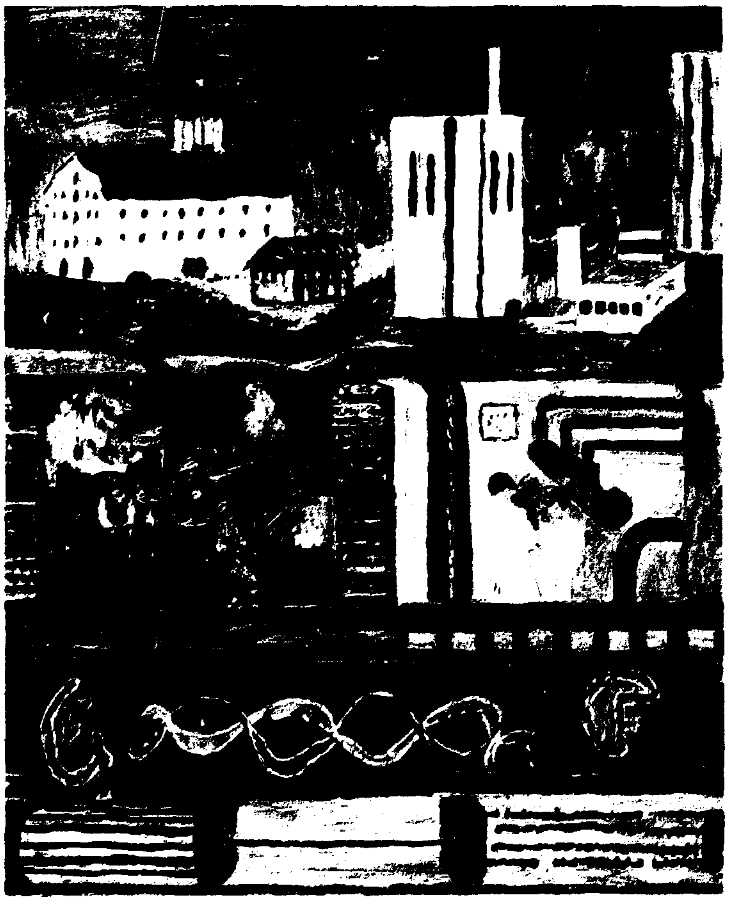
INGENJÖRSVETENSKAPSAKADEMIEN

Man and Technology in the Future



Lectures from an international symposium arranged by
the Royal Swedish Academy of Engineering Sciences (IVA)

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Man and Technology in the Future

Lectures from an international symposium arranged by the
Committee on Man, Technology and Society at the Royal Swedish
Academy of Engineering Sciences (IVA) in the fall of 1992

The Royal Swedish Academy of Engineering Sciences, IVA, is an independent, learned society. Its programs aim at fostering the engineering and economic sciences, as well as promoting the growth of the business sector. In cooperation with the business community and institutions of higher learning, IVA initiates and recommends steps to strengthen Sweden's industrials skills base and international competitiveness.

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Preface

The Royal Swedish Academy of Engineering Sciences (IV A) has set up a committee known as *The Committee on Man, Technology and Society.* The members of this committee form an interdisciplinary group for the study of the interaction between scientific and technological advances and the way in which society evolves.

Since its establishment, the committee has arranged studies and discussions on such topics as the role of technology and architecture in shaping the modern social environment, and the interaction between technology and political-cultural programs such as functionalism. A great deal of interest has been devoted to the influence of the working environment on the health and well-being of human beings. The intricate mix of politics and engineering sciences embodied in the concept "social engineering" has been critically examined, as has the role of technology in the judicial, legal and regulatory processes in society.

Most of the committee's activities have focused on the present relationship between man, technology and society. Often these discussions contain many elements of the history of technology and social evolution. However, attempts have been made to assess the future influence on society of key developments in biotechnology, electronic communication and systems analysis. In order to pursue this path still further, the committee decided to arrange an international symposium on the topic *Man and Technology in the Future* at the village of Forsmark on the Baltic coast of Sweden.

Why Forsmark? Forsmark was selected because it is one of the cradles of Swedish industrialism. In the sixteenth and seventeenth centuries, the village was renowned for the manufacture of high quality steel, a commodity which was exported all over Europe. The prosperity of the Forsmark iron ore industry was due to access to high quality iron ore and charcoal, as well as to water power and an extremely skilled labor force.

In the twentieth century, when technology generated new methods for the large-scale production of steel based on cheap raw mater the small works at Forsmark could no longer compete on the tional market and were forced to close down.

However, Forsmark was reborn when advanced technology in the form of nuclear energy production plants came to the village. The Forsmark Power Group, the owner of these major installations for the production of electricity from nuclear fuel, has preserved and restored the original village and ironworks, and they are now used for conferences and other educational purposes. The link between the past and the future is clearly demonstrated, not only by the preservation of the sixteenth and seventeenth century environments in close proximity to the modern industrial, almost futuristic nuclear reactors, but also by the use of the letter "F". This was stamped on every bar of iron which left the factories, and "F" has now become the company symbol of the Forsmark Power Group.

We would like to express our gratitude to the following organizations for their financial support; the Sven and Dagmar Sahlén Foundation, the Swedish National Board for Industrial and Technical Development (NUTEK), Vattenfall AB, and the Marcus and Amalia Wallenberg Foundation.

Arne Engström
Chairman
The Committee on Man, Technology and Society
Royal Swedish Academy of Engineering Sciences (IVA)

Contents

Will There Be Changes in Planning Large Systems?

Dr Curt Nicolin

The answer to the question in the headline is YES. You don't need much knowledge to realize, that in a changing world the answer must be yes. However my presentation can hardly end here.

Instead I will analyse one aspect of change, which I think is very vital, profitable and simple. Yet this is a change that meets with strong resistance from people handling very large projects. Changing traditions always requires hard work to convince people that change is possible. I have tried for a long time and on the whole failed with this particular item. Therefore I have made a mathematical analysis, in the hope that the result will be more convincing than a hundred arguments. My study is in no way scientific. You may regard its quality in the same way as you regard a rule of thumb.

Assumptions

I assume, that the time it takes to produce a large installation is arrived at by the formula: $T \simeq 0.15 \times \sqrt{\text{construction cost}}$. T = time in hours elapsed manned production time.

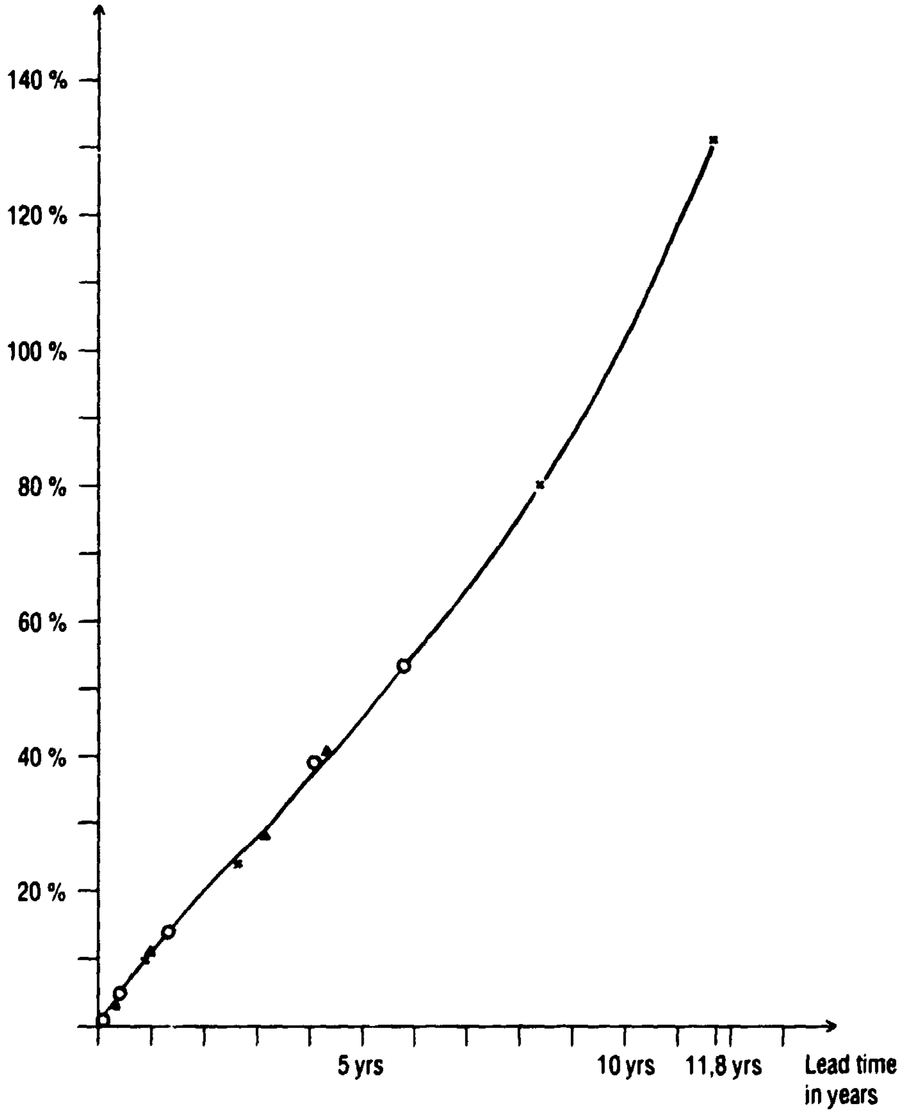
This formula has been extensively tested for small products and projects. The time values are only achieved by good performers.

The cost is in Swedish Crowns.
The formula is a rule of thumb.

Further, I assume, that the long-term borrowing interest rate is 11 percent. Furthermore, I assume that very large projects are generally financed by progress payments. For this study I assume that progress payment is made on January 1 each year of the construction period. I further assume, that the supplier of the progress payments has 15 percent solidity and that equity is demanded to give a return of 15 percent after tax, which means 21.4 percent before tax in Sweden.

I have studied projects to the tune of 100 million Swedish Crowns up to 20 billion Swedish Crowns. Then I have accumulated interest and interest on interest by adding the interest on interest once a year. I have added the total amount of interest and interest on interest for the whole project and divided it by the construction cost and arrived at a percentage for the cost. *Figure 1* illustrates the outcome of this study.

Figure 1. Accumulated interest on progress payments in percent of construction cost



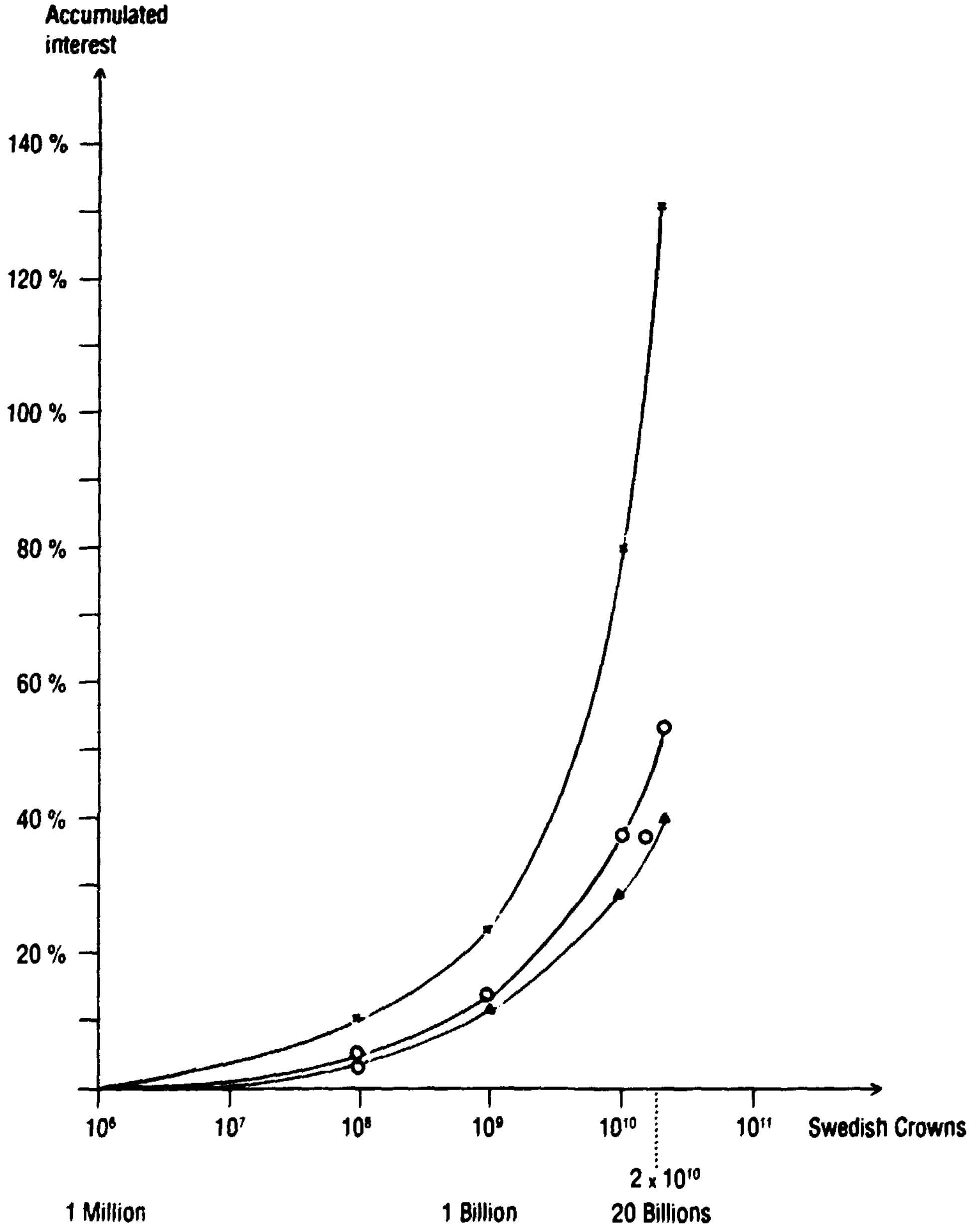
Formula for lead time: $T \approx 0.15 \times \sqrt{\text{Construction cost}}$

With one- and two-shift operation I assume that the work takes 1,800 and 3,600 hours respectively per year. (That is optimistic, I think.) Three-shift operation would mean 4,950 hours per year.

The results have no scientific status, but they should clarify basic relationships.

Figure 2 presents the interest cost against construction time for a completed project. This chart reveals that in principle interest cost in relation to project cost is only a variable of lead time.

Figure 2. Accumulated interest on progress payments in percent of construction as a function of the project size



If not self-evident, it is logical.

Assume that we run a project, for example a highway, with three independent entrepreneurs, and they each get one third, this should yield the same result, as if we were working on three shifts.

Assume, that we have a bridge, that costs 20 billion. We split into three teams, and they all work three-shift. What would be the result? The interest percentage of construction cost would fall from 130 percent to roughly 20 percent. That's what I call a saving!

You might say that shift-work costs more. But the capital used in the construction will cost less, as it represents a fixed cost. Furthermore, it could well permit the use of more efficient tools, something that would not be profitable when operating on a single shift.

If we treat a job to the tune of 1 billion in the same way, lead time would be 4 months instead of 2.6 years, and interest would fall from 24 percent to roughly 5 percent. Unrealistic—maybe—but not impossible!

Another observation—somewhat unexpected—is that the relationship is almost linear.

Some construction work may not meet my formula for lead time. In factory work, lead time is normally three to ten times longer. To reach the time indicated by my formula very careful planning is vital.

First, I will introduce probability. Regardless of whether we manufacture or buy thousands of different components, we only have a certain probability that they all will be ready on the target date.

Priority orders are often used to speed up delayed orders. If there are a lot of them, they may create chaos.

The normal planning-chance of meeting assembly needs, if every component has a 98 percent chance of meeting the target time, would for the 10 components be 83 percent. Remember that a 98 percent probability rate is high, and that 10 components are not a lot *(figure 3).*

In *figure 4,* I indicate a solution.

The small components will reach a probability rate of 99.9 percent or higher, so that the total probability rate might be 97 percent instead of 83 percent. The small components represent a relatively small capital.

Figure 3. Alternative 1

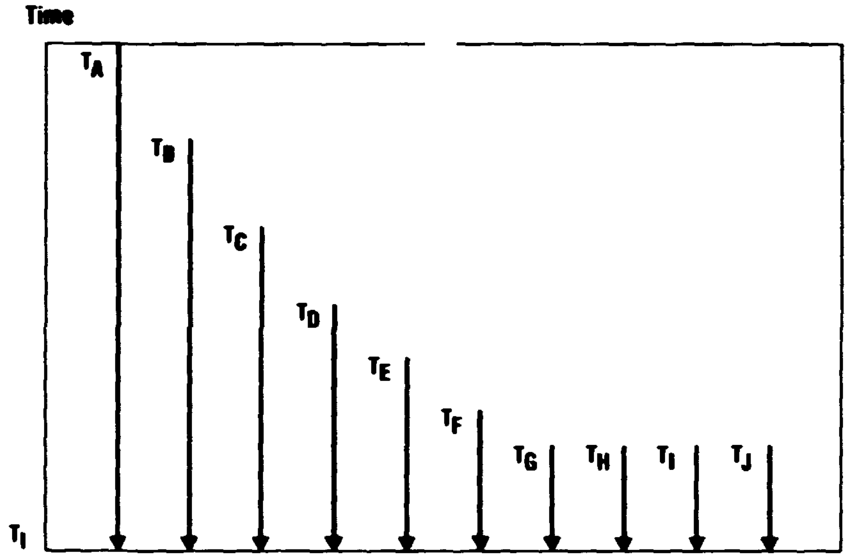
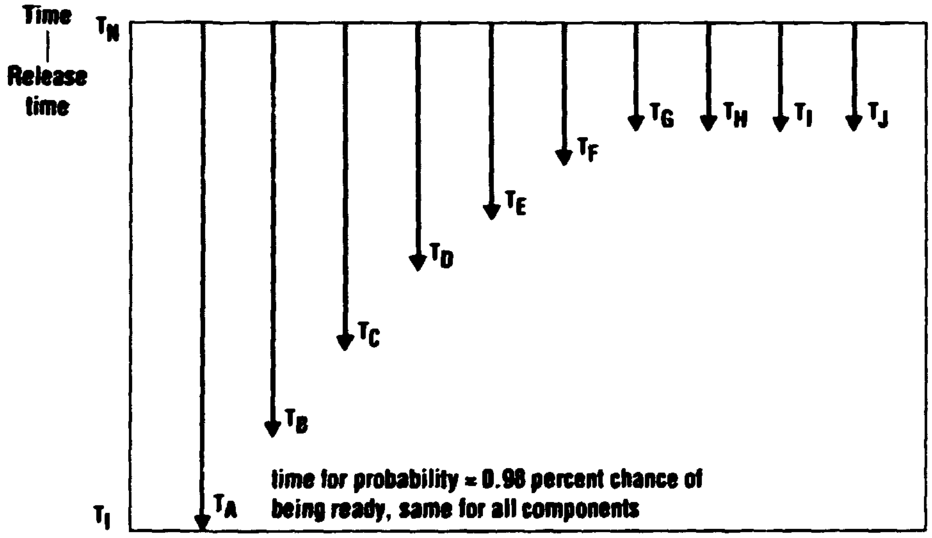


Figure 4. Alternative 2



The total sum of the inventory might even decrease.

