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PROJECT STATUS REPORT: ENERGY SYSTEMS

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Introduction

Wolf Häfele

The first status report of the IIASA Study Project on Energy Systems is meant to give information about the present stage of the Energy Project. Its addressees are mainly the scholars and members of the IIASA itself. But at the same time this also allows for a somewhat broader dissemination of this information. Such a status report cannot be a brief substitute for the sum total of all information available. To obtain this more thorough and exhaustive information we must refer to the scientific papers that have been finished so far. The purpose of this status report is rather to present a profile of the Energy Project as a whole. This is important to note as it is not possible to deal with all conceivable aspects of energy systems--the IIASA Energy Project is by far too small for such a parallel and broad approach. Instead, the various lines of attack are carefully selected in such a way as to serve as possible benchmarks within the scope of energy systems. It is then, of course, decisive to demonstrate the meaning and the interaction of these benchmarks. To contribute to this goal is another important aspect of this status report.

A zero order approach to explain the scope of energy systems was made on the occasion of the IIASA Planning Conference on Energy Systems in July 1973, and explicit reference shall be made to the proceedings of this conference. So we refrain from repeating all these deliberations.

Perhaps the most striking feature of the energy problem is its drastic change of nature in the course of time. In the past as well as today the energy problem has been largely a problem of resources and of the distribution of scarcities, while in the long run there will be virtually inexhaustible resources for the production of energy, such as the fast breeder or solar power. The perhaps most crucial systems aspect of energy, therefore, is to evaluate the aspect of the timing of the energy problem: Which problem comes first, and when does which problem come in? This approach stresses the need for the establishment and evaluation of strategies with a view to supporting and expediting the understanding necessary for actual decision making.

It is along this line that the work on reactor strategies has been stressed. The nuclear option for the long range supply of energy is best understodd and much information is available there. The work on reactor strategies studies the conditions for the transition from fossil to nuclear fuels. Of interest there is in particular the interaction between the limited resources for oil and gas, cheap uranium and the requirements for reactor construction capacity. The approach is to consider model societies of 250 million people in 1970. This makes it possible to eliminate the open-ended question whether the model adequately enough reflects the details of actually existing societies, so that the questions of such transition can be concentrated upon and dealt with more directly. At the time the status report was being edited, the paper on Strategies for a Transition from Fossil to Nuclear Fuels was completed. Therefore reference is made to this IIASA Research Report (RR-74-7), appearing simultaneously with this report, and it is not necessary to repeat a previous unfinished version of this work here.

The Strategy paper employed discounted total costs as an objective function in the linear programming model. It is obvious that for an assessment of the nuclear option as a whole it is necessary to describe the other aspects of this option comprehensively, and this leads to the second line of attack, the unified description of the nuclear energy (fission) option. Today we are on the threshold of installing civilian nuclear power on a truly large scale, and this requires the installation and operation of a so far unexperienced large fuel cycle. This leads to a number of assessments within the nuclear option. What is the appropriate level of reactor safety in comparison with the safety of long term waste disposal? How do the normal operating losses that are involved compare with the provisions for physical protection? Are they consistent, and what does consistency mean in this context? At present this work is being executed on the level of expectation values. This is not sufficient and now (June/July 1974) we hope to advance to the level of utilities.

Besides the evaluation of the aspects of timing, the comparison of options such as nuclear fission or solar power is a recurrent theme of the work of the Energy Group. The unified description of each of the options in question, therefore, is at the core of our work. After the completion of the unified description of the nuclear option, which is expected for this summer, we hope to deal with the solar option accordingly.

A more near-term aspect of the energy problem is the mathematical modeling of energy demand and supply. Besides the task of establishing such models ourselves, it is also the function of IIASA to act as a clearing-house on related information. Efforts have been made to compile information on such existing mathematical models. After the presentation of the status report but prior to its publication, the IIASA Energy Project held a Working Seminar on Energy Modelling (Laxenburg, May 28-29, 1974). On this occasion a more complete version of the review on energy models developed in various countries was presented. Besides the early and short description of this work in the present status report, one should also see the forthcoming IIASA proceedings of this subject.

The mathematical modelling of energy demand and supply is important because it serves as a sensor that relays the details of today's and future economies to the level of assessment making, be it technological, environmental or others. For instance, what is the level up to which energy conservation is feasible, and what are the consequences? What are the implications if the partition between secondary energy in the form of electricity and in the form of non-electricity is changed? Such questions have strong implications for instance in the strategy paper mentioned above (RR-74-7).

If one wants to deal with energy problems it is mandatory to deal with the problem of resources. The deeper one gets into this problem the more complex it becomes. An effort is under way to compile data and incorporate as many countries and regions of the world as possible. We also hope that in this way it will be possible to identify systems effects of the use of energy resources, such as pollution, waste, land use, interaction with the hydrosphere and others. It is obvious that here we are at the beginning.

Societies that could be related to our model societies and energy resources are not separated. The world contains many of these at the same time but they are at different stages of evolution and use. The question therefore arises: What are the actual interactions between these societies and resources? We have started to make preparations for a model of world trade and world research and development in the field of energy. At present we have a high level of aggregation. Three classes for the size of resources and three demand classes are considered and a two-dimensional matrix is used to relate these classes and place the various countries within this matrix.

At IIASA's Energy Planning Conference in July 1973 much emphasis was given to bringing the aspect of energy embedding into the forefront. The handling of waste heat was of particular interest there. The Energy Group has established contacts with the British Meteorological Office (BMO) and the National Center for Atmospheric Research (NCAR). It was possible to consider a few typical cases of global circulations. More results are imminent and much more work is expected. More specifically it is the problem of placing large primary energy parks in the open ocean that is being considered. The Energy Project will try to make the aspects of siting and land use the third main theme within and without the Energy Project.

Another line of attack that is expected to act as a benchmark is the problem of hydrogen as it complements electricity as a secondary form of energy. In so doing the question of market penetration again relates to the general and pervasive theme of timing. A report on the recent Miami Conference completes the hydrogen picture to some extent (RR-74-4).

Finally we are reporting on the smaller albeit somewhat permanent effort on the verification problems of nuclear material accountability.

Note on
"Strategies for a Transition from Fossil to Nuclear Fuels"

The second presentation was jointly delivered by W. Häfele and A. Manne and dealt with "Strategies for a Transition from Fossil to Nuclear Fuels."

As explained in the Introduction, this contribution is not reproduced here. Instead, the completed version of this paper is issued separately as a IIASA Research Report (RR-74-7) complementing this Status Report.

Unified Description of the Nuclear Energy Option

Rudolf Avenhaus

Introduction

One of the long term goals in the framework of our project is to evaluate and to compare different energy options, for example nuclear energy, solar energy and geothermal energy. In order to achieve this we chose the following way. We consider a model society of a given size with a given energy consumption and assume that all of the energy needed is provided by one of the options mentioned. Only after we have evaluated all the aspects of at least two of these options separately shall we try to compare different ones.

It is the aim of my presentation to report on the work which has been done so far by Prof. Häfele, Dr. McGrath and myself in the case of the nuclear energy option. Especially I would like to emphasize the methodological aspect of this work for the following reason. Whereas all the single aspects of the various risks inherent in the nuclear energy option have been treated and evaluated during the last 25 years, according to our knowledge no effort has been undertaken up to now to find a common basis for all these risks.

The starting point of our consideration is the asymptotic Liquid Metal Fast Breeder Reactor and High Temperature Gas-Cooled Reactor System discussed in the presentations of Prof. Manne and Prof. Häfele-- more specifically, the system with a power production of 3600 Gigawatt which is meant for a society of $360 \cdot 10^6$ people with an energy consumption of 10 kWatt per capita. Whereas it is not necessary to go into the physical details of the reactors themselves we have to consider the whole nuclear industry which is necessary for the operation of the reactors. As an illustration let us consider that part of the nuclear fuel cycle which belongs to the FBR system (Fig.1).

Natural uranium is brought into the system; after some chemical processing uranium oxide pellets are manufactured which are put into the fuel elements. At the same time, plutonium-uranium-oxide pellets are produced with the help of the plutonium bred in the reactor. There is even one more sort of pellets in the FBR which is part of the HTGR system; I will not go into the details of this. The plutonium-uranium elements are brought into the reactor and stay there for about 3 years. Thereafter, the spent fuel elements are taken out and are processed in the reprocessing plant: the fission products are separated from the plutonium bred and the uranium not used; plutonium and uranium go again into the fabrication plant whereas the fission products go after some further treatment into the final waste storage. Some figures: to maintain this fuel cycle, per year 751 t natural uranium has to be fed into the system; the recycled quantities are 9882 t of uranium and 924 t of plutonium. Because of mass balance reasons the amount of material leaving the cycle must be the same as that entering the cycle. It leaves the cycle in form of waste. The total waste of the cycle amounts to 1702 t per year. This is a large amount by weight. By volume it is 300 m^3, corresponding to a cube of 7m length. Having established this nuclear fuel cycle we can ask: What are the problems of embedding this system into the society? In Table 1 we have put together all conceivable risks. There are normal operations releases of various radionuclides which either decay quickly and therefore pose only a problem to the neighborhood of the plant. If the releases per unit time are of the same order of magnitude as the decay per unit time they build up to an equilibrium dose, or they accumulate if they are very long-lived. There are all kinds of accidents considered here: those in reactors, reprocessing and waste storage facilities, and transportation accidents. Finally, there are different kinds of sabotage and blackmailing conceivable.

In the following, I would like to give some explanations and thoughts on the method of the evaluation of these risks and show how it is done in an actual case. At the end, an idea will be given about the status of the work and what has to be done further.

Method of Evaluation

Before I describe the method of evaluation, I would like to say that all the following considerations are for the determination and comparison of orders of magnitude, and not for the determination of precise numerical values.

Having this in mind one can describe all the problems mentioned in the following way. Let us consider a source which constantly releases per unit time a certain amount Q of radioactivity into the air. The physical unit for this is the Curie which counts the number of radioactive decays:

$$Q \left[\frac{Ci}{sec}\right] .$$

The radionuclide released is distributed into the neighborhood of the source; this is described by a quantity $\frac{\chi}{Q}$ which we call distribution factor and which takes into account all the physical and meteorological effects involved in this process:

$$\frac{\chi}{Q} \left[\frac{sec}{m^3}\right] .$$

The result of this distribution is that we have at a given point a concentration of radioactivity in the air

$$Q \cdot \frac{x}{Q} \quad \left[\frac{Ci}{m^3}\right] .$$

This concentration causes a certain burden B for the human body which depends on the nature of the specific radionuclide. This burden is measured in $\frac{m\ rem}{y}$. Therefore, if ρ is the quantity which translates the concentration into the burden we have

$$\underset{\left[\frac{Ci}{sec}\right]}{Q} \; * \; \underset{\left[\frac{sec}{m^3}\right]}{\frac{x}{Q}} \; * \; \underset{\left[\frac{m\ rem}{y} \Big/ \frac{Ci}{m^3}\right]}{\rho} \; = \; \underset{\left[\frac{m\ rem}{y}\right]}{B} .$$

One can interpret this formula in the following way. The first term describes the emission E, the second transforms this emission into an ambient dose rate A in the environment and the third term transforms this ambient dose rate into a burden B:

$$E \; * \; (E,A) \; * \; (A,B) = B .$$

In case we do not have a continuous release of radioactivity, but an accident situation where with a certain probability P per unit time the total amount of $\tilde{Q}$ $[Ci]$ is released, we have the following determinant for the burden:

$$\underset{\left[\frac{1}{sec}\right]}{P} \; * \; \underset{[Ci]}{\tilde{Q}} \; * \; \underset{\left[\frac{sec}{m^3}\right]}{\frac{x}{Q}} \; * \; \underset{\left[\frac{m\ rem}{y} \Big/ \frac{Ci}{m^3}\right]}{\rho} \; = \; \underset{\left[\frac{m\ rem}{y}\right]}{B}$$

To formulate it in mathematical terms in this case we take the expectation value of the burden; that is, we describe this situation as if there were a constant release of radioactivity per unit time. The corresponding dose rate we will call a substitute dose rate.

Without going into further details at this point, I would like to remark that with some modifications which take into account the physical details of the specific situation it is possible to quantify all the risks listed above.

Some remarks have to be made on the translation factor ρ. The determination of the value of this factor for all radionuclides as well as the determination of standards is within the responsibility of the International Commission for Radiological Protection (ICRP) in London. One should imagine the difficulty of this problem; the mode of incorporation of specific radionuclides plays a role. They act on different organs in different ways -- there are long-term and short-term effects. This means that one has to compare quantities which in principle cannot be compared; thus, multiobjective evaluations have to be performed and severe decision problems arise. In addition, difficult extrapolations have to be made as one does not know much on very long term effects of minute doses. One has to perform highly hypothetical calculations which practically never can be tested by experiment.

The ICRP has mastered these problems on the basis of informal judgment and expertise. Nevertheless, as especially the latter consideration is interesting for us and has been studied in a different context, and as these problems meet general interests of our Institute, we intend to study the decision processes of the ICRP in some more detail-- perhaps in collaboration with the forthcoming IIASA project on biomedical systems.

First Example: Normal Operations Releases of Iodine 131 and Iodine 129

Let us consider as a first practical example the case of the normal operations releases of Iodine 131 and Iodine 129 from the reprocessing plant. The half life times of these two isotopes are 8 days for Iodine 131 and 17,000,000 years for Iodine 129, that is extremely different.

According to present day technology (this means according to the decontamination factors DF as they are achieved today) one has a constant release of 57.5 and 0.57 Ci/yr (Table 2).

Although Iodine 131 is very shortlived one has to take it into account because it poses a risk, especially to the thyroid. The dose rate resulting from the release of one single reprocessing plant is 63 $\frac{\text{m rem}}{\text{y}}$ in the environment of that plant; the equilibrium value is 0.69.

In the case of Iodine 129 the situation is different insofar as it does not decay within the time horizon we have in mind, say 100 to 1000 years. This means that we have to take into account the effect of a constant build up of concentration and therefore of dose rate in the air volume of the society.

In both cases we have, at least after some time, a dose rate which is higher than that permitted by the ICRP. This means that the decontamination factors have to be improved. In case of Iodine 131 one can easily calculate the necessary value, whereas in the case of Iodine 129 one has to fix a certain reference time and then determine the decontamination factor in such a way that the accumulated dose is lower than the given standard. This problem poses severe questions of principle. This I would like to mention here only. The result of our calculations is that in both cases the decontamination factors have to be improved by two orders of magnitude.

In Table 3 an impression is given on the result of our calculations in case of all relevant normal operations releases. As one can see, in some cases the decontamination factors are sufficient and in no case do they have to be improved by more than a factor of 100.

Second Example: Accident in a Liquid Waste Storage

Almost any high-level waste management scheme involves an interim storage of the wastes as liquid, the reason being that there are practical and economic advantages to be gained by allowing many fission products with short and intermediate half lives to decay prior to additional waste processing.

In terms of consequences the most severe accident would result from a permanent loss of cooling in the tank. In such a case the semi-volatile radionuclides and a fraction of the remaining fission products would be released to the air.

Assuming that the liquid wastes are stored for 5 years between fuel reprocessing and final waste disposal and assuming that there is $1m^3$ of liquid waste per ton of spent fuel elements, the total quantity in storage at any time would be

a) in case of the FBR:
$1.807 \cdot 10^4 t/y * 5y * 1m^3/t = 9.05 \cdot 10^4 m^3$, and

b) in case of the HTGR
$1.01 \cdot 10^4 t/y * 5y * 1m^3/t = 5.05 \cdot 10^4 m^3$.

Let us assume that an average tank capacity is $3000m^3$. Then the total number of tanks is

$(9.05 \cdot 10^4 + 5.05 \cdot 10^4) / 3000 = 47$.

We will assume that in case of an accident all of the semi-volatile radionuclides and 5% of the remaining fission products are released. Then we can use our formula explained earlier which describes the dose rate in the environment of one tank:

$$B = P * \sum_i Q_i \rho_i * \frac{x}{Q} \left[\frac{m\ rem}{y}\right] .$$

We do not have any experience about the value of the accident probability P as up to now such an accident did not happen; however, this does not mean that one could not calculate some rough figures. If we postulate that the substitute dose rate resulting from such an accident is well below the dose rate set up by the ICRP, say 10 $\frac{m\ rem}{y}$, then we obtain as a postulate to P

$$P \leq 10^{-4} \left[\frac{1}{tank\ y}\right] ,$$

which means that such a "maximum credible accident" is not allowed to happen more often than once every 10 000 years.

Overview on the Results Obtained so Far and Further Work

In Table 4 an overview of all the problems of embedding a large nuclear fuel cycle into a society which we have considered is given. All characteristic constituents for one specific form of a risk are given: location, mode of occurrence, technical parameters regulating the risk and present day values of these parameters.

As a first approximation of an overall evaluation, we have chosen the same reference hazard value for every single risk under consideration, and we have calculated the values of the technical parameters necessary to meet the requirements of the reference hazard value. Thus, we have reached a consistent set of values for the fuel cycle under consideration.

Let me pause here, and make a general remark along the line of what has been said in the introduction. All of the single calculations presented have been made already for a long time; there is no case where we have presented a principal new calculation. What is new here is the fact that we have considered all embedding problems at the same time and that we have tackled the methodological problem,namely to describe and to evaluate all embedding problems with a unified method. In that sense we believe that the set of values presented is the first of this kind.

Naturally, the values calculated depend on the reference hazard value chosen. According to the scheme the total actual value is the sum of all these values, or 13 times the single value.

In Table 5 the postulated values of the technical parameters are given in some more detail as a function of the total hazard value H. This table represents the present status of our work and I would like to say some more words on the work which has to be achieved still.

As already mentioned we have chosen the expectation value of the dose rate which results from a specific case--normal or accidental releases. However, there are differences in the public acceptance of a certain risk which may be expressed in the following way: the public reaction to an airplane accident with 300 casualties is not the same as the public reaction to 300 car accidents with the same number of casualties. In other words, the expectation value of the dose rate may not be the appropriate quantity to be considered in all cases. In addition, we chose the same reference value for all problems considered, and this is by no means a necessity.

These problems are basically methodological problems; thus one may say that the work which has to be done still is the solution of the methodological problem. The mathematical tool for this is called utility theory. It is a happy coincidence that in our Institute here we have some top experts in this field. Therefore it is our idea to apply this theory and try to find the appropriate utility measures for all the risks under consideration. Only after this has been achieved can we try to formulate and to solve the optimization problem: minimization of the burden to the society under the boundary conditions set up by the system. Here, it is to be noted that neither is the "burden" as yet defined in appropriate ways nor are the boundary conditions given-- we have to formulate them ourselves.

Once we have achieved this--we hope in the middle of this year-- we can try to start the corresponding work for another energy option--we have in mind solar energy--and finally to compare both of them.

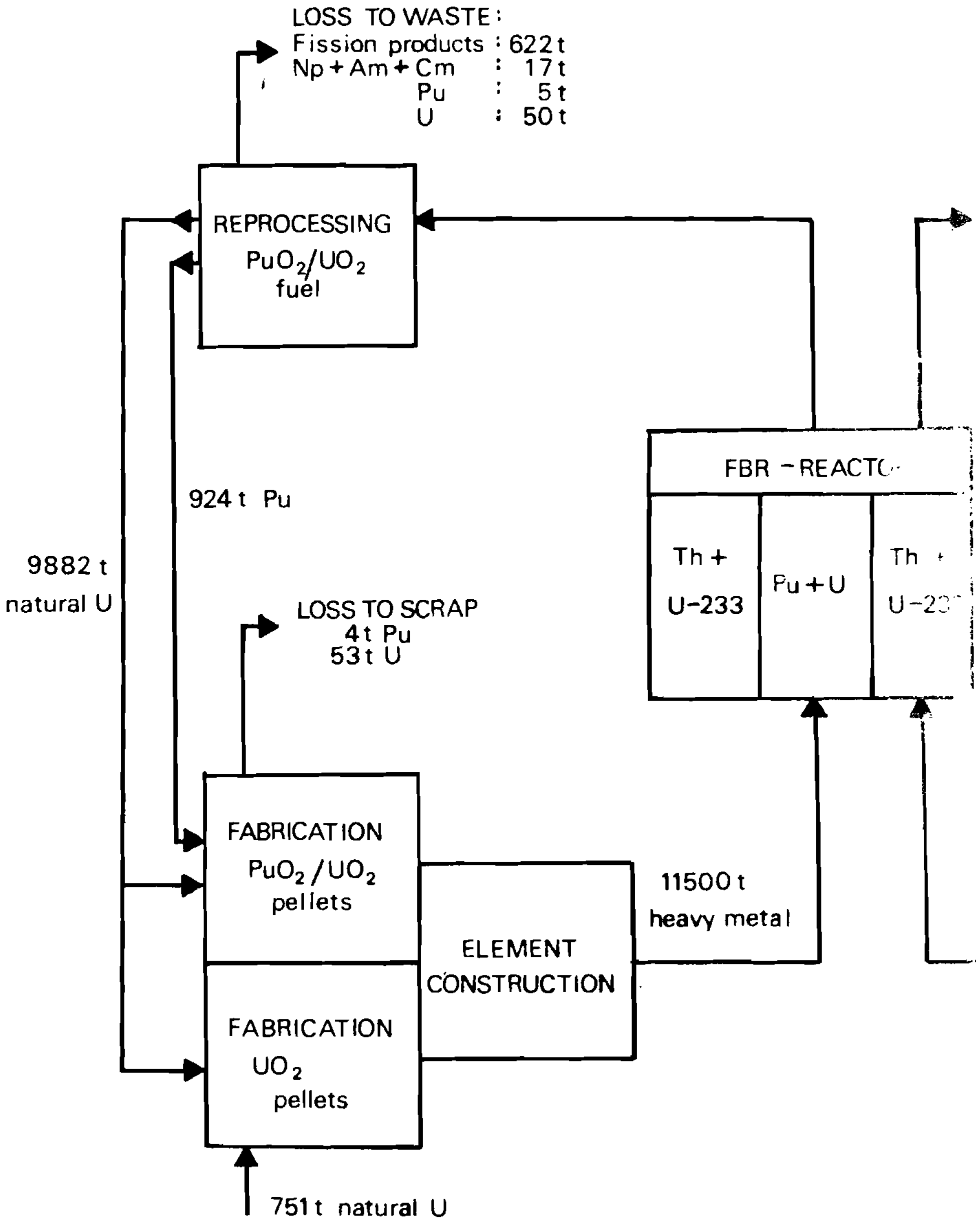

Figure 1. FBR – Part of the Asymptotic Integrated Reactor System; Material Flows per Year

Table 1.

Nuclear Fuel Cycle Risks

1. Normal operations releases
   - 1.1 Point sources
   - 1.2 Equilibrium doses
   - 1.3 Accumulated doses

2. Accidents
   - 2.1 Reactors
   - 2.2 Reprocessing facilities
   - 2.3 Temporary liquid waste storages
   - 2.4 Final waste storage
   - 2.5 Transportation

3. Sabotage and Blackmailing
   - 3.1 Intentional release of radioactive material
   - 3.2 Destruction of facilities
   - 3.3 Explosive device

Table 2. Normal Operations Releases of I-131 and I-129 from the FBR-Reprocessing Plant

	Half life time	Release $\left[\frac{Ci}{y}\right]$	Point source dose $\left[\frac{m\ rem}{y}\right]$	Equilibrium dose $\left[\frac{m\ rem}{y}\right]$	Accumulated dose $\left[\frac{m\ rem}{y} / y\right]$	Present Decontamination factor	Necessary Decontamination Factor
I-131	8d	57.5	63	0.69	-	10^3	10^5
I-129	$17 \cdot 10^6$y	0.57	-	-	1.07	10^3	10^5

Table 3. Present (p) and necessary (n) Decontamination Factors for Normal Operations Releases

	FBR-Reactor-System			HTGR-Reactor-System		
	Reactor	Reprocessing	Waste-Solidification	Reactor	Reprocessing	Waste-Solidification
^{85}Kr	p : 10^3	p : 1 n : 10^2	-	p : 10^3	p : 1 n : 10^3	-
^{133}Xe	p : 10^3	-	-	p : 10^3	-	-
^3H	-	p : 1 1)	-	-	p : 1 1)	-
^{131}I	-	p : 10^3 n : 10^5	-	-	p : 10^3 n : 10^5	-
^{129}I	-	p : 10^3 n : 10^5	-	-	p : 10^3 n : 10^5	-
Actinides	-	p : 10^8 n : 10^{10}	-	-	p : 10^8 n : 10^{10}	-
Semi-Volatiles	-	-	n : 10^5 2)	-	-	n : 10^5 2)

1) However, ^3H has to be separated from the waterways

2) Today, there is no waste solidification

Table 4. Overview on Risks and Numerical Evaluation

	Normal Operations Releases					Accidents					Sabotage and Blackmailing		
	^{85}Kr	^{131}I	^{129}I	Actinides	Semi-Volatiles	Reactor	Reprocessing	Temp. Waste Storage	Final Waste Storage	Transportation	Release Radioactive material	Plant destruction	Explosive device
Hazard $\left[\frac{m\ rem}{y}\right]$	Equ. dose	Point source dose	accumul. dose	accumul. dose	Point source dose	← Point source dose →							
Location of hazard	Whole country	plant site	Whole country	Whole country	Plant site	← Plant site →				anywhere	anywhere	Plant site	anywhere
Mode of occurance	← Constant in time →					← Random →							
Reference hazard value	← Same for all risks $\left[\frac{m\ rem}{y}\right]$ →												
Technical parameter	← Decontamination factor →					← Reliability →			Reliab. Accid. rate	Reliab. Accid. rate	Reliab. rate of attempts	← Rate of attempts →	
Today's value of technical parameter	10^3	10^3	10^3	10^8	-	10^{-7} $\left[\frac{1}{y}\right]$				3.10^{-5} $\left[\frac{1}{No.Tr.}\right]$			

Table 5. Postulated Values of Technical Parameters.
Total Reference Hazard Value: $H\left[\frac{m\ rem}{y}\right]$.

Normal Operations Releases	
Kr - 85, I - 131, I - 129	$DF^{1)} > \frac{13}{H} \cdot 10^{6}$
Semivolatile Actinides	$DF > \frac{13}{H} \cdot 10^{11}$
Accidents[2)]	
Reactor	$\frac{H}{13}\cdot 10^{-10} \leq P^{3)} \leq \frac{H}{13}\cdot 10^{-6}$
Reprocessing	$\frac{H}{13}\cdot 10^{-4} \leq P \leq \frac{H}{13}\cdot 10^{-3}$
Temporary waste storage	$\frac{H}{13}\cdot 10^{-6} \leq P \leq \frac{H}{13}\cdot 10^{-4}$
Final waste storage	$\frac{H}{13}\cdot 10^{-8} \leq P\cdot F^{4)} \leq \frac{H}{13}\cdot 10^{-6}$
Transportation	$\tilde{P}^{5)} \leq \frac{H}{13}\cdot 10^{-6}$
Sabotage and Blackmailing	
Release of radionuclides, Plant destruction	$P\cdot X^{6)} \leq \frac{H}{13}\cdot 10^{4}$
Explosive device	$P \leq \frac{H}{13}\cdot 10^{-4}$

1) DF : Decontamination Factor
2) Dependent of number of facilities
3) P : Accident probability per year
4) F : Fraction of storage content
5) $\tilde{P}$: Accident probability per transport
6) X : Amount of plutonium

Analytical Review of Energy Modelling

Jean-Pierre Charpentier

I will not try to define what a model is. I will only say that a model consists of a schematic representation, by means of mathematical equations, of theories or of economic and/or technical facts (real or expected).

