the distant future.

The fourth energy system comes under the second group of systems based on non-renewable energy sources. This system is understood as the production of energy by burning hydrocarbon fuels such as coal, oil, natural gas, bituminous shale, and so forth. The generation of thermal and electric power from the combustion of hydrocarbon fuels is at present the best known and most efficient way of meeting man's energy requirements. Here we can only single out some of the specific features in the development of machines operating on hydrocarbon fuels.

First and foremost, it should be mentioned that the last few years have been marked by vigorous attempts on the part of a number of research workers and designers to perfect the internal combustion engine, which has now been around for three quarters of a century. These attempts have been geared towards eliminating reciprocally moving parts and replacing them by rotating parts.

Gas turbines and engines of various designs with a rotating piston (or pistons) have in one or two cases already taken the place of the classical piston engine. But neither gas turbines nor the new rotary engines have solved the main problem, which is to improve efficiency. It has even been the other way round - in a number of instances the efficiency has been reduced. We may assume that attempts to perfect internal combustion engine design will go on and lead to some positive results, but the yardstick by which to assess the success of any such attempts is whether or not the engine is more efficient in terms of the consumption of liquid fuel, the world reserves of which are diminishing with every year that passes.

One of the major advantages of the fourth energy system is the possibility of conveniently storing, transporting and controlling the sources of energy involved, namely the hydrocarbon fuel. The principal disadvantages are the high heat consumption and operational cost, together with pollution of the environment by the combustion products. And finally, a fundamental drawback is the shortage of fuel, already discussed, and the need to conserve it as metallurgical and chemical raw material.

The fourth energy system is the one chiefly employed by man to meet his power requirements. As we have already pointed out, hydrocarbon fuels provide for almost all human requirements at the present stage. In view of the signs that a power crisis is approaching, this energy system will continue to be the centre of attention. The main goal will be to attain the highest possible efficiency and economy in power plants using fuel of this type. No less a problem will be to find ways of saving fuel through reduction in the consumption of power by industry, and the power supply per production unit in industrial plants and in the transportation sector.

The shortage of hydrocarbon fuels which is beginning to develop and, on the other hand, the very great advantages to be gained from using this type of fuel, especially for transportation purposes, have led scientists throughout the world to make further improvements in existing types of heat engine operating on the principle of the fourth energy system and to seek new ones. In addition to making improvements in the classical internal combustion engine (both carburettor and diesel models) and seeking new rotary engine designs and more efficient steam- and gas-turbine engines, scientists in a number of countries of the world are working out newer and more effective ways of utilizing hydrocarbon fuel so as to obtain thermal, mechanical and electrical power.

As one of the more promising trends we can mention combined turbine plants operating on a gas-steam cycle and possessing an efficiency of more than 40%. Another interesting line of development is the magnetohydrodynamic plant, in which fuels of this kind are used to form a high-temperature plasma intersecting a magnetic field and generating an electric current. Mention should also be made of the continuing efforts in the field of fuel elements in which the hydrocarbon fuels may theoretically be used with an efficiency as high as 80%.

The fifth system includes methods of obtaining energy by use of intranuclear processes. Within this system thermal and electrical power can be obtained through fission of the atomic nucleus as well as through thermonuclear fusion.

The chief advantage of the fifth energy system is that it affords a means of siting a power plant in any region of the globe, once it has been provided with a long-term supply of the requisite amounts of specially prepared nuclear fuel. The disadvantages of nuclear fueled plants include the high cost of their production and the fuel for them, the need for a costly radiological protection system, and the difficulties involved in radioactive waste disposal. The most serious problem is that of the nuclear fuel, as the uranium oxide and other types of nuclear fuel used at present are, strictly speaking, materials in very short supply. Furthermore, the cost of uranium is going up every year on account of increasing demand and decreasing reserves.

Another drawback of the fifth energy system is the fact that it is virtually unusable for means of transportation, particularly road vehicles, railways and aircraft. For the time being nuclear energy can, for the most part, be used only to provide heat and electricity. Unfortunately, we have not yet built nuclear energy storage batteries of sufficient capacity and reliability for installation in all means of transport. Moreover, at the present juncture we still cannot consider the swing towards nuclear propulsion in shipbuilding as advisable on account of the high cost of the nuclear power plants involved and the difficulties inherent in operating them.

Calculations show that with the wide-scale use of nuclear reactors of the present-day design to generate electricity, the world's uranium reserves will very soon be used up. For this reason the development of nuclear energy throughout the world is being conceived more in terms of the design and operation of what are known as fast-neutron breeder reactors. Theoretically it is quite possible to build such reactors and the problem of nuclear fuel would thereby be solved for a very long time; once it had been placed in the reactor, the fuel would last for a very long time. What is more, scientists are also working to bring about controlled thermonuclear fusion, which is an even more promising idea than the process involved in the breeder reactor.

But the central and most practical problem facing scientists in the field of nuclear power production is still the development of the breeder reactor. At present the following three types of breeder are being studied: first, the liquid-metal fast-neutron reactor, in which liquid sodium transfers the heat from the reactor to the point where steam is generated; second, the fast-neutron reactor with gas (helium) cooling. Both systems involve the use of breeder reactors in which the nuclear fuel can be doubled in eight or nine years. And finally, a third type is the breeder reactor with a molten salt.

In all three cases there are still a large number of unsolved problems. At present many scientists are showing a preference for the liquid-metal breeder reactor, but its construction entails a series of difficult problems. Liquid-metal reactors are now being developed in the United States, Britain and France.

Generally speaking, the development of breeder reactors of the different designs requires a tremendous financial outlay. The scale of the expenditure incurred is shown, for example, by the fact that not even the United States is able to work on all three breeder reactor types at the same time, as this would require a tremendous amount of money. It is worth pointing out that the first liquid-metal breeder reactor is being constructed by United States Government bodies as well as a number of private firms, the project being co-financed by the State and the private companies. Further development of the fifth energy system is fraught with considerable difficulties; a large amount of theoretical and applied scientific research still remains to be done, and the design strategy will have to be carefully selected, since the working "front" is so extensive that it is impossible to follow up all possible lines of research.

Nuclear power engineers are currently faced with a serious decision: should they develop the modern reactors more quickly and consume large amounts of uranium, or should they step up research on the construction of breeder reactors. In this connection it should be noted that many scientists from different countries believe that the first breeder reactor will be started up by the end of the present century. The United States has announced the commissioning of the first commercial fast-neutron reactor for 1985. Prototypes of these reactors may well have been constructed by the '90s, and not only in the United States. But the main question is still, to what extent will these reactors be economically viable and technically feasible, and how quickly could they take over from the hydrocarbon-fuel-based power plants of the fourth energy system.

The sixth and last energy system also falls within the group based on the use of non-renewable power resources. We are referring here to the biogeochemica transformation of energy, in which system heat energy is obtained by means of chemical reactions involving nitrates and phosphates and other substances of thi kind.

These compounds, as we know, are used as fertilizers in agriculture. The energy-producing effect of the nitrates and phosphates is quite unique in this case, but it is indirect in the sense that man utilizes the energy via the food chain or through the use of plants and animals. Direct production of energy from phosphates and nitrates is unfortunately not controllable for the time bein and can only be brought about by the action of explosives. Explosives, particul those with a nitrate base, release energy in large quantities, though the action is extremely brief.

The use of explosives for peaceful purposes is a matter of common knowledge. We need mention only the directed blasts used for sinking shafts in mines, excavation of trenches, construction of dams, and so on. In industry explosives have come to be used for processing metals. Explosion shaping has become a common production process in recent years and is based on the application of large amounts of energy over very brief periods of time.

Clearly, as far as the sixth energy system is concerned, we cannot make any calculations based on the destructive energy of explosives, since the proble of energy and power resources consists in finding forms of energy for constructi rather than destructive purposes. However, many of the principles underlying, in particular, modern weaponry could also be used in the search for new energy sources. At present it is difficult to assess the potential value of the power sources in this sixth energy system, but we should not rule out the possibility of explosives being used to produce energy in the future, in the same way that it has proved possible to utilize nuclear fission for that purpose in the reactors of nuclear power stations.

The formation of energy sources of this curious type of "fuel" of biogeochemical origin is linked with the action of living matter on the "bone material" of our planet. As we know, living matter has a geochemical effect on the lithosphere. The "pressure" of life on non-living matter is so great that structural changes occur in it and a huge amount of "internal stress" energy builds up. This energy can be "discharged" after certain preparations have been made. The question is whether we can control this process. After all, in principle the combustion of hydrocarbons and explosion of nitrate compounds also resemble each other, and represent oxidation and substitution reactions. The difference between these processes is the rate at which the reaction takes place: in one case it is slow and in the other very fast. A controlled explosion or chain of explosions - this is probably the best way of formulating the main problem of the sixth energy system.

We have examined the six basic energy systems within which the problems of providing energy and finding power resources to satisfy man's requirements have been, are being, and will be solved.

Let us now consider, in the light of our need to solve the problems we have been discussing, the criteria that could be applied in assessing energy sources. In the realization that there is a great deal of descriptive and reference literature already available on the subject, we shall not deal with the physico-chemical parameters of natural and man-made fuels or the many technical characteristics of energy sources. Our aim here will be to select certain specific criteria typical of the present-day approach to solving the energy and power resources problem. Since there are many such criteria, we will deal only with the most important ones.

The first relates to the physico-chemical properties of the energy sources. For example, the higher the calorific value of the fuel, the more valuable it is. On the other hand, the lower its ash content, the more advantageous it is to use the fuel, and so on.

The second criterion is the geographical distribution of the resources, their mode of occurrence and accessibility for mining purposes. This criterio too, does not require any special comment.

The third criterion is the cost of recovering and processing the energy sources, and transporting them to the point of primary consumption. Nowadays this criterion needs to be viewed somewhat differently than, let us say, 30 or 50 years ago. For example, the extraction of oil or gas is simpler on land than at sea, yet at present oil rigs are steadily advancing out to sea, and eve into the ocean, since there is less and less oil to be found on land. It is al known that the conversion of coal into liquid or gaseous fuel is still much mor expensive than the use of oil or natural gas, yet many countries are obliged mo and more to resort to processing operations of this kind, owing to a lack of ga and oil. And finally, everyone realizes that there is very little point in carrying fuel from Australia to North America, yet the shipment of enriched uranium ore, even from Australia, is extremely profitable for the United States

The fourth criterion relates to the feasibility and economic advantage of converting one type of energy into another so as to reduce the cost of transporting fuel, or to provide motive power for mobile transport systems. An example of this is the production of liquid or gaseous fuel from coal. By this criterion, not every source of energy can be used directly, for instance, in transportation or for combustion and high-temperature heating. The use of nuclear fuel for such purposes is possible only after it has been transformed into electricity.

As the fifth criterion we should take the possibility of attaining maximum efficiency in converting one form of energy into another. This criterion also needs no further comment, since it is perfectly obvious that the higher the thermal efficiency of the fuel used, the more advantageous it is.

And finally, the sixth criterion, which covers the concept of safe handlin of energy sources in relation to man and the environment. Whereas this criteri has been understood for a long time as far as man is concerned, it is only comparatively recently that people have turned their attention to pollution of the environment by sulphur and nitrogen oxides and the increased carbonic acid content of the atmosphere. Another example is the radioactivity released when nuclear fuels are used. It is this risk of radioactive contamination and expos that makes it impossible, or extremely difficult, at the moment to use nuclear fuel for transportation systems and even for large-scale power generation.

In the light of all these facts we can reach certain conclusions and make some suggestions as to ways in which the problems of energy and the utilization of power resources could be solved.

First, the problem cannot be viewed separately from the problems of the environment, water resources and the state of the atmosphere, from the prospects for further economic progress, and, above all, from the outlook for scientific and technical progress. In other words, any approach to a solution of the problem should be programmed and based on systems analysis. The relationship between the energy problem and ecological, economic and technological problems in the development of civilization is becoming increasingly intimate and even now it has become practically impossible to predict the solution of any of the problems discussed separately from that of the others.

Second, the energy problem has itself to be regarded as a set of system categories. These include the energy systems discussed above, in each of which we have to take into account the availability, extent and accessibility of the reserves; the possibility of transforming energy from these sources into another form that can be used by man; the feasibility of storing energy or power resources, together with their transportation, and ways of utilizing energy as economically as possible and without unfavourable ecological consequences. Thus, the energy problem can be viewed as a series of systems with a standardized set of programmed characteristics.

Third, the possibility of introducing a particular energy system is closely related to the quality characteristics adopted or attained and to the solutions applied in ecological, economic and technological contexts. This possibility is also conditional upon the criteria for assessing the energy sources, discussed above. An important consideration in this matter is the fact that the development of the different types of energy sources will be more and more contingent upon economic conditions both as regards consumption of the sources in the process of energy conversion, and the utilization of the energy during production and utilization. It is probable that the energy content of a product and the power supply per production unit will tend to decline steadily - a product or process requiring less energy will be regarded as an achievement.

Fourth, ecological requirements will inevitably force man to generate and consume more and more "clean" energy. Here, attention should be chiefly focused on control of "thermal" pollution, particularly as regards waters and the atmosphere. The efforts to control thermal pollution may soon assume world-wide proportions and will call for a fundamental reappraisal of all the energy sources in use. What we are going to do with the surplus heat and how we can preserve the cold spots on our planet may prove to be the determining factor in selecting a particular energy system or source.

Ecological requirements and the task of controlling "thermal pollution" will clearly force us to consider the problem of energy and power resources within a single programmed planetary context that takes into account the balance of all forms of energy reaching the earth, reflected from it and absorbed by it, together with the earth's internal heat energy, gravitational energy and the earth's rotational energy. A special place in this balance should be assigned to the energy absorbed and given off by the biosphere, in particular, by the living matter contained in it. A programmed approach means in this case determining whether the high rate of energy transformation by the biosphere, and more particularly by man, could lead to a disruption of the energy balance of our planet and bring about irreversible consequences.

A prominant place in this analysis should probably be given to the first energy system, and especially geothermal energy. Finding out whether we can control the relationship between the earth's internal energy and the solar radiation reaching it may prove an interesting problem for systems analysis as applied to the over-all energy problem.

Fifth, any forecast relating to the solution of the energy crisis should make allowance for the future development of water resources. The concept of composite exploitation of water resources ought probably to include energy automatically. Figuratively speaking, not one drop of water should be consumed without work being done to produce or store energy. Another extremely important factor is the use of the thermal capacity of water resources as an energy source.

A programmed study of water resources from the standpoint of power generation probably cannot be limited merely to questions of setting up hydroelectric power stations or pumping plants. The important heat processes associated with water (such as evaporation, rain, sea and air currents, as well as other types of interaction between water bodies and the atmosphere) require constant attention and programmed research based on systems analysis. It is, after all, water that transfers a tremendous amount of thermal energy from one spot to another. Understanding and learning to make use of the low-temperature thermal gradients of surface and atmospheric waters is an extremely interesting and promising task for systems analysis.

Sixth, whether or not we solve the energy problem will be determined by the extent of our scientific and technical progress. To predict the development of energy systems without forecasting technological development would be a mistake, to say the least. Certain branches of technology have traditionally served the development of power engineering and it is probable that the prediction of the development of such branches as a function of other associated aspects of scientific and technical progress can be very much of service in analysing possible approaches to solving the energy and power resource problem. It could be an interesting field of research for specialists in applied systems analysis to work out these connections and determine the relationships.

Seventh, a critical assessment of the state of human knowledge with regard to specific energy systems or sub-systems should be made. It stands to reason that there is no point in studying over and over again what has already been thoroughly investigated, let us say over the past 100 years. This applies, for example, to sub-systems associated with the use of hydrocarbon fuels. What is of great interest are the systems which have been less thoroughly studied, such as those based on nuclear fuel, or sub-systems utilizing geothermal sources of energy. When deciding on topics for a more detailed programmed study, a high degree of selectivity should be shown. For example, it would be worthwhile to make just such a study of the nuclear fuel and geothermal energy systems described above.

At the same time, one should not disregard certain aspects of the systems already thoroughly studied. It is important, for instance, to investigate the potential capacity of systems based on hydrocarbon fuel, but not only in terms of improving the efficiency with which these fuels are converted into energy, but also as regards more rational utilization of the energy obtained. It should be assumed that the problem of economizing on power resources and energy could become acute if progress in the development of nuclear power plants, particularly breeder reactors, does not prove to be as rapid as is hoped for. An approach to the use of energy based on systems analysis is a highly relevant matter both for now and for the future.

How Can Man Live with Fission?

Alvin M. Weinberg

I propose to examine the dilemma man might face because, if he is to survive in anything like his present numbers, he will need an inexhaustible energy source; and, if we are prudently realistic about our options for inexhaustible energy sources, we must assume--despite various optimistic counterclaims--that only nuclear fission can be relied upon as this source. The fission breeder, though a practically inexhaustible source of energy, is potentially beset with certain difficulties: reactor safety, diversion of fissile material, accidents during transport, waste disposal, dismantling of old reactors, and routine radioactive emissions.

These potential difficulties have led to strongly polarized views as to the future course man ought to take. On the one side are the technological optimists (including myself) who insist that the difficulties of fission tend to be exaggerated; what difficulties there are can be remedied, or at least reduced to acceptable proportion, by technological improvements. On the other hand there are those such as the Swedish plasma physicist Hannes Alfven who reject fission as being an unacceptable long-term source of energy.

Those who reject fission urge two courses of action: first, to reduce man's per capita energy demand; and second, to expand research on alternative inexhaustible energy sources--solar, geothermal, fusion--in the hope that at least one of these can eventually provide our prime energy without posing the potential hazards of fission. In the meantime, while we wait for these alternatives, we ought to depend on fossil fuels.

I cannot fault either the desire to reduce our per capita energy expenditure, or an expanded effort on solar, geothermal, and fusion energy. However, there is no assurance that either of these strategies will work. As for reduction of U. S. per capita energy expenditure, say by a factor of two, even if this were economically feasible, it would merely delay for a time our need for an alternative source of energy. Moreover, this strategy says nothing about the rest of the world which now uses energy at one-sixth the U. S. rate. As for solar, geothermal, and fusion, despite the optimism that pervades much of the literature on these sources of energy, it is not at all certain that any of these will turn out to be sound for technical or economic reasons or a combination of both. I will discuss this point further at the end of this prospectus.

I therefore return to the fission breeder and state: Granted that the fission breeder is an imperfect source of energy that imposes a serious social burden on the society, it may well be the only one we shall have. Can we visualize, first, developments in fission technology that would reduce the social burden placed on our society by the fission breeder? And can we visualize in some detail the changes in our social organizations and institutions that will further reduce the dangers inherent in fission technology, and thus make this technology acceptable, if not to the most extreme skeptics, then to the more moderate critics of fission energy?

The Potential Dangers of Fission Energy

In my paper "Moral Imperatives of Nuclear Energy," which I include as an appendix, I give, in Tables 1 and 2, a summary of the potential dangers of nuclear energy. (Note that I do not consider incidental releases from nuclear reactors a threat; the present "low as practical regulations" reduce the allowable radioactive releases from a properly operating reactor to negligible proportions.)

In "Moral Imperatives of Nuclear Energy," I envisage, as an upper limit, a world of 15×10^9 people producing heat at the rate of 300×10^9 kilowatts, all from fission breeders; as a lower limit, I assume the current energy budget of 5×10^9 kw. The sheer size of the nuclear enterprise under the high assumption is staggering: 24,000 breeders, 150×10^3 tons of plutonium in inventory, 36×10^6 megacuries of radioactive fission products in equilibrium! Can we seriously contemplate such a huge commitment to nuclear energy? Can we identify fixes, both technological and social, that might allow us to live comfortably with fission energy on this scale?

Table 1. Problems of Nuclear Energy

1. Safety of Reactors
2. Transport of Radioactive Fuel
3. Ultimate Disposal of Radioactive Wastes
4. Clandestine Diversion of Fissile Materials
5. Disposal of Old Reactor Sites
6. Waste Heat
7. Waste By-products of Mining Uranium

Table 2. Dimensions of the Assumed Asymptotic Nuclear Enterprise

	Low Assumption 5×10^9 kw	High Assumption 300×10^9 kw
Number of reactors	400	24,000
Pu in inventory	2.5×10^3 T	150×10^3 T
Bred Pu produced/year	2.5×10^2 T	150×10^2 T
Number of reactors built/year	8	480
Number of spent fuel shipments/year (assume 100,000 MWd/T, 1/2 T Pu/shipment)	35,000	2,100,000
Number of fuel shipments in transit (6 days/shipment)	600	36,000
Radioactive fission products in equilibrium	0.6×10^6 MCi	36×10^6 MCi
Ratio of nuclear energy to solar energy absorbed by earth	1/24,000	1/400

Technological Fixes

First, what improvements in fission technology do we see that might reduce the burden of risk imposed by fission breeders? Several of these are discussed in "Moral Imperatives of Nuclear Energy"; I include them along with other possibilities that have occurred to me. However, I do not intend this list to be exhaustive; indeed, some of my suggestions may be impractical for one reason or another.

I. Reactor Siting

This includes several options, not mutually exclusive. Among these options are:

A. Nuclear Parks

1. Advantages

a. Internal lines of communication, hence less vulnerable to diversion.

b. A huge complex is likely to have stronger resources (people, facilities) to handle emergencies.

c. A complex of many reactors will be built over many years; the building team will therefore become more expert as it goes from reactor to reactor. The reactors themselves will be better built and more reliable.

d. Confining radioactive operations to a few sites limits the areas that may conceivably be contaminated by accidents.

2. Disadvantages

a. Vulnerability - to common-mode failure such as enemy action, earthquakes, accident, etc.

b. Limit to how much electricity can be transmitted from a single site.

c. Local heat island limit.

d. Increased cost of transmitting electricity.

On balance, I think the advantages outweigh the disadvantages: I simply do not see how we can continue deploying reactors and chemical plants in the absence of a siting policy that limits radioactive operations to a few places.

B. Underground Siting or Multiple Containment

How much safer an underground reactor would be probably ought to be studied more exhaustively. Some estimates of the cost of undergrounding are quite low, but these are not full studies insofar as I know. Berm construction has been proposed, and this may deserve serious study. Multiple containment vessels may afford as much safety as does the more expensive underground construction.

C. Ocean Siting

Eventually the ocean will become the most desirable heat sink, simply because of its heat capacity. Siting reactors offshore is a special case of a general trend toward siting heavy industry offshore.

D. Combinations

Nuclear parks and underground siting; nuclear ocean parks. The latter seem rather plausible to me, especially with the trend toward building non-nuclear industrial complexes offshore.

II. Reactor Design

Can reactors be designed, ab initio, to be invulnerable to the China Syndrome--that is, a failure of the containment vessel and melting through of the radioactive fuel? One expensive way to achieve this is to reduce the power per reactor, though I do not know--for a given type of reactor--whether anyone really knows what the upper limit to the size of a reactor that is invulnerable to the China Syndrome might be. Other ideas for defeating the China Syndrome include core catchers and, as previously mentioned, underground siting of reactors and multiple containment.

Redundant safety systems that would make an anticipated transient with failure to scram an inconceivable event are clearly desirable.

III. Quality Assurance

These are hardly technological fixes. Nevertheless, the "Zero Defect" movement in the aerospace industry suggests that very high degrees of perfection are attainable.

IV. Radioactive Waste Disposal

A. Development of Non-Leachable Solids

Non-leachable solids could be developed that would not contaminate water even if the geologic repository were flooded as the result of human inadvertency or unforeseen geologic event.

B. Clean Separation of the Actinides from Fission Products

Actinides would be separated clearly from fission products and returned to the reactor to be burned.

In a paper entitled "Management and Disposal of Wastes from the Nuclear Power Industry," by J. O. Bloemke, J. P. Nichols, and W. C. McClain and submitted to Physics Today, the authors point out that, if the long-lived actinides can be removed very sharply from the fission products, the remaining wastes, without the actinides, remain very hazardous for a period of several hundred years rather than the many thousands of years required if the long-lived alpha emitters remain in the wastes. (The question of long-lived fission products, such as ^{99}Tc, ^{135}Cs, ^{93}Zr, and ^{129}I, still may need resolution.) The Measure of Hazard used by the authors is the amount of water required to dilute the wastes to a level below that judged safe according to current radioactive concentration guides. There are naturally occurring pitchblende ores which are as hazardous now as unseparated wastes would be in some tens of thousands of years. If the actinides are separated out, this time is shortened to less than 1000 years. Though sharp separation of actinides (and probably a few other species) may be very desirable, the technology to do this does not now exist. However, there is probably no reason, in principle, why such sharp separations could not be developed; it would be a rather expensive development, but almost surely is feasible.

This still leaves the question of what to do with the actinides. As long as the reactor enterprise continues, the actinides can be burned in the operating reactors. However, there will always be some unburned actinides in the reactor--even if one, say, substituted ^{235}U as the fuel for burning the higher actinides. Thus the strategy of separating the actinides and burning them, though it reduces significantly the problem of storing wastes, requires devices that get rid of the actinides. Though we think of these now as being reactors (which always have some inventory of actinide in them), high-powered, neutron generating accelerators may turn out to be feasible in the next 25 to 50 years. One would of course expect that, if the society is sophisticated enough to operate high-powered neutron generators, it is sophisticated enough to operate reactors that can burn out the actinides. Yet if for some reason we decided to turn away from fission, we would probably want a non-fission neutron source to get rid of the actinides. Of course, if fusion worked, we would have a ready-made source of relatively cheap neutrons for this purpose.

C. Fanciful Methods of Waste Disposal

These include shooting to the sun, incorporation in the earth's mantle, disposal in polar ice caps.

Some of these technological fixes are more realistic than others. I would judge most of them to be easier than development of fusion, economical solar energy, or energy from hot rocks.

Social Fixes

Each technological fix will reduce a specific social burden imposed by fission. A detailed catalogue of the effect of a technological fix on the social burden should be made. However, no matter how good fission technology becomes, there undoubtedly will remain possible dangers that can be avoided only through intelligent, long-term intervention. Perhaps the most pervasive of these human interventions is the necessity for a long-term social commitment simply because ^{239}Pu has such a long half-life. (This assumes we cannot completely burn out unwanted plutonium.) Beyond this is a commitment to expertise of a very high order--again a commitment that will last for many, many generations. What can we do to ensure the longevity and viability of the social mechanisms that seem to be required if we concede that we shall always be dealing with the huge amounts of ^{239}Pu?

What is required is a cadre that, from now on, can be counted upon to understand nuclear technology, to control it, to prevent accidents, and to prevent diversion. Moreover, in this ultimate world, nuclear reactors will be in Uganda as well as in the U. S. A., in Ethiopia as well as in England. And one must ensure the same high degree of expertise in the underdeveloped country as in the developed country.

Thus the first order of improvement in social institutions undoubtedly must be carried out on a national level. Nuclear reactors are now operated by utility companies that are, traditionally, not heavily research-oriented. Is it possible to find mechanisms for improving the quality of utility operation--say to bring the general level of the energy utilities up to the level of the telephone utility? Is nuclear energy compatible with a fragmented utility industry--or must utilities merge to create super-critical entities at least for operation of reactors, if not for distribution of the electricity from them?

One suggestion (proposed by Sidney Siegel) that is relevant to the situation in the United States would be to establish a national corporation patterned after COMSAT to take charge of the generation of nuclear electricity. Such an organization would have technical resources that must exceed those available to even a large utility; and a high order of technical expertise in operating reactors and their sub-systems is essential to ensuring the continued integrity of these devices.

Each country now has its own AEC that sets standards or, in some cases, actually monitors or operates reactors. Perhaps this will be sufficient forever. Yet, no government has lasted continuously for 1000 years; only the Catholic Church is the best example of what I have in mind; a central authority that proclaims and to a degree enforces doctrine, maintains the long-term social stability, and has connections to every country's own Catholic Church.

The present International Atomic Energy Agency (IAEA) has some of the elements of such a trans-national authority. At present, one of the most important functions of IAEA is to convey information concerning nuclear technology throughout the world. This function is especially important since at every stage in the development it is highly desirable that each cadre learn from the experience, particularly the mistakes and narrow escapes, of other cadres everywhere in the world. One such path might be simply to strengthen IAEA--possibly to such an extent that it will acquire many of the powers of the International Authority envisaged in the old Baruch-Oppenheimer plan.

The nuclear community tends to address this set of problems by trying to avoid anything that will "foreclose options for future generations." For example, disposal of wastes as liquids in tanks is considered a temporary expedient; eventually, when the technology matures, these wastes will be solidified and permanently sequestered outside man's environment. Perhaps this is the only realistic way to approach these matters; to examine and reexamine each of our technological paths to ensure, insofar as we can, that we do nothing that future generations cannot undo. A systematic review of the nuclear enterprise from this point of view may itself be useful; after all, a physical bound on man's ultimate production of energy at one time seemed to be too remote to be worth worrying about, yet now we are seriously worried about just this contingency. Perhaps a reexamination of the various elements of the nuclear enterprise will uncover actions that do foreclose options for the future.

The most obvious of these is the production of ^{239}Pu itself. Man must, from now on, live with this immensely toxic substance. In some ways, the mere existence of ^{239}Pu forecloses some options; we must forever be careful about diversion of ^{239}Pu into dangerous hands. Again we return to a combination of social and technological approaches. Considerably more attention has been paid to the technological approaches to maintaining our options; we probably ought to examine whether our social visions match our technological inventiveness.

I do not pretend to see at all clearly just what social institutions man will need to live forever with fission. It may be that nothing beyond what we are now doing is sufficient--that the national atomic authorities, held together loosely by the IAEA and by various bilateral agreements, are sufficient. But somehow, as one contemplates the huge stretch of man's future, this seems to be inadequate. I would therefore recommend that a small study be instituted to try to conceive social and technical mechanisms, as well as the general directions in which these ought to develop, to ensure our capacity to live in acceptable equilibrium with fission.

Other Scenarios

It may turn out, after seriously studying the question, that one will conclude that Alfven is right--man cannot in the very long run live with fission. What options will then be open, again assuming that neither fusion, solar, or geothermal will be available? There will be only one possibility in this extreme case: the world population will have to fall to some level that can be sustained with renewable energy sources--food, hydro, some solar heating, tides, winds, ocean thermal gradients, and combustible wastes. I do not know whether any serious study of this alternative is available; we do not know how many people the earth can support and at what level of energy consumption under this assumption. Probably the number is around 10^9, but this ought to be established more carefully.

A more likely scenario may be the following. Of the three alternatives to fission--fusion, geothermal, and solar--only certain kinds of geothermal and solar are known to work, for a price. Geothermal from hot rocks (as contrasted with geothermal from hot water or hot steam) is not known to be feasible at any price; yet only hot rocks represent a really large (though not inexhaustible) source of energy.

Thus we might be left with solar as the only inexhaustible energy source, aside from fission, that we know is technically feasible, but at a very high price. Let us suppose that solar electricity can be generated for, say, five times the present cost of electricity. What would the social consequences of this assumption be? How many people, at what living standard, could the earth support with this primary source of energy?

The United States now spends about eight percent of its gross national product (GNP) on energy. If the cost of energy increased five-fold, this would reduce our living standard significantly, but hardly enough to make life in any sense unbearable. What such an increase in the cost of prime energy would do to other countries is a graver question. In particular, at this cost of prime energy large-scale desalting of the sea probably is out of the question (unless major inventions are made), and this may set an upper limit to the number of people the earth can support.

Attempts to visualize the social consequences of a five-fold increase in the cost of energy probably would be of some use even now. As our commitment to fission increases, so does our social commitment necessary for living with fission. We shall have to decide at some time--perhaps 50 to 100 years from now--whether our commitment to fission will be a permanent one. It would therefore seem prudent to have available an assessment of these options. The two alternative options I have mentioned--relatively little renewable energy, or solar at five times present costs--are the only ones which according to our current knowledge are realistic. If we understood the consequences of these options more clearly, perhaps we could better answer the questions: (1) Can man live with fission forever?, and (2) Should man live with fission forever? I would therefore recommend a study of these options and their social consequences as part of the overall study.

The Heat Balance Limit

Hovering over all our considerations of ultimate technical limits to man's use of fission energy is the heating of the earth. This is relevant to the question "How can man live with fission?" only insofar as a very large amount of energy produced by fission--or by fusion and geothermal (but not solar)--may cause irreversible climatic changes--for example, melting of the ice cap. Thus we must know what the total tolerable global energy limit is so that, if we see any danger of approaching it, we can take the appropriate measures--both social and technical--to reduce our energy expenditure.

Man now produces about 1/20,000 as much energy as the earth absorbs (and re-radiates) from the sun. This energy, in zeroth order, increases the average temperature of the globe by about 4×10^{-3} °C--apparently a quite tolerable amount overall but, in some sites where the energy is concentrated, possibly an uncomfortable concentration. At some man-made energy budget, the global temperature will rise to such an extent as to cause irreversible, and catastrophic, climatic changes. What is this upper limit?

In simplest approximation again, a 50-fold increase in man's energy budget (corresponding to the previously postulated 300 x 10^9 kw) will raise the global temperature by about 0.2°C. However, there may be subtle positive feedback effects (temperature dependence of the earth's albedo, increased greenhouse effect) which some climatologists claim would raise this somewhat more than 0.2°C, and there is at least some opinion that holds that increases of this order might be enough to melt the polar ice cap. Here, then, is a matter that requires serious and consistent scientific investigation: to give the best possible estimate of the large-scale climatological consequences of increases in man-made energy. <u>I would strongly urge that this question be taken up in a most long-term way by devoting, say, a sizeable part of the National Center for Atmospheric Research (NCAR) to the matter</u>.

What Should Be Done

The burden of this memorandum is that man's alternatives to fission are so tenuous and uncertain that we would do well to prepare ourselves, socially and technologically, to come to comfortable equilibrium with fission for millenia, if not longer. In particular, there are a number of specific questions, both technological and social, that ought to be addressed immediately; these deal with what we should do during the next decade or two rather than with what distant generations can do 500 or 1000 years from now.

Immediate Short-term Technological Questions

Of these I put waste disposal and reactor safety at the top. Questions on which really hard answers are needed include:

1. Demonstration of sharp separation between actinides and fission products.

2. Resolution of the ^{93}Zr, ^{135}Cs, ^{129}I, ^{99}Tc problems. The first three probably can be handled by dilution with non-radioactive species; what about ^{99}Tc?

3. Clearer understanding of possibility of disposal in space.

4. Nuclear parks.

5. Underground siting--should all reactors go underground as Edward Teller insists?

6. New estimates of the possible magnitude of a Class IX (most severe) reactor accident; this should include a comparison with other natural catastrophes such as the Bangladesh typhoon.

7. Further improvement in reactor safety.

8. Problems associated with dismantling the fission enterprise if in 50 years this became desirable.

9. Realistic estimates of the total radiologic burden (from "as low as practical" releases) imposed by a complete commitment to fission.

10. Assessment and development of technology to completely seal geologic disposal formations.

11. Possibilities for further automating reactor operation so as to reduce even more the degree of human intervention required in such an operation.

12. Establish a center to work consistently on the global heat problem.

13. To what extent do our present courses of action foreclose future options; to what extent do they keep future options open?

<u>Immediate Short-term Social Questions</u>

1. Is present structure of the utility industry capable of dealing with nuclear energy? Or should some regionalized super-utilities be created to take care of operation, the utilities themselves becoming distributors?

2. Should we deal more openly with the public with respect to emergency planning for possible reactor accidents?

3. Should states in the U. S. A. be urged to establish siting policies--i.e., each state designate specific places where nuclear power will be generated?

4. Can the IAEA serve a significant role with respect to the problem of:

a) Diversion?

b) Reactor standards?

c) Dissemination of information affecting reactor safety?

5. Why is the attitude toward all these questions so different in the Soviet Union and the United Kingdom than it is in the United States?

Long-term Questions

1. Should something like the Baruch plan be re-invented so that nuclear energy becomes eventually an internationally controlled enterprise?

2. Does a long-lived nuclear cadre make sense? Can one conceivably plan for such a cadre at this stage?

3. Should some continuing institution be given a mandate to worry about these social questions?

4. Are the long-range questions so vague and beset with so much uncertainty that one would be wasting one's time to really worry about them now?

Obviously most of these questions, particularly the ones with strong technological components, fall heavily in the province of AEC. Any study that might be undertaken would therefore need the support and encouragement of AEC. Beyond this, the views on these matters are so controversial that, before a serious study is even contemplated, there ought to be a discussion convened by a neutral body, say the Woodrow Wilson International Center for Scholars or the National Academy of Sciences, to see whether these matters have merit. I would visualize convening a small group of interested and knowledgeable people who might discuss the issues raised in this memorandum.

Discussion

Someone referred to an article by Gofmann, in Futures, which said that there is a vast difference between 99.9 and 99.99 shielding of reactors. Mr. Weinberg completely dismissed Gofmann's comment, pointing out that with radioactivity the sensitivity of detection is such that to speak of 99.99 is ridiculous. Even very large reactors only release a millicurie or so; routine release is not the problem.

The questioner said the article also touched on sabotage. Mr. Weinberg said this was a reason for having clusters. One could turn them into armed fortresses. His questioner replied that we have experience with complicated technical systems being taken over by a few determined people, for example in the case of airplanes. He asked whether Mr. Weinberg had ever considered what type of commando group would be required to take over a reactor cluster. He also noted the danger of proliferation of plutonium, adding that only seven kilograms are required to make one bomb. Mr. Weinberg responded that clustering eases that problem as well since all the plutonium remains within the system; none enters or leaves it. With respect to sabotage, the easiest form would be to blow up all of the devices necessary for cooling. This could be combatted by having redundant inlets.

Mr. Weinberg was asked what scale clustering he envisioned. He replied perhaps thirty or fifty million KW in each cluster. This would require air cooling or perhaps placement of the entire system in the ocean (an idea also being studied for dirty heavy industries). It is unclear how much clustering in a nuclear park is tolerable. Mr. Haefele suggested that the upper limit may be determined by the amount of waste heat and by meteorological considerations, and the lower limit by the need to maintain an independent fuel cycle. He asked whether blackmail had been analyzed as a possible problem; operators may be involved in sabotage. The fewer the parks, the more of a problem blackmail may become. The first speaker remarked that, judging by the instability of the last 1000 years, he was very worried by the implications for the future of any decision. If we decide to proceed, we are making a Faustian bargain for the sake of raising our living standards and for coping with a huge population increase. We are making a trade for which the population three or four hundred years hence may not want to pay. They may consider it a curse in the ground. Mr. Weinberg replied that this is a restatement of the same problem. In the nuclear community one considers the situation in terms of not foreclosing options. We have already foreclosed some; we did that when we produced the first gram of plutonium. The world is different just because plutonium exists. One could argue that every technology makes an irreversible change, a commitment. In this case, that commitment is distilled into one substance.

His questioner asked whether small temperature gradients could be exploited. Currently the thermal efficiency of geothermal processes is very low (below 10 percent) and there is a great amount of waste heat. Mr. Haefele replied that each of the energy options has systems problems. Exploitation of geo-thermal sources may produce earthquakes. We have learned that we must be careful about detecting these hidden problems; we must compare the side effects. What the public does not understand is that all of the sources present problems. You have the choice of disposing of plutonium or of producing earthquakes. Mr. Haefele added that a few years ago he would have thought it impossible to have a workable global monitoring system for the safeguard of nuclear materials. However, in the last few years, the IAEA has operated such a system on a truly universal basis. This has been a great breakthrough, in no small part because a problem was solved that so-called "realists" had considered impossible.

The participant asked whether anyone had looked at a scenario of an asymptotic society based on fusion reactors. Mr. Weinberg reiterated that his initial assumption was that only fission would be available and stated that he had not checked the other assumption. He remarked that both Messieurs Haefele and Starr have pointed out that although fusion is better from this view point, it too, is hardly perfect. One is still speaking of something like 24,000 x 10^8 curies of tritium.