The most important thing is of course to make very clear where the critical line goes and to arrange everything which is not on the critical line with wide margins, while maintaining close surveillance of the work at the critical line.

We have many projects that have long lead times for other reasons too, i.e. lack of capital resources, but this is very poor business.

The system that I have described rests on a failing embodied in our traditional working methods. The buyer provides the total capital for work in progress, but the entrepreneur has the tools to shorten the lead time.

The party that has the tools or knowledge to create miracles should have a sizable share of the value of achievement. That can be arranged in many ways, which I don't intend to go into now.

As with all progress, one must start by convincing people that progress is possible.

In the field of infrastructure the public sector is generally the customer. And unlike the private business sector, the public sector does not keep accounts. It lacks a balance sheet, and this fact can very often prove costly.

It is a basic principle of management, that the party who can improve the use of capital, that is to say, reduce the amount of capital necessary to arrive at a certain product, should also own that capital and make all the improvements to his profit that he can by more intense use of physical capital. When it comes to large projects, the customer provides the capital needed to finance the project in process. The entrepreneur who constructs the installation sees no extra profit, if he cannot reduce the interest on that capital. In other words, there is no stimulus for him to be efficient in this respect. That is wrong. And it is in part the answer to the question: why does it take so long to build large projects?

Let me emphasize my point with an example. In the manufacturing industry we have an opportunity to increase continuously the intensity of utilization of physical capital. But a power company building hydropower and nuclear stations and power networks has in principle only one chance—when new installations are being built. The company then has to build faster and more cheaply to reduce the capital cost.

Furthermore, long lead times often have other costs that don't appear on the books of the business parties. Take for instance Haga Norra today. I bet you, that the general public loses more hours than the workers are spending on the project to turn the crossing in to a two-level crossing.

I hope you excuse me for having been so technical. I hope that this has contributed to the understanding of how much we can gain by shorter construction time in large projects.

And it is certainly a possibility. Just seize it!

Energy for Coming Generations – IVA's Views on Future Energy Systems

Dr Gunnar Engström

Introduction

The general aim of the Royal Swedish Academy of Engineering Sciences is to "promote engineering and economic sciences and industry for the benefit of our society". IVA's activities are based on the expertise and experience of its members and others associated with the Academy.

IVA has always been active in the field of energy. IVA was established in 1919. A driving force then was the coal crisis that Sweden experienced after World War I. IVA has given high priority to energy issues ever since.

In its study *Energy for Coming Generations*, the Academy seeks to highlight long-term issues concerning research and technical development in the energy field. *Energy for Coming Generations* constitutes IVA's analysis of what technical solutions would seem to offer the highest potential for the future, and also what is required for this technology to have an impact on the marketplace.

The objectives of the study were twofold. First, to make an impact on the government bill on research policy due for presentation in February 1993. Second, to intensify and clarify the discussion on long-term aspects within the energy sector, that is, in industry, the administration and the research community.

Structure and methodology of the study

The recommendations are based on three studies.

The first study, *Swedish Energy Research 1975–1992: Ambitions and Reality*, dealt with the following issues:

- scope of the Swedish government's energy R&D,

- reasons for choices of priorities and larger projects,
- the results of the R&D efforts.

The second study, *Successful Development of Energy Technology*, analyzes ingredients essential to successful, commercial technical development. Important issues are:

- mechanisms for the evaluation of technical potential and new technology at firm level,
- the market penetration of new technology,
- the structure of the Swedish energy industry and its influence on technical development,
- effects of government policy measures on technical development and use of new technology.

The third study, *Energy Research: Options for the 21st Century*, analyzes technological opportunities, key technologies and development needs for the future in the energy field. Important issues include:

- key technologies in the short- and long-term perspective in Sweden and abroad,
- centers of excellence for these technologies,
- research needs in Sweden and abroad,
- strategies for Swedish energy R&D.

On the basis of these three studies, IVA's Council for Energy Policy formulated conclusions and recommendations for measures to be taken in Sweden. These recommendations are directed both at the private and the public sector.

The main method for collecting and analyzing information has been small informal work-shops with specialists. In total, more than 50 such meetings with between 5 to 25 participants have been held in the course of this two-year project.

Swedish energy research 1975–1992: ambitions and reality—some conclusions

At the beginning of the 1980's, the Swedish resources devoted to energy R&D were the highest per capita in the OECD-area. Resources in Sweden have since then decreased to a level still slightly above average. This is mainly the effect of a decrease in resources allocated at "later" stages of the R&D-process, that is, resources going to development, demonstration, etc.

Priorities differ, however, quite markedly from those in almost all other countries. Sweden has had a much stronger focus on "alternative" energy sources, that is, wind power, solar energy, efficient use of energy etc, while the resources going to fossil energy and nuclear energy (which dominate in most other countries) are proportionately less.

Our evaluation shows that the most significant result of the research is increased competence in certain fields of technology. These include windpower, bioenergy, environmental impact and energy efficiency.

There are few examples of commercial application of the research even if there are some examples of how that research has speeded up the market penetration of new technology. Important examples of this can be found in the pulp and paper industry, iron and ore industry and in construction.

Research has also had some negative effects on technological areas that have not been a part of the program. These areas have lost ground or been hampered by the considerable resources available for "alternatives". Such technological areas include electric power technology, hydropower technology and, during the 1980's, nuclear technology.

Successful development of energy technology

The energy sector is important in Sweden. The most significant contributions to technical development have taken place in the electricity sector where Sweden has a large and important electrotechnical industry, power industry and also a large electricity-intensive industry.

For many years, a great deal of technical development has been conducted in Sweden. Technology has been developed to meet the needs of Swedish customers and has then been transformed into successful products on the international market. Nowadays, very little technology is developed primarily with Swedish customers in mind. This is one consequence of decreasing Swedish investment volume and increasing development costs.

The study has analyzed the effects of government subsidies on the development of new technology. Our conclusion is that these subsidies have had negative effects. Project development support from the government has almost always been allocated to projects that would have been undertaken anyway or to projects which should not have been carried out at all.

This can in part be attributed to the low efficiency of these types of policy tools, but also to the lack of coordination between economic support and other policy measures, such as energy taxes.

Our conclusion is that there is no need to subsidize industry's product development. If the government introduces regulations, fees, taxes, etc in order to influence developments, such a system must be sustainable and reliable. Such a system of regulations and fees must take into account international developments so that sufficiently large markets can be created.

Energy research: options for the 21st century

The study has analyzed the state-of-the-art and technological opportunities in different areas of science and technology, and proposes a strategy for Swedish energy R&D.

Research has two objectives. One is of course to advance the science. Another objective is to create new competence. Increased competence through participation in the research work is also an important element in the results. In most cases this objective is the most important one. Therefore we recommend a research strategy that includes a broad spectrum of research activities designed to enhance national competence in all energy-related areas of relevance for the future.

There has been a tendency in Swedish energy R&D to give priority to research areas where Sweden has little scientific and industrial strength and to give less attention to areas where we are more competitive. IVA recommends a change of strategy. Special efforts should be made in those particular areas where Sweden already has or can create comparative advantages.

Traditionally there has not been a very clear view on the objectives of Swedish energy R&D. Obviously two major aims are to make the energy system more environmentally sound and more cost-effective. However, there are two more aspects that should be considered. The present energy systems lack flexibility. A flexible energy system makes it easier to cope with crises, for instance, shortages of oil, and it also makes it easier to take advantage of new research findings and new technologies. Swedish government energy R&D has also paid too little attention to research grants as a means to increase Sweden's international competitiveness. Thus the study has formulated the following policy for Swedish energy R&D:

Swedish R&D in the field of energy should make a significant contribution to the development of a cost-effective, environmentally sound and flexible energy system and increase Sweden's international competitiveness in industry and research.

Key technologies include systems technology, advanced maintenance technology, nuclear technology (including both fusion and fission), gasification and combustion technology, material engineering, surface physics and chemistry, together with biotechnological research directed at natural and artificial photosyntesis.

Systems technology is essential for the development of the transport sector, for electric power, environmental control and energy conservation. The complexity of the energy system calls for a comprehensive view and understanding of the interaction between different sectors of the energy system and society as a whole. Thus, development efforts directed to a particular sector have to be evaluated with regard to their contribution to the overall effectiveness of the energy system. Research concerning factors which affect energy use, and other relevant research in the social sciences must therefore continue to receive priority.

Materials engineering is vital to developments in for instance gasification and combustion engineering, building design, fuel cells, solar cells, measuring and control technology and nuclear waste technology. A research area related to materials engineering is thin film and surface physics. Developments in this area are vital to the development of fuel cells, solar energy conversion, catalysts and sensor technology. Areas of research closely related to materials engineering and thin film technology include chemistry, physics, mechanics och materials and solid state physics.

Developments in biotechnology can be vital for developments in solar energy conversion, biomass production, capturing carbon dioxide, and possibly direct conversion of biomass. Areas of research closely related to biotechnology include biology, physics and biochemistry.

Nuclear power technology is vital for maintenance, operation and improvements in existing nuclear power plants. The option to develop the next generation of nuclear power plants should be kept open. In the longer term, fusion and transmutation can also become viable alternatives. Research in nuclear power technology is relevant also to elementary particles physics, plasma physics and accelerator technologies.

Energy for coming generations: conclusions and recommendations

In our concluding study we have formulated our recommendations in 16 statements.

1 The objectives of Swedish R&D in the energy field should be:
- to make a significant contribution to the development of a cost-effective, environmentally sound and flexible energy system,
- to increase Sweden's international competitiveness in industry and research.

2 Energy-related research, development and demonstration activities (RD&E) should also in future be designated national programs with separate funding.

3 Political consensus concerning energy research policies is vital for a stable, long-term research program.

4 An increased proportion of all government appropriations to energy RD&E should be allocated to basic and applied research at universities and colleges.

5 The government should take steps to give financial support to cooperative industrial research efforts.

6 Direct government grants to individual companies for development, demonstration and purchasing of new energy equipment and systems should be phased out.

7 The broad spectrum of programs which supports technological development in the energy field should be replaced by *one* program concentrating on academic research and *one* program focusing on cooperative industrial research.

8 The structure and content of Swedish energy research programs must be more closely related to developments on the international scene. Sweden should take an active part in the planning and implementation of international R&D programs.

9 By creating a consistent, credible and sustainable system of regulations, fees and taxes, the Government should be able to influence the development of the energy system in a fruitful way. Such a system of regulations and fees must take into account international developments so that sufficiently large markets can be created.

10 In order to increase the impact and facilitate the diffusion of new knowledge, R&D cooperation between different actors in the energy sector should be strengthened.

11 Industry should be given better opportunity to participate in the preparation of decisions concerning the direction of energy-related research and training at universities and colleges.

12 A broad spectrum of research activities designed to enhance national competence must be conducted in all energy-related areas of relevance for the future.

13 Special efforts should be made in those particular areas where Sweden already has or can create comparative advantages.

14 The complexity of the energy system calls for a comprehensive view and understanding of the interaction between different sectors of the energy system and society as a whole. Thus, development efforts directed to a particular sector have to be evaluated with regard to their contribution to the overall effectiveness of the energy system. Research concerning factors influencing energy use, and other relevant research in the social sciences must continue to receive priority.

15 Energy use in the transport sector, bioenergy and nuclear energy are areas of application where the need for R&D is particularly great and where Sweden has the right prerequisites to make special contributions. Another area which has been identified, mainly because of its international and environmental potential, is fuel cells, solar cells and electric batteries.

16 Systems technology, advanced maintenance technology, nuclear technology (including both fusion and fission), gasification and combustion technology, materials engineering, surface physics and chemistry, together with biotechnological research directed at natural and artificial photosynthesis are all particularly important areas for research in view of the goals expressed in paragraph 1 and the application areas mentioned in paragraph 14.

Appendix 1

Study 1:
Swedish Energy Research 1975–1992: Ambitions and Reality
This study analyzes the motives, scope and direction of Swedish energy R&D from 1975 onwards.

Study 2:
Successful Development of Energy Technology
This study identifies and analyzes ingredients essential to successful commercial technical development.

Study 3:
Energy Research: Options for the 21st Century
This study indicates technical opportunities, key technologies and development needs for the future, focusing on the Swedish energy system, as well as on Swedish participation in international developments.

Study 4:
Energy for Coming Generations. Conclusions and Recommendations
Conclusions and recommendations for measures to be taken by public and private actors in the energy sector in Sweden.

Appendix 2

Energy Technology Applications of Strategic Importance to Sweden

- energy use in the transport sector
- bioenergy (biomass)
- nuclear fission
- fuel cells, batteries, solar cells

Key Technologies—Priorities

- systems studies
- operations and maintenance engineering
- nuclear fission and electric power engineering
- materials technology
- gasification and combustion technology
- surface physics and chemistry
- nuclear fusion
- specific areas of biology/biotechnology (e.g. photosynthesis)

Appendix 3

Basic science	*Cooperation with*	*Applications*
Biotechnology	Biology Physics Genetic technology Biochemistry Enzymes	Solar energy conversion Biomass production Capturing CO_2? Gasification Direct conversion of biomass?
Materials	Chemistry Physics Processing Mechanics of materials Solid state physics	Improvement in existing systems Combustion engineering Building design Fuel cells Solar cells Measuring Control and supervision Nuclear waste
Nuclear Power	Physics of elementary particles Plasma physics Accelerator technologies	Maintainance, operation and improvement of existing fission plants. Next generation of fission plants. Fusion? Transmutation
Systems Engineering	Behavioral Science Sociology Applied technologies	Transport Electrical power Environmental control Energy conservation
Thin Film and Surface Physics	Chemistry Physics Processing Solid state physics	Fuel cells Solar energy conversion Cleaning processes Catalysts Sensors

Risk Considerations in Large Systems

Professor Bo Lindell

Introduction

This paper reviews the conceptual problems involved in risk considerations for large technological systems. After a discussion of the concepts of risk and probability, the author deals with the application of these concepts in risk assessments for systems in which catastrophic events may occur. It is suggested that the basic protection principles recommended by the International Commission on Radiological Protection are generally applicable, although their application to probabilistic events necessarily involves a number of value judgments. One such judgment involves the evaluation of consequences necessary for cost/benefit analysis of the appropriate degree of protection. Another type of subjective judgment which is often not acknowledged occurs in the interpretation of very small probabilities, where the validity of the necessary models or assumptions can only be subjectively assessed. A final conclusion is that the most catastrophic consequence of a failure in a large system may be neither immediate economic losses or detrimental environmental impact but rather disastrous long-term political and societal effects.

Definitions

The subject of this presentation may be interpreted in many different ways. Therefore it is necessary to limit its scope and to specify the task at hand. This calls for some definitions. A technological system may be anything from an industrial plant to a widespread network of interdependent devices, as in the case of electric power transmission, as long as it is operational and based on engineering experience.

The implication of "large" in the title is that severe consequences may occur if something goes wrong. There are large technological systems, the normal operations of which may be criticized for being costly or having an unacceptable environmental impact, but such negative qualities are irrelevant in the present context where we are to consider risks rather than certainties. Thus we must define "risk".

What do we mean by "risk"?

The concept of risk is closely related to stochastic events. An undesirable occurence that is inevitable is thus not a risk but a deplorable certainty and will fall outside the scope of this presentation.

Among engineers and in the natural sciences "risk" is usually seen as a phenomenon which can be assessed and expressed in quantitative terms. Unfortunately, there is no standard definition. There are those who use the word "risk" as a synonym for the *probability* of an undesired event and those who by "risk" mean the *consequence* of that event. Finally, in nuclear safety, people often use "risk" as a synonym for the *mathematical expectation* of consequence, that is, the product of the probability and the consequence.

In risk assessment, both probabilities and consequences have to be considered and must be reported separately. To try to combine them, as by taking their product, may be misleading. For example, an event with an annual probability of 10^{-3} and a consequence of 1,000 deaths if it occurs, has a mathematical expectation of one death per year. If this information were presented out of context, it would not reveal the fact that the only possible consequences each year are either no harm at all (with a 99.9 percent probability) or 1,000 deaths (with a probability of 1 per million). To use the mathematical expectation as the basis for decisions in this case would therefore be quite arbitrary.

In reality, the perceived risk is more closely related to the consequence than to the probability, probably because people can visualize the consequence but not the probability. It should also be remembered that not everyone is trained to think quantitatively. Most people are likely to think of "risk" as a non-quantitative threat of something to be feared rather than as something that can be represented by numbers.

What do we mean by "probability"?

There are two elementary textbook definitions of probability. One, related to games of chance, defines probability as the ratio of the number of cases favourable to an event and the total number of possible cases. On this basis, the probability of throwing a "six" with a die is 1/6. The other defines probability as the limit of the frequency n/N of favorable events (n) as the total number of events (N) tends to infinity.

The main use of the concept probability, is in the prediction of average results in random experiments or of the number of favorable or unfavorable random events in a given population over a specified time, that is, in predictions of frequencies. It follows that the probability has a predictive value only for the average individual (human or technological unit) in the population. Such prediction may be totally irrelevant in an actual individual case if the population is heterogeneous with regard to properties which may influence the probability.

A modern definition of probability is simply the degree of belief in a statement or outcome, conditional on some postulated assumptions being true. Once a model has been chosen, a probability can be assessed. The result is valid only to the extent that the model is valid, a reservation which is often forgotten.

Probabilistic safety analysis

Probabilistic safety analysis (PSA) is a sophisticated science which has been of immense value in many fields of technological safety but in particular that of nuclear safety. Two major components of a PSA are event-tree analysis and fault-tree analysis.

An *event-tree analysis* begins with a postulated event and then analyses the possible consequences step by step. This will lead to sequences of events branching toward more or less severe final consequences. Each step involves alternatives for which probabilities may be estimated, some on the basis of frequency experience, some more subjectively. These probabilities may then be combined to yield a probability for each final consequence.

The value of this analysis is that it will reveal sequences of importance from the safety point of view, either because of high probability or because of particularly severe consequence.

The *fault-tree analysis* will start from a postulated consequence and, in a similar manner, work backwards to analyze the possible causes step by step. This will reveal the sequences most likely to lead to the postulated consequence.

Practical reactor safety technology is largely based on "defense in depth", which means that potential human and mechanical failures are taken into account by a system of several levels of protection, including successive barriers to prevent the release of radioactive material into the environment.

PSA studies of nuclear power reactors have been of great value in an iterative process to improve safety. Detailed studies and long experience have provided information for data banks so that components of event- and fault-trees may be combined for thorough analysis. The advantage of a PSA is that the branches most likely to produce severe consequences may be identified and subsequently blocked or eliminated.