This representation is first qualitative, and is then put into quantitive form. With the addition of a game of either data or numerical hypotheses, this permits us to understand, or illuminates for us, phenomena so complex that the human mind would often be unable to appreciate them without this tool.

In spite of all this, a model cannot solve every problem at the same time as this tool is itself restricted; for instance, the goal of the model which has just been explained to you focused mainly on 2 points:

1. the technological comprehension of the newly proposed energy system: the FBR reactor which generates electricity and the HTGR reactor which produces heat;

2. the timing of requirements with respect to fissile fuels.

As interesting as this model may be, one must bear in mind the fundamental hypothesis of the demand on which this model is based: 10 or 20 kW/cap.

In fact, we must be aware that a model does not always provide an absolute answer but rather a conditional one: the results obtained must always be considered parallel to the hypotheses of the data diagrams considered.

Now, these hypotheses often require in themselves the preparation of different models in order to confirm them or discover their weak points.

In the present case, this will, in fact, be done within the Energy Group with the forthcoming completion of a model which investigates the energy demand.

We must note that a major effort must be made on the demand approach, more intensive study being required.

It is still too early to discuss the problem. Let us therefore return to the consideration of our particular review of energy modelling, of which a first version was distributed on the occasion of The Energy Modelling Meeting held May 28-29, 1974.

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Summary

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I Review of Energy Modelling

1. Some Considerations on Energy Modelling

A. Goals[1]

Various countries have completed econometric models for the total energy economy in order to understand the working of the energy markets better and to help the public authorities intervene more efficiently.

Four essential aspects may be identified:

a) Quantification of the assumed interrelations between the various factors which have affected the demand and supply of energy in the past.

b) Forecasting of the future evolution, particularly of the reversal of trends, which cannot be anticipated by traditional methods (correlation, extrapolations...).

c) Evaluation of the effects of various general political measures.

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[1]Interesting considerations on this point are developed in the report: ST/ECE/Energy/13/Add. 1 of May, 17, 1972, of the "Economic Commission for Europe" - United Nations.

d) Optimization of the development and structure of the entire energy system.

In the early stages, we will confine ourselves only to quantitative econometric models as these are the furthest elaborated result of a long course of evolution and no standard solution has yet been found to the problems which they pose. We will thus leave aside (or at least we will not deal with them at the same time, or in the same form) the qualitative descriptions (even those which are accompanied by a series of data, e.g. the RAND study of the electric energy consumption in California) as well as the very simple models in which the various factors are not totally interconnected. (I am thinking here, in particular, of all extrapolationary models or models of simple correlation.) Excluding these models from our review for the time being, in no way means that I attribute a negative value judgement to them. Quite the contrary, since, due to the fact that they are so simple and clear, I already know to what extent they can be of use to all those concerned with energy forecasting. These methods will not be itemized in this review uniquely for reasons of homogeneity. In spite of this, an exception to the rule will be made when a new and interesting econometric aspect occurs: e.g. the study of correlation made by Brookes (U.K.) who introduced the concept of useful energy.

B. Historical Account

Around the fifties the idea of building models was conceived in most countries, but the actual development of this idea may be traced to the mid-sixties. This new impetus resulted, above all, from reactions to the inability of traditional methods to forecast important changes in the energy supply (petrol or coal at that time). The isolated extrapolations and regressions were not able to indicate the reversal of particular trends, whilst it was possible that this might be achieved with models.

Another fact which also accelerated the development of models was the increasing recognition of interest in long-term planning. This must include the optimization of the entire energy system and not be limited to individual plants. This last remark enables us to understand the interest, which has begun to be apparent, in models which permit the linkage of certain sub-models (with very specific goals) in such a manner as to treat the energy system in its entirety (cf. Hutber's model in U.K.). Finally, an increasing number of international problem studies have appeared and are continuing to be published: e.g. Deam's (U.K.) models with regard to the petroleum market, or Klein's model (University of Pennsylvania) of the interconnection of the various national economies; or the study, at present being carried on by the Commission des Communautées Européennes, of the energy market of Europe. For our review, we will not, in the early stages, be dealing with world models of the kind designed by Mesarovic and Pestel.

History of Energy Models

1940 - 1945

Start of R.O., completion of military models during the Second World War.

Energy

End of 1950

Spread of computers 1. electronic processing data 2. perfecting of energy statistics	)Beginning of energy)modelling particu-)larly of modelling)for specific sectors.

Mid 1960

Problem due to important changes in connection with the energy supply: coal or fuel oil. Difficult problem of general economic policy: expected developments ⟹ need for long-term planning	)Global econometric)models: e.g.)Netherlands, 1962)USSR, 1963)France, 1960

About 1970

Beginning of international exchange. Problem of international evaluation of the effects on the national energy economies of a demand consisting of energy agents which have resulted in international exchange (e.g. Deam, CEE, Klein).

C. Limits of the Models

Even if the purposes to be achieved by the models may be extensive, it is, nevertheless, more reasonable to attempt to see the limits of this method.

Five essential limits may be distinguished:

a) The models, however well they may be built, cannot capture all the aspects of reality;

b) They cannot be sufficiently detailed; this is often the case with regard to computer progressing;

c) They are based, up to a certain point, on the personal judgements of the author, and to a lesser degree refer to sociological studies of the components of the various agents, specifically in the demand models. This problem makes the objective preparation of international models in particular, very difficult;

d) Their value depends on the value of the basic information, which is very often either difficult to obtain, or provided in a form which does not correspond to the envisaged mathematical study;

e) Last, the mathematical tools at the disposal of the model builder that are of a form to be truly operational are still few in number. In practice, the majority of models had recourse to linear programming.

2. Classification of Models and Criteria of Choice

A. Classification

To date, taking into account the relatively small number of models for which we have a complete description at our disposal, the only criterion for selection is the date of its creation. We will only deal with models which are less than 5 years old or which are still used today.

The models are classified on the following chart:

MODEL CLASSIFICATION

AREAS of APPLICATION			NATIONAL			INTERNATIONAL		
			Author	Country	Kind of Model	Author	Country	Kind of Model
Econometric Models	Energy is the main problem	One kind of fuel	e.g. Häfele-Manne	IIASA	"Model Society"	e.g. Deam	U.K.	World petroleum market
			E.D.F.	France	Invest.	Houthakker	U.S.A.	
			Panach - (CEA)	France	Nuclear Simulation			
		Several kinds of fuel	e.g. K. Hoffman Baughman	U.S.A.	Supply and demand inter-fuel competition	e.g. Battelle	C.E.E.	
	Linkage between energy and general economy		e.g. FINER	France		e.g. Klein	U.S.A.	Linkage between cliff economies
Miscellaneous techniques (e.g. regressions etc.)			e.g. Brookes	U.K.	Correlation "useful energy"			
			"Mic-Mac" method	France				

In May 1974 we had at our disposal at IIASA:

a) 5 - 7 models described in great detail;

b) 10 models described concisely;

c) Approximately 50 short model descriptions or documents relating to various studies which cannot be termed models but which may be useful for building them.

We now have at our disposal:

- about fifty well described models;
- about a hundred diverse documents: concisely described models or the beginnings of studies which may be used for models.

B. Standard Summary

For the meeting at the end of May, we published a first review in which the models at our disposal are summarized in a standard form. This review contains approximately sixty standard summaries of different models.

The following chart (Annex 1) provides an example of this, based on the model of K. Hoffman (U.S.A.), who carried out a study for the U.S.A. on the best way to relate the energy demand for each sector of the economy to a given structure of production, taking into account the various costs.

Figure 1 shows how the flow of energy between supply and demand for a given country may be represented diagramatically. In this way the model developed by Hoffman tries to find the optimal technical structure of the U.S. energy system. The model provides a feasible path between 13 exogenous supply categories and 15 exogenous demand categories. The objective function is the minimized solution of the present amount of the cost of the different possible paths. Three kinds of constraint must be satisfied: the level of each kind of demand, the possibility of each kind of supply system, and the admitted level of the different pollution.

Now, let us look at the summary chart (Annex 1):

Item 1 is only devoted to bibliographical data: the name of the author, the title of the model, and where it is published.

Item 2 describes the subject and goal of the model. But as it also seems very important to know exactly which lines have been followed in the description of a model, I have added:

Item 3 "System described": it should give a general idea of the complex interactions within a system described.

After this general description of the system studied and the goals aimed at by the author, the two following items

"Modelling Techniques" and "Input Data"

try to make a clear distinction between what is endogenous and what is exogenous. The item "Modelling Techniques" tries to give the description of all logical aspects of the model. The mathematical aspect is not detailed and only the main concepts which explain the internal structure of the mathematical representation are drawn up.

In each selected model we will try to give an idea of the volume of the input data and to make a clear distinction as to what is exogenous, although this notion is not always clear in the original papers.

The item "Output Data" only indicates the kind of results given by the model. The quantitative values supplied by each model often are too large to be incorporated in such a summary.

Finally, the item "Observation" is mainly devoted to possible future developments of the models.

C. Subsequence Studies

a) When we have sufficient information and models we hope to select 4 or 5 of these which we will try to process directly on the IIASA computer.

b) In the forthcoming month we will prepare a model for the study of the energy demand which, as we have already pointed out, often has to be left out in most models.

II Forthcoming Energy Meeting

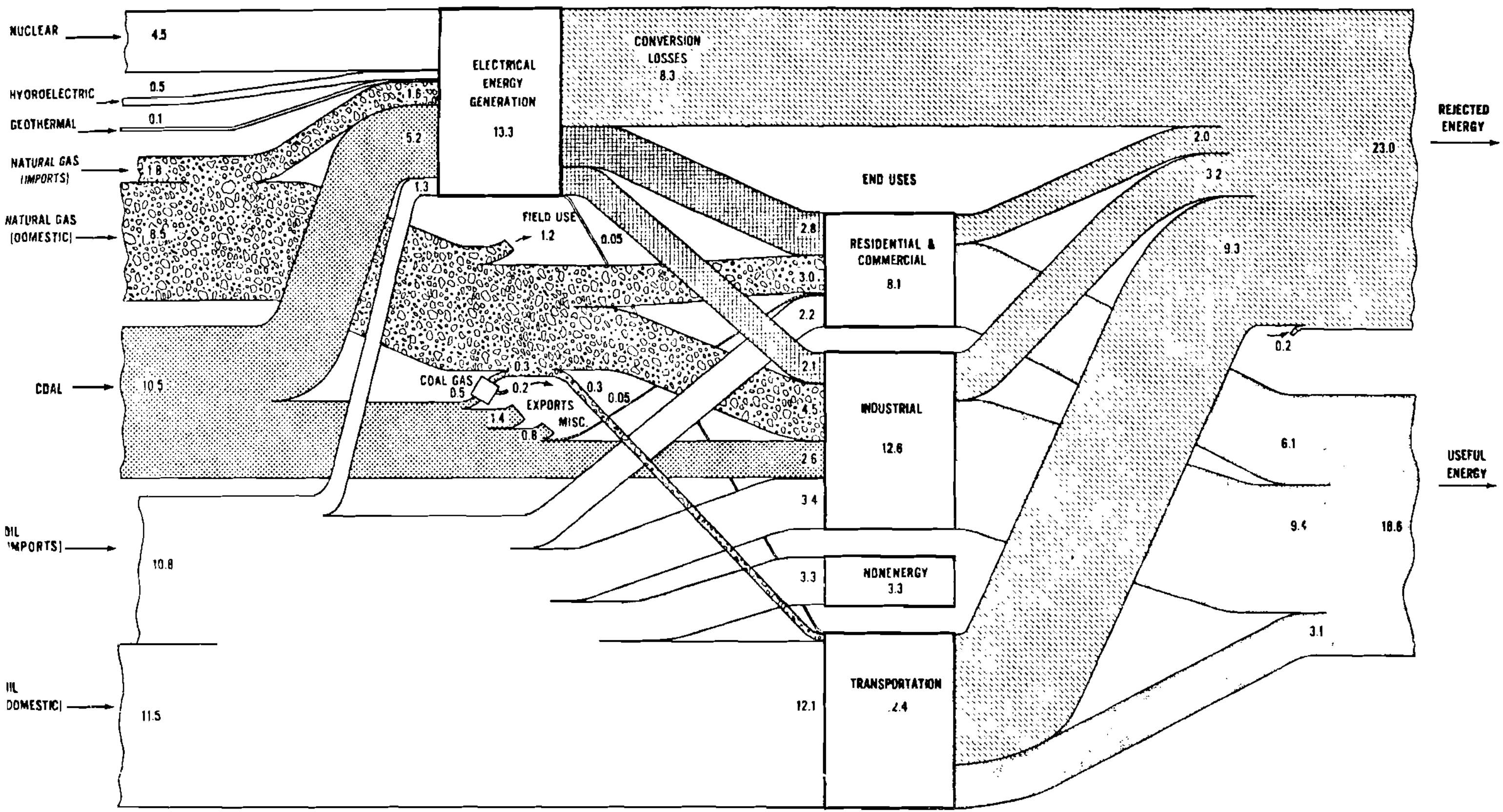
A meeting of energy modellers took place on May 28th and 29th at Laxenburg. There were approximately 60 participants, with at least 1 representative of each of the IIASA member countries.

(annex 1)

1/ Bibliographical data		Kenneth Hoffman (Brookhaven National Laboratory) "A unified planning framework for energy system planning" Polytechnic Institute of Brooklyn, USA - June 72
2/ Subject and goal		Optimal technical structure of the US energy system. Includes final demands and primary consumption. The model reflects a wide range of energy technologies and interfuel substitutability. It traces paths from primary consumption to final demand for each type of fuel.
3/ System described by the model		This model is concerned with the substitution of different fuels at the level of disaggregated demand and supply. In addition, it estimates the volume of each type of pollutant produced by the energy system.
4/ Area	time	Static model for a particular point in time (the model has been applied to the years 1985 and 2000).
	space	USA as a whole
5/ Modelling techniques		Optimization model using linear programming. The model provides a feasible path between n= 13 exogenous supply categories and m= 15 exogenous demand categories. The objective function is the minimized solution of the present amount of the cost of the different possible paths. Three kinds of constraints must be satisfied: the level of each kind of demand, the possibility of each kind of supply system and the levels of the different pollutions. An expanded model is under development with 27 supply categories and 22 demand categories.
6/ Input data		<u>Physical</u> <u>n= 13 supply categories are considered as follows:</u> - 8 kinds of central stations that produce electricity as an intermediate energy form: Hydropower, geothermal, coal-steam electric, LWR electric, LMFBR electric, gas turbine electric, pumped storage electric and solar energy. - 4 general purpose fuels that are directly delivered to consumers: oil products, natural gas, synthetic fuel (hydrogen) and coal gas and coal. - 1 decentralized electric supply system known as: total energy (up to 5 MW output) (diesel generators or gas turbine or fuel cells.) For each supply category, the model needs the knowledge of: - the supply constraint given in units of 10^{15} Btu - the amount of energy that can be delivered by a particular supply category, limited either by the energy conversion capacity or by the quantity of available energy resources. <u>m= 15 demand categories are considered as follows:</u> The demand is divided into 2 sub-categories: 1) <u>exogenous demand which means: different categories of energy demand:</u> space heat, air conditioning, electricity at 3 different load factors, water desalination, pumped storage, production of synthetic fuels, water heating, miscellaneous thermal heating, air transport, ground transport (public and private), iron production, cement production, and petrochemy and synthetic materials. 2) <u>endogenous demand:</u> for the electricity mentioned above the model takes into account the load duration curve of the system. For certain demand categories, it is possible to mix the different plants in order to optimize the global load factor curve. The load structures on a seasonal and weekly basis are taken into account. <u>Ecological</u> The model incorporates air pollutants and other wastes generated by energy conversion activities that are proportional to the amount of energy delivered: CO_2, CO, SO_2, NO, particulates, hydrocarbon, radioactive wastes and thermal wastes. Other pollutants and land use will be incorporated in the expanded model. <u>Economic</u> The coefficients of cost in the objective function reflect the necessary cost of the facilities used in the energy supply system as well as fuel and other operating costs. The necessary cost of capital for the electric supply category is a function of the plant load factor which is also a function of each specific demand category.
7/ Output data		<u>Physical</u>: The model gives for a specified level of each demand the optimal utilization of the different available supply systems. <u>Economic</u>: The model gives the total cost of the energy system but the resulting optimal path is greatly dependent of the different input costs. <u>Ecological</u>: The model gives the volume of the different polluting emissions.
8/ Observations		a) This model is static, it can be used only for one year. For that year it is necessary to know the demand and the supply categories. The level of the different kinds of demands can be obtained by using an input-output model. b) The price elasticity of demand is not taken into account in the current model but is being added to the expanded model.

This summary has been reviewed by the author of the model.

1980



(UNITS: MILLION BBLS./DAY OIL EQUIVALENT)

FOLD OUT "C"

Figure 1

Analytical Review of Energy Resources and Their Estimation

Nikolai Kourochkin

Introduction

This part of the Energy Project is concerned with energy resources, and more specifically with non-renewable resources. It would seem a rather simple thing to state that there exists only a limited amount of natural energy sources and that therefore it is necessary to use them economically and to find a new technology within a certain number of years for replacement of these energy sources when they are depleted. Yet this simple statement brings some interesting problems to light. The fact is that nobody does know, even by approximation, how much of these energy resources are to be found in the earth. In addition to this there is a very uneven spread of these resources over the many countries of the world. And then, their qualitative characteristics, their cost of extraction and their pollutant content differ from place to place, and from country to country. All these facts affect the energy policies, both internal and international, of the various countries and the time they have available for development of alternative energy sources and technologies. Uncertainties, insufficient knowledge and changing economic, technological and political conditions will always be with us. Even the most searching and imaginative estimates can never represent a final inventory; at best they represent a statement reflecting the status of knowledge at the time the estimates are made, and they must be revised periodically to take account of new developments. However, assessment, as reliable as possible, of existing knowledge of energy resources is in order. That is why the methodological problems confronting this part of the Energy Project are many.

The problem of estimating energy resources

Growth of energy demand and growth of processing facilities force all countries throughout the world to pay great attention to the estimation of their energy resources. Accuracy of estimation is limited

a) by lack of knowledge about the extent and the quality of unknown deposits;

b) by uncertainties concerning feasibility and cost of recovery processes;

c) by the lack of uniformity of appraisal methodology (see Appendix I), and

d) by the use of various energy resources terms.

For example, estimates of well-explored deposits generally agree with each other within 10 to 15%; estimates of resources, however, that have not yet been fully explored and need more advanced technology or higher prices for recovery may differ by factors of 2 to 10 or sometimes even more.

One of the main difficulties is that there are many different terms concerning availability of natural resources: "reserves", "resources", "proved, probable, possible", "measured, indicated and inferred", "marginal, submarginal", "primary reserves", "proved economic fluid injection reserves", "originally in place", "ultimate reserves" and so on and so forth; the USSR uses six categories of resources: A, B, C_1, C_2, D_1 and D_2. Without uniform classification it is difficult or impossible to compare all these estimates (see Appendix II).

IIASA's Energy Project is inclined to use the classification developed by Mc Kelvey (see Fig. 1), as follows:

Reserves This term refers to economically recoverable material in known deposits. The degree of certainty with which this amount is known is indicated by the terms proved, probable and possible, sometimes also called measured, indicated and inferred.

Resources This term refers to all material that is potentially recoverable, and includes, besides the reserves mentioned before, those deposits that are known but cannot economically be recovered now, and an estimate of not yet discovered deposits.

For more details about classicification used in different countries and a comparison with terminology to be used by the Energy Project, see Appendix II.

For any decision-maker dealing with energy resources it is important to know not only the total amount of energy resources in any given deposit but also its recovery factor. The average recoverability of coal in the world is considered to be equal to 50 per cent of the deposit; this was derived from current underground mining experience in the U.S.A.[1)] The recovery factor for oil ranges from 15 to 50 per cent of oil in place or even more in some Middle East fields [2)]. For the world as a whole the recovery factor is estimated at about 40 per cent [3)].

Publications by international agencies, and by institutions in many countries, furnish the data on availability of reserves and resources. Information on the world's hydrocarbon reserves is provided by the American journals World Oil and Oil and Gas based on answers to questionnaires sent worldwide to both government and private oil companies. It should be kept in mind that government regulation, tax legislation, conservation or optimism on the part of both private and government forecasters, and a host of other factors, influence the furnished reserve data. For instance, according to Petroleum Press Service [2)] the U.S.A. has strict regulations for the declaration of the reserves which have historically been limited to the production of one well in a specific area, mainly for protection of investors; depreciation allowances also have some influence on data provided.

It is not surprising, therefore, that additions are made yearly to the published reserves data in North America, due to these factors and to changing technology and further drilling. Revisions and extensions account for about 80% of the annual additions to reserves, the rest being due to new recoveries (see Table 1).

Survey of Energy Statistics

The data in the various publications differ from each other substantially. These differences have to be investigated and evaluated, and a reasonable solution acceptable to all users of these data has to be found. To give an example, the U.N. Statistical Office in its publication [4] excludes lubricants and greases from its consumption data, but OECD and EEC statistics of energy[5] include these in the total consumption of oil and oil products, the difference amounting to about 13 per cent.

Different conversion factors are used in the statistical material of various countries when changing original data into a common unit. Energy sources differ in calorific value; this is true for the many kinds of coal, and also for petroleum products at different temperatures and pressures.

Even units common to various publications are not exactly the same: in the conversion tables (see e.g. Table 2) it is shown that the calorific value of a kg coal equivalent used in EEC statistics (7000 kcal/kg) differs from that used in U.N. statistics (6880 kcal/kg) or in the U.S.A. publications (7260 kcal/kg), depending on the use of gross or net calorific value.

There is also the problem of measuring thermal, hydro and nuclear electricity in a common unit. Sometimes, for instance, coal equivalent of fuel required to produce 1 kWh is used and that varies according to the efficiency of the thermal stations of different countries which, to compound the difficulties, also changes over time (from 0.6 to 0.35 kgce); in other statistics inherent heat value (0.125 kgce per 1 kWh) is used.

What is desperately needed is a common denominator which can easily be converted into the units that the various countries use for their own statistics and purposes.

In order to end this confusion the Energy Project intends to publish a "White Book on Energy Resources", in which data available in many publications on reserves and resources are evaluated, processed in an analytical and systematic manner, and published, using a measure that carries no ambiguities. It will be updated periodically. The first steps to gather the available data have already been taken: IIASA's Project on Energy Systems has established contacts with other international agencies, and with institutions and experts in many different countries.

World Energy Resources and Their Geographical Distribution

Estimates of hard coal reserves (proved, probable, possible) for the whole world range from 6,500 to 14,000 billion tons (see Table 3). Most of the estimates are close together, between 7,000 and 8,000 tons. This can be explained by the nature of the coal beds; the extent of the deposits can be quite reliably predicted by geological mapping. Reserves of lignite are smaller, but still substantial. On the whole, there is no urgency to revise these estimates year after year, as the reserves are very large and the reserves/production ratio, the "static life", for the world as a whole is about 3,700 years.

The "static life" of the reserves indicates how long the reserves will last at the present rate of production and can be calculated for each kind of resource for a country, a region, a continent or the world. It is the ratio between reserves at the beginning of a year and the production of that year.

The largest coal reserves are in the USSR, the USA, and China; together these countries have over 90% of the world's coal reserves. The USSR has enough coal to last for 9,300 years, the USA for 2,200, and China for 2,600 years.

Estimates of hydro resources are similarly close together. Soviet scientists estimate a total of 32.9×10^{12} kwh or 4.1×10^{9} tons coal equivalent[6)], McKelvey[7)] and others about 3×10^{9} tce.

The case is different for oil and gas; estimates vary by a factor of 8 for oil, by a factor of 5 for gas: $130 - 1370 \times 10^{9}$ tce and $120 - 580 \times 10^{12}$ m^3 or $160 - 775 \times 10^{9}$ tce respectively. Estimates of reserves of oil and gas change year by year; the life expectancy of world oil and natural gas reserves has a tendency to increase in spite of rapid growth of production. While oil production increased between 1940 and 1973 by a factor of about 9, the reserve/production ratio increased from 15 to 35 years, because of discoveries of large oil fields during this period. For natural gas the reserve/production ratio stayed about constant: 40 years. The distribution of oil and gas reserves over the whole world is somewhat wider than that of coal; 5 countries, including the USSR and the USA, possess 65% of the oil reserves, and 5 others, again including the USSR and the USA, 73% of the gas reserves. The share of North and South America in the world's proved reserves of oil and gas is diminishing rapidly while their consumption is growing. Europe's share is growing, because of newly-found reserves in the North Sea area.

When looking at the distribution of these energy resources over the various countries, it seems appropriate to look at the ratio of these countries' own proved reserves to their own consumption. For some industrial countries this ratio is very small indeed (see Table 4), even if for the world as a whole proved reserves might be enough to last several decades in the case of oil and gas, and several centuries for coal.

The estimates for shale oil differ tremendously, as might be expected with a resource that might become economically exploitable only now. Estimates vary by a factor of 3000 because of varying oil contents and differences in thickness of seams and depth (see Table 3).

Known uranium reserves are expressed by two different costs of extraction, less than \$10 per lb U_3O_8, and \$10-15 per lb. U_3O_8. The compilation of these estimates, done by USAEC and by OECD-IAEA, is connected with the development of nuclear reactors which need low-cost uranium. Resources with much lower concentration of uranium ore are said to be abundant, and will be used in the breeder reactor where the price of the ore is not of great importance for the production of low-cost electricity.

For resources other than uranium, no good figures for cost of extraction exist. However, now that, through political intervention, the price of crude oil has risen to previously unthought-of prices, the search for unknown deposits has gone on feverously. This also means that resources so far not economically exploitable--those in the group known as paramarginal resources--have moved over into the group "proved and economically exploitable" reserves, and that some of the "probable" and "possible" reserves have moved into the category of "proved" reserves. Statistics to be published in 1974 and following years will certainly reflect these changes and will result in much larger "reserves" of all energy categories.

Offshore Oil and Gas Reserves

In the last 10 years the search for hydrocarbons has been directed more and more to the areas beneath the sea. The continental shelves and the arctic and antarctic regions are under such intensive exploitation that reserve data might change drastically. The total number of possibly oil- and gas-bearing basins in the world equals about 350, of which about 200 are situated under the world's oceans. Soviet scientists have estimated that about 50% of the world's potential oil and gas resources can be found under the ocean floor.

In the middle of 1973, offshore hydrocarbon reserves were estimated to be about 24% of total proved reserves. The production from offshore wells is now about 20% of total oil and gas production, and is expected to exceed 30% by 1980. At the moment, it is not yet technically possible to develop basins more than about 500 m under sea level.