A fusion expert among the participants agreed that it is uncertain whether fusion works at all and if it does, whether it is economical. However, he felt that there is a fair chance that it will be economical in some years. It is similar to the breeder reactor, as pointed out by Drs. Haefele and Starr. Going from a D-P to a D-D reactor will not produce a large change; one is still producing tritium. Fusion reactors may, however, affect other considerations, such as the number of reactors. Also, the fuel cycle determines the minimum size for a fission reactor but is not as determinative for a fusion reactor. However, the tendency to larger units will still exist for economic reasons. Mr. Haefele added that economic factors also affect the size of the fuel cycle for fission reactors. In a fusion reactor, the fuel cycle is internally contained. Thus one has a large, homogeneous reactor. Admittedly, we do not yet know the lower bound on size.

It was asked what the half-life is of tritium as compared to plutonium. Mr. Haefele noted that the problem in the case of the fusion reactor is not the half life of the tritium, but that until now fusion engineering has used niobium which has a half life of 30,000 years. However, while plutonium is necessary for fission, niobium is not necessarily required for fusion. The proper fusion materials are yet to be identified.

Someone else asked Mr. Weinberg how the quantitative risk from breeder reactors compares with that from the present stock of nuclear weapons in the world. Mr. Weinberg replied that he did not know exactly, but when this point was raised informally with some persons who did know, they said the risk of inadvertant detonation of a nuclear weapon is large by comparison. A social commitment already existed when an atomic bomb was made.

One participant observed that it has been said that the whole idea of a fast breeder reactor is tenuously based on fuel cycle economics. For example, the feasibility of chemical reprocessing is still uncertain. If the FBR fails, then we do no better than the thermal reactor with its limited fuel supply. More refined techniques require the expenditure of vast quantities of energy to achieve a small multiplicative factor. One might argue that this is true of fusion as well because of the energy required for containment. Must we live with this? Mr. Weinberg disagreed with both assertions. Containers based on super-conductivity require little power. Secondly, although he is not certain that the FBR will succeed economically, he suspects that it will in at least the next fifty or one hundred years. He said that he is convinced that fission is probably our only option, and whether the reactors are breeder or only near-breeder affects his calculations only slightly. Mr. Haefele added that today's economic conditions force a low breeding ratio. Under the scenario's economic situation, one could achieve more.

Someone else suggested doing further work on the probability of serious accidents and comparing the results to risks currently taken.

Mr. Raiffa commented that there seemed to be a consensus that it would be attractive for IIASA to work on long range models. He supports that view but also wants ties to current problems. In that sense, the siting problem is very appealing, as it has components in all three time periods. He said he was glad that the world is concerned about the necessity of considering other power sources and suggested that IIASA could play a pivotal role in the exchange of research. He asked whether the group thought that IIASA could do basic research in this field; there are already prodigious efforts being made in energy research. Minimally, IIASA could assume the role of a coordinator sponsoring conferences on the state of the art in different sub-fields. One question is whether this would duplicate efforts elsewhere. He did not, as yet, see a unique position which IIASA could establish for itself in these areas.

Prof. Raiffa referred next to the "Faustian gamble" and said he was disturbed by the emotional aspect of the problem. It must be tackled seriously without letting the emotional content destroy the analysis. In any case, he doubted the problem is quite so dramatic; the relevant decisions will be taken over a period of years. Mr. Weinberg responded that IIASA's proximity to the IAEA provides some protection against "emotional heat" if such work is done jointly. Moreover, it was unclear to him that in fact there is much political heat attached to the issue. He suggested beginning with the siting problem as in any case it has fewer overtones. Mr. Raiffa agreed and noted that that study could be independent of the longer-term analysis but supported by it. Dr. Weinberg observed that one could call the whole situation Faustian, and there are people who want no use of nuclear energy at all. The problem is to convince reasonable but misinformed people that we <u>can</u> live with fission; one version of <u>Faust</u> concludes with Faust finally making a deal with God and acquiring wisdom.

Mr. Haefele interjected that, in order to live up to the systems analysis approach, one must discuss the alternatives to living with fission. One of the participants commented that this was a perfect systems problem as there were many alternatives all with associated benefits and costs. It would be a great and fruitful task for IIASA to weigh them. He felt certain that the large variety of conditions in the world lead to a solution in which the whole gamut of alternatives would be used in different mixtures in different regions. We must have several alternatives ready within a limited time, unlike in the past when we have developed them singly, neglecting all other options. It is also important to tie the problem to economic subsystems, as the energy must be paid for, perhaps by slower growth or a lower standard of living. These may turn out to be a blessing.

Another participant seconded these comments. He then remarked that although we have a number of alternatives, we seem to be under the influence of only nuclear energy and are neglecting other possibilities. One of these is biology. Bio-chemical energetics and biological sources of energy may prove valuable. Even some atomic scientists have suggested that we pay more attention to solar energy. A fresh look is also needed at those old types of energy conversion based on gravitation. We do have alternatives. The best way to apply systems analysis is to look at all of them and try to calculate their consequences. Secondly, Mr. Weinberg's picture was based on the assumption that all of the world's energy would come from fission. The situation would probably look equally bad if all energy were envisaged to come from any other single source. We will have to combine approaches; this again is a systems analysis task for IIASA. Mr. Chernilin remarked that energy is an important part of the IAEA task; it is trying to determine how nuclear energy fits into the problem. He said he was sure that cooperation between the two institutions would be mutually beneficial. He then commented that he wished to continue in the line of previous remarks. Mr. Weinberg's numbers were of course extreme, but the same awful effects would emerge if such an analysis were done for any other type of energy. The real question is how much we are willing to pay. It is not proper to think of a single source of energy; we will require a combination. The problem of efficiency is very important. Moreover, it is very strange that we are still relying on the acnievements of early nineteenth century physics. We must look at the problem in the short term, that is, to the end of the century, and in the long term, that is, over the next 1000 years. The short term problem requires precise consideration of efficiency and of use of multiple forms of energy.

Someone remarked that he was confused about the aims of IIASA. Systems analysis in the broadest sense is the scientific research itself, such as that conducted to look for new sources of energy. IIASA could perhaps do research on these sources; a previous speaker suggested developing biological energy. However, systems analysis, differently understood, can only handle already discovered and developed forms of energy.

Mr. Haefele answered that obviously IIASA cannot undertake substantial research and development in the traditional sense on new sources. However, our experience with nuclear and other large technical systems shows that a system composed of many components is more complex than is their sum. Approaches for studying this exist. In the nuclear energy field one is trained to deal with such combinations. Secondly, we have finite resources and thus must think ahead. At IIASA we cannot do disciplinary research. The task of the systems analysis group is to identify questions and communicate with other institutions; it must go from a list of ideas to specific questions. Mr. Raiffa agreed that IIASA cannot do fundamental research. Instead, it can attempt to prick others to do some and can suggest ways of organizing and managing it. Mr. Haefele noted one exception to this; IIASA can do basic research on systems analysis methodology.

Another participant drew attention to the fact that the amount of nuclear energy discussed by Mr. Weinberg for an asymptotic society only equalled in magnitude ½% of the solar energy striking the earth. Thus it could be used with no risk; the only question is how to use it. Wind energy, similarly, (estimated as 2 to 10 KW), could be used with no effect on climate. Mr. Haefele disagreed and added that, moreover, wind energy is of negligible magnitude when compared with energy demands.

Someone asked a question about the organization of the energy research project. He wondered whether individuals would be invited to structure their own problem or to work on already identified tasks. Mr. Haefele deferred discussion of that point until Friday.

The Medium Term Energy Situation in Japan
the Role of Nuclear Energy

Keichi Oshima

Introduction

The main point to consider for medium term energy situation between 10 to 20 years from now is that on one hand, one cannot make a simple extrapolation of the present situation, but that, on the other hand, the time span is not long enough to expect drastic changes by entirely new technological innovations, such as fusion, solar, and geothermal energy.

In this period, the situation will strongly depend on the outcome of the present technological developments under way and of the changes in industrial and social demands and structures. In this regard, the role of nuclear energy will be the most important issue for the medium term period of 1980 to 1995, even though the share of nuclear energy in the total energy supply will not be predominant.

In Japan, because of the advantage in resource, transportation, and storage--crucial for a country like Japan dependent on imported energy--and because of the possibility of large technological development to solve the natural resource and environmental problems, nuclear energy is expected to be the most important clue to cope with the difficult energy situation in the medium term future. Some of the aspects of the role of nuclear energy are presented below, with reference to the Long Term Program of the Development and the Utilization of Atomic Energy of Japanese AEC.

Utilization of Nuclear Energy

In Japan, the increase of energy demand is very high, 3.4 times in the ten year period from 1960 to 1970, and its dependence upon imported energy is also increasing rapidly--from 44.2% to 83.5% in the same period. Even though some reduction in the growth rate of GNP is expected, the upward trend is predicted to continue. The total energy demand in 1985 is estimated to be between 933 million and 1,029 million kilo litre oil equivalent, which is more than three times the demand of 310 million kilo litre in 1970.

Of this total energy supply in 1985, 406 billion kwh is expected to be supplied by nuclear power generation of 60,000 MW, which is about 9 to 10 percent of the total. In comparison, oil will supply 68 to 70% and coal, about 16.8%.

The percentage of nuclear energy in the total supply is not very high, but its share in the power generation will be rather substantial. In 1985 nuclear power generation will be 25% of the total capacity, and in 1990 the capacity will be increased to 100,000 MW, which is 33% of the total. It is expected that nuclear power will become highly competitive to oil burning power generation by the end of 1970's and that the major part of the newly constructed power plants will be nuclear in 1980's. This trend can be accelerated by the future world oil situation of increasing crude oil price and instability of supply. Because of ease in transportation and storage in Japan, nuclear energy is counted as domestic energy even though all natural uranium must be imported.

The major type of reactor will be LWR. In early 1980's, advanced thermal reactors of the heavy water type may come to be commercialized, while FBR is expected to be introduced to commercial operation in late 1980's.

Such a rapid increase in nuclear power production requires careful consideration for not only safety and environment but also for the choice of proper sites for plants, with good understanding from the public. In Japan, the acquisition of land for large nuclear power plants can become tight, and R & D on the siting of nuclear power plants on soft ground, islands, and undergrounds has been urged in order to widen the range of suitable places.

<u>Development Programs</u>

One of the most important features of nuclear energy is that it is highly technology-oriented rather than oriented to availability of natural resources. As pointed out by Prof. Haefele in his general paper, the success in commercial use of fast breeder reactors will lead to practically unlimited supply of uranium resources. Therefore, the advancement of technology will have a large impact on the outlook of the energy situation.

Entirely new technologies usually requires some 20 to 25 years of development for practical use, and in the medium term projections only the developments which are underway at the present can be considered. In this regard, the program to develop the FBR is the most important issue. In case of Japan, the target of its commercial use is in the later part of 1980's.

Another aspect is the use of nuclear energy in non-electric use, such as iron and steel making, chemical process, desalination, and regional heating. The use of energy in the form of electricity is less than 30% of the total and the development of reactors and processes for non-electric use is most important for Japan. For this purpose,development of HTGR, generating a temperature of 1000°C or more at the outlet of the primary coolant, has been started in Japan.

Nuclear Fuel

Supply of nuclear fuel is the important factor for the nuclear program. The complete nuclear fuel cycle is to be considered for this purpose but only supply of natural uranium and enriched uranium will be mentioned. The supply of these materials depend very much on the development of the FBR.

In 1985, annual demand of 12,000 S/T of natural uranium is expected and will rise to 15,000 S/T by 1990. The supply has to be secured by import and by development of uranium mines overseas. The government and industry are taking measures to secure the future supply.

As for enriched uranium, the present estimation is 5,000 tons SWU/year by 1980 and 11,000 tons SWU/year by 1990. Around 1980, it is predicted that the capacity of the U.S. will be saturated and some international or national projects for a new plant must be considered. Development of a centrifuge process is now under way, but it is predicted that an international joint plant will come first.

All such activities for the future supply of nuclear fuel must be started now. And, since fuel demand will depend greatly upon progress in developing new types of power reactors, a comprehensive overall program is essential for nuclear energy policies.

Public Acceptance

Nuclear energy is expected to play an important role in the medium term future energy situation, because it widens the range of future options with development efforts.

However, the most important factor to be considered is public acceptance of the program. If the public will not accept the construction of nuclear plants, the whole program will fail.

Safety, preservation of the environment, and radioactive waste disposal are the main problems to be solved. Extensive R & D efforts will be performed to accomplish this.

On the other hand, it must be emphasized that public acceptance involves not only such technical aspects but also social aspects such as distribution of benefits, emotional fear to radioactivity, and even social attitude towards growth.

In this regard, the consideration of medium term energy situation needs a comprehensive systems approach in order to have a proper understanding.

Discussion

Someone noted that, with respect to the auction logic of Mr. Hutber's world model, Japan is a case where the transportation algorithm can be seen to apply. Oil comes from far away, therefore there is heavy investment in the nuclear field. Mr. Oshima observed that Japan received the full impact of fluctuations in foreign prices since it has no oil of its own. This instability is important, even though its main effects are psychological.

Someone asked how the plants will be cooled. Mr. Oshima said sea water will be used. There was some thought of adding a cooling tower system because of public objections to using water for cooling. His questioner noted the need to study the climatic effects of this.

One participant remarked that Japan is a very interesting case because it is an island with a high population density, no oil of its own, and very rapid economic growth. But, he added, every society must pay for everything. Japan will have to pay for its rapid growth. He recalled Mr. Haefele's discussion of load densities and asked if there had been any studies of this in Japan. Second, he mentioned that Japan is apparently trying to solve its energy problems with light water reactors, and asked how it plans to deal with waste heat disposal and with coverage of peak demand periods?

Mr. Oshima first responded to the question on growth by remarking that it is a very difficult point. The planning program he had presented tried to reduce growth but failed. It is unclear how growth can be slowed. The problem is intimately tied to social attitudes. If industries are cut, the government will be obliged to support them, but then they will grow again. The population fears cutting growth in some drastic way, for example, by overshooting the reduction program. Last year only one-third of the scheduled power stations could actually be built; some shortages resulted. These were not too serious, but a continuation of this pattern over three years would result in drastic shortages and radical reductions in industry and other economic activities. There is a feeling that Japan is nearing some limit, and it will hurt less if this limit is achieved in a controlled way. With respect to the question about waste heat, Mr. Oshima said that the use of sea water for cooling does not present serious questions. A great increase in thermal density, however, may be serious. The radioactive waste problem is most severe with respect to reprocessing plants. In the past, one had thought of dumping the wastes in the ocean! Someone else asked if permanent vault storage had been considered. Mr. Oshima said that that is the current plan. The questioner noted that such a plan requires the assumption that in 10,000 years there will still be Japanese speaking people who understand nuclear technology. It was asked who in Japan is in charge of growth. The speaker found it remarkable that one could want to decrease GNP but instead get an increase. He also asked whether 25% is the limit for the market share of electricity. Mr. Oshima replied that growth is overseen by an economic planning agency run by a commission which is chaired by a representative of industry. It has many subordinate sections which make projections. Policy programs are approved by the Prime Minister and his cabinet and adopted as national programs. Although these are only guidelines and carry no sanctions, government policy, the utility companies, and the development bank of Japan all act in accordance with it. The program is not a plan as in a planned economy but only a guideline. In the past, all estimates were consistently low, and the government was not able to slow economic growth.

Someone noted that expectations are often self-fulfilling. In the U.K. the government wants five percent growth but only gets two or three because that is all the industrialists think it will be able to achieve and invest accordingly. In Japan they think it will continue at ten percent, so it does.

Mr. Oshima referred to the question on electricity to say that current estimates come from industrial statements of needs. If prices changed, the estimates would, too. The person who posed the question noted that elasticities and prices must be compared separately for different consumer groups. He maintained that electricity might be cheaper than oil even if therms cost more. Two other participants were skeptical of this.

Mr. Oshima returned to the question on pollution density and said that there is currently a study of ecological effects being conducted at the University of Tokyo.

Mr. Oshima was then asked what method of storing energy is planned for the electrical system; he replied that pumping stations will be used. Their capacity equals about two or three percent of the total electrical production. It was asked if serious consideration had been given to off-shore siting. Dr. Ishida replied that there had been only a paper study.

Another participant asked what Japan's energy policy is in its program for underdeveloped countries. In particular, were there plans to install nuclear plants in these areas? Mr. Oshima said current plans focus on installation of conventional energy sources.

Hydrogen and Energy

C. Marchetti

Dr. Marchetti, head of the materials division of EURATOM research center, Ispra, gave a major talk explaining the features of a future hydrogen economy. In so doing, he followed essentially the lines of a paper of his that was published in the Chemical Economy & Engineering Review (January 1973).

With the kind permission of the journal, his paper is therefore reprinted in these Proceedings because it appears to be the easiest way to report on the deliberations of Dr. Marchetti.

Reprinted by courtesy of the Chemical Economy & Engineering Rev:

Hydrogen and Energy

by C. Marchetti*

1. Introduction

The challenge of the century for chemical engineers—thermochemical cycles to produce hydrogen—may bring a revolution in the technology and management of energy and food.

Hydrogen has a peculiar position in nature:
—it is the most abundant element;
—it plays a key role in fueling the universe;
—it is the first chemical product in photosynthesis i.e. the chemical mediator between sunlight and the biosphere.

Hydrogen can become the main energy mediator between the newly harnessed nuclear energy and human society, so avoiding most of the political, ecological, long-term procurement problems connected with the use of fossil fuels. Via proper microorganisms it can be employed to produce "primary" food, easing the pressure on agriculture. This fact will have even more revolutionary consequences.

2. The Objective

Practically all the energy we use comes from the sun. Directly via the biosphere and fairly indirectly via the fossil fuels, which can be considered long-term stores of solar energy. Nuclear energy provides a completely independent energy source, much larger energy reserves and a very different geopolitical distribution of the raw materials: uranium and thorium. And so it is natural to try to link our energy system to this new source.

Up to now, however most of the research and development effort has been concentrated on the production of electricity, and for good reason. In fact, a substantial 20-25% of the primary energy input in a developed society is used to make electricity whose production is concentrated in large units where reactors can better show their economics. But almost nothing has been done to penetrate the remaining three quarters of the primary energy market that is, fuel, ore processing and miscellaneous, where our society is geared to burning a wide variety of chemicals.

The fact is that nuclear reactors are essentially very large sources of heat, that the energy market is split in a host of small customers; and that heat is not easily transportable and storable. So, in analogy with the electric system, the problem was set to find a flexible intermediate, producible in large blocks, into which nuclear heat can be stored as chemical energy and economically distributed.

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The reflections and discussions that went on in vari places in the world, from the late sixties, have brought consensus of the scientific and technological community, point at hydrogen as the candidate global energy carri Hydrogen in fact has a certain number of very desira properties:

(1) It can be produced from water, a cheap and plent raw material.
(2) When burned, it reverts to water, a nonpolluting che cal.
(3) It can be transported overland by pipeline at low c and by sea, in tankers, as liquid hydrogen.
(4) It can be easily stored, particularly in ground str tures, like exhausted gas fields.
(5) It has an extreme flexibility of utilization with gr advantages in many cases over current fuels e.g. airplanes, and for fuels cells. Practically all the ene market can be covered by hydrogen.
(6) Following points 3, 4, 5, it can be produced very large units e.g. of 1000 gigawatt order, so tha can best use the economy of size, whenever technol cally possible.
(7) It has already a large market as a chemical, a v important strategic asset as it will be seen.

The most important, or at least the most publicized, dr back is that it is quite inflammable anl explosive. Bu deeper scrutiny on this point shows that, all considered is not really worse than natural gas, a fuel fully accep in industry and in the homes.

Given the atom as the primary energy source and hydro as the ideal energy carrier, the objective of our resea was stated since the beginning very simply: find the b process to produce hydrogen from water using heat of grade available from commercial nuclear reactors.

3. The Means

The discussion of the means to produce hydrogen leads to the core of the problem: heat being available at t peratures of 300°C (water-cooled nuclear reactors) or 500°-800°C (high temperature gas reactor), how can we it to break the water molecule and produce hydrogen oxygen?

An apparently straightforward solution would be that making electricity and electrolyzing water. Unhappily is a very twisted one, because this poor energy is han many times, to make steam first in the boiler, then chanical energy in the turbine, then in the generator e trical energy, which is rectified, and fed to the electroly tha: piles up capital and cascades inefficiencies.

: is true that industrial electrolyzers, looked at as elec-:al machines, are very inefficient (50% of the theoretical), y "diluted" (less than a Watt/cm^2), and very expensive 50/kW) so one might conceivably think these electrolyzers ıld find someday their Edison or their Newton to improve ımatically their efficiency. But even with unit efficiency l zero capital cost, their potential for producing what, er all, is just a fuel, from a sophisticated form of energy : electricity did appear to us very dim.

low the simplest way to break a molecule is to heat it :il it cracks, a well-known and much used process. But ter molecules are very tough indeed and start breaking sizable fractions around 2,500°C, a temperature well above potential of present-day commercial reactors.

'ollowing the old proverb: "If you can't carry a load in : journey, make two", we thought of breaking the water ılecule in two steps or more if necessary, with the help intermediate chemical products, each step requiring heat temperatures available in commercial reactors.

The second condition, to make the process a clean trans-mation of just molecular heat into chemical energy, was ıt all the chemicals involved should be recycled. Respect-; these conditions our process could be visualized as a ıck box containing chemicals, where the inputs are heat d water, and the outputs oxygen and hydrogen, plus some egraded" heat.

The background philosophy in looking for a chemical ɔcess as a competitor to electrolysis was based on these ints:

Thermochemical processes tend to be much cheaper than :lectrochemical ones, per unit of energy handled.

The energy would hopefully be handled only once, while in :lectrolysis it is handled four of five times.

Processes to make electricity (and electrolysis) rely on nature technology and important breakthroughs appear mprobable.

The history of new chemical processes, e.g. in petro-:hemistry and plastics, shows very steep learning curves.

Starting from the considerations and respecting the :onditions imposed, M. De Beni invented our first process, Mark-1, using Ca, Br and Hg compounds as the recyclable :hemicals[1].

) Thermochemical Processes for Water Splitting

The Mark-1 cycle

This four-step chemical cycle was found by De Beni in 1969 'ig. 3) and it is briefly described in[2]. It works with com-unds of mercury, bromine and calcium.

The following is a set of reactions in the cycle:

1) $CaBr_2 + 2H_2O \xrightarrow{730°C} Ca(OH)_2 + 2HBr$ (water splitting)

2) $Hg + 2HBr \xrightarrow{250°C} HgBr_2 + H_2$ (hydrogen switch)

3) $HgBr_2 + Ca(OH)_2 \xrightarrow{200°C} CaBr_2 + HgO + H_2O$ (oxygen shift)

4) $HgO \xrightarrow{600°C} Hg + 1/2\ O_2$ (oxygen switch)

Whose sum is :

$$H_2O \longrightarrow H_2 + 1/2\ O_2$$

The attractive characteristics of the Mark-1 process are e following:

(a) The maximum temperature required is 730°C, that means about 850°C for the primary nuclear reactor coolant, a temperature well in the range of actual HTGR's; it can however profit from higher temperatures when the development of the HTGR's makes them available.

(b) The system has a single purpose, i.e. all the heat from the reactor is efficiently used to produce hydrogen.

(c) All reaction products are easily separated.

(d) All by-products formed during the reactions can be reinjected at some points in the cycle, permitting a virtual 100% recovery of the chemicals without sideloops.

The principal drawbacks of the process are:

(a) The use of mercury with the related problems of potentially high inventory costs and the possibility of pollution in case of leakage has been much criticized. For this reason we have dedicated much effort to the kinetics of reaction 2 where most of the mercury in the metal state is held.

As shown in Fig. 7 we can now run this reaction at a very high rate, so that the inventory may be less than one m^3 Hg/Gwth of input in the plant.

Also from the point of view of availability of Hg we feel pretty safe. Our computer[58] indicates the existence of Hg minerals capable of yielding some million tons of Hg at prices substantially equal to the present ones.

(b) The use of highly corrosive chemicals, especially hydrobromic acid, and the consequent problems in relation to construction materials.

(c) The large amount of materials circulation per unit product.

Chemical studies[3]

Very little information on the reactions involved in the Mark-1 cycle was found in the literature and so we undertook an experimental program aimed at determining their equilibria and kinetics.

(1) On the hydrolysis reaction we found a paper by Robinson et al.[4] which describes a series of experiments where various salts, such as halides, sulfates, phosphates and carbonates of alkaline earths, were hydrolized. The experimental tests were performed in a way that they did not allow the determination of equilibrium values for the hydrolysis, however, they did show that, in the halide family, the most hydrolyzable salt is calcium bromide.

Our experiments on the hydrolysis of calcium bromide were done first using steam at 1 atm; in this condition we can expect the formation of calcium hydroxide up to the temperature of 500°C and the formation of calcium oxide at higher temperatures. Using the data of Brewer [5] and the Bulletin of the Bureau of Mines[6] the computed values for the equilibrium constant range from 8.10^{-10} at 227°C to 3.5 10^{-6} at 727°C. From our tests we found that values for the equilibrium constant did range from 2.9 10^{-7} at 300°C to 1.12 10^{-2} at 727°C. Our calculated and experimental values are presented in Fig. 4.

Other tests with 20 atm. steam led to an apparent equilibrium constant of 1.9 10^{-2} at 727°C while additional tests with 37 atm. steam yielded an equilibrium constant of 5.10^{-2} at 800°C:

The minimum working pressure necessary to produce $Ca(OH)_2$ has been determined by measuring the decomposition pressure of calcium hydroxide at temperatures up to 800°C (Fig. 5). The advantage of going to $Ca(OH)_2$ is that the endothermicity of the reaction is much reduced.

The rate and equilibria of hydrolysis have a very strong feedback on the efficiency and economy of the process, so we are investigating this reaction in detail. For example, experimental work is in progress to evaluate a flow sheet based on a temperature of 830°C for the hydrolysis reaction producing HBr at concentrations as high as 60% by wt. The boiling point of $CaBr_2$ being 820°C in this temperature range, the hydrolysis reaction may occur partially or totally in the gas phase. According to these conditions, studies are in progress for evaluating this possibility.

The advantages come from an amelioration of the thermal efficiency; the HBr concentration step being suppressed; and from a strong increase in the reaction rate of mercury with HBr, with the consequent decrease of the inventory of this element in the process (see later). These variants are developed to be prepared to take advantage of a possible increase in temperature of the HTGR's.

(2) Also on the reaction between mercury and hydrobromic acid, there was no valuable information in the literature and we had to start from scratch, i.e. trying to see if the reaction occurs at all.

The experiments were originally made by reacting a mercury drop in glass vials with an excess of concentrated hydrobromic acid 48% by wt. The temperature dependence of rate constant is shown in Fig. 6. Fig. 7 shows the very strong influence of hydrobromic acid concentration on the rate of hydrogen formation at 200°C.

Analytical problems that did arise in the determination of the reaction products have been solved and the analytical procedure is described by Serrini[8]. Due to the overpotential for hydrogen evolution over mercury surface we also tested the effectiveness of some metals as depolarizers.

Some observations during this research led us to foresee the possibility of reacting mercury and hydrobromic acid at temperatures below 200°C. The purpose was to use for this endothermic reaction low grade heat recuperation from other steps of the process in order to improve the total efficiency.

A different way to react mercury with HBr was in fact found by Schütz[14], our mercury specialist, using the intermediate reaction:

$$Hg_2Br_2 + 2HBr \rightleftarrows 2HgBr_2 + H_2$$

The rate of this reaction is already quite high in the temperature range between 90°C and 125°C. It requires precise control because it is strongly dependent on the ratio of hydrobromic acid and mercurous bromide. The mercurous bromide can be prepared by reacting mercury with a solution of mercuric bromide (in hydrobromic acid) according to the equation:

$$HgBr_2 + Hg \longrightarrow Hg_2Br_2$$

(3) About the reaction of mercury bromide with calcium hydroxide no information at all was available in the literature. The first tests did show that a brown precipitate is obtained. After boiling the solution for some minutes this brown precipitate is transformed into the usual red mercuric oxide. Nevertheless, a certain amount of mercuric bromide is held in solution by the calcium bromide formed. For this reason we have studied the influence of temperature, initial concentration of mercuric bromide, and the excess of calcium hydroxide.

(4) The dissociation of mercuric oxide is the only step of the Mark-1 cycle for which data were available in the literature. Dissociation pressure have been measured[9] and are known with a sufficient accuracy for our needs. In Fig. 8, HgO dissociation pressure versus temperature is shown. Between 450°C and 600°C the dissociation pressure varies from 1 to 20 atm.; this range is well suitable for practical applications.

Since we need to know also the rate of recombination of oxygen and mercury vapor in order to define how fast the vapors must be cooled to avoid excessive back reaction, we are also studying the kinetics of HgO formation for temperatures up to 650°C and pressures up to 30 atm.

Many other chemical and physicochemical data are measured or collected, e.g. the vapor pressure of concentrated calcium bromide solutions; the heat of dehydratation of calcium bromide; the pressures and phase composition for the liquid-vapor equilibrium in the ternary system H_2O-HBr-$HgBr_2$.

The flowsheet

A block diagram of the cycle is shown in Fig. 1. The basic flowsheet is given in Fig. 9, reference temperatures are also given. (HF represents the circulation of the heating fluid).

In order to reduce to a minimum and hopefully suppress the stripper and concentrator the hydrolysis reaction of $CaBr_2$ is realized in two steps: 60% at 750°C and the rest at 780°C. It has been experimentally verified that in this way the hydrobromic acid is produced at the azeotropic concentration, 48% by wt.

The maximum temperature in the cycle is always compatible with the 50°C originally foreseen as the maximum temperature available for the primary nuclear reactor coolant.

The thermal efficiency

The efficiency can be defined as the ratio between H combustion heat and the primary heat necessary to produce it. Such definition is somehow equivocal because the higher and lower combustion heats are quite different for hydrogen. Including the heat of condensation of water one has 3,000kcal/Nm³, excluding it 2,500kcal/Nm³.

Thermodynamically it is more convenient to use the higher combustion heat, but when one burns hydrogen in air usually water is not condensed and the lower combustion heat should be considered. Unless otherwise stated we use the lower value. With the heat source at 750°C, the heat sink at 25°C, and operating the water decomposition process in a reversible way, with materials (water, hydrogen and oxygen) entering and leaving the process at 25°C and 1 atm. (i.e. using the higher combustion heat) the thermodynamical efficiency is 85%[13] [15].

To calculate our practical efficiencies we made a computerized model of the plant. The model however is used mainly to assess the sensitivity of the flow sheet toward the different physical parameters, in order to evaluate and balance our research efforts. The calculated efficiencies keep changing and tend to increase with time. Our latest figures give 55% (using the lower heating value of the hydrogen produced).

The structural materials

he chemicals circulating in the various steps of the cess are hydrobromic acid (vapor and solution), mercury lts and vapor); calcium bromide and calcium hydroxide solids or in solution; oxygen, hydrogen and water. For st of them fairly compatible materials are available for st of the range of temperatures in which we are interested. roblems arise with hydrobromic acid. About this duct little is known, and indication of its ability to ıck materials derived from the behavior of hydrochloric l.

/e are screening metallic materials and refractories zes. The most resistant in the critical range of 200°-'C are Tantalum, Molybdenum, Zirconium-Niobium ys, Zircaloy-2, Niobium, Alumina. We are also testing nless steels.

he short-term objective is to select the materials for a t plant. The materials for a large plant are beyond present scope since they require a very large screen- and development effort, as it is always the case with chemical processes.

Mark-1 family

he lines of development of Mark-1 take into considera- the possibility of substituting some of the elements ch are employed. In particular we may use:

instead of Hg: The essential advantage may be the ıination of Hg, the disadvantage is that a higher maxi- m temperature is required (about 900°C) for the decom- ition of copper oxide. The reaction foreseen is not the ıplete dissociation of CuO, formed in the reaction between Br_2 and $Ca(OH)_2$ but the partial decomposition of CuO Cu_2O and O_2; the Cu_2O must then be reacted with the robromic acid.

instead of Ca: The advantage could be essentially a plification of the flow sheet. It is more difficult however ıydrolize $SrBr_2$ than $CaBr_2$, but we may have reactions nd 4 of Mark-1 carried through in just one step. The , which is formed in the hydrolysis, could then react ı $HgBr_2$ yielding $SrBr_2$ and the reaction could occur in ı a way that mercury and oxygen are formed separately not as an oxide.

Mark-2

ıganese cycles

ıis case is representative of the various cycles potential- nteresting on thermodynamical grounds, but still "hook- somewhere. We keep applying to them some laboratory k and much reflection in order to see if they can be ntangled. This philosophy has been very successful ı Mark-1 and we have reasons to think it will be also :essful with this cycle.

lkali hydroxides are able to react with some metals give mixed oxides and hydrogen. In an article by iams and al.[11] it has been claimed that sodium hydro- reacts with manganese at temperatures higher than C oxidizing it to MnO_2, and liberating hydorgen.

between is the oxides of manganese MnO_2 in the stable ı in molten sodium hydroxide, then the following cycle ımes possible:

) $Mn_2O_3 + 8NaOH \longrightarrow 2(MnO_2 \cdot 2Na_2O) + H_2O + H_2$ at 600°C

) $2(MnO_2 \cdot 2Na_2O) + \text{water} \longrightarrow 8NaOH_{aq} + 2Mn(OH)_4$ at 100°C

) $8NaOH_{aq} \longrightarrow \text{water} + NaOH$ at 400°C

) $2Mn(OH)_4 \longrightarrow Mn_2O_3 + 4H_2O + 1/2\ O_2$ at 700°C

Thermodynamic data for the $MnO_2\ (Na_2O)_2$ compound is lacking, so we decided to do some tests to check the reaction between Mn_2O_3 and NaOH. In spite of the results given by Williams we did not observe any reaction; even the substitution of KOH for NaOH did not give more positive results. In fact, when reacting manganese metal with the alkali hydroxide, the maximum valence state we obtained so far is 3.

We have tried to modify the chemical cycle by using alkali carbonates in place of the hydroxides. The modified cycle becomes:

(1) $Mn_2O_3 + 4Na_2CO_3 \longrightarrow 2(MnO_2 \cdot 2Nn_2O) + 3CO_2 + CO$ at 800°C

(2) $2(MnO_2 \cdot 2Na_2O) + \text{water} \longrightarrow 2Mn(OH)_4 + 8NaOH_{aq}$ at 100°C

(3) $CO + 3CO_2 + 8NaOH \longrightarrow 4Na_2CO_3 + H_2 + 3H_2O$ at 400°C

(4) $2Mn(OH)_4 \longrightarrow Mn_2O_3 + 2H_2O + 1/2\ O_2$ at 800°C

With the first reaction one could benefit from the higher free energy of carbon monoxide formation with respect to carbon dioxide at high temperatures.

We have tested the reaction between Mn_2O_3 and alkali carbonate at the maximum temperature allowed by the evaporation of carbonates (800°C) with various stoichiometric ratios, but again we did not observe any reaction. Even when manganese metal was reacted with carbonates, the maximum valence state attained was 3, and the valence 4 is attained only in oxidizing atmosphere. In this case, however, only CO_2 is formed, and a cycle cannot work under these conditions.

It should be stressed that both variations of this cycle appear possible on thermodynamic grounds.

Mark-3

Vanadium cycles

A study of the halides of the transition metals led us to conceive a cycle working on chlorine and vanadium. In the meantime we found that researchers of the Allison Division of the General Motors Corporation[12] had already described exactly this same chemical cycle as being the most promising one among a group of four in which Ta, Bi, Hg and V are respectively the working elements, together with chlorine.

The reactions for the vanadium cycle are the following:

(1) $Cl_2 + H_2O \longrightarrow 2HCl + 1/2\ O_2$ at 700 or 800°C

(2) $HCl + 2VCl_2 \longrightarrow 2VCl_3 + H_2$ at 100°C

(3) $4VCl_3 \longrightarrow 2VCl_2 + 2VCl_4$ at 700°C

(4) $2VCl_4 \longrightarrow 2VCl_3 + Cl_2$ at 100°C

The first reaction of this cycle is industrially well-known. The available thermodynamic data for the vanadium chlorides allow an acceptable yield for each reaction at the temperatures indicated. Little experimental work was done at the Allison Division on Reaction 2. They tried in fact to react VCl_2 with gaseous HCl. In spite of the expected favorable equilibrium they didn't find any evidence of a reaction taking place.

We have planned to do some work on the reactions involving vanadium chlorides, to find more favorable conditions.

The Mark-7 cycle

Based on the reaction between water and chlorine, another cycle has been defined by Hardy and successfully tested[10]. The hydrochloric acid which is formed in the reaction is transformed in iron chloride, which reacting with water produces hydrogen.

The reactions are the following:

$$3\ H_2O + 3Cl_2 \xrightarrow{800^\circ C} 6HCl + 3/2\ O_2$$

$$18\ HCl + 3Fe_2O_3 \xrightarrow{100^\circ C} 6FeCl_3 + 9H_2O$$

$$6\ FeCl_3 \xrightarrow{400^\circ C} 6FeCl_2 + 3Cl_2$$

$$6FeCl_2 + 8H_2O \xrightarrow{600^\circ C} 2Fe_3O_4 + 12HCl + 2H_2$$

$$2\ Fe_3O_4 + 1/2\ O_2 \xrightarrow{400^\circ C} 3Fe_2O_3$$

On the basis of the preliminary experimental tests a flow sheet has been made. A simplified version is given in Fig. 10; the hydrochloric acid circulates in the cycle varying its concentration from 20 to 95% by weight. Calculations made on the basis of this flow sheet give thermal efficiency values ranging from 40% to 45%.

Other cycles

The search for new thermochemical cycles is going on fairly intensively in other places in Europe (e.g. Aachen University, Jülich Nuclear Res. Center) and in U.S.A. (e.g. General Electric, Gulf General Atomics, Atomics International, Institute of Gas Technology). Prof. Knoche of Aachen University is particularly active in inventing new processes.

One of the cycles which has been recently published by him has the special characteristic needing only three reactions:

$$H_2O + Cl_2 \longrightarrow 2HCl + 1/2\ O_2 \qquad (900^\circ C)$$

$$2HCl + 2CrCl_2 \longrightarrow 2CrCl_3 + H_2 \qquad (200^\circ C)$$

$$2CrCl_3 \longrightarrow 2CrCl_2 + Cl_2 \qquad (1,000^\circ C)$$

Another one has the characteristic of including only well-known reactions(13):

$$3Fe + 4H_2O \longrightarrow Fe_3O_4 + 4H_2 \qquad (500^\circ C)$$

$$Fe_3O_4 + 9/2\ Cl_2 \longrightarrow 3FeCl_3 + 2O_2 \qquad (1,000^\circ C)$$

$$3FeCl_3 \longrightarrow 3FeCl_2 + 3/2\ Cl_2 \qquad (350^\circ C)$$

$$3FeCl_2 + 3H_2 \longrightarrow 3Fe + 6HCl \qquad (1,000^\circ C)$$

$$6HCl + 3/2\ O_2 \longrightarrow 3H_2O + 3Cl_2 \qquad (500^\circ C)$$

The excessive materials recirculation make this cycle an improbable winner; however it belongs with Mark-7 to a very interesting family of cycles using Fe, Cl and O.

Possible evolution of thermochemical processes

High temperature is a desirable goal because by increasing the maximum temperature at which heat is available:

—The number of possible processes increases.
—The efficiency of these processes tends to increase.
—The processes tend to become simpler: The polar star could be water-cracking with only one step (plus separation) and 100% theoretical efficiency. However high temperatures lead to difficult materials problems and the most probable course in the author's opinion will be th successful processes will cluster in the temperature ran between 800° and 1200°C, sticking to more or less co ventional chemical engineering practices.