As a spin-off effect, absolute probability values for some severe consequences such as severe core damage may be calculated. However, such probability estimates are subject to a number of reservations, mainly because of what is called "the issue of completeness", that is, some essential branches may have been overlooked in the PSA. This will be discussed below.

Catastrophic events

An important part of risk considerations in relation to large technological systems concerns events that have far-reaching effects, that is, catastrophes. There are numerous different definitions of a "catastrophe", based on both economic loss and the number of people injured or killed. A universal economic reference may be misleading, because the definition would depend on the economy and living conditions in the society concerned. As regards the number of fatalities, tolls from between 10 and 100 deaths have been suggested to define a catastrophe. Many authorities optimize protection on the assumption that society should be able to afford to spend about one million dollars per random life saved. This puts the equivalent economic loss at about USD 100 million, a value considerably higher than the USD 1–10 million often considered to define the lower boundary of catastrophic losses.

Deciding on protection against probabilistic events which are undesirable but not catastrophic, does not involve conceptually new principles in addition to those used in protection against likely harm. Protection against catastrophes, however, involves the problem of the irrelevance of the mathematical expectation of consequence. How should we deal with an "infinite" consequence which has a "zero" probability?

In this case, most people are more concerned about the magnitude of the consequence than comforted by the minuteness of the probability. Experts warn against using the product of probability and consequence as a basis for decisions. Underlying this is a healthy distrust of assessments of extremely small probabilities. Those who present such estimates often forget that the assessed values are conditional on the validity of the assumptions and models. Their validity is not a stochastic quantity and can only be given subjective probability values. The problem has been illustrated by a cartoon in the Parker and Hart series "The Wizard of Id". The news cryer on the tower proclaims:

> "Eleven o'clock and time for the news!
> "There is a 30 percent chance of rain tonight...
> "... a 60 percent chance of rain tomorrow...
> "... and a 90 percent chance I'm wrong on both counts!"

It is interesting to find that the importance of the validity of underlying assumptions has long been comprehended as common sense with regard to weather forecasts. Probably no-one would challenge the idea that meteorologists are able to make good short-term forecasts provided that their basic information is relevant. It is usually understood that it is not the method of forecasting but rather the validity of underlying assumptions and models which causes the uncertainty. In our choice of the best assumptions we often have no better guidance than our conviction, which we seem to trust to 100 percent.

It has been well established by psychological tests that, in cases where test persons express a likelihood of 100 percent that they are correct in their answers to questions for which they think they know the right answer, they are, in fact, almost as often wrong as those who feel uncertain. To state that the probability of the validity of an assumption is 99,9999 percent therefore hardly deserves more credence than a statement of, say, 99 percent.

A consequence of this is that assessments of catastrophe probabilities of the order of 10–6 per year or less are not very useful in decision-making, a conclusion which is usually also drawn by insurance companies who see insurance against extremely unlikely events more as a gamble than as an action based on scientific grounds. The science of dealing with the zero-infinity problem comes close to what Weinberg calls "trans-scientific", that is, a situation where the traditional methods of science could conceptually apply but would never provide the true answers. However, it is not a unique occurrence if political decisions have to be taken under conditions of great uncertainty.

The basic ICRP recommendations

During the past decade, the basic protection principles recommended by the International Commission on Radiological Protection (ICRP) have met with acceptance also outside the field of radiation protection. Stated briefly, they are as follows:

1. All human practices should cause more benefit than harm ("justification of practice").

2. All harm and risk should be kept as low as is reasonably achievable ("optimization of protection").

3. For reasons of equity, the optimization result should be restricted by limits to protect the most exposed individuals ("individual risk limitation").

In principle, these recommendations apply to the consequences of events which will almost certainly happen but they also apply to events which are not very likely to happen.

Probabilistic events

Once an unlikely event occurs, various scenarios may apply involving risks to individuals and harm to the community as a whole. In a simplified example with only one scenario, involving a probability (p) of harm to each one of N individuals, the total number of affected individuals has a mathematical expectation of $E_1 = pN$, conditional on the occurrence of the primary event. If the event probability is r, the *a priori* probability of harm is r p for each individual, and the *a priori* mathematical expectation of harm is $E_0 = r\,pN$.

In the extreme of the "normal" case, $r = 1$. The basic recommendations then call for limitation of the annual individual probability p (individual risk limitation) and for the reduction of the annual value of E_1 as far as can reasonably be achieved (optimization of protection).

In this case, E_1 is not only the mathematical expectation of the total number of affected individuals but also a typical outcome. The actual outcome has a standard deviation equal to the square root of E_1. This means that if the mathematical expectation is greater than one individual, the actual outcome may be precisely E_1, which may therefore serve as a measure of the collective detriment from each type of harm in optimization assessments.

In the extreme probabilistic case, the annual event probability is $r \ll 1$. The individual risk limitation can still apply to the product $r\ p$, that is, to the *a priori* annual probability of harm. However, in this case the mathematical expectation of the annual number of affected individuals (E_0) is not a number that might actually occur. The actual outcome will either be zero individuals (with the high probability $1-r$) or a large number near pN (with the small probability r). In this case, it is therefore quite arbitrary to base the optimization assessment on the expectation E_0, that is, on the product of the event probability r and the likely consequence pN, given the event.

In reality, the consequence will not be limited to a number of affected individuals as in the above simplified example. There will be many types of harm, from slight injuries to death, but also psychological trauma and economic losses. The total societal impact may include additional consequences with implications for the future. For example, a major consequence of a nuclear catastrophe will be widespread land contamination which may prevent normal land uses for decades, with all the collateral political implications. There may be secondary effects, as when the Three Mile Island accident, despite insignificant environmental consequences, caused considerable economic problems for the nuclear industry because of the loss of public confidence.

There have been various proposals for optimizing protection in the probabilistic case where it is of little advantage to base assessments on the mathematical expectation of collective harm. If r is the event probability and Q is the consequence (including and weighting optimally all types of consequences), it has been suggested that some other expression than the product $r\ Q$, for example, the product $r\ Q\ a$, be used, with $a > 1$ to give more weight to the consequence than to the event probability. Another possibility is to work on the basis of utility values, that is, on some agreement on scores for combinations of r and Q.

Consequences in the future

Any practice which produces environmental pollutants which will endure for a long time before decaying or becoming biologically harmless may build up unacceptable contamination levels if it continues over many years. It is then not sufficient to base release control on the current situation, the control has to be based on the worst future situation. There are two conceptual tools for handling this problem:

the *commitment* concept and the assessment of the *collective detriment per unit of practice.*

The harm commitment from one year of practice is the total resulting harm caused over all subsequent years from that year. If the practice continues indefinitely, the maximum harm caused in any one year in the future can be shown to be equal to the harm commitment from one year of the practice. By limiting the annual harm commitment rather than the annual harm, one can therefore keep the future situation under control.

If the limitation of the total harm or collective detriment is applied to the commitment from a unit of practice (for example, the production of one GW year of electric energy) it may be dimensioned on the basis of the expected maximum future magnitude of the practice. The likely expansion of the practice is then also taken into account. Furthermore, relating the harm commitment to a unit of the practice gives a useful input to justification assessments.

These concepts are used in a number of countries in radiation protection control with respect to the normal operation of nuclear power plants, but for obvious reasons they are not very useful for probabilistic events if the annual event probability is less than, say, 10^{-3}.

Waste repositories

Final disposal technology for dangerous waste products is also a technological system for which risk considerations are concerned with the distant future. Repositories for high-level radioactive waste present two types of risks. One is the very small probability of a genuine accident, that is, a failure of a well designed repository at an early stage, with severe consequences because of the high activity of the material. The other is a high probability of consequences of far less severity because of either slow leakage or drastic disrupture after a very long time, perhaps thousands of years or more.

In the latter case, risk considerations include calculations of the annual harm probability for any individual living at a time T after the construction of the repository. These calculations involve an integration up to time T of the annual probability f(t) of disruptive events multiplied by the probability of harm, given such an event.

Similar assessments may also be applied to repositories for dangerous toxic waste. In this case, as for very longlived radionuclides, the question is how far into the future should our concern be extended? There have been proposals for discounting future harm just as one discounts future expenses. However, this pseudoeconomical approach usually implies that we can almost totally neglect harm that will not occur until after a few generations. A more cautious approach, more often adopted, is to reject discounting but limit the integration period to 10,000 years, on the assumption that the next glacial period would then interfere with any harm assessments. There is also the additional problem of changes in species and in human societies and developments in science and technology which may upset present assessments.

A limit to societal risk?

It has also been proposed, although not by the ICRP, to set a limit for the societal impact. Some large technological systems would not then be accepted, regardless of event probabilities, if a possible consequence were to exceed some established limit. A problem with this proposal is that, in an event tree analysis, many technological systems might show a leading sequence leading to a catastrophic consequence, although with such a small probability that it would never be considered a realistic possibility.

It is sometimes said that any human undertaking, when subject to an event tree analysis, could be shown to lead to severe catastrophes given a very unlikely sequence of events (driving my car I might hit and kill a man who would otherwise have warned the US president not to fly with the airplane in which there was a bomb, so the president was killed and his sudden death led to a misunderstanding in nuclear weapons security causing a nuclear war by mistake...). A universal limit to societal impact would therefore prevent almost everything.

This objection can be dismissed by allocating the responsibility correctly. Many other things besides driving one's car could have the same effect. The possibility of disaster in this particular case would only be eliminated if nuclear weapons were eliminated. If a fault tree analysis shows that the catastrophic consequence is much more likely caused by one or several other primary causes, then the practice in question (such as driving my car) should not be prevented. But the problem remains for those technological systems which have a true potential for causing major catastrophies. How do we rule out impossible event sequences?

Setting a limit for societal impact is almost identical to turning down a proposal in a justification assessment, the only difference being that a pre-set limit to the magnitude of consequences implies a once-and-for-all generic assessment.

It is only natural in this connection to remind the reader of the obvious fact that large military systems, and particularly nuclear weapon systems, have a very great potential for catastrophic consequences. If any system were to be ruled out on the basis of the magnitude of the possible consequence, these would be the ones, particularly since the frequentistic experience of major wars gives little reassurance of low probabilities. It is an interesting observation that just the atmospheric testing of nuclear explosives to date has been estimated (by the United Nations Scientific Committee on the Effects of Atomic Radiation) to have caused a collective radiation dose to the world's population 7.5 times that caused by the Chernobyl catastrophe.

The value of life

The ICRP principle of optimization of protection is generally adopted in the field of radiation protection but is increasingly used also in other areas. It is one of the recommendations issued by the Swedish Risk Academy ("Riskkollegiet") in 1992.

Protection may be optimized by many methods. The most common one is differential cost/benefit analysis on the assumption that protective measures will not influence the benefit of the practice for which the optimization is carried out. In this simple form, the only variables are the degree of actual or potential harm (Y) and the protection cost (X). Protection is optimized when $dX/dY = 0$, since this is the condition of maximum net benefit.

In order to carry out such assessments, it is necessary to express X and Y in the same units, which usually means expressing the harm Y in monetary terms. If the harm is merely material, monetary quantification is straightforward. However, if the harm involves loss of human lives, cost/benefit analysis by implication defines the maximum sum of money (A) which society is willing to pay marginally in order to save an anonymous human life in a statistical sense. The additional principle of boundary conditions set by individual risk limits prevents inevitable harm to identifiable individuals.

The value of A must by necessity fall within rather narrow limits. Conceptually, it is determined by the amount of money made available for protection. This amount obviously has an upper limit set by the annual GNP and the necessity of societal expenses directed to other things than immediate life-saving (a society with all its efforts directed to life-saving would not be able to sustain the GNP needed for optimal life-saving). In technologically advanced countries this may mean an upper limit for A in the vicinity of USD 5–10 million per life.

A lower limit is set by the annual GNP per capita. It would be foolish of any society not to save productive person years at a cost less than the annual GNP per capita.

For reasons of equity it may be argued than any person year, not just the productive ones, should be saved at the same cost. The lower cost limit for saving a human life would then be of the order of USD 0.1–0.2 million.

Between these extreme values, a number of national authorities have selected values of A for their protection programs. In Sweden, the National Road Administration has used a value somewhat higher than one million dollars. The Swedish Radiation Protection Institute has a policy of using values roughly between USD 1–4 million (SEK 5–25 million), depending on circumstances.

The infinite value of life

The value of A has also been assessed in studies where individuals have been asked questions formulated in such a way that their own willingness to pay could be deduced from the answers. The result of such studies reveals that there is one group of people who feel that A should have an infinite value, while the remainder give values which are usually within the range shown above, that is from USD 0.1–10 million. Since the answers must be influenced by the amount of money actually available to those responding, the answers must probably be supplemented with other information in order to indicate how much money should be made available.

Those who feel that A should have an infinite value often criticize cost/benefit assessment as being unethical as "it puts a price on human life". This criticism is based on a misunderstanding. The value given to A does not reflect any view on the *value* of a life, it only indicates how much money society has available for life-saving on the condition that it would continue to be able to sustain its life-saving capacity. A system with optimized protection causes the minimum amount of harm. It would be unethical not to spend at least a sum equal to A in order to save a life, but it would also be unethical to pay much more than A per life as long as more lives would be saved if the money were spent elsewhere.

The ethical problem is not connected with the use of cost/benefit assessments of protection, using an appropriate value of A. It arises when the value of A is determined or when a decision is taken on how much public money should be used for life-saving purposes. This was also the conclusion drawn by a working group appointed by the Pontifical Academy of Sciences in 1983. They concluded that it is the responsibility of protection authorities to seek the public's acceptance of a level of protection which is the highest possible without conflict with other legitimate needs and duties of the community. The use of cost-benefit analysis to optimize protection, they said, "has nothing to do with valuation of human lives but is a device for conserving lives".

We never save lives but years of life

Since we will all die, we can never "save" lives. What we can do by eliminating risks, is to save years of life and preferably years of high-quality life. The reasoning above would therefore have been more logical if it had referred not to a maximum marginal sum A to save a life, but rather to a corresponding sum B to save a year of life.

Assessments indicate that a typical loss of life years by way of accidental deaths in industry in highly industrialized countries is 35 years. The ICRP has estimated that the average loss of life years due to radiation-induced cancer in an exposed population of all ages, for those dying of such cancer, is about 15 years.

It is important to retain the distinction between expected loss of life years for those affected and the mathematical expectation of loss of life years for all those who are at risk. Those who will die of radiation-induced cancer after life-long exposure can expect a loss of life years of 15 years, with a probability distribution around the mean so that some will lose more years and some fewer. This is essentially independent of the *apriori* level of risk. In the whole exposed population, however, the mathematical expectation of lost life years will depend on the level of risk, since it is the product of the probability of dying from radiation exposure and the 15 years lost if death occurs. At an annual dose of 1 mSv (the present ICRP dose limit to members of the public) over a lifetime, the mathematical expectation of lost lifeyears for an average individual is about 3/52 weeks. This short time period, however, is merely the product of a probability of 0.4 percent of dying from the exposure, and a loss of 15 years if that happens. The way of presenting this risk is likely to influence its acceptability.

The Swedish Cancer Committee (1984) estimated that 11 or 16 years of life (for males and females respectively) are lost by those who die of cancer in Sweden and that the total elimination of cancer would therefore not increase mean life expectancy in the whole population by more than 2–3 years. The latter information given out of context is sometimes misunderstood because it conceals the fact that there is both a high individual risk (a probability of about 20 percent) of dying of cancer, and an appreciable loss of life years if this actually occurs.

A further development of the concept of saving years of life rather than just lives is to weigh each year saved by some measure of quality in order to obtain an index called "QUALY" (QUality Adjusted Life Years). However, the advantages of this complication are doubtful and the use of QUALY has met with criticism. Also the theoretically attractive assessment of saved years rather than saved lives has been criticized as both unnecessarily complicated and risking discrimination of the old.

Other harm than death and dollars

Risk considerations with respect to large technological systems have traditionally dealt with economic losses, risk of death, and harmful effects on the environment. However, there may be socially disruptive effects over and above these consequences. The impact of the Three Mile Island catastrophe (which it was from an economic point of view) on the nuclear industry throughout the world has already been mentioned. The Chernobyl catastrophe, in addition to the possible 30,000 cancer deaths (according to present risk estimates) and enormous economic losses, produced a severe psychological and social impact in many countries. If there were a highly unlikely accident at the Swedish Barsebäck nuclear power station involving a containment breakdown and winds towards Denmark, the contamination of Copenhagen would be economically catastrophic, but the social consequences in the country and for relations between Denmark and Sweden might be even more disastrous.

In many large technological systems where there is a potential for catastrophes affecting human lives and the economy, there are other aspects which have to be considered. This is true for such diverse types of catastrophes as the major breakdown of a national electricity grid system or failure to detect in advance the negative health effects of a pharmaceutical product which has been distributed widely.

The traditional risks and consequences are reviewed by a number of national authorities and some international bodies. However, no authority deals with the overall picture of catastrophic impact on society, perhaps partly because the possibility seems so remote. The ultimate decisions on acceptance in cases where this possibility exists are taken at the political level once experts have pronounced the probability to be extremely slight. The risk to the decision-maker of being wrong is negligible. The annual probability that an unlikely catastrophe will occur and expose him or her to severe criticism is small in comparison with the probability of other unpleasant things (such as death) to which a decision-maker is always exposed. Such political decisions may therefore be taken without professional comprehension of the risk situation.

I have deliberately chosen not to discuss the detrimental impact which some large technological systems may have on our environment, endangering not only man but also other species. This is not because such harm is necessarily of less importance but because most of the damage which human beings have inflicted on the environment is of a deterministic rather than a stochastic nature and therefore does not fall into the risk category as "risk" has been defined here. Most environmental pollution or destruction caused by industry, agriculture and households is a deplorable fact rather than a probabilistic possibility. Few catastrophes affect flora and fauna more than they affect man. Environmental protection is therefore more effectively directed at what is being done than at what might happen.

Appendix 1

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The Future Societal Impacts of Telecommunications

Professor Peter Weissglas

Technology and modern society

Technology has always played an important role in human society. We talk about epochs such as the Stone Age, the Bronze Age, or the Iron Age, illustrating that the most important characteristics of these periods were the materials technologies in use.

In modern times our reliance on technology is increasing, and it is appropriate to say that today we stand on the threshold of the Information Age.

The 20th century has been very strongly influenced by three major inventions all conceived around 1870. I am thinking of the Otto engine, which powers our cars, the telephone and electricity generation.

Most other products prior to modern electronics are either derivatives of or supplements to these major inventions.

It is not unreasonable to assume that the 21st century in the same way will be dominated by technology based on two major inventions made almost exactly 100 years after the invention of the car engine, the telephone and electricity generation. Those two inventions are the semiconductor chip and the optical fiber.

The transistor, on which our electronic chips are based, was invented in 1948. It was followed by the first small-scale integrated circuit about 10 years later. The first really large-scale integrated circuit appeared around 1970, at the same time as the optical fiber was invented.

Considering that only 20 years have elapsed since these two major microelectronic components appeared, their influence on society has been remarkable.

Computers are to be found everywhere, and telecommunications are already reshaping most business activities from banking to retail and industrial manufacturing.