Large amounts of oil and gas were recently found and are still being found in the North Sea; production has just started. This will greatly lessen the dependence of at least some West European countries on imports from the Middle East and Africa (see Table 7).

Large amounts of oil and gas are also being found in the Arctic. The total onshore oil and gas reserves combined with those on the continental shelves north of the Arctic Circle equal about 80% of the total world proved oil and gas reserves.

Also in the Antarctic some oil and gas deposits were found by U.S. research teams. Further investigations will continue.

Environmental Aspects of Extraction of Energy Resources

Environmental problems connected with continuing exploitation of energy resources are already large now and will become formidable. Increasing off-shore oil production in coastal waters presents many problems; The pollution dangers in arctic and antarctic regions may affect the role of these areas as the "refrigerators" of the earth, a role yet little understood. Besides the many kinds of pollution already existing, caused by burning of coal and oil and by nuclear electric stations, increasing attention should be directed to the wastes created by the mining of the energy sources.

The waste from coal mining in the form of broken up overburden and rock is estimated to be equal in volume to the yearly production of coal, 4 - 5 1/2 billion tons in the year 2000. The ash left from the use of this coal constitutes as much as 20% of the volume of coal used. When uranium ores are mined, for their 1500 ppm of fertile uranium, the total amount of rock moved per year will equal about 200 million tons and will be much larger when the low grade uranium deposits are mined. The total amount of rock (and ash) to be disposed of per year might equal about 4.5 - 7 billion tons (see Table 8) by the end of this century.

Depletion of Energy Resources

A very rough calculation (Table 9) can be made about the length of time mankind can count on using the world's fossil resources. In the section on distribution of resources we have already discussed the "static life" of the reserves. A more realistic way of determining the time at which certain resources will be available is to take into the rate of growth of production. If the 1970 world production of fuels is P, the annual production in any future year Q, and the doubling time for production "a", then the annual production at any year from the base year can be calculated from the formula

$$Q = P \cdot 2^{t/a} \quad . \qquad (1)$$

The cumulative world production in t years is then given by

$$\int_0^t Q_t dt = P \cdot a \int_0^t 2^{t/a} \cdot dt/_a$$

$$= \frac{P \cdot a}{\ln 2} (2^{t/a} - 1) \quad . \qquad (2)$$

From this equation it can be calculated that all recoverable reserves as now known will be extracted in 70 years, that is by the year 2040, if the annual growth rate of energy production is 5%. Even if through further intensive geological prospecting and through technological progress the recoverable reserves would in the meantime have increased by a factor of, say, 8 (a larger increase is hard to imagine), the energy reserves would be depleted in 110 years, i.e. in the year 2080. If the growth rate is smaller than 5%, let's say about 3%, then the reserves would last longer, about 100 years; and again, with an eight-fold increase of the reserves, they might last another 70 years (see Table 8). However, an assumed growth rate of 3% per year in the use of energy might be conservative in view of technical progress of the developing countries and the growing population of the entire world.

In this connection it should be mentioned that these resources, especially oil and gas, are not only sources for energy, but also raw materials for the chemical industry. About 4 to 5% of the total fossil fuel production is now used for non-energy purposes in the petrochemical industries. No economical substitute is known. If all fossil fuels are depleted, mankind will also have no more materials for these non-energy needs. Already in the last century the greatest Russian scientist, D. Mendeljov, said "Burning oil and gas in furnaces is the same as burning capital."

Author's note: Additional tabular material is available on request.

Acknowledgement: I am greatly indebted to Mrs. Truus Koopmans for her invaluable help in drafting this report.

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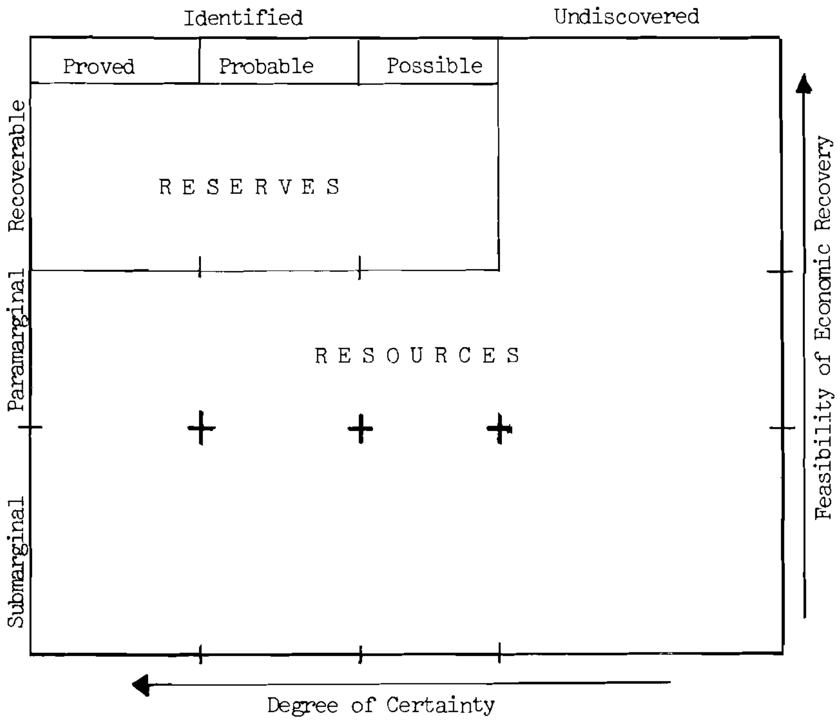

Fig. 1. Classification of mineral reserves and resources. Degree of certainty decreases from left to right, and feasibility of recovery decreases from top to bottom [8)]

Identified recoverable reserves - deposits whose location and general magnitude are established and that are recoverable at or close to present prices and with established technology. Generally the figures include estimates of other authors described as measured, indicated and inferred, or proved, possible, and probable reserves (for definitions, see F. Blondel and S.G. Lasky, Mineral reserves and mineral resources: Econ. Geol., Vol. 51, 1956, p. 686-697).

Undiscovered recoverable resources - deposits whose specific location is unknown but whose presence and character are indicated by geologic evidence.

Known paramarginal and submarginal resources - deposits whose location and general magnitude are established and that may become recoverable as technology advances or economic conditions change, but cannot be recovered now.

Undiscovered paramarginal and submarginal resources - deposits whose specific location is unknown but whose presence and character are indicated by geologic evidence.

Table 1.

Annual Estimates of Proved Crude Oil Reserves in the U.S. 1946 through 1972

(million tons)

Year	Total of Discoveries, Revisions + Extensions	of which %			
		Revisions	Extensions	New Field Discoveries	New Reservoir Discoveries in old Fields
1946	364.2	47.2	43.6	a)	9.2
1947	337.6	30.4	51.5	a)	18.1
1948	519.9	51.6	37.9	7.1	3.4
1949	436.7	18.9	53.1	17.1	10.9
1950	351.1	25.9	52.1	15.9	6.1
1951	604.7	40.2	50.9	4.7	4.2
1952	376.6	27.1	54.9	10.2	7.9
1953	451.5	38.4	43.7	10.4	7.5
1954	393.6	18.7	60.9	10.7	9.7
1955	393.3	24.2	59.1	7.7	9.0
1956	407.4	27.1	57.2	7.9	7.8
1957	332.2	19.2	63.6	8.6	8.6
1958	357.3	36.6	51.3	5.8	6.3
1959	502.4	41.4	48.5	4.5	5.6
1960	324.0	33.3	55.9	6.0	4.8
1961	364.0	40.9	45.5	4.0	9.6
1962	298.8	34.8	47.7	4.2	13.2
1963	297.8	44.4	39.5	4.4	11.6
1964	365.1	33.7	53.3	4.8	8.2
1965	417.6	58.5	26.0	7.8	7.7
1966	406.0	62.1	27.5	5.4	5.1
1967	405.8	64.2	24.2	4.2	7.4
1968	336.3	53.8	31.6	6.8	7.8
1969	290.4	59.3	29.0	4.5	7.1
1970	1738.4	16.5	5.0	77.6	0.9
1971	317.6	69.0	24.2	3.9	2.8
1972	213.4	52.6	29.5	7.9	10.0
1946-1972	11604.3	36.7	39.1	17.4	6.8

a) All discoveries were classified as "New Reservoirs"

Source: Reserves of Crude Oil, Natural Gas Liquids and Natural Gas in the U.S. and Canada and U.S.Productive Capacity as of December 31, 1972 (AGA, API, Canadian Petroleum Association) 1973, p.24.

Table 2. Conversion Factors [a)]

Units	Joule (Newton x meter)	BTU	kcal	kg hard coal equivalent	kWh
1 g of matter (energy equivalent)	$9 \cdot 10^{13}$	$8.52 \cdot 10^{10}$	$2.15 \cdot 10^{10}$	$3.12 \cdot 10^{6}$	$2.5 \cdot 10^{7}$
1 kg of U-235 ≈ 20000 metric tons of TNT	$8.4 \cdot 10^{13}$	$8 \cdot 10^{10}$	$2.1 \cdot 10^{10}$	$2.91 \cdot 10^{6}$	$2.33 \cdot 10^{7}$
Earth's daily receipt of solar energy	$1.49 \cdot 10^{22}$	$1.41 \cdot 10^{19}$	$3.56 \cdot 10^{18}$	$5.17 \cdot 10^{14}$	$4.14 \cdot 10^{15}$
Sun's daily output of energy	$3 \cdot 10^{32}$	$2.84 \cdot 10^{29}$	$7.17 \cdot 10^{28}$	$1.04 \cdot 10^{25}$	$8.33 \cdot 10^{25}$
1 BTU	$1.056 \cdot 10^{3}$	1.0	0.252	$3.66 \cdot 10^{-5}$	$2.93 \cdot 10^{-4}$
Q	$1.056 \cdot 10^{21}$	$1.0 \cdot 10^{18}$	$2.52 \cdot 10^{17}$	$3.66 \cdot 10^{13} = 36.6 \cdot 10^{9}$ tce	$2.93 \cdot 10^{14}$
1 kcal	$4.184 \cdot 10^{3}$	~ 4	1.0	$1.45 \cdot 10^{-4}$	$1.16 \cdot 10^{-3}$
1 kWh	$3.6 \cdot 10^{6}$	3412	$0.86 \cdot 10^{3}$	0.125 [b)]	-
1 kg hard coal equivalent	$28.824 \cdot 10^{6}$	$27.295 \cdot 10^{3}$	$6.88 \cdot 10^{3}$	1.0	8 [b)]
1 metric ton hard coal equivalent (tce)	$28.824 \cdot 10^{9}$	$27.295 \cdot 10^{6}$	$6.88 \cdot 10^{6}$	$1.0 \cdot 10^{3}$	$8.0 \cdot 10^{3}$ [b)]
1 metric ton of crude oil	$43.235 \cdot 10^{9}$	$40.943 \cdot 10^{6}$	$10.32 \cdot 10^{6}$	$1.5 \cdot 10^{3}$ [c)]	$12.0 \cdot 10^{3}$

a) These figures are based on C.Starr "Energy and Power", Scientific American, Vol.224, No.3, September 1971, pp.48-49; UN World Energy Supplies 1962-1965 Statistical Papers, Series J, No.10, 1967, pp.6-8.

b) In this case the heat content of 1 kWh_e is given. However, if we take the amount of coal, gas or oil needed to produce 1 kWh_e, we get quite another conversion factor, which depends on efficiency steam power stations. This factor varies from year to year within each country and from country to country; for 1972 somewhere between 0.6 and 0.3 kgce per kWh_e.

c) J.Darmstadter, "Energy in the World Economy", Resources for the Future Inc., Baltimore, 1971, p.829.

Table 3. Estimates of World Fuel Resources (in 10^9 tons of coal equivalent)

Fuels	UN 1971	World Power Conf. Survey 1962	World Energy Conf. 1968	K. Hubbert 1970	T.A. Hendricks 1965	McKelvey 1969	USSR estimates 1968	Author's estimates 1974
Coal (proved, probable, possible)	7600	7700	6500-13000	6973	-	11960	11308	11500-13500
Oil (proved, probable, possible)	404	180	180-300	408	1257	884	743	720-850
Oil in bituminous rocks	-	-	-	-	-	226	-	-
Natural gas liquids	-	-	-	-	90	120	1	100-150
Natural gas (proved, probable, possible)	233	147	160-226	377	720	775	229	520-640
Shale oil (proved, probable, possible)	111000	203 (shale oil and tar sands)	-	39	-	2826	114	-
Tar sands (proved)	1		-	62	-	-	-	-
Hydro (proved, probable possible)	3	1	-	3	-	3	4	4 - 5

Source: UN A/Conf. 49/P/420, 1971 "World Energy Requirements and Resources in the Year 2000"; World Power Conference Survey of Energy Resources, 1962; World Energy Conference, Moscow, 1968, General Report, Section AI; M.K.Hubbert, "Energy Resources for Power Production, Proceedings IAEA Symp. on Environmental Aspects of Nuclear Power Stations, New York, August 1970, IAEA-SM-146/1; T.A.Hendricks, "Resources of Oil, Gas and Natural Gas Liquids in the United States and the World", U.S.Geological Survey, Circular 522 (U.S. Government Printing Office, 1965); V.E.McKelvey and D.C.Duncan, "United States and World Resources of Energy", Mineral Resource Development Ser., No.26, II (1969) 9; N.Melnikov, "Energeticheskie Resourci SSSR Toplivno-energetichiskie resourci", Moscow, 1968.

Note: 1 metric ton of crude oil and natural gas liquid is taken as equal to 1.5 tce.

Table 4. Some figures on Western Europe's oil and gas reserves, production and consumption in 1972

	Oil reserves 10^6t 1972	Gas reserves 10^9m^3 1972	Oil production 10^6t 1972	Gas production 10^9m^3 1972	Oil reserves/production ratio (years)	Gas reserves/production ratio (years)	Oil consumption 1972 10^6t	Gas consumption 1972 10^9m^3	Oil reserves/consumption ratio (years)	Oil reserves/50% consumption ratio (years)	Gas reserves/consumption ratio (years)	Gas reserves/50% consumption ratio (years)
Western Europe	1800	4930	19.4	127.0	92.8	38.8	695.5	131.5	2.6	5.2	37.5	75.0
Fed. Rep. Germany	75	350	7.1	17.2	10.6	20.3	141.0	27.5	0.5	1.0	12.7	25.4
Denmark	75	50	a)	-	...*	-	19.0	-	3.9	7.8	-	-
Great Britain	850	1150	0.2	27	4250	42.6	114.5	27.5	7.4	14.8	41.8	83.6
Netherlands	100	2450	1.6	58.0	62.5	42.2	41.0	34.0	2.4	4.8	72.1	144.2
Norway	550	500	1.7	-	323.5	-	9.0	-	61.1	122.2	-	-
France	10	185	1.5	7.3	6.7	25.3	111.5	14.0	0.1	0.2	13.2	26.4
Austria	25	15	2.5	2.0	10.0	7.5	11.0	3.5	2.2	4.4	7.5	15.0
Spain	10	15	a)	-	-	-	33.0	0.5	0.3	0.6	30	60
Turkey	75	40	3.4	-	22.1	-	9.5	-	7.8	15.8	-	-
Italy	30	175	1.2	15.5	25	11.3	100.0	16.5	0.3	0.6	10.6	21.2
Others	-	-	0.2	-	-	-	106.0	8.0b)	-	-	-	-

Notes: a) included in others b) Belgium/Luxemburg

Source: Annuaire de l'Europe Pétrolière 1973, p.p. 79-90.

Table 5.

Proved off-shore reserves of oil in 1973

(in million tons)

World on-shore and off-shore oil reserves	90348
World off-shore reserves	21360-21590
World off-shore reserves, %	23.6 - 23.9
Europe	1825 - 2055
the North Sea	1600 - 1800
Spain	~ 10 - 40
the Caspian Sea	~ 215
Africa	780
Nigeria/Gabon	~ 640
Gulf of Suez/Red Sea	~ 140
Asia and Middle East	11832
Persian Gulf	~ 11570
South East Asia	~ 260
Japan	~ 2
North America	1700
California	~ 600
Alaska (Cook Inlet)	~ 70
Gulf of Mexico	~ 1030
South America	4873
Lake Maracaibo	~ 4670
Trinidad and Tobago	~ 185
Brazil	~ 15
Peru	~ 3
Oceania	350
Australia (Bass Strait)	350

Source: ANEP, p.21.

Table 6.

Proved off-shore reserves of natural gas in 1973
(in trillion cubic meters)

World on-shore and off-shore reserves	58300
World off-shore reserves	14160
World off shore reserves, %	24.3
Europe	2130
the North Sea	2000
Italy	100
the Caspian Sea	30
Africa	90
Egypt	60
Gulf of Suez/Red Sea	30
Asia and Middle East	8080
Persian Gulf	7080
South East Asia	1000
North America	1770
Canada (Artic Islands)	340
Canada (East Coast)	300
Alaska (Cook Inlet)	60
Gulf of Mexico	1070
South America	885
Lake Maracaibo	740
Trinidad and Tobago	115
Peru	30
Oceania	1205
Australia (North-West Shelf)	400
Australia (Bass Streit)	235
New Zealand	570

Source: ANEP, 1973, p.21.

Table 7a. Western Europe's Oil and Gas Consumption and Production (million tons and billion cubic metres)

	1950	1972*)	1975**)	1980**)	1985**)
Oil consumption	60.8	695.5	835	1080	1400
Oil production a)	3.7	19.4(2)	100(80)	195(170)	280(250)
Share of own oil in consumption %	6.1	2.8	12.0	18.1	20.0
Natural gas consumption	1.3	131.5	200	280	350
Natural gas production a)	1.3	127(27)	180(60)	230(100)	275(125)
Share of own gas in consumption %	100.0	96.6	90.0	82.1	78.6

Notes:

a) The North Sea production in parenthesis

*) Estimate
**) Forecast

Source: ANEP, 1973, Tables 5, 6, 12, 13, 15, 16, 20, 21.

Table 7b. Western Europe's Primary Energy Consumption by Energy Carrier (million tons HCE)

	1950	1972*)	1975**)	1980**)	1985**)
Total	630	1725	1950	2500	3200
Solid fuels	480	390	350	320	300
Oil	90	1020	1200	1550	2000
Natural gas	-	160	220	330	400
Primary electric power	60	155	180	300	500

Notes:

*) Estimate
**) Forecast

Source: Ibidem, Tables 2, 3, 22, pp. 79, 80, 90.

Table 7c. Import Dependence of Western Europe's Primary Energy Supply, %

	1972	1975	1980	1985
Including North Sea production	60	57	55	54
Excluding North Sea production	62	66	69	70

Table 8.

World coal and uranium production in 1970-2000 and waste from mining of these energy resources.

	1968	1969	1970	1971	1972	1980[a)]	2000[a)]
World coal production, 10^6 tons	1754	1780	1816	1789	1808	2200	2800-3800
World lignite production, 10^6 tons	741	765	792	802	810	1000	1200-1700
Total of coal, 10^6 tons	2504	2545	2608	2591	2618	3200	4000-5500
Amount of rocks, 10^6 tons b)	2500	2550	2600	2590	2600	3200	4000-5500
Ash content, 10^6 tons c)	120-500	130-510	130-520	130-520	130-520	160-640	250-1100
World uranium production (U_3O_8) tons d)	20870	20950	21537	22374	23174[e)]	73740[f)]	321800[f)]
Amount of rocks, 10^6 tons g)	10	10	10	15	15	40	180
Total amount of wastes from coal, ash and uranium, 10^6 tons	2630-3010	2690-3130	2740-3130	2735-3125	2745-3135	3400-3880	4430-6780

Notes:

a) Author's estimates b) Cover rock is assumed to equal the amount of coal production c) Ash content is taken to equal 5-20% of coal d) Excluding the USSR and other countries with planned economies e) Uranium resources. Production and Demand, OECD, August, 1973, p.16. f) Nuclear Power 1973-2000, WASH-1139, USAEC, p.14 g) U content in ores is taken to equal an average 1500 ppm (L'industrie française de la production et de la transformation de l'uranium" presented at Congrès de Vittel, 11-15 September, 1973, p.6.

Source: World Energy Supplies 1961-1970, UN, New York 1972, Statistical Papers, Series J, N15 pp.6-50; Statistical Yearbook 1972, UN, New York 1973, pp.177-184.

Table 9. Depletion of World Fuel Resources (tce)

Fuels	Resources		Recoverable Reserves	
	10^9	%	10^9	%
Total	12212	100.0	3430	100.0
Coal	11240	92.0	2880	84.0
Oil	743	6.1	372	10.8
Natural gas	229	1.9	178	5.2

1) $P = 7 \cdot 10^9$ tce annual world energy production in 1970. Annual rate of growth of energy production in the world in 1950-1970: $r = 5\%$. Doubling production each $a = 15$ years.

2) $p = 7 \cdot 10$ tce; $r = 2.8\%$; $a = 25$ years

$$Q = P\ 2^{t/a}: \int_0^t Q_t dt = Pa \int_0^t 2^{t/a} \frac{dt}{a} = \frac{P \cdot a}{\ln 2} (2^{t/a} - 1)$$

t in years	year	$2^{t/15} - 1$	$22P(2^{t/15} - 1)$	Production for t years in % of reserves
15	1985	1	151	4.4
30	2000	3	453	13.2
45	2015	7	1057	30.8
60	2030	15	2265	66.0
68	2038	22	3345	97.5
110	2080	160	24200	88.2 (from 3430 x8=27440 tce)
t in years	**year**	$2^{t/25} - 1$	$36P(2^{t/25} - 1)$	**Production for t years in % of reserves**
25	1995	1	252	7.3
50	2020	3	757	22.1
75	2045	7	1767	51.5
100	2070	15	3780	fully depleted
125	2095	31	7812	28.5 (from 3430 x 8 = 27440 tce)
150	2120	63	15876	57.9
175	2145	127	32004	fully depleted

Source: Calculated from N. Semenov, "Ob Energetike Budushzego," *Nauka i zhizn* No. 10, pp. 16-32. Moscow, 1972.

Appendix I

Methods of energy resources estimation

Earl Cook describes the following three methods of estimation used in the USA.[9)]

a) The economic method. Economists assume that resources will become available when demand and prices increase. This assumption reflects a faith in technology stronger than that of many engineers and geologists, it rests on the belief that resources will be created by technology as indicated by the market. For this judging which physical resources exist, this method is not recommended, as it takes substitution of energy sources and changes in future technologies into account and might even make existing reserves obsolete.

b) The geologic-analogy method. It is here assumed that resources exist in unexplored regions in the same ratio as in well-explored regions of similar geologic characteristics; that greater depths or less hospitable regions with the same characteristics will be explored - when prices rise.

c) The exploration-history method.
Historical data of production, proved reserves, proved discoveries, and rate of discovery per foot of drilling over time are projected into the future to fit a logistic curve, which then predicts the path of depletion of the resource.

d) A fourth method using statistical and probabilistic methods especially for estimation of deposits in specific petroliferous basins is proposed by Kaufman [10], and is still to be developed further.

In the Soviet Union the method of comparative geological analysis is followed for the estimation of possible resources of oil and gas.

A combination of procedures is used:

a) Estimation for promising but unexplored regions by using the volume of oil or gas found per km^2 in already fully explored regions of similar geological structure.

b) Estimation for an unexplored part of a district by use of the mean volume of oil and gas found in the average structure typical for the whole district.

c) Estimation through knowledge of characteristics of the geostructural elements of a region.

d) Estimation according to the stratigraphy of the region, layers of the Cenozoic, Paleozoic and Mesozoic periods having the greatest concentration of oil deposits.[11]

A judicious use of any of the methods briefly described above, under b - d is likely to give an insight into future development of resources, keeping in mind that in the end the assumptions used by economists as indicated under a) might have great impact on the quantities of resources exploited and to be exploited.

Appendix II

Comparison of the classifications of reserve and resource estimates in various countries

Resources are divided into two groups:

1) Reserves which have been evaluated as far as quantity, quality and present economic exploration possibilities are concerned.

2) Resources of no present advantage which at some future time may become profitable under more favorable economic or technical conditions.

We are here concerned only with comparing estimates for the first group.

Government offices, state geological bureaux, and companies estimating and evaluating known reserves and searching for new ones exist in western countries. In the USSR and other Eastern Europe countries evaluation of reserves and resources is made by government institutions only. In spite of existing differences in categories of evaluation and in utilization of resources in these various countries, the terminologies used can be compared as is done below.

Geological and economic literature in the West has accepted a classification which describes reserves by the terms "proved", "probable", and "possible".

"Proved" reserves ("proved" in Great Britain and Canada, "proved or measured" in the US, "certain" in

France), are measured according to estimating procedures adopted by the U.S. Bureau of Mines. These procedures were also followed by the World Power Conference in 1968.[12)] According to P. Averitt measured reserves are reserves "for which tonnage is computed from dimensions revealed in outcrops, trenches, mine workings, and drill holes. The points of observation and measurement are so closely spaced, and the thickness and extent of the coal are so well defined, that the computed tonnage is judged to be accurate within 20 per cent of the true tonnage. Although the spacing of the points of observation necessary to demonstrate continuity of coal differs from region to region according to the character of the coal beds, the points of observation are, in general, about half a mile apart".[13)]

While these characteristics apply to coal reserves, similar definitions exist for reserves of oil and gas, and for uranium.

The category "proved reserves" corresponds approximately to the term "sicher + wahrscheinlich" and "nachgewiesen" of the nomenclature used in the FRG. These terms can be roughly equated with categories A + B for oil and A + B + C for coal used in the USSR statistics.

"Probable" reserves in the classification used in the US, Canada, Great Britain and France corresponds to the category "angedeutet" in the FRG. They are also called "indicated" reserves and are defined as reserves "for which tonnage is computed partly from specific measurements and partly from projection of visible data for a reasonable distance on the basis of geologic evidence. In general, the points of observation are about 1 mile apart, but they may be as much as 1 1/2 miles apart for beds of known continuity".[13)]

These various terms of classification can be compared partly with the reserves of category C_1 used in the USSR classification. The category "possible reserves" used in Canada, Great Britain, France and the US corresponds roughly to the "vermutet" reserves in the FRG. According, again, to the definition of the US Bureau of Mines, "possible" or "inferred" reserves are reserves "for which quantitative estimates are based largely on broad knowledge of the geologic character of the bed or region and for which few measurements of bed thickness are available. The estimates are based primarily on an assumed continuity in areas remote from outcrops of beds, which in areas near outcrops were used to calculate tonnage classed as measured or indicated. In the interest of conservatism, the areas in which the coal is classed as inferred are restricted as described under the heading "Areal Extent of Beds". In general, inferred coal lies more than 2 miles from the outcrop or from points for which mining or drilling information is available".[13)]

As is said above, similar descriptions exist for the various categories of oil and gas reserves.

For oil and gas the following outline of the Soviet classification may indicate the difficulties of the comparison.

Category A: Fully proved production; fully explored geological characteristics (certainly our "proved" category;the German "aufgeschlossen")

Category B: Less fully investigated geologically, but already with production in progress from some (at least 2) wells ("proved"?)