There is still the possibility that eventually water-crac ing will be explored by physicists-technologists of the ki that in the Los Alamos National Lab. developed reacto for space propulsion. A crossbreeding of these very hi temperature reactors (they have been operated, for sho periods, at coolant temperatures up to 2,300°C, the coola being hydrogen) of plasma and of magnetohydrodynam (MHD) technology in order to separate the products, mig lead to a very sophisticated breakthrough.

The important job at least during the first years, consis in mapping processes. We found a dozen of them, and a aware of another half a dozen invented in other place especially in the U.S.A. and in Germany. And still ma may be possible.

Prof. Knoche at the University of Aachen has develop a logic and set up a computer program to make a kind preselection of processes that might be thermodynamical possible, releasing the investor from the combinatorial ta and concentrating him on the task of evaluating. Althou conceive to produce semiworked material this progra may greatly speed up the process of exploration.

A complete class of processes we have neglected due the lack of appropriate organic chemists, are the on using organic reactions, at least for the colder part of t cycle. But it might be a fertile field especially if o looks for cycles drawing their heat from water reactor i.e. from heat sources at 300°C, and using more convention cracking (at around 2,500°C) has a theoretical efficiency (theoretically 55%).

What are the possible efficiencies?

The thermodynamical treatment of these processes relatively lenghty, and we suggest to those interested th they consult the excellent papers of Funk[15] and Knoche[18 It comes out that efficiency is higher than Carnot's esse tially because we are not producing mechanical energy, b a chemical with a certain enthalpy and free energy.

Using heat in the range of temperatures available no (500°-800°C) the theoretical efficiency is around 75% (usi lower heating value for H_2). Using heat in the range temperature that can be expected from HTGR's in t next 20 years as a development of present technology (800 1,200°C) the theoretical efficiency is around 85%. Wate cracking (at around 2500°C) has a theoretical efficiency 100%, and so the range is given.

Just for the sake of completeness one could say tha conceptually, efficiencies higher than 100% are possib with heat sources above 2,500°C but clearly the fact h no practical importance.

The actual efficiency that will be reached is a matter luck and ingenuity. Probably the situation is more favo able than in the case of a power station because chemic reactions have less limitations than rotating machiner To give an example a computer simulation of our late version of a Mark-1 plant, with fairly realistic condition gave an efficiency of 55% or nearly 80% of the theoretic value.

High efficiencies are important for two reasons:

—the obivous one of saving heat laboriously produced,
—the more implicit one, that inefficiency appears as wast heat.

Now waste heat can be considered as a pollutant, or ma be difficult to dispose of in a plant that naturally tends become gigantic; in both cases it may strongly limit number of possible sites for the plant.

What may be the alternative routes?

conceptually interesting route has beer. proposed by ıgh[16]. The very hot plasma of a fusion reactor 10^8°C) is injected with aluminum atoms which are ited and emit ultraviolet light. This light passes through ım which is photochemically decomposed into hydrogen oxygen[16]. The temperature is kept low enough to vent recombination so that the gases can be separated cryogenically.

he system has a very good potential at least from a sical point of view, i.e. there are very little thermodynam- limitations to very high efficiency and the plant ;ht come out very simple.

he main drawback is that it demands second-generation on reactors, where energy comes from the reaction + D = He^4 + energy in the plasma, so it should be kept m for the years 2000's.

ther possibilities have been cursorily investigated, e.g. cesses where the water molecule is broken partly rmally, partly electrolytically[12]; or processes where the ıl product is ammonia.

he processes of the first kind are probably bound to mble on the same stones as straight water electrolysis. second kind instead may lead to very interesting pos- ilities, because the process requires less energy and ;ht be simpler, and because ammonia, apart from its sent market, is one of the candidate "hydrogen carriers" fuel cars. Clever chemical engineers may even find a y to make methanol react CO or CO_2 with ammonia.

What are the alternative primary energy sources?

part from nuclear reactors especially designed for the pose e.g. producing very high temperatures, and fusion ctors that still fall in the nuclear category, the other primary energy sources that present themselevs to the ıd are solar energy and geothermal energy.

olar energy properly concentrated may be very suitable run a system of the kind of Mark-1 as single-stage con- trators of proper design may produce a 900°C heat rce. Processes taking advantage of the fact that this rgy is in form of light may also be devised. For instance phosphor piling up photons and discharging ultraviolet ıt of proper frequency may bring to a closer reach Gough's a of steam photolysis. Chlorophyl e.g already does ıething of this kind.

'or geothermal energy there are two drawbacks:

'or the time being, temperatures do not appear interest- ıg e.g. less than 250°C, as in the case of the geothermal timulation project studied in Los Alamos.

ocalized power appear too small by two orders of magni- es.

is clear that many lines can connect two points. To t out the straight one will cost much thinking and sweat. the reward for the winner is immense: abundant, clean, ap energy and a $100 billion market to start with.

The Consequences

The structure of the potential market

/hen we first started thinking of hydrogen as a potential didate as a "vector" for nuclear energy, in a sense parallel and analogous to electricity, we divided the energy market into various large blocks: Ore reduction, transportation, home etc. and started analyzing the applicability of hydrogen to each sector.

Sieving the pertinent literature we found that in every sector, for special and intrinsic reasons, somebody had thought of using hydrogen and in many cases work was continuing. Just to give some examples referring to the most important blocks:

- —in the case of iron ore, the reduction with hydrogen to sponge iron was pursued to take advantage of very special local conditions in view of alleviating the consequences of the increasing prices of metallurgical cokes,
- —in the case of ground transportation, the driving force was the possibility of modifying existing cars to make them nonpolluting with only minor modifications,
- —in the case of air transportation, the unique lightness of LH_2 plus the possibility of using it as a heat sink in supersonic planes, held the promise of more efficient and cheaper air transport,
- —in the case of home usage, American gas utilities had sponsored an "All gas house". Methane being a fairly unreactive molecule the natural gas was converted to produce hydrogen in order to adapt it to the fine requirements of a home, e.g. for catalytic burning, lighting, and producing small amounts of electricity in a fuel call. So a "Hydrogen house" was in fact born.
- —in the case of food, the possibility of using electricity from solar cells to make hydrogen and oxygen by electrolysis and using these gases to run a "food machine" for astronauts, was the driving force to study the cultivation of hydrogenomonas for the production of proteins and other nutrients.

All that it clearly very important because:

- —it shows that hydrogen has intrinsic advantages for many applications,
- —nuclear hydrogen will find the market ready, just as nuclear electricity did.

Let us pass now in brief review such new applications. The pertinent literature is quite spread in time, but due to the increasing interest in hydrogen, some of them have been described in great detail at the 163rd National Meeting of the American Chemical Society in Boston (April 1972) and at the 7th Intersociety Energy Conversion Engineers Conference in San Diego (IECEC September 1972). The proceedings of these conferences are very interesting reading as they sum up much of the work in this field currently being done in the United States.

Iron ore reduction

This subject is taken first because steel-making will probably be among the first to profit from "nuclear hydrogen", and also because it will be a large customer.

The reduction of iron ores to produce sponge iron, by the overall reaction:

$$(1)\quad Fe_2O_3 + 3H_2 \longrightarrow 2Fe + 3H_2O$$

alone or in conjunction with the reaction:

$$(2)\quad Fe_2O_3 + 3CO \longrightarrow 2Fe + 3CO_2$$

is a well studied subject. Various commercial processes exist e.g., H-Iron[18], HyL[19], Purofer[20] also numerous plants have been built[21] most of them, however, relatively small.

As a rule of thumb, the amount of hydrogen needed to produce by direct reduction 1kg of iron is roughly one cubic meter. That makes the arithmetics of assessing the size of the market exceedingly easy.

The direct reduction brings the craft of iron-making back to the origins. The Hyttites and the Egiptians, in fact, didn't have furnaces hot enough to melt the iron, so the minerals were reduced by the hot CO and probably H_2 coming from the partial combustion of charcoal The product was sponge iron that was later consolidated and densified by hammering.

In the modern version the iron ore powder is preferably reduced in a fluidized-bed reactor at temperatures between 500°C and 800°C, depending on the particular scheme. As the first reaction indicated is slightly endothermic, and the second one fairly exothermic in the range of temperatures considered, in some processes a mixture of CO and H_2 is used to obtain athermicity.

Since these processes are quite easy to visualize for a chemical engineer, and the literature quoted is quite informative we will not delve in further details.

The perfection of the blast furnace technology, the amount of capital invested and the economy of scale being still in an evolutionary phase today, make it very difficult for new processes to gain a foothold on a world basis, even if they are more profitable on paper or at the pilot plant stage.

But the rising trend of prices for metallurgical cokes, the introduction of antipollution measures and the reduced development potential of the blast furnace, will be powerful incentives to turn to other processes. The ones based on hydrogen, mixed perhaps with CO, appear most promising in the long run.

It is clear that H-Iron or one of its variants, like the HyL or IRSID sponge iron process, fit best a hydrogen economy, because they use pure hydrogen as the reductant. But if more complex direct reduction systems, using a mixture of H_2 and CO, as in the Futakushi process, appear more favourable, it is very easy to adapt them to pure hyrogen source. In fact the CO_2 in the exaust gases may be brought back to CO by using the water shift reaction backward.

Just to give an idea of how nuclear reactor sizes and steel mill sizes match together, we estimated that a commercial HTGR of 2500 MWth, plus an associated thermochemical water splitting plant of the kind of Mark-1, would produce enough hydrogen to feed a 3.5 million ton/year sponge iron plant.

Such a technique, dissociating the problem of iron ore reduction from that of fuel procurement, could greatly change the geography of iron-making. A reduction of the ore at the mine, with the commercialization of a semi-worked "raw iron" to be elaborated elsewhere, would roughly reduce by a factor of two the materials to be carried around.

Ground transportation

The car is a very important item in the mind of people and it is the basis of a very important industry, so great concern comes from the fact its engine is an important source of pollution. A very simple solution would come from the use of hydrogen as the fuel. The combustion products, water, very small amounts of nitric oxides, traces of unburnt hydrogen, would pass the most stringent antipollution rules (Fig. 11).

Hydrogen engines are not new. Already in 1927 the Zeppelin Company had I.C. engines adapted to burn hydrogen. The objective was to make use of the hydrogen normally vented by the airship to control its altitude. These engir were successfully tested in 1928 in a trip across the Medit ranean. Other types of engines were adapted to hydrogen the following years both for civil and military purpose, e Erren developed reliable diesel engines working on hydrog air or hydrogen-oxygen. A fascinating account of these ea developments is given by Weil[22].

The engine can remain essentially the same or with mir modifications in some cases. The Wankel engine is p ticularly suitable. In our opinion the most appealing so tion, just to take one out of the bunch, is that developed Schoeppel at the University of Oklahoma[23]. Hydrogen simply injected in the cylinder through a small hole in t spark plug, at the end of the compression stroke. Such system has the great advantage of leaving the engine co pletely unmodified, so that a dual fuel system with hydrog in town and gasoline outside is easy to apply. This featu is a very useful one, because the real problem of the hyd gen car is in the tank: carrying an amount of hydrog giving the same range as a tankful of gasoline is in fact tough problem to solve.

The most promising routes are:

LH_2: It has three times the volume of gasoline for t same energy content. It must be kept at 20°K. Dewars w proper characteristics (boil-off < 1% per day) alrea exist[24]. It is not an easy system to start with, but it inherently simple and static. It holds a long-term promi It must be pointed out that, before taxes, the present c of LH_2 and premium gasoline in the U.S.A. are practica identical for the same energy content[24], [25].

NH_3: Liquid ammonia has a pressure vs. temperatu curve similar to propane and it might be carried in bott as many cars do now with propane. An ammonia crack is required. The new low-temperature catalysts for ammo synthesis[26] could lead to a realistic low-temperature cra er taking the necessary heat from the car exaust. Comb tion engines can be operated with ammonia as a fuel[2 but pollution reappers under a different disguise.

Metal hydrides: In particular MgH_2 [28], [29], [30] (F 12). They decompose releasing hydrogen, or are reform adsorbing hydrogen, according to the hydrogen pressu above them (Fig. 13). They can hold hydrogen at densit higher than LH_2. The carrier metals tend to be heavy[2

Gas cylinders: This is a really proven technology. The are 40,000 cars in Italy only, running on methane carri in cylinders. But hydrogen is about three times less ergetic, per volume, than CH_4. So the ranges become short. Very light gas cylinders made of fiber-reinforc resins and metal liners[31] could greatly improve the situ tion both from the point of view of volume and weight. G cylinders could be the first step in carrying hydrogen nonpolluting cars for town service. In country roads the c could be switched to gasoline.

Details on hydrogen cars and hydrogen tanks can be fou in the literature on this subject, essentially American[2 [23], [32].

The problem of a viable hydrogen car is a very import one, because:

- cars and trucks use from 10% to 20% of the gross ener budget, in developed countries,
- pollution from cars and trucks is becoming a very r problem in densely populated areas, and
- gasoline is an expensive fuel, and "chemical hydroge prices are competitive on an energy basis[24], [37]. T means that this market would be economically accessi very soon in an expanding hydrogen economy.

Air Transportation

'his is a very interesting field for three main reasons:

: tends to use the best in available techniques,
t puts a great premium on weight, and
akes an increasing share of the energy market.

'or the same energy value LH_2 is 2.5 times lighter than fuel but unfortunately three times bulkier; LH_2 is also excellent heat sink that can be used to cool the air-frame l the engines.

'hese properties have lured aircraft designers for a long ıe[33], [38], and for the past twelve years NASA has sponed design and research work on supersonic planes that ıuld reach speeds up to mach 8; they have an aluminium)y fuselage and relatively low sonic boom [34], [36], [35], g. 14—Fig. 15).

'he U.S. Air Force has already tried successfully LH_2 fuel ng a B-57 with wingtip LH_2 tanks. Lockheed has assessed ıth very encouraging results) a commercial airplane with ge wingtip LH_2 tanks.

'he complex details of this subject are well described in quoted literature. We wish to draw your attention to ee particular points:

'he fuel carried by a commercial airplane is three to four imes larger than the payload. Therefore, the driving force oward lighter fuels is clearly very strong.

'he trend toward higher speeds makes LH_2 compulsory. ıbove mach 3.5 LH_2 is the only effective fuel.

'ollution at take-off and landing could be taken care of ight now by using relatively small wingtip LH_2 tanks. 'his might be a fairly simple and evolutionary way to ntroduce the LH_2 technology, with a limited but very useful ask, and without stringent economic restraints.

Hydrogen in the home

listorically speaking the first large customer for hydrogen ; been the home. Many cities in the last century had "gas rks" producing in various ways a mixture of CO, H_2 and rts that was piped to the homes for cooking, lighting and ıting.

)epending on the manufacturing method, the hydrogen ıtent of this "town-gas" did vary roughly from 50% to 80%. 'resently town gas has been almost completely replaced by ural gas, i.e. methane, but it is on the way to taking a ıst astute revenge.

ι group of American gas utilities and pipeline companies is ually financing a $50 million target project for realizing ıong other things an "all-gas home", a kind of counterpart the much-publicized "all-electric home"

Iow the quite unreactive methane molecule is not very table to many home appliances where energy must be plied in a fine and precise way. So the idea came out to orm the gas right at the house and distribute it essentially H_2 (eventually diluted with some CO_2)[39], to take vantage of the high reactivity and flexibility of hydrogen.

This "all-hydrogen home" idea is being developed mainly the Institute of Gas Technology, in Chicago. It works the lowing way:

ighting is made via a phosphor spread on the inside of ın open tube, very similar in appearance to a normal luorescent lamp. Small amounts of hydrogen coming in contact with the phosphor combines with oxygen from air ınd excite a bright luminescence in the phosphor (candoluninescence)[40]. The operation is cold.

leating is obtained by diffusing hydrogen through (decoraive) panels made of porous plastics or wood, and im)regnated with a proper catalyst. Hydrogen combines with oxygen and the panel constitutes a distributed and even source of heat[39].

—Cooking trays follow the above principle, but use porous metals or ceramics. The trays are flameless, intrinsically safe and lend themselves to a fine regulation[41].

—Cooling can be made with absorption refrigerators, using again a catalytic burner as the heat source.

—Electricity which is still needed, to run at least the vacuum cleaner, is produced by fuel cells. This is an item still under development; many fuel cells exists, but a simple one, sturdy, cheap and capable of unattended operation for many years, is not easy to make[39].

Summing up the situation, hydrogen can take over easily all the energy load of the home, with some problems still for the hard core of electricity consumption. The home and affine commercial uses account for 20%-30% of the primary energy consumption. It is a very "diluted" market requiring a capillary distribution net, but it is a rich and a large one.

Production of food

A turning point in human history occurred with the discovery and invention of agriculture, at the end of the neolitic age. Agriculture, with respect to hunting and gathering, gave rise to higher yields per unit surface and per unit manpower, leading to a surplus of food in a small area and thus permitting a significant fraction of society to concentrate on specialized arts and crafts in systems of strong communication coupling: the towns.

Since then agriculture has spread widely, but as a whole has improved relatively little. On the other hand human population is growing fast and not only is moving to overshoot available agricultural resources, but also occupying for other purposes valuable agricultural land. The privileged position of agriculture comes from the fact that chlorophyl links the biosphere, and us, to the primary source of energy: the sun.

Now, as we said, the basic and revolutionary discovery of our century is a primary source of energy independent of the sun. If we find a lnik between the biosphere and this new source, chlorophyll and agriculture are going to lose their privileged position and the corresponding limitations are likely to fall. Hydrogen can be the link.

Actually a certain number of microorganisms are able to use hydrogen as a source of energy and a reductant and thrive on a completely inorganic substrate: e.g. Hydrogenomonas, or Clostridium aceticum. The source of carbon is CO_2 in both cases[42]. Hydrogen's free energy is used in quite an efficient way to synthesize all sorts of things necessary to build and run the biological machinery, such as proteins, vitamins, carbohydrates (or alternative energy storages). The energy conversion efficiency—i.e. energy in organic products to energy in hydrogen—is quite high and of the order of 50%. On the other hand the multiplication rates of microorganism, are exceedingly fast; the biomass has doubling times of the order of hours.

Now the average man needs a caloric input of 2500-3000 Cal/day, corresponding to a rounded mean power of 150W. Taking into account all the losses from nuclear energy to hydrogen, and from hydrogen to food synthesized by microorganisms, to have 150W "at the mouth" one should count on roughly 0.5-1Wth at the reactor level. This means that our famous 2500MWth HTGR, may be the primary energy source to feed a few million people.

At the Institute of Microbiology at the University of Göttingen under the direction of Prof. Schlegel research on the production of proteins for human consumption, using Hydrogenomonas, is presently going on. As monocellular organisms tend to be too rich in nucleotides for a balanced human diet, the idea they are following is to make the Hydrogenomonas "secrete" extracellular proteins. Just as a cow secretes milk. This, via proper selection, may permit the production of selected proteins tailored to their final use.

Apart from the selected proteins for human consumption, the biomass would probably be used to feed efficient "converters" like poultry, transforming them into chicken and eggs. This is not to say that man will start feeding over night on monocellular food and that agriculture is bound to disappear overnight. But this possibility is philosophically appealing and in any case very comforting.

Chemical Hydrogen

The world production of hydrogen reaches today 20×10^6 tons/year, roughly equivalent to 200 billion Nm^3. Half of it is used to make ammonia. About 30% goes into refinery processes (Table 1).

The last use is growing very fast because:

—Hydrocracking and hydrotreating processes are increasing in importance,
—hydrodesulfurization of fuels is being made compulsory to reduce pollution, and
—demand for substitute natural gas (SNG) is increasing.

Aside from the global size of the hydrogen market, two characteristics make it very important to us. These are:

—The size of the plants is large enough to accomodate the production of a water-splitting plant associated to a full-fledged HTGR. For instance, our famous 2500MWth HTGR could feed a plant producing about 1.6 million tons NH_3/year, probably a medium-size one in the next decade.
—The price of chemical hydrogen is three to four times higher than the price of fuel, for the same caloric value.

A most probable evolution of this market in the next 30 years will be that ammonia production will reduce its pace of growth, and that the growth in hydrogen production will be essentially supported by SNG production. Since the new sources of natural gas, in Alaska, Siberia, Australia, and in the North Sea, are fairly small compared to projected NG consumptions in the next decades, a large amount of gasification, in the hundreds of millions of tons/year bracket, may be expected, especially if an independent source of relatively cheap hydrogen comes up.

Hydrogen is the key to gasification; each ton of coal requires about 300kg of hydrogen for its gasification to SNG and a ton of oil about 150kg. As our famous 2,500 MWth HTGR is espected to produce about 350,000 tons H_2/year assuming 50% efficiency, it could support the methanization of half a million tons of coal/year or of one million tons of oil. These figures are clearly only orientative.

Hydrogen distribution and storage

The first objection raised in any discussion of the distribution of large quantities of hydrogen is that air hydrogen mixtures are explosive. This is true, but it is equally true that methane/air and hydrocarbons/air mixtures are highly explosive and do cause considerable death and destruction every year; yet this does not slow down the growth of consumption of these fuels, even at the expense of others, such as coal, which are far less explosive-prone but dearer and less easy to handle.

Incidentally, when the first motorcars appeared, the danger represented by the various dozens of liters of gasoline in their tanks was regarded as so prohibitive that in England they had to be preceded by a man on foot waving a red flag—a precaution which would certainly be more useful today, though for other reasons.

The fact is that the question must be tackled with a healt sense of the hazards involved, and the answer found throug empiricism and technology. We are therefore very glad show in Fig. 16 a network of hydrogen pipelines linking va ious firms in Germany with large-bore pipes and an overa length of about 300 kilometers. Similar networks exist the United States, notably in Texas, as part of more comple systems for carrying chemical intermediates between r fineries and petrochemical works.

The other point to make is to evaluate how much th transportations will cost. We have made an orientative stud with the help of SNAM, the Company that distributes natur gas in Italy, in orler to see the effect of the physical pro erties of hydrogen on the characteristics of an optimize pipeline[43]. The results are summarized in Table 2.

The following three points deserve attention:

—Optimum pipe size tends to be larger than for natural ga for the same energy transported.
—Pumping stations tends to be much more distant than f natural gas.
—The optimized cost of transporting energy is not substa tially different for the two cases, especially if we take a count of the fact that hydrogen pipelines will eventual carry more energy.

Our optimization is for the moment only partial and geare to local conditions. So we can expect further improvement The fact that pumping stations are so far apart has the in portant consequence for relatively small countries such Western Europe or Japan that hydrogen needs to be pump only at the source. For that reason in our Mark-1 proces we are studying the conditions for obtaining high-pressu hydrogen right from the reaction producing it and so avoi ing any pumping at all. If hydrogen has to be transporte overseas; the analogy with natural gas suggests liquefacti and cryotankers, but other improbable systems may st emerge, as for example that of using blimps[44].

The largest experience in making and transporting LH can be found in the U.S.A. due to the very large amounts LH_2 used as propellant in rockets[45] [46]. It is stored spherical containers up to about 5,000 m^3 (Fig. 17). Co tainers up to 50,000 m^3 could be built without further bas development[47]. Boil-off due to the heat flowing in throug the insulation, is a few parts per thousand/day. These da are important especially because they show that the bas technology exists to build large sea tankers.

People in the U.S.A.[48] have given some consideration piping hydrogen as a liquid. At the present stage of tec nology this method does not appear to be competitive. might become so for certain special cases, e.g. if hydrog is transported by sea and is already in liquid state. O would then have the extra advantage of having it liquid the terminal point for easy storage. Or if cryogenic cabl for transporting electricity would follow the same route a share the cost of the installation[48].

Liquid hydrogen being routinely transported with ro trailers, railway wagons and barges[49] [59] (Fig. 18) mig at the end be the form which will accepted as a fuel f vehicles. This may be another incentive to transport it as liquid in the trunk lines, especially if it starts as a LH_2 arri ing by sea.

The storage of hydrogen can strictly follow the practi of natural gas storage:

—The pipelines, by allowing changes in pressure, alrea constitute an important capacity (hours).
—The acquifers can be used to hold gas "bubbles" wi enough capacity to take care of the peak load of a town[51

:averns have been leached in salt domes with gas capaci-ies in the range of $100 \times 10^6 Nm^3$ [52].

Exhausted gas fields can be used to store hydrogen and he capacities can be very high. The Groningen gas field n Holland, could contain enough hydrogen to satisfy all nergy needs of Western Europe for a few years.

:he argument that with respect to methane the hydrogen lecule being lighter is more "leaky" is somehow weaken-by the fact that it is also less energetic. As a first ap-ximation the energy leakage is equivalent.

Hydrogen and electricity

:he fact that hydrogen can:
e carried over long distances cheaply and unobtrusively n buried pipes,
e stored underground,
e transformed in various ways into electricity

s much stimulated the imagination of people in the elec-: utilities, plagued by siting problems, ecologists and peak ds [53] [54].

The paper given by Hausz et al. of TEMPO General Elec-: at the IECEC 1972 [55] represents perhaps the most roughly elaborted specimen of these considerations. Hausz alyzes the economical consequences of a pipeline grid dis-buted all over a region or a country, hydrogen and oxygen duced at a remote site. Electricity would be locally gen-ted by fuel cells or by relatively small gas-steam turbine nerators, a kind of internal combustion steam engines. th are capable of ultimate high efficiencies (up to 60-70%). jected heat would be distributed locally following the con-t of the total energy system (Fig. 19).

On the size of the plants

From the viewpoint of internal economics of the plant, the ger the better, as generally is the case. For the first in-llations, if the hydrogen plant captive to an ammonia nt, the size will be determined by a balanced optimization. will be large enough however to use the biggest reactors ailable [56].

When a distribution hydrogen-net is set up, linking many ducers to many consumers, then the problems encountered electric grids, when properly interpreted, can give some d indications. For instance: one of the conditions gener-y respected in an electric grid is that the power of a sta-n should never be higher than 10% of the power of the nomically connected grid. This is because in case of fail-e of one station the system, by stretching a bit, can take the load. The interesting counterpart of this condition is it since Edison's time the size of the power units did double ery seven years in neat accordance with the fact that the tensity" of the grids did double every ten years, due to increase in electricity consumption and their extension l double every 15-20 years due to the evolution of power es.

Now, drawing on the analogy, one has to take into account fact that electrical energy cannot be stored as such, but drogen can, the most obvious and promising system being it of using exausted gas fields for large capacity, and perly adapted aquifers or caverns leached out in salt lay-s for medium to small capacity [50] [52]. Another point is it transporting hydrogen by pipeline is roughly one order magnitude cheaper than transporting electricity [43]. To e a feeling of the situation, a 48-inch hydrogen pipeline y carry up 50GW, this is equivalent to the total electric nerating power installed in Japan.

The expected consequences are:

—In relatively small countries like Western European ones and Japan, there will be just one grid covering all the territory and perfectly interconnected.
—The capacity of the stores will take care not only of the accidental outage of one or more stations, but also of the daily and seasonal peaking.
—The 10% limit for the size of the simple station can be released.
—The hydrogen stations can work near 100% capacity.

Following the preceding points these stations will tend to become gigantic, the appropriate unit of measurement being in the range of the 100GW. For a long time the only limitation will probably come from the size of nuclear reactors available. This question of size is very important because, when the technology is mature, size has a very beneficial effect on prices. Assuming e.g. the crude but not uncommon relationship Cost=Size$^{0.75}$, multiplying size by a factor of 16 reduces cost by a factor of two. And in the very competitive energy market this may make the difference between night and day.

Strategy of penetration

Once one has solved all the technical problems, one has to go into the arenà and be competitive. Most likely our hydrogen will not begin its career as a fuel, because the market for hydrogen as a chemical has the perfect structure for assimilating new technology, and because hydrogen is worth now about three or four times as much as a chemical than as a fuel of the same heat value.

The first customers will most probably be new ammonia plants. They will have the right dimension to use all the production from a hydrogen plant employing an optimum-size commercial reactor and they pay a premium for very pure hydrogen. To best use the by-product oxygen, which is worth almost as much as hydrogen, per Nm^3, at present market prices, the site of this ammonia plant should be near a large steel mill, or an oxygen pipeline (Fig. 20). Heavy water, the second by-product, has no problems of transportation, although a nearby final concentration plant would help in various ways. Selling properly the by-product is extremely important for the first plants, because at current prices they are worth almost as much as the hydrogen. Doubling the gross income of the plant at very little cost evidently is bound to make the crucial first step much easier (Table 3).

Once on the chemical market, even with the crutches of the by-products at first, the conquest of the whole of it, and then of the whole energy market will follow with the logic of a theorem. In fact one of the characteristics of this hydrogen is that its cost is almost purely technological, i.e. a manufacturing cost. The cost of uranium, which is the only mineral nominally consumed, at the present reference price of \$20/kg has an incidence of less than 1%. (For a specific HTGR reactor and with actual prices for hydrogen we calculated 0.25%).

Now manufacturing costs decrease according to well-known learning curves which have been put in compact mathematical form [57]. One the other hand minerals in general [58] [59], and fossil fuels in particular tend to rise in cost due to the combined fact that as time goes on ore bodies become leaner, and more expensive to discover. Accordingly it is only a question of time for the descending curve of "nuclear hydrogen" cost, first to become independent of the crutches of the by-products, then to cross the raising cost curves of coke, natural gas, oil and coal.

Since the market can accept very soon very large unit sizes, the effort should go not only to make the processes efficient, but also to direct the technology toward very large plant sizes. In practice the most probable situation will not be a sudden and integral substitution of a certain fuel, this never happened before, but a gradual intermingle and phase out: the extreme flexibility of hydrogen will make the transition very smooth.

For example:

—In iron ore reduction, the new capacity in steel mills can have direct reduction units to produce sponge to substitute for scrap.
—SNG produced by coal and oil gasification, using nuclear hydrogen, will carry into the classical fuel market the fraction of its energy coming from nuclear reactors.
—Cars able to switch from gasoline to hydrogen may slowly switch to hydrogen only.
—Airplanes with wingtip LH_2 tanks for take-off and landing, may see their tanks grow until they carry all the fuel needed for the entire trip.

It is not unreasonable to think that oil companies will take over this new source of energy and will benefit most from it. They have the capital, the technology, the aggressiveness to do it. After all, a water-splitting nuclear plant is not very different from an oil field.

Uranium procurement

A very pertinent question is: to come out from the problems of fossil fuels procurement, are we not going to fall into the problem of uranium procurement? A very searching study made by Brinck[58] [60] on this subject shows that on a world scale there is no reason to be alarmed. In the current range of costs, reserves range in the billions of tons of uranium (Fig. 21). Assuming breeder reactors, one ton of uranium may be worth one million tons equivalent of oil in the form of hydrogen, and this puts cheap uranium reserves in the high brackets. But these reserves are again not eve ly distributed over the earth, and a philosophically mo satisfying solution would be welcome.

This solution exists, at least in principle. Seawater co tains about 3.4μg of uranium/liter. It may seem little but is not. Let us take for example a nuclear power static cooled with seawater. The amount of uranium carried b the cooling water is an order of magnitude more than th uranium fissioned in the power station! Now the proble of recovering uranium from seawater has been studied i Great Britain[61] [62] and in Japan[63]. Titanium dioxide a pears a promising absorber and the economics of the pr cess are in the correct range if the necessity of constructin large civil works is obviated[62]. The uranium content the sea is about 5 billion tons.

Conclusion

This rapid journey in the realm of the hydrogen econom leads us to the following conclusions:

—All the energy needed for a technological society can b supplied in the form of electricity and hydrogen.
—The natural trend of technological evolution lies in th direction.
—Hydrogen is the perfect energy carrier from the point view of the environment.
—Nuclear reactors can be used to produce hydrogen wit thermo-chemical processes having great potential fo development.
—The sea can be the ultimate source of fissionable materia

We added Table 4 to stimulate imagination. One shoul never underestimate the power of dream in fostering huma action.

Table 1 World consumption of hydrogen (1970)

Ammonia synthesis	about	$100\times10^9m^3$
Methanol synthesis		25
Other chemicals		10
Hydrotreating/desulfurization		30
Hydrocracking		30
Refinery fuel (off-grade hydrogen)		10
	Total	$200\times10^9m^3$

Table 2 Transportation costs for hydrogen and natural gas

Energy Gcal/sec	Type of gas	Optimal distance between stations km	Capital costs 10^6\$/Gcal/sec		Transportation cost \$/Gcal/1000km	H_2/CH_2	
			Pipelines	Pumping stations		Capital	Transp. cost
1	H_2	500	242	10	1.23	1.44	1.36
	CH_4	150	166	10	0.90		
2	H_2	500	190	10	0.98	1.43	1.40
	CH_4	150	131	8	0.70		
3	H_2	500	163	10	0.85	1.42	1.39
	CH_4	150	114	8	0.61		
4	H_2	500	145	10	0.77	1.39	1.38
	CH_4	200	104	8	0.56		

Note: Length of the pipeline: 100 km - Max. pressure: 65 atm.

Table 3 Orientative economic analysis for the first water splitting plant

ssumptions	
Reactor investment/kWth	\$50
Fuel cycle cost/kWth h	0. 5mils
Market price for H_2	15mils/m^3
〃 O_2	12mils/m^3
〃 D_2O	\$60/kg
Operation	8, 200hr/year
Efficiency	50%
ross product value, about	\$40
unning costs	
Fuel	\$ 4
Operation	\$ 2
apital charges	
Reactor (int. & depr. 16%/year)	\$ 8
Chemical plant (int. & depr. 25%/year)	\$26
reakeven investment for the chemical plant	100\$KWth

ote: The site is chosen in order to sell the by-products at current prices.

Table 4 Target energy island

Year	1991
Site	Atoll in the Pacific
Reactors	5–10 HTGR + Breeders or HTG Breeders
Nuclear power	1 TWth (10^9kWth)
Efficiency	60% (lower heating value H_2 produced/heat consumed)
Hydrogen produced	500 million tons oil-equivalent/year
Lagoon size	2, 000 × 2, 000 × 20 meters
Cooling water	500 billion tons/year (500km^3) pumped from the deep and warmed up to surface water temperature
Uranium recovered	From sea water (50% effic.) 600 tons/year (dbsorption on Titanium dioxide)
Uranium consumed	In the plant (80% fissioned) 500 tons/year (nongrowing crossbreeding reactor system)
Transportation	Liquid hydrogen in tankers
Investement	10^9 kWth × 50\$/kWth = 50 billion \$. Includes: on site Uranium extraction, Fuel cycle, Liquefying plant.

Fig. 1 The very tight static link between useful energy and Gross National Product is dramatically shown in this figure (Ref. 64). The dynamics is given in fig. 2.

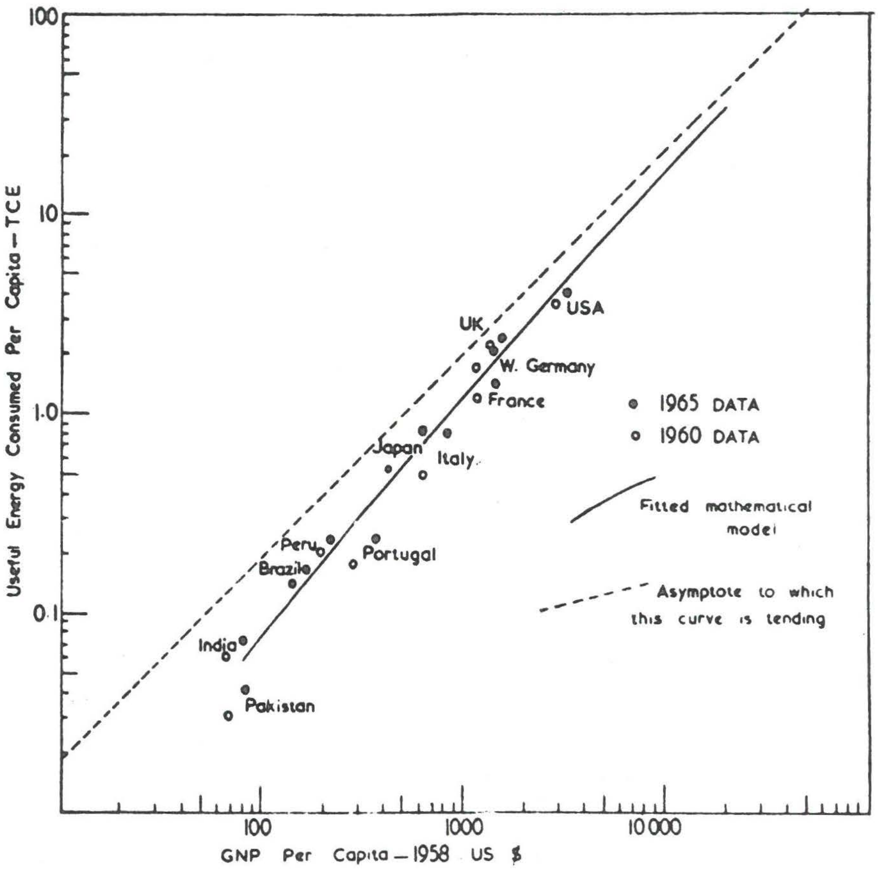


Fig. 2 The fact that Japan is the fastest growing industrial power is reflected in the figures referring to energy consumption. They show also a fast growing problem.

Region	Average Annual Percentage Rate of Change 1950-65	1965-80	Percent of World Total 1965	1980
United States	3.0%	3.5%	34.2%	26.8%
Canada	5.1	5.5	2.9	3.0
Western Europe	4.4	4.0	20.0	16.8
Japan	9.9	7.9	3.3	4.9
Middle East	10.2	9.4	0.9	1.5
Other Asia	7.6	8.2	2.8	4.3
Oceania	5.0	4.8	1.2	1.1
Latin America	7.6	7.4	3.5	4.8
Caribbean	8.6	8.4	2.0	3.1
Other Latin America	6.5	5.9	1.5	1.7
Africa	5.4	6.5	1.7	2.0
North Africa	4.6	5.6	0.3	0.3
Other Africa	5.6	6.7	1.4	1.7
U.S.S.R.	7.4	6.5	15.9	19.1
Communist Eastern Europe	5.8	4.6	7.1	6.5
Communist Asia	14.4	7.6	6.5	9.1
WORLD	5.1	5.2	100.0	100.0
Excluding Communist area	4.2	4.7	70.5	65.3

Fig.3 Mark-1 process.