Although the title of this essay refers to telecommunications alone, it would be impossible to isolate the effects of communication as such from the effects of data processing and storage and other uses of microelectronic technology. The systems we now see evolving are networks where data transfer, storage and processing take place in a distributed manner. Isolating one technology from the other becomes impossible. I will therefore discuss the impact of microelectronics as one single technology.

Looking at an industrialized country it is tempting to say that the Information Age is already here. We already depend on computer networks. It could also be argued that modern society moves and evolves at an accelerating pace. Whereas it took (perhaps) 80 years for the inventions of the 1870s to reach their full societal impact, the inventions of the 1970s only needed 20 years. My hypothesis is that this line of argument is incorrect. First of all the technologies as such are not yet sufficiently mature to exert their full influence. Furthermore, once technology reaches its mature stage we need to build up an appropriate infrastructure to make the full use of the technology possible. Finally, even with a mature technology and an established infrastructure, the adaptation of human behavior to totally new possibilities probably takes a generation.

Based on these arguments, my projection is that the technology will mature during the first decade of the 21st century. Infrastructures will be built up gradually in the period 2000–2020, and around the year 2050 our descendants will be living in a true Information Age.

Microelectronics

The first transistor came into existence in 1948. Today we can buy a memory chip capable of storing 4 million bits of information on 1 cm^2 of silicon. Each individual transistor has minimum features of about one half micron or millionth of a meter. In industrial research laboratories ongoing development will increase storage capacity by further reducing the dimensions of the individual transistor. Development to date now has been very predictable and it is probably safe to predict that some time between 2000 and 2010 we will be able to buy memory chips with a capacity of 1 billion bits (1 Gb). The market price of such chips will most likely fall to less than 10 US dollars.

To get an idea of the practical storage capacity of such chips, consider a circuit board with one hundred 1 Gb chips. This board would have a surface area of a few dm^2. The storage capacity of such a board would be equivalent to about 1 km of shelf space filled with books or sufficient to store several films.

The difference between this type of memory and the magnetic or optical memories already in use lies in the access speed and the possibility of multiple access provided by the chip memories. It would be possible, for example, for several TV viewers to look at the same film simultaneously on different TV sets and start their viewing at different times. This multiple high speed access to the data bases of the future opens up tremendous possibilities.

The same technology used in memory chips is also used to build processors for computers. The 1 Gb per chip technology generation makes it possible to build palm-sized computers with the same capacity as the largest supercomputers available today.

Chip technology is also used to build the electronics used in the radio links which form the basis for mobile telephones. More potent chips will offer smaller size, lower power consumption (and thus longer battery life), more communication channels by using higher frequencies and lower cost. Thanks to such developments, it is reasonable to predict a development where all kinds of terminals such as telephones, video phones, computers, telecopiers, cash registers, instruments, etc., will be cordless. An infrastructure of base stations connected to a wired network will be needed. The range of a base station in densely populated areas may be as limited as one corridor of an office building.

Specialized chips are already used to monitor and govern industrial equipment to reach even higher levels of automation. New types of cheap miniaturized microelectronic sensors are also being developed. We already have the electronic eye or the sensor chip used in commercial TV cameras. Similar sensors capable of night vision are emerging. Also other human sensors can be emulated in, for example, "electronic noses", advanced microphones, etc.

Thin film transistors built on the back of glass plates containing liquid crystals are already coming into use as displays, and undoubtedly the next one or two decades will give us high resolution multicolor flat panel displays of almost any size.

The current generation of printers based on small semiconductor laser chips will similarly be perfected. High-speed printers with color quality and resolution equal to the art reproductions of today seem very likely to emerge within a decade or two.

Without the invention of the optical fiber all the microelectronic products described above would have been difficult to link up to extended networks. The valuable use of extremely powerful stand-alone machines would be very much reduced compared to what can be expected now with the almost infinite capability of data communication based on fiber.

An optical fiber is a 0.1 mm diameter cylindrical quartz glass fiber with a central core of 0.01 mm capable of conducting infrared light almost without attenuation. Only 50 percent of the light is lost over 30 km of transmission length, which makes transmission possible over very large distances without any electronic repeaters. The information transmission capacity of such fibers is enormous. Commercial equipment already transmits 2.4 Gb/s, and development for 40 Gb/s is in progress.

To further enhance communication capacity, development is focusing on the use of several light frequencies or "colours" simultaneously. Each "color" constitutes its own information channel. Using this technique a total capacity per fiber of 1,000 Gb/s would seem to be possible. A single optical cable could contain as many as 100 fibers. The optical cable does not look very different or differ much in size from the power cable to an ordinary desk lamp and could have a total capacity of 105 Gb/s.

This communication capacity is sufficiently high to have one half of the current population of the world at one end of the cable talking to the other half at the other end. All simultaneously!

Once investments have been made to build up a cable network infrastructure, it will be possible to support services such as video phone and massive data communication between sophisticated microelectronics terminals.

Information Age infrastructure

If we return for a moment to the beginning of the 20th century, we can observe how technology for the automobile, the telephone and electric power distribution gradually matured. Without roads, telephone lines or power lines the technology was not of much use.

Similarly, modern telecommunications technology requires efficient networks in order to become established. Just as the first cars drove on upgraded farmroads, data communication today takes place via upgraded conventional telephone lines.

We have yet to make the necessary investments in a new generation of telecommunication networks dedicated to digital transmission and based entirely on optical fiber supplemented with base stations for wireless terminals.

Just as roads for motor cars developed in two generations via dedicated two-lane roads to modern motorways, we may expect to see a first-generation network referred to today as ISDN (Integrated Services Digital Network) and a later high capacity generation BISDN, the B standing for broadband.

The laws and standards required to make road traffic possible were comparatively simple, for instance, "drive on the right hand side" or "yield right of way to vehicles approaching from your right", etc. The traffic in telecommunication networks is much more complex, which necessitates international standards of a much more elaborate kind. Developing these standards is as complex as developing the equipment itself.

Technology for debiting consumers who may access the network thousands of miles from their home addresses to use a service at a distant location requires the development of millions of lines of software code and international standards, as well as commercial agreements.

The road networks and telephone and powerline networks are not the only components of the infrastructure which were necessary for the 19th century inventions to achieve their full societal impact. It is sufficient to mention car and truck manufacturers and their suppliers, repair shops, gas stations, road maps, parking lots, etc., to illustrate what is needed. Road traffic alone with its associated suppliers, infrastructure and services today accounts for about 15 percent of the GNP in most countries.

Information and telecommunications technology is already expected to overtake road traffic in economic importance within the next few years. *This is all the more remarkable as the infrastructure and the* services do not yet exist!

Experiments implementing the telecom network infrastructure locally have been carried out in several places. In such experiments, for instance in Biarritz in France, a number of households were provided with ISDN fiber networks. The experiments clearly show that the services available are as important as the actual network. The absence of a developed services market limits the use of the technological opportunities.

An interesting example of using old technology to offer new services is the French Minitel system, where regular telephone directories have been replaced by simple computer terminals connected to the telephone network. In addition to replacing the telephone directories, the Minitel system allows the users to access a variety of databases, as well as computer mail services. Even after 10 years of large-scale use, only a small number of services have been developed so far.

If the right type of databases were developed and access provided on a commercial basis, most types of information could be available via the Minitel system. For example, it would be possible to store the contents of all the books in the US Library of Congress in a database as long as there were an efficient information retrieval system. It could also be possible to construct a database providing product information including sales organizations and prices for all types of products. The cost of setting up these databases is enormous, however. A number of tricky issues regarding pricing and payment mechanisms, safeguarding proprietary information, integrity issues, etc., have to be dealt with. Educating potential customers to use the services is another major task which must be completed before a sufficiently large market will exist to motivate investments in services.

For other types of services such as videophone or video-conferencing, we have the same type of problems as with the first regular telephones. Why buy the first telephone when there's nc-one else to talk to?

Future societal impacts

Even if we have to wait another half century to see the full impact of information technology, the short term effects on society are tremendous.

We can already see major effects, for example:

- automation in manufacturing and reduction in the number of people employed in industry,
- improvements in all traditional products thanks to the use of computer-aided design, as well as the use of electronics in the products,
- internationalization of all business activities, attributable in part to easy telecommunications,
- the rapid spread of information world-wide via television and other news media,
- increased speed and volume of capital flow owing to computerized banking,
- credit and charge cards replacing cash,
- fax replacing traditional mail,
- changes in educational needs due to new, emergent technology,
- computerized warfare,
- computer crime,
- advances in medicine as a result of the use of information technology.

Important as these effects are, we still live in a society which probably resembles 1960 more than that year resembled 1900. Where will the really great changes take place?

Maybe the turbulence we are currently witnessing on the financial markets forebodes some of the things we are going to see in the future. Computerized banking has increased the speed and volume of international capital flows tremendously.

Telecommunication and information networks provide financial players with instant round-the-clock information from all the international markets. As a consequence of these developments it appears that only the very largest nations can maintain a financial and monetary policy of their own. Perhaps we are already past the point of no return where unification of countries into major trading and currency unions such as the European Union and NAFTA will be necessitated regardless of political wishes.

At any rate, technology will continue to have a marked effect on financial transaction. It is also almost inevitable that a combination of smart cards and cash points connected via wireless links and fiber networks to bank accounts will make the cashless society a reality.

Education is another area which will be strongly affected. Schools and universities have been remarkably stable over many centuries. It is unlikely that this will continue. The rapid changes in technology to which everybody is exposed have already created a need for continuous education, that is, a need for every individual to upgrade his or her knowledge continually.

Computer-based training techniques are being developed. These are likely to replace traditional methods. Maybe we will see a development where social training will be the major role of the teacher and the school, and technology will take over most of the teaching and training functions.

One of the big question marks is how markets for information will develop and what effects they will have on society. Today most types of information are supplied free of charge. This creates little incentive for the market to improve access and information quality. From an economic-theoretical point of view it even seems difficult to see a real market for information. The marginal cost of reproducing information is close to zero so in a perfect market the price must also be near zero.

Software has similar characteristics to information viewed as a product. The cost of reproduction is low. To create a software market it has been necessary to combine technology and legislation. Separation of source code and object code, software barriers to prevent illegal copying and laws which make unauthorized copying illegal are the methods employed to make a software market viable. No techniques have as yet been developed to protect information in a similar fashion.

One may even speculate that some of the current imbalances in trade are due to the lack of legal protection of information. For instance, it is unquestionable that the US still dominates strongly in basic research in most fields. The results of this research are published freely. If the US could put an appropriate price on its information export, perhaps the trade balance in relation to Japan would look different.

On the one hand, the idea of restricting the free flow of information just to create a commercial market for information seems strange. On the other, progress and economy may be retarded because there is little incentive to invest in the generation of information and knowledge as long as they cannot be marketed at a reasonable price.

The pressure for information technology and telecommunications to generate totally new markets will be strong as the proportion of the world population involved in direct production will decrease owing to the use of these technologies.

The need to develop new markets combined with the need to build a new infrastructure and customer readiness will determine how soon the information society will mature. As with all technologies great possibilities and serious threats coexist.

The Shrinking Window of Information—Large Technological Systems and Data Communication

Professor Lars Gustafsson

Which is the largest existing technological system? That depends on how 'technological system' is defined; are we talking about hardware exclusively or is software taken into consideration as well? And what do we mean by 'large'? Is it the level of complexity or rather the volume of investment which is the decisive factor? Or might it be the number of people involved in the operation of the system, for example, the number of operators or the number of operators together with the number of people affected by the activity?

Viewed as a coherent system, the global civil aviation network is certainly large if we use this sociological definition. But the number of people affected per annum or per hour by the European telephone network is of course much larger than the number contributing to the global air traffic statistics.

This sociological way of defining the size of a technological system in terms of the number of operators and the number of people in some way or another affected by its workings, generally produces surprising results. It becomes, for example, quite reasonable to regard written language as the largest of all existing technological systems. Many things speak in favor of seeing it in that light. Written language, of course, consists of both software and hardware. For those who find simple puns amusing we could say that this is a case of a system where the hardware started very hard and became softer and softer. I am referring, of course, to the development from rock-carvings to ink on paper and from there on to electronically created and magnetically stored letters thanks to computer technology. While the hardware has undergone considerable change, the software has remained surprisingly constant over a very long period of time. The only really great invention, substituting the phonetic alphabet for ideograms, is already over two thousand years old. Many material media have been used as bearers of the written language, from old Babylonian tablets and the ninth-century runestone at the Church of Rök to luxury bound editions of Stéphane Mallarmé's poetry and neon letters in big cities.

What they all have in common is their ability to freeze the moment and to give the fleeting instant at least the appearance of duration over time. The most fundamental of all facts about human existence—the mother of all philosophical reflection, one might say—is of course that as human beings we do not have any real existence over time. The tennis player at the net, concentrated on the ball, and only on the ball is at that moment really without memories and lacks any conscious conception of the future. He might serve as an image of what man might have been without written language. Of course, we will never know how life without written language might really have been, because there is no object of comparison, written language alone being capable of providing us with the documents of a mental life without documents.

The huge technological system which the written language constitutes has two effects of utmost importance to our thoughts. It makes them enduring and repeatable. Time starts to feel like a substance and can be revoked. It gives us a chance to reach beyond the narrow confines of the subjective instance, in psychological measurements appreciated to last two to three seconds, and the somewhat wider constraints of natural memory. Thoughts can be passed on, criticized and compared, and that beyond the existence of their author. To the extent that we accept one-way communication as communication, written language provides us with a means for the dead to talk to the living, and, in the process of interpretation, for the living to speak to the dead. In spite of its great size, or perhaps exactly because of it, the technology of written language is simple and easy to learn, especially in phonetic languages of course. There is no longer a natural limit to production possibilities, especially since the hardware over time has become more or less immaterial. The production of written language can be seen as a vast continuous technological project, with whole generations taking part, a project for which no end is in sight. There are of course an almost infinite number of different levels of difficulty to be overcome, extending from the early attempts of the little child to make readable letter-forms to the sovereign handling of formalized language in the formulas of modern mathematical and physical texts.

It is of course trivial to claim that all our other systems of technology are dependent on this gigantic technological system. No physics, no chemistry, no mathematics without the written language.

The most fundamental fact about written language is probably that is makes possible the communication of a message without demanding the physical presence of its author.

The oldest written message in a Nordic language, the well-known inscription on the Gallehus Horn: "I Leeguest made this horn", triumphs with its presence long after the horn has for ever left the hand of its creator, and this magical property of making somebody present who cannot really be so, never ceases to fascinate us even if the runic magic has had to yield to a more rational theory of signs.

The radiance which can emanate from a pre-Socratic fragment from some obscure philosopher, only preserved in a few citations in the text of some hostile and greedy patrist, and inserted with purely critical and polemic intention has something of this everlasting victory of written language over time about it. Victory over time but also over the tyranny of the moment. Heraclitus is at the same time absent and present in the world of fragments; he is joking with us out of the void of his absence.

Rational afterthought of course tells us that the hope of literary immortality expressed by many poets since the time of Horace is ephemeral. Sooner or later will come the moment when every word written by all of us present here will be lost. And worse still: sooner or later the entire culture forming the framework of our writings will be forgotten. Shakespeare's dramas, Kurt Göde's proof, Einstein's papers, the early science fiction of H. G. Wells and Borge's fairies will all be caught up in that slow but sure gyration which leads down into the tunnel of oblivion.

A few things may endure a little longer; papyri have a strange ability to survive in the dry sands of Egypt and to come back to tell us that there were more Socratic Dialogues, some of them weird and rather alien, and that the origins of our different religions were more complicated than we might have been able to guess. And other long-lived traces of the force of the written language are of course to be found on Babylonian clay tablets and Sumerian coins. But the main rule is without mercy; and this is the same for the hardware of written language as for everything else in this vast universe. Everything sooner or later has to run through the ordinary cycles of hot plasmas, thin gases, dirty ice. Or vice versa, depending on the circumstances. From a broader time perspective, to write in this world always means to write in water.

After this excursion into a realm traditionally regarded as belonging to the poets—the ongoing flirtation with 'immortality' which may easily be shown to be impossible from the very outset, and the lamentations over the fact that it actually is so—it might be time quite soberly to state the fact that the intention of the invention of written language probably never was to attain immortality. We do not write down telephone numbers in our books in order to preserve them for ever, but just until the moment when we really need them. We realize that we might need the number on some occasion or that we might need to pass it on to somebody else. Like other technological systems, this one has also grown out of functional needs.

So written language creates a prolongation of the instant, repeatability, and something that may be equally important: objects of comparison. And, of course, its does create a fast-changing mass of information, accessible in principle though much less accessible in practice, whose real dimensions are little known to us. We know that the major libraries contain some 10 to 12 million volumes, but that does not tell us very much about the real volume of written material. What is printed is after all, only a very small part of what is actually written and stored at a given moment. The volume of written material might be many orders of magnitude larger than the volume of printed material. How many volumes of written, but unprinted, material does a modern US law firm produce within a year? Probably many times more than a normal research institute is able to produce in ten.

In different technological and sociological contexts, people are often in the habit of talking as if the momentarily existing mass of information of mankind were at our disposal. Access to modern electronic hardware and networks seems to contribute to that conviction. It is, however, illusory.

The informational obstacles are of two types:

First, there are the obvious social limitations. Not all systems of discourse are open to everyone. Some are confidential. With others everybody is simply not entitled to join the discussion. As little as everybody is permitted to have an opinion about everything, so nobody has access to all written information, if only because he or she would never be able to understand it all. To this set of social limitations, which the late Michel Foucault used to call 'the forms of the discourse' comes a—shall we call it 'phsysiological' limitation which strangely enough very often seems to be completely forgotten.

While the aggregate of theoretically accessible information in the form of written language seems to be a fast-expanding mass of huge dimensions, the human physiological capability to assimilate a part of this mass is a constant or as close to a constant amount as we can get in these contexts. This it the 'window' to which I refer in the title of this lecture.

Let us take a person, man or woman, who learns to read at the age of ten, reaches the age of eighty, and who remains active for all of his or her life. Such a person intellectually active on the level of a 19th century university professor (who might have had less committee work than is normal today) is probably able to read a book of the average length of 200 pages, let us assume, every week of the year. That would make 520 books in ten years, and consequently 3,640 book in seventy years. Objections of different sorts can of course be raised with respect to this calculation. Some will find it too conservative and others too optimistic. Feel free to correct. But whatever corrections you care to make, the difference you will arrive at will remain microscopic compared to the really interesting difference, that is, between the theoretically accessible amount of information in the world and its libraries and archives at a certain moment in time, and what a particular person actually can access, that is, read in a lifetime. You can store 3,640 books in a PC with a big hard disk configuration.