Category C_1: Based on geological + geophysical data, and by analogy with other well-explored fields; with at least one producing well (this could be "proved" and "probable")

C_2: Reserves in new structures in already established producing oil + gas fields, estimated only, on basis of geological + geophysical data (this may be the "possible" category)

Category D: called predicted reserves:

D_1: undiscovered reserves, based on general analysis of geological structure deemed favorable for accumulation of oil and gas ("undiscovered resources")

D_2: similar to D_1 but even less studied as far as geological structure is concerned ("undiscovered resources").

This classification does not indicate economic and technological feasibility of production of reserves/resources. A further distinction is made to cover this aspect, "zabalansovye" reserves corresponding to para- and submarginal resources, and "balansovye" reserves corresponding to reserves and resources exploitable under present conditions.

Preparations for a Model of World Trade and World Research and Development in the Field of Energy

Michel Grenon

The initial idea of the present work was to complete or to supplement studies of model societies with actual cases, and to investigate various energy strategies, especially regarding energy trade and energy research and development, according to the relative position of the various countries examined.

This work was begun only a few weeks ago. Hence results which are presented here are, of course, of a very preliminary nature.

Choice of Parameters

Many classifications of countries according to their energy situation already exist. For instance, if only one parameter is selected, it is generally the amount of the reserves of one fuel, or the amount of the production, or the partial amount of the production which is exported. With two parameters, the most often used representation makes use of the consumption of energy per capita versus GNP per capita (well known regression curves and/or regression formula(1).

We propose, as a first step, to use as the basic two parameters the energy consumption per capita and an indicator of the energy reserves per capita (this represents the energy stock of any individual in a given country, or his "energy expectation").*

As we can expect a broad dispersion of the representative points, we are not looking for correlation curves but rather for "regions". To do so, we arbitrarily divide the representative space into nine regions, by dividing the consumption per capita axis Ox and the reserves per capita axis Oy into three parts each (low, medium, high):

a) consumption per capita. Here the problem is simple, and for the two cutting values we propose the following:

- on the low side, 2 tce, corresponding roughly to the average world energy consumption per capita. On the left are developing countries, on the right are developed countries;

- on the high side, 8 tce. For the time being, essentially two countries are beyond this limit: the USA and Canada.

In our study, this upper limit is an "active" limit, a kind of "red line". We advocate a "European model" of energy consumption, and warn against emulating the "American model"; we think that it is the responsibility of developed countries not to go beyond this point, and to propose this "European model" as a maximum goal for the other countries.

b) energy reserves per capita. Here the problem is much more complicated and, at the time of this report, we had not yet definitely chosen a final splitting for energy reserves. In fact, two different ordinates can be selected:

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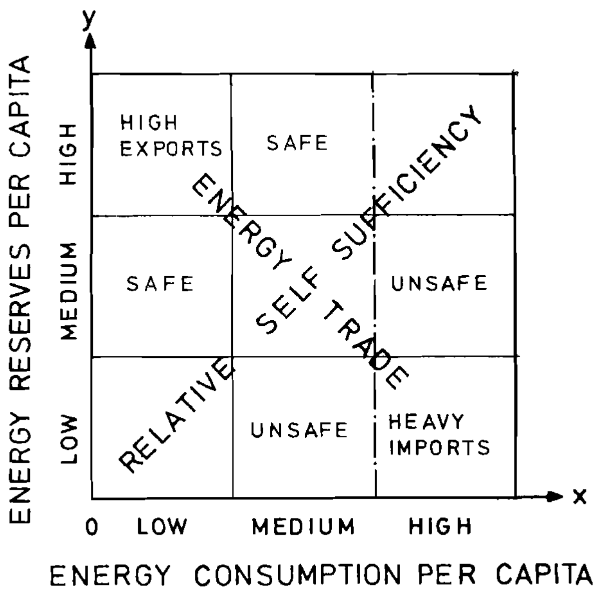
*The tce (metric ton of coal equivalent) is used as a common unit in this report.

- an absolute ordinate, in tce, with, for instance, the two divisions at 50 and 250 tce, or else at 100 and 1000 tce;

- a relative one, in years of consumption per capita, say for instance 10 (or 25 or 30 years, equal to one generation) and 100 years or 500 years. Due to present uncertainties relating to energy and economic growths, we would, in adopting such an ordinate, use the static, and not the dynamic index.

With these assumptions, the basic matrix may be represented as follows:



The diagonals show relative self-sufficiency, or direction of energy trade, and on both sides, safe or unsafe energy positions.

Comments on Energy Mix

We can use such a representation for a given country i using the total energy mix or by giving useful values for the various kinds of primary energy j, so as to assess the general situation, or else a particular fuel situation.

If we use the division between various fuels, we have x_{i1}, x_{i2},...x_{in} for energy consumption per capita (j for coal, oil, natural gas, oil from shale, uranium, etc.) and y_{i1}, y_{i2},...y_{in} for energy reserves per capita (j indicating the same fuels).

We can also distinguish for energy consumption, the possible k sectors, such as xijk, where the various indices k represent the industrial, transportation, residential, etc. sectors, and compare the various countries either for one fuel or for one sector.

In the same way, we can distinguish, for the reserves, the various types of reserves, yijm, where the various indices m represent proven reserves, probable reserves, possible reserves, ultimate reserves, etc.

Regions of consumption or coalitions of producers can be aggregated*.

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*Some research using such a representation and other formalisations has been initiated on the application of game theories to various coalitions.

When dealing with actual cases, it can be seen that the figures vary broadly according to the various countries. For the USA, for instance, energy consumption is about 11 tce per capita; coal reserves are about 5,300 tce, but the oil reserves are only 37 tce per capita. For the USSR, the energy consumption is about 4.5 tce per capita; coal reserves are about 16,800 tce per capita, and oil reserves 50 tce per capita. If we turn now to a consuming country like France, the energy consumption is around 3.9 tce per capita; coal reserves are 55 tce per capita, and oil reserves 0.41 per capita. Oil producing countries naturally present a completely different picture: the population of Iran consumes 0.9 tce per capita; coal reserves are about 34 tce per capita, and oil reserves are 418 tce per capita. Saudi Arabia consumes almost 1 tce per capita, has no coal reserves, and its oil reserves are 3,700 tce per capita*. Only Kuwait has the same "energy wealth" per capita (20,500 tce) as the giants USSR or USA with their coal reserves.

Energy Trade

Taking one given country, say a consuming country, we can represent its energy imports and the various countries with which the consuming country is doing energy trade. The dimensions of the arrows are proportional to the amounts of energy imported.(See next page).

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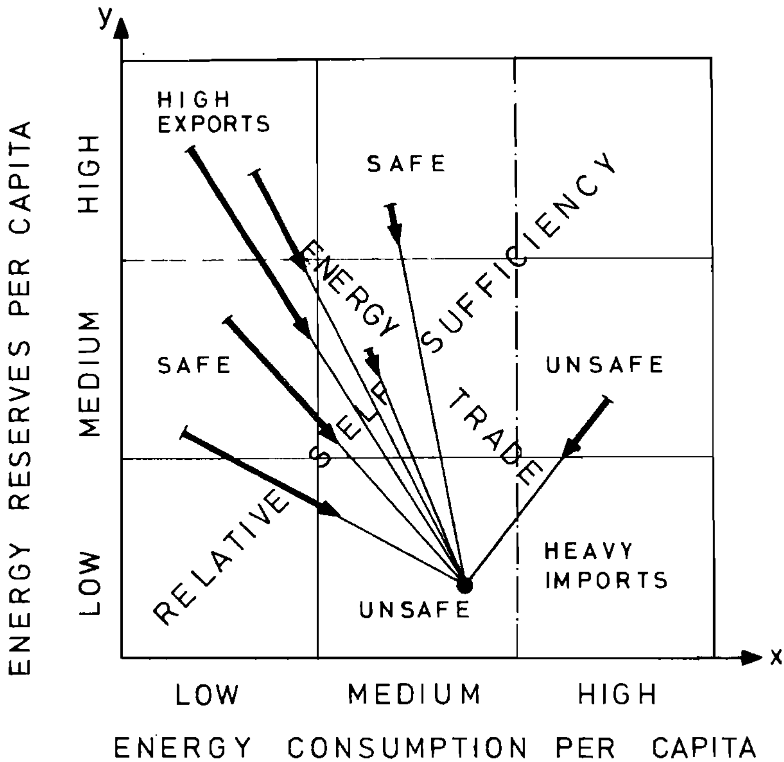
*These figures (for 1971) have been provided by Mr. Kourochkin, of the Energy Group. A complete matrix is being prepared, including almost all the countries of the world.



PATTERN OF TRADE

Evolution with Time

It is possible to trace the evolution with time of a given country. Changes of position are due to various factors, as summarized in the following table:

Direction	Meaning	Possible mechanisms
↑	Increase of reserves	Discovery New technology
↓	Decrease of reserves	Consumption Abandon
←	Decrease of consumption	Technology (i.e. efficiency) Conservation Change of living-style Political decline
→	Increase of consumption	Development "Passivity"

A given consuming country, for instance, can have shifted with time from low consumption-high reserves to a position of medium consumption-low reserves, and the time-curve can show the actual trends.

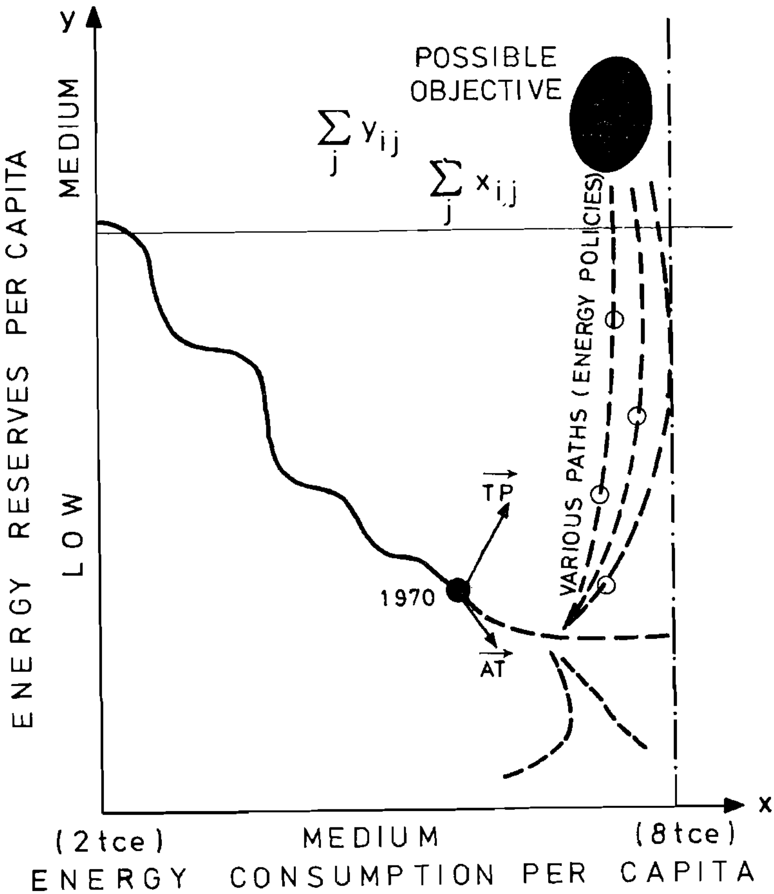
One interesting possibility is to try to use such a representation for forecasting the possible future evolution of a given country. The difficulty here is to deal with possible evolution of estimations for the reserves, and how to take into account the possible progressive use of solar energy and/or geothermal energy, that is to say, renewable resources.

In fact, we have not included hydraulic energy in our tables, but this is not of too much importance because the share of hydro-electricity is most often less high than that of fossil fuel, does not participate in energy trade, and is relatively decreasing. The problem is more complex if we assume a growing (say after the year 2000) of solar and/or geothermal energy. One possibility is to assume a "virtual" reserve of 100 or 500 years of actual production, which will allow to continue comparisons between various countries. Another possibility, in case solar and/or geothermal should really become important, would be to shift to a three axis representation, OX consumption per capita, OY reserves per capita and OZ production per capita; production itself is composed of two parts, one of non-renewable reserves and one of renewable reserves, the relative importance of which may possibly change with time. Should, in the long run, solar and/or geothermal resources be the only resources, the representation will have rotated from plane XY to plane XZ.

In fact, we are mainly interested in the short and medium term (Phase I and Phase II of Prof. Häfele's three phases of energy evolution), and with the related problems of energy research and development.

One major question after the oil crisis (which was, in many aspects, a political crisis) is to get some idea of how far various countries will develop "Projects Independence", which will have as a result the relative decrease (this may be an absolute value as well) of world energy trade; in the same spirit, one other major question would be to assess to what extent producing countries will possibly progressively decide in favor of energy conservation and production pro-rationing, with the same possible effect on world energy trade. Our mode of classification of the various countries is aimed at such a study of world energy trade in the short and medium term. But it is also related to its counterpart, namely Energy Research and Development.

The evolution of a given country can be represented as a continuous curve, as shown below:



Generally, taking for example a European country, the consumption has increased, although irregularly, and the reserves (most often, coal reserves) have decreased through depletion or abandonment. The actual trend ($\overrightarrow{AT}$) is in the same direction, more or less similar to a composition of energy imports on which this country relies heavily. To improve its energy situation, the given country would possibly like (assuming it has an energy policy....) to shift to the region as shown: consumption would be still higher, but tentatively kept under the 8 tce limit, and reserves would be increased. How to achieve such an increase of the reserves? In our figures, we have taken into account for the present time (1971 values) only the proven fossile reserves. Later on, say in 1985, part of the proven reserves will have been depleted, but probable reserves would become proven reserves, and we can assume that possible reserves would have become probable reserves*. For instance, for Germany, coal reserves deeper than 1200 m. (which are very important) are not taken into account for the time being; they could become recoverable in 1985 or 2000, depending on technological development, and evolution of world energy costs. The same applies to North Sea oil or, as a farther possibility, to Mediterranean oil.

Regarding uranium, which we have not mentioned until now (because its role in the energy mix was still not important), this is another example of how to change, in the medium term, the position for the reserves. Generally, we assume in this study that known proven uranium reserves will be used with Light Water Reactors until 1985-1990, and then progressively with Breeder Reactors after 1985-1990, according to "penetration" curves as proposed by USAEC or the OECD (such a shift changes the conversion factor for expressing uranium reserves in tons of coal equivalent). In fact, the energy reserves position of a few countries, like the USA, Canada, Australia, South Africa, France,

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*Once more, this shows how urgent it is to improve dramatically the knowledge of the reserves.

Niger, etc., is revised upward by the inclusion of uranium reserves. In France, for instance, rough addition of 50,000 tons of uranium adds about 1 billion tce (by taking 1 grm. U235 ≈ 2.7 tce), with LWR (not taking into account conversion efficiency).

It can be considered, whether it be for deep coal mining, for off-shore oil (in shallow waters, and still more so in deep waters), or for nuclear energy, that the ability of a given country to change its energy position depends on its "Technology Potential". One of the aims of this study is to try to assess the "Technology Potential" of various nations for changing their energy situation. Determination of this potential will include, for instance: relative percentage of GNP devoted to Research and Development, ratio of Energy-oriented R & D to the general R & D budget, industrial structure, etc.

Assuming that it is impossible for a given country to change its energy evolution curve at a right angle, part of its path for the near future is already more or less predetermined. From then on, various paths will possibly be followed:

- decrease of reserves and then a decrease in consumption, due, for instance, to a political decline;
- continuous decrease of the reserves and increase of the consumption, relying more and more on energy imports;
- stabilization of the reserves (not using them), and continuous increase of consumption;

- "agressive energy policy" i.e. tentatives to increase the reserves, and to limit the increase or possibly decrease the consumption. According to the country, to geological possibilities, to economic conditions, to technological potential, etc., there are various ways to achieve such a goal, depending, for instance, on a choice between possible fuels: coal*, oil, uranium, etc., not to speak of solar and/or geothermal for a more distant future. These are represented on the figures by various curves, on which special points represent decision-making processes.

A First Applieation

We have selected a few countries (16), which are either industrialized, oil exporting or developing; Table 1 gives the main values taken into consideration (for 1971).

Figure 1 shows a classification of these countries with only proven fossile reserves. In these figures, the reserves are given in absolute values, in tce, and the scales are logarithmic. For the reserves, variation goes from 2^3 (8 tce) to 2^{15} (32,768 tce).

For the USSR, USA, Canada, the European countries, Japan, and China, most of the reserves are due to coal, as can be seen from Table 1. In the figure, the effect of population can be seen very clearly for oil producing countries: Kuwait is on the very high side, and Indonesia on a surprisingly low side.

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*It must be remembered that the "definitions" of reserves include present known recovery technology.

In Figures 2, the same results are shown by using as ordinates the ratio of reserves to consumption, in years. In 2(a) and 2(b) the same results are presented in two different ways:

- 2(a): x gives the values with actual, present consumptions,
  and o gives what these values would become if the consumption of energy becomes uniform, at an 8 tce value;

- 2(b): these last values, related to an 8 tce consumption are listed on the 8 tce axis.

The combined effect of population <u>and</u> an increase of energy consumption changes the relative positions considerably*. Indonesia, for instance, today a strong energy (oil) exporter, has few reasons to maintain this position for a long period, or else it will be unable to continue its development through lack of energy.

Comparing actual present values for the USA and Germany, it can be seen that, although the absolute value of the reserves is much higher for America, the relative index is only twice as much in years of actual consumption because of the different levels of the population and of energy consumption per capita.

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*It may be argued that it is not reasonable to foresee such rapid increase. This is true for developing countries without energy, and much less true for developing producing countries: Kuwait was very near to the 8 tce limit in 1971. In Iran, energy consumption doubles about every 4-5 years; in Algeria, industrialization also increases the consumption of energy very fast.

We personally believe that such considerations, especially the newly introduced concept of energy reserves per capita, will probably increase in importance as the various nations become more "energy-nationalist".

(1) See for instance Joel Darmstadter, "Energy in the World Economy"

Table I

Country	Population Millions	Reserves Hard Coal Mtce	Reserves Lignite Mtce	Reserves Oil Mtce	Reserves Gas Mtce	Total Reserves Mtce	Consumption per capita tce	Reserves per capita tce	Reserves / Consumption Yrs.	Reserves / 8 tce Yrs.
USA	207	1,100,000	121,800	7,716	11,843	1,241,359	11.244	5,997	533	750
USSR	245	4,121,600	421,914	13,304	27,015	4,582,833	4.535	18,705	4,124	2,338
Germany	59.2	70,000	18,000	118.5	582	78,700	5.223	1,330	255	166
France	51.25	2,800	9	21	307.5	3,138	3.928	61.3	15.6	7.7
U.K.	55.6	15,500		594	1,689	17,783	5.507	320	58	40
Canada	21.6	61,000	7,230	1,689	2,356.5	72,275	9.326	3,346	359	418
Iran	30	1,000		12,397	5,522	18,919	0.895	631	705	79
Saudi A.	8			29,457	3,019	32,476	0.988	4,077	4,070	510
Kuwait	0.83			17,055	1,828.5	18,883	7.888	22,723	2,880	2,840
Venezuela	1.08	53		2,949	1,344	4,346	2.518	4,039	1,604	505
Indonesia	125	845	600	2,188	220	3,853	0.123	30.8	250	3.8
Japan	105	19,248	520	4.5	24	19,796	3.267	188.5	57.7	23.5
Brasil	95.4	10,675		169.5	39	10,883	0.500	114	228	14.3
Algeria	14.8	20		1,925	6,625	8,750	0.492	580	1,178	72.5
Morocco	15.2	96		1.5			0.205	6.4	31.3	0.8
China	787	1,011,000	210				0.561	1,284	2,289	160.5

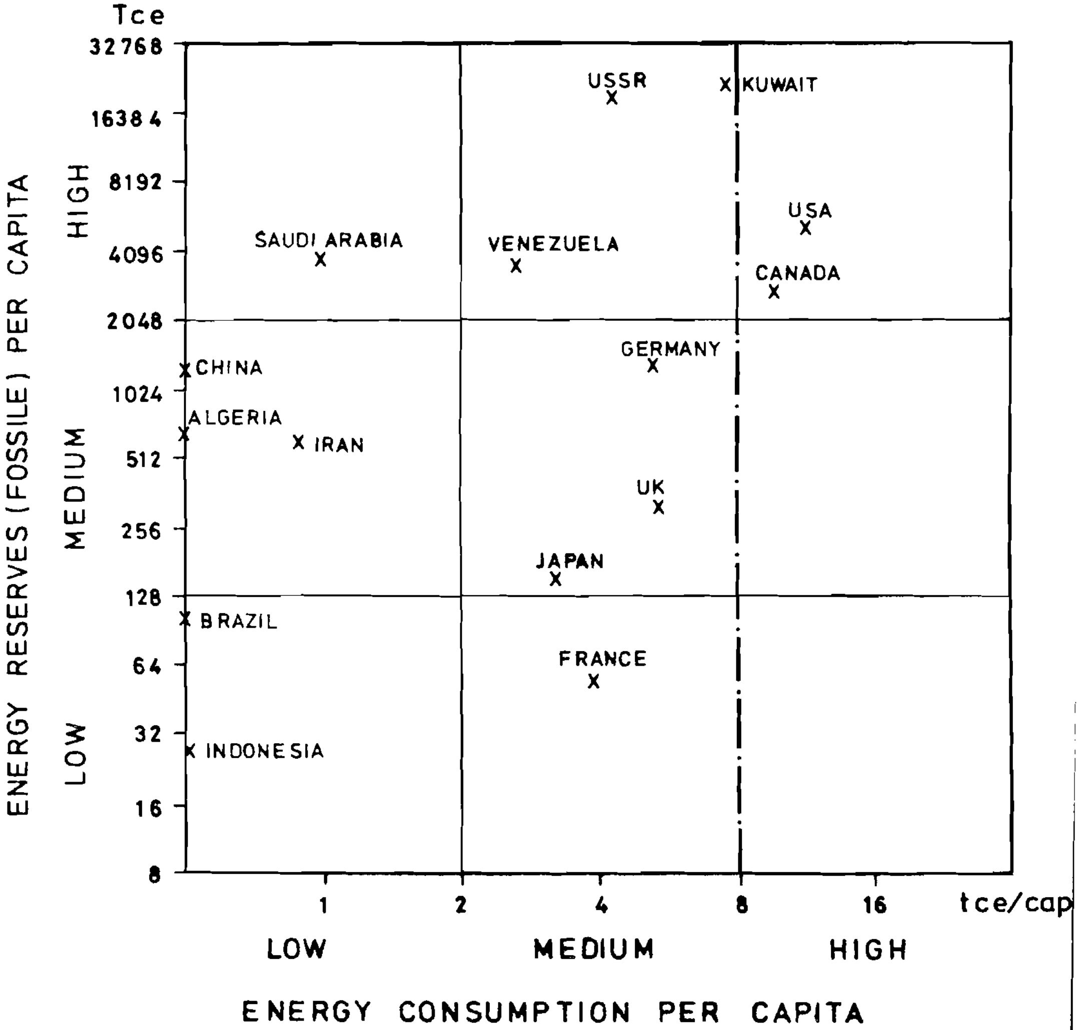

FIG 1. CLASSIFICATION OF A FEW COUNTRIES (FOSSILE) RESERVES PER CAPITA IN tce

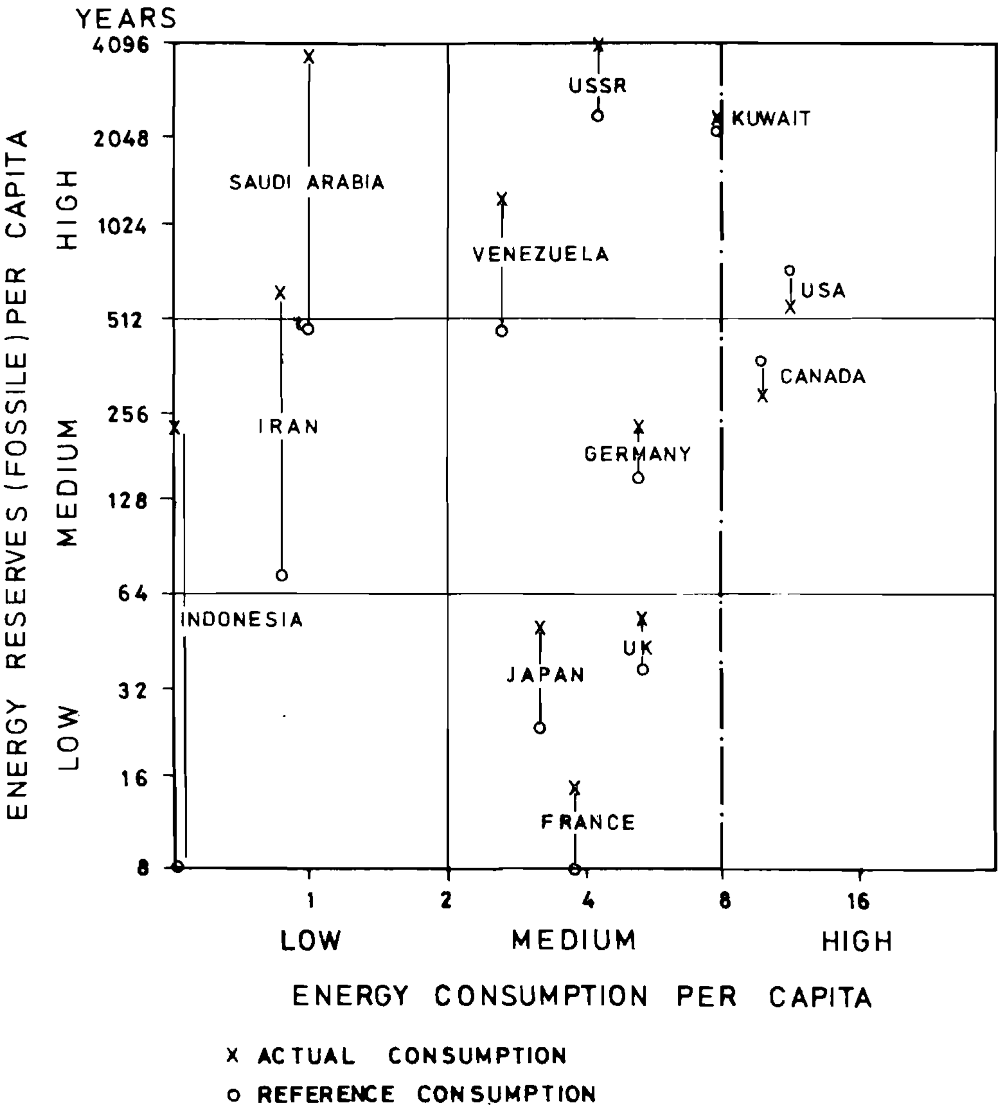

FIG 2(a). CLASSIFICATION OF A FEW COUNTRIES (FOSSILE) RESERVE PER CAPITA, IN YEARS

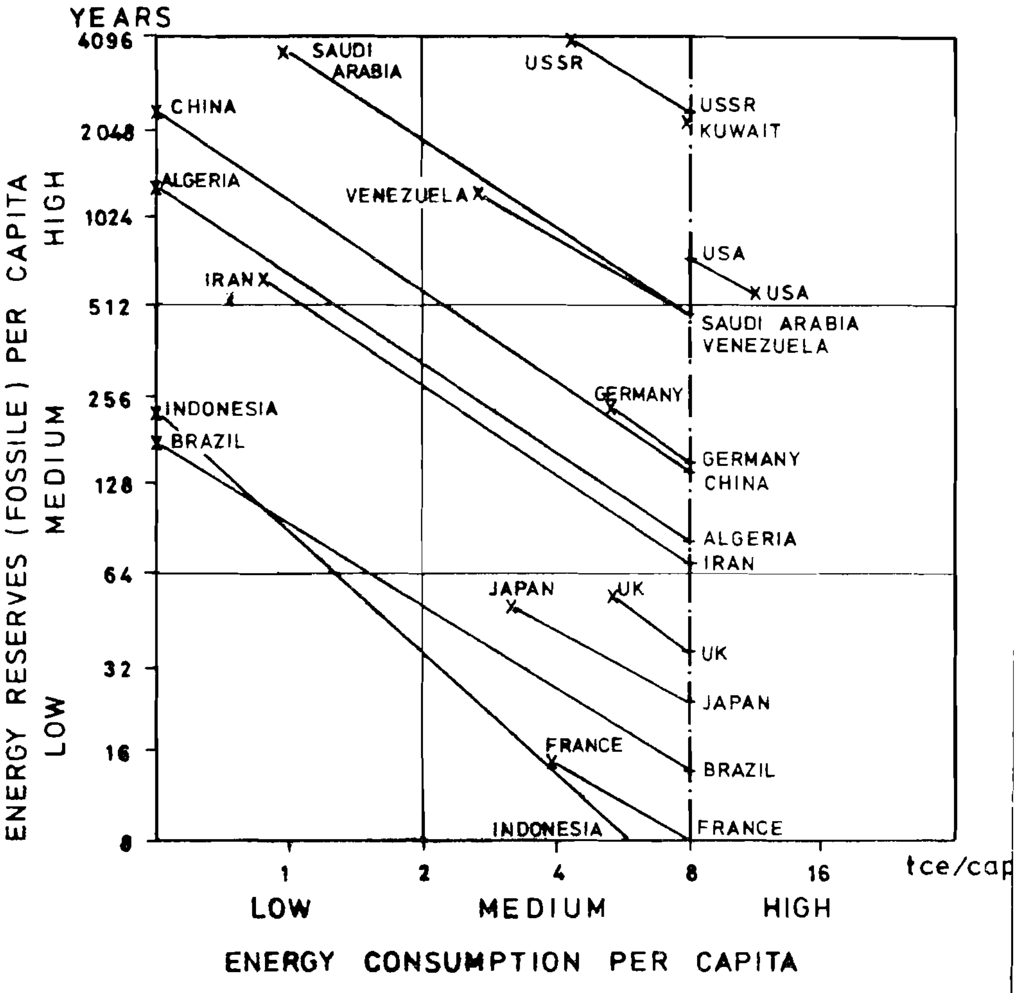

FIG 2(b). CLASSIFICATION OF A FEW COUNTRIES (FOSSILE) RESERVES PER CAPITA, IN YEARS

Interactions between Large Amounts of Waste Heat and the Climate

Wolf Häfele

The Oak Ridge National Laboratory (ORNL; A.M. Weinberg and P. Hammond) was farsighted enough to make a start in studying the interaction of waste heat with the atmosphere by use of the now existing global circulation model available at the National Center for Atmospheric Research (NCAR) at Boulder, Colorado. A population of 15 billion people employing 20 kW/capita was considered, which led to a waste heat release of ≈ 10 Q/year. The distribution of this population was analogous to our present population pattern. In Fig. 1 the results as prepared by W. Washington of NCAR* are shown. The map gives the temperature differences against a reference case without the waste heat of 10 Q/year. While the linear temperature average as a whole is very small (below 1^{o} C) it is obvious that the regional changes involved often are substantial. One should recall that the redistribution of moisture in the atmosphere can be felt and will be significant even earlier than the temperature changes.