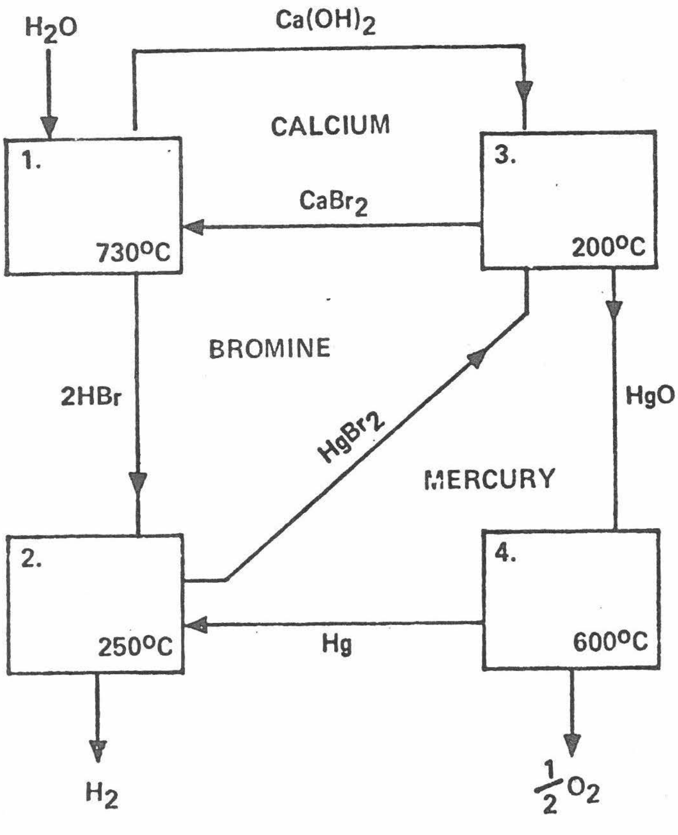


Fig. 4 Hydrolysis equilibrium constants as a function temperature

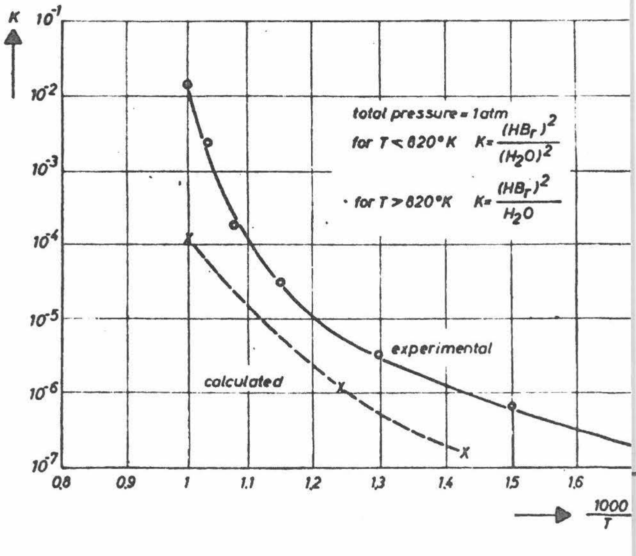


Fig. 5 $Ca(OH)_2=CaO+H_2O$—Decomposition pressures

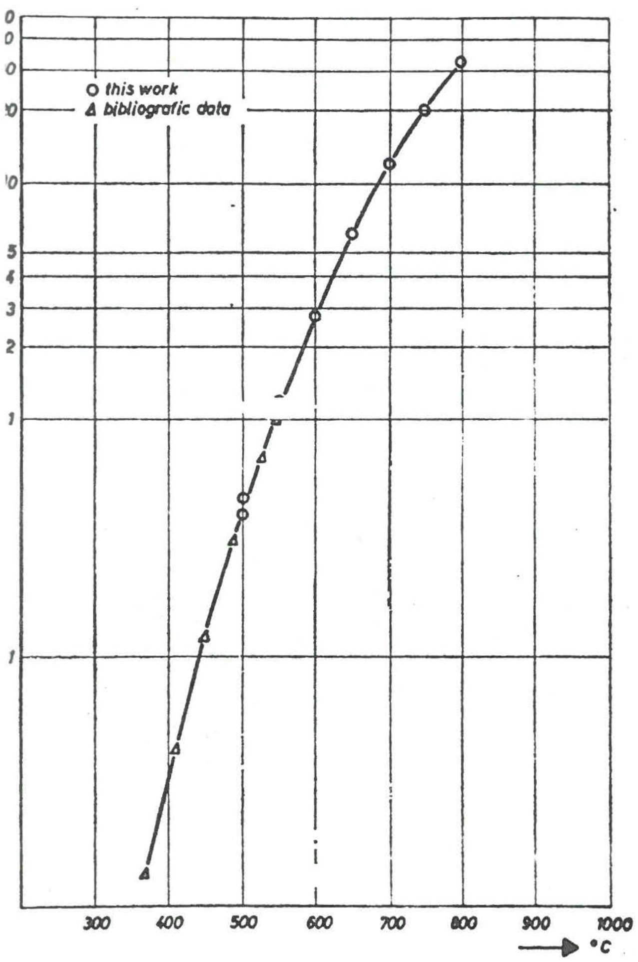
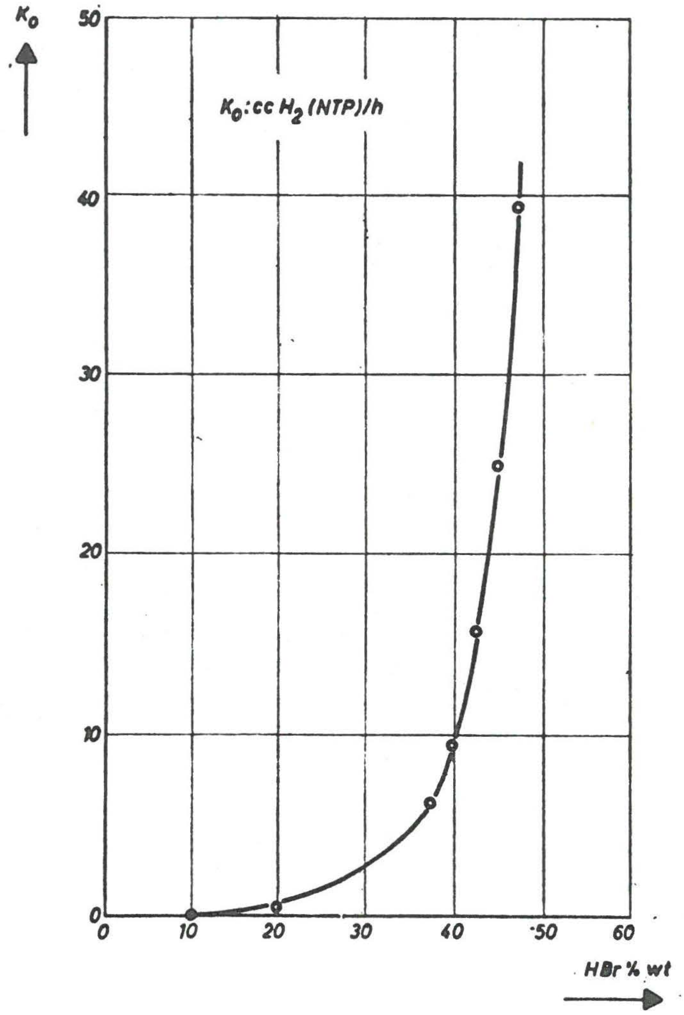


Fig. 7 $Hg+2HBr=HgBr_2+H_2$—Hydrogen formation rate at 200°C Influence of HBr concentration



. 6 $Hg+2HBr=HgBr_2+H_2$—Temperature dependence of rate constant

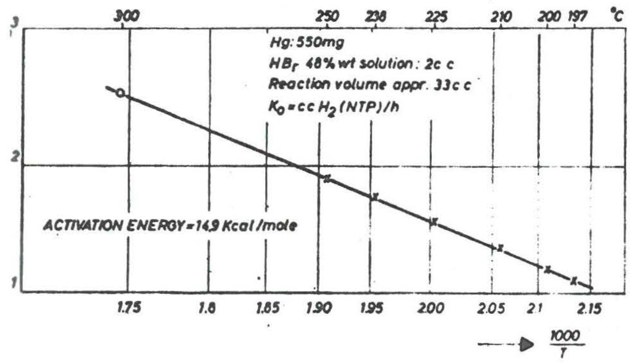


Fig. 8 $HgO=Hg+1/2\ O_2$—Dissociation pressures

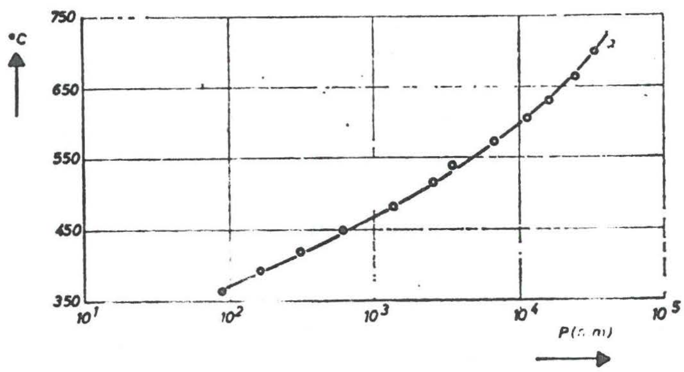


Fig. 9 Mark-1 flow-sheet (HF, heating fluid)

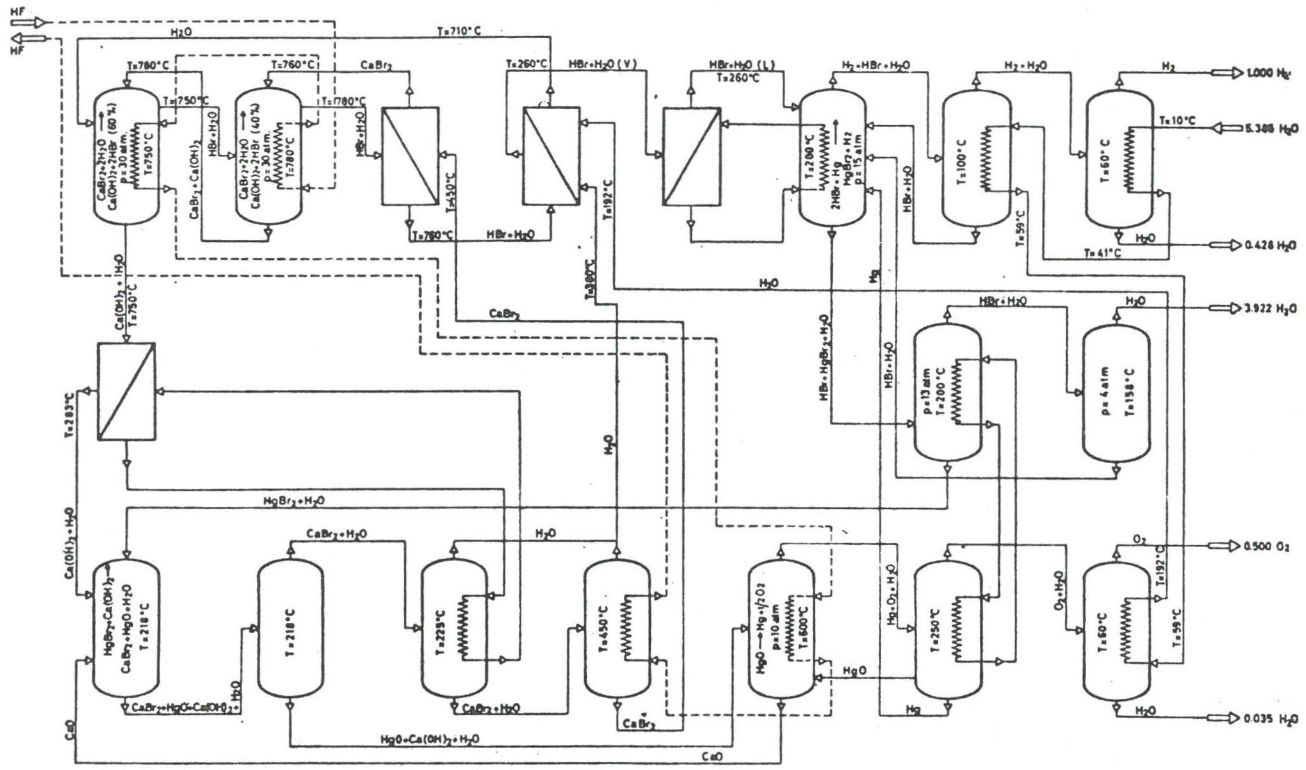
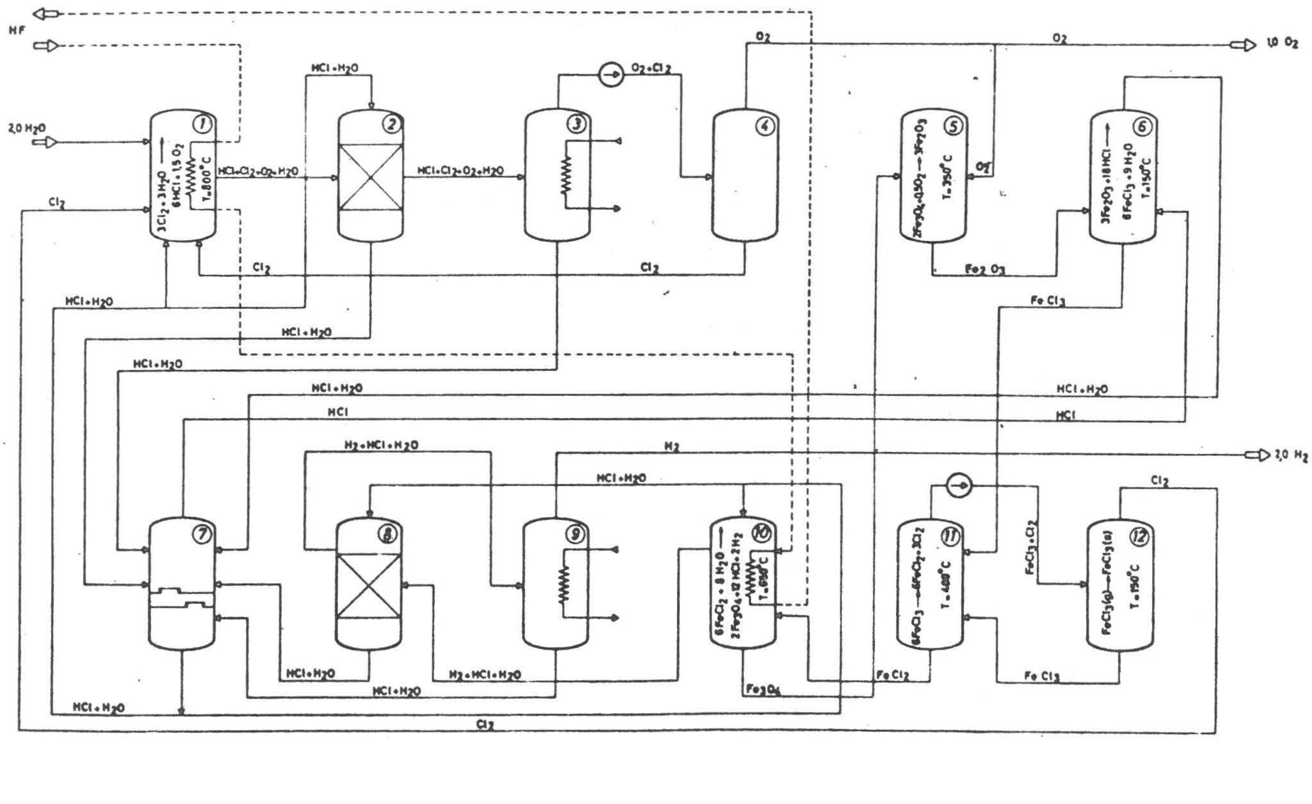


Fig. 10 Mark-7 flow-sheet (HF, heating fluid)



ig. 11 Nitrogen oxydes from gasoline engines and from "hydrogen injection" engines (Schoeppel)

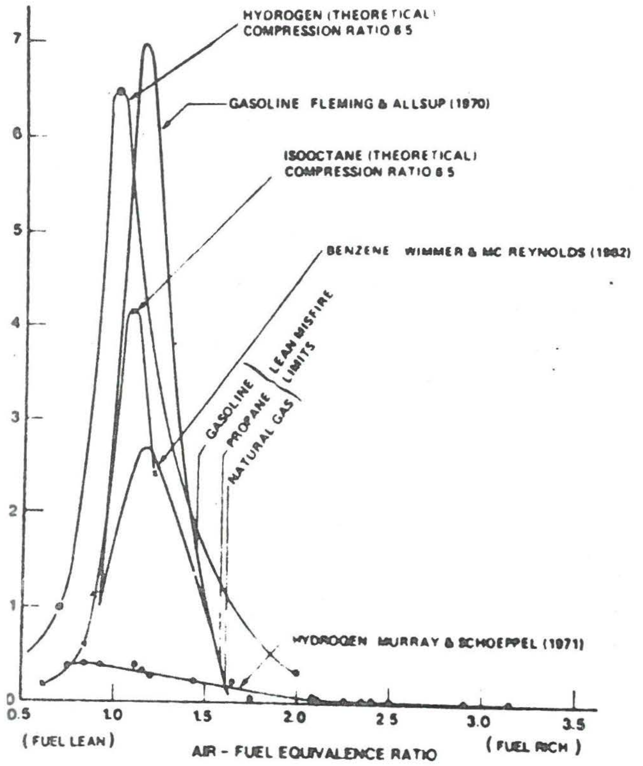
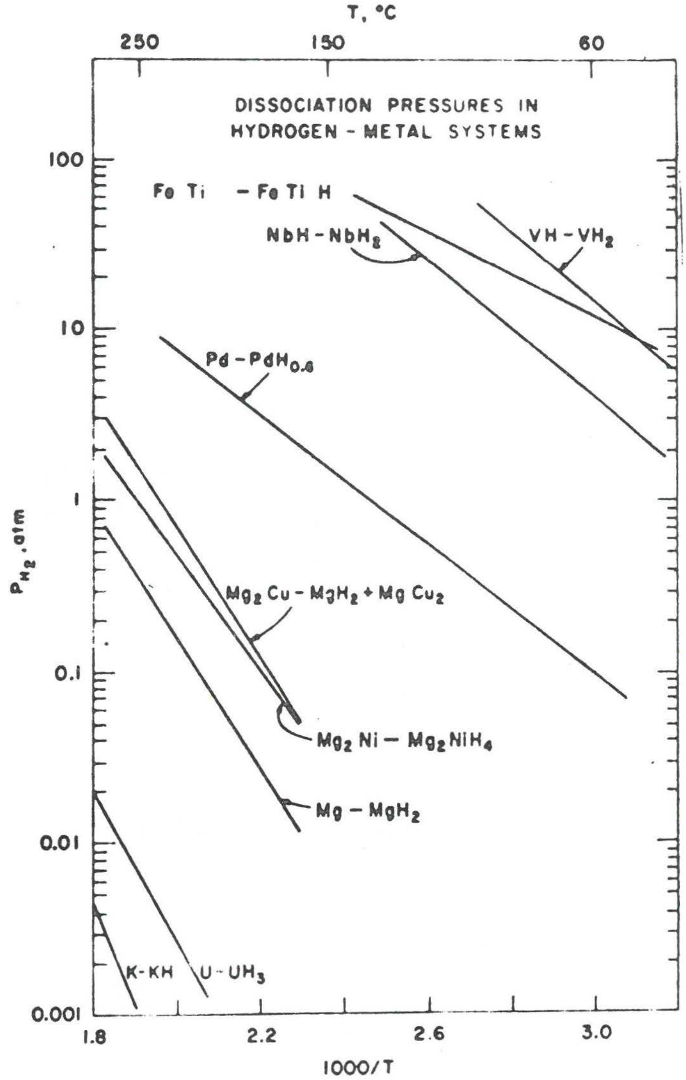


Fig. 12 Equilibrium pressures of H_2 over different hydrides



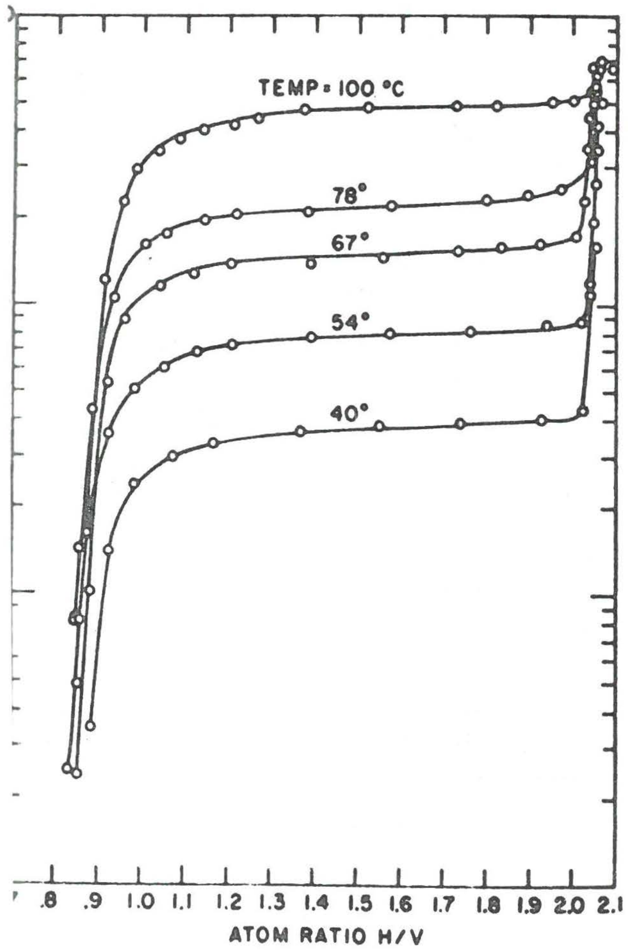


Fig. 13 Typical hydrogen pressures over a metal hydride as a function of fraction of hydride already decomposed (left)

Fig. 14 Sketch of an hypersonic airplane showing the use of the airplane body to produce a shockwave compressing air for the ramjet engines

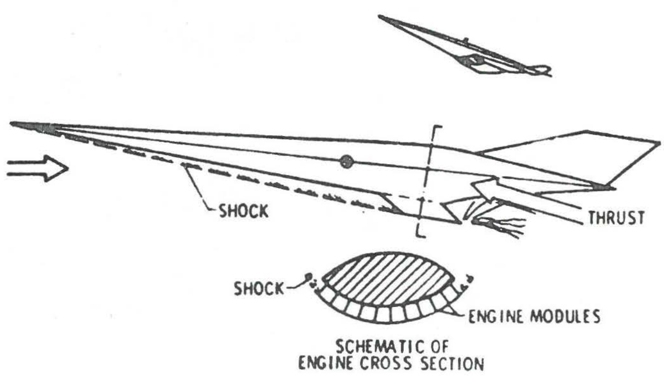


Fig. 15 Trends of LH_2 costs in USA

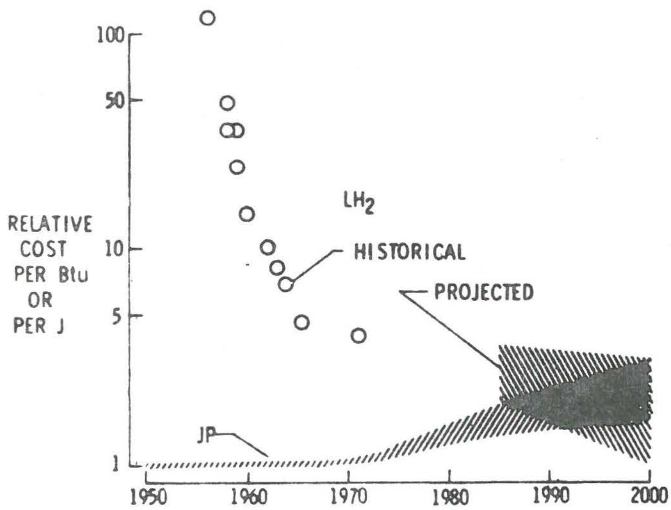


Fig. 17 Cryogenic LH_2 containers at the Nuclear Rocket Development Station in Nevada

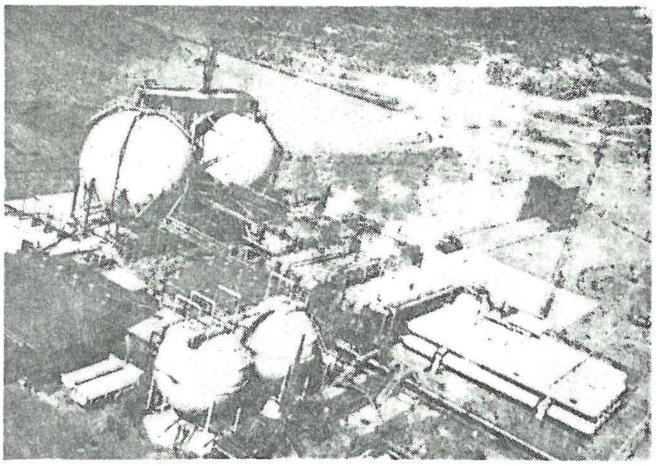


Fig. 18 Cryogenic barges to carry LH_2 and LOX

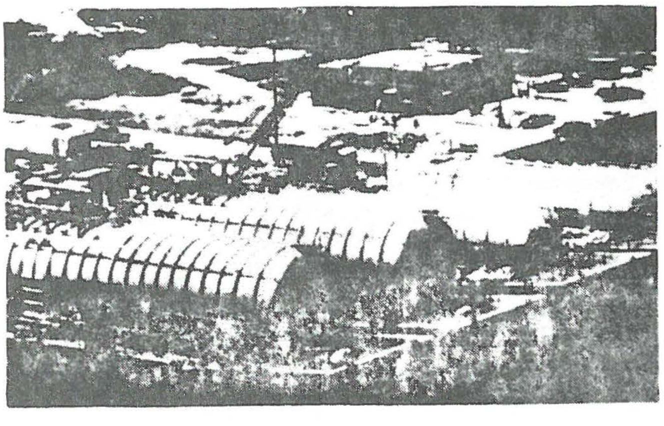


Fig. 16 An hydrogen distribution network in Northweste Germany. Total length about 300 Km

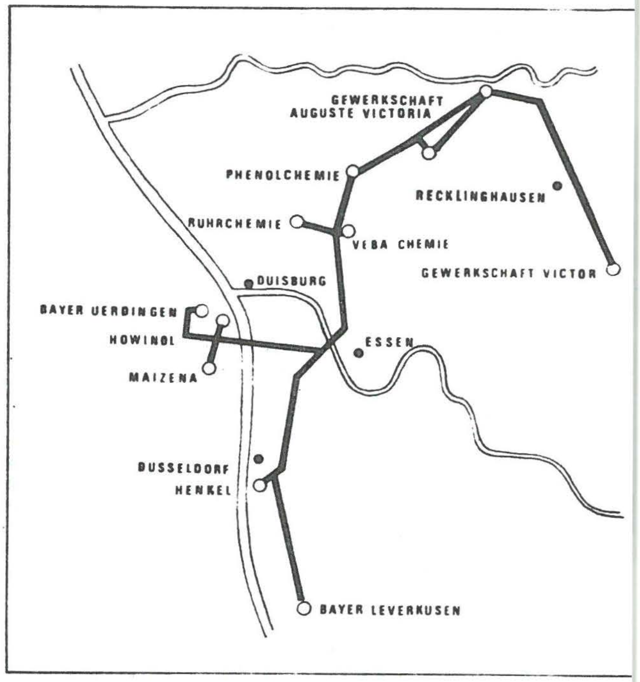


Fig. 19 An hydrogen economy as seen by TEMPO-Gene Electric

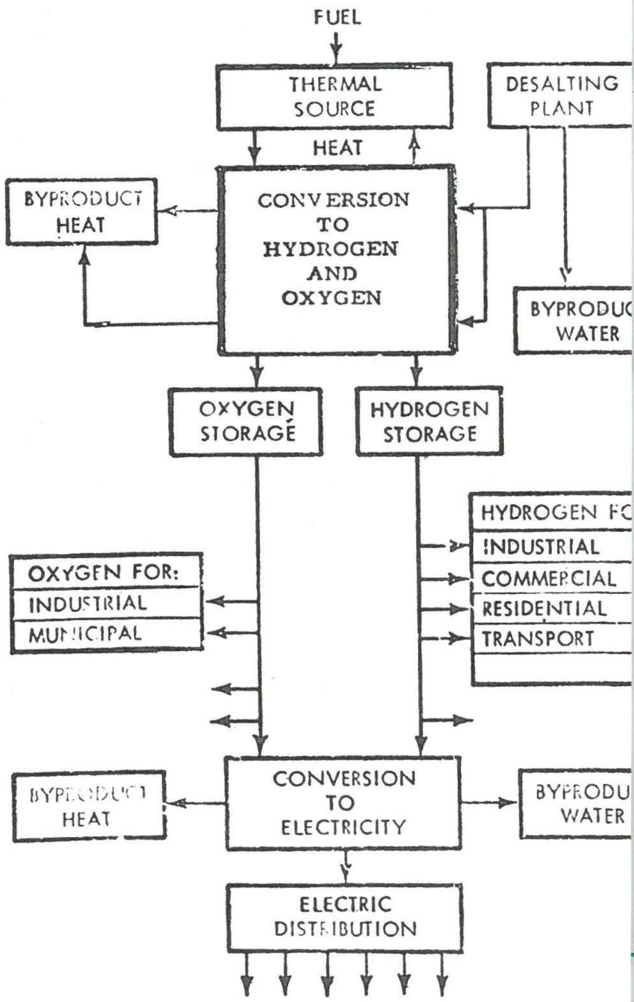


Fig. 20 An oxygen pipeline in Northwestern Europe

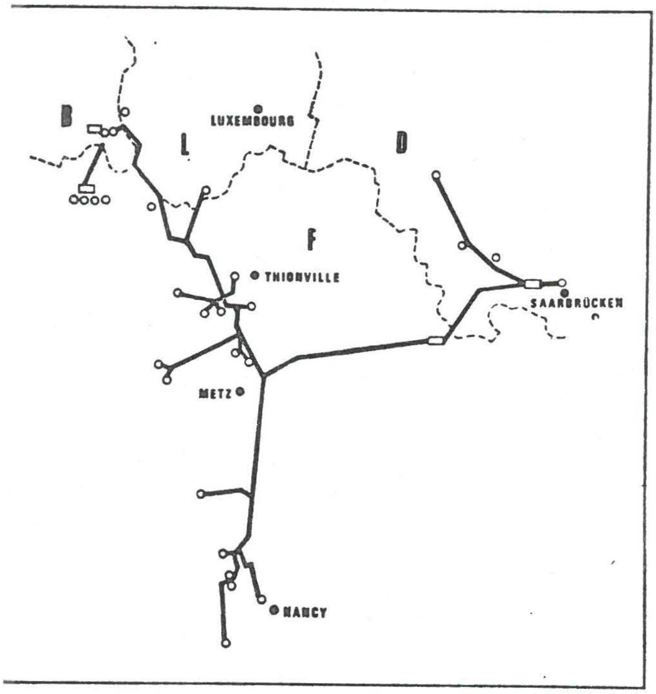


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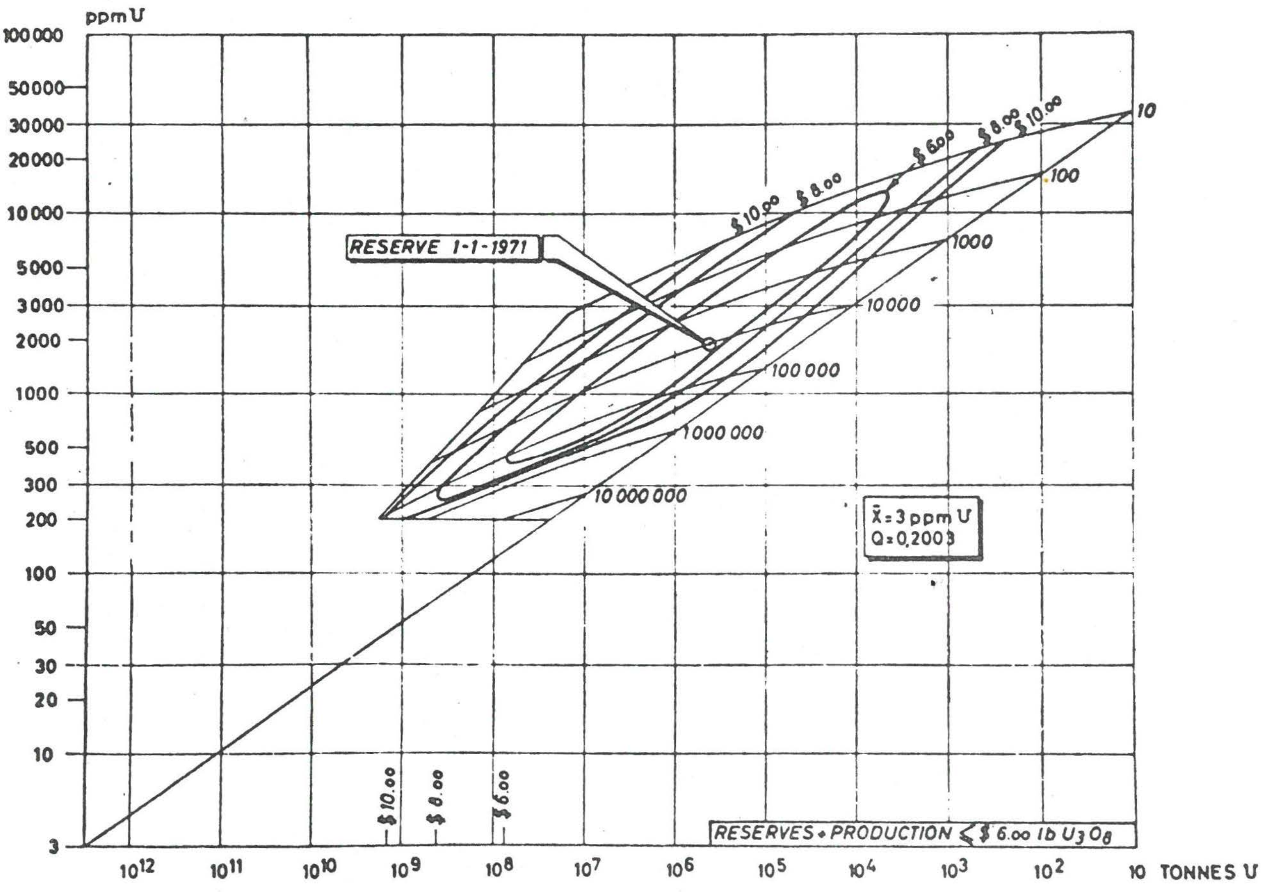
Fig. 21 Forecast for world uranium reserves



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Discussion

Mr. Marchetti was asked what pressure is used in the hydrogen pipeline in Germany. He replied that a pressure of twenty to thirty atmospheres is used because that is the compression used by the consuming industries. Much higher pressures are feasible.

One of the participants asked whether solar energy could replace nuclear energy in the hydrogen production process. Mr. Marchetti said that any kind of energy could be used; "heat has no smell." The point is that you require temperatures in the right range.

Someone else asked about the efficiency of the process. Mr. Marchetti said that the theoretical efficiency is eighty-five percent. The actual range could be between fifty-five and sixty-five percent, and that range is the development target.

One of the participants asked Mr. Marchetti to explain what the problems are with his system. What is the hitch? For example, in the Mark 7 cycle, is the problem the decomposition of $FeCl_3$? Mr. Marchetti responded that one problem is obtaining materials for containing the system. Both the dry chlorine and the wet HCl may be troublesome to contain. There is also a question as to whether chlorine at these temperatures can be handled at all. There may be problems from corrosion products or from the quantities involved in these processes. Of course, there are unknown problems.

It was asked why the idea of using hydrogen in this way had only arisen now; we have had hydrogen for a long time. Mr. Haefele answered that the massive production of hydrogen was precluded in the past by high cost and by technical difficulties. The combination of nuclear and chemical technology could make it feasible now.

One of the participants asked whether, in principle, it would be possible to use simple chemical processes instead of an atomic reactor for hydrogen production, or whether very high temperatures were always necessary. Mr. Marchetti replied that that is conceptually possible but has not yet been done. It is thermodynamically feasible. He had considered using heat from the LWR, which is lower in temperature, but has not yet found the right chemicals for such a process. His questioner next inquired whether the production of hydrogen could be combined with processes in living substances. Mr. Marchetti said yes, in a sense; living substances do produce hydrogen. The Japanese are working on such a process using CO_2 and two photons; the efficiency is about ten percent.

One of the other participants mentioned that there exists a theoretical scheme to use heat instead of sun energy to decompose water in a closed cycle with certain bacterial enzymes. The questioner continued by asking for comparative figures on the production of gaseous fuel from oil, coal, and water. Mr. Marchetti said that the system is flexible and could intermingle all three. Methane is a good carrier for energy; it can be given thirty percent more heat value. One idea is to flow nuclear energy into fossil fuel. Coal presents even more possibilities. One can burn it in hydrogen, obtaining methane. Both hydrogen and oxygen can be used to gasify coal. Precisely what is done depends upon the amount of available hydrogen. He noted that there is a TEMPO scheme for distributing hydrogen and oxygen in pipelines and using them in steam turbines by injecting them into the steam. One gets an efficiency of sixty or seventy percent, comparable to that of electricity, but this scheme has two advantages: the reactors can be out of sight, and there can be many small units, say of 100 mega watts, linked by thin lines.

Mr. Haefele commented that he had placed the HTGR and new technologies for pipelines and for using coal in the medium time range. HTGR heat can initially be used for coal gasification. The point is that the various approaches and technologies are compatible. One can get smooth transitions between solutions.

One of the participants disputed Mr. Marchetti's claim that all energy needs can be met by hydrogen. He noted that we used to make light by using gas lamps. The problem is economic rather than technical. He observed that the unit size question is related to the competition between economies of scale and producing more and more on the same scale. Transporting energy presents problems; it is expensive in terms of efficiency. In particular, there are special problems with electric transmission lines. There are social constraints on building new lines in dense areas; alternating current cannot be interconnected into large systems without a great deal of caution. Finally, the speak noted that an electrolytic process to make hydrogen was not mentioned. It has been said that that would be too expensive. However, if an equivalent amount of research and development were invested in such a process, it might be economically viable. The use of hydrogen to produce electricity was also not mentioned. Mr. Marchetti replied that if the Mark I process is used there is a good match between the heat source and the system and, therefore, a high thermal efficiency. The energy is used inside the plant, and we have a closed system. The production of electricity is then another question which must be evaluated in its own context.

Mr. Marchetti observed that his thesis has two parts. He said he is convinced that the hydrogen economy is right. The only question in his mind is whether the way he has proposed of reaching it is right.

One of the participants suggested using hydrogen as a reactor coolant. Mr. Marchetti agreed that technically that would be good. The point is that introducing too many novelties at once invites practical failure. Thus, he based his work on a commercial reactor. In Mark I steam is heated rather than chlorine to avoid criticism of the heat exchanger. Hydrogen might be criticized as a coolant because it is flammable. Social acceptance constrains the technological choices.

Another participant asked whether conventional sources of heat could be used for the process. If so, why not use them? Why not use fossil fuels, for example? Mr. Marchetti said that of course conventional sources could be used. However, fossil fuels would not be because that would be inefficient; they are a source not only of heat but also of reductants.

Someone asked whether the hydrogen economy would affect the water cycle. Mr. Marchetti responded that it would only affect water procurement. The magnitude of water involved is much smaller than that of water evaporation.

The Problem of Embedding Energy into the Atmosphere and The Present Ability of Climatology to Advise on It

H. H. Lamb

Summary

The observational and theoretical sides of climatology are reviewed. The subject had a history of rather serious neglect for half a century or more, and much work is now needed to put the working material of climatology in order and approach the pressing demands for diagnosis and prognosis, which now confront the subject. A program is indicated and the organization necessary is touched on. Finally, the possibilities of answering some of the most urgent problems connected with the prospective output of additional heat from Man's activities are surveyed.

Introductory Remarks

Mr. Chairman, Gentlemen

I am honored to have been invited to take part in this meeting, and I am only sorry that a domestic emergency delayed my arrival.

From the moment of receiving the invitation, I regarded this as a great opportunity to acquaint myself with the energy problems of the future, the new and vital problems that will shortly come before mankind and which IIASA has been set up to grapple with.

But, when I heard that you counted on me to introduce the thinking about the problem of embedding "Man-made" energy--ultimately in great quantities--into the atmosphere, and the application of computer modelling of the atmosphere to study this, I began to think that you had asked the wrong person.

However, after comparing notes with my friends who are actively engaged in developing mathematical models, I have come to the view that, after all, a detached person in about my position may be able to give you the comprehensive overview which you need.

The Development of Climatology and Present Status of the Subject

My own work, and the main effort of the new Climatic Research Unit which I have set up (1st January 1972) in the University of East Anglia at Norwich, is aimed at laying the foundations of a geophysical climatology and, in particular, providing the essential observational base, a long record of the behavior of the natural climate in the past and up to the present time. You may be surprised that this obvious first need of any science is still lacking in climatology, but it is so. Nevertheless, the necessary data are now being brought to light by modern techniques and contributions from the most diverse fields of science and learning, and the situation is very promising. This has been a much neglected science until recent years, though pioneered excitingly long ago by G. Hadley, Pierre Cotte, Alexander von Humboldt, and others.