This, obviously, shows the importance of choosing our reading in a truly selective way, but it also shows the limitations of care and selection. (If we start to choose too carefully, we will only lose coherence. If we create for ourselves some sort of context-less list of classic books we might run the risk of not understanding anything at all. We do not derive much pleasure from Pindar or the Homeric Hymns if we do not know anything about the cultural contexts and conceptual backgrounds of these texts. So that road, the establishment of a canon, a body of superior texts, is also closed to us. I shall return to this aspect of the problem in a moment. The really interesting thing about what I call 'the physiologically accessible volume of information' is that for all practical purposes it comes as close to a constant as is possible. And this constant, which I have calculated to some 3,500 volumes may be taken as the basis for an index in the same way as we calculate, for example, the value of a currency over time. Let that basis be 1.

If you will permit me to take an example with which I am slightly familiar—Swedish book production. A librarian, Dr Sten G Lindberg, has calculated that Swedish book production amounted to 4,068 volumes at the end of the 17th century[1]. In other words, somewhere in that century there was a physiological possibility to read the entire Swedish literary production of that age before the end of one's lifetime, and thus for the quotient between the constant and the theoretically accessible amount of information to reach one. In our times, even using the very limited example of Swedish literature, this quotient has diminished enormously. According to the same source, 10,475,311 titles were published between 1900 and 1979. Here, clearly if the divisor (3,500) were good scotch whisky and the dividend (10,475,311) water, you would not be able to taste the scotch. It should be observed that my example, for practical and pedagogical reasons, is limited to one sector of the written language in a very small language. The real figures are of course of a quite different dimension, but show the same tendency, a fast-growing misproportion between physiologically accessible and theoretically accessible information. If the former is seen as a window to the latter, that window is diminishing with enormous speed, because it occupies a rapidly shrinking proportion of the building in its entirety.

For an individual human being, there is no other window. As long as we have the sort of written language we have, with phonetic symbols and reading by human eyes, the upper limit for the reception of symbolized information seems to be bound approximately to the limit it has now.

And only very imaginative SF-writers, mainly of the cyber-punk variety, dare to imagine an intake of information into the human mind by some sort of direct cable. Forced feeding is never very pleasant, and even if I realize the potential usefulness of having Liddell & Scott's Lexicon of classical Greek piped directly into my memory, I still think I would fight like a lion against anybody who wanted to try that experiment on my memory. Memories are the most personal thing we have.

The most interesting aspect, perhaps, of our index is that our part of existing knowledge is growing smaller at the same speed as available knowledge is increasing. A professor at Uppsala University at the time of the Cartesian discussions could speak with so much more authority about the problems involved than practically anybody today, because his relative part of the accessible knowledge about the questions

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[1] See Lars Lönnroth & Sven Delblanc. *Den svenska litteraturen.* Vol 1. Stockholm, 1987, p 12.

involved was so much bigger than anybody could physically achieve today. This is a paradox.

Let us not make the mistake of confusing proportions, which is what this lecture is fundamentally about, with quantities. Of course, a 17th century reader of natural science or philosophy had access to a much smaller selection of sources of information than we have. So if we define our freedom in terms of multiple possibilities, our freedom is greater than that of our learned or unlearned ancestors. This of course says something about freedom: beyond a certain level it seems to create a new uncertainty.

How do we choose our life's reading, when it can only constitute a fast-shrinking proportion of what is theoretically accessible?

The idea of a canon of fundamental, or at least essential, books seems to me to become less and less reasonable, the smaller the shrinking window becomes.

An important reason for introducing a canonical reading list (as late as the early eighties, when I went to the United States, many ambitious colleges used to provide their students with such normative or advisory lists of The Great Books) is of course the idea that a common canon makes possible a common exchange of ideas, images and concepts.

The lively debate about so-called cultural diversity, which has been carried on in recent years on US campuses, has mostly articulated itself as a demand for reading which mirrors a larger field of experience than is perhaps now the case. Thus there is an ideologically and politically tinged demand from different groups—ethnical, sexual and geographical—demanding that the curricula and reading lists of our universities should better mirror minority experience. Among the objections to this demand has been exactly the argument that a common intellectual conversation needs a treasury of common intellectual experiences. If everybody reads his own books, the search for common ground can become difficult, because of a lack of objects of comparison.

Political as this discussion might seem, it might be the case that it has some roots which are of a non-political, that is, a technological nature.

The growing technological system of written language might itself be a reason why the idea of a list of canonical books seems less and less realistic as time passes. The various egalitarian and ideological motivations in the US debate seem to me rather to conceal the underlying problem than to articulate it. Because if there is no longer a canonical literature, in the sense that one existed for the learned of the 17th century, with Plato, Aristotle, Cicero, Horace and Vergil among the standard names on the list, I cannot see how a feministic or ethnic canon could take over its role. In proportion to the possible, the realization of such a canon would leave us as feeble, as lonely on the vast ocean of possible choices as any other choice. As the proportions change for the worse, our confusion, our feeling that any choice will do because they are all insufficient, only increases. The well of wisdom has run over, we do not stand at a well any longer, but rather sail a sea, where we have insufficient means of navigation.

If, say, we meet a modern young student who wants to know something about the philosophy of religion, about theophanies and their interpretation, what are we supposed to do? Shall we recommend him to read Augustine's *Confessions* or Philip K. Dick's *Valis* books, the latter clearly Science Fiction, but in many respects able to convey the particular nuances of religious experience to our student in a style and a vocabulary much closer to him.

For the old professors in my Swedish upper secondary school in the 1950s, there would have been no question about what to recommend, but for me, a US college professor in the 1990s, there is such a problem of choice which I have to formulate for myself and my students from time to time in full earnest.

Because any reasonable searching and selecting in the theoretically accessible volume of printed information must of course in some way be guided by the context of already existing contexts in the mind of the reader. To some extent what we choose to read, and are able to understand, is always guided by what we have already read. (In approximately the same way as what we see in paintings to a very large extent is guided by what paintings we have already seen in our lifetime.)

It is customary to describe large technological systems as dangerous, or, at least, which we have just learned is not the same thing, risky. What are the risks connected with the large technological system of written language? There is of course the obvious one—all the other more or less risky systems are dependent on this one. No nuclear power stations without physical theory, and no physical theory without written language. But are there any inherent risks connected with the system of written language, besides the fact that it has made all the other large systems possible? What is the danger built into written language itself? As an act of interference with human nature, written language must reasonably be one of the biggest possible. What did it do to mankind? The point is of course that we will never know. Without written language our prescriptural history is beyond documentation and vanishes as an object of comparison. We simply do not know, because we do not have any real historical knowledge about a social state without written language.

Can anything interesting be said about data systems in the context of the diminishing window?

If what has been said here is—in general—correct, they do not make much difference. They make it possible to store and to distribute information to an extent unheard of in earlier technological systems. But they cannot solve the fundamental problem of the limited reading speed of a biological system.

This problem seems unsolvable if we do not go to extreme assumptions, which only seem feasible within the context of extreme Science Fiction. It may be the case that in the near future we might be able to read Shakespeare's First Folio onto a hard disk with a super scanner of some sort or another, or to specify a Gödel number which might be regained in reasonable time, but how much does that help those of us who only have normal eyes, a normal brain and an ordinary life span?

And, assuming that it would really be possible to pipe in megabytes at high speed by cable into the back of our heads—would that really be an acceptable life style? Is an intimate symbiosis between man and machine really a development which we would be inclined to welcome?

As nothing of this seems very realistic either in the scope of our lifetime or our grandchildren's, it might be more profitable to ask about more immediate results of the shrinking of the window. One is probably diversification: in my youth, all Germanists, say, were schooled in approximately the same canon of texts and taught approximately the same things from *Nibelungenlied* to Thomas Mann, and this common knowledge made of course a common competition and a common conversation possible. In the academic world of our days one might find in the same department experts on Peter Handke, the former East German economy and that same old *Nibelungenlied*.

The pessimist says about this, and with some justification, that it is a symptom of the dissolution of the old academia into a new archipelago of insular small dominions. And the optimist says, also with some truth, that this dissolution is the consequence of a new information technology, where the handling of the informational tools is more important to learn than one particular application of them. And one can of course say that it is only with modern electronic data processing that some of the fundamental tendencies of the great project of written language come to maturity: that is, extremely simple fundamental constituents, enormous flexibility and access from many different abstract and physical directions.

If the modern condition creates confusion, it must also be said that this confusion contains promise.

Or as we recall from Sören Kierkegaard's *The Concept of Fear*: the moment of fear and vertigo is the moment when we fully realize the depth of our liberty.[2]

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[2] Sören Kierkegaard *Begrebet angst* in Samlede Værker 2nd ed., A. B. Drachmann, J. L. Heiberg and H. O. Lange, eds. Copenhagen, 1920–1931, Vol 6. In English: *The concept of dread*, transl. by W. Lowrie, London, 1944.

Social Institutions and Nuclear Energy

Professor Alvin M. Weinberg

Twenty years have passed since, at a meeting of the AAAS in Philadelphia, I referred to nuclear energy as a "Faustian Bargain".[1] To quote from that speech: "We nuclear people have made a Faustian Bargain with society. On the one hand we offer—in the catalytic nuclear burner (that is, the breeder)—an inexhaustible source of energy. Even in the short range, when we use ordinary reactors, we offer energy that is cheaper than energy from fossil fuel. Moreover this source of energy when properly handled is almost non-polluting. Whereas fossil fuel burners emit oxides of carbon, nitrogen, and sulfur ... there is no intrinsic reason why nuclear systems must emit any pollutant except heat and traces of radioactivity.

"But the price that we demand of society for this magical source is both a vigilance and a longevity of our social institutions that we are quite unaccustomed to."

Since I wrote these words, the first nuclear era has largely run its course. Although a few nuclear reactors are still being ordered—for example in Japan, South Korea, Taiwan, and France—no nuclear reactor has been ordered since 1976 in the United States; and in Russia, as well as in many other European countries, nuclear energy is at a standstill. We are now better able to judge how well nuclear technology and society have fulfilled their parts of this nuclear Faustian Bargain. Have we nuclear people provided an energy source that is inexhaustible, cheap, and non-polluting? Has society demonstrated the vigilance and stability demanded by the widespread use of nuclear energy? If the answer to these questions is no, then is nuclear energy doomed to the ultimate failure predicted by James Conant in his 1953 Presidential Address to the American Chemical Society? Or can we still look forward to a second nuclear era in which nuclear fission plays a continuing, and even expanding role as a source of energy?

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[1] A. M. Weinberg, Social institutions and nuclear energy, *Science 177*, 27–34 (1972).

Technical success and failure in the first nuclear era

The first nuclear era has seen two major successes—the achievement of economically competitive power using conventional reactors, and the demonstration of inexhaustible energy using breeder reactors.

Economics

Some 426 nuclear power reactors with a net capacity of about 318 gigawatts (GWe) were connected to the world's grid by the beginning of 1990. Another 96 reactors with a capacity of almost 79 GWe were under construction, making a total capacity of about 400 GWe. Since 1 GW of electricity at 60 percent load factor, requires an expenditure of about .05 quads/year of primary energy, the world's fleet of reactors converts about 20 quads of heat energy into electricity. This represents about 6 percent of the world's primary energy. Some of these reactors have been financial disasters, but many more have been economically competitive. On average, over the whole world, nuclear energy, based on ordinary non-breeder reactors, has met the economic competition of the most expensive fossil fuel (oil), and in some cases, even of coal.

The Breeders

Breeding in several large liquid metal cooled fast reactors and in the light water thermal breeder was demonstrated during the first nuclear era. For example, the French PHENIX, a 25-MW fast breeder has actually recovered 1.13 new atoms of ^{239}Pu for each plutonium atom burned in the reactor. The ultimate fuel of such a fast breeder is ordinary uranium: the plutonium as it is recycled "catalyzes" the burning of the uranium. The fast breeder therefore burns 50 percent of the natural uranium fed to it, rather than the 2 percent burned in an ordinary light water reactor. The fast breeder actually, not merely in theory, enables mankind to extract the all but inexhaustible energy contained in the residual thorium and uranium distributed throughout the earth's granites. "Burning the Rocks" is no longer just a theoretical possibility.

Why has the actual demonstration of power breeding—long regarded as the Holy Grail of nuclear development—passed more or less unnoticed (although G. Vendryes, who led the French effort did receive both the Fermi Award and the Japan Prize for this achievement)? Part of the reason is that, the fast breeder is too expensive. We had always realized that the breeder would become competitive only if uranium became sufficiently costly. As long as uranium was plentiful and cheap—say USD 15/kg—the breeder, with its high capital cost, could not compete. But if uranium became expensive, the breeder would eventually compete with non-breeder reactors. What we could not foresee was when this would happen. Suppose the LMFBR cost say, 25 percent more to build than a conventional, non-breeding, light water reactor (LWR). This higher capital cost of the LMFBR would eventually be compensated by a lower cost of fuel, since the breeder requires only 1/25 as much uranium ore as does a non-breeder LWR. This argument was barely valid in 1972 when a 1,000 MW LWR cost about USD 400/kWe, and, according to our estimate, an LMFBR would cost USD 500/kWe. To compensate for this difference of USD 100/kWe, we estimate now that the cost of uranium would have to rise to perhaps USD 75/kg (1971 USD) compared to its current cost of ~USD 15/kg (1991 USD). But by 1991, the capital cost of large LWRs had risen perhaps 5-fold in current dollars. Thus the difference in capital cost between an LMFBR and an LWR now is estimated to amount to about USD 500/kWe. The compensation price for uranium has soared to over USD 500/kg. At this price, uranium from sea-water burned in ordinary LWRs is a possible inexhaustible source of energy. In short, the vision of the LMFBR as an inexhaustible energy source is tainted by its high capital cost.

In this respect, breeder reactors resemble solar energy: we use in principle inexhaustible, low, even zero, cost fuel, but breeder reactor projects are plagued by high capital costs. Is high capital cost an inevitable deficiency of the inexhaustible energy sources—fission breeders, solar energy, and, possibly, fusion reactors? I cannot say at this time. As for the breeder, one can hope that, as technology develops, capital costs will fall, or even that other breeders, such as the molten salt or high temperature gas-cooled thermal breeder, which are based on an entirely different technology, may prove cheaper than the dominant LMFBR.

In the very long run, capital costs may be less important provided breeder reactors prove to last, say, 100 years or longer instead of the 30 to 40 years of today's reactors. Once an energy-producing device has been amortized, the cost of energy becomes largely independent of its original capital cost. If fuel and operating costs are low, then energy costs are correspondingly low. Dams are the best examples of very long-lived, low-operating cost prime movers that eventually produce very cheap energy. For example, the original low dam at Aswan continues to generate 200,000 kW of electricity at very low cost almost 90 years after the dam was completed. If reactors, solar energy systems, and fusion devices prove to be more "immortal" than we now deem them to be, they will, over their entire life-span, produce energy at much lower costs than those estimated at the time these devices were built. We see such a tendency in the trend toward life extension in relation to the oldest American reactors. Owners of reactors (as well as of other central generating plants) find it cheaper to refurbish old power plants than to build new ones. Indeed, the newest reactors are being designed for 60, rather than 40, years of life; and many parts of a reactor installation, for example the massive shields and the containment structure, should last much longer than 60 years.

Reactor Safety

At the beginning of the First Nuclear Era, we were aware that a high powered nuclear reactor could suffer a serious accident. Since we could not estimate either the probability of such an accident nor the consequences thereof, reactors were housed in containment structures. No matter what happened to the reactor, the radioactivity would be contained: the consequences would be "zero", and therefore the probability of accident was unimportant.

The first containment vessel, the 225 foot sphere that enclosed General Electric's Submarine Intermediate Reactor (SIR), was designed to prevent any radioactivity released in an accident from escaping. The SIR operated at 60 megawatts of heat, and short of an accident happening when the containment shell was inadvertently left open, the consequences of even the most severe accidents were "zero".

But commercial reactors, in order to compete with conventional power plants, had to be large—generating 200, 500, eventually 1,300 megawatts of electricity (.4,000 megawatts of heat). No longer could it be said with absolute certainty that a reactor melt-down would be contained, even with the stoutest containment systems then available. Thus the focus of reactor safety changed. Since we could no longer guarantee that *no* radioactivity would be released, no matter what happened to the reactor, we had to invoke probabilistic arguments. Yes, even a contained reactor might release large amounts of radioactivity, but if the *probability* of such a release was sufficiently small, nuclear reactors would still be regarded as safe. Thus was ushered in the era of probabilistic risk assessment. "Risk" was defined by F.R. Farmer[2] as the product of probability, P(C), of a release in an accident and consequences of the release, C:

$$R = P(C) \times C.$$

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[2] F. R. Farmer, Reactor safety and setting; a proposed risk criterion, *Nuclear Safety* 8, 539–548 (1967).

A reactor would be deemed safe "enough" if R, as estimated by say, fault tree analysis, was small "enough."

The prototype of probabilistic risk assessments was Prof. Norman C. Rasmussen's Reactor Safety Study, which was issued in 1975[3]. Although probabilistic risk assessment had been used in the aero-space industry, Rasmussen was the first to systematize the method and to apply it to nuclear reactors. Based on analyses of the Peach Bottom Boiling Water Reactor and the Surry Pressurized Water Reactor, Rasmussen estimated that the median probability of a melt-down in an LWR was 5×10^{-5} per reactor year (RY) with an uncertainty factor of ten either way. Most of these events would be relatively innocuous; the worst possible accident, causing 3,300 immediate fatalities and 45,000 delayed fatalities had a probability of 10^{-9} per reactor year. Since the Rasmussen study, probabilistic risk assessments on all American reactors have been mandated: the core melt probability of the reactors that have been re-analyzed have ranged from 10^{-3}/RY to 10^{-6}/RY. With 300 LWR reactors operating during the First Nuclear Era, the probability of a core melt, based on Rasmussen's estimate, is $300 \times 5 \times 10^{-5} = 1.5 \times 10^{-2}$/RY; is this acceptable? The Three Mile Island accident, (a melt-down with essentially no off-site consequences) occurred after 700 reactor years of operation of LWRs. Rasmussen has argued that the TMI-2 accident occurred at about the time predicted by his analysis. Since TMI-2, no light water melt-down with off-site consequences has occurred, although there have been narrow escapes. Again, this is not inconsistent with a median core melt probability of $\sim 5 \times 10^{-5}$/RY for the entire world's fleet of ~300 light water reactors. (I do not mention the Chernobyl disaster since it occurred in an uncontained, entirely different reactor—one for which a priori core-melt probability is higher than 5×10^{-5}/RY.)

We come back to the question: How safe is safe "enough"? Does a very low probability of accident compensate for very serious consequences? Were we completely consistent, I should say the answer is yes. We tolerate dams, which fail with a probability of $\sim 10^{-4}$/dam year, even if, as in the great Bai He dam failure of twenty years ago in China, some 200,000 people perished. We surely ought to tolerate industrial catastrophes whose likelihood is say, of the same order as the collision of a small asteroid with the earth—the Tanguska object struck in 1908 with an energy release of 10 Mtons of TNT. Yet the public's attitude

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[3] *Reactor Safety Study: An assessment of risks in U.S. commercial nuclear power plants,* Nuclear Regulatory Commission Report WASH-1400 (NUREG-75/014).

toward lotteries suggest that measuring risk, and therefore acceptable safety as P x C, ignores something deep within us. That the likelihood of winning, say, USD 10^7 in a lottery is much less than 10^{-7} simply does not deter people from buying a ticket. Would assurance that the probability of a major radioactive release is less than 10^{-7}/yr persuade the public to accept a nuclear reactor nearby? Judging from the extraordinary controversy surrounding the siting of nuclear reactors, I would judge that this is not the case. Put differently, a rebirth of nuclear energy will probably require a reduction in the probability of a melt-down, and, perhaps more important, a deterministic, nonprobabilistic cap with regard to the worst consequences of even the unlikeliest event.