The surprising result obtained by W. Washington now is that in both cases negative thermal pollution and random noise errors in the temperature surface distribution lead to very similar patterns of temperature changes. This is shown in Fig. 2 and Fig. 3. The most obvious interpretation is that almost any kind of excitation induces a certain kind of pattern of temperature changes. While keeping in mind that the set of equations governing the climate is highly non-linear one is tempted to speak of "eigenmodes". Before this background contacts have been made with the British Meteorological Office (BMO), Bracknell, Berks., England. Fortunately

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* Washington, Warren M.,"Numerical Climatic Change Experiment: The Effect of Man's Production of Thermal Energy", Journal of Applied Meteorology, Volume 11, August 1972, p. 768-772.

enough it was possible to carry out a numerical experiment with the global circulation model that is used at the BMO (note: this model covers only the northern hemisphere). An ocean anomaly east of New Foundland was considered that covered an area of 1000 km x 1000 km and involved a surface temperature increase of 2 ^{o}C, so that additional heat outputs to the atmosphere of $2 - 3 \cdot 10^{14}$ W result. As this equals $\approx$ 6 - 10 Q/a it fits nicely with the heat output considered by the ORNL/NCAR research. The results are shown in Fig. 4. Again a pattern of temperature changes evolves. Fig. 5 shows the case for a random error ($-2\ ^{o}C \leq \Delta T \leq +2\ ^{o}C$) and in this case, too, similar temperature changes evolve.

At present we have a numerical experiment running at the BMO in which the heat (sensible heat) release of twice 1.5×10^{14} W is considered. One such place for heat release is a spot west of England, the other is east of Japan. The underlying idea is to simulate the heat releases of extremely large primary energy parks in those parts of the open ocean. Of course, these upper limits are unrealistic. The waste heat of primary energy parks would be given to the waters of the surrounding oceans and not to the atmosphere and in either case 1.5×10^{14} W is an unrealistically high value. But we have chosen this approach to have a case that will lead us out of the background noise. Then we will work ourselves backward to more realistic cases.

The ideas for this line of attack are twofold: On the one hand we are interested in identifying locations on the surface of the earth where the release of large amounts of waste heat leads to minimum reactions of the climate, upon the assumption that such locations would be suited as sites for large primary energy parks. On the other hand we would like to explore the idea whether there is some kind of upper limit to the release of large amounts of waste heat. If one looks at this problem in an unsophisticated way the answer appears to be no: The solar input to the earth is 1500 Q/a (on the ground, average). In comparison, any foreseeable releases of energy induced by man are quite small. But as the examples given above show it is more the excitation of some kind of "eigenmodes" which is the legitimate concern.

More work along these lines is going on in IIASA's Energy Project.

POSITIVE THERMAL POLLUTION

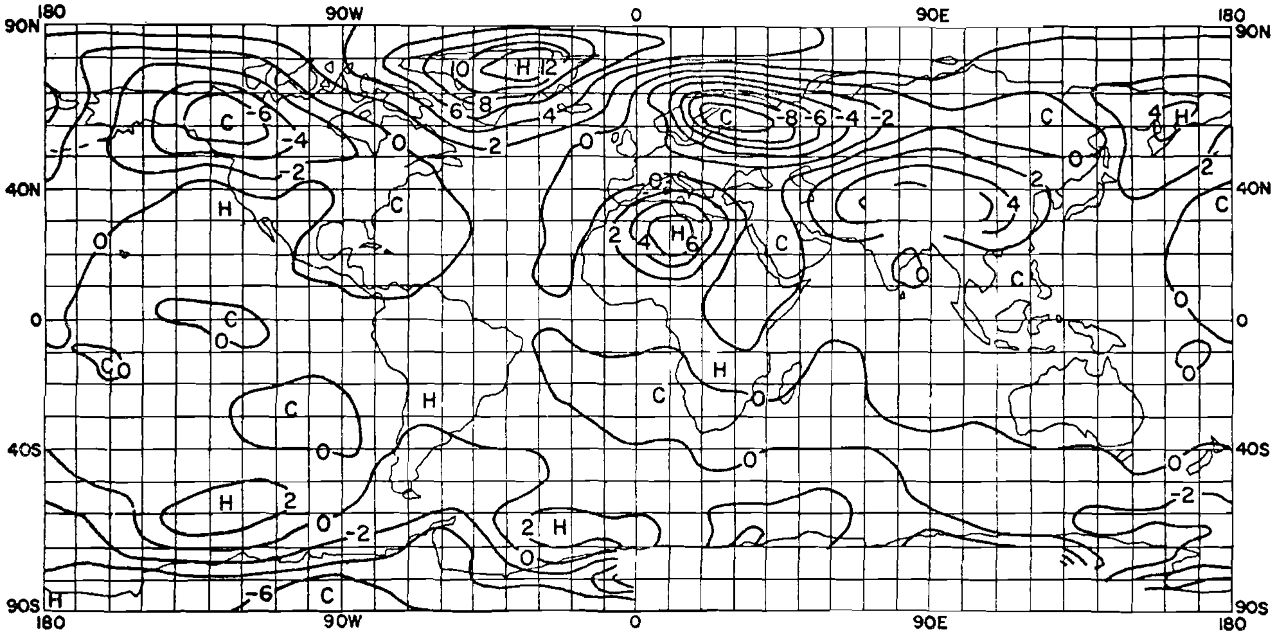

Figure 1

Source: W. Washington of NCAR

NEGATIVE THERMAL POLLUTION

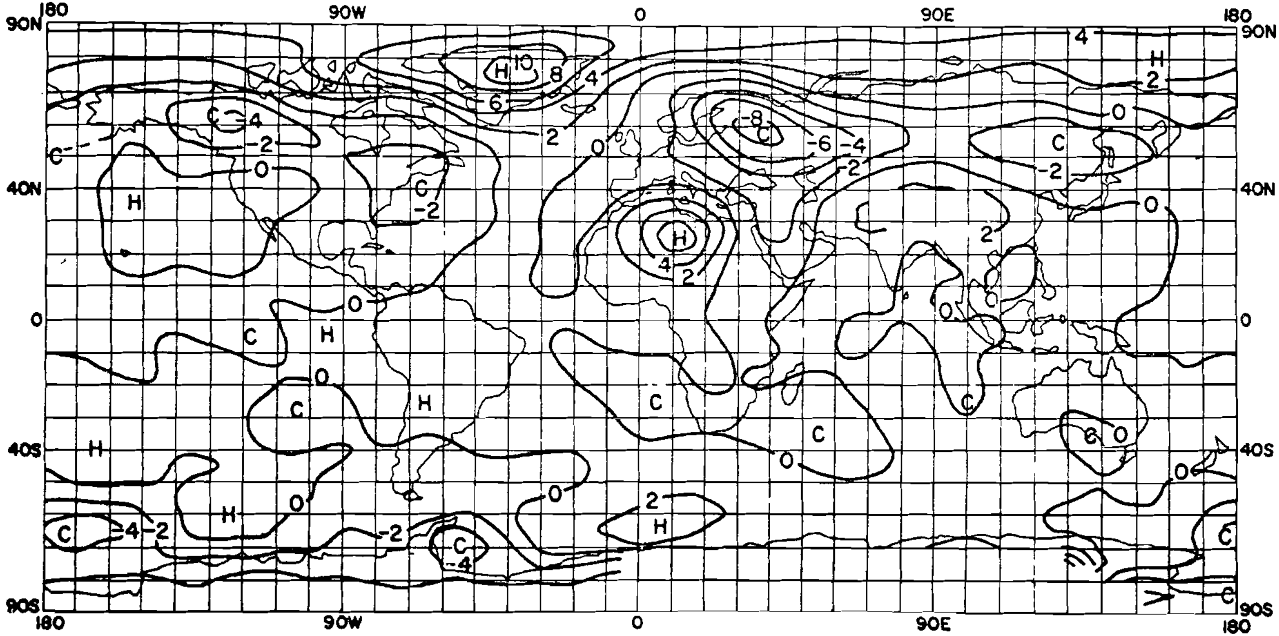

Figure 2

Source: W. Washington of NCAR

RANDOM ERROR EXPERIMENT

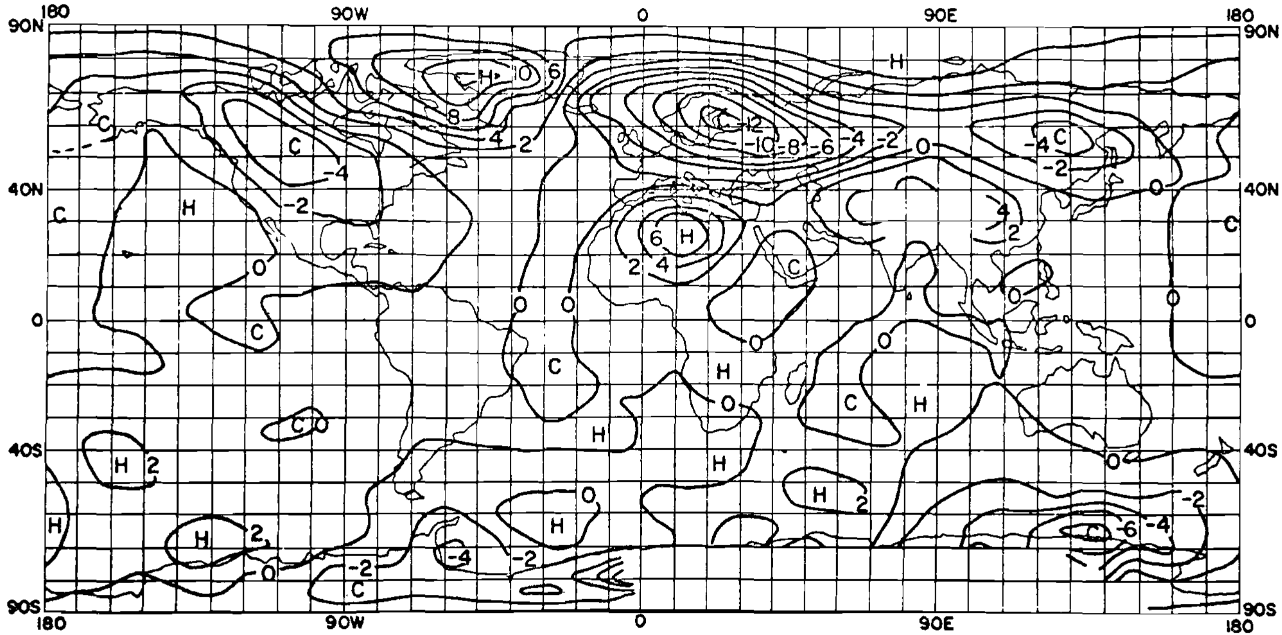

Figure 3

Source: W. Washington of NCAR

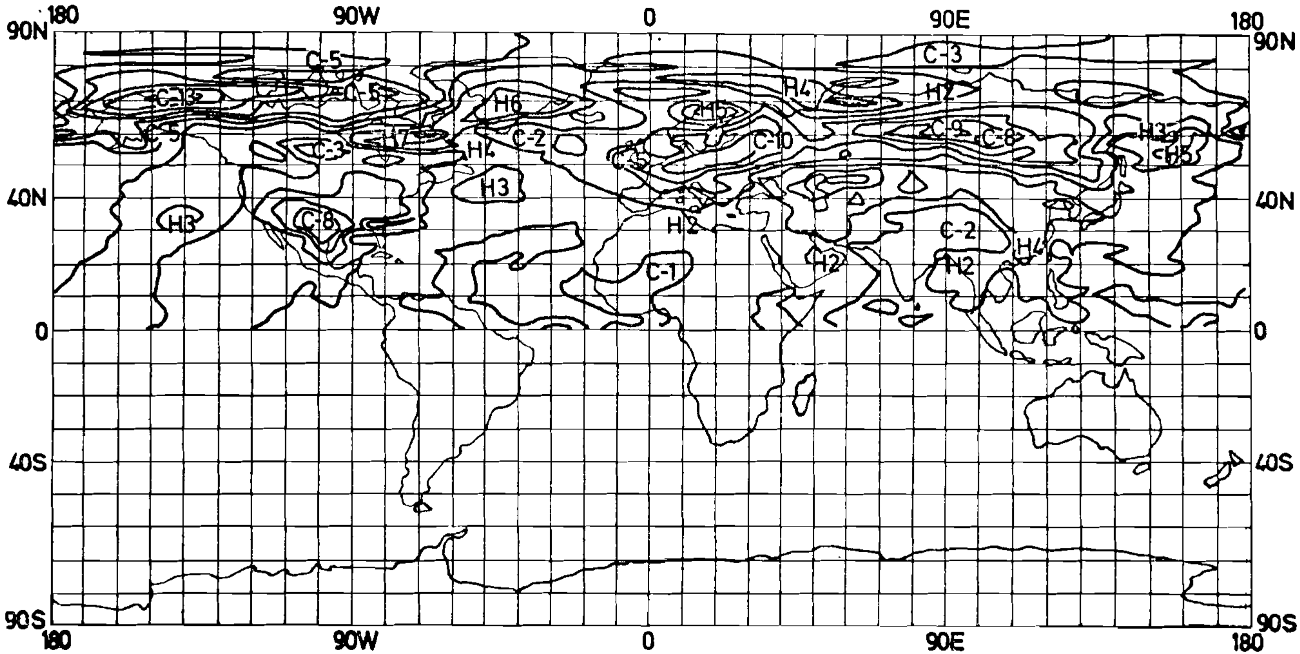

Figure 4

POSITIVE THERMAL ANOMALY IN NEWFOUNDLAND (MODEL 2)

Source: British Meteorological Office, Bracknell, England

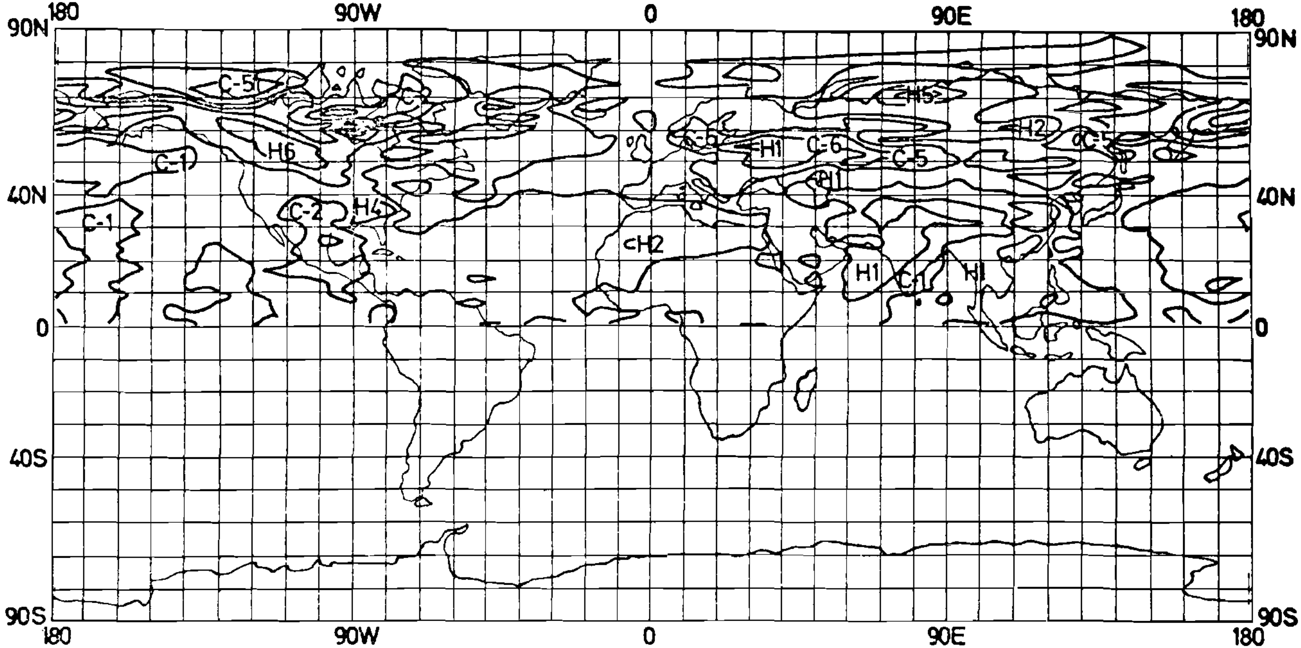

Figure 5

RANDOM ERROR EXPERIMENT (MODEL 2)

Source: British Meteorological Office, Bracknell, England

Climate and Water: Interfaces with the Energy Problem

Wolf Häfele and Cesare Marchetti

What precedes refers to an analysis of the possible meteorological consequences of the distributed use of energy. But the large scale use of nuclear energy may introduce a new problem: that of a very localized release of heat, in very large amounts, where the intermediate energy vectors, electricity or hydrogen, are produced. This heat may become in time comparable to that released in a distributed way over the continents, and the spots where it is released may be very limited in number, in order to satisfy the numerous boundary conditions for nuclear power siting.

The line of thought we are assessing now is the following:

The ocean is obviously the only place that can provide sufficient cooling capacity, but thermal plumes have to be avoided. This is mainly because of the interference with the biosphere of large bodies of water 10-15^{o} warmer than "natural." This warmer water covering probably thousands of square miles would certainly not be accepted by conservationists, being an obvious threat to all sorts of equilibria, biological and climatological, and so it has to be avoided at any price.

For this particular point the solution appears fairly simple, if not inexpensive: in the tropical and temperate areas where these stations are more likely to be located, the ocean is layered in temperature, with an upper layer relatively well mixed and at high temperature.

In order to fix the ideas, we may say that this upper layer has a temperature of 20° C and a thickness of 50 meters. Below this layer, temperatures taper down, in the next 50-100 meters, to perhaps 7° C and then stay constant. This transition layer is called the thermocline.

In order to avoid the thermal plume it is then sufficient to take the cooling water under the thermocline, and to adjust its flow so that its temperature, when it leaves the plant, closely matches that of the water in the upper layer.

The secondary effects of this operation are: a certain increase in the local upwelling, and in the thickness of the upper warm layer in order to provide the outward driving force. The first effect is in general considered beneficial by oceanologists, the second disappears in the background noise for powers of the order of 100 GW/km. In spite of being second order effects by respect to the "hot plume case," they deserve a most careful study, especially when the energy released at a single spot may amount to various TW.

Now if local effects can be avoided by carefully "erasing" the plume, the same cannot be said at a global level, as this energy is going to reappear somewhere.

Here comes the second line of our approach: this energy should emerge in a <u>neutral region</u>, i.e. in a place where it can be properly dissipated with minimal "teleconnections" with the global weather pattern.

This is obviously the toughest part of the problem, both because long term global meteorology is a science still in its infancy, and because the most unexpected teleconnections have recently been discovered by Namias (e.g. droughts in

Sahel being related to blocking in Scotland).

In order to delineate the background for these choices, let us enter, very schematically, into the mechanism of earth energy balance. Energy coming in from the sun is absorbed by the atmosphere and by the earth surface, and is reradiated as infrared mainly from the atmosphere, in a region we may roughly indicate between 6 and 8 km. The temperature of this layer is fairly low and variable with the season. Just to fix the ideas, let us say it is -20° C between 0° to 60° latitude, and -50° C from 60° to 90°. Energy absorbed at the surface of the earth is transported to the emitting layer mainly as latent heat of the water vapor carried upward by air circulation.

Apart from this vertical energy transport, there is a horizontal transport, generally poleward, through air and ocean currents. The yearly main value of this energy flow, at our latitudes, is around 100 GW/km (410^{19} Kcal/year or 160 Qs at the 40° parallel).

In the case of the oceans, through the shear of the winds and Coriolis forces, the upper warm layer of water is in a sense collected and converted into large currents flowing west of the ocean basins. (E.g. the Gulf and Kuroshio streams in the northern hemisphere, each carrying north something around 20 Q/year.) This energy is liberated in the northern part of the oceans, in form of water vapor transferred to the dry and cold air coming from the polar regions. This vapor is carried upward by thermals and finally releases energy into the IR radiating layer of the atmosphere at high latitudes. So very schematically a large fraction of the radiation unbalance of the tropics is transferred through sea currents plus evaporation to the polar regions which act as a kind of global cooling radiator.

Now we are trying to assess the extra cooling capacity somehow available in these regions and to find the proper mechanism to transfer waste heat there horizontally with a minimum of interference along the way, and a minimum of teleconnections at the final vertical transfer point.

The importance and novelty of this approach lies in the fact that we are taking an active position towards the problem of large scale waste heat disposal; and instead of just trying to forecast the consequences of our increased use of energy, we try, through an operation of global engineering, to minimize its effects by the search for optimal heat dumping sites.

In order to establish the techniques and the proper contacts with the oceanographers and long term weather forecasters, we will choose a couple of sites, which intuitively appear promising, and try to analyze in detail the fate of heat dumped there.

One of these sites should be near the east coast of the U.S., above the northern rim of the Gulf current. The expected effect is an increase in evaporation from the sub-arctic sea at the level of Greenland, with increased precipitation in contiguous regions, and a northward displacement of the troposphere subsidence, with a corresponding increase in the local temperature of the radiating layer.

The other site should be the Kerguelen Island in the South Pacific. In this case the mechanism would be different as the water from the site would be circulated around the Antarctic by the circumpolar current and would probably increase the humidification of the winds emerging from the polar subsidence, increasing the precipitations presumably in the Southern Pacific on the rim of the polar circulation cell.

A Possible Solution to Some Waste Heat Problems

Richard Patzak

The work of Mr. Marchetti comprises options only from a global point of view and for the more distant future. Since we have to cope with problems of waste heat also in the present and in the near term future, I have studied in more detail the waste heat problem from a regional point of view. The problem of waste heat arises since it is impossible--according to the second law of thermodynamics--to convert heat-energy completely into any other form of energy. Losses of energy are inevitable. The ratio of losses and useful energy is called efficiency. The efficiency parameter of the presently driven machines or devices varies between approximately eight and approximately forty percent. And we cannot hope to increase this percentage. This means that an increased amount of energy consumption will implicitly cause an increased amount of waste heat in the future. In addition to these conversion losses there are also losses by transportation of energy regardless of the type of transportation. In the case of electricity we will perhaps be able to avoid these losses with the help of super-conducting cables.

All forms of released heat might have an impact on climate where energy is used abundantly. Therefore we should try to separate the places where energy is generated (e.g. Primary Energy Parks) and the places where energy is consumed (especially in cities) and to connect these places with convenient secondary energy carriers (e.g. electricity, or to transport it in pipelines in the form of chemical binding energy). But the useful energy also is ultimately transformed into heat (according to Fig.1).

Up to now it was not necessary to uncouple supply and consumption for the ecological equilibrium was not significantly disturbed by power plants with relatively small capacities. But in future times we will probably have to switch to plants with huge capacities in order to meet the increasing demand of an increasing number of people. And in these power plants the problem of waste heat release is of growing importance. From the climatological point of view, these power plants are so-called "hot-spots" in the temperature distribution of the world's surface, which might generate microclimates in the surroundings of these plants. Wet cooling towers of power plants already do so.