Because examination of the first 100 years records of daily weather observations, mostly of the cities of Europe and eastern North America, showed that the climate of the last quarter of the nineteenth century had by chance reverted to values very close to those of the last quarter of the eighteenth century when many of the records began, it was too hastily concluded that changes of climate (apart from the supposedly random differences of each year from the next and a few shadowy cycles of 11 to 35 years duration) belonged only to the geological time-scale. This idea took firm root and characterized the teaching of meteorology and climatology for 50 years. Hence, climatology became a very dull subject, the mere bookkeeping branch of meteorology. Apart from rather few and isolated figures (C. E. P. Brooks, C. C. Clayton, W. Küppen, M. Milankovitch, G. C. Simpson, and A. Angström), during this period little original thinking seems to have been devoted to the processes by which climate is maintained. Some of the pioneer work directed towards developing a capacity for long-range (monthly or seasonal) weather forecasting, particularly by Sir Gilbert Walker in India and Franz Baur in Germany, was relevant but attracted little attention or sympathy among the leading figures in meteorology.

Meteorology was, in fact, concentrating increasingly on improving the position as regards daily weather forecasting by advancing the mathematical handling of the dynamics and kinematics of the atmosphere. Particularly from the 1940's onwards, but to a considerable extent even before that, recruitment and advancement to the highest positions in the meteorological services in the leading countries concentrated on mathematicians, who over the last 25 years have led the development of numerical daily weather forecasting and the introduction of the giant computers to that end. The other most important line in the meteorology of recent decades has been the employment of physicists with the abilities needed for developing the new instruments of observation, radar, radiosonde, rocket, and satellite. Very few of these people turned their interest to climatology. And it may be seen as the end product of this development that the World Meteorological Organization abolished its Commission for Climatology in 1969.

In the meantime, indications of a long record of fluctuations of climate, not only in the remote past but also in postglacial and historical times, were being amassed by paleobotanists, glaciologists, and others, who had no contact with meteorology and were obliged to hazard their own interpretations of their data. Latterly the field has been widened out to include notable contributions from (a) such studies as varves in lake deposits and the paleontology of the deposits on the ocean bed, (b) the introduction of physical (isotope) methods of dating and measuring paleotemperatures in the stratigraphy of ice sheets and ocean bed deposits, and (c) the application of numerical methods to the interpretation of tree rings and pollen data.

Other work in the last 30 years, on homogenizing long records of the daily observations made with the standard meteorological instruments at a worldwide network of places, has shown that climatic fluctuations continue right up to our own times. In particular, the global average surface temperature (taking successive 5-year means) is seen to have risen by almost half a degree Centigrade (and by several degrees in the Artic regions) from 1880 to the 1940's, and has fallen by 0.3°C since. Meantime the average precipitation in parts of Soviet Central Asia at first doubled and since 1950 has declined half way to its mid-nineteenth century level. In England, where usable temperature records go back to 1680, and where the variations of prevailing temperature seem to be generally in the same sense and of about the same magnitude as the world average, the long-term mean temperature rose by about 1°C from the beginning of the record to 1930-1950, and declined by 0.3°C to the 1960's. The cold period of the late seventeenth century seems to have been worldwide and had been preceded by a temperature fall of the order of 1.3 to 1.4°C from the warmer climate of the period AD 950 to 1300. These figures change the length of the growing season in England by three to four weeks.

These are natural climatic fluctuations, which apparently go on all the time and constitute a background against which any effects due to Man must be measured. Inadequate knowledge or understanding of them must jeopardize our ability to establish the impact of Man-made effects. Their existence, and the now widespread appreciation of their previously unsuspected magnitude, has pitchforked a demand for climatic forecasting for agriculture, industry, insurance, trade, and tourism, as well as for all sorts of forward planning, quite apart from advice on how Man's activities might modify the climatic trend.

The size of the natural temperature decline from the early Middle Ages to the seventeenth century amounted to about a quarter of the difference between present conditions and the global mean temperature indicated for the periods of maximum glaciation in the past. The renewed falling trend of world temperature since about 1945 is the longest-continued downward trend since the earliest thermometer records, and it has been accompanied by increases of the downput of rain and snow in the 1960's amounting to 15 to 30% in various parts of the Alaskan Rockies and the Baffin Land-Labrador area, and by about 50% in the region about Novaya Zemlya.

There is an urgent need, first and foremost, to assemble and map the facts of the past climatic record, year by year and period by period, as far back in time, over as much of the earth, and in as much detail as the available data will permit. The material must then be analyzed in such ways as will bring out the circulation patterns and processes which bring about the changes, giving particular attention to the magnitude of the effects of each process, and the geographical range and characteristic course and time scale of its evolution. Modern methods of spectral analysis applied to time series of climatic, glaciological, and related data bring to light quasi-periodic phenomena, commonly on time scales of about 2 (or 2 to 3) years, 5½, 10-12, 18-19, 22-23, 80-100, 170-200, and 400 years; indications have also been reported of important periodicities of 1,000-1,300 and 2,000-2,600 years. Mapping the 2-year and 22-year oscillations phase by phase already suggests that it will be possible to monitor the progress of the current individual cycle and identify any anomalous behavior while it is still relevant for forecasting. It should also be possible in this way to reach a better understanding of interference phenomena arising through the superposition of different processes and their different time scales. But basic to all such research is the need of a long enough past observation record to trace the operation of a large number of previous cycles of each process.

In some cases, the time scales of quasi-periodicities identified in climatic data suggest associations with external causative agencies which show fluctuations of the same period: solar fluctuations in the case of the 5½, 10-12, 80-100, 170-200 and 400-year fluctuations, tidal force variations in the case of the 18-19-year fluctuations. In other cases, the circulation maps already available have made it possible to trace the characteristic evolution of the general atmospheric circulation and climatic data (temperature, sea ice, precipitation) following events whose incidence is aperiodic; such cases are the persistent veils of volcanic dust in the upper atmosphere after great explosive eruptions and extensive anomalous areas of warm or cold ocean surface, ice and so on.

Many years work will be needed in this observational climatology to provide the basic knowledge of the facts of the climatic record and the processes involved in it. It is probably sound organizationally that the work should be concentrated in just a few centers. At present the only centers engaged in improving the accessibility of the observational material and presenting it in suitably analyzed form for research are:

a) the Center for Climatic Research at the University of Wisconsin, Madison, U. S. A. (where most work is done on derivations of the climate and circulation patterns over North America and the Pacific and Atlantic Oceans in the periods AD 1700-1850 and much earlier postglacial times).

b) three American universities: Brown, Columbia (Lamont-Doherty Geological Observatory), and Oregon State (collaborating under the CLIMAP program, with funds allocated by the National Science Foundation, to map the climatic patterns of the last several glaciations and interglacial ages).

c) the Climatic Research Unit at the University of East Anglia, Norwich, England (where most effort is concentrated on the last 1,000 years, particularly the period since the introduction of meteorological observing instruments).

d) the Main Geophysical Observatory, Leningrad (where solar, geophysical, and oceanographic aspects are explored, chiefly with the observations of the last 100 years). There are liaisons with the Arctic and Antarctic Research Institute, Leningrad and the Academy of Sciences (Institute of Geography), Moscow; and climatic forecasts are attempted.

The programs concerned at all these institutions, except those in the U. S. S. R., were started since about 1960. The Climatic Research Unit at Norwich, begun in 1972, has so far no staff engaged beyond 1975 because of the lack of financial support, following a ruling of the Meteorological Committee of the Natural Environment Research Council in the United Kingdom (in November 1972) that "there is not much point in attempting to reconstruct the facts of climate in the past in any detail."

Nevertheless, the theoreticians developing mathematical models of the atmosphere and oceans need the results of the proposed groundwork on the past observation record, to test the validity of their models and to indicate the appropriate values of empirical coefficients in their equations.

The Present Status and Capacity of Mathematical Modelling of Climate

When I asked the dynamical climatology research branch of the U. K. Meteorological Office if one of their mathematical modellers would care to contribute this part of what I have to say, I was told that the capacity of theoretical modelling to contribute anything reliable to the understanding of any delicate balances in climate did not yet exist. I quote:

> A number of people in the field are against using general circulation models for this kind of investigation .... Hence the small number of papers published on the subject. They can see that it can very possibly lead to numerical modelling getting itself a bad name.

What I have to present from the reports of modelling experiments shows clearly that it is premature to look for usefully precise results from them.

There are two kinds of models in meteorology and climatology, both of which have been used for preliminary trials in the connection which we are concerned with:

a) general circulation (dynamical and thermodynamical) models, similar to those used in numerical daily weather forecasting, and

b) climatic (mean state) models.

The models of type (a) proceed from specification of the initial state of the atmosphere over a large part of the globe, using observations at up to 10 levels in the atmosphere at a network of points characteristically 300 or 500 km apart, and by applying the equations of motion and expressions for the exchanges of radiation, sensible and latent heat and moisture, go on to calculate the future states of the atmosphere, at as many levels, at intervals of 10 to 30 minutes.

For forecasting purposes, it is found that the correlation between the computed and the observed sequels falls to zero in about 10 days. One fundamental difficulty is that the atmosphere uses up its initial store of energy in about 5 days; and the heating patterns by which the store is renewed, which are vital to forecasting the subsequent developments, are themselves greatly influenced by the cloud distribution (and sometimes the snow cover) which the atmospheric circulation has by that time produced. Moreover, cloudiness is so far not well forecast by the models: a cloud is only maintained by them so long as precipitation is being produced. (The cloud is produced and forthwith precipitated.) Other basic difficulties arise from the error margins inherent in the initial observations and through the development of systems which at the outset were too small for the resolving power of the observation network. Research is now largely concentrated on incorporating models of the ocean and its processes with the atmospheric models, and on introducing the two-way interactions between the atmosphere and the ocean; but the fundamental difficulties mentioned above remain.

Experiments have been conducted by E. N. Lorenz [9] and W. M. Washington [19] in the United States on the effects of observational errors and the development of small systems on the output of the models. Errors in various sizes are found to double in 3 to 8 days. Although optimism reigns among some of the meteorologists committed to developing the mathematical models needed for forecasting as far as possible into the future by computation, it seems to be generally thought unlikely that this method will ever produce forecasts of acceptable reliability beyond 7 to 15 days. However, it is also clear that the very largest-scale circulation features, which constitute the framework or steering pattern of the future weather development over a hemisphere, are the ones that are least affected by the errors discussed; they may, therefore, have some longer-range predictability.

Experiments have therefore been made with continuing the computations to 80 and even 100 days into the future. At this point costs have limited the experiments because of the huge amounts of time needed for the calculations, even on the greatest, and most expensive, computers. Errors arising from a 1m/sec initial error introduced into the observed wind near the maximum wind level, in the neighborhood of the jet stream, in a January situation, grew rapidly over the next 20 days, but had ceased to grow further during the last third of the computations [19]; at this point the discrepancies in the derived temperature field were as great as 10°C in the lower atmosphere over parts of northern Europe, Asia, and Canada, to the cold side of the jet stream. It is suggested that this may correspond to the real variability of the atmosphere. Another experiment with the same (NCAR) general circulation model, introducing an additional heat flux of up to 78 langleys/day ("thermal pollution") in the densest parts of the present metropolitan population clusters and 13 ly/day averaged over the areas of the population clusters in general, in the January situation, produced similar departures from the normal development to those found in the previous experiment [19].

Experimental calculations to ranges of 50 to 100 days thus produce global distributions somewhat similar to the general character of the existing climate but without any useful resemblance to the specific situations arising in specific circumstances. And it is not clear that the thermal pollution experiment mentioned, where the extra heat flux was very great, produced any departure from the normal development which was distinctive or significantly greater than those produced by observational errors. The statistics of situations appearing in the steady state phase, or approximately the last third, of computation experiments resemble the statistics of global climate (with equatorial rains, an arid zone, and travelling rains associated with the belt of westerlies in middle latitudes); but neither the positions nor the magnitudes agree satisfactorily with observation. Moreover, it must be admitted that there is so far no real knowledge of how much rain actually falls over the seas which cover 17% of the earth; because the problems of measuring rainfall at sea have never been solved, a wide margin of uncertainty exists. Also, knowledge of the radiation budget of the earth cannot be considered as finalized, since the accepted estimates of global albedo have been successively revised over the last 15 to 20 years from 43% to 29%, and now it is reported that the albedo of the great sandy deserts must be revised upward from about 30% to 40%.

The prohibitive cost of computations beyond an ultimate limit of about one year influenced the experiment reported by Manabe and Bryan [10] in which a 9-level atmospheric model was combined with an ocean model in such a way that the processes occurring in 100 ocean years were geared to 1 atmospheric year in the last stage of a 3-stage computation which took 1,200 hours of computing time on the UNIVAC 1108 computer of the Geophysical Fluid Dynamics Laboratory of ESSA at Princeton University, U. S. A. The results of comparing the computed development of the atmosphere alone and of the combined model, incorporating the ocean, in this experiment were qualitatively reasonable: the upwelling of cold water near the equator, it was found, greatly reduced the rainfall over the tropical ocean, and the warm current moving poleward off the subtropical east cost of the continent increased the rainfall there, but there were 5°C errors of surface temperature in low-middle latitudes and over 10°C in high latitudes.

Experimenting with a much simpler (and more economical) 2-level model due to Mintz and Arakawa, Gates [7] reports results of similar quality for a January situation. The calculated temperatures were 5°C too high at 6 km in the upper air over the equatorial and tropical zones, but were better nearer the surface; the calculated cloudiness was about half that observed; the precipitation were about double and over too broad a belt in low latitudes. Evaporation in the tropics (so far as we can regard its true amount as known) was found to be 50% too great, and the winds in the jetstream system were 60% too strong.

The much simpler climatic mean state models, which merely explore the average budgets of radiation, and the heat transported by the mean winds and ocean currents, as well as the average effects of convection and turbulence in the atmosphere and ocean, are attractive because of their economies of cost and effort. This is especially so while the detail produced by the dynamical models is unrealistic. The climatic average models, however, also fail to give decisive answers (so far) wherever any delicate balances are involved. Perhaps the most widely accepted, and useful, result from the work in this category so far is the computation by Manabe and Wetherald [11] of the effects of introducing increasing amounts of (Man-made) carbon dioxide into the atmosphere, using a model in which not only the radiation exchanges within the atmosphere but also the convective activity was affected. Relative humidity and the amount of cloud-cover were assumed constant. This indicated that doubling the carbon dioxide content would raise the equilibrium temperature at the surface of the earth by 1.9°C.

Rasool and Schneider [15] have indicated that increasing the suspended aerosol content of the atmosphere by a factor of 4 should have the opposite effect, lowering the mean temperature of the surface of the earth by 3.5°C, due to back-scattering of the short-wave solar radiation while leaving the passage of the earth's long-wave radiation almost unaffected.

A good deal of the experimentation with these models has concentrated on exploring the effects that would be likely to arise from removal of the floating ice on the Arctic seas. This should be relatively the easiest local or regional anomaly to handle, since it implies changing the mean surface temperature of the whole Arctic region by about 25°C (an anomaly far greater than nature provides). The results, though possibly realistic, are inconclusive in an interesting way. Budyko [2], reviewing his own and other model calculations, found that the best estimate of the average surface temperature that would prevail in the polar region in winter with an open Arctic Ocean is about +1°C. This value differs from the freezing point of sea water by less than the margin of error of the calculations. Moreover, the year-to-year variability about such a value suggests that within a few years the ice might re-form. Another model calculation by Sellers [18] suggests that the ultimate effect of disappearance of the ice, without any primary change in the energy available over other latitudes, would be to raise the overall average temperatures prevailing north of 70°N by no more than 7°C, a result which implies that the ice would soon reappear. More important consequences might be the changes that would be produced in the downput of rain and snow. Most calculations indicate that, with an open ice-free Arctic Ocean, more rain and snow than now would fall over the central Arctic and the surrounding lands in high latitudes, possibly leading to the onset of glaciation as snow accumulated on the mountainous regions and existing ice-caps, while the northern hemisphere land areas in general, farther from the Arctic coasts, would suffer from a drier regime than now. This conclusion was first indicated by Drozdov [3] empirically from consideration of the observations of the warmest and most ice-free years in the present century. Much the same is also implied by a recent computation by Newson [14], with the dynamical model developed in the U. K. Meteorological Office, which showed that winter temperatures prevailing over latitudes 50-60°N over Europe and Asia and 25-50°N over North America with an ice-free Arctic would be lower than now (by 6 to 8°C in some inner continental areas), presumably owing to a much increased frequency of anticyclone development over the continents between 50 and 70°N.

Other points of interest from such calculations, particularly those by Fletcher [5] and Budyko [2], are that an additional heat input to the Arctic of 30 k cal/cm^2 would suffice to melt a 4 m thick floating ice layer on the Arctic Ocean. (The existing pack-ice reaches this thickness only in the middle and in narrow pressure-ridges.) The natural fluctuations from year to year are reckoned by Fletcher to supply an extra 6 to 8 k cal/cm^2 in the warmest summers.* Thus, it appears quite conceivable from these calculations that the whole of the floating pack-ice in the Arctic could be melted in the course of a few warm years; though, in fact, the total recession of the ice during the warm decades in the first half of the twentieth century amounted to no more than 10 to 15%, and the loss of about one-third of the thickness of the ice as measured by Nansen in the 1890's. Recent paleontological evidence from the ocean bed indicates that the central Arctic has not been

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*For comparison, the total solar heat reaching the surface in one summer in the central Arctic is 73 k cal/cm^2, though in an average summer only 18 k cal/cm^2 is absorbed. The average total heat transported yearly to the region from other latitudes, mainly by the winds, is about 70 k cal/cm^2.

without its ice cover over any significant period in the last 70,000 years.

The Problem: Man's Thermal Pollution of the Environment Now and in the Future

According to Flohn [6], the best estimates of Man's total output of heat, mainly from the burning of fossil fuels, in 1970 are 0.03 langleys/day or 0.11 ly/day averaged over the land areas. The latter figure is approximately the same as the average flux of geothermal heat from the earth's interior. However, estimates for the area of concentrated population and industry in western Europe between the Ruhr, Antwerp, and Namur (500,000 km^2) suggest an over-the-year average of 17 ly/day, and in the great centers such as Hamburg and Paris 100 ly/day; for Manhattan (central New York) 250 ly/day. Present average rates for Montreal are believed to be 117 ly/day in summer and 313 ly/day in winter. These are, however, essentially point sources of heat.

These figures may be compared with the following magnitudes of heat release in nature in the present climate [8: chapter 2]:

Solar energy supply at the outer limit of the earth's atmosphere	overall average	720 ly/day
Net radiation absorbed at the earth's surface	overall average	200 to 250 ly/day
Latent heat released by condensation in rain-bearing clouds over the equatorial oceans and over the oceans off the Pacific coast of Canada, off NW Europe, eastern U. S. A., and Japan	yearly average	200 to 300 ly/day
Uptake of feelable ("sensible") heat from the ocean over the Gulf Stream and Kuro Shiwo	yearly average	90 to 120 ly/day
Extreme inputs of heat into the atmosphere, in fast-moving cold airstreams in winter over 1000-km-paths over the North Atlantic between Iceland and Britain;		1400 ly/day
over the Gulf of Alaska		2200 ly/day

Forward estimates of Man's heat output, "ultimately" reaching 3×10^{14} watts with a population of 20,000 million (2×10^{10}), are equivalent to an output of 4.1 ly/day averaged over all the land areas and possibly 78 ly/day over substantial areas within the greatest concentrations mapped by Washington [19] (eastern, southern, and southwestern U. S. A.; central America; eastern South America and across that continent in 31-35°S; Europe south of 60°N, with north-west Africa; 25-60°N in the sector 30-50°E; Siberia between 50 and 60°N to 95°E; Persia-Afghanistan-Indian subcontinent; China, Japan, and all east Asia between the equator and 50°N; Indonesia; a strip of southern Australia with New Zealand; and the Republic of South Africa).

Contributions from Empirical Climatology and Direct Observation

The Present-Day Urban Print-Sources

Observations within the great cities with populations over 1 million in the temperate zone indicate that average temperatures there over the year now (i.e., 1950-1970) range from 0.7 to 2.0°C above those prevailing in the immediately surrounding countryside. In cities of similar size in latitudes below about 40° the corresponding figures range from 0.5 to 0.8°C. Extreme values of the urban "heat-island" difference occur under "radiation" conditions with light winds, clear skies, and a vertical lapse rate of temperature which discourages convection; the inner city areas may then be 4 to 5°C warmer than the surrounding countryside on summer afternoons and 5 to 10°C warmer than the surrounding country on clear cold nights.

Increased convection over the urban areas seems to produce greater precipitation totals, up to 10% above the surrounding areas.

As is well known, Man's pollution of the atmosphere with excess moisture in winter and in cold climates, in urban and industrial areas, and near railways, motorways, and airfields, increases the frequency of fogs, though these tend to be lifted off the surface and replaced by a very low stratus of cloud-sheet over the most tightly builtup areas where there is most output of artificially produced heat.

Dispersal of the added heat and moisture is most rapid in conditions of strong wind and vigorous convection.

In general, the addition of heat at the base of the atmosphere tends to promote convection in the atmosphere; addition of heat to the surface of water bodies tends to suppress convection within them and the heat accumulates in the uppermost layers.

The writer is not acquainted with any evidence to suggest that the thermal structure of an airstream is significantly affected after passing over any present-day urban or industrial areas, though numerous examples of the increased burden of particulate matter, noxious gases, and water vapour are well known.

Considerations Relevant to the Larger and Greater Heat (and Moisture) Sources of the Future

Recent discoveries (Bjerknes [1]; Namias [12, 13]; Ratcliffe and Murray [16]) of the influence on the global atmospheric circulation and climate of extensive areas of warmer than normal ocean surface indicate that future inputs of "Man-made" heat on a similar scale might distort the prevailing wind-flow and the distribution of temperatures and precipitation on a hemispheric or global scale.

Namias found that anomalous warming of the uppermost layers of the Pacific Ocean between 25 and 30°N 140-170°W, largely through a weather situation favouring increased insolation and still water during June 1968, amounted to an average additional heat influx of 42 ly/day. In an extension of the area, about 32.5°N, 142.5°W, the anomaly was estimated at 136 ly/day. Sea surface temperature anomalies of up to 3°C developed, and the water temperatures were affected over an area of the order of 4000 km from west to east and 31,000 km south to north and down to 120-150 m depth. This resulted in an extensive warm anomaly which lasted through the following 8 months and apparently induced extra cyclonic developments in the lower middle latitudes over the Pacific in the following winter, with heavy rains in California and snows in Washington and Oregon. Abnormal warmth had set in in much the same ocean area in 1961 and persisted until 1967, apparently repeatedly producing atmospheric circulation patterns which led to wet winters in California and cold winters over the eastern two-thirds of North America and in Europe.

The hemispheric pattern of changes of the prevailing barometric pressure and winds in winter associated with warm sea in this area of the central N. Pacific has recently been published by Farmer [4].

Similar hemisphere-wide patterns of influence on the prevailing winds, temperatures, and downput of rain and snow associated with warm or cold sea in the western North Atlantic, on time scales from a few months to over 70 years, have been published by Ratcliffe and Murray [16] and Lamb [8].

It is thought that the heat budget anomalies are of similar magnitude in the Atlantic and Pacific cases. Both operate in middle latitudes and amount to changes in the extent of warm water at the edge of the principal warm ocean currents. The effect is presumed to be due to increased heating differentials across the jet stream and additional energizing of the circulation by release of latent heat of condensation downstream, affecting the convective activity. Greatest effects in terms of surface winds and weather are found 2000-4000 km farther east (i.e., downstream in the sense of the upper winds) and occasionally in resonance areas spaced around the hemisphere.

Anomalies of similarly great magnitudes and even greater extent (order of 10,000 km east-west by 500 km north-south) develop in some years along the equator in the Pacific Ocean. Bjerknes [1] has shown empirically, and Rowntree [17] has tested by simulation with a dynamical model atmosphere, that the warm sea situation in this area tends to intensify the jet streams in a low latitude, particularly in the Pacific sector (and to favour increased anti-cyclonic development over both polar regions).

Artificial heat sources of comparable intensity might be expected to have similar effects, particularly if they were aligned zonally (west-east) along the prevailing drifts of the atmosphere and if they were accompanied by the supply of additional moisture. It may also be important that the additional heat input should be either (a) close to the warm side of the middle latitudes jet streams, or (b) in the region of tropical/equatorial convergence and convective activity. All these conditions, including the geographical stipulation (a), should apply to the population area covering Euoope and western Asia, as well as China in winter. The same is true, with stipulation (b), in the case of India in summer. The conditions are less clearly satisfied by the population areas in the Americas, which are more meridionally aligned, so that the prevailing drifts of the atmosphere cross them on short routes.

The lesson seems to be that large-scale deviations of the wind circulation and the steering of rain-giving disturbances, and the production of regional (if not global) anomalies of heat and cold, may arise at just as early a stage as the temperature anomalies become significant in the primary producing areas. An increased heat input in latitudes where the rate of convective vertical exchange of heat within the atmosphere would be immediately increased should lead most readily to increased escape of heat by long-wave radiation to space.

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Discussion

One of the participants noted that people at the (U.S.) National Center for Atmospheric Research were including consideration of man-made sources of heat in their work. He referred to Mr. Lamb's comment that climatology has been "dead" in the recent past but is now receiving new interest. He suggested that one of IIASA's functions might be to help maintain pressure for development of this field. He asked Mr. Lamb whether it would be possible to have more reliable answers for these problems in ten years if resources were freely available. Mr. Lamb, noting that he was giving a personal opinion, responded that great improvements could be expected in our knowledge following a combination of theoretical and observational attacks. His questioner noted that the world is placing great responsibility on climatologists; it would be awkward if their answers were wrong. Mr. Lamb agreed, adding that today we can say that natural variations of the order of one-half or one degree centigrade have great dislocating effects on the human economy; the discussion included mention of changes an order of magnitude greater.

Mr. Haefele commented that we do not have much lead time for our energy decisions, which he could readily imagine would depend upon climatological considerations. We have perhaps ten years left for the major decisions and hence ten years to understand all of the relevant factors. Secondly, he recalled the close interaction between water, energy, and weather and remarked that even if global climate does not change very much, patterns of weather, such as rainfall, may be easier to influence. Mr. Lamb agreed and said that studies of natural weather anomalies support this conclusion. Mr. Haefele added that effects on the economy might appear even sooner than effects on the climate. The questioner asked whether efforts in climatology were limited by the amount of available money. Mr. Lamb said that this was clearly the case. The United States has begun to invest heavily in this research, especially for long-term climate reconstructions. The Wisconsin Center is attracting funding. However, his own unit may well close in 1975 for lack of money, and it is the only unit working on the period for which we have the most data. Modelling is receiving about as much support as it needs. The observational, or data acquisition, side needs help.

Someone agreed with the point and noted that there is disagreement on data. He reminded the group that there are two aspects to be considered simultaneously: climatological changes caused by nature and inadvertently influenced by man, and artificial, intentional modifications of the climate. Man is near the point where he can maintain the climate at an "acceptable" level; the problem is defining acceptable. WMO has groups working on both aspects. Mr. Haefele interjected that man would do well to understand the climate before trying to change it.

Mr. Raiffa commented on the remark that IIASA might encourage interest in this field. He said he could easily envision having one or two meteorologists at IIASA and issuing ringing proclamations, but he was unsure how much this would help. The planning symposium for the organization project had suggested that IIASA might investigate which other organizations are researching these areas and then design new organizations to handle these problems. It could serve a mid-wife role. The participant who made the remark replied that climatology is an example of an extremely important problem that, in part because of its importance, "falls between the chairs." He urged encouragement of such work through the national member organizations. Mr. Raiffa remarked that it was unclear to him how this could be done. In any case, IIASA could not do climatological work itself.

Mr. Haefele noted that IIASA minimally requires an internal capacity to understand various fields and their relationships to the research projects. For example, there should be at least one or two economic modellers able to identify problems, to articulate the right questions, and to direct these problems to the appropriate disciplines. The same holds true for climatology. Mr. Raiffa concurred and suggested that IIASA might also be effective by holding conferences on rather specific topics. Mr. Haefele replied that once questions are identified, a working group might be convened to make sure the in-house specialists have not erred. Mr. Raiffa suggested having a meteorologist at IIASA as a scientific administrator to convene such conferences and to keep interest alive. One of the participants agreed and added that the study group on thermal pollution at the University of Essen in Starnberg decided that the influence of energy on the climate is important. No climatologists were at this meeting, so a new group was convened. Mr. Raiffa said that in doing any of this it would be critical to develop contacts with organizations like WMO. He asked for suggestions on methods of developing such contacts.

One participant remarked that his experiences with international organizations suggested that it would be wise to hire a short term expert to draw up a program, especially for research in cross-cutting fields, more especially if other experts are available for consultation. The consultant would have a limited task with a time limit and could draw up a coherent program that would fit into its research environment.

Someone else said that his experience in international organizations argues against relying upon meeting of experts. Such reliance means that the staff spends all of its time organizing meetings; one does need expertise for this task. The most convenient way to obtain the necessary advice is to hire an expert on a short term basis for a specific, detailed job. The length of time is a function of the need for his expertise. In the case of climatology, two or three years would be reasonable, but this then is just the normal length of a IIASA appointment.

Mr. Lamb mentioned that WMO is contemplating sponsoring a symposium on climatic fluctuations and the future of our climate. Twice in the past decade they have established a working group on climatic fluctuations.

Embedding Energy in the Environment

P. C. Roberts

Nature of the Problem

The processes of energy production and energy consumption give rise to deleterious effects manifesting as specific pollutants, noise, visual intrusion, and accident risk. Analysis which seeks optimal management of the production and consumption processes must take into account not only the markedly non-linear relationships which exist, but also rapid change occurring in time. It is suggested that these complexities demand advancements in analytical technique beyond the current state of mathematical programming. The use of extended input/output tables which has been proposed is not well suited to handling the non-linearities which must be encompassed.

Structure

For consideration of the interactions, it is convenient to reduce the variables to three:

1. Total energy flow produced or consumed.

2. Cost of abatement measures.

3. Extent of disbenefit.

In pursuit of generality in the structure, the total energy flow can be either that produced or consumed, in either a local or global context. The actual sources of energy, whether carboniferous, fissile, or solar yield different disbenefits and require different abatement measures but do not affect the categorisation. Disbenefit is less well defined than the other two variables, and though it may be preferable ultimately to reduce this to a monetary measure it is convenient to think of it as a definite pollutant level, e.g., the concentration of sulphur dioxide in the atmosphere.

The expected relations between the variables are shown by the full lines in Figure 1. The reasoning behind this figure can be illustrated from a coal burning power station.

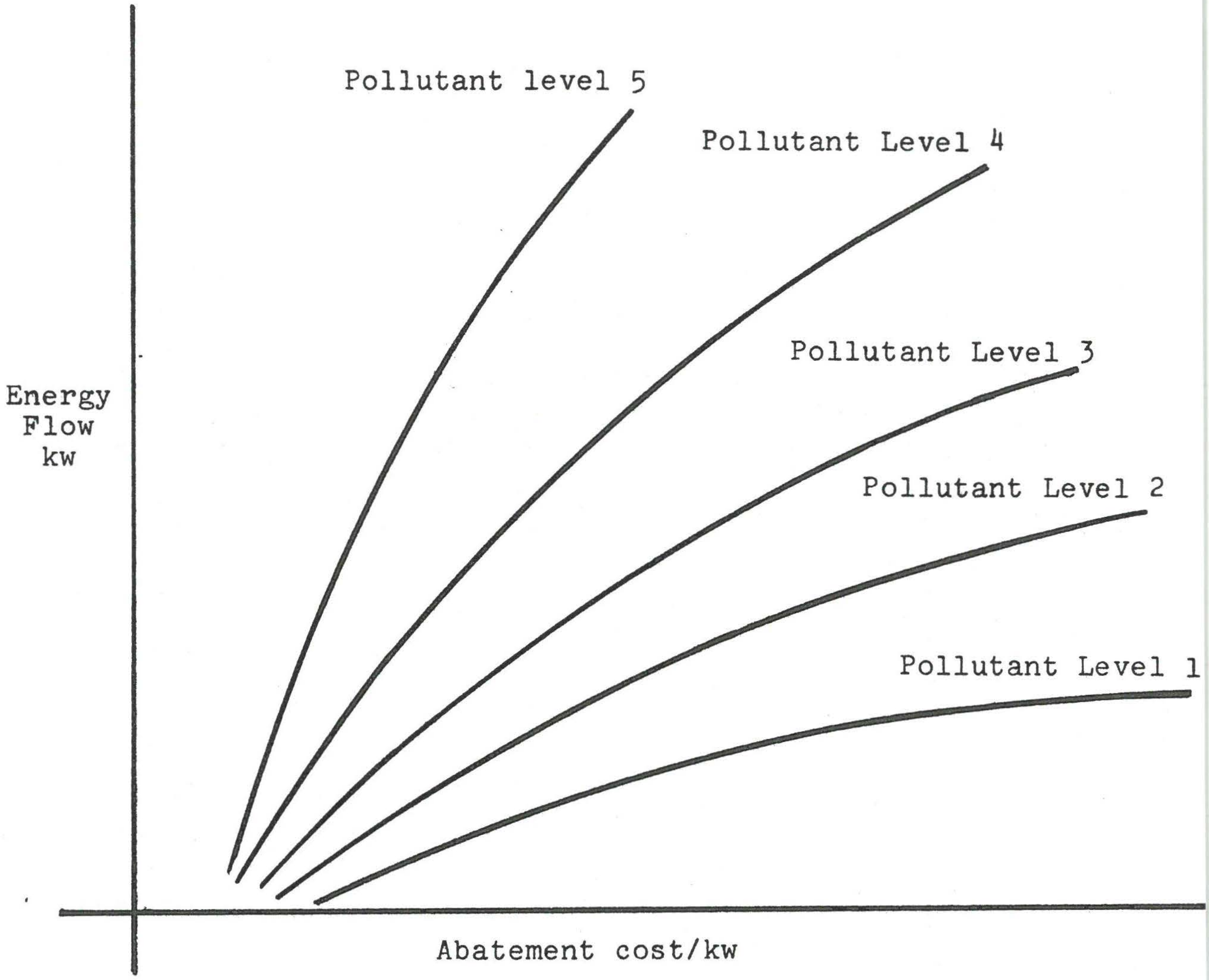


Figure 1

Suppose that 95% of the sulphur is extracted and 5% appears in the flue gases. If four more such power plants are sited in the same locale with the same extraction efficiency and the same cost of extraction, this will correspond to a movement in the figure, parallel to the vertical axis with five times as much energy produced at the same cost of abatement/kw and generating a higher pollutant level in the atmosphere. Alternatively, the extraction may be improved so that 95% of the sulphur is removed and only 1% escapes, but from five power plants, thereby maintaining the atmospheric pollutant level the same as initially. This corresponds to a movement along one of the full (isopol) lines of the figure with cost/kw increasing more than five times because of the increasing technical difficulty of pushing extraction rates towards 100%. The isopol lines are shown with decreasing gradients because for all deleterious effects, the cost per unit of energy flow in consumption or production increases more than proportionately with increased energy flow to retain the environmental impact constant.

In general, we observe that the attitude of society requires progress parallel to the vertical axis (increased energy flow) to be accompanied by additional effort in averting the undesirable side effects. In Figure 2 the vertical broken line is unacceptable. The curved broken line represents a series of possible tradeoffs between the increasing disbenefits as energy flow rises and the cost penalty of abatement.

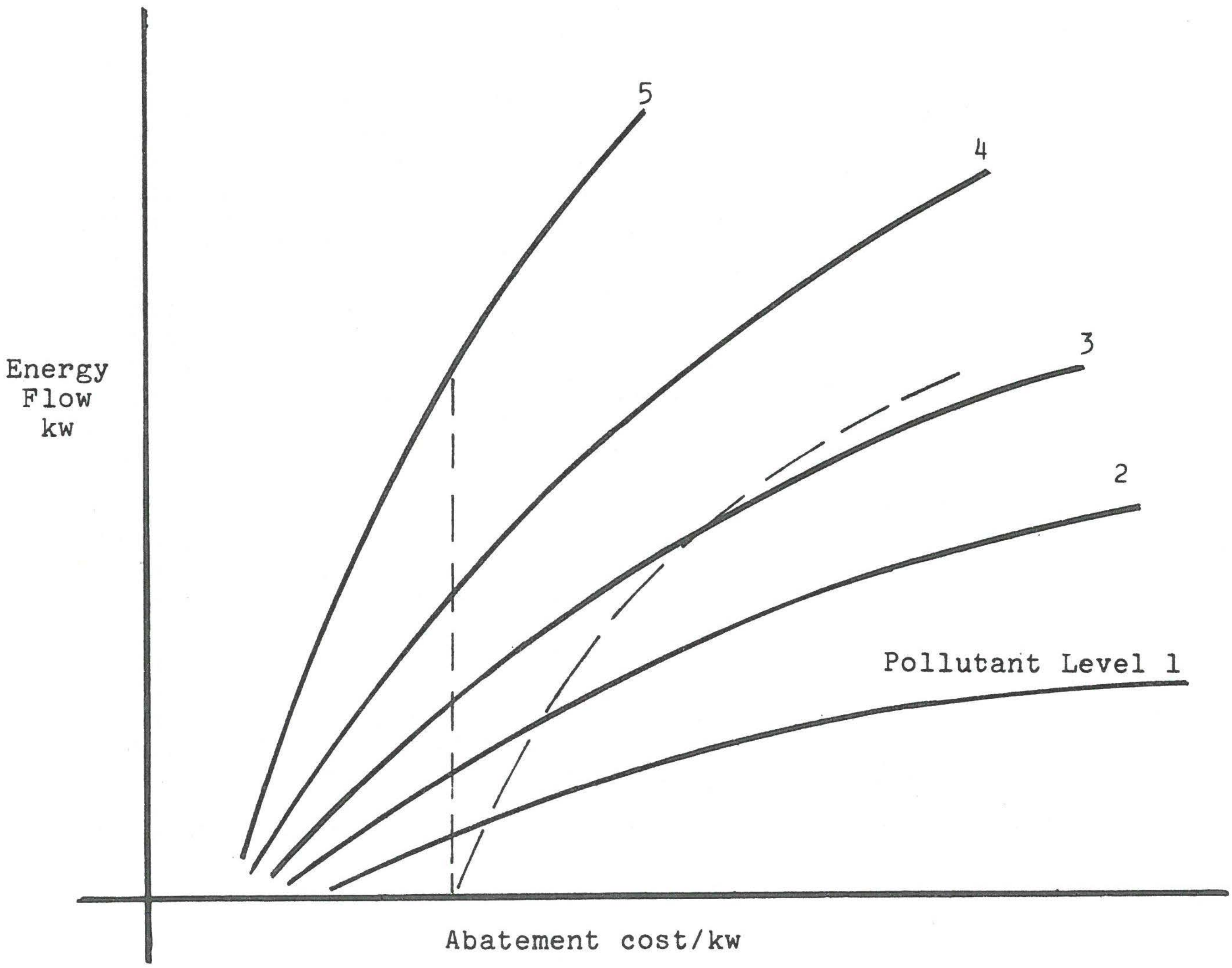


Figure 2

Tolerance Level

If it were possible to define, in monetary terms, the disbenefit associated with specified pollutant concentrations, the optimal management policy, for a given state of abatement technology, could be deduced. However, the response to a deteriorating environment is complicated by three identifiable factors.

1. Habituation towards a slow decline of environmental quality is a readily observable phenomenon. In the case of noise this may occur not only from the natural process of adjustment to change, but also from physical damage to the hearing mechanism which actually reduces the sensation experienced when exposure to loud noise occurs. Provided that the onset of noise, ugliness, filth, or danger is slow (possibly over generations), the ability of the human animal to habituate to it is truly remarkable.