Waste Disposal

Conant's pessimism about nuclear energy was based on his belief that the problem of radioactive waste disposal was intractable. And, as our experience in the United States has demonstrated, disposal of radioactive wastes is proving to be much more difficult than anticipated.

As I pointed out in my article twenty years ago, two different strategies have always been available. First, store the wastes above ground in carefully monitored, shielded structures; or second, sequester the wastes in geologically stable underground depositories. The first alternative would require perpetual surveillance (a nuclear priesthood?), and, by implication, a degree of institutional stability that we cannot count upon. Basically for this reason the United States, as well as the rest of the world, has opted for the second option, which requires minimal surveillance. But no-one seems to want a geological disposal site in his vicinity. The impasse between the Department of Energy and the State of Nevada over permission merely to characterize the proposed high level site at Yucca Mountain is placing strains on our constitutional federalism reminiscent of school desegregation if not of slavery. What would the Federal Government do if the State of Nevada used its police or National Guard to prevent the drilling of exploratory wells at Yucca Mountain?

Concerns over the safety of geological disposal of high-level wastes have little scientific basis. In this respect, waste disposal is different to reactor safety. A high-powered reactor generates enormous amounts of energy; in the worst accident, as at Chernobyl, huge amounts of radioactivity can be spread because there is an enormous driving force—the energy released in the accident—to spread the radioactivity. Large numbers of people can receive large doses of radiation in the worst accident. By contrast, the wastes, once they are encapsulated, produce little energy. A Chernobyl-type explosion is inconceivable, although a local release, say during transport, is not inconceivable. Small doses to many people through leaching, or large doses to a few people are not inconceivable: but large doses to large numbers of people are inconceivable.

Since all the exposures, say from leaching are low and are incurred at low-dose rate, the estimates of the number of cases of cancer caused by such inadvertency depend entirely upon what one assumes to be the dose-response at low dose and dose-rate. Despite 50 years of intensive investigation, the dose-response at such low levels of exposure remains uncertain. Even the latest report on Health Effects of Exposures to Low Levels of Ionizing Radiation, BEIR-V[4], though inclining toward a linear, no-threshold response at low dose, concedes that at doses of the order of background, there may be *no* health effects. In this respect we are hardly better off now than we were 20 years ago: the effects of low level radiation remain a matter of dispute. But even if one takes the most pessimistic dose-response—roughly one additional cancer for 10 person-sieverts, a geologic depository poses essentially no risk to the public.

Yet the public continues to view nuclear wastes with dread. For this reason Slovic[5] has recently argued that we will have to revert to the above-ground, monitored storage system—say for 100 years. The spent fuel would be kept on site so that transport of fuel will be avoided. Monitored retrievable storage is the Swedish strategy: spent fuel is being stored in an elaborate central storage installation (CLAB) at the Oskarshamn reactor site and will be kept there for at least 50 years. One can better contemplate social stability over say, a century, than over 10,000 years. Implicit in Slovic's suggestion is the hope that in the next 100 years, as the energy-environment crisis deepens, the public's attitude will change; and further, that scientific understanding of how to design "inherently safe" waste packages will improve.

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[4] Committee on Biological Effects of Ionizing Radiations, *Health effects of exposure to low-levels of ionizing radiation, BEIR V,* National Academy Press, (Washington, DC, 1990).

[5] P. Slovic, J. H. Flynn, and M. Layman, Perceived risk, trust, and politics of nuclear waste, *Science 254,* 1602–1607 (1991).

Proliferation

Nuclear people, though conceding that proliferation of nuclear weapons must be controlled, insist that the connection between nuclear power and nuclear proliferation is weak. A nation bent on proliferation would base its program on isotope separation of ^{235}U or on dedicated plutonium producing reactors, not on power reactors. The case of Iraq has borne out this contention: the Iraq program appears to have been based on calutron and centrifuge isotope separators and a research reactor, OSIRAK, that could convert slightly enriched uranium into weapons-grade ^{239}Pu. As long as there is no reprocessing, a power reactor cannot yield weapon material. Since the breeder, which requires reprocessing, produces electricity that is costlier than electricity from an LWR with no reprocessing, there is no economic incentive to build proliferation-prone breeder reactors. Of course this might change in the next century when uranium becomes scarce; but by then many political changes will be required if the proliferation of nuclear weapons is to be controlled.

Successes and failures of social institutions

That the safety of nuclear installations requires vigilance, responsibility and stability of the underlying social institutions is suggested if not demonstrated by the experience of these past twenty years. One reads Medvedev's[6] account of the accident at Chernobyl with horror as one realizes that the disaster there would not have happened had the "culture" of the Soviet nuclear enterprise more nearly resembled that of the West, with its more open self-criticism. Not that the Western nuclear culture had been without fault. The Three-Mile Island accident was surely avoidable—but at the time the utilities that operated reactors did not take seriously Rasmussen's warning that the probability of core melt was 5×10^{-5}/RY. (At a meeting in Gatlinburg, Tennessee, in 1978, when confronted with Rasmussen's prediction that an accident like TMI-2 was likely within the decade, the utility representatives at the meeting seemed unaware of the implications of this prediction.)

TMI-2, and even more, Chernobyl, have caused the nuclear culture to change. The Institute for Nuclear Operations, INPO, was founded to facilitate transfer of information between different reactors and to establish standards of performance for reactor operators and owners. And, after Chernobyl, the World Association of Nuclear Operators

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[6] E. Medvedev, *The truth about Chernobyl,* Basic Books, New York (1991).

now links essentially all of the world's power reactors in a network that promotes exchange of information and establishment of world-wide performance standards. These nuclear-operator instigated institutions are in addition to the International Atomic Energy Agency (IAEA) and the various national nuclear regulatory bodies, such as the U. S. Nuclear Regulatory Commission.

How the former Soviet nuclear enterprise will survive the vast political changes going on there is not clear. Ukraine has recently announced that it will close the three undamaged reactors of Chernobyl; the reactors in the former East Germany are also to be closed because they do not conform to West German safety standards.

Despite the extraordinary political instabilities and changes of the past few years, there has been no nuclear disaster directly attributable to these social instabilities. Even in the face of war, the Vietnamese research reactor at Da Lat, the Slovenian reactor at Ksrko, and the Israeli reactor at Dimona have not been damaged, although the OSIRAK reactor was destroyed by Israel before it went critical. Nevertheless, vigilance and continuity on the part of those responsible for the reactors will surely be required if the nuclear enterprise is to continue.

Should there be a second nuclear era?

Fission is a fluke of nature; the emission of more than one neutron per fission, a requirement for a chain reaction, is even less foreordained by some cosmic principle.

What would the world have done had Fermi's chain reaction of December 2, 1942, been impossible? (Eugene Wigner in his memoirs says that in 1935, when Szilard had patented a neutron-based chain reactor, even though fission had not been discovered, Wigner decided that there was no fundamental law of physics that precluded a neutron chain reaction)[7]. One can hardly believe that society would perish were chain reactions impossible. Other sources of energy plus conservation would be exploited more fully. After all, fission energy provides only 6 percent of the world's total energy—hardly an amount that, one way or another, the world could not do without.

Yet in the long run I believe it is imperative to pursue, even to expand the use of nuclear energy. The primary reason is the inexorable growth

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[7] *The collected works of Eugene Paul Wigner, Volume V, Nuclear Energy,* Edited by A.M. Weinberg (Springer-Verlag, Heidelberg, 1992).

of world population, especially in China and India, and with it the corresponding increase in energy demand, particularly in the developing countries. In China, transport of coal now accounts for 60 percent of all rail traffic; energy analysts in PRC see difficulties in expanding the coal transport system to keep up with the expected energy demand. Other energy sources, including nuclear, will probably be needed.

The ultimate case for continuing the nuclear enterprise is the increase in CO_2. The atmosphere contains 750 Gtons of carbon as CO_2. The total fossil fuel yet to be recovered is estimated at about 200×10^3 quads, containing about 4,000 gigatons of carbon. If all fossil fuel were burned, the carbon content of the atmosphere could be increased three-fold or more.

Would this be a catastrophe? That the added CO_2 would cause a warming unprecedented in geologic history is the belief of most climatologists who have studied the matter, but some experts disagree.

On the other hand, all agree that continued burning of fossil fuel changes the chemical composition of the atmosphere. Freeman Dyson in 1976 was the first to insist that such CO_2 fertilization of the atmosphere would alter ecological balances among plant species. Some argue that on balance this fertilization would be desirable. Others, such as F.A. Bazzaz of Harvard, warn that there will be derangement of the ecological balance, and the new equilibrium between competing plants may be undesirable. Given the vast ecological implications of increased CO_2 in the atmosphere, it would be prudent to limit the burning of fossil fuel during the coming century.

Should solar energy or fusion become available at an affordable price, let us by all means use them. But until these sources have been demonstrated, simple prudence dictates that nuclear energy be deployed on a massive scale. Prof W. Haefele[8] suggests a deployment of some 2,500 large reactors by the middle of next century; I suggest 5,000 would be needed to stabilize CO_2 at say, 1,000 gigatons of carbon in the atmosphere.

Technical fixes for a 5,000 GWe nuclear system

Were the median coremelt probability to remain at 5×10^{-5}/RY, we would expect a serious core melt every four years in a 5,000 GWe nuclear world. This is probably unacceptable. Thus a deployment of

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[8] W. Haefele, Energy from nuclear power, *Perspectives in Energy 1, 13–40* (1991).

nuclear reactors large enough to affect the equilibrium CO_2 content in the atmosphere will require significantly lower core melt probability per reactor than that estimated by Rasmussen.

What would be an acceptable core melt probability in such a nuclearized world? If one melt per century were accepted (remember the Tanguska meteorite fell in this century), the core melt probability per 1,000 GWe reactor cannot exceed 2×10^{-6}/RY. But only 1 in 10^4 of Rasmussen's core melts are major catastrophes; if one assumes that core melts every four years are acceptable, but major catastrophes are acceptable only once in a century, existing reactors ought to be acceptable even in a CO_2-sparing nuclear world.

Both the core melt probability and the consequences will undoubtedly be reduced by newly designed reactors. As for reducing the core melt probability, TMI-2 and even more, Chernobyl, have sent reactor designers back to the drawing board to design more forgiving, even "inherently-safe" reactors. Though the notion of passive safety in reactors was received with suspicion when it was first brought forward by P. Fortescue in the United States, K. Hannerz in Sweden, and H. Reutler and G. Lohnert in Germany, the idea is now well accepted. There are many proposed reactors that depend in varying degree upon passive safety systems. These range from the PIUS and the modular-HTGR, which depend almost entirely upon passive safety systems, to the Advanced Boiling Water and Advanced Pressurized Water Reactors that are improved LWRs. Altogether about a dozen different designs have been put forward in response to a perceived need for a reactor that is less subject to core melt than 5×10^{-5}/RY, and that is perceived by the public as embodying passive safety.

As for reducing consequences, Haefele suggests that were it possible to place a cap on the very worst possible reactor accident, so that "major" catastrophes were ruled out altogether, nuclear energy would become acceptable. After the TMI-2 accident, much effort was spent on determining the "Source Term" in a core melt. Why did less than 20 curies of ^{131}I escape from the containment, even though several million curies escaped from the core? The conclusion reached by the so-called IDCOR[9] study was that the water vapor released after an accident tended to cause I and Cs to plate out inside the containment. In other words, Rasmussen had greatly exaggerated the source term, and therefore the consequences, in his worst accident.

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[9] *Nuclear power plant response to severe accidents,* a report of the Industrial Degraded Core Rulemaking Program (IDCOR), 1984.

But Rasmussen did not consider catastrophic failure of the pressure vessel—an event that is most unlikely but not quite impossible. In this case the containment would fail, and the source term might be large. This has led to attempts to design containments that are strong enough to withstand a catastrophic rupture of the pressure vessel in an LWR. What is being proposed is a technical fix: a design that is catastrophe proof. This idea has also been promulgated by Rustum Roy for encapsulation of radioactive wastes: put the wastes in a form that is chemically—that is, thermodynamically—stable against attack by the fluids that might invade the depository. One depends much less on geology, which is somewhat unpredictable and more on thermodynamics to guarantee safe waste disposal. This idea is embodied in the copper canisters proposed to contain high level waste in Sweden. (The proposed disposal site contains native copper—prima facie evidence that copper canisters would be stable in the Swedish repository.)

Technical fixes and social institutions

If our institutions have not always been up to the challenge of nuclear energy, yet for various reasons nuclear energy must be widely deployed, our society has two choices: first, fix the institutions; and second, change the technology so that it becomes acceptable even if the social institutions remain deficient.

I have already spoken of various improvements that have been made in the management of the nuclear enterprise in the wake of TMI-2 and Chernobyl: INPO, WANO, and IAEA are more attuned to nuclear safety. Though we can never say that these changes preclude the possibility of a core melt with significant off-site release, the record since the TMI-2 accident has been encouraging: 3,000 reactor years of operation of Light Water Reactors without another "class-9" accident (core melt with serious off-site consequences). We nuclear people realize that another TMI-2 might spell the end of nuclear energy, and all effort must be expended toward maintaining the highest standards of operation and maintenance of the existing fleet of reactors. (I must confess that this is pretty much what I said in 1972, six years before TMI-2.) The burden of proof falls on the operators of the world's reactors. Unless they can keep the existing fleet out of trouble, nuclear energy will falter.

A world-wide deployment of many thousands of nuclear reactors, even passively safe reactors, will require much stronger institutions to deal with weapons proliferation. I am unable to say just what institutional structures will be necessary. A most obvious possibility is that the IAEA will acquire even greater status and power than it now has. The strengthening of the IAEA as a result of the Gulf War, and the revelation of Iraq's nuclear weapons program, is an example of how the social institution charged with responsibility for monitoring and regulating the non-proliferation regime, has responded to a threat to that regime. Indeed, the right and power of IAEA to inspect even undeclared nuclear facilities probably ought to be formally recognized by a strengthened non-proliferation regime. But such changes can hardly be foreseen outside the world political context. As President Bush's New World Order, with its decline of national sovereignty develops, I would expect super-national agencies like IAEA to extend their control over the world's nuclear system.

The new, passively safe technologies, place fewer demands on the social institutions responsible for building, operating, and maintaining the nuclear enterprise. These technologies are very promising, but none of the new generation of reactors have been built. I have therefore advocated a new major R&D effort, similar to the effort launched in the 1950s at the beginning of the nuclear era, to build several experimental prototypes of passively safe reactors. By the turn of the millennium we could then judge better whether the passively safe systems work as designed, and whether they can allay the public's fears about nuclear energy.

Will there be a second nuclear era?

In a way this is an irrelevant question. After all, the first nuclear era has *not* ended everywhere. Japan, for example, is building large advanced LWRs, while there are as yet no specific plans to build the newer, passively safe reactors. Moreover, the U. S. utility industry has recently published a plan to begin deployment of the new reactors by 1996. So the Second Nuclear Era may emerge rather smoothly as a continuation of the First Nuclear Era, with the newer reactors being evolutionary modifications of existing reactors with some passive safety, rather than revolutionary, almost entirely passively safe reactors.

But what the future holds for nuclear energy surely depends on the public's attitude. This was first expressed by Enrico Fermi in 1944, almost 50 years ago. At a meeting (which I attended) of the New Piles Committee at the Chicago war-time Metallurgical Laboratory, Fermi expressed the matter in words something like this, "We are creating radioactivity on a massive scale for the first time in human history. It is not clear whether the public will accept an energy source that produces so much radioactivity." Will Fermi's doubts, or more, Conant's prediction of nuclear energy's failure prove correct? Or will our human ingenuity, exemplified by the new generation of nuclear reactors, the greatly improved institutional framework for the nuclear enterprise—and indeed, George Bush's New World Order with its sanctions, even military sanctions, to prevent nuclear proliferation, be sufficient to persuade the public to accept energy from uranium? We nuclear people, despite the buffeting we have received during the First Nuclear Era, are convinced that our ingenuity is equal to the challenge, and that there will be a rebirth of nuclear energy in the 2000s.

Accelerator-Reactor Combination to Reduce Nuclear Waste

Professor Karl-Erik Larsson

Introduction

Nuclear power was introduced 50 years ago under war conditions, in strict secrecy and without any public interference. It was a question for experts and selected scientists. Today after 30 years of commercial nuclear power, the situation is reversed. We live in an open society. Even technological leaders have to listen to public opinion. If political leaders do not listen to public opinion their power position will be short-lived.

The same is probably true for technical applications of scientific discoveries in our times. If a technology does not gain public acceptance, it is dead.

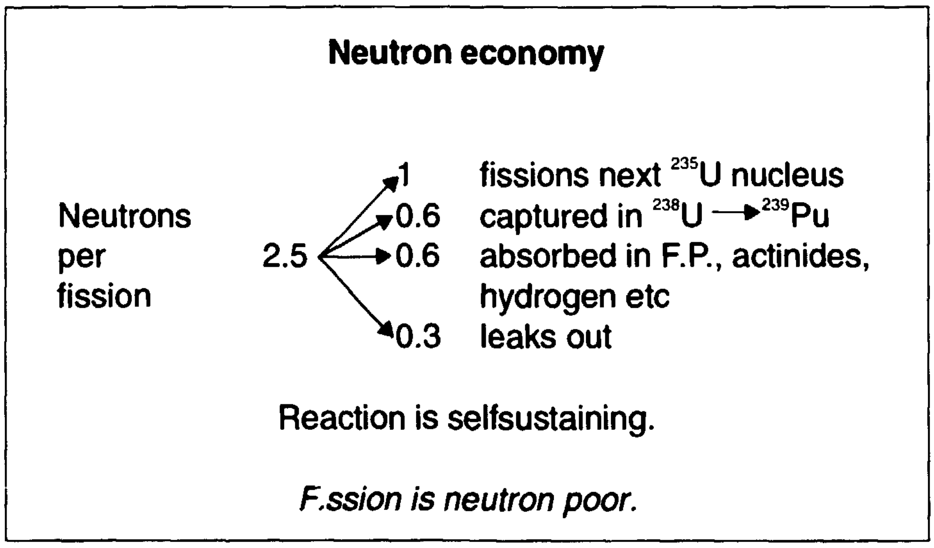
Of the various post-war high-technology ventures, nuclear power development has become the primary target of public discussion and suspicion. If we limit these considerations to the peaceful uses of nuclear power, the basis for public concern and suspicion is two-fold:
(1) high-level long-lived radioactive waste and
(2) the fear of a possible big reactor accident resulting in the spreading of large amounts of radioactive and poisonous materials over large areas.