We must therefore consider some other possibilities of getting rid of the waste heat. One possibility which I studied in greater detail is the radiation of heat into space without interaction with the atmosphere:

A figure of this system (Figure 2) shows the position of this system element in the system of environmental pollution. All downward arrows are reasons for these problems; all upward arrows are possible solutions. One can see that radiation could be one alternative for cooling towers or for cooling huge power plants with sea water since not all countries--e.g. Austria--have direct access to the sea.

Now I want to say a few words about the physics of this technique. The radiant intensity distribution of infrared radiation of a black body (and we consider the earth as black or almost black in the infrared emission spectrum) is given by the quantum mechanical equation of Max Planck (Fig. 3).

Exactly this result is obtained when the upgoing radiation close to the surface, say at a level of a hundred meters, is measured. If you measure the energy distribution at a height of approximately 100 km, for instance, with the help of a satellite, you will obtain the shape of this curve (Fig. 4). The curve is strongly dependent on the special weather situation, especially on the water vapor and CO_2 content.

One can see that in the frequency range up to 8μ and from 13μ onward there is a very strong attenuation, and between these mentioned boundaries the curve almost coincides with the Planck curve. This range is called the frequency window of the infrared spectrum. This window would be more obvious if the picture were not falsified by the radiation of the atmosphere which itself radiates: according to Kirchhoff's law it radiates exactly in that frequency range where it attenuates most. The dotted line in Fig. 4 indicates the frequency window as it would appear if the contribution of the atmosphere would be disregarded. That means that in the frequency window there is almost no interaction of the outgoing radiation with the atmosphere for a small interaction with the ozone molecules. But also this small interaction might have an impact on the ozonosphere. The ozone layer of the atmosphere lies at a height of about 25-50 km. It is in dynamic equilibrium of generation and dissociation of ozone and is absolutely necessary for human life as it serves as a shield against the dangerous ultraviolet rays.

Although the energy of the IR-Quantum is too small to split an ozone molecule, there have recently been speculations that the heating of the ozone layer might have unforeseeable consequences for the structure of our atmosphere.

In order to make use of this frequency-window phenomenon, one should try to find a material whose emission spectrum has a distinct peak in the range between 8μ and 13μ. It has already been demonstrated experimentally that PVC, for example, can be a probable solution to this problem. In the case of a power plant of 1 GW capacity the waste heat is of about 1600 kW. This amount of heat comes out in the form of water with a temperature of about 40^oC. In order to cool it down to 10^oC one would need a pipeline grid of about 5 km^2 made of PVC pipes or covered with a PVC foil. Under the changing aspects of energy economy I think that this could be--at least in special cases--a possible technique, but more analysis is required along these lines. I have made contact with Prof. Trombe who is an expert in the field of radiation in the atmosphere, and the experiments he carried out seem to be very promising for our purpose.

There is another interesting fact which arose from these considerations. With the help of a computer it is possible to calculate the shape of this window under different weather conditions, and it can be shown that the often quoted impact of the variation of the CO_2 content is probably overestimated for the radiation budget of the earth. There are many models which try to calculate the variation of the surface temperature of the earth, when the CO_2 concentration is doubled, as estimated for the future. The most extreme results obtained by these models on a global basis are on the one hand an increase of 2^oC and on the other hand a decrease of 3^oC, depending on the assumptions one has to make so that the calculations become possible at all. According to my estimates almost nothing will happen if the CO_2 concentration is increased. Too often the mistake is made to overestimate the greenhouse-effect of the troposphere (taking into account that the atmosphere is not as stable as a glass pane). But in the case of water vapor, all calculations show that the concentration of water in the air has a great influence on the radiation equilibrium. In this respect, too, more quantitative results are not available. This is the main reason why we in the Energy Group put our emphasis on the interface of water and energy. If the results from this research are good we can incorporate this interface, which is getting more and more important, into the overall model of handling energy.

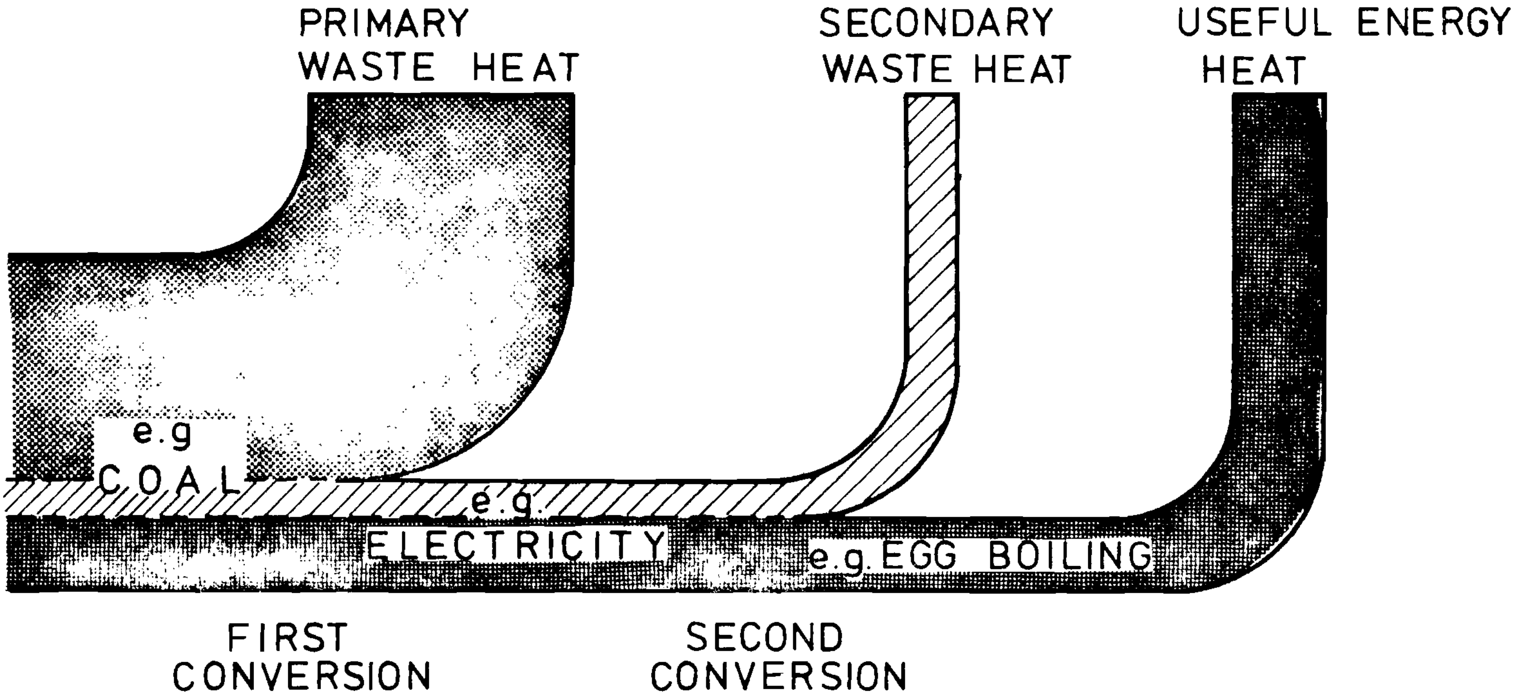

FIG 1: ENERGY FLOW EXAMPLE

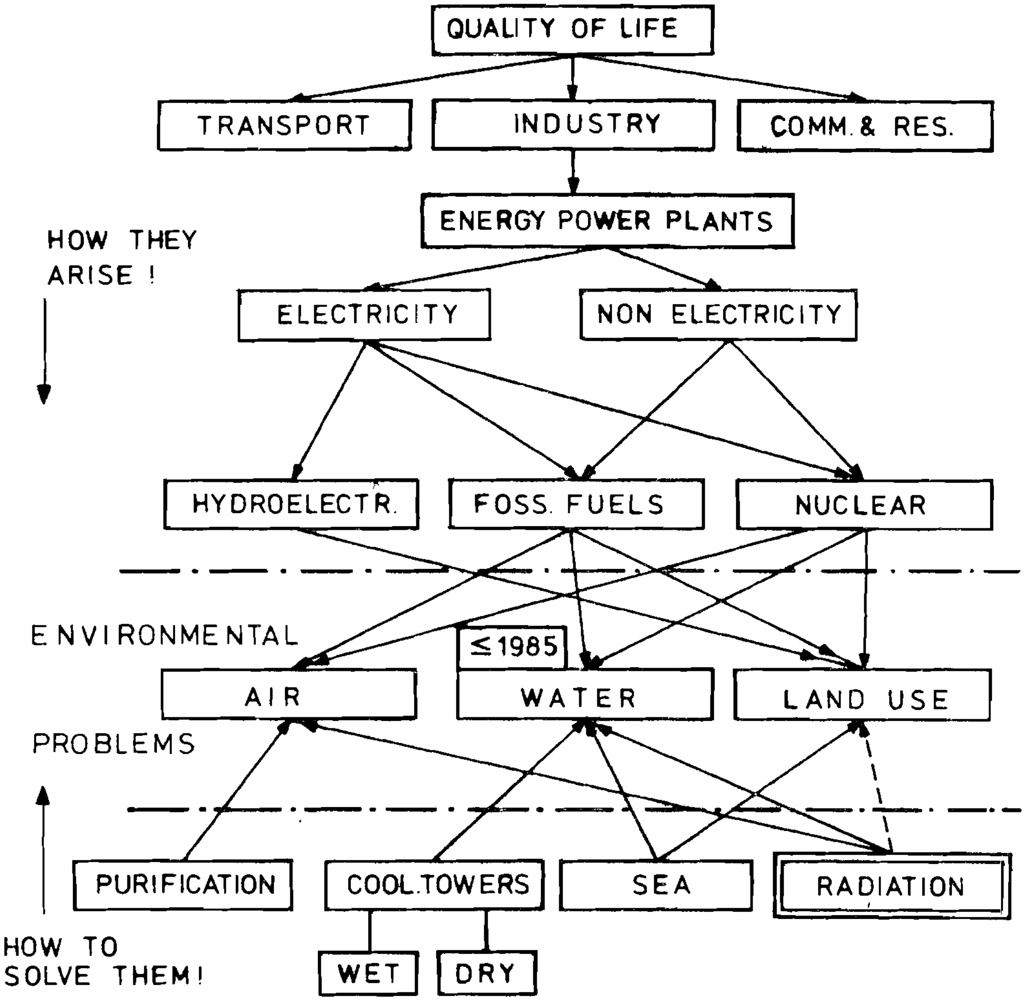

FIG 2: POSITION OF THE WASTE HEAT RADIATION SYSTEM IN THE WHOLE ENERGY SYSTEM.

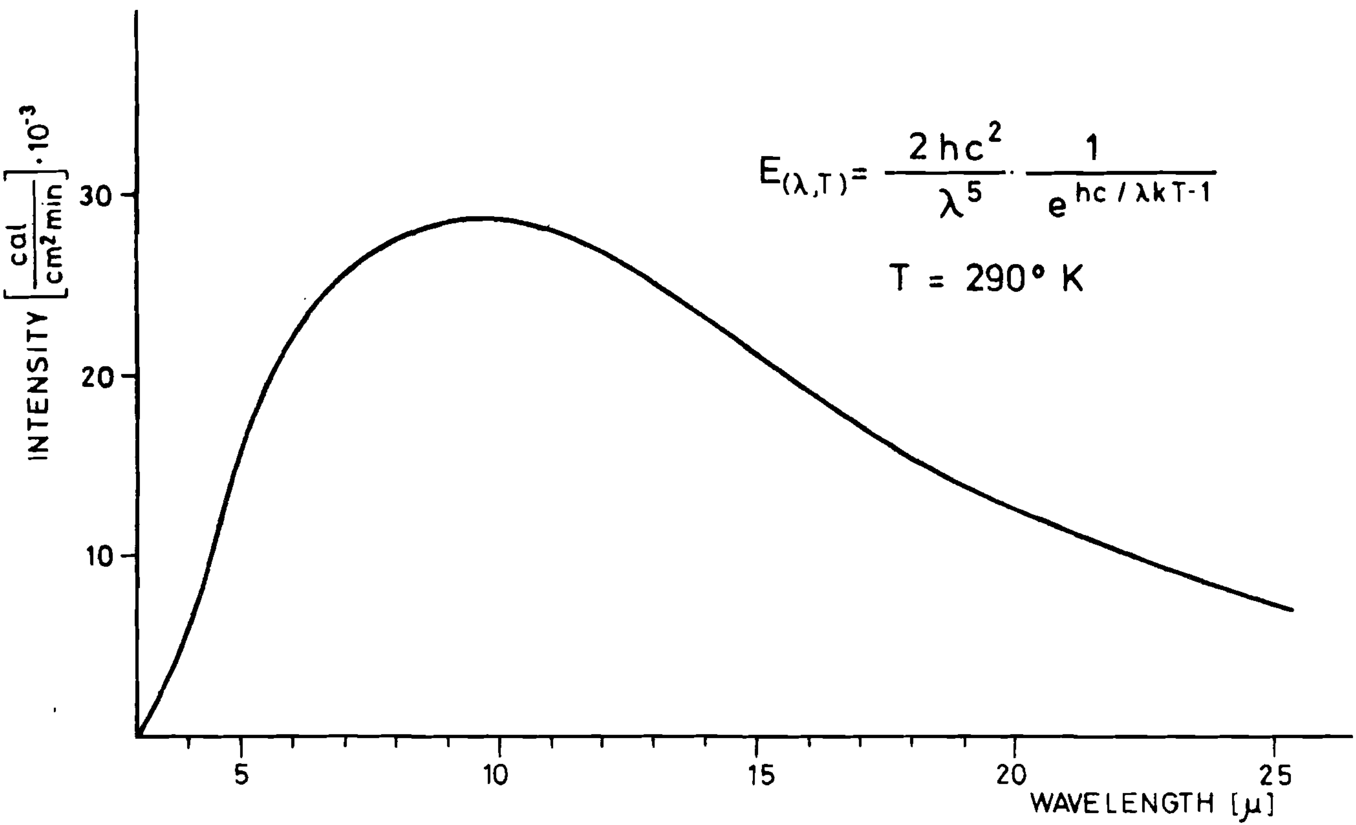

FIG. 3: THE RADIANT INTENSITY DISTRIBUTION OF THE I.R. EMISSION SPECTRUM

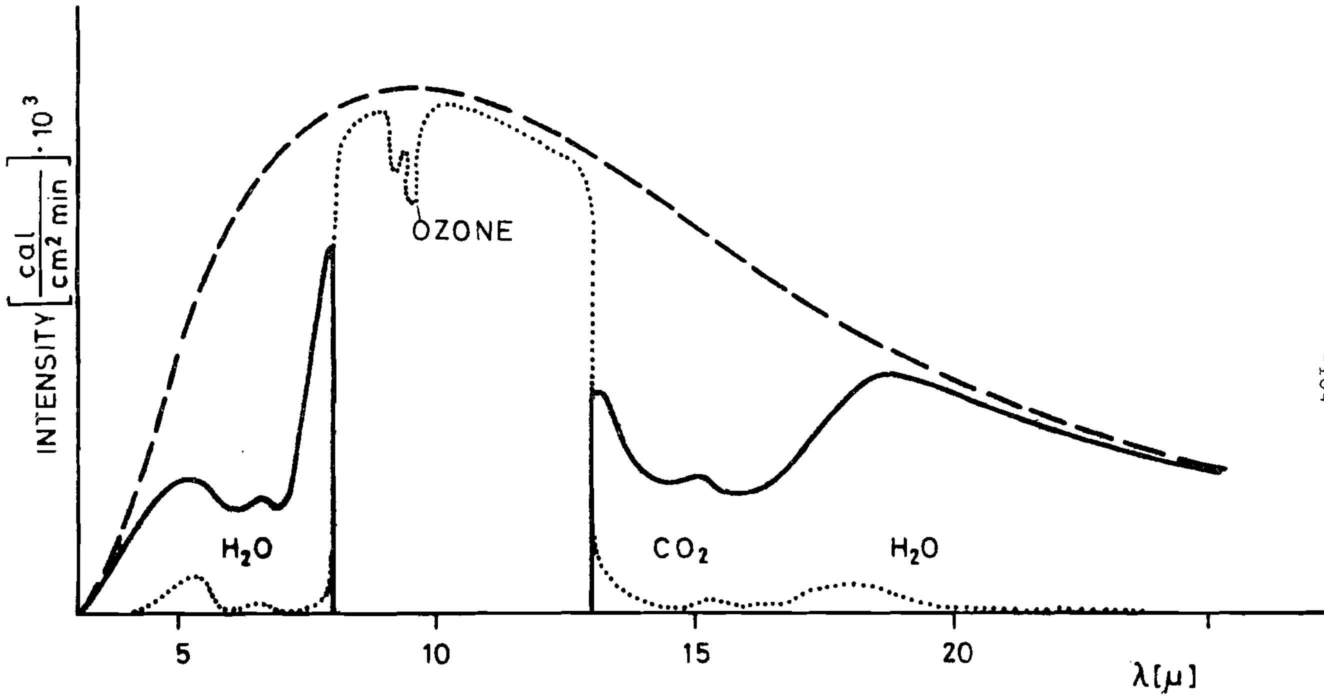

FIG. 4: FREQUENCY WINDOW OF THE I.R. EMISSION SPECTRUM

Hydrogen: Mechanisms and Strategies of Market Penetration*

Alan S. Manne and Cesare Marchetti

1. Introduction and Summary

This conference provides clear evidence of the growing interest in hydrogen as an energy vector and of the increasing variety of efforts to devise water-splitting processes based on non-fossil forms of primary energy. The time seems appropriate for assessing the economic potential of hydrogen in the energy game and for estimating the discounted value of this potential. We need quantitative estimates of the time lags, probabilities of success, and the costs of R. & D. in order to provide guidelines for the allocation of the substantial sums of money that will be needed for a successful and timely development program.

In this paper, we shall describe two successive models--one for quantifying the benefits and the other for optimizing the level and the structure of the research effort. Our aim has been to devise sufficiently simple analyses so as to keep intuition on the track. These models require numerical values for certain parameters, and in each case we have attempted to work with prudent estimates. Because of the inherently subjective nature of these parameters, we have run

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a series of sensitivity analyses. In all cases--even with the most pessimistic assumptions concerning a non-growing, slow-learning society--the prospective benefits appear high.

Compared with these benefits, the costs of exploratory research are so low that it would make good sense for the U.S. alone to support 50-100 parallel projects during the next five years. These would include laboratory and bench-scale experiments and then unit operations tests. By the end of the 1970's, it should be possible to determine which projects are the most promising candidates for pilot plant construction. Demonstration plants would be built during the middle 1980's, and these would be followed by large-scale commercial facilities during the 1990's. This is the scenario for which we shall attempt to estimate the costs and benefits.

2. Hydrogen and the Energy Market

Most presentations of the "Hydrogen Economy" emphasize the use of hydrogen as an energy vector with superior properties: clean-burning, cheaply transportable, and readily storable. Once we start looking at the size and structure of the energy market, we soon see that it will take many years before hydrogen is extensively used as a fuel. From the very beginning, however, water-splitting will help to economize on fossil resources. The new technology can first be used to replace those quantities of oil and natural gas that are now used in the manufacture of chemical hydrogen.

This application will come first because it commands a high price per BTU and because demands are concentrated in large units, e.g. ammonia plants and oil refineries. Concentration means that a water-splitting plant could use the output of a large high-temperature nuclear reactor. The process heat source could be identical to that used for electricity generation. A large and proved reactor type will provide the cheapest source of nuclear process heat. In this way, large water-splitting plants could precede the construction of a distribution net for hydrogen.

For orientation on the numerical magnitudes, see Table 1 and Figure 1, reproduced from Meadows and De Carlo [4]. Note that there are wide ranges of uncertainty in these long-term forecasts of hydrogen demand, but that ammonia and petroleum refining continue to be the principal customers for hydrogen through the year 2000.

In the following section, our calculation of benefits will be extrapolated from the U.S. "low adjusted" figure of 15.5 trillion SCF of hydrogen for the year 2000. This is $4\ 10^{15}$ BTU, equivalent to 2.3% of that year's aggregate demand for primary energy (see Associated Universities, AET-8 [1, p.15]). Despite this small percentage, hydrogen will be an enormous industry. Assuming a price of $6 per million BTU, the annual sales of hydrogen would amount to $24 billions for the U.S. plus an even greater amount for the rest of the world.

TABLE 1.—Contingency forecasts of demand for hydrogen by end use, year 2000
(Billion standard-cubic feet)

End use	Estimated demand 1968	U.S. forecast base 2000	Demand in year 2000: United States, Low	United States, High	Rest of the world[1], Low	Rest of the world[1], High
Anhydrous ammonia	872	3,060	2,460	4,490	7,200	12,700
Petroleum refining	775	4,580	2,340	32,640	6,000	36,000
Other uses[2]	413	1,450	1,450	24,660	2,000	25,000
Total	2,060	..	6,250	61,790	15,200	73,700
Adjusted range	...	...	15,500	52,530	24,950	63,950
			(Median 34,015)		(Median 44,450)	

[1] Estimated 1968 hydrogen demand in the rest of the world was 2,995 billion cubic feet.
[2] Includes hydrogen used in chemicals and allied products, for hydrogasification of coal and oil shale, in iron ore reduction, and for miscellaneous purposes except plant fuel.

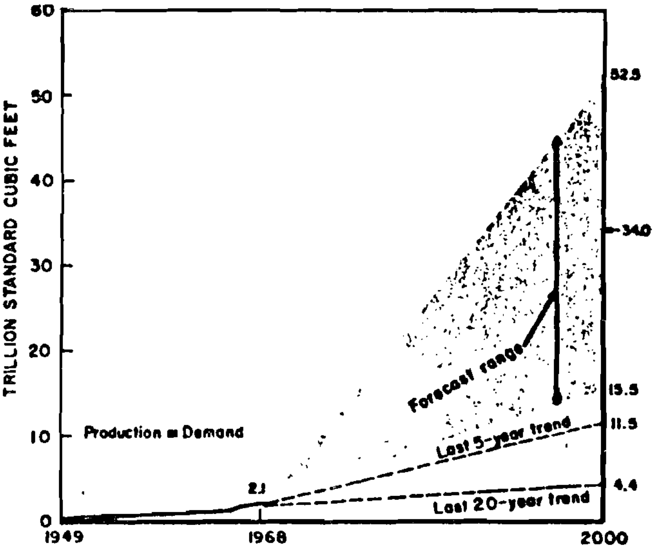

FIGURE 1.—Comparison of Trend Projections and Forecasts for Hydrogen Demand.

Source: Meadows and DeCarlo (1970).

Why might it be reasonable to project a price of \$6 per million BTU for hydrogen from fossil fuels? With today's mature technology for steam reforming, it takes roughly 2 BTU of oil or gas primary energy input per BTU of hydrogen output. To cover non-fuel operating costs plus a return on capital, the price of hydrogen is approximately three times the price per BTU of oil or gas. Implicitly, then, we are projecting an oil price of \$2 per million BTU or \$12 per barrel for the year 2000.

Until water-splitting captures most of the hydrogen market, it seems likely that hydrogen prices will be determined, not by the costs of water-splitting but rather by the costs of steam reforming and similar processes based upon fossil fuels. This might put large profits into the pockets of the innovating enterprises--sufficient profits to more than offset their initial teething troubles and R. & D. expenses.

Once water-splitting has captured the entire market, hydrogen prices will be dominated by the evolution of costs for this new technology. These costs will be lowered successively by economies of scale for individual plants and by the cumulative learning experience acquired by the water-splitting industry. We shall focus upon the latter component because it is more easily correlated with the size and dynamics of the market.

It is convenient to summarize these dynamics with the learning parameter λ, defined as the percentage reduction in manufacturing costs for every 1% increase in the industry's cumulative production. That is, let Q_τ denote the industry's output in year $\tau \leq t$. Then the average costs and the price in year t+1 are given by

$$P_{t+1} = k \left(\sum_{\tau=-\infty}^{t} Q_\tau \right)^\lambda \quad . \qquad (1)$$

The price history of the chemical industry suggests that, with a well supported R. & D. program and a fast expanding market, manufacturing costs may be reduced by roughly 20% with every doubling of the cumulative production. This would imply that the learning parameter $\lambda = -.3$. In the following calculations, to be on the conservative side, we have supposed that $\lambda = -.2$, and that a doubling of the cumulative production will reduce costs by only 13%. This would put water-splitting technology in a sleepier league than methanol or PVC. This is not very reasonable in view of the enormous interest--economic, intellectual and political--linked to an already launched hydrogen economy. On the other side, nuclear reactors and associated chemical plants will be affected by the low metabolic rate characteristic of large animals, and this will tax their rate of evolution.

In addition to the learning parameter λ, equation (1) contains a constant of proportionality k. We have estimated this parameter by supposing that a constant amount of new capacity will be added during each of the 10 years preceding year 0, the date of capture of the entire chemical hydrogen market. The cumulative production during these preceding years will therefore be 4.5 times the production in year 0. Hence, $k = P_o/(4.5Q_o)^{-.2}$.

3. The Demand curve for Hydrogen; Market Simulation

Even before water-splitting captures the entire chemical market, hydrogen will begin to be used for steel making and for air and road transport. For these applications, hydrogen has intrinsic advantages which will more than compensate for its high price. In the case of air transportation, this is due to hydrogen's high heating value per unit weight. Because it increases the productivity of an airplane, hydrogen would be preferable to conventional jet fuel even if its price per BTU were three times higher. Similarly, hydrogen should command a premium price per BTU for steel making and for road transport in areas where the air is heavily polluted. During the 1990's, it is likely that these applications will represent only a small percentage of the hydrogen market. Nonthe-less, they will prepare the way for the period of large-scale expansion beginning, say, in the year 2000.

Once water-splitting captures the premium-price chemical market, the industry's further expansion will depend upon its ability to lower costs and prices. Each time the fabrication cost of hydrogen can be reduced, a new set of customers will be attracted. As a shortcut summary of price responsiveness, it is convenient to define the elasticity η. This parameter indicates the percentage expansion of the hydrogen market associated with each 1% reduction in the current price. For the reference case, it has been supposed that the elasticity $\eta = -2$. This seems like an underestimate of the elasticity of demand for hydrogen in view of its small share of the energy market and its significant advantages for steel making, air and road transport. The demand for hydrogen is surely more elastic than that for electricity, a well-established energy vector. In the case of electricity, it has been estimated that $\eta \simeq -1$ (see Doctor and Anderson [2, pp. 37-40]).

For projecting demands, we shall suppose that future growth may be factored into two components: one that is dependent upon the hydrogen price and one that is independent. The first of these effects is summarized through the elasticity parameter η, and the second through the growth parameter γ. The growth parameter allows for those long-term trends in hydrogen demand that are related to the growth of population, per capita income, per capita use of energy, and the rate of learning how to utilize hydrogen in place of conventional fossil fuels. It is supposed that at constant prices, the demand for hydrogen would grow at the constant annual rate of 5% after the year 2000. This trend factor lies well below the above 10% growth rates experienced during the 1960's, but recall that this was a period during which prices (in constant dollars) declined at the rate of 2.5% per year. The trend factor γ refers only to the rate at which hydrogen demand would grow if its price were to remain constant.