2. The term "cognitive dissonance" has been coined to define the disparity between an individual's belief concerning his environment and the objective state of it. For example, there is a disbenefit associated with coal mining, in that the miners risk pneumoconiosis. The miners' appreciation of this risk was at variance with the risk now being established accurately by the accumulation of records over some decades. In the same way it is difficult for laymen to appreciate the risk associated with the diffusion of radioactive products into the environment. Cognitive dissonance tends to become smaller as records accumulate and dissemination of information permits people to be better informed.

3. Changing attitudes to tolerable environmental states are most obviously related to affluence. An individual enjoying adequate standards of food, housing, welfare, and leisure evidently prefers to spend his surplus purchasing power on quietness, cleanliness, safety, and elegance.

It is necessary to make assumptions about the tradeoffs that will be made in the future as a result of these three separate effects progressing simultaneously. The first operates in reverse sense to the second and third, and the combined effect is particularly difficult to estimate for operating decisions with repercussions into the distant future (for example, the storage of long-lived isotopes in waste from nuclear power stations.)

Strategy for the Analytical Approach

It would appear to be well worthwhile to quantify the diagram of Figure 1 for differing sources and for differing types of disbenefit. The envelope of feasible trajectories corresponding to the broken line of Figure 2 can be calculated from maximum acceptable costs on the one hand and maximum acceptable disbenefit levels on the other. It is likely that further constraints can be used to define the trajectories based on the conjecture or rising expectations in respect to a safer, cleaner environment. Experience suggests that the requirement will be not necessarily for an absolute improvement but for a greater return, i.e., the ratio of useful additional energy to worsening of the environment must itself be increasing.

Whether this concept can be justified or not, the structure proposed provides a framework to simulate possible trajectories and thereby facilitate an improved basis for decision making.

Discussion

During the talk, a more precise definition of "E/C" was requested. Mr. Roberts explained that C included all energy used in constructing a power station including, for example, steam to operate the cement plant and E includes all energy coming out of the station. The units are one over time.

Someone began the discussion by agreeing that the problem of affluence is globally important and not only in the context of energy.

Someone else added a fourth item to Mr. Robert's list of means of accomodation, namely, the development of technologies to minimize deleterious side effects. If cancer were as curable as pneumonia, the reaction to nuclear energy might be different. Mr. Roberts was skeptical on the grounds that such compensatory measures "sweep the problem under the rug." One can insulate buildings against sound and then allow airports to get noisier, but people go outside, too.

One participant remarked that all of these models, including those of the Club of Rome and of the Blueprint for Survival, are based on the assumption that technology is not changing. It is difficult to forecast how it will change. All of the models also assume that technology necessarily has waste. However, there are wasteless technologies that incorporate the recycling of materials into the technological cycle. In those cases, there is less need to pay to fight pollution. He asked Mr. Roberts for his opinion of these technologies that remove elements throughout the process for use by neighboring technologies. Mr. Roberts said that we have the ideal model for such a wasteless economy in nature itself. It is obvious from the 600 million year history of plants and animals that they have been recycling with no "pollution", if we assume that all life is equally valuable. If we want a wasteless technology, we could model on the natural system; we could design artifacts for recycling and slow down to the speed of nature, where the fastest animal, the cheetah, moves at 60 miles per hour.

Another participant added that we must define what we mean by waste. A power station itself is a waste; we simply want the energy it produces for something else. It seems that we are using more and more energy, but less and less useful energy; unless energy is inexhaustible, this is insupportable. Only solar energy is really unlimited. Even fission and fusion are finite, implying an ultimate collapse, even assuming consumption levels off. One can alter the asymptomic value by accepting higher levels of pollution. Mr. Roberts replied that certainly the asymptomic value depends upon your assumptions; he had assumed an energy consumption of one percent of solar energy. One could go higher, for example to the situation where the ice caps would melt.

His assumption was just to allow a sketch of orders of magnitude. However, it did seem to him that no responsible planet would knowingly alter its climate drastically. He referred to the question of waste to say that surely all energy from power plants is ultimately waste, but that this is equivalent to saying that the planet is polluted by humans. It is entirely a question of point of view. His questioner replied that, to the individual, affluence is what one can do. Each person wants power stations for what they can do for him. As power stations convert our energy into capital, the question is what price we are willing to pay for energy.

Another participant pointed out that Mr. Haefele had said that the supply of nuclear energy is immense. The last speaker said he thought the figure was 200 years, but the participant replied that it is closer to one million years at ten Q based on Mr. Haefele's price assumptions. The earlier speaker responded that the previous night Mr. Oshima had indicated that Japan would use one-fifth of the world's proven reserves by 1990. The response was that the breeder reactor makes even common rocks into energy reserves. Mr. Haefele noted that there is confusion about what reserves are; their definition depends on social and economic conditions. Moreover, breeder fuel represents only .1% of busbar (electricity generating costs) cost rather than 10% for a non-breeder reactor. Thus, one could pay even 1000 dollars per pound for ore without great economic effect. The breeder multiplies reserves considered for a LWR by a factor of 50 or 100. But the point is that the FBR exploits the fuel better. It burns everything and thereby multiplies the reserves not by a factor of 50 or 100 but of 50 000 or 100 000.

Materials Accountability and Pollution Control

Robert Skjoeldebrand and Rudolf Avenhaus *

Abstract

An attempt has been made in this presentation to show the analogies which could exist between an environmental pollutant accountability and the requirements on plant operators for the existing and functioning IAEA safeguards system. For this purpose the relevant features of the IAEA safeguards system have been outlined, especially the basic mathematical concept of the material balance and the organization of the system based on this concept. The case of single pollutants in isolated plants is discussed in some detail as in this case the closest similarity to the existing system is to be found. The treatment of different plants and different pollutants raises the question of appropriate standards. Pollutants accountability in a region poses new problems because of lack of data; mathematical modeling of atmospheric processes becomes necessary. Economic consequences of constraints imposed for environmental reasons have to be analysed. The presentation concludes with some remarks on the political feasibility of a global pollutants accountability system as already envisioned by some scientists.

*The authors are indebted to Dr. W. Haefele of IIASA and Dr. D. Jacobs and Dr. J.T. Roberts of IAEA for help and valuable suggestions.

Introduction

As has been stressed in the first paper of this conference [1] the embedding of energy in the environment is one important aspect of any consideration of energy systems. Especially the accountability approach to pollution control has been regarded as a valid tool in that connection (see e.g., Ref. [2]) and shall be outlined in the following.

In the introduction of Ref. [1] it has been mentioned that quantification is mostly not problematic for energy systems. At least in the case of the environmental impact of pollution this is not true as proven by the wide ranging and often inconclusive arguments raised. Therefore, in this case there is in particular a need for a good mathematical model for a systems analytical approach.

The analogy of the accountability approach to pollution control with the application of international safeguards to nuclear materials which could be used for nuclear weapons has been pointed out several times (see, e.g. Ref. [3]). This analogy is quite striking particularly if considered from the point of view of the operator of a plant, whether it be a plutonium fuel fabrication or a thermal power station. In both cases it is a question of keeping potentially harmful products under control while performing a legitimate and beneficial process. Furthermore, pollution in the last instance is an international and a global problem as would be the loss of significant quantities of plutonium.

In the latter case there exists an international safeguards system which is now in operation and it may therefore be interesting to review its elements. It is important to note that the new IAEA safeguards system was developed to meet the requirements of the Non-proliferation Treaty through an international effort both on technical and political levels. There existed an old safeguards system against which criticism has been raised because:

a) It had no clear formulation of technical objectives

b) operators and states could fear openendedness in application

c) there was some fear for arbitrariness in its application.

Thus an effort grew when UN commended the Non-proliferation Treaty in 1969 to reshape the old IAEA safeguards system. It had been emphasized from the beginning that a systems analytical approach was necessary [4], [5]. At different places in the world considerable development work was spent, consolidated through IAEA panels and working group meetings. These efforts culminated in the work of the Safeguards committee of the IAEA which met with interruptions from summer 1969 to autumn 1970 and represented a unique process of working out a document for a political model agreement which is still very much technical in base [6].

The IAEA Safeguards System

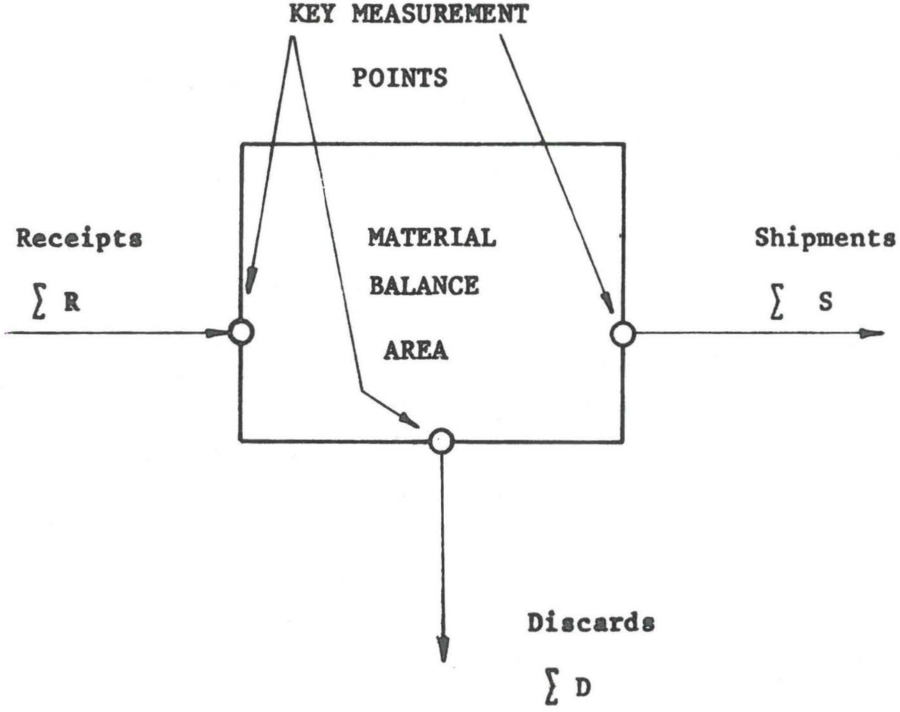
The three basic measures of the IAEA safeguards system are [7]:

- Material accountancy
- Containment
- Surveillance.

The first of these three measures has been recognized to be a measure of fundamental importance with the other two as important complementary measures. As material accountancy is of special interest in the context of this paper it will be considered exclusively in the following. Special emphasis will be laid on the difference between the plant level of material accountancy being the first requirement on any operator of a plant processing or using safeguarded material and the organization of the IAEA system in general.

The first step in the establishment of a materials accountability system on a plant level is to define an area which may or may not coincide with geographical boundaries of a plant for which the quantity of nuclear material in each transfer into or out of the area can be determined and the physical inventory can be determined when necessary. For this material balance area (MBA) key measurement points (KMP) have to be defined where the flow or inventory of nuclear material may be measures in an appropriate way.

Once the quantity of material in a MBA is determined a book inventory may be maintained by recording measured flows into and out of the area at the appropriate KMP's. At the end of an inventory period a physical inventory is taken; the correspondence between the nuclear material contents of the MBA on paper and in fact is the basis for judging whether or not any material is unaccounted for (see Fig. 1). There are many reasons for a non-zero difference between the book and the physical inventory: hidden inventories, unmeasured losses, measurement uncertainties and diversion. Therefore, statistical techniques have to be applied for judging whether or not a difference is significant with respect to a potential diversion.



time t_o :

Beginning Physical Inventory PI_o

time t_1 :

Book Inventory

$BI = PI_o + \sum R - \sum S - \sum D$

Ending Physical Inventory PI_1

$MUF = BI - PI_1$

Fig. 1 : The Material Balance Concept

This formalism can be and is applied to a variety of situations (reactors, stores, fabrication plants, reprocessing plants, enrichment plants, etc.); different approaches have been developed for specific cases as itemized units, process areas, low flow-high inventory or high flow-low inventory.

The MBA formalism is extremely simple in the case of a singl MBA and a single inventory period but it becomes complicated if one tries to interlink different inventory periods or different MBA's in a country with an advanced fuel cycle as such a procedure is normally accompanied by an increase of the uncertainty of the statement.

However, what is even more important for the IAEA international safeguards system which is now functioning, is the fact that this MBA formalism could be internationally accepted, as it has been. Additionally, this formalism provided the basis for all safeguards studies, both in selection to how safeguards was to be applied and, e.g. future manpower requirements for verification.

The IAEA safeguards system as it is organized now consists of three basic elements:

First, some requirements for the operator of a plant are required, which form the basis of the safeguards system, viz:

- Definition of MBA's

- Establishment of a system of measurement or other determination of nuclear material contents; and

- Keeping of appropriate records for materials accountability, closing of materials balances by taking physical inventories and evaluation of MUF, hidden inventories and losses.

Second, the national or regional safeguards authority submits the information to the IAEA. This information includes those features of the design of a nuclear plant which are relevant to safeguards application; especially, however, it includes data on all inventory changes in all MBA's and all physical inventory takings. This world-wide reporting of material data is now established and functioning. The national or regional authority may or may not have its own independant verification function.

Third, the verification of this information through inspections carried through by authorized IAEA inspectors. Here, the question of inspection effort becomes a central problem.

The way how this safeguards system has to be and was analyzed from a systems point of view has been described in Ref. [8]. Without going into the details of that considerations only the question of efficiency shall be mentioned. Efficiency has been defined as the relation of the guaranteed probability of detection, the material assumed to be diverted, the false alarm rate chosen and the effort spent [9]. The emphasis on the guaranteed probability of detection means that the fact has to be taken into account that the operator will divert material in a sophisticated way, if he will divert at all therefore, the minimum of the probability of detection with respect to all possible diversion strategies, has to be determined. An example for a simple case (one MBA, one inventory period) has been given in Fig. 2.

In the framework of the consideration given above one may state that the problem of safeguards ultimately can be formulated in terms of some few parameters however, that there are not enough equations for determining the values of all parameters (in our example, one equation for four parameters). Thus, the values of some ultimate parameters have to be fixed in a subjective way.

Pollutants Accountability in the Single Plant Case

It is evident that the MBA formalism described above can be applied for accounting for pollutants from industrial plants.

Consider the case of an oil fired power plant. Here, sulphur comes in with the oil, it leaves the plant in form of SO_2 together with the offgases through the stack if there are no filters which keep the SO_2. If there are filters, then a certain percentage of the sulphur is removed from the offgas however, it is kept in the filters and one has to ask where the sulphur goes therefrom. If there is an oil desulphurization foreseen - which transforms a power plant into a chemical facility [10] - then the sulphur is kept in form of some chemical compounds before the oil goes into the process and one has to ask what happens to these chemical compounds. In any case it is important to observe the flow of the sulphur including the final deposition of the sulphur compounds removed from the offgas or from the oil otherwise one would have kept the sulphur out of the air but sent it eventually in form of chemical discards into the groundwater, in other words one would not change the final effect.

It is obvious that the establishment of a material balance for the sulphur in an oil fired power plant is very similar to the case of the plutonium material balance in a reprocessing plant. More specifically one has a high flow-low inventory situation in case the deposited sulphur is not taken into account.

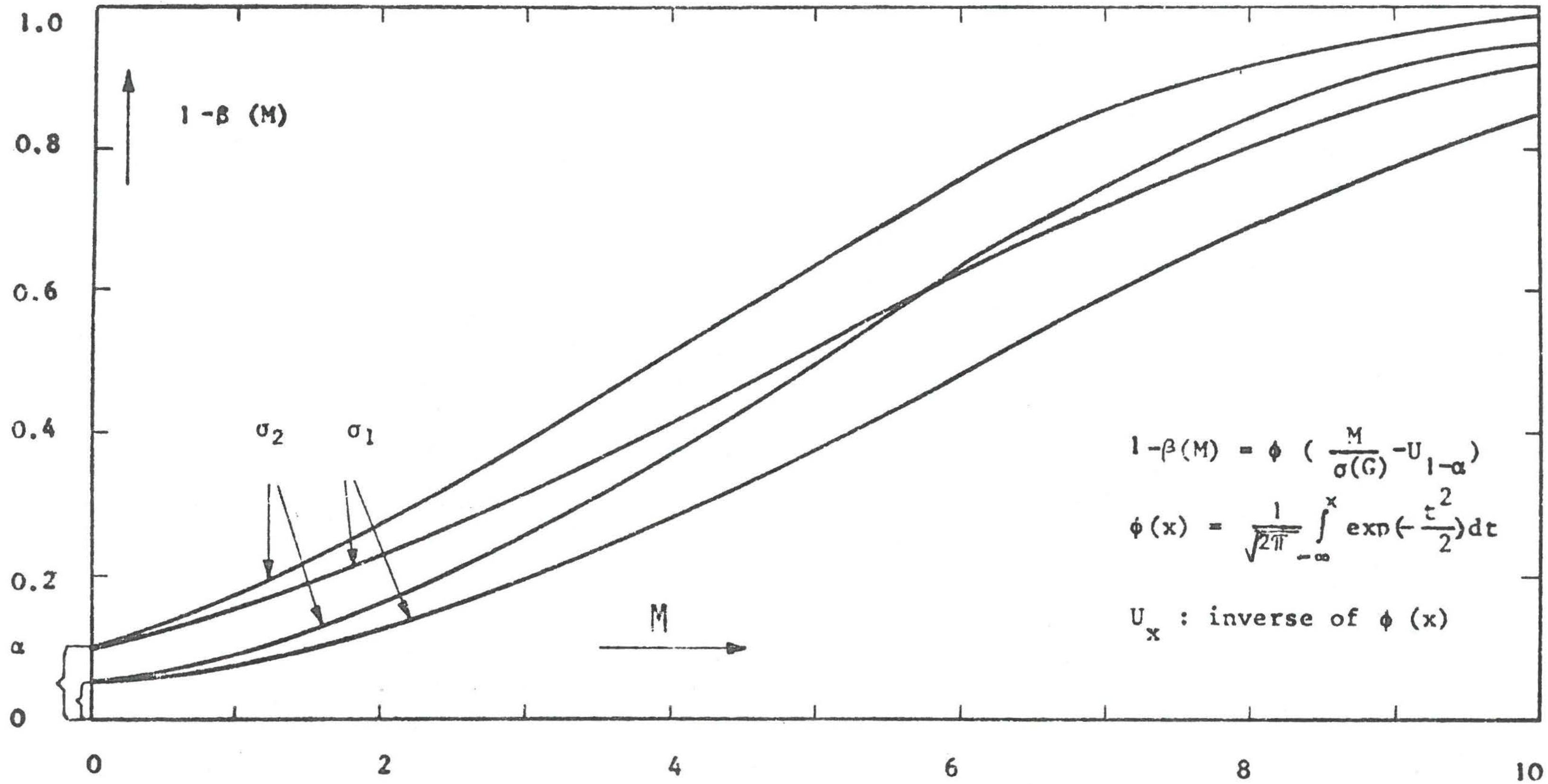


Fig. 2: Effectivity of a Safeguards System (power curve)

Typical relation between the parameters probability of detection $1-\beta(M)$, amount M assumed to be diverted, false alarm probability α and effort G, for the case of one material balance area and one inventory period ($\sigma_1 = 3.75$, $\sigma_2 = 3.03$)

The final element of the verification of the material balance through inspections which is so important in the safeguards case may at the present stage not be relevant to the discussion of pollutant accountability. At present it is not so much the fear that more SO_2 is released to the atmosphere than it is permitted, the problem is that "our knowledge of the flow of materials through the economic system and their loss or purposeful discharge to the environment is extremely limited, especially with respect to the industry" [11]. Only in case strict standards for the emission of pollutants are set up which may impose an economical burden to the plant operators the question of illegal release of pollutants and therefore, of the verification of data may become important.

The question of standards cannot be solved for an isolated plant, the situation of the environment has to be taken into account. In order to illustrate this Table 1 is given which shows the emission of different pollutants in g per KWh produced [12]. It is clear that the application of the same standards to different plants would cause a heavy economical burden to some of the plants. The desulphurization of coal directly e.g. is not possible at all.

Thus, a balance between the disadvantages caused by the pollutants on the one hand and the burden to the different plants, caused by strict standards has to be found.

Additionally, the problem arises to compare different pollutants. A first attempt has been made in Ref. [13] where the damages caused by different pollutants were compared on the basis of the relation of actual emission and maximum emission allowed for. This procedure however, turns the problem to the problem of establishment of appropriate standards for different pollutants. Work on standards is progressing (US EPA Air quality standards, German VDI Handbook Reinhaltung der Luft, WHO Long-term goals), but a consistent scheme has not yet been reached.

It should be noted that in the safeguards case a similar problem had to be solved when different nuclear material (low and high enriched uranium, plutonium) had to be compared. This led to the concept of "effective kilogram" [6].

Pollutants Accountability in a Region

Looking at the different pollutants produced by the electrical industry alone (see Fig. 3), it is clear that the balancing of all the pollutants in a region requires methods completely different to those applied in the case of a single plant. Additionally, there are further difficulties which shall be detailed in the following:

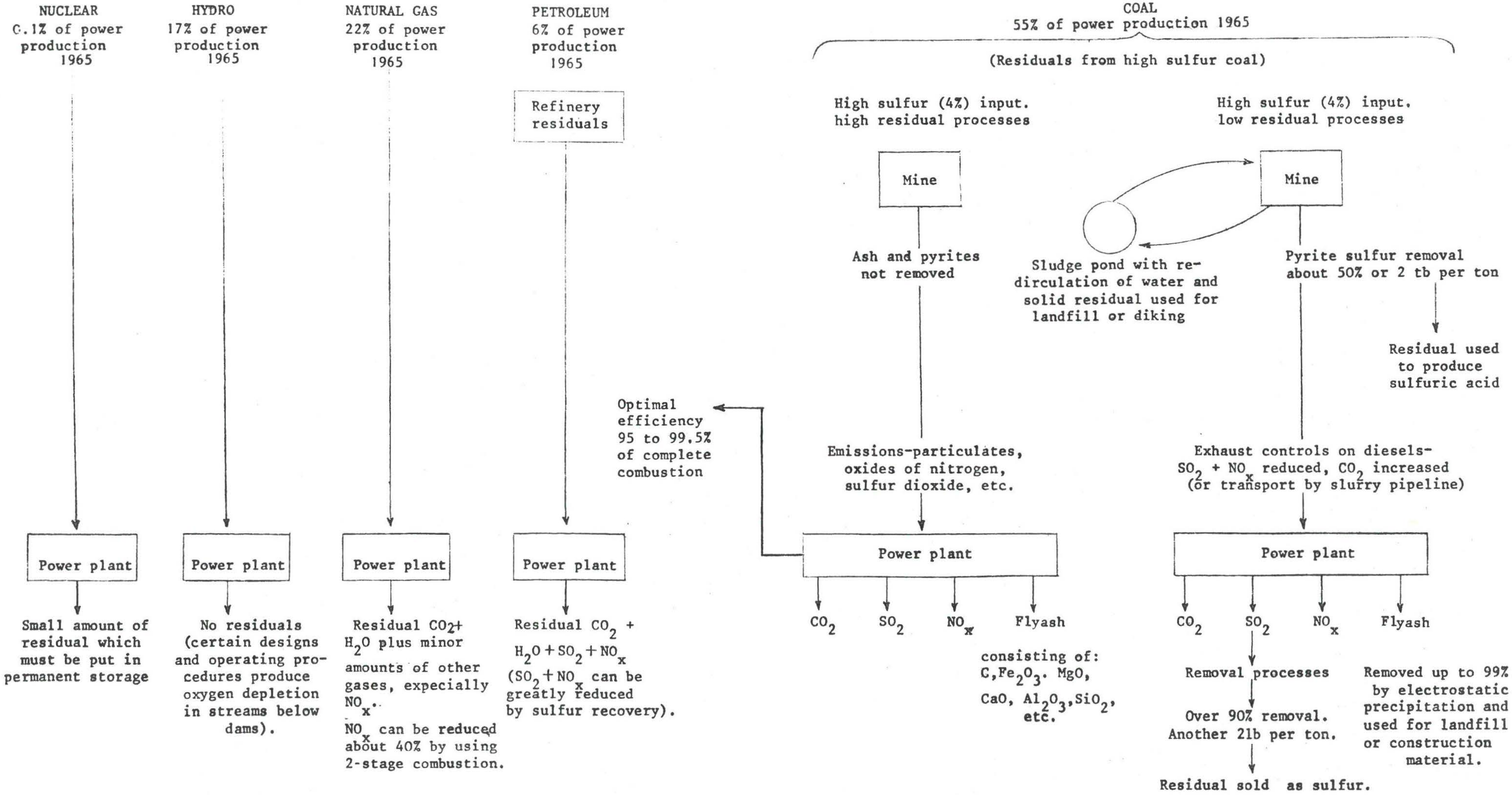


Fig. 3 : Residuals from the Thermal Electric Industry

(Source: Kneese, Ayres, D'Arge: Economics and the Environment)

fuel	SO_2	particles	NO_x	Fluor
Coal	6.0	1.4	2.1	0.05
	7.7	2.7	3.45	0.11
Oil	7.4	0.7	2.45	0.004
Gas	0.002	-	1.9	-

Tab. 1 : Power plant Emissions in g Pollutant per KWh

(Source : Buker e.a., Kernenergie und Umwelt)

Consider the air volume of a given region as a material balance area in the sense described earlier. To establish a material balance for the pollutants in this material balance area means to determine:

a) the inputs over a given period of time (i.e. all the emissions into that volume)

b) the outputs over a given period of time (i.e. the removals by washing out by rainfalls, decays, etc.)

c) the physical inventory at the beginning and at the end of an inventory period.

Now the problem is the following:

The inputs can be measured at least in cases where they come from point sources (e.g. facilities), they can be estimated to a fairly good degree in the case they come from spread sources, e.g. from households or from transportation by estimating the members of e.g. households and cars and their average emission.

The inventory can be measured by means of monitoring systems as they are already established in certain regions (Los Angeles, Ruhr area, etc.) it is only the question whether or not all pollutants are measured and what is the measurement accuracy. A broad review of monitoring problems of this kind is given in Ref. [14]. The outputs can not be measured directly and the production of new pollutants by synergistic effects (e.g. smog formation) cannot be measured directly.

One may argue that one can evaluate the outputs over a certain period of time by determining the difference between beginning inventory plus inputs minus ending inventory however, that is not in the sense of the material balance as one never gets full knowledge on the processes involved.

In the case of safeguards this is a well known problem: In many cases waste has not been measured directly but determined "by difference" of measured throughput and physical inventory. Losses or diversion then never can be detected by definition.

What is necessary for the solution of this problem in case of environmental accountability is a physical (better meteorological or hydrological) model which describes the processes of formation and decay as well as washing out of pollutants in and from the atmosphere. Once such a model has been fully established it can take the place of the missing "output" measurements.

However, such models have to be tested and in principle they can be tested only if a complete measurement system is available. This problem can be solved only by an iterative process.

Models of the type postulated above have been started already for different regions, e.g. the Ruhr area [12], and the Tennessee Valley Region [15], [16]. Models are very complex but still have some great simplification, e.g. in centroid treatment of population distribution and doses. Other regional models make very great simplifications and it is very difficult to judge their validity.

Economic Aspects

It is only after mastering the problems of standards and models that one can get a better idea of emission constraints for individual plant and regional levels. Constraints however, will lead immediately to costs.

One example is the fact that already today oil fired plants have to keep a certain amount of oil with low sulphur content which has to be used if the conditions of the weather are extremely unfavourable [10]. The desulphurization of oil has been estimated to cost 50 c/bbl%S $\hat{=}$ 10c/MBT%S with Middle Eastern crudes containing 1.5 - 3% S [17].

This example may serve to highlight some additional basically economic questions as

- any desulphurization equipment is costly therefore, a longer utilization of the plant is necessary;
- there is a strong size cost degression which results in a bigger plant trend.

The obvious final solution of the sulphur problem is refinery desulphurization. However, this would result today in an annual production of 50 Mt S. The world market today is only 31 Mt S. Thus, the question rises where these amounts of sulphur will end up.

This general situation is somewhat different from the specific case of the nuclear power production and the nuclear industry connected with it. Here, the essential constraints were firmly established from the start for safety and protection, also the basic requirement was placed on the operator to measure and account for his actions (strict liability principle).

It is interesting to note that in that situation the introduction of safeguards did not mean much in practical additional requirements or costs, 2% in kWh cost is probably a high estimate.

A similar picture is expected for conventional energy users: the imposition of a material accountability requirement would cost very little compared to what the emission controls would cost.

A larger number of attempts have been started now to include the environmental aspects of energy production into economic considerations. A review on the state in this special field is presented in Ref. [18].

There is one approach that deserves special interest as it can be considered to a certain degree as the translation of the accountability idea into the area of economic modeling: the input-output approach. It has been proposed first by Leontief [19] to take into account environmental aspects within the framework of this aspect. A practical example for this procedure on a regional level has been given in Ref. [20].

Concluding Remarks

An attempt has been made in this presentation to show the analogies which could exist between the environmental pollutant accountability and the requirements on plant operators for the existing and functioning IAEA safeguards system.

The situation in respect of the latter is that

a) the formalism and the models have proven workable - both for the operator and for the safeguarding authority

b) the measurement and accountability requirements on the operator have proven workable and valuable to him

c) the reporting requirements have proven workable

d) it has been possible to define the verification requirements so that inspections can be performed with an overall reasonable budget (the 1974 budget amounts to a staff of 100 members and US $ 3 M including R & D).

There is a long way to go from a mathematical model to its practical implementation on a local, regional and international scale, not to mention its use in an international verification or control system. However, this is possible, as has been demonstrated in the case of the IAEA safeguards system: the material accountability concept has proven to be a viable basis for an international data collection and verification system.

It has to be stressed that there was an international political urgency which called for setting up the IAEA safeguards system. The urgency may not be the same in environmental pollution control if one remembers the problems of establishing a register of radioactive waste discharges.

It is too early still, for a discussion of an implementation of an international pollutant accountability system although it has been envisaged already by some scientists [21]. The material balance model is a workable one also for pollutants control in industrial plants although it lacks some elements; even in case the data basis exists, there may be difficulties to get at it.

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Discussion

Mr. Raiffa asked whether the written documents contained material on the political process involved in making the required subjective estimates. Mr. Haefele said that this topic did not appear here but was treated in a paper written for the 1971 Geneva conference on the peaceful application of nuclear energy.

Mr. Avenhaus was asked whether there had been any attempt to study extant stock-keeping systems. In the speaker's experience as a consultant to one, great leakages occur for no apparent reason. He suggested looking at hospitals and heroin, or at institutions that deal with precious metals, to determine the parameters on a more empirical basis. Mr. Avenhaus replied that his group had received estimates from the German firm DEGUSSA which handles gold and silver. They only keep a careful book inventory, but have no physical inventory. The questioner commented that there are other groups which do do physical stocktaking. Mr. Skjoeldebrand replied that they had looked at procedures used elsewhere for sensitive materials. The sad fact was that these procedures were often incomplete. One advantage of the safeguard system is that it has logical and firm requirements; this is an innovation. It was asked whether Mr. Skjoeldebrand meant that this system is superior to anything used previously. Mr. Haefele said yes, and explained that, because of the political environment, formalism was necessary. Prudence had to be made tangible.

Another participant noted that a problem with an inventory scheme for a reactor is that if you measure twice, the errors are large relative to the amount of releases that would occur. From the normal decay process there is a release of 10^{-5} per month. This is true unless you measure at the point of release, which would make the most sense in any case as the greatest risk lies there. Mr. Haefele replied that a careful answer to that point would require an hour and would be tangential.

Mr. Raiffa noted that he could see potential methodological problems here, for example, in statistical sampling or in game theory. He wondered whether gaps existed in the literature and ventured the opinion that the fields had already been well-covered. He asked whether Mr. Haefele meant to develop the methodology further, or rather to apply it to other fields, like pollutants. Mr. Haefele said that the notion is more the second, that is , to employ this experience carefully and meaningfully. There are still theoretical questions but they are a secondary focus of attention for IIASA.

Someone suggested that IIASA apply this methodology to the practical case of pollution control. In his country, allowable amounts of fossil fuel pollutants are set at the regional level. These are divided among industries on the basis of what the industries claim they can do. It would be important to apply accountability analysis to determine what each sector or industry can in fact do to control its pollutants, and to use the results to rationalize the regulatory process.

Risk Estimation and Evaluation

Harry J. Otway

It would be well to start by defining what we mean by the terms risk estimation and risk evaluation. Risk estimation, as it will be used in this paper, refers to the process of quantifying, as far as possible, the risks presented by the operation of a particular facility. In this paper we will generally be talking about biological risks to humans but the definition need not be limited to this. Risk, however, is definitely an expression of the probability of a specific outcome occuring due to a specific cause and is a measure of the reliability of the particular facility.

Risk evaluation is the comparison of these estimated risks with other risks existing in society in the light of the societal reaction to these other risks - in the vocabulary of this meeting, embedding into the society. This may be done from the standpoint of trying to determine if the magnitude of a specific risk is or will be acceptable, or to determine an acceptable value of estimated risk as a guide for establishing design goals for system and component reliabilities.

In this paper we will be dealing mostly with mortality risks although it is clear that risk is only one of the social costs associated with technological efforts. The examples given here are applied to electrical power generation but the principles are also applicable to larger areas of technology assessment and acceptance.

RISK ESTIMATION EXAMPLE - NUCLEAR POWER PLANT ACCIDENTS

We have made risk estimates for two nuclear reactors[1,2], a 1000 MWe pressurized water reactor at a hypothetical site and the Omega West Reactor (OWR), a 8 MWth tank-type research reactor located at Los Alamos, New Mexico, U.S.A. For reasons which will become obvious shortly I will discuss both analyses together.

Risk, for this example, is the probability of an individual meeting a given fate from a particular cause. Specifically, it would be the probability of death from a reactor accident and would include the probability of the accident occuring, the probability of radioactive material being carried to one's location, and the probability of dying after receiving the radiation dose. The specific risks considered here are the somatic risk of death (both early and late) from neoplastic diseases due to whole-body irradiation, thyroid carcinoma (iodine isotopes), the genetic risk, and non-specific life-shortening risk.

The Method

The first problem is to find a relationship between accident consequence and accident probability to be used as a source term for an estimate of risk. Our approach was to take a sample of the complete accident population and to use this sample as a basis for establishing a probability density function of fission product release for the reactor. In this case the complete accident population consists of all accidents, in all combinations of systems or component failure, which would result in a release of fission products to the environment. Our sample of this population consisted of all of the accidents which we could imagine that might lead to an external fission product release. This sample is inherently limited by the facilities of the human imagination and cannot, of course, result in a statistically random sample since those potential accidents that we cannot imagine, as well as those involving significant common mode interaction, are unavailable to be sampled. However, this sample, while not random, is also not intentionally biased, so we are approximating a random sample of all possible accidents by a sample based on recognizable accidents. Thus assumption is not completely unreasonable because there is a great effort to bias against common mode failures in design.

Determination of the Source Term

The accident envelope (Fig. 1) may be generated by assessing the probability of specific accidents occuring using standard fault-tree techniques.

The fission-product release value for the assumed accident situation, along with its probability, constitutes one point in the accident envelope. This procedure may be repeated for different combinations of system failures to produce additional points. The source term for the risk estimate was the probability density function of fission-product release formed from the release-probability envelope of Fig. 1 using a nonlinear least squares computer programme.

The accident envelopes found for the OWR and the 1000 MWe PWR were so similar that the fitted probability density functions of release were essentially identical. Therefore the risk calculations described here could be for either reactor located at the Los Alamos site. However it must be mentioned that the PWR analysis, which pre-dated the controversy over emergency core cooling systems, assumed that once this system successfully responded to a demand signal it would perform its function as designed. That is, any failure to function would be due to random failure and not because of a lack of understanding of the physics of the system. If this be not the case then the PWR risk analysis must be re-evaluated.

Many of the failure rates used in the OWR analysis, especially for emergency systems, were calculated based on OWR test data or operating history. The effect of certain types of common mode interactions is included in these data, which were collected over a period of years on the actual systems, so that any designed-in common mode interactions within a system or between systems are included in the data and, consequently, in the statistical estimates of failure rates. Of course, these data do not include common mode interactions which might appear only under accident conditions, such as damage due to flying missiles generated during the accident or accident-produced temperature or humidity conditions.

We further attempted to make some allowance for common mode failures within systems by using conservative values for system failure rates. For example, when failure rates based on test data or operating history were used, the 90% confidence value for the system failure rate in question was employed in calculating the nominal probabilities of specific accidents. If no failure was noted, the 99.9% confidence value for system failure rates was used for the 90% confidence level calculations of specific accident probabilities. For this analysis, all emergency system failure rates were calculated based on actual data from the OWR.

A more formal calculation of dependent failure probabilities between primary and emergency systems[2] provided results which did not differ greatly from those to be presented here.

The Risk Considered

We conservatively assumed that the consequences of irradiation are linear with dose, that there are no threshold or rate effects, and that there is no repair of radiation damage. We do not suggest that these conditions represent reality - only that they provide a reasonable upper limit of risk. It appears that threshold, rate, and repair effects do exist and make the actual risks lower than those suggested here. Numerical values of the probability of death per unit dose and the sources of these estimates follow.

Whole Body Somatic Risk. The risks included in whole body somatic risk are death from leukemia and from carcinomas other than of the thyroid. For doses up to 150 rad, a linear relationship of 30×10^{-6} per person/rad has been used as the probability of death from each of these[3]. For higher doses, the response would be based on the acute effects of radiation.

Thyroid Carcinoma. Assuming that the product of morbidity and mortality is roughly constant for all ages, the chance of death from internal ^{131}I irradiation of the thyroid has been taken as 1×10^{-6} per person/rad[3].

Nonspecific Life Shortening. After radiation exposure of animal populations, increased mortality is noted, which is not associated with any single disease but seems as though the animals had undergone accelerated physiological aging.

An estimated 7% lifespan reduction per 100 rad is used here as an approximate upper limit of risk. This may also be expressed as a mortality probability of 700×10^{-6} per person/rad.[4]

Genetic Risk. In predicting genetic risk, the term "genetic death" is used. A genetic death may be defined as the eventual extinction of a gene lineage. This might occur through the reduced fertility or sterility of someone carrying the gene or through stillbirth, abortion, or early embryonic or prereproductive death. The term is somewhat misleading in that a genetic death may not represen a somatic death; a genetic death (sterility, for example) may not have an associated corpse. Therefore, calculation of radiation-induced mutation frequency is meaningful only in comparison with the natural rate of mutation. The natural genetic death rate, based on normal mutation rates and genetic equilibrium, may be estimated as $200\ 000 \times 10^{-6}$ per person/generation.[4] We have chosen 7200×10^{-6} genetic deaths/rad as a conservative value for radiation-induced mutations. About 2.5% of this would be expected in the first generation

Risk vs Distance and Direction

A sample risk vs distance result for Pasquill F weather (down-canyon wind) is shown in fig. 2. This is one of a group of curves that results from calculat of dose vs distance with the dose values multiplied by morbidity/mortality probabilities. The probability of occurrence of the various Pasquill conditions has not yet been included.

Local meteroology is important in considering the OWR which is located in the bottom of a long, narrow canyon. The local meteorology enters in as a series of weighting probabilities applied to the curves represented by Fig. 2 to obtain Fig. 3 which shows lines of constant somatic mortality risk (thyroid carcinoma, leukemia, and other carcinomas) superimposed on a schematic plan of Los Alamos. Note that these are not lines of constant risk density. The airpor shown in the Figure and a Plutonium processing facility (not marked) each present an additional, additive, risk in their immediate vicinities.

Evaluation of these Risks

The individual risks portrayed in Fig. 3 may be crudely placed in perspective by comparison with other risks commonly accepted by society. We can try to gain an appreciation for numerical values of risks by looking at some selected U.S. accident statistics. (Table 1).