The representatives of nuclear power production do all they can to eliminate these fears both physically and psychologically within the framework of present reactor generation. But unfortunately the Chernobyl accident and Harrisburg have happened and the nuclear waste is there.

Shortcomings of current nuclear power generation

The basis for the nuclear chain reaction is that about 2.5 neutrons are released per fission. Because the reaction is selfsustaining only 1.5

Figure 1 illustrates that the 2.5 neutrons released per fission are not enough to simultaneously keep the chain reaction going, breed new fissionable material, fission other actinides and transmute long-lived radioactive fission products.



neutrons are available for capture in fertile uranium-238 (^{238}U) converting it to fissile plutonium-239 (^{239}Pu), capture in fission products, actinides, hydrogen in water etc., and for leaking out *(figure 1)*. The available neutrons are too few to produce breeding and to transmute highly radioactive fission products or to fission actinides. What can be done in this respect in the thermal neutron fluxes of maximum 10^{14}n/cm^2/s in present day reactors is already done when the used fuel is removed from the reactor. This leads to the annual production of certain waste products in a standard power reactor of 3,000 MWt as indicated in *tables 1 and 2*. Out of all fission products about 10 percent have long half-lives. These products form the long-lived radioactive waste problem as indicated in *figure 2*.

For economic reasons, the power requirement is large and as the allowed fission rate per unit volume is limited for technical reasons, the reactor volume is large containing about 100 tonnes of uranium. And because fuel rods are an expensive item a high burn-up of its uranium contents is required. The fuel has to stay in the reactor for two to three years. This means that the reactor contains large amounts of highly radioactive waste products—tonne quantities. Due to material limitations (radiation damage) the burn-up is limited to a few percent, say 3–4 percent, of the total uranium contents of about 3 percent enrichment of uranium-235 (^{235}U). Depending upon the type of reactor, boiling water or pressurized water, the reactor vessel and pipelines are exposed to internal pressures of 70–150 bars with a corresponding risk for vessel or pipeline rupture.

*Table 1. Transuranium waste nuclei from a PWR**

Plutonium Isotopic Mixture

Nuclide	kg/yr	Halflife (yrs)	Atoms (x 10^{25})
^{238}Pu	4.52	88.	1.13
^{239}Pu	166	2.4 x 10^4	41.6
^{240}Pu	76.7	6.6 x 10^3	19.2
^{241}Pu	25.4	14.4	6.4
^{242}Pu	15.5	3.8 x 10^5	3.9
		Total	8.65 x 10^{25}

Higher Actinide Mixture

Nuclide	kg/yr	Halflife (yrs)	Atoms (x 10^{25})
^{237}Np	14.5	2.1 x 10^6	3.66
^{241}Am	16.6	432.	4.13
^{242m}Am	0.022	141.	
^{243}Am	2.99	7.4 x 10^3	0.73
^{243}Cm	0.011	28.5	
^{244}Cm	0.58	18.1	0.13
		Total	8.65 x 10^{25}

* These amounts are annual production after ten years of decay for a PWR running at 3.0 GWt with fuel burned to 33,000 megawatt-days per metric ton requiring the removal of 33 MTU spent fuel per year.

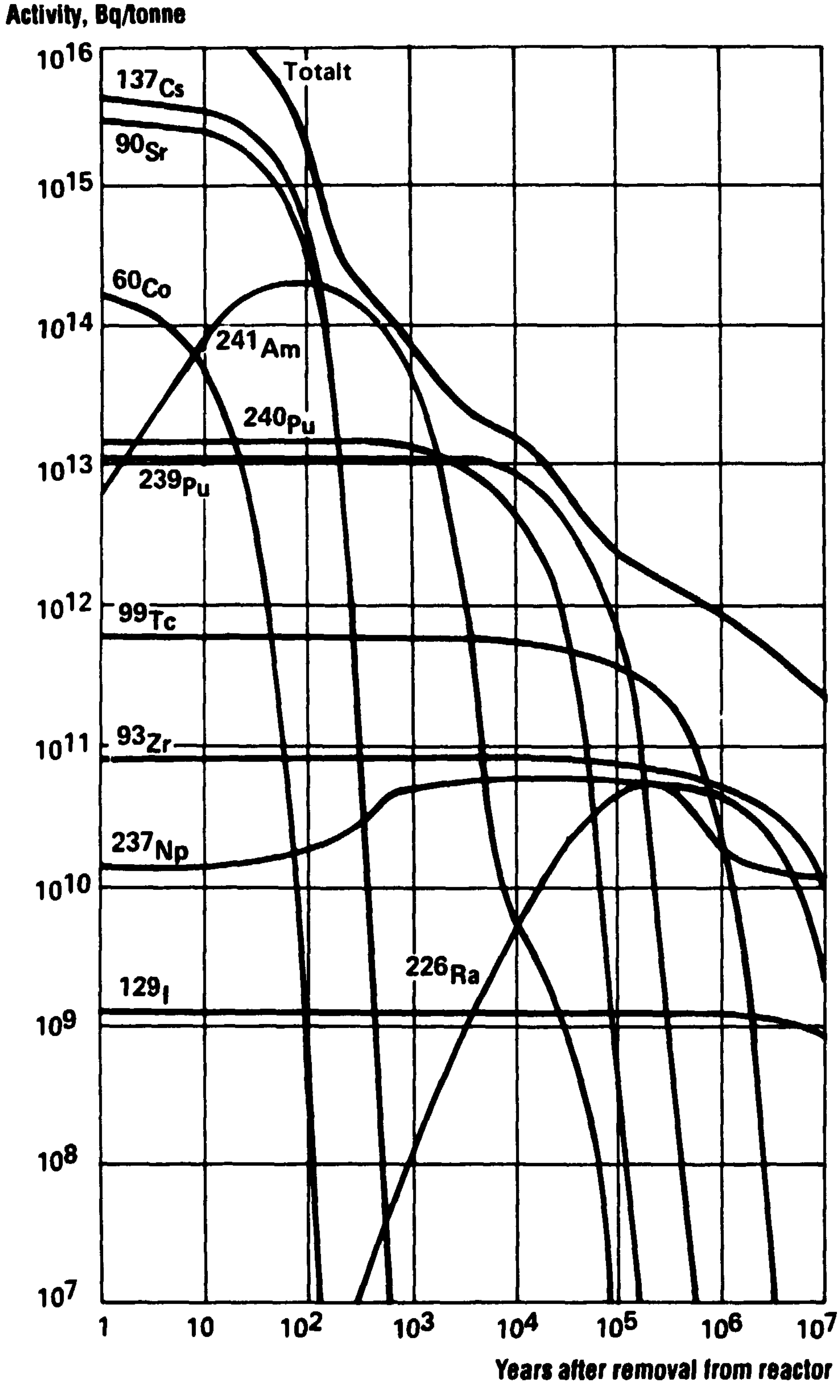
*Table 2. Comparison of Fission Product Production Rates***

Nuclide	$T_{1/2}$	^{238}U	^{239}Pu	PWR
	(yrs)	(Atoms/yr x 10^{25})	(Atoms/yr x 10^{25})	(Atoms/yr x 10^{25})
^{79}Se	6.5 x 10^4	0.32	0.10	0.13
^{86}Kr*	10.7	1.0	0.22	0.26
^{90}Sr	28.8	15	4.4	9.0
^{93}Zr	1.5 x 10^6	17	9.3	15
^{99}Tc	2.1 x 10^5	12	15	15
^{107}Pd*	6.5 x 10^6	0.27	17.8	4.1
^{126}Sn	1 x 10^5	0.64	0.64	0.46
^{129}I	1. 6 x 10^7	3.5	3.0	2.7
^{136}Cs*	3 x 10^6	15	18	4.2
^{137}Cs	30	17	17	14
^{151}Sm*	90	0.79	1.9	0.16

* Transmutation is not necessary for these.

** These amounts are annual production after ten years of decay for a PWR running at 3.0 GWt with fuel burned to 33,000 megawatt-days per metric ton requiring the removal of 33 MTU spent fuel per year.

Figure 2. Radioactivity of various isotopes as a function of time after removal from the reactor core. Time measured in years. Neptunium-237, plutonium-239 and -240 and americium-241 are actinides. Cesium-137, strontium-90, technetium-99 and iodine-129 are fission products.



To sum up, the list of major shortcomings in the present nuclear reactor concept may look as follows:

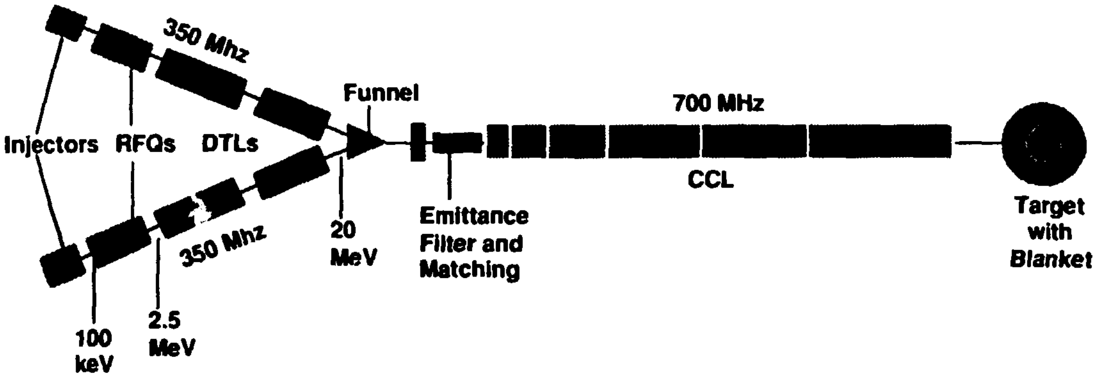
1. Only about 1.5 percent of natural uranium is burnt in Once-Through-Reactors
2. Long-lived radioisotopes are left as nuclear waste.
3. Reactors contains large amounts of radioactive products.
4. Residual heating of reactor cores requires emergency core cooling.
5. Self-sustaining chain reaction leads to possibility of reactor excursion.
6. Reactor systems operate at high overpressure, 70–150 bars.

It should be remembered that used fuel is often called *waste* which is not correct. Typically only 3 percent of used fuel is waste. The rest is potential nuclear fuel.

New possibilities of waste transmutation and fission energy production

It is obvious that the basic fault with the driving mechanism in current nuclear reactors is the inadequate neutron production per fission. This number can however be enhanced by combining the fission process with the spallation process produced when high-energy protons strike targets of heavy atoms like lead or tungsten. A proton of 1,600 Mev of energy may give rise to as many as 50 neutrons. Normally proton currents in for instance linear accelerators have been limited to about 1 milliampere. With recent technical developments it has been announced that currents of the order of 100 milliamperes may be produced. Such a proton beam represents a power of the order of several hundred megawatts. This proton current hitting a lead target would produce a neutron source of a strength of 10^{20} n/s. If such an intense source of fast neutrons is surrounded by a blanket of a good moderator like heavy water or graphite a very high thermal neutron flux, up to the order of 10^{16} n/cm^2/s, will be set up *(figure 3)*. As the rate of any nuclear reaction in a flux of neutrons is proportional to the product of concentration, N, of nuclei, the crossection, σ, for reaction and the neutron flux, ϕ, it means that the transmutation rate by neutron capture or fission will be very high. The half-life for transmutation is proportional to $0.7/\phi\sigma$. So if the blanket is loaded with either radioactive waste products or with fissionable materials like the actinides, rapid transmutation will take place. Also it is clear that fertile materials like thorium-232 (^{232}Th) or ^{238}U may be converted to the fissile materials uranium-233 (^{233}U) or ^{239}Pu, respectively, by irradiation in this blanket.

Figure 3. Concept of accelerator, target and blanket. Acceleration energy between 800 and 1,600 Mev, proton current 100–200 milliamperes, length of accelerator 400–1,600 meters depending upon degree of sophistication of technology.



By combining the nuclear sciences of fission and spallation and the technologies of nuclear reactors and accelerators a new concept of waste destruction and simultaneous fission energy production is born (ATW). The principle of such an accelerator-driven nuclear system is outlined in *figure 4*. The system consists of five parts:

1. Accelerator.
2. Spallation target.
3. Blanket for transmutation, breeding and energy production.
4. Chemical separation plant.
5. Energy extraction and electrical power production unit.

The high *thermal* flux of neutrons, 10^{16}n/cm^2/s, set up in the blanket dramatically shortens the half-lives of both actinides and fission products *(figure 5)* as compared to the situation in a normal present-day power reactor with flux of order 10^{14}n/cm^2/s. Actinides like neptunium-237 (^{237}Np) or americium which in current reactors act as neutron absorbers will in the accelerator-boosted machine act as nuclear fuel and produce extra neutrons *(figure 6)*.

A remarkable effect of the high thermal neutron flux is that a very low actinide concentration of the order of 0.1 volume percent leads to a maximum actinide transmutation rate *(figure 7)*. Therefore the total inventory of actinides in the blanket which is *operated at under-critical level* (multiplication constant k~0.8–0.9) is as low as about 100 kg. If transmutation were to be performed in a fast reactor system, as has been customary, the actinide loading would be a hundred times as high, of the order of 10,000 kg. Also, in a fast reactor fuel, pins are irradiated

Figure 4. Principle parts of an accelerator-driven transmutation and fission energy producing system. Long-lived actinides and fission products in, stable or short-lived residual products out.

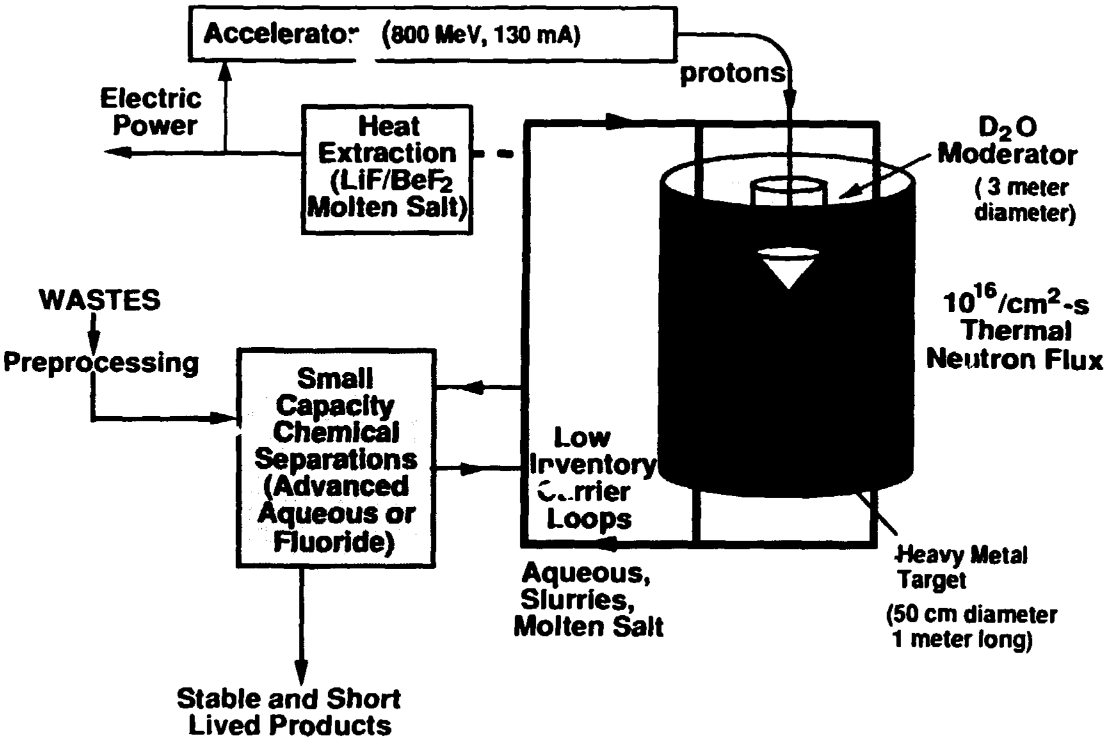


Figure 5. Effective half-lives of some important fission products and actinides as a function of the neutron flux to which they are exposed. Observe particularly the difference between 10^{14} and 10^{16} values of half-lives.

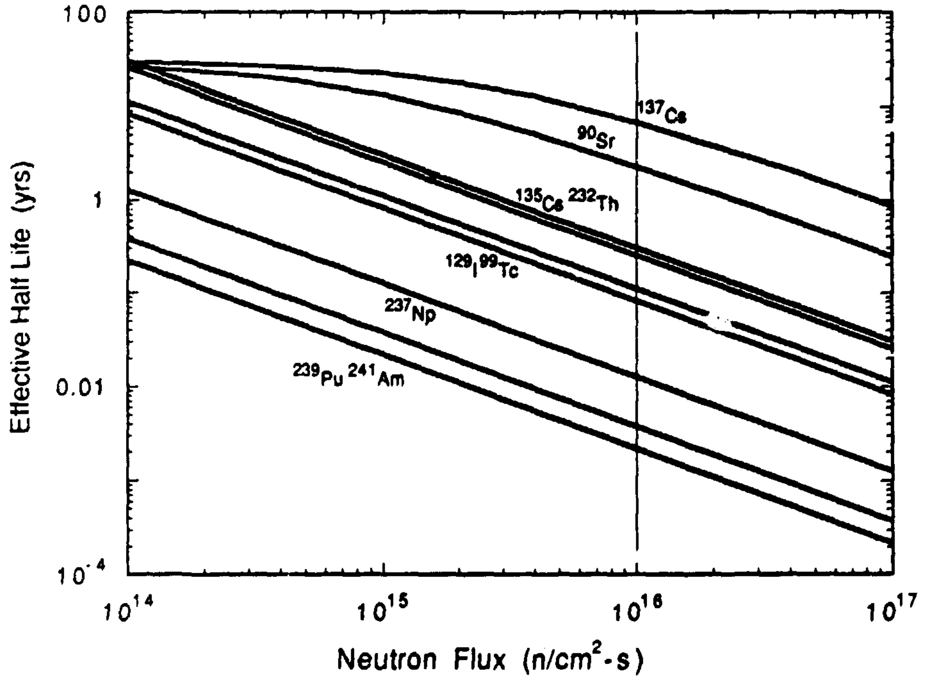


Figure 6. Illustration of destruction of neptunium-237 in a flux of 10^{14} n/cm^2/s requiring three neutrons (the long zig-zag route) and in a flux of 10^{16} n/cm^2/s requiring two neutrons (the short straight route). In both cases about 2.8 neutrons are released in the final fission process. So therefore in the lower flux neptunium acts as a net absorber, in the second case as a net neutron producer. The reason is given by the factors giving the half-life for transmutation: half-life=0.7/ $\phi\sigma$.