It will be convenient to represent prices and quantities as index numbers relative to their values in year 0. We may then write the market demand curve as

$$\begin{bmatrix} \text{quantity} \\ \text{demanded} \\ \text{in year t} \end{bmatrix} = \begin{bmatrix} \text{long-term} \\ \text{growth factor} \\ \text{at constant} \\ \text{hydrogen prices} \end{bmatrix} \begin{bmatrix} \text{price} \\ \text{elasticity} \\ \text{factor} \end{bmatrix}$$

$$Q_t = \left[\gamma^t \right] \left[P_t^{\eta} \right]$$

$$= \left[1.05^t \right] \left[P_t^{-2} \right] . \qquad (2)$$

Having specified numerical values for the parameters appearing in the dynamic equations (1) and (2), it is straightforward to trace the evolution of the hydrogen market over time (see Figure 2). It turns out, for example, that P_{10} = .725, and that Q_{10} = 3.099. Expressed at annual rates, this means that prices decline at the rate of 3%, and that demand increases at the rate of 12% during the decade beginning in 2000.[1] These growth rates slow down a bit during subsequent years. Intrepidly extrapolating to the year 2050, we note that the hydrogen demands would still lie well below the total primary energy demands even if these were to grow at the annual rate of only 2.7%. These projections leave ample scope for the continuing employment of our colleagues in the

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[1]As a rough check, note that $(\gamma-1) + (\ )(-.03) = .05 + (-2)(-.03) \approx .12$.

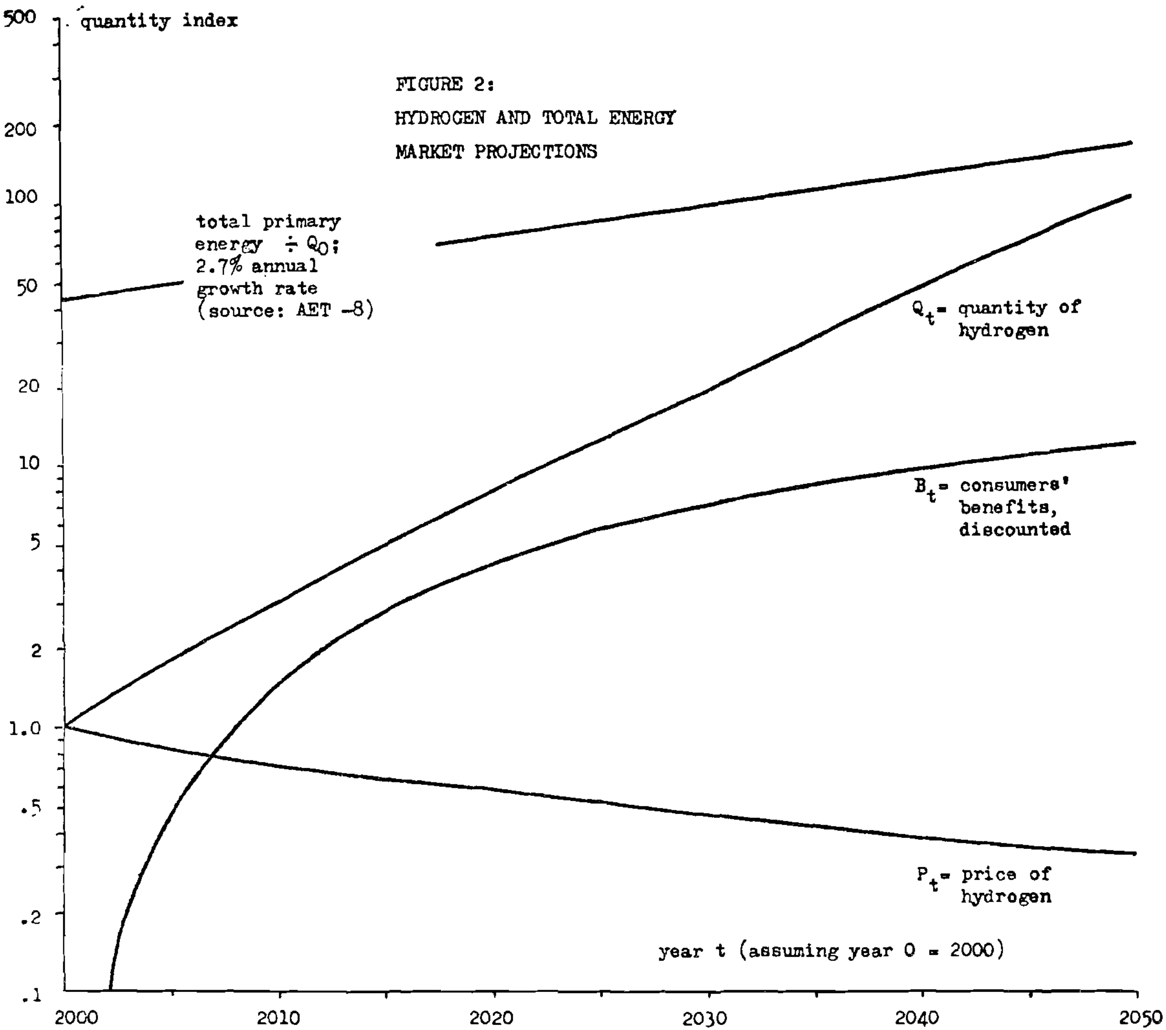

FIGURE 2:
HYDROGEN AND TOTAL ENERGY
MARKET PROJECTIONS

electricity industry, but probably not for those in oil, gas, and coal.

4. Evaluation of Benefits

In itself, this market simulation does not permit us to evaluate the benefits of water-splitting. We do so through the "consumers' surplus" measure illustrated in Figure 3 for year t = 10. It can be seen that if the hydrogen price remained constant at its initial level $P_0 = 1$, demands would grow at the constant rate of only 5%, and that the value $Q'_{10} = 1.05^{10} = 1.629$. We would then observe that the consumers' surplus from water-splitting was zero, for this means that the new technology would provide no price reduction to consumers. In our basic case, however, there are substantial price reductions, and $P_{10} = .725$. Accordingly, there are Q'_{10} consumers each of whom have enjoyed the price reduction of $(P_0 - P_{10})$. In addition, there are other consumers who have been attracted to using hydrogen by the price reduction, but who would have been unwilling to pay P_0. Altogether, the consumers' benefits in year 10 are measured by the shaded area C_{10} shown in Figure 3. Similar calculations may be performed for each year t = 0, 1, 2, ... 50. With an annual discount rate of 10% before taxes, the present value of these benefits in year 0 is[2]

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[2]Year 0 has been defined here as the date at which water-splitting has captured the entire hydrogen market--roughly the year 2000. Recall that this technology will already have been incorporated in commercial-scale plants during the entire preceeding decade. In evaluating the present value of the benefits in equation (3), we have taken no credit for consumers' cost savings until after year 0.

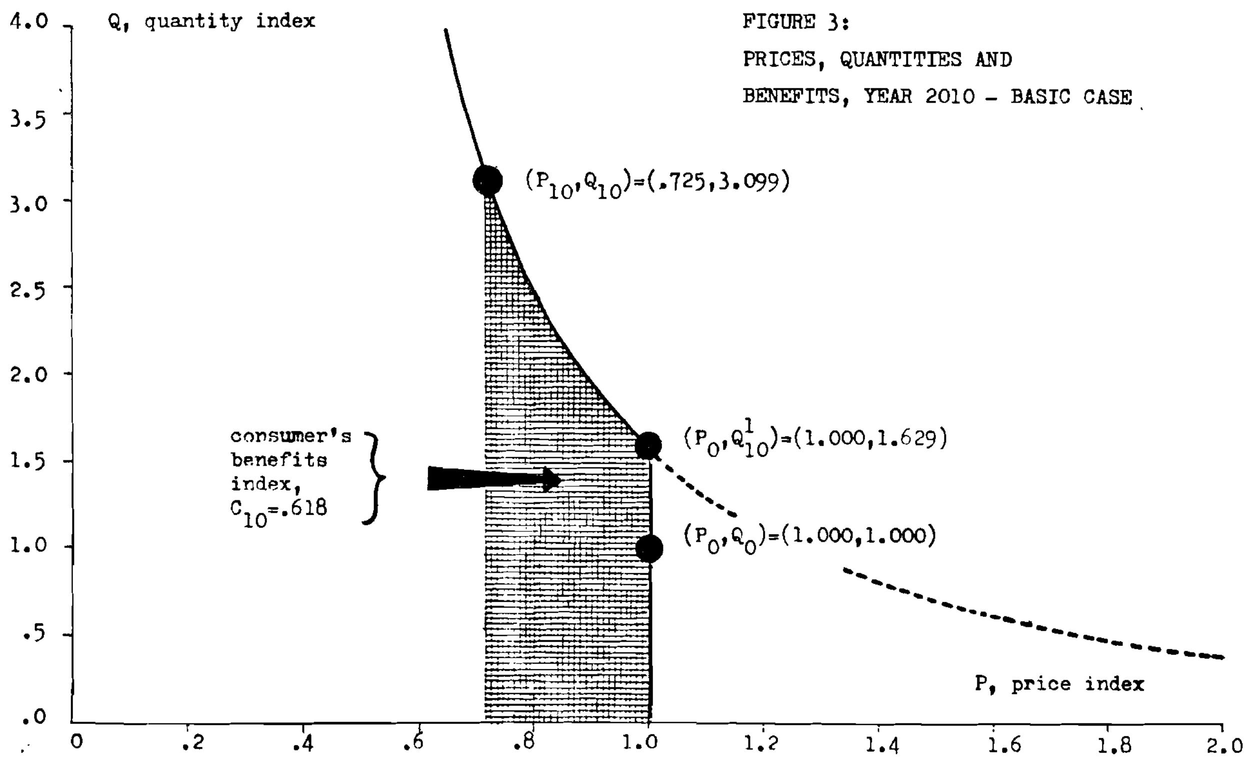

FIGURE 3:
PRICES, QUANTITIES AND
BENEFITS, YEAR 2010 – BASIC CASE

$$B_t = \sum_{\tau=0}^{t} \left[\frac{1}{1.1}\right]^t C_t \quad . \tag{3}$$

According to Table 2, the benefits index $B_{20} = 4.319$. To convert this into the dollar value of benefits in the year 2000, we must recall that P_0 corresponds to \$6 per million BTU, that $Q_0 = 4\ 10^{15}$ BTU, and that P_0Q_0 = \$24 billions. Accordingly, the value of water-splitting discounted to the year 2000 is (\$24 billions)(4.319) ≈ \$100 billions. Discounting to 1975 at the annual rate of 10%, the present value of consumers' benefits from water-splitting would be of the order of \$10 billions.

For those who wish to test the effects of other numerical parameter values, we have run a series of progressively more pessimistic calculations than the basic case. For example, if consumers are "unresponsive" to the price of hydrogen, the elasticity $\eta = -1.5$. This would reduce the discounted benefit index B_{20} by a relatively small amount--from 4.319 to 3.685. With slow learning (the "low I.Q." column with $\lambda = -.1$), there would be a slow rate of price decline, and the benefits index $B_{20} = 1.743$. With a "no growth" society, $\gamma = 1.00$, and the benefits $B_{20} = 2.026$. Combining these pessimistic assumptions, we arrive at the rightmost column , a "living fossil" society. Even in this case the benefits index would be .819 (\$24 billions) ≈ \$20 billions discounted to the year 2000 ≈ \$1.8 billions discounted to 1975.

Table 2. Effects of an economically competitive water-splitting process

	Basic case	Pessimistic assumptions			Most pessimistic case
		"unresponsive"	"low I.Q."	"no growth"	"living fossil"
Case identification number	1	2	3	4	5
η demand elasticity	-2.0	[-1.5]	-2.0	-2.0	[-1.5]
λ learning parameter	- .2	- .2	[- .1]	- .2	[- .1]
γ hydrogen demand growth factor, annual, at constant hydrogen prices	1.05	1.05	1.05	[1.00]	[1.00]
P_{10}, price index, year 2010	.725	.737	.865	.758	.883
Q_{10}, quantity index, year 2010	3.099	2.575	2.179	1.741	1.205
B_{10}, benefits index, discounted through 2010	1.550	1.408	.679	1.016	.438
B_{20}, benefits index, discounted through 2020	4.319	3.685	1.743	2.026	.819
B_{30}, benefits index, discounted through 2030	7.208	5.868	2.742	2.589	1.014
B_{20}, dollar value of benefits discounted to 1975 ($ billions)	9.6	8.2	3.9	4.5	1.8

5. A One-time Decision Model for R. & D. Expenditures

Now that we have made a rough estimate of the potential benefits, we may formulate a model for optimizing the level of research and development expenditures on water-splitting. Given the magnitude of the benefits, there is reason to believe that it pays to investigate several technologies in parallel--electrolytic, thermochemical, and direct thermal dissociation. The primary energy source is likely to be nuclear fission, but it could also be solar, geothermal, or fusion. There are a large number of possible ways to split the water molecule. For example, 16 thermochemical cycles have been identified at just one laboratory, the Ispra Joint Nuclear Research Centre (see EUR 5059e [3, p. 13]). Many additional cycles have been proposed, and are being discussed at other sessions of this conference.

Now suppose that for investigating just one water-splitting technology, it requires 5 years for laboratory and bench-scale experiments and for unit operation tests. Altogether, the present value of the costs for one exploratory investigation will be, say, $10 millions. It will be convenient to express these costs as a fraction of the potential benefits. Accordingly, if the present value of the potential benefits is $10 billions, the ratio of costs to gross benefits for a single "experiment" would be $c = .001$.

Each of these individual investigations would be risky, and there is no assurance of success on any one attempt.

By taking a sufficiently large number of such gambles, however, there is a high probability that at least one will be a winner. A "success" might be defined as a water-splitting process for which a commercial-scale plant would be capable of producing hydrogen at a cost of $6 per million BTU, including a return on capital. This would then be competitive with hydrogen from steam reforming during the 1990's when oil prices might be $12 per barrel (at today's general price level).

For simplicity, it is supposed that each line of water-splitting research has an identical and independently distributed probability of success. Let p denote the probability of failure. For example, if the probabilities of success are only 1 in 20, the failure probability $p = .95$. Then the expected benefits minus the costs of a single investigation will be

$$(\$10 \text{ billions})(1 - p - c) = (\$10 \text{ billions})(1 - .95 - .001)$$
$$= \$490 \text{ millions.}$$

From the viewpoint of the U.S. economy as a whole, it can be seen that this would be a highly favorable gamble. It can also be seen that there are diminishing returns from parallel R. & D. efforts--especially if we make the fairly realistic assumption that there are no additional benefits from developing more than one successful water-splitting process. To analyze this quantitatively, let x denote the number of parallel investigations. It will be convenient to choose the unit of benefits and costs as 1.0 rather than $10 billions. Then a one-time decision model for optimizing the level of R. & D. expenditures would be the following unconstrained maximization problem:

$$\begin{bmatrix}\text{expected}^{3}\\ \text{net benefits}\end{bmatrix} = \begin{bmatrix}\text{payoff from}\\ \text{one or more}\\ \text{successes}\end{bmatrix}\begin{bmatrix}\text{probability of}\\ \text{one or more}\\ \text{successes}\end{bmatrix} - \begin{bmatrix}\text{research and}\\ \text{development}\\ \text{costs for x}\\ \text{parallel in-}\\ \text{vestigations}\end{bmatrix}$$

$$f(x) = \begin{bmatrix}1\end{bmatrix}\begin{bmatrix}1 - p^{x}\end{bmatrix} - \begin{bmatrix}cx\end{bmatrix} . \qquad (4)$$

If x is sufficiently large so that we can work with first derivatives rather than first differences, the optimal number of investigations may be calculated by setting $f'(x) = 0$. Therefore

$$f'(x) = (-\log p)p^{x} - c = 0$$

$$\therefore \text{optimal } x = \frac{\log[c/-\log p]}{\log p} . \qquad (5)$$

The implications of equation (5) are shown on Figure 4. Somewhat paradoxically, the <u>higher</u> the probability of failure, the greater becomes the optimal number of experiments to be

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[3] One extension of this basic model is being investigated by Jean-Pierre Ponssard at IIASA. Working with an exponential "utility" function, he has shown that for decision makers who are averse to taking risks, the optimal number of investigations is generally <u>larger</u> than for the expected value criterion adopted here.

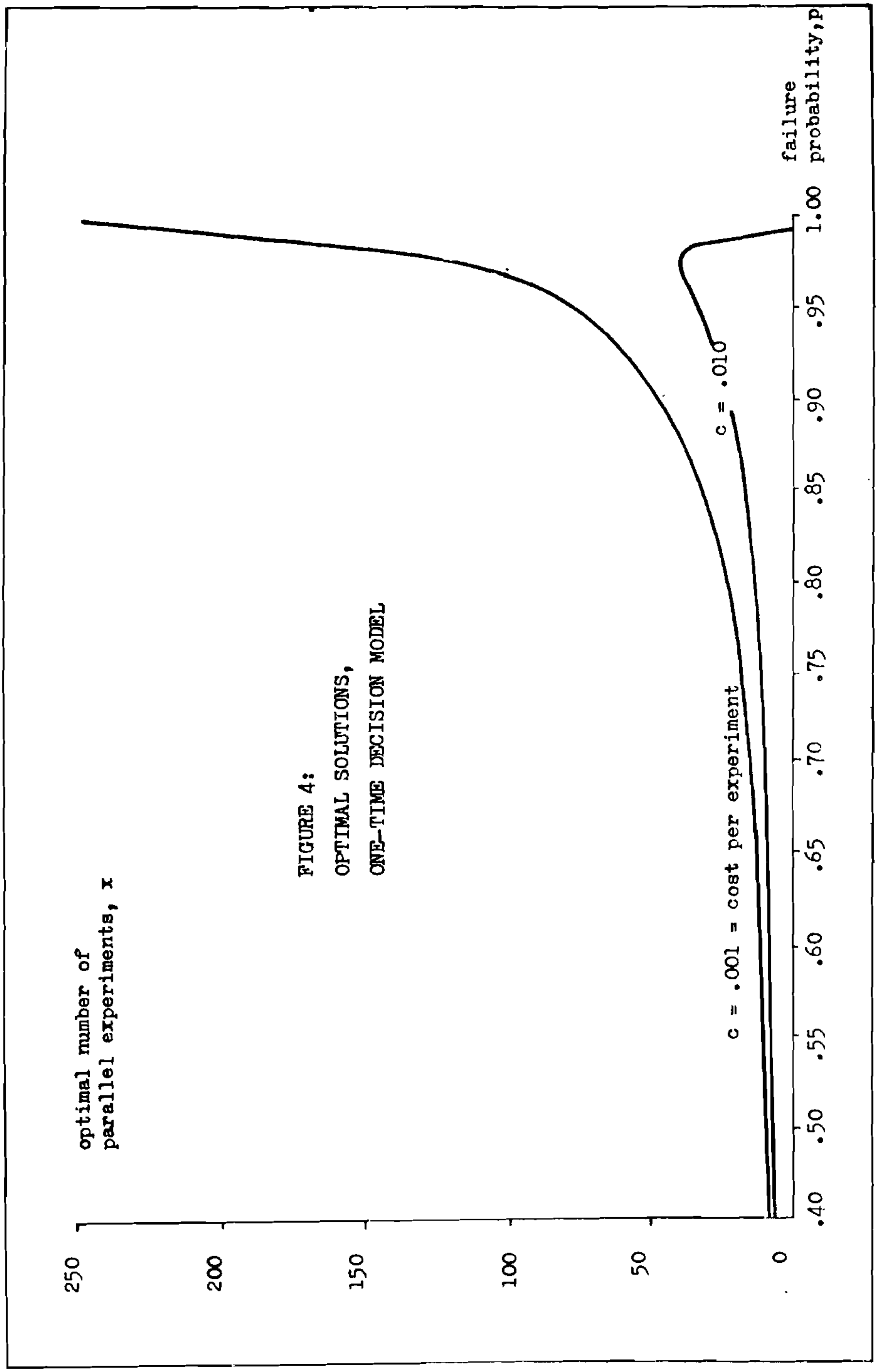

FIGURE 4:
OPTIMAL SOLUTIONS,
ONE-TIME DECISION MODEL

undertaken in parallel. For example, suppose that there is a \$10 billion payoff from water-splitting, a \$10 million cost of each experiment, and therefore $c = .001$. If the probability of failure is .5, it is optimal to undertake only 9 experiments. With the less favorable situation in which $p = .99$, the optimal number becomes 230! Needless to say, this monotone increasing relation cannot be extrapolated indefinitely. It is no longer valid for an unfavorable lottery --that is, for $c > 1 - p$. Hence $x = 0$ for $c = .01$ and $p > .99$.

Some additional insights may be obtained from Figure 5. This shows the expected net benefit function $f(x)$ for 3 alternative values of the failure probability p--keeping the cost of experiments fixed at $c = .001$. The maximum point along each of the 3 curves is indicated by an arrow. It can be seen that these 3 optimal values of x are identical with those on Figure 4.

Figure 5 suggests that if we are uncertain about the value of p, there would be no more than a 20% loss in optimality if we set $x = 100$. This number of experiments would be "robust" for values of p ranging between the extremes of .90 and .99. With 100 experiments and with $p = .95$, the probability of discovering one or more successful processes would then be $1 - .95^{100} = .994$.

6. A Sequential Decision Model

Now consider the case of sequential decisions, but continue to suppose that the experimental outcomes do not lead

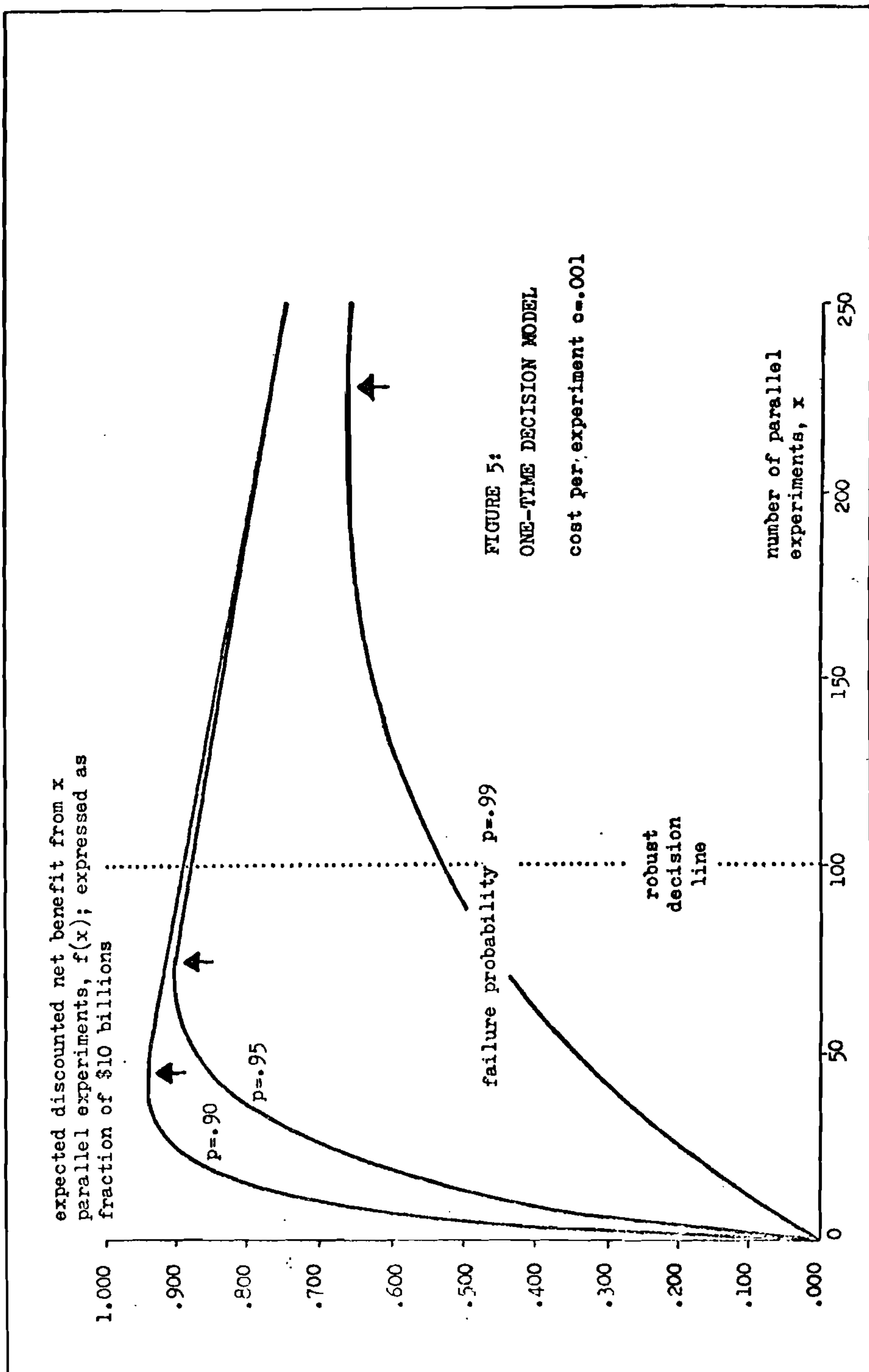

FIGURE 5:
ONE-TIME DECISION MODEL
cost per experiment c=.001

us to revise our prior estimates of the probability parameter p ("Bygones are bygones."). Today (at time 0), we select x, the number of processes to be investigated during the initial experimental period of, say, 5 years. At the end of this period for bench-scale and unit operations experiments, we learn whether all of these attempts have been failures. If so, there is another opportunity to enter this same type of lottery. If x was an optimal number for the first set of experiments, it will again be optimal for the second set. Similarly, at the end of 10 years--even if all of the preceding experiments were failures--it remains optimal to investigate x more technologies during the third set of experiments. And so on ad infinitum.[4]

This sequential decision process yields a higher value of expected discounted net benefits than f(x) in equation (4). To see this, let β denote the discount factor for each five-year period of experimentation. (For example, if the annual discount rate is 10%, $\beta = (1/1.1)^5 = .62$.) Let g(x) denote the expected discounted net benefits from undertaking x projects at each five-year interval--assuming that all previous experiments have ended in failures. It can then be seen

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[4] This sequential decision model has an inherent weakness. There is a small but positive probability that even after a long series of unsuccessful experiments, we will not discontinue the search for water-splitting processes. This logical difficulty may, of course, be overcome by introducing Bayesian revision of the prior probability parameter p.

that

$$\begin{bmatrix}\text{expected net} \\ \text{benefits from} \\ \text{one five-year} \\ \text{period of} \\ \text{experiments}\end{bmatrix} \begin{bmatrix}\text{discounted sum of} \\ \text{probabilities for} \\ \text{each possible five-} \\ \text{year period of} \\ \text{experiments}\end{bmatrix}$$

$$g(x) = \left[1-p^x-cx\right] \quad \left[(\beta p^x)^0 + (\beta p^x)^1 + (\beta p^x)^2 + \ldots\right]$$

$$\therefore g(x) = \frac{1-p^x-cx}{1-\beta p^x} \quad . \tag{6}$$

Figure 6 contains the numerical results for the sequential decision equation (6). As in Figure 5, the cost per experiment $c = .001$. Again, the net benefit curve is shown for three alternative values of the probability parameter: $p = .90$, $.95$ and $.99$. It will be seen that the maximum value of $g(x)$ is in each case slightly higher than the corresponding value of $f(x)$, and that the optimal value of x is smaller--e.g., for $p = .95$, the maximum values of $f(x)$ and $g(x)$ are, respectively, .904 and .920 (expressed as fractions of the $10 billion benefits). The maximizing values of x are 75 and 60 experiments.