People are not equally exposed to all these hazards and, indeed, some are not exposed to some hazards at all, but many of these accidents are common in society, so the risks they provide are representative of the "average" risk to the "average" person. These statistics may also be indicative of how we form our subject feelings about certain hazards. If an accident is improbable, as shown in Table I, it is typically less known, and the chance of the "average" person knowing of someone suffering this particular fate is also small.

Fatal accident providing hazards on the order of 10^{-3} per person/year are uncommon. When a risk approaches this level, immediate action is taken to reduce the hazard. This level of risk appears unacceptable to everyone.

At an accident level of 10^{-4} per person/year, people spend money, especially public money, to control the cause. Money is spent for traffic signs and control, and police and fire departments are maintained with public funds. Safety slogans popularized in the U.S. for accidents in this category show an element of fear e.g., "The life you save may be your own".

Mortality risks at the level of 10^{-5} per person/year are still considered by society. Mothers warn their children about most of these hazards (playing with fire, drowning, firearms, poisons), and some people accept a degree of inconvenience, such as not travelling by air, to avoid them. Safety slogans for these risks have a precautionary ring "Never swim alone", "Never point a gun at another person" "Keep medicines out of children's reach".

Accidents with a probability of about 10^{-6} per person/year are not of great concern to the average person. He may be aware of them, but he feels that they will never happen to him. Phrases associated with these occurrences have an element of resignation "Lightning never strikes the same place twice...", "An act of God".

The foregoing observations are by no means hard-and-fast rules. For example, as pointed out by Soames[(5)] a considerable amount of money (mostly private) is spent on earthquake protection. However, when this sum is apportioned among the total U.S. population the "average" per capita cost is not large. In geographical areas where seismic activity is concentrated this risk may approach the level of 10^{-5} per person/year, removing some of the apparent discrepancy.

The intent of this discussion was to point out that there is a general lack of concern about accidents having averaged mortality risks of 10^{-6}/year. This will provide a numerical comparison for evaluation of the results of the OWR risk estimation.

The warehouse immediately northwest of OWR is the nearest uncontrolled structure. The highest individual somatic risk to the population is about $5 - 10^{-10}$/year which, relative to the values discussed earlier, is negligible. The risk added by the OWR would increase the chance of accidental death for an "average" person with "average" accident exposure by 0.0001%. Based on "typical"values of industrial hazard pay a person exposed to a somatic risk of 5×10^{-10}/year would be entitled to receive about U.S. $0.01 per hundred years of exposure. The nonspecific life shortening at the point of highest individual risk may be expressed as 25 sec/year of continuous exposure.

The total risks, the sum of all individual risks over a 30 year period, are compared to some other common risks in Table II. For comparison, a community this size (13,000 excluding suburban areas remote from the plant) would have about 2,6000 natural genetic deaths per generation, assuming natural mutation rates and genetic equilibrium. On the basis of national accident statistics, one would expect about 270 accidental deaths in the community in a 30-year period.

This must be regarded as only a very rough attempt to evaluate the importance of the estimated risks. Many complicating factors, not taken into account here, will be discussed in the next section.

RISK EVALUATION

A very primitive example of risk evaluation was mentioned briefly in connection with the nuclear power plant example. Risk evaluation is a complicated and intriguing exercise because of the number of variables involved and the problems in comparing unlike things - the comparison of "apples and oranges". For example, there are really no actual data on the acceptance of power plant risk because there is, as yet, no data base. One must attempt to evaluate statistical expectations of risk with other, but different, risks in the light of their acceptance by society.

Individual Risk vs Benefit

Prof. Häfele has already referred to Starr's "quasi-laws" relating to risk acceptance[6]. Figure 4[7] shows a graphical portrayal of a tentative separation of risks tending to be found "acceptable" and "unacceptable". Note that this is a function of expected per capita benefit.

We must observe here that this material is not yet known with certainty. For example, that there is some lower level of risk below which the risks are not noticed seems, on the surface, obvious. However, there are some modes of death, however unlikely, which may be of more concern than their probabilities would indicate because the perception of these risks is not in line with their actual magnitudes.

The upper limit of "acceptable" risk is seen to be asymptotic to the average rate of death due to natural causes. Why this should be is not at all clear. In fact, that it should be so is somewhat mysterious because the "average" death rate from natural causes is approximately equal to the age-specific death rate for 60 year-old people. It is hard to see why the subconscious risk computer of society should be aware of the 60 year age-specific rate. This is especially true when one considers that in many of the specific examples analysed by Starr the age distributed of those at risk is considerably different from that of the general population. The examination of age-specific accidental death rates might help in understanding this. It does seem clear, however, that there must be some limiting level of risk above which risks are unacceptable to almost everyone regardless of benefit.

Note that the relationship between risk and benefit in the figure is almost linear, yet other data have indicated a cubic function. Figure 5[6] shows the cubic relationship between mining accident risk and compensation. However, note that if we change the abscissa values to hourly wage less $ 2.00 we disallow the portion of the wage the worker would receive were he not exposed to mining risk (e.g. time keeper at the mine gate). We then have a curve for accident risk vs. risk compensation pay (Fig.6). This shows a linear correspondence between risk and benefit. This must not be interpreted as an attempt to detract from Starr's work because he has been instrumental in arousing interest and stimulating work in this area. Rather we want to point out that there are still unknowns and vague points worthy of study.

The Perception of Risk

The question of risk perception has been brought up in the discussion sessions. This is an important point because people react to a given risk in view of how large they think it is, not how large it actually is.

There is actually nothing new in quantifying subjective and esthetic values. For example, the auction sale of a rare art object requires that a monetary value be placed upon it. Although the value is largely esthetic, far greater than the cost of materials and labour, this value is quantified. A cut flower is totally non-functional. Yet a quantitative value for a flower may be determined by enquiring in a flower shop and this value is determined by market conditions. The message here is only that we routinely deal with the quantification of esthetic and subjective values. The problem of assessing the relative importance of subjective values is interesting and difficult, but still worthwhile attempting because, if conservative estimates of the magnitudes of some of these additional variables indicates they are small in comparison to others, they may then be eliminated from further consideration in the decision making process thereby removing some of the uncertainties.

An example of the measurement of perceived individual risk may be found in the field of psychosomatic medicine. Wyler et al[8] through the use of survey techniques, haveattempted to quantify the subjective aspects of illness. For this survey, the concept of seriousness of illness included such factors as prognosis, duration, threat to life, etc.; but, more important, it also included the emotional and aesthetic factors which influence one's perception of how serious a particular illness is. In this study, a list of 126 disease items was shown to a sample of medical out-patients. They were then asked to rate these diseases in a quantitative manner using a given illness as a modulus item. The quantitative rankings given by out-patients to various diseases were also compared to the results of the same survey applied to a group of physicians, whose knowledge of disease might lead them to rank disease items in a different manner than the general public. The differences in ranking between the two groups, the general public out-patients and the group of physicians, turned out to be very small. The Spearman rank order correlation coefficient between the two groups was a highly significant 0.947. The geometric means of quantitative rankings of these disease items was used to form the Seriousness of Illness Rating Scale (SIRS). This survey was later tried with a second group of physicians to check reproducivility with excellent results;[9] and as a further check, the cross-cultural consistency was estimated by testing groups in Ireland and Spain[10] again with resultant high correlation coefficients.

In asking the sample groups to rate illnesses, peptic ulcer was given an arbitrary value of 500 points. The respondants were asked to compare the seriousness of each of the remaining illnesses to that of peptic ulcer. That is, to rate the relative seriousness, using all their experience - direct and indirect, objective and subjective - in arriving at an answer. It is important to note that this method of ranking definitely includes the emotional, aesthetic and moral prejudices associated with various diseases. A samply of some of the diseases included in the SIRS and their mean ratings is shown in Table III.

Note that the rank order of various diseases does not correlate at all with their mortality prospects or even with the associated pain or inconvenience. However the subjective impressions of disease have indeed been quantified. Syphilis, for example, which has high negative moral connotations in society, but which is seldom fatal if treated promptly, was given slightly less than half the rating given cancer. Sexual inability, with obvious emotional aspects, was rated about half as serious as heart attack. Such items as bad breath and dandruff may appear to be overvalued when compared to other disease items. However, if advertising is any indicator, the fear of bad breath and dandruff have generated a sizeable industry in many countries. The point here is that it appears that it is indeed possible to give some quantitative significance to the emotional, moral and aesthetic factors attached by people to various ailments.

For some time a correlation between psychic stress and physiological disease has been observed, that changes in persons' lives seem to occur in clusters prior to the onset of physical illness. Hinkle[11] showed that it was the individual's perception of stress which was correlated with illness. Experience with over 5,000 patients was used to tabulate some 43 life-change events which require a degree of individual social adaptation[12]. Some of these items were objective changes such as marriage, divorce or vacation, others were far more dependent upon the individual's subjective interpretation of them, such as sexual difficulties or significant changes in work or eating habits.

This list was used to form the Social Readjustment Rating Scale (SRRS) which was administered in a questionnaire form similar to that just described for the SIRS. The personal adaptation to marriage was used as the modulus item and arbitrarily assigned a value of 500 points and respondants were instructed to compare each item to marriage and assign a numerical value to the required social readjustment. The SRRS test was given to groups of white Americans[12] Japanese[13] American minority groups[14] Western Europeans[15] and Spanish[10]. In each case there was a high degree of reproducibility within cultural groups and also a high degree of cross-cultural correlation. Cross-cultural correlations for the SRRS were not as high as that found for the SIRS. However, this was believed due to the fact the illness and the perception of illness is rather similar in different cultures, whereas the readjustment to social change is culturally specific, depending more upon particular cultural values. A correlation has since been found between life-change magnitude, as measured by the SRRS, and the onset of serious illness, using the SIRS as a measure of relative seriousness[16]. Some items from the SRRS are shown in Table IV.

Again, the important point to be brought out here is that elements subjective in nature have been quantified in a reproducible manner.

These examples have little direct relationship to the use of risk evaluation principles for technology assessment, but seem to indicate that the problem is not completely unmanageable and that work has been done on techniques.

Catastrophic Events

Another interesting question is the effect of severe-consequence, low-probability events upon risk acceptance. Many are of the opinion that the consequences of these events cannot merely be weighted because of the severity of the consequence. However data gathered by geographers on the perception of flood risk indicate that events of intermediate consequence and probability are of more concern.(17) An unofficial examination of insurance data indicates that the monetary claim settlement per life lost decreases as the number of deaths per disaster increases. Some tentative theories have been advanced in explanation.

Historical Precedents

Learning from historical precendents has also come up in the discussions. One example that comes to mind is that of bursting steamboat boilers in U.S. river transport in the mid 19th century. Prof. Burke, of UCLA, has done an excellent analysis of these catastrophes and the social reactions which led to the solution of this problem.(18) There are other historical examples which could be profitably studied.

Life Values

When risk levels are to be used to determine reliability design criteria the question of multiple objectives arises. For example, biological risk must be considered as well as the direct economic losses associated with decreased reliability. This requires making trade-offs between economic factors and life values. There is a growing body of literature on the value of life saving using methods ranking from calculation of the present value of future earnings to self-insurance type questionnaires. Surprisingly enough, these estimates show rather good agreement considering the obvious difficulty in making such judgements[19]. (Sinclair[20] does not find such good agreement among the life value estimates. A careful review of these data might prove interesting). A very limited study[21] indicated that this economic risk criterion might indeed be the more restrictive in the case of one nuclear power plant.

SUMMARY

A start has been made in the area of risk estimation. Space programmes and nuclear power have done much to help improve the understanding of reliability engineering. It is now possible in many cases to make reasonable upper-limit estimates of risk. While by no means routine these problems are amenable to solution with continued effort. Performing risk estimates for particular facilities or industrial sectors would not appear to be a fruitful activity for the IIASA although contributions might be made to a generalized theory of risk estimation through the analysis of existing data.

Risk evaluation is a more vague area because of the need to compare unlike objects in abstract units. Some good work has already been done but many of the items discussed earlier are still in a preliminary stage of understanding.

Investigators in many disciplines are working on various aspects of these problems although their work is not necessarily directed toward risk evaluation in the context in which we are interested. For example, psycho-somatic medicine has done much on the comparison of perceived vs. actual risk and on the quantification of subjective (and cross-cultural) values; experimental psychologists have attempted to quantify the perception of voluntary and involuntary chance taking; geographers have studied long-term human behaviour with respect to recurring natural disasters. In addition, there are many historical examples on the acceptance of technological risk.

The author believes that co-operation with researchers in these various disciplines could produce information adaptable to risk evaluation which would be well worth the effort required. This might be an appropriate research activity for the IIASA.

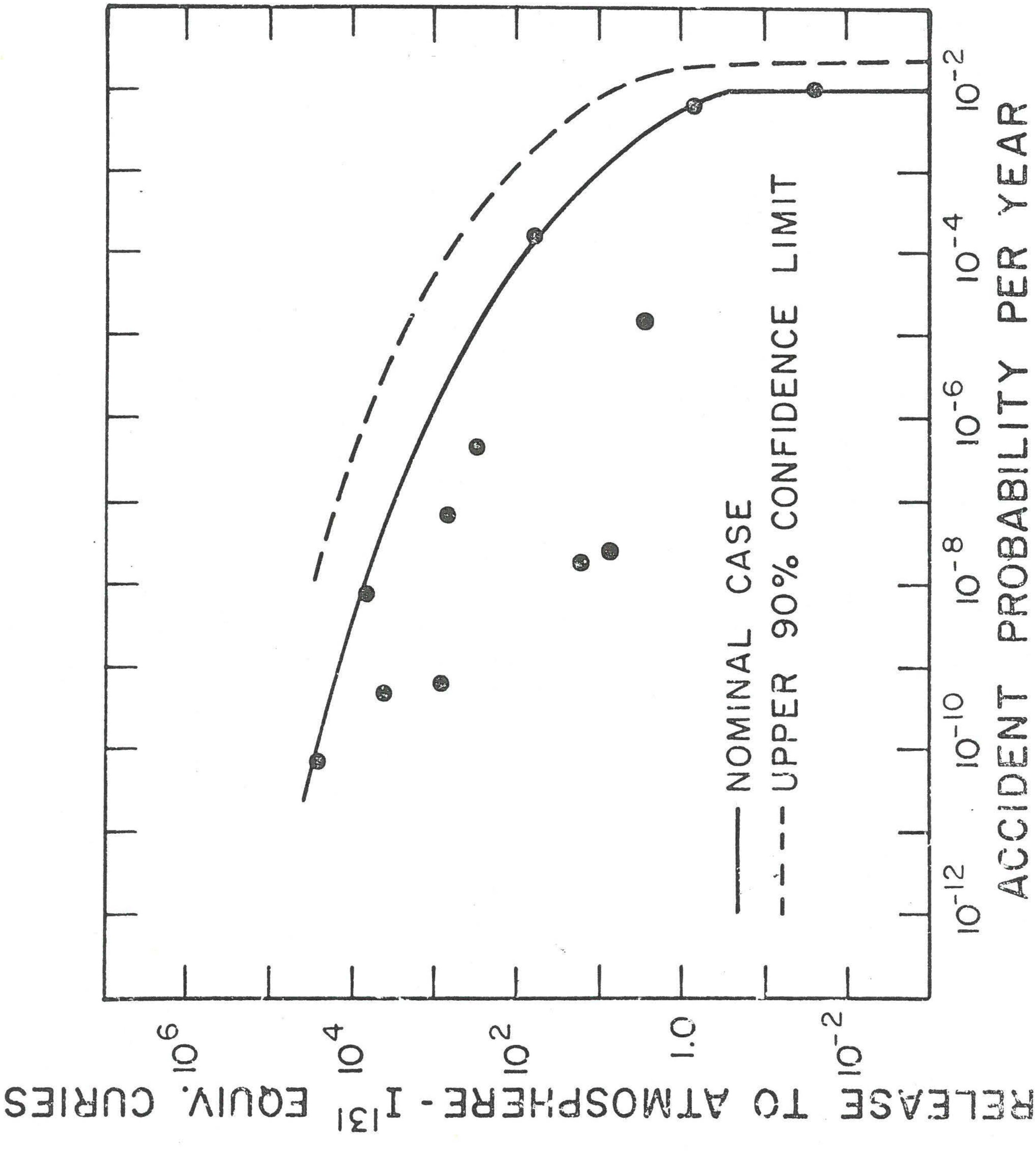

Fig. 1. Accident Envelope for the Omega West Reactor.

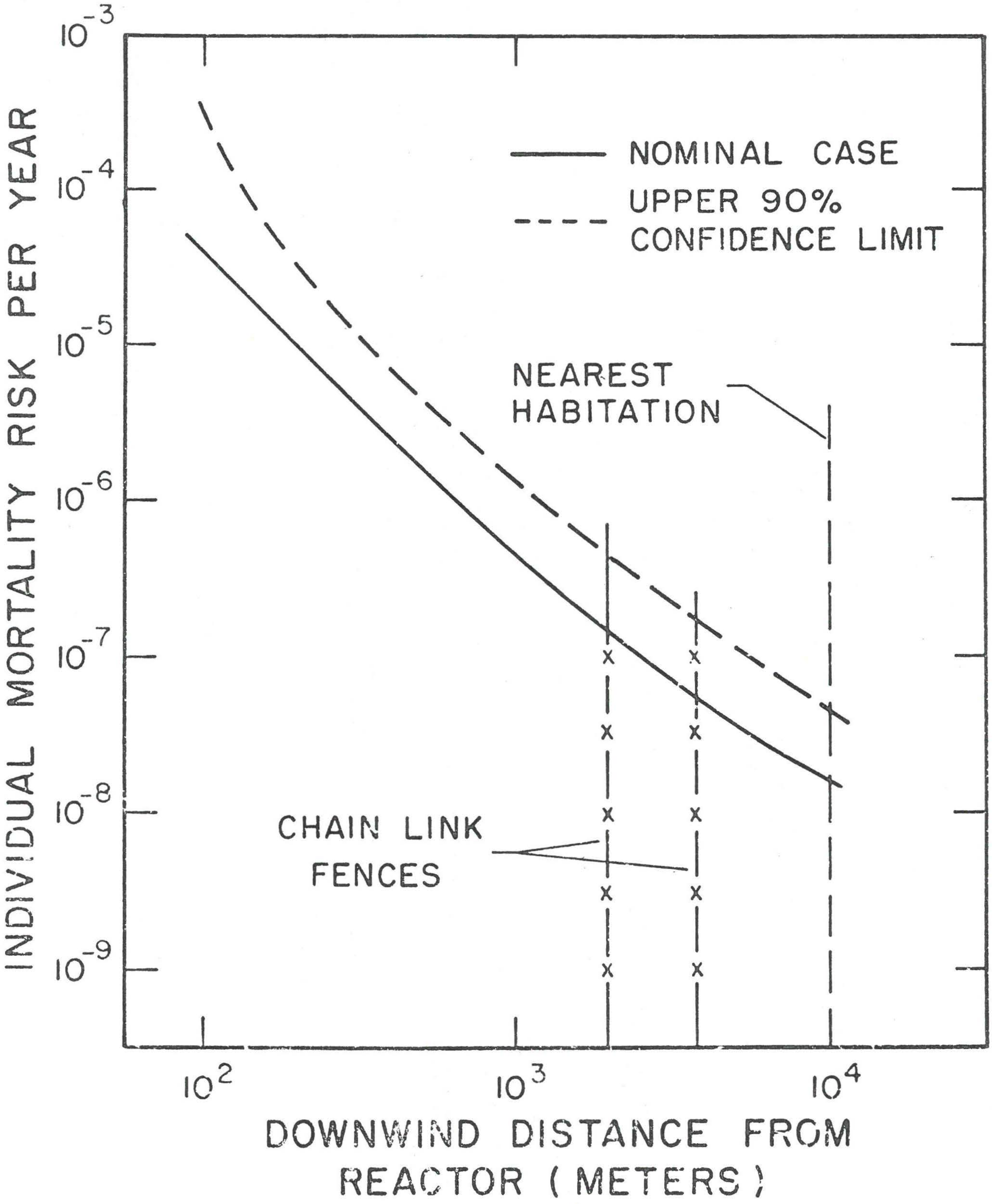

Fig. 2. Mortality Risk vs. Distance for Pasquill Type F Weather. Wind Speed 1 m/sec.

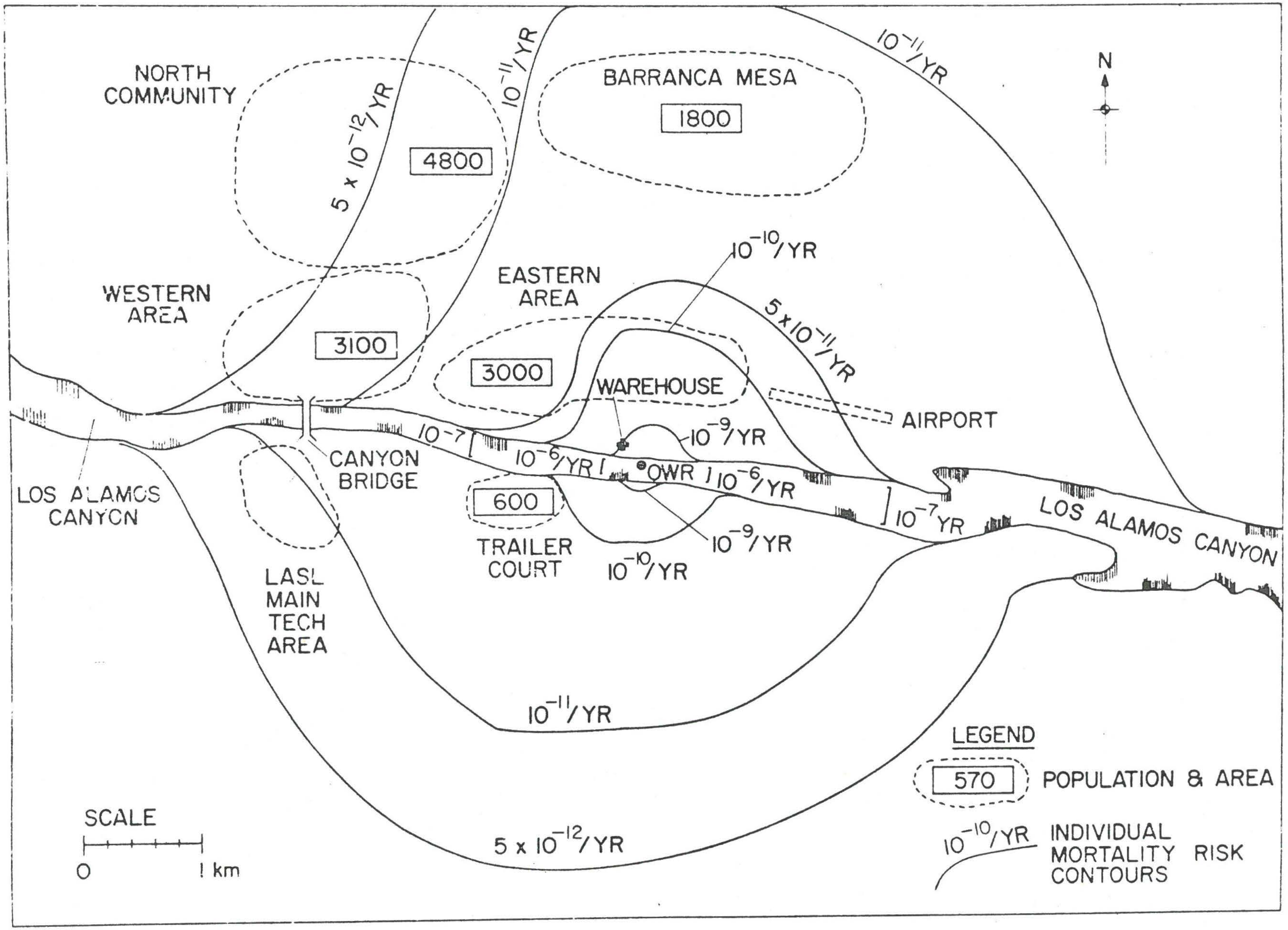

Fig. 3. Individual Mortality Risk Contours Superimposed upon a Plan View of Los Alamos.

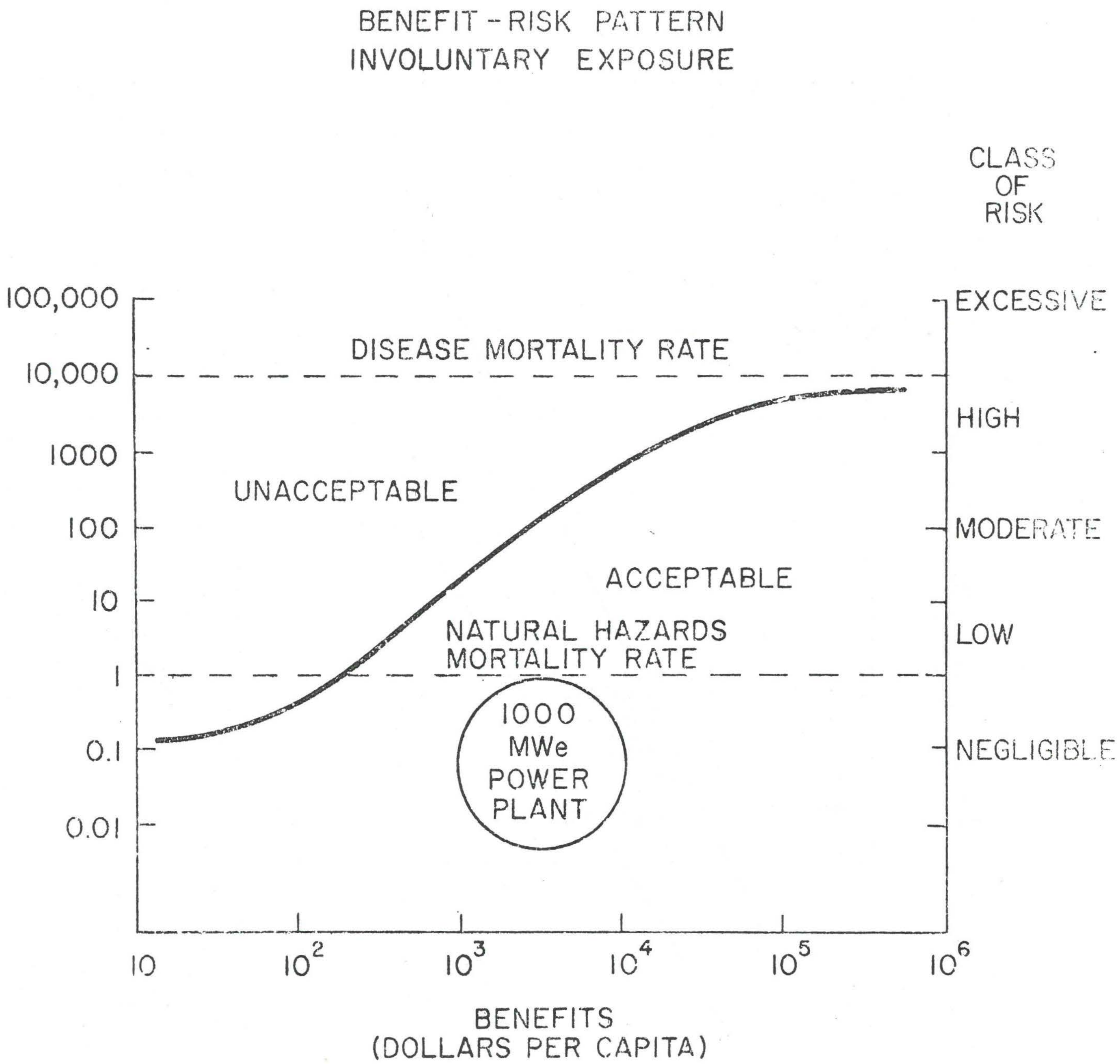

Figure 4 Benefit-risk Pattern for Involuntary Exposure

MINING ACCIDENT RATES VS. INCENTIVE

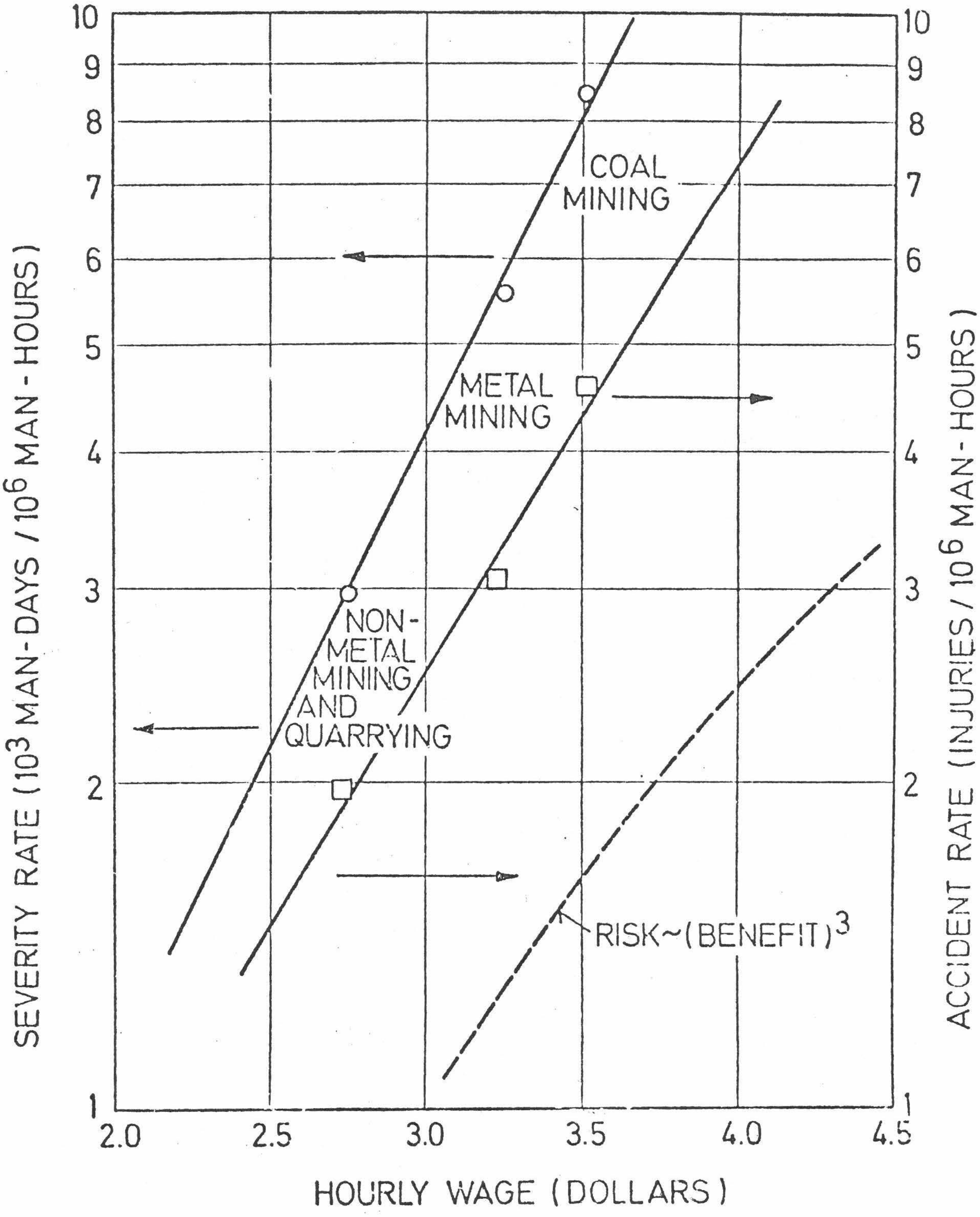

Fig. 5. Hourly Wage vs. Accident Severity.

(Ch. Starr, BENEFIT - COST. STUDIES IN SOCIO - TECHNICAL SYSTEMS, April 1971)

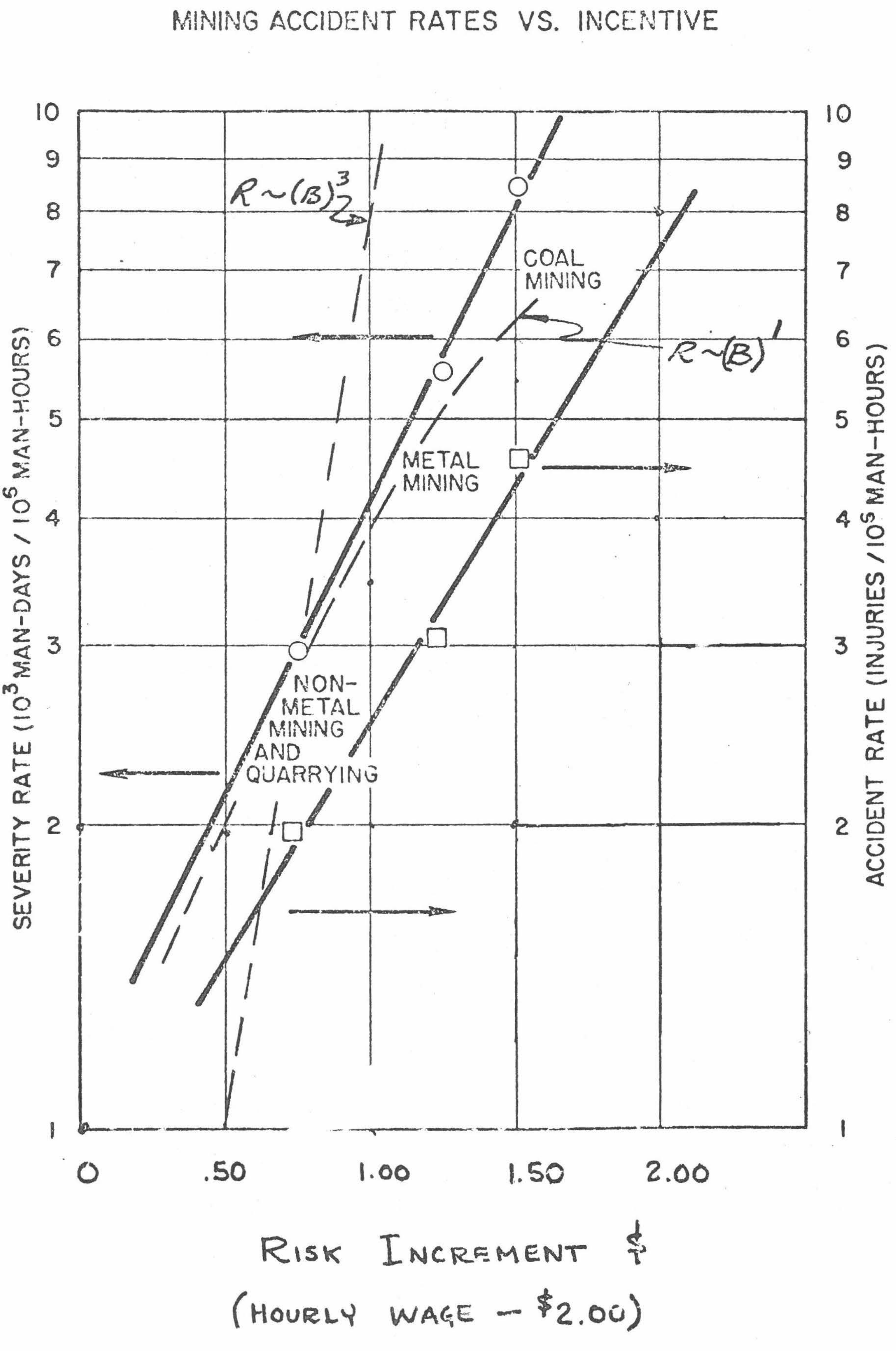

Fig. 6. Hourly Hazard Pay vs. Accident Severity.

TABLE I

SOME U.S. ACCIDENTAL DEATH STATISTICS FOR 1966

Type of Accident	Total Deaths	Probability of Death per Person Per Year
Motor Vehicle	53,041	2.7×10^{-4}
Falls	20,066	1.0×10^{-4}
Fire and Explosion	8,084	4.0×10^{-5}
Drowning	5,687	2.8×10^{-5}
Firearms	2,558	1.3×10^{-5}
Poisoning		
Solids and Liquids	2,283	1.1×10^{-5}
Gases and Vapors	1,648	8.2×10^{-6}
Machinery	2,070	1.0×10^{-5}
Water Transport	1,630	8.1×10^{-6}
Aircraft	1,510	7.5×10^{-6}
Inhalation and Ingestion of Food	1,464	7.3×10^{-6}
Falling or Projected Object	1,459	7.3×10^{-6}
Mechanical Suffocation	1,263	6.3×10^{-6}
Therapeutic Medical and Surgical Procedures	1,087	5.5×10^{-6}
Railway (Except Motor Vehicle)	1,027	5.1×10^{-6}
Electric Current	1,026	5.1×10^{-6}
Hot Substance, Corrosive Liquid, Steam	408	2.0×10^{-6}
Animals (Nonvenomous)	131	6.6×10^{-7}
Lightning	110	5.5×10^{-7}
Venomous Animals and Insects	48	2.4×10^{-7}
Streetcar	9	4.5×10^{-8}
Radiation	1	–

TABLE II

POPULATION RISK SUMMARY*

RISKS FROM OWR		SOME COMPARISON RISKS	
NEOPLASTIC DISEASE	5.1×10^{-5} DEATH	525 DEATHS	NATURALLY OCCURRING NEOPLASTIC DISEASE
NON-SPECIFIC LIFE SHORTENING	1.2×10^{-3} DEATH	270 DEATHS	ACCIDENTS (ALL CAUSES)
GENETIC RISK			
1st GENERATION	3×10^{-4} G. DEATH	2600 $\frac{\text{GENETIC DEATHS}}{\text{GENERATION}}$	NATURAL GENETIC DEATH RATE
SUBSEQUENT GENERATIONS	1.2×10^{-2} G. DEATH		

* BASED UPON 13,000 PEOPLE AT RISK FOR A 30 YEAR PERIOD

TABLE III

SOME ITEMS FROM THE SERIOUSNESS OF ILLNESS RATING SCALE

	RANK	MEAN SCORE
LEUKEMIA	1	1080
CANCER	2	1020
MULTIPLE SCLEROSIS	4	875
HEART ATTACK	7	855
MUSCULAR DYSTROPHY	11	785
STROKE	13	774
BLINDNESS	15	737
CHEST PAIN	29	609
PEPTIC ULCER*	37	500*
SYPHILIS	42	474
SEXUAL INABILITY	50	382
PNEUMONIA	55	338
IRREGULAR HEART BEATS	62	302
WHOOPING COUGH	73	230
MEASLES	90	159
ACNE	104	98
COMMON COLD	118	62
BAD BREATH	120	49
DANDRUFF	126	21

*Modulus Item

TABLE IV
SOME ITEMS FROM THE SOCIAL
READJUSTMENT RATING SCALE *

	RANK	MEAN VALUE
DEATH OF SPOUSE	1	1000
DIVORCE	2	730
JAIL TERM	4	630
DEATH IN FAMILY	5	630
MARRIAGE**	7	500**
FIRED AT WORK	8	470
SEX DIFFICULTIES	13	390
DEATH OF CLOSE FRIEND	17	370
TROUBLE WITH IN-LAWS	24	290
CHANGE IN RESIDENCE	32	200
VACATION	41	130
MINOR LAW VIOLATION	43	110

* RESULTS OF AMERICAN SAMPLE

** MODULUS ITEM

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Comment on Risk and Reliability Evaluations in Nuclear Energy

K. Barabas

Mr. Chairman, ladies and gentlemen:

Let me present a short contribution to the main paper of Professor Haefele, especially with respect to the risk and reliability problems. I will concentrate only upon nuclear energy.

Please allow me first to make some comments to Professor Haefele's comparison of environmental problems of fossil and nuclear energy. I could fully accept his philosophical approach to the risk of both types of energy generation. But, I would like to add that in reality we still have large technical and economical problems with other than CO_2 pollutants from fossil power stations and especially with SO_2 and sometimes also even with radioactive pollutants as stated for example in some Federal Republic of Germany measurements. There is no doubt that such pollutants represent large risk for the environment and therefore we are sure that nuclear energy--even with the potential risk, which always exists in principle--will play important role in improving our environment.

It is very well stated in Prof. Haefele's paper that the risk of nuclear energy could be made smaller than any given low figure by increasing the reliability of the technological systems of nuclear power stations. For this, reliability analyses and control play the most important role in achieving safe utilization of nuclear power.

As far as reliability analyses of technological systems are concerned, we fully agree that such a method of risk assessment is much more logical and realistic than the Maximum Credible Accident (MCA) method used in early stage of nuclear energy development. For the industrial stage of nuclear energy applications, a method for reliability analyses must be developed, and therefore we support such methodological work to be included into energy project of IIASA.

Research including work on the importance of reliability analyses and control is being performed in Czechoslovakia. Description of that work has been given in Mr. Kovanic's paper presented at the IAEA symposium on reactor control held in Prague in November 1972.

I would like to mention one point of our activity in this field which could interest you. There is a close connection between the setting of emergency levels of control and safety systems between the reliability and safety of a power station. All signals characterizing the state of the plant have--as a rule--some random components. Therefore, the choice of emergency level of the safety system represents a statistical decision problem. Risks of wrong decisions are dependent on the quality of estimates of important parameters. Some new results of optimum estimation theory have become available--as mentioned Mr. Kovanic's paper--making it possible to improve considerably the efficiency of estimating procedures. Operational experience, such as covariant matrices of parameter vectors, together with covariant matrices of noise vectors, can be used in new estimators to improve the statistical accuracy of the estimates and to minimize the risks of wrong decisions.

Some of the results obtained have been used also for reliability calculation of emergency electricity supply for the first Czechoslovak Nuclear Power Plant at Jaslovské Bohunice. As a result of that calculation, the reliability of the first project assuming electricity supply from 110 kV and 220 kV lines and from one hydrogenerator has been improved by introducing an additional fully independent source of energy supply provided by diesel generators. Other systems of that station have also been subject to reliability analysis.

As far as reliability control is concerned, we believe that this is one part of management to achieve reliable performance.

Such management must cover the phases of design, construction, fabrication, and installation, and especially the commissioning and operation phases. The most important items of such management are, in our opinion, the following:

1) Measurement and analyses of unreliability of existing units, and feedback information to designer, supplier or operator to avoid unreliability of a new design. Fault report procedures and a data collection system should be established in order to exchange experience obtained not only within the given state but also among states. The role of international organisations, and also of IIASA, to establish such an international information system is very important.

2) Development of reliability guidelines and standards for the designer, equipment supplies, and operation in order to formulate all the technical requirements for achieving reliability.

3) Establishment of an effective quality assurance programme to monitor equipment quality during fabrication and installation.

4) Establishment of an effective commissioning and operational test programme including periodical inspections and operational diagnostics for monitoring equipment quality and systems reliability during the operational life of the station.

5) Establishment of adequate training of the staff involved and qualification tests of reactor operators.

All the above items of management to achieve reliable performance are being developed in Czechoslovakia under the supervision of the Atomic Energy Commission which is the licensing authority. This includes nuclear safety inspections for all nuclear installations located in the Czechoslovak Socialist Republic.

Finally, I would like to point out that the IIASA energy project including a study of reliability and risk evaluation of energy generation is welcome and supported by Czechoslovakia. As I mentioned, some of the problems are under development in my country, and we are fully prepared to cooperate with IIASA.

Discussion

One participant welcomed the considerations of risk, but said that a definition of risk is difficult to devise. In portfolio theory, it measures the variability of returns. Here, it is being taken as the probability of mortality. This is only part of the picture. One question is whose risk we are measuring: risk for the individual, or risk aggregated over the population. He stated that methodologists are currently interested in the problems of rare events and of multi-attributed objective functions. Risk must go beyond the risk of mortality or accidents to include other things as well.

Secondly, he commented that most of the discussions and models at the meeting seemed to be deterministic, with disagreement on the estimates and the numbers to feed into this deterministic world. He urged using stochastic models for our world of uncertainty. Then, one would deal not with risks, but with probability distributions. One would make forecasts in probabilistic terms. One way to do this would be to begin with a deterministic model and use sensitivity analysis, that is, running the model with different inputs, to isolate critical variables. The next step would be to use probability distributions for these variables in a formal model. Finally, one would perform the analysis or simulation. The main point is that IIASA should include stochastic elements in its analyses.

Someone agreed that modelling is done in the face of uncertainties but questioned whether the uncertainties were of a type that could be dealt with by probability theory. "Real" uncertainties, such as whether a certain breakthrough will be made, cannot be handled this way. The only sensible approach here would be to build models to incorporate expected developments, costs, and times to study them to determine the phasing-out of conventional processes, the research and development strategy, and payment patterns. Random processes should be reserved for other problems.

The first speaker agreed that technological forecasting is important but suggested the value of probabilistic forecasts of technological developments. With respect to the distinction between "real" uncertainty and other types, he said that, without going into a discussion of the philosophy of probability, an uncertainty is an uncertainty. "Probability" does not necessarily mean the use of particular stochastic models. Subjective probability is included and ultimately all probabilities are subjective. Experts' probability distributions provide an important input to analyses.

Mr. Raiffa noted that great semantic problems arise as one moves from a deterministic world to an uncertain one. In the past, economists trichotomized the world into spheres of certainty, risks where there are (repetitive elements for which you could determine long term frquencies), and uncertainty. The second speaker seemed to be referring to the risk case. Currently, there is a raging controversy within and between countries. Much theory has developed independently, and few people have read each other's literature. This problem may present a golden opportunity for IIASA to exploit its cross-national and cross-disciplinary nature.

Another participant added that in the specialty fields of engineering and science, scholars generally know the literature and experts of other countries but know very little literature across disciplines. This can be demonstrated objectively by examining citation indexes and by noting the probability that an article appearing in a journal from one field will be cited in a journal of another field. IIASA might study the citation indices for literature about uncertainties and probability, to determine objectively, for example, which literatures are impinging upon each other. IIASA could then try to bring together those people in different fields who could communicate, as shown by their citation patterns.

One participant remarked that although stochastic models may be too mathematically complex, he would still encourage their use.

Someone else cautioned that there is a danger that IIASA would get bogged down if it delves too deeply into probability. It is not that there is no role for statistics, but that if statistics are used for forecasts, one gets mired down. One should definitely do sensitivities, especially if they have physical meaning, for example, in terms of limits or biased distributions, but that should be the extent of the approach.

One participant remarked that most of the important climatic changes will occur as changes in probability distributions. They will be apprehended by the public as natural disasters, but in fact the mechanism is a change in the probability of the events.

Someone noted that power systems are built with calculated levels of risk, for example, the risk of being short of power. However, when they du run under normal power, this is never perceived as the outcome of a calculated risk but instead as someone's error.

Another participant said he knew of two examples where probability theory was used in practice; both produced results impossible to accept from a practical point of view. The first, developed eleven years ago, used Monte Carlo techniques to generate power demand. The second, which he developed provided an estimate of the probability that in the future some level of conservation of electrical energy would be observed. This result was unreasonable, too. (Fig. 3)

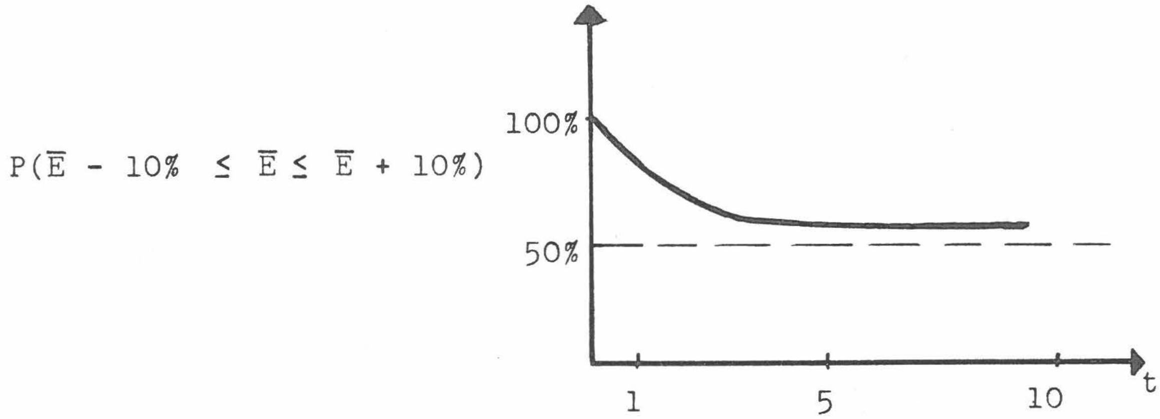

Figure 3

From this, he concluded that while stochastic approaches are theoretically possible, their practical results are negative.

The comment was made that even when formalistic probabilistic studies are successful, they do not give the decision maker much more than formalistic if applied decision analysis is meant to develop decision tools.

Mr. Raiffa pointed out that one can be analytical about subjective inputs. He characterized the foregoing discussion as a microcosm of healthy differences in view point. He noted that there were misconceptions about terminology. A common language is required, and cannot be quickly obtained.

"Risk" and Energy Systems: Deterministic Versus Probabilistic Models

Robert L. Winkler

Introduction

At the conference on "Energy Systems" that was held in Baden July 17-20, 1973, the discussion regarding models and model-building was, for the most part, limited to deterministic models. Only at the end of the conference, in the discussion of "risk and reliability problems," was the question of deterministic models versus probabilistic models brought up. The brief discussion that ensued indicated that there exists some hesitancy on the part of model builders in the energy systems area to include probabilities in their models. Such model builders recognize the presence of uncertainty in the situations they are modeling, but they appear to feel uncomfortable about formally representing this uncertainty in terms of probabilities. This uncomfortable feeling may be due to several factors, including a lack of familiarity with probabilistic models, a question about the source of probabilities for probabilistic models, a feeling that deterministic models are perfectly adequate, and a concern that probabilistic models regarding energy systems would be too complex and difficult to handle.

Unfortunately, because the question of deterministic models versus probabilistic models arose so late in the conference, adequate time was not available for a full discussion of the question. Of course, a full discussion would require several days with many papers and presentations. Since that is not immediately feasible, this paper represents an attempt to present an overview of some of the issues that are involved in the question of deterministic models versus probabilistic models.

The contents of this paper may be summarized as follows. In Section 2 an argument is made for the use of probabilistic models in situations in which there is uncertainty about some of the variables of interest. The next two sections consider questions of implementation: the question of moving from deterministic models to probabilistic models and the question of "determining" probabilities to use as inputs to probabilistic models. In Section 5 an area related to energy systems for which the notion of probability has been used, the area of "risk and reliability", is considered briefly, and the distinction between uncertainty concerning events, or variables, and preferences concerning outcomes, or consequences, is discussed. Section 6 contains a short summary emphasizing the implications of this paper for future research in the area of energy systems.

Why Use Probabilistic Models?

Model-building activities in the area of energy systems have focused almost exclusively on deterministic models. These models are deterministic in the sense that they assume that the variables of interest are known to take on certain fixed values. That is, the model builder acts as though the variables are known and fixed, even if it is clear that they are not. For example, an important variable in the study of energy systems is future demand for energy. A variable such as the total demand for energy in the world in the year 1980 might be included in a model of energy systems. Of course, it is recognized that a variable such as this is not observable several years in advance. The usual procedure is to arrive at an estimate of the demand for energy in the year 1980 and to treat this estimate as a certainty equivalent. The term "certainty equivalent", which comes from the area of statistical decision theory, indicates that even though one is not certain about the value that the variable will assume, one acts as though one were certain, treating the estimate as if it were an actual value that had already been observed.

Unfortunately (from the point of view of ease of analysis), the world is not deterministic in nature. Certain variables, such as variables relating to current technology, current demand for energy, etc., are known or can be estimated precisely enough so that they can be assumed known for most purposes. For many other variables, however, particularly variables involving future points in time (e.g., future demand for energy, future advances in technology), there may be a considerable amount of uncertainty. This uncertainty can be represented formally in terms of probability and can thus be incorporated into models of energy systems. The use of probabilistic models gives the model builder an opportunity to represent the "current state of knowledge" much more accurately than is possible with deterministic models.

One reason that the model builder should be concerned with using probabilistic models instead of deterministic models, then, is that probabilistic models enable the formal consideration of uncertainty. Important problems such as the study of energy systems involve a considerable degree of uncertainty with respect to many of the variables of interest. For many variables, some information is available, but the variables are not known for certain. In the case of variables involving the future, it would be nice to possess clairvoyance and to be able to foretell the values that will be assumed by these variables; unfortunately, this is not possible. To represent such variables in deterministic models by using estimates as certainty equivalents is to ignore the uncertainty concerning the variables. In acting as though one had more information than one actually has, one is, in fact, ignoring information. For example, in acting as though the demand for energy in 1980 were known for certain in 1973, a model builder is ignoring information that indicates that the actual demand in 1980 might be considerably above or below the value that is being used as a certainty equivalent.

Of course, the fact that deterministic models ignore uncertainty about variables is not sufficient to justify the use of probabilistic models in place of deterministic models. The most important aspect of the model for decision-making purposes is the output of the model, not the model itself. For instance, if deterministic models always yielded results identical to those of probabilistic models, then the simplification of not formally representing the uncertainty in the world (i.e., the use of deterministic models) would provide perfectly adequate results and would have the advantage of improved tractability (in comparison with probabilistic models). From statistical decision theory, it is known that under certain conditions, an entire probability distribution may be replaced by a single certainty equivalent, such as the mean of the distribution, without affecting the results of the model. For example, if the "payoff functions" for the various actions in a decision-making problem can be represented as linear functions of a particular uncertain quantity (random variable), then knowledge of the mean of the probability distribution of that uncertain quantity is sufficient for decision-making purposes. In this situation, the mean provides as much information (for the specific decision-making problem of interest) as does the entire probability distribution, so the mean can be used as a certainty equivalent.

There are situations, then, in which the use of certainty equivalents leads to perfectly acceptable results. Even if these situations, care is needed in the choice of a certainty equivalent, as this choice should depend on the structure of the decision-making problem at hand. In some instances, such as the example in the preceding paragraph, the mean should be used as a certainty equivalent. In other instances, the use of the median or some other fractile is indicated. For example, the extreme tails of a distribution may be very important, in which case the .001 fractile or .999 fractile of a distribution is much more useful than a value from the "center" of the distribution. It appears that such considerations have been ignored in the determination of estimates to be used as inputs to deterministic models of energy systems.

Although it should not be ignored, the question of the determination of appropriate certainty equivalents in situations where certainty equivalents are adequate representations of entire probability distributions is much less important than the question of whether certainty equivalents are adequate representations of entire probability distributions. In complex models that include many variables, it is generally invalid to replace probability distributions of the variables with certainty equivalents. That is, the replacement of the probabilistic model by a deterministic model that uses certainty equivalents leads to different inferences and decisions. This is particularly true when uncertainties exist about many variables and when the variables are not independent. In complex situations such as energy systems, the number of variables is large and there are obvious dependencies among variables. For instance, the demand for energy is clearly not independent of the price of energy, and the demand for energy in, say, 1985 is not independent of the demand for energy in 1980. As a result, a probabilistic model that takes into account such stochastic dependence will generally yield results different from a deterministic model using estimates as certainty equivalents. (This point will be discussed further in Section 3.) In the case of complex situations such as energy systems, the differences may be quite substantial.

Probabilistic models, then, have the advantage of formally representing the model builder's uncertainty about variables of interest, including stochastic dependency among variables. Such models are thus more realistic than deterministic models in that they do not ignore the uncertainty inherent in most real-world situations. Furthermore, probabilistic models have the advantage of being adaptive with respect to new information. As new information becomes available about the variables of interest, the probability distributions used in the model can be updated, so that at any point in time, these probability distributions represent the current state of information. For example, the information that a particular new technological advance has been discovered may cause revision of probability distributions regarding future costs of providing certain types of energy, regarding future technological advances, and so on.

The adaptive nature of probabilistic models has very important implications for decision making. It enables the model builder to treat the decision-making process as a dynamic process. This means that it is possible, within the framework of an uncertain world, to formally consider the interrelationships among decisions that are made at different times. The effect of today's decisions on tomorrow's alternatives, the possibility of delaying a decision until further information is available, the anticipation of future decisions, and so on, can all be formally considered within the framework of probabilistic models. A considerable amount of theoretical work in this area has been conducted in the past decade, and the theory of adaptive probabilistic models and of dynamic decision-making models is quite well developed.

In summary, the world we live in is an uncertain world, it is a changing world where new information continually becomes available, and it is a world where decisions made at one time may have strong effects on alternatives available at other times. Deterministic models simply fail to include some of the salient aspects of this world, and this failure casts doubt upon the results of such models, both in terms of inferences about the future and in terms of decisions that are based on the models. In comparison, probabilistic models are capable of providing a more realistic view of the world that faces the model builder. Probabilistic models allow for uncertainty by the inclusion of probability distributions to represent the uncertainty; they allow for new information by being adaptive and revising probability distributions as new information is obtained; and they allow for interrelationships among decisions at different times by being dynamic and formally considering such interrelationships. In theory, at least, the argument for probabilistic models to deal with complex systems such as energy systems seems compelling. The next two sections of the paper consider the question of implementation.

Moving from Deterministic Models to Probabilistic Models

In the previous section, an argument was made for the use of probabilistic models instead of deterministic models in situations in which there is uncertainty about some of the variables of interest. This argument may have given the impression that the position of this paper is that deterministic models are of little value. On the contrary, the building of deterministic models can be viewed as a very important first step in the development of probabilistic models. Building deterministic models is by no means an easy task, particularly in the case of complex situations such as energy systems. While a deterministic model that involves the use of estimates as certainty equivalents does not take into account the uncertainty present in the real-world situation, it does provide a result for a particular scenario. This scenario is simply the situation in which all of the variables take on exactly the values given by their certainty equivalents.

If the particular scenario represented by a deterministic model were sure to occur, then the deterministic model would provide an accurate representation of reality. Of course, because of the uncertainty about the real world, everyone recognizes that any single scenario is highly unlikely to occur exactly. At the Baden conference on energy systems, this was exemplified by disagreements concerning the appropriate values to use as estimates in some cases. One participant commented with respect to a particular model that one shouldn't place too much reliance on the results of the model because the model incorporated an estimate of the demand for energy in the year 2000 and there is considerable uncertainty as to what that demand will be. In effect, the comment implies that one should not place too much reliance on the results generated from a single scenario.

The first step in moving from deterministic models to probabilistic models is to consider several scenarios instead of just one. In other words, try different sets of values for the variables of interest and see how the results vary as the inputs are varied. This approach is called sensitivity analysis. In this manner, it may be possible to identify some variables for which the uncertainty is not crucial (with respect to the results of the model) and other variables for which the uncertainty <u>is</u> crucial. That is, large variations in the estimate of a particular variable may not lead to changes in the essential nature of the results of the model. The model is then said to be insensitive to changes in the value of that variable. On the other hand, very small variations in a second variable may lead to substantial changes in the results. The model is then said to be highly sensitive to changes in the value of the second variable. This sort of analysis helps the model builder identify variables for which a probabilistic analysis would be most valuable.

In a sense, a sensitivity analysis indicates how adequate a deterministic model is. If many scenarios are considered, and the results of the model (whether in terms of inferences or in terms of decisions) do not change much, then the deterministic model provides a good approximation to a probabilistic model. In this case, unless a great deal of precision is desired, it may not be worth the time and effort required to develop a probabilistic model. If the different scenarios lead to different results, on the other hand, then the deterministic model is highly suspect and a probabilistic model would be quite valuable.

It must be emphasized that in conducting a sensitivity analysis, it is important to vary the values of different variables simultaneously. Because of dependencies among variables, it is not sufficient to adjust just one variable at a time. This implies that a thorough sensitivity analysis requires a large number of scenarios, with all sorts of combinations of values of the variables investigated. As the number of scenarios increases, of course, the time and effort required increase and the results of the sensitivity analysis become more difficult to interpret. The larger the number of variables and the greater the degree of dependence among variables, the greater the difficulties are.

An even more serious problem involving sensitivity analysis is that although the sensitivity analysis may give the model builder some idea of the potential variations in the results, it does not do so in a probabilistic manner. For example, suppose that a deterministic model, using certainty equivalents, is built to predict the demand for energy in the year 2000, and the point prediction turns out to be 2 Q/yr., where 1 Q = 10^{18} BTU. Suppose further that the model includes many variables (values of the demand for energy at intermediate times, technological advances, etc.) and that a sensitivity analysis is conducted, using a large number of scenarios. The sensitivity analysis indicates that the demand for energy in the year 2000 might be as small as 1 Q/yr. or as large as 4 Q/yr. This is a very large range of values, but it still does not provide any information about the probability distribution of the demand for energy in the year 2000. It may be that the distribution is relatively tight, with a probability of, say, .90 that the demand will be between 1.9 Q/yr. and 2.2 Q/yr.; in which case more extreme values are possible but not too likely. On the other hand, it may be that the distribution has a large dispersion and that the probability is .90 that the demand will be between 1.2 Q/yr. and 3.5 Q/yr., in which case the "extreme" values are not so unlikely. From the sensitivity analysis it is not possible to tell how likely the various scenarios are and thus how likely the various results are.

Therefore, although a sensitivity analysis may give the model builder some idea of how sensitive the results of a deterministic model are to variations in the inputs, it is only a first step beyond the deterministic model. The next step is to build a reasonably simple probabilistic model. Such a model can be constructed by considering a few "representative" values of each variable of interest and assessing a probability distribution over all possible combinations of values. Note that it is not sufficient to consider just marginal distributions of the variables; in order to include the interrelationships among the variables, a joint distribution is needed. In practice this joint distribution is usually broken down into a marginal distribution and a series of conditional distributions. For example, it can be expressed as a product of the marginal distribution of the first variable, the conditional distribution of the second variable given the first variable, the conditional distribution of the third variable given the second variable, and so on. Usually this is expressed schematically in terms of a tree diagram, with the initial "fork" containing "branches" representing values of the first variable, each of which is followed by a second fork with branches representing values of the second variable, and so on. In a sense, this tree diagram can be thought of as a procedure for considering various scenarios, with probabilities assigned to the scenarios. The tree diagram makes it relatively simple to see the logical relations among the variables and to understand the stochastic nature of the model. Note, by the way, that the question of the source of the probability distribution is being avoided here and will be discussed in the next section.

The type of probabilistic model described in the preceding paragraph provides a representation of the uncertainty in the situation of interest. With complex systems involving many random variables, tree diagrams quickly become cumbersome. By utilizing results from the theory of probability, the theory of stochastic processes, and so on, it is possible to generate models that are somewhat easier to work with. Conceptually, however, the idea is the same in the simple probabilistic model as it is in fancier probabilistic models, and the degree of sophistication used in the development of a probabilistic model depends on factors such as desired "closeness" of approximation, computational ease, and so on.

In summary, a deterministic model provides a first step in the analysis of a problem involving uncertainty. A sensitivity analysis can then be used to indicate how variations in the inputs affect the results. Care must be taken in the interpretation of the sensitivity analysis, however, since such an analysis is not probabilistic. In rare instances, the results of the sensitivity analysis may be completely unequivocal (e.g., when virtually all scenarios considered lead to the same result), but in most cases the sensitivity analysis is limited to indicating where a probabilistic analysis would prove most fruitful. The next step is to build actual probabilistic models, with the degree of sophistication of the probabilistic inputs depending on the situation at hand. In general, the process of constructing a probabilistic model is a sequential process, with the model-building activities at each step depending to some extent on the results of the previous step. The aim, of course is to balance off the realism of the model with such factors as the cost of building and solving the model.

The Assessment of Probabilities

Suppose that the premise of Section 2, that it is advantageous to use probabilistic models instead of deterministic models in situations where uncertainty is present, is accepted. Then, using an iterative approach such as that described in Section 3, certain variables are identified as important random variables, or uncertain quantities, and the model builder decides to treat these variables probabilistically. How can this be done (i.e., how can a probability distribution for the variables of interest be arrived at by the model builder)?

The objective in assessing a probability distribution for a variable or a set of variables is to represent all of the information available concerning the variable(s). Instead of trying to summarize all of this information in terms of a single estimate, as in the deterministic models, the model builder wants to summarize the information in terms of a probability distribution. Experts provide a very important source of information. With regard to energy systems, experts on the demand and supply of energy, experts regarding technological developments, experts regarding social and political considerations, etc., might be consulted. These experts could be asked to assess probability distributions for the variables of interest. In the past decade a considerable degree of work has been done in the area of probability assessment. This work, which is continuing, provides procedures that can be used to elicit probability distributions from experts.

Probability distributions obtained from experts are, of course, subjective probability distributions, and as such they may differ from person to person. When subjective opinions differ a great deal it is often desirable to probe the differences in an attempt to find out the root causes of the differences. For example, two potential causes are different interpretations of terms and experience with different sets of background data. In order to somehow "pool" different opinions, it may be useful to consider probability distributions obtained from a group of experts rather than a single expert. Questions such as the consensus of experts' probability distributions and the consideration of group assessments of probability distributions have received an increasing amount of attention recently. In situations such as energy systems, where experts are available and a great deal of the available information is of a subjective nature, the subjective probabilities of experts provide a key input to models of the situations.

Another source of information is past data. In terms of energy systems, past data regarding variables such as demand and supply of energy costs of power plants, inflation rates, and so on, can be obtained. Attempts can then be made to fit stochastic models to the data and to use these models to generate probability distributions for the variables of interest. Sophisticated results from stochastic processes, time series analysis, and other areas relating to statistics and probability may prove valuable in attempting to analyze the past data and to make predictions concerning future variables.

Most probabilistic models of complicated systems involve uncertainties of both kinds: uncertainties that require subjective assessments and uncertainties that can be investigated in terms of objective data. In fact, when objective data are available but sparse with regard to a particular variable, it is generally desireable to consider both subjective assessments and objective data for that variable, and this sort of situation may be the rule rather than the exception. Indeed, it often may be that the only way to exploit objective data about one set of variables is to incorporate subjective assessments about the same variables or about another set of variables. The refusal to include subjective probabilities in a model may force the model out of the probabilistic mode into the deterministic mode, and as a result objective data as well as subjective assessments wind up being ignored. Sometimes an attempt is made to incorporate objective data in a model while ignoring subjective assessments, but this just amounts to throwing away information, particularly in view of the fact that the model-building process is basically subjective anyway (e.g., elements of the model-building process such as the choice of variables, the representation of relationships among the variables, and even the way in which objective data are used in the model are ultimately subjective in nature).

Ultimately, the model builder must decide upon a probability distribution to use as an input to the model. In doing so, he may utilize probability distributions based on analyses of past data, and any other information that may be available. If, for example, the model builder feels that a particular expert has been overly optimistic with respect to a particular variable in the past, it might be decided to adjust that expert's probability distribution somewhat to correct for the optimism. If the assumptions underlying a statistical analysis are somewhat in doubt, it may be decided to adjust the probability distribution that is based on that analysis. Moreover, just as a sensitivity analysis can be conducted with a deterministic model, a sensitivity analysis can be conducted with a probabilistic model to investigate the sensitivity of the results to variations in the probability distributions. This may provide the model builder with some idea of what aspects of the probability distribution need particular care and what aspects are not so crucial. The overall objective, naturally, is to arrive at a probability distribution that represents the current state of information with regard to the variables of interest.

An important topic related to the assessment of probabilities is the revision of probabilities on the basis of new information. As noted in Section 2, one important aspect of probabilistic models is the adaptive nature of the models with respect to new information. As new information is obtained, Bayes' theorem provides the formal mathematical mechanism for revising probability distributions. The application of Bayes' theorem requires the assessment of likelihoods that represent the impact of the new information with regard to the variables of interest. These likelihoods are then formally combined with the original probabilities to yield a revised probability distribution. The assessment of likelihoods is similar to the assessment of the original probability distribution; experts may be consulted, certain statistical models may be useful, and so on.

To give a detailed discussion of the assessment of probabilities and the revision of probabilities on the basis of new information would require too much space. The purpose of this section was to cover briefly some of the notions involved in the assessment and revision of probabilities . These notions, together with the discussion in Section 3 of moving from deterministic models to probabilistic models, should provide some indication of how the suggestion of using probabilistic models can be implemented. For more detailed discussions of these notions and of probabilistic models in general, see Raiffa [2] and Winkler [4].

Risk and Reliability

One area related to energy systems for which the notion of probability has been used is the area of "risk and reliability". (e.g., Otway, Lohrding, and Battat, [1], Starr, Greenfield, and Hausknecht, [3]). In this context the term "risk" generally refers to the possibility of effects detrimental to health or, in the extreme, causing death, directly related to installations such as nuclear power plants. These concerns are based on factors such as the potential emission of pollutants (including radioactive pollutants) and the possibility of large-scale "accidents". The "risks" are measured in terms of probabilities that may represent mortality rates, probabilities of various types of accidents, and so on. In turn, these probabilities are related to the "reliability" of the installations in question, hence the term "risk and reliability".

The events of concern in "risk and reliability" studies tend to be relatively rare events, and the probabilities are very small. Such events are difficult to deal with, partially because they occur so seldom that it is difficult to build up any sort of experience with them. In other areas, rare events are considered (in a "risk" context) regularly, and it may be possible to look at such well-established areas to see how rare events are handled and how the concept of risk is considered. A prime example is the area of insurance, where for a certain premium, an insurance company will assume the risk associated with a particular rare event.

Probabilities such as those mentioned in the preceding paragraphs are certainly relevant with respect to models involving power plants, particularly where alternative types of power plants are being considered. With respect to the modeling of energy systems, however, this is but a small portion of what one might call energy systems. As indicated in the previous sections, probabilities should be considered for many different types of variables relating to energy systems, and it would seem that probabilities relating to risk and reliability are no more valuable than probabilities relating to other aspects of energy systems. The probability of adverse health effects or death due to a particular type of installation is important. But what about the probability of a severe energy shortage within the next two decades? What about the probability that the cost of a particular form of energy will increase tenfold over the next decade? What about the probability that technological developments will lead to a new, cheaper form of energy that is not now known? Probabilities such as these all seem very important and very relevant for the modeling of energy systems, but they do not seem to be considered (at least formally) in current models relating to energy systems.

In a sense, the use of probabilities in "risk and reliability" studies entered through the back door, under the category of "risk". Indeed, it appears that in such studies probabilities such as the probability of death are treated as measures of risk. This is in accord with the everyday use of the term "risk" by the layman, but it is an oversimplification from the standpoint of statistical decision theory. In statistical decision theory, a decision maker's attitude toward risk in general is measured by a utility function that represents the decision maker's preferences for various outcomes, or consequences. For any specific decision-making problem, the action chosen by the decision maker should depend on the probability of various consequences <u>and</u> on the preferences for the various consequences. Probability <u>is</u> used to represent the uncertainty concerning the various consequences, but this does not provide any information about the decision maker's preferences.

For inferential purposes, probabilities will suffice. For decision-making purposes, some consideration must be given to "values", or preferences for consequences. Furthermore, the consideration of probabilities should be separated from the consideration of values; the formal decision-theoretic framework can be used to take both aspects into consideration in determining an "optimal" decision.

The consideration of values is a difficult question that requires careful investigation. For most problems of interest, and certainly for large-scale problems such as energy, the consequences of concern involve multiple attributes. Decisions regarding energy systems involve considerations such as the costs of alternative systems, the cost of energy to the consumer, the impact on the environment, the impact on the climate, and so on. Some work has been done in recent years regarding multiattribute utility, and hopefully this will prove useful in the modeling procedure. Another point of interest is that large-scale problems invariably involve societal effects as well as individual effects, and the question of aggregating individuals' preferences or talking of "society's preferences" is a complex and difficult one. Nevertheless, issues such as this need to be considered in modeling large-scale systems.

In summary, the area of "risk and reliability" has utilized probabilities to some extent, but there are many more ways in which probabilities would be useful in the study of energy systems, potentially even more useful than in the context of risk and reliability. Moreover, the term "risk" suggests considerations of preferences for various consequences, and such preferences are an important input for decision-making models. It is important to distinguish between uncertainty concerning variables and preferences concerning consequences; these two concepts should be considered separately and brought together by the formal model.

Implications for Future Research on Energy Systems

As noted in Section 2, model-building activities in the area of energy systems have focused almost exclusively on deterministic models. In this paper an argument is presented for the use of probabilistic models. The world we live in is an uncertain world, and probabilistic models enable the model builder to formally include uncertainty in models. Because the world is not deterministic, the results of deterministic models must be viewed with some suspicion; in contrast, probabilistic models have the advantage of being adaptive and allowing decision making to be treated in a dynamic sense.

Deterministic models represent a first step in model-building, and it is an important first step. Sensitivity analysis provides further information and may help to suggest variables for which a probabilistic treatment would be most useful. The probabilistic models themselves can range from very simple decision trees to very complex models that use advanced mathematical results. The probability distributions that represent the model builder's uncertainty may be based on probability distributions assessed by experts, on past data, on forecasts generated by sophisticated statistical procedures. Once the probabilities are assessed, the model can be solved, using analytical techniques if possible and numerical methods otherwise.

One small aspect of energy systems, that of risk and reliability, has received probabilistic treatment, as noted in Section 5. In addition, probabilities should be considered for many different types of variables relating to energy systems.

Furthermore, an aspect other than uncertainty should be considered: preferences for various outcomes, or consequences. This can be thought of as the "value" side of the question. To the extent that models of energy systems have decision-making implications, consideration of values as well as consideration of uncertainties should prove most valuable. The overall objective, of course, is to make the model as realistic as possible, including as much information as possible, within the constraint of keeping it workable.

The major implication of this paper with regard to future research on energy systems is that probabilistic models should be investigated. Initially, this might best be accomplished by starting with a deterministic model that has already been constructed and moving to a simple probabilistic model. To avoid getting bogged down in details with an initial application, the model chosen might be a relatively small-scale model. Hopefully the use of probability could then be extended to more complex models. Two parallel streams of research, one involving continuing work on methodology related to probabilistic models and one involving applications of probabilistic models to energy systems, would complement each other quite well.

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Summary by the Conference Chairman

W. Haefele

In summing up the deliberations of this conference it might be useful to recall briefly the purpose of this conference.

The study project on energy systems of the International Institute for Applied Systems Analysis is at its beginning. This conference was meant to help to clarify what the scope of the problem really is. If compared with the traditional treatments of certain technical energy problems it is the term "system" that broadens the energy problem. What are energy systems? There is remarkable readiness among some technical and industrial people to accept the so far unexperienced challenges that today go along with the production and handling of energy. But there is a strong desire to know more definitely what these challenges eventually are. Will there be tomorrow new surprises? Therefore the question arises: Do we ask the right questions?

The principal speech of the Conference Chairman was intended to identify the scope of the problem of energy systems. It was not the idea there to report on results in the ordinary sense. It now appears that in the course of the conference no new major problems came up. While the question about the right questions principally remains we can now at the end of this conference be somewhat more assured that the scope of the problem of energy systems is somewhat understood.

The next part of the conference dealt with the near term situation and its inherent trends. Mr. Barratt elaborated on the important aspect of oil. He made a distinction between the situation in the US and other countries like for instance Canada. But also explanations on the world-wide partition between oil producers and oil consumers were given in detail. This presentation was complemented by the report of Mr. Janin. Electricité de France is a very large organization and this makes the meaningful application of large LP codes possible. But he also pointed to the difference between formal optimizations and the realities of existing infrastructures. The wishes of the consumers, the interplay between social and external costs were elaborated on. Mr. Oshima gave a similar report but on a different situation. He reported on the intermediate aspects of the energy situation in Japan. This country prepares for the really large scale application of nuclear energy as nuclear energy is considered to have a quasi domestic fuel supply, an overriding aspect for Japan. He reported on the very strong coupling between energy and the gross national product (GNP). It was astonishing to learn how difficult it is to decrease the rate of increase for the GNP. Attention should be paid to the fact that Japan's approach to nuclear energy is part of an overall scheme that may be what Mr. Weinberg called "a coherent doctrine". The area of mathematical modelling covered a major part of the conference. Mr. Hutber reported about a model that covered not only one country or a group of countries but most of the globe. His model is employed to sense the various relationships including the aspects of large transports. Mr. Hoffmann explained then his model which deals with the economy of an industrialized country a few decades from now. Fuel interchangebility, consequences of certain policies and regulations, the impact of environmental considerations were among the points of attention.

Messrs. Zvetanov, Knop and Dudin enlarged the scope of mathematical modelling by reports on activities in their home countries. The relation of prices and more general objective functions for optimizations were a major point in their contributions. The discussion revealed the major problem of the relation between the domain of the model and reality. Models have to select necessarily a limited number of parameters. Often much sophistication is employed to make the model within its own limitations self-consistent and elaborated while at the same time the identification of parameters and thereby the relation of the model to reality remains a crude thing.

As an introduction into another part of the conference Mr. Ananichev reported on energy conversion. He brought out the point that it is not sufficient to administer shortages. It is rather necessary to have a vision and to properly assess the role of technology. He stressed the wish to consider the globe as a system that is driven by an external force, the sun. Against such a background the alternatives for a global energy supply should be carefully investigated. The discussion revealed the fact that this requires probably sophisticated scenario writings. Warnings came out not to translate today's conditions into tomorrow's situations.

The deliberation of the conference went further. The observation was made that tomorrow's situations will be largely characterized by the problem of the embedding of energy and its related system problems. The large scale of the use of energy and the finiteness of the media of embedding lead into complex interactions. Nuclear power is probably a pilot venture for that as it is

- pushed at a truly large, world-wide scale
- followed over long time periods
- made to make a qualitative step in technology

- implemented with much precautions and planning.

It should be remembered that the term "big science" was coined with such experience in mind. If one generalizes from that one concludes that system problems

- are caused by large scale human ventures and the finiteness of the globe

- require a certain degree of sensibilization for detecting them early

- lead into the necessity to study alternatives.

The comparison of alternatives always brings up the problem of comparing different values: "apples and pears." This leads as a task for systems analysis into the formulation of new problems that can be understood by discipline oriented scientists. Systems analysis must also provide ways and means to couple such analysis to the decision making process of today.

Mr. Weinberg's talk exemplified this. In putting the question: "Can man live with fission?" he arrived at the question of reactor siting as a salient problem that is actual on the one hand and has all the long range systems implications on the other hand. Mr. Marchetti's talk on hydrogen was the necessary complement to Mr. Weinberg's considerations. Hydrogen together with electricity as a secondary fuel implicitly allow for many adjustments. Again this leads into the necessity of modelling.

Mr. Lamb then introduced the problem of climate as Man's impact on climate is probably the ultimate limitation for the use of energy. The dimension of the problem became obvious. The role of the water cycle and its interweavings with energy and the weather came into focus. The discussion made it clear that more work is required to assess the meaningful function of systems analysis in this very large field. Mr. Roberts' contribution helped to bring these considerations into the perspective of the problem of growth and the related modelling.

The final part of the conference covered aspects that are special in the traditional, discipline oriented sense but overriding from a systems point of view. Mr. Skjoeldebrand reported on the success of building up and implementing a system for safeguarding nuclear material. The point here is not so much the mathematics or the logics of that but rather the fact that this system is global in nature and truly implemented including all aspects of politics and day by day life. Safeguarding of nuclear material is a systems problem and therefore it is worthwhile to consider extensions, probably into the domain of pollution.

The contributions of Mr. Otway introduced the problem of risk evaluations and the handling of risk as a parameter in optimizations and decisions. The discussion made it obvious that this is a most general theme that is by no means restricted to energy systems. It will be probably a theme that goes through most of the activities of IIASA as it is also clear that the methods for dealing with risks are in their infancies. In that connection Mr. Barabas pointed to the subject of quality control. Often this is looked upon in traditional terms of fabricating goods, but the mathematical tools of reliability control bring this field into a new context. Mr. Winkler's observations on probabilistic methods versus deterministic methods threw a light on that also.

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