For the sequential as well as the one-time model, it remains a robust decision to set the number of initial parallel experiments $x = 100$. This numerical result makes good common sense. Given an opportunity to enter a favorable lottery, we cannot go far wrong if the size of the initial gamble is 10% of the ultimate prize. <u>If these numbers are</u>

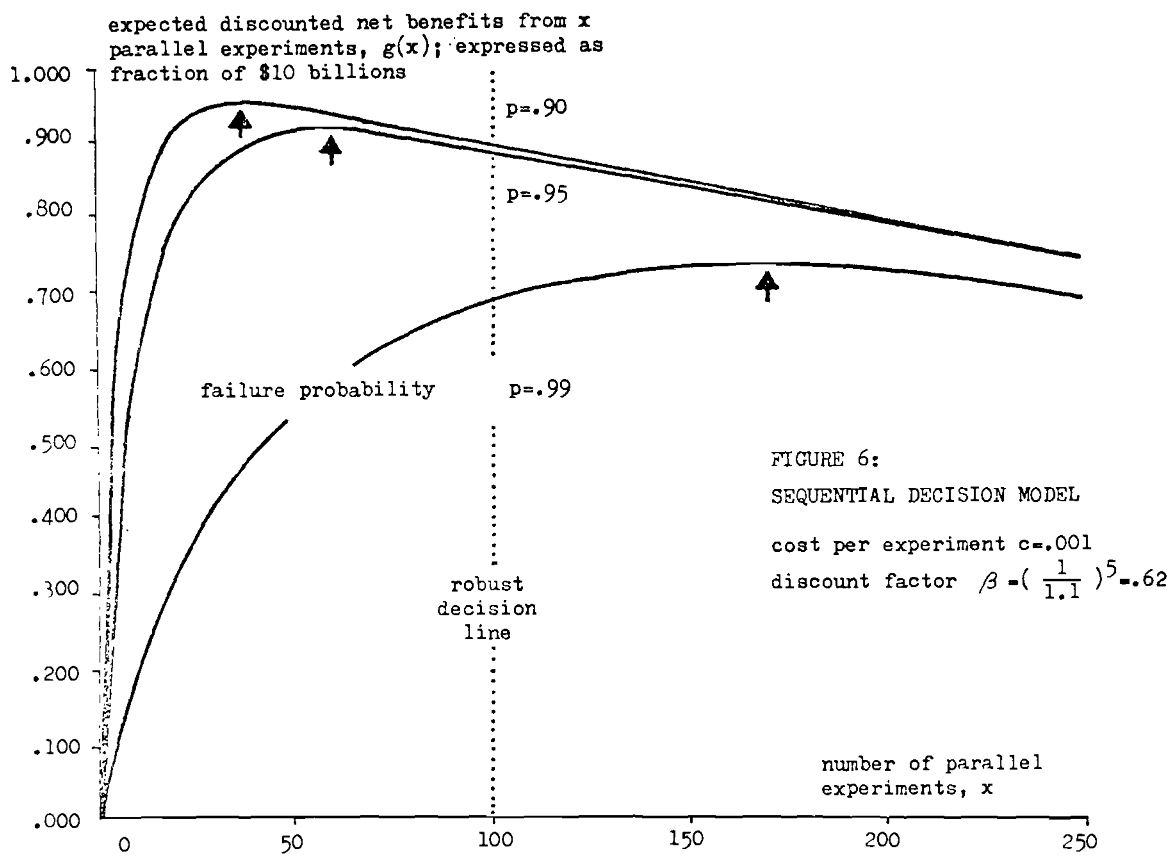

FIGURE 6:
SEQUENTIAL DECISION MODEL

cost per experiment c=.001
discount factor $\beta = \left(\frac{1}{1.1}\right)^5 = .62$

at all realistic, it would not be difficult to justify the expenditure of $1 billions in the search for economically competitive water-splitting processes.

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Computerized Work on Material Accountability Verification

Rudolf Avenhaus

Introduction

I would like to report here on some specific statistical considerations which are of importance in the framework of the planned review on material balance verification. As I have pointed out in two seminars in the last year the concept of material accountability and its verification as it is applied, for example, in the case of nuclear material safeguards consists of two steps:

i) The operator of a plant performs all measurements which are necessary for the establishment of the book inventory of a plant over a certain period of time and for the physical inventory at the end of that period of time, and

ii) The inspector verifies these measurements by means of independent measurements according to a random sampling scheme. If he has found no significant differences he takes all values of the operator and closes the material balance, i.e. he compares the book and the physical inventories which should not be significantly different from zero in case no diversion of material takes place.

According to this scheme two possibilities (strategies) of diversion exist:

i) Data falsification in such a way that the material balance is closed.

ii) Diversion without any data falsification such that the uncertainty of the measurements covers this diversion.

Test Procedure

The inspector has to perform two types of significance tests:

i) He compares his measurement data with those of the operator with the help of the D-statistics:

$$D = \sum_{i=1}^{R} \frac{N_i}{n_i} \sum_{j=1}^{n_i} (X_{ij} - Y_{ij}) \quad , \tag{1}$$

where X_{ij} respectively Y_{ij} is the operator's respectively inspector's measurement result for the j-th batch of the i-th class, where n_i respectively N_i is the number of checked respectively the total number of batches in the i-th of the R classes.

The Null and the Alternative hypotheses are given by

$$E(D/H_0) = 0 \quad , \quad E(D/H_1) = M_1 \quad , \tag{2}$$

where M_1 is the amount assumed to be diverted. Let α_1 and α_2 be the error first and second kind probabilities:

$$\begin{aligned} \alpha_1 &:= \text{prob } \{D > X/H_0\} \quad , \\ \beta_1 &:= \text{prob } \{D \leq X/H_1\} \quad , \end{aligned} \tag{3}$$

where X is the significance threshold of the test. We call 1 - β, the probability of detection. Then one obtains

$$1 - \beta_1 = \phi\left(\frac{M - U_{1-\alpha_1}\sigma_{D/H_0}}{\sigma_{D/H_1}}\right) , \quad (4)$$

where ϕ is the Gaussian distribution function, U its inverse, σ_{D/H_0} and σ_{D/H_0} the standard deviations of D under the Null and Alternative hypotheses.

ii) The inspector performs a significance test for the difference between the book and the physical inventory MUF: = BI - PI where the Null and the Alternative hypotheses are given by

$$E(MUF/H_0) = 0 \quad , \qquad E(MUF/H_1) = M_2 \quad . \quad (5)$$

Let α_2 and β_2 be the corresponding error first and second kind probabilities. Then one obtains similar as above

$$1 - \beta_2 = \phi\left(\frac{M}{\sigma_{MUF}} - U_{1-\alpha_2}\right) . \quad (6)$$

<u>Common False Alarm Rate and Probability of Detection</u>

The inspector wants to calculate the efficiency of his <u>total</u> test procedure; this means he wants to calculate the total probability of detection 1 - β:

$$1 - \beta = 1 - \text{prob}\{D \leq X_1 \Lambda MUF \leq X_2/H_1\} , \quad (7)$$

and furthermore, he wants to fix his false alarm probability α_1 and α_2 in such a way that the total false alarm probability α,

$$1 - \alpha = \text{prob}\{D \leq X_1 \wedge MUF \leq X_2 / H_0\} \tag{8}$$

results. However, there is a stochastic dependence between these random variables because the operator's measurement values are used twice in this scheme. Therefore, one cannot factorize the formulae (7) and (8). Instead, one obtains

$$1 - \alpha = \frac{1}{2\pi\sqrt{1 - \rho^2}} \int_{-\infty}^{U_{1-\alpha_1}} dt_1 \int_{-\infty}^{U_{1-\alpha_2}} dt_2 \exp\left(-\frac{t_1^2 - 2t_1t_2\rho + t_2^2}{2(1 - \rho^2)}\right) \tag{9}$$

$$\beta = \frac{1}{2\pi\sqrt{1 - \rho}} \int_{-\infty}^{U_{1-\alpha_1} - M_1/\sigma_D} dt_1 \int_{-\infty}^{U_{1-\alpha_2} - M_2/\sigma_{MUF}} dt_2 \exp\left(-\frac{t_1^2 - 2t_1t_2\rho + t_2^2}{2(1 - \rho^2)}\right) \tag{10}$$

where

$$\rho = \frac{\text{cov}(D, MUF)}{\sigma_D \cdot \sigma_{MUF}} \tag{11}$$

is the correlation coefficient. One can show that $\rho > 0$ in this framework. For $\rho = 0$ one would obtain

$$1 - \alpha = (1 - \alpha_1) \cdot (1 - \alpha_2) \quad . \tag{12}$$

This is a well known relation in the area of simultaneous statistical inference. Thus the first problem is to give the numerical values for (9) which is a generalization of (12).

Numerical Calculations for the False Alarm Probability

We want to plot the function

$$\alpha_1 = f(\alpha_2)$$

with α and ρ as parameters. For this purpose the bivariate normal distribution tables available are not precise enough. Bonferroni's inequality gives

$$\alpha > \alpha_1 + \alpha_2 \quad , \tag{13}$$

which limits the region; additionally one can take from (9) that the curves are symmetric to the line $\alpha_1 = \alpha_2$.

Mr. Nakicenovic of our group has performed extensive simulation calculations on our facilities here, the results are shown in Fig. 1 (linear interpolation between the points obtained) and Fig. 2 (graphical interpolations).

<u>Example for the Probability of Detection</u>

It is important to know whether the stochastic dependence between the two statistics D and MUF leads to an increase or to a decrease of the probability of detection $1 - \beta$ compared to the case $\rho = 0$.

In order to get a first impression, we have calculated the probability of detection for $M_1 = M_2 = M/2$ and $\alpha_1 = \alpha_2$ for given M and α as a function of ρ. In order to be able to do this we had to generate first the relation $\alpha_1 = \alpha_2$ as a function of ρ for given α; that is, the values on the diagonal in Fig. 2. The result of this auxiliary calculation is shown in Fig. 3. The result of the calculations of the probability of detection is shown in Fig. 4. As expected, the probability of detection decreases with increasing ρ. However, it does not increase very much; therefore an approximation by the case $\rho = 0$ would not be too bad.

Concluding Remarks

There are two basic reasons for performing these calculations:

i) As already indicated, one wants to determine the "efficiency" of the combined inspection scheme and see how well the approximation $\rho = 0$ works.

ii) One wants to fix α and not α_1 and α_2 separately in order to reduce the degree of subjective choice of values of basic parameters. Therefore, one has to know the relation between α, α_1, and α_2.

To conclude, we will apply the general numerical results obtained so far to the specific case we considered already in the work which has been performed in the course of the last year in collaboration with the International Atomic Energy Agency in Vienna.

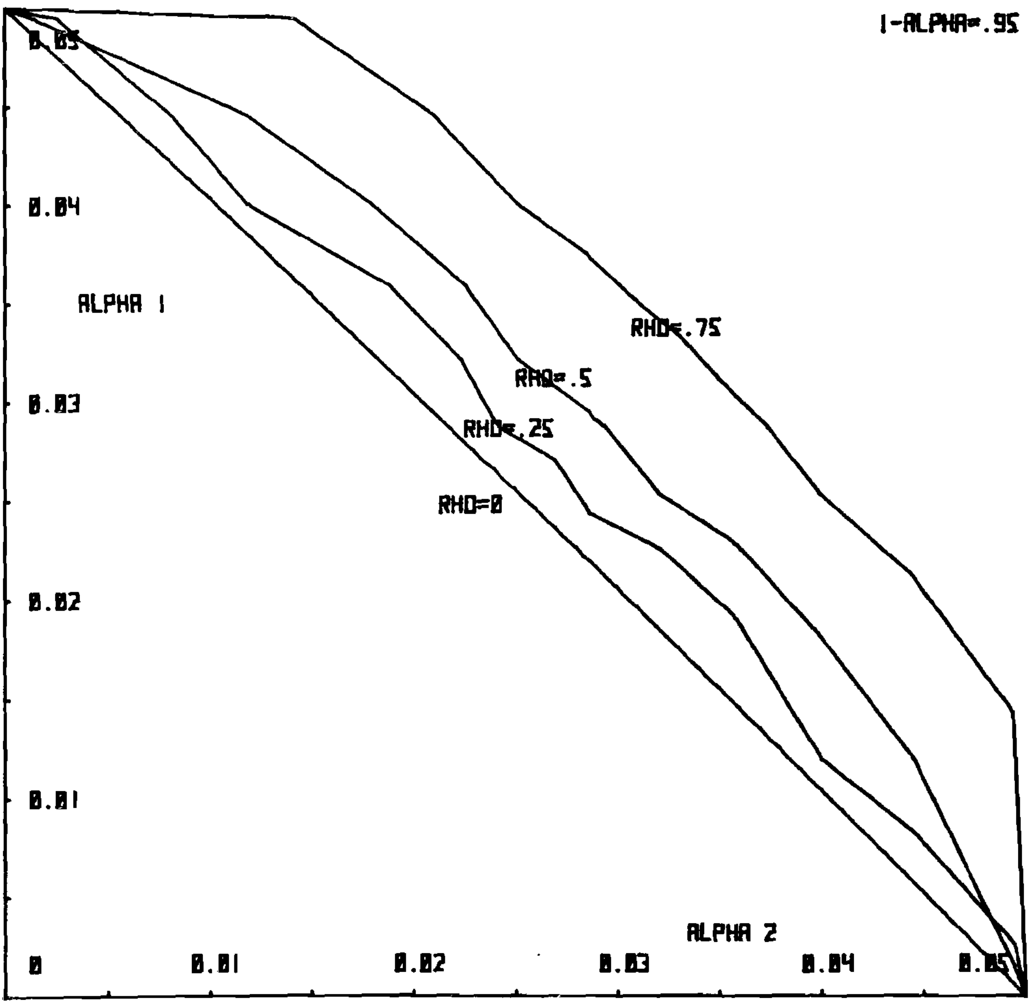

FIG. 1: GRAPHICAL REPRESENTATION OF THE RELATION BETWEEN ALPHA 1 AND ALPHA 2, WITH RHO AS A PARAMETER, ALPHA=0.05, AND LINEAR INTERPOLATION BETWEEN THE CALCULATED VALUES, EQ. (9)..

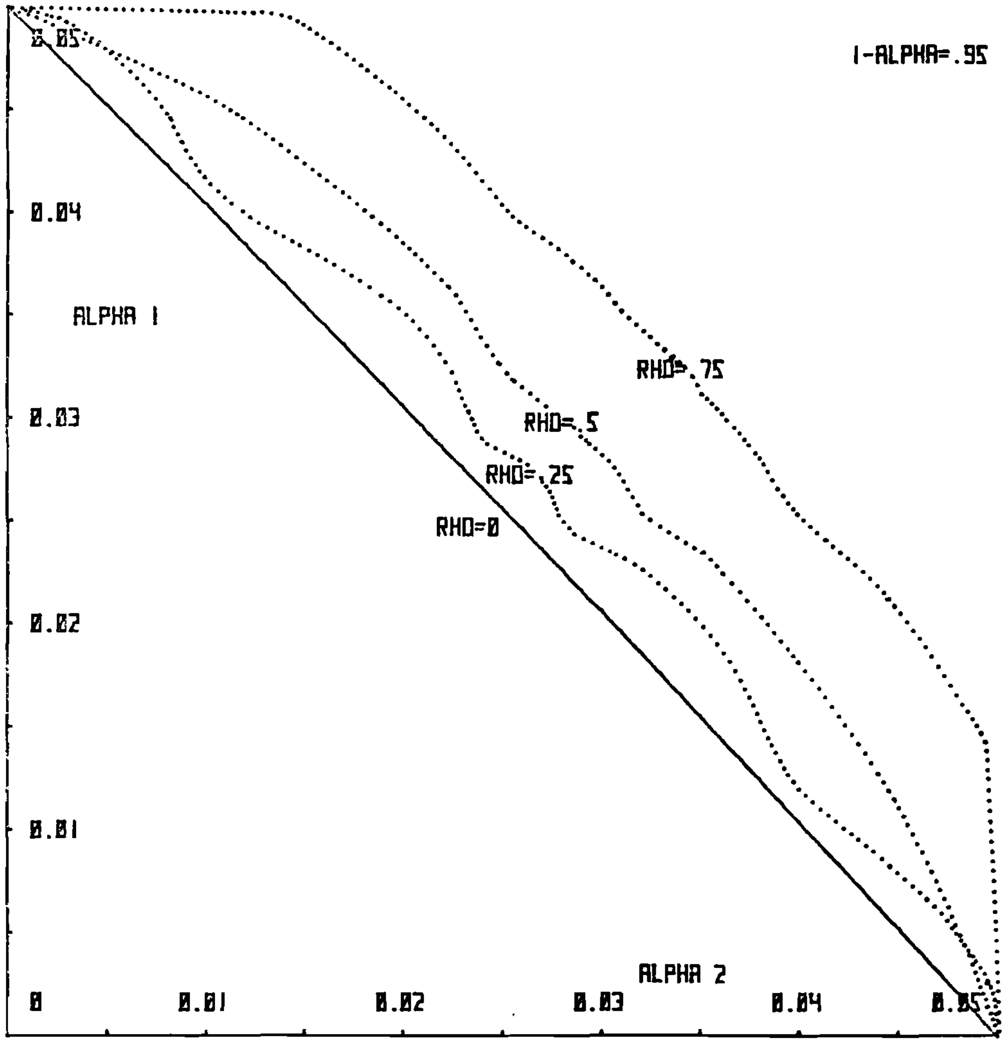

FIG. 2: GRAPHICAL REPRESENTATION OF THE RELATION BETWEEN ALPHA 1 AND ALPHA 2, WITH RHO AS A PARAMETER, ALPHA=0.05, AND NON-LINEAR INTERPOLATION BETWEEN THE CALCULATED VALUES, EQ. (9).

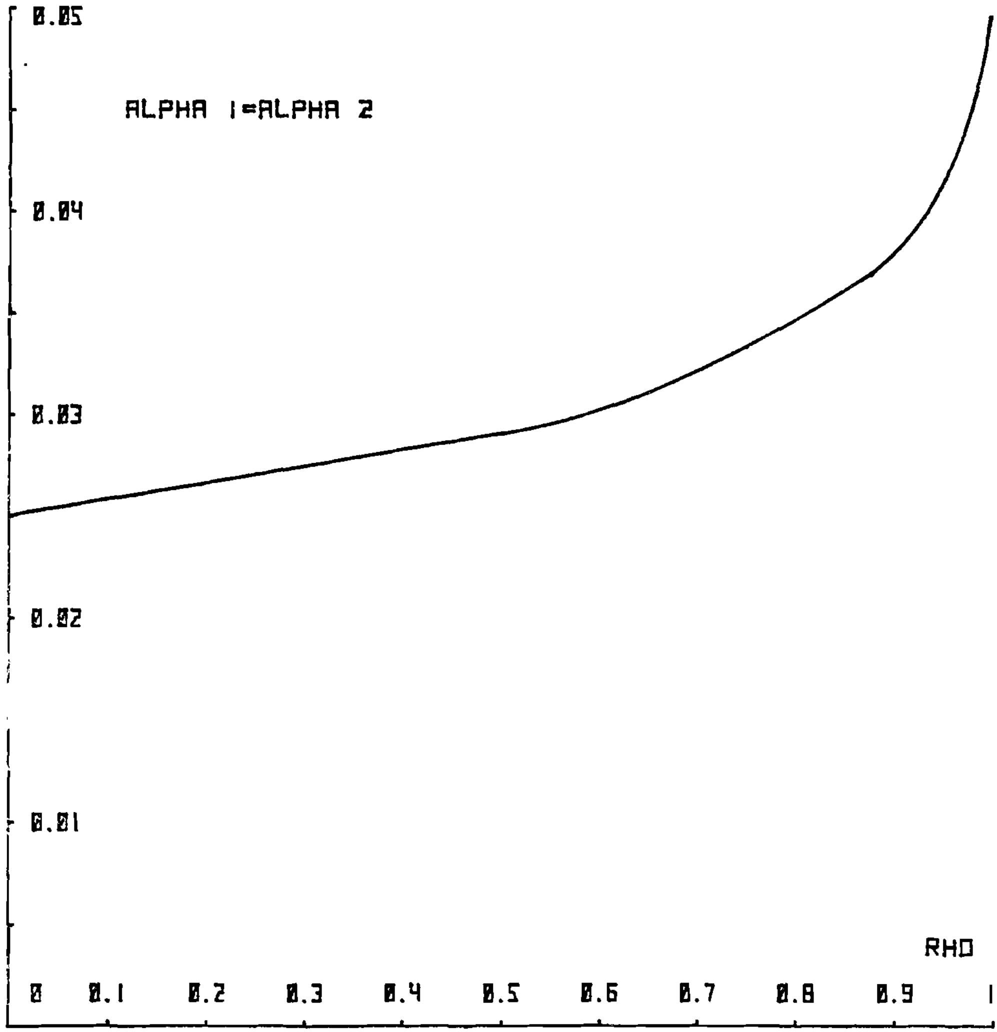

FIG. 3: GRAPHICAL REPRESENTATION OF THE RELATION BETWEEN ALPHA 1=ALPHA 2 AND RHO, FOR ALPHA=0.05, EQ. (9)..

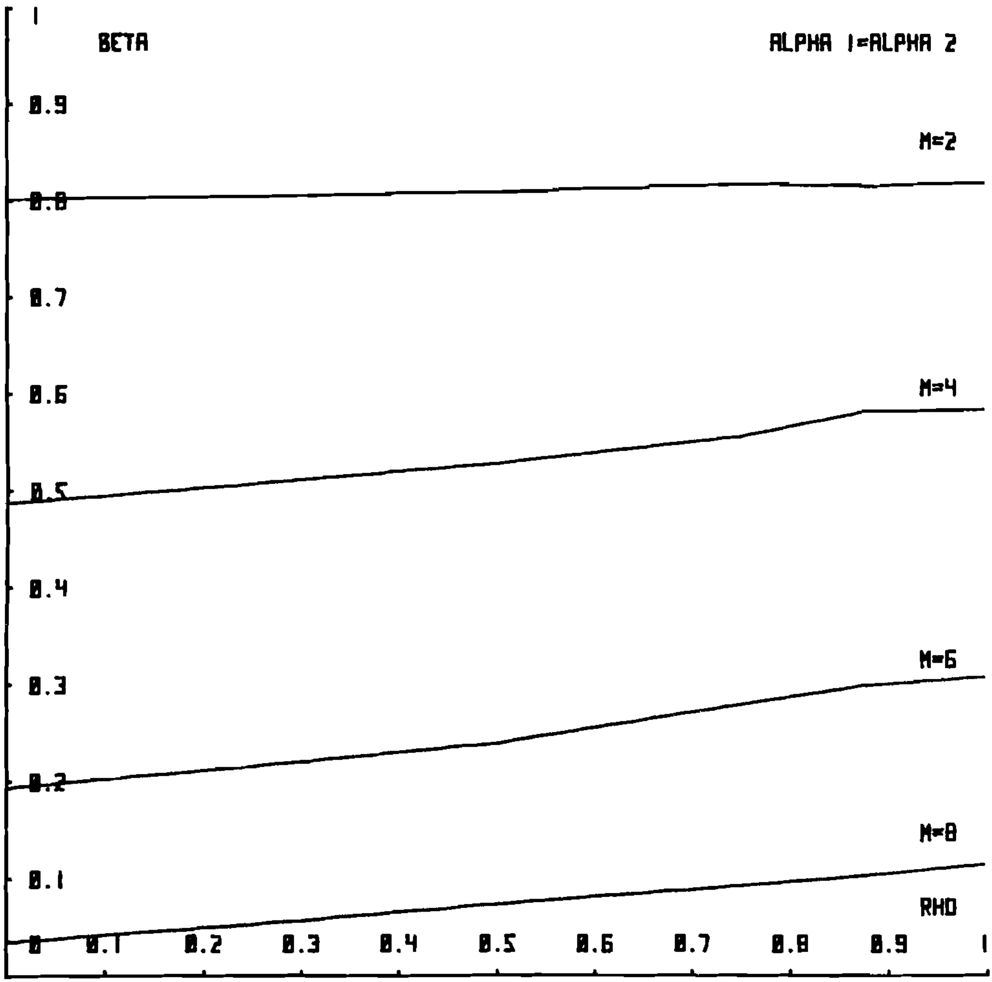

FIG. 4: GRAPHICAL REPRESENTATION OF THE ERROR SECOND KIND PROBABILITY BETA, AS A FUNCTION OF RHO WITH M AS A PARAMETER, FOR ALPHA 1=ALPHA 2, ALPHA=0.05, M 1=M 2=M/2, $SIGMA_D^2 = SIGMA_{MUF}^2 = 2$, EQ. (10).

Concluding Remarks

Wolf Häfele

The descriptions of the work of the Energy Group which have been presented so far may have helped to visualize the profile of the work as a whole. It is more than obvious that much more work is required.

We will continue with the clearing-house work on mathematical models of energy demand and supply as well as on resources. We expect these activities to go on into the foreseeable future. Both activities are of a kind that does not indicate a natural point of completion. In particular, we will lay stress on scenario work on energy demands.

After having completed the work on the nuclear option in a first iteration by this summer we will work on the solar option. At attempt will be made to come to some kind of strategic evaluation as well as to a unified description of the systems effects involved. If this can be accomplished it is then the comparison of the nuclear option with the solar option which will be attempted. This is a challenge, especially from the methodological point of view, and particularly in performing this task we do need help from the methodological side.

The work on climate will be reaching its full momentum only now. Along with it goes the attempt to identify the interface between energy and moisture of the atmosphere and thereby, the hydrosphere. We hope to be in a position to have a small working group on this subject by the end of the year.

A start will be made in the field of risk evaluation. Now, in early June, 1974, a joint research subproject of the International Atomic Energy Agency (IAEA) and the Energy Group of IIASA is established; such work will be instrumental in assessing systems effects and in facilitating unified descripitons of the various options in question.

A special effort will be made to apply utility theory to such assessments and unified descriptions. In so doing we will try to make use of work that has been pursued at Harvard and M.I.T. A more immediate case here is the problem of nuclear reactor siting. This problem is most naturally suited to establish links with the Water Project, the Urban Project, and the Ecology Project. The integration with the other projects will, in any event, be a major line of attack.

As regards scheduling we are working against the target of the summer of 1975. By that time we hope to have enough results to present a more comprehensive view of energy systems. The IIASA Planning Conference on Energy Systems of July 1973 may be regarded as a zero order approximation of the energy problem. In this light, the now envisaged IIASA conference of the summer of 1975 could come out to be a first order approximation.