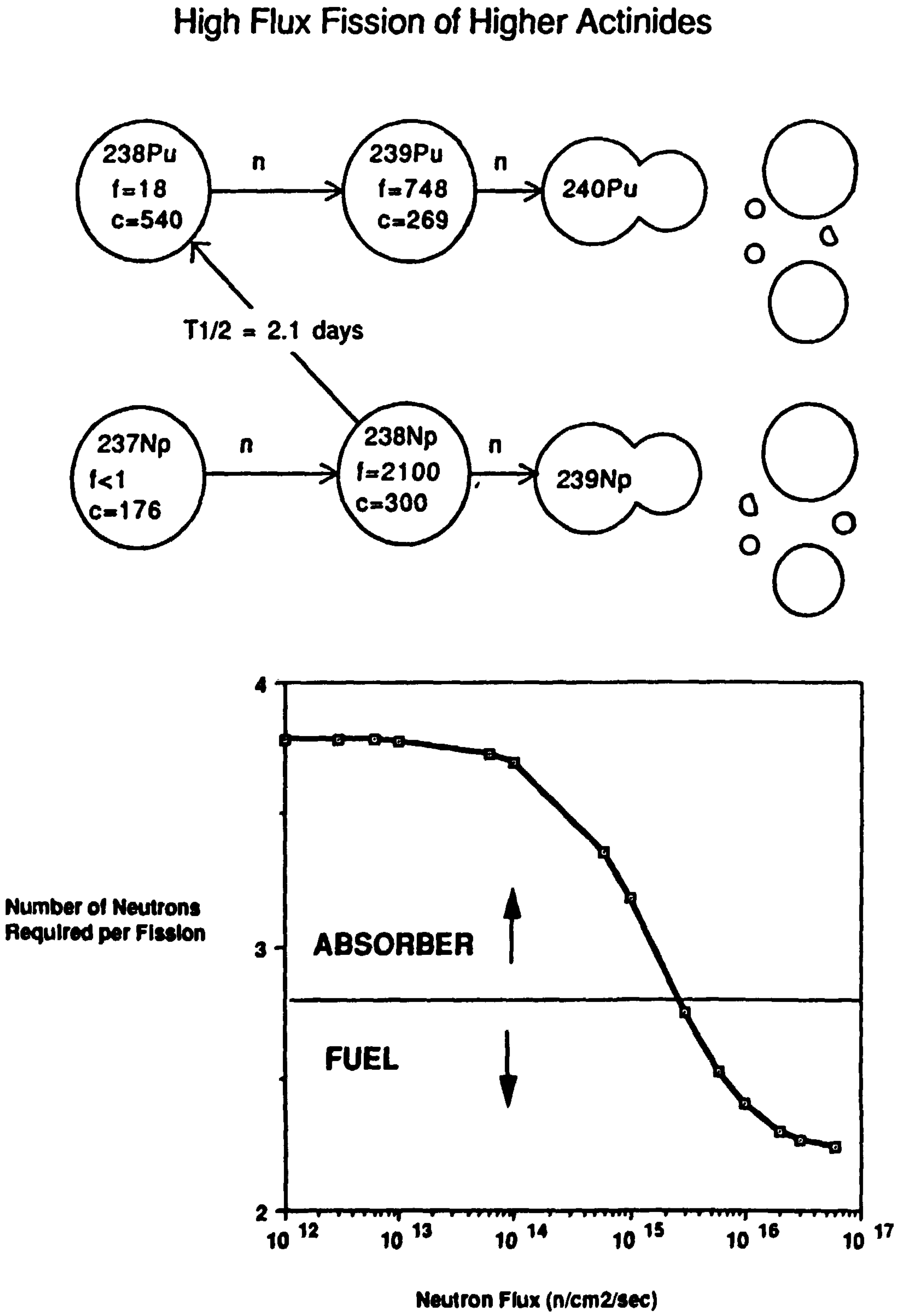
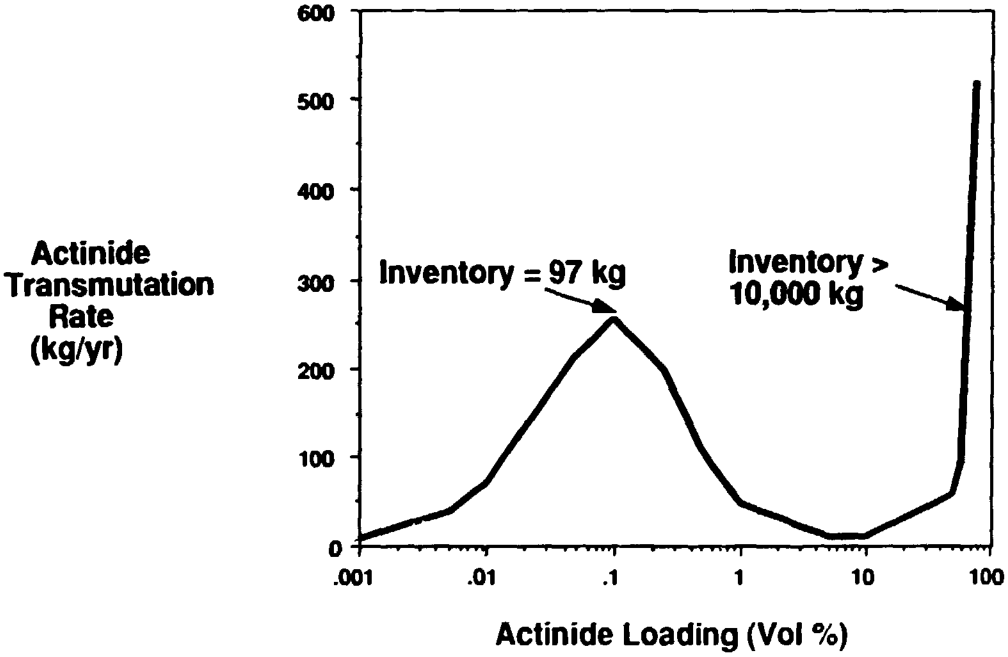


Figure 7. Under conditions of the current very high thermal neutron flux, a maximum rate of transmutation of an actinide material is found to occur at very low concentration of this actinide in the high flux region. Calculation shows that at an actinide loading of 0.1 volume percent when the inventory in the core is 97 kg the transmutation rate is about 270 kg/year. For higher concentrations of the actinide, the transmutation rate goes down due to self-screening. The high inventory of more then 10,000 kg at very high actinide loading corresponds to the situation in a fast reactor system in which transmutation is brought about by fast



for long periods in a static arrangement as in present day PWR- or BWR-types of power reactors. In contrast, in the high flux blanket the substances under irradiation have to pass through this reaction region as fluids at good speed. There are no fuel pins. The present fuel fabrication plant is replaced by a chemical separation plant. Such a plant should normally be a part of any nuclear power plant to make full use of the various products present in used fuel, of which 3 percent may be true fission products, less than 1 percent plutonium isotopes, about 0.1 percent other actinides like neptunium, americium, curium and 96 percent uranium not used at all. The optimum use of nuclear fuel existing in nature or produced in reactors is a chemical problem. To make the nuclear enterprise a sustainable energy source not leaving any appreciable quantities of long-lived radioactive waste to future generations, the chemical problems must be solved.

In order to shed further light on the different capabilities of fast neutron systems reactors or of accelerator-driven and intense thermal neutron systems like the present ATW-system, the effective half-lives for transmutation in these two systems are given in *table 3*. The superiority of the intense thermal neutron flux is evident.

In a future symbiotic accelerator-reactor system the principle of operation could then be as indicated in *figure 8*:

The reactor part consists of three concentric cylinders, with an outer diameter of the order of four meters. In the outer region, preferentially ^{232}Th (^{238}U is possible but it produces ^{239}Pu which is not desirable for several reasons) in the form of a solution of a salt is irradiated. It is quickly circulated to the associated chemical plant where the transmutation product is separated out. It gives the newly bred fuel, ^{233}U. The untransformed material is circulated back to the irradiation volume. After some time the ^{233}U is made to form a fluoride compound to be mixed with fluorides of beryllium and lithium-7. This fluoride mixture

Table 3.

Fast neutron systems (reactor or accelerator-driven)

- Difficulty in fission product transmutation
- Large inventories required
- Reactivity control concerns for high-flux reactor systems

Effective half lives for a flux of 4x10^{15} n/cm^2/s

Radionuclide	σ (Trans) (b)	Effective $\tau_{1/2}$(yrs)
^{239}Pu	2	2.7
^{237}Np	2	2.7
^{99}Tc	0.2	28
^{137}Cs	0.025	26

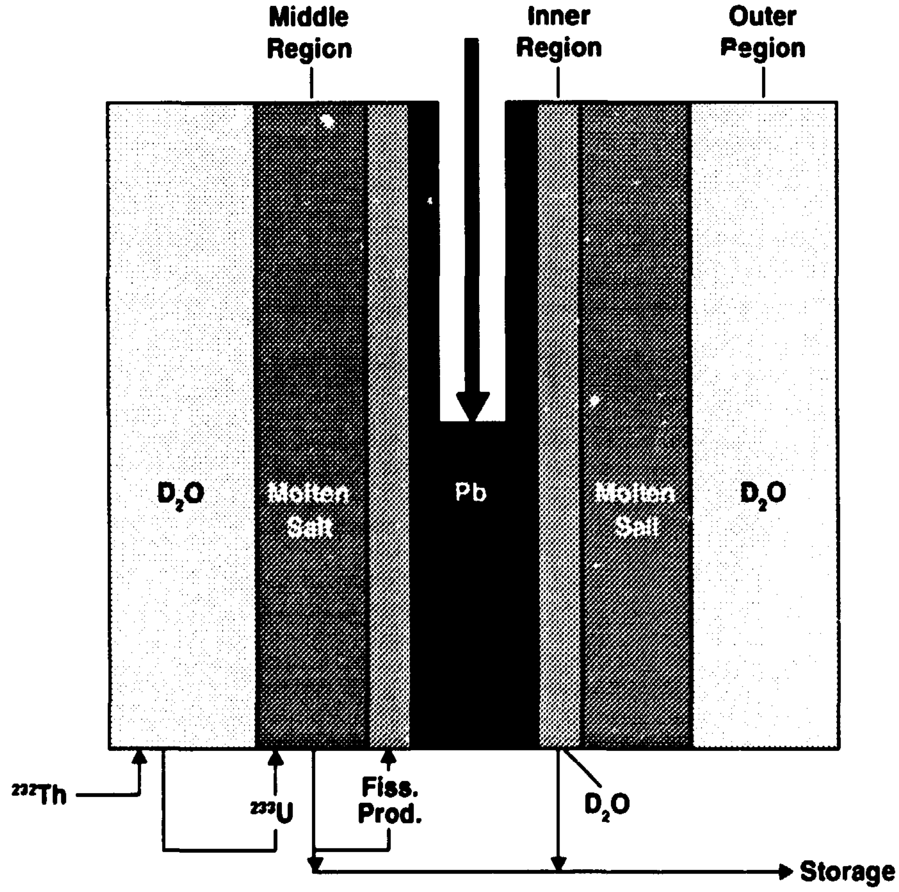
Intense Thermal Neutron Flux

- Rapid burning of low-cross section radionuclides
- Two-step fission of higher actinides
- Low inventory, high throughput system
- Smaller capacity chemistry separations

Effective half lives for a flux of 1x10^{16}n/cm^2/s

Radionuclide	σ (Trans) (b)	Effective $\tau_{1/2}$(yrs)
^{239}Pu	750	0.003
^{237}Np	(35)	0.06
^{99}Tc	20	0.15
^{137}Cs	0.25	2.9

Figure 8. Function of the target-blanket: outer region for breeding new fissile fuel, middle region for burning this fuel, inner region for transmutation of long-lived fission products. Short-lived or stable products to storage.



is passed into the middle region of the reaction vessel in the form of molten salt, say at 550 °C. ^{233}U undergoes fission, the salt is heated up and is transported out at over 700 °C to heat exchangers where hot steam is generated and used for electrical power generation in the normal way. The molten salt flows further to the chemical plant where fission products are continously separated out. Long-lived products are circulated for instance in slurry form to the innermost region of the blanket, where after repeated circulation they are transmuted to short-lived or stable products. The system is a thermal breeder which distroys its own long-lived waste products. We notice that the reaction region is under critical levels, so no reactor excursion of Chernobyl-type is possible.

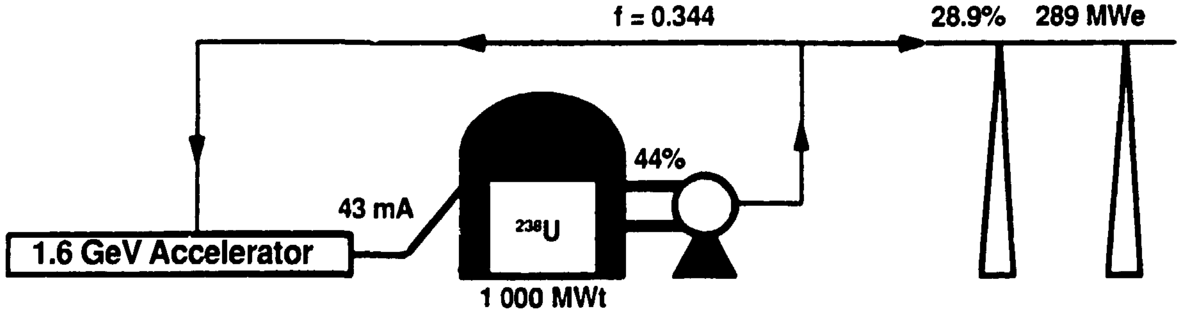
Assuming all problems solved, it would be possible to produce nuclear fission power derived from neutron economy alone as illustrated in *figure 9*. One accelerator could operate a bigger blanket unit or several smaller ones if the accelerator current were kept at 100–200 milliamperes. It is seen that the net efficiency of the system for delivery of electric energy to the grid is of the order of 30 percent.

It has been estimated (compare *figure 10*) that one accelerator driving five blankets could in principle burn all actinides, transmute the most important long-lived fission products and breed a smaller amount of plutonium from ^{238}U coming from ten present-day power reactors of 3,000 MWt each at the same time delivering about 4,000 MWe to the grid (compare *table 4*). This means that one such system should be able to transmute and fission the undesirable waste products created annually in a present-day nuclear power system of 10,000 MWe.

It can be shown that the reason for such an outcome is that the combination of fission and spallation processes enhances the effective number of neutrons per fission from 2.5 to 3.8, that is, a 50 percent increase.

Figure 9. Performance of accelerator-transmuter derived from neutron economy for the two possible cases of breeding.

1. Energy Production from ^{238}U Without Long-Term Fission-Product Storage



2. Energy Production from ^{232}Th Without Long-Term Fission-Product Storage

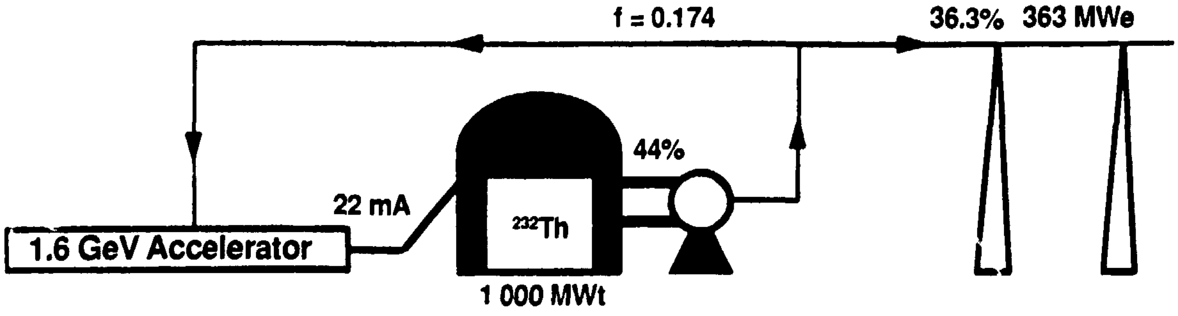


Figure 10. Energy park for waste transmutation. Ten ordinary present-day reactors deliver used fuel to partitioning plant. In a steady-state situation the five blankets operated by one accelerator burn the actinides and transmute the long-lived fission products at the same rate as they are produced in the ten reactors. By breeding a smaller amount of the ^{238}U *present in the used fuel the net result is that the transmuting system also delivers 4,200 MWe to the grid.*

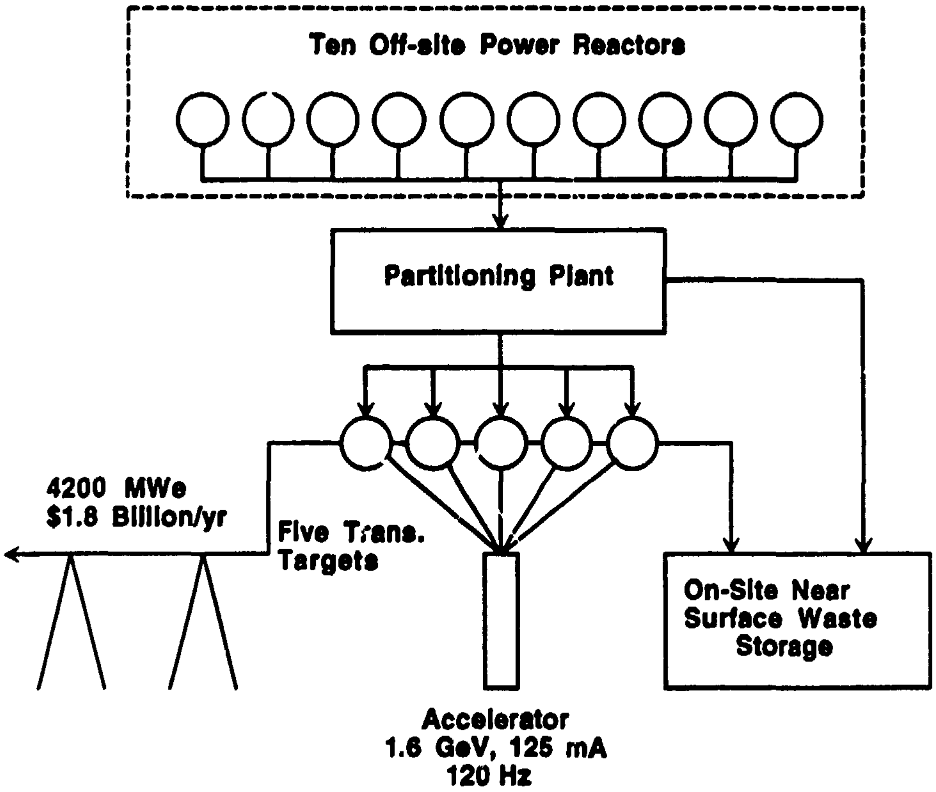


Table 4. Burn-up of commercial actinide and fission product waste

Number of target-blankets driven	5
Acc. current per target-blanket at 1.6 GeV	25 ma
Pu isotopic mixture transmuted	580 kg/yr
Higher actinide mixture transmuted	70 kg/yr
^{238}U burned as plutonium transmuted	185 kg/yr
Fission products (30-year delay) trans.	130 kr/yr
Blanket fission thermal power	2,120 MWt
Electric power to grid per target-blanket	840 MWe
Total electric power to grid	4,200 MWe
Percent power to accelerator	10%
Percent loss of neutrons	13%
k_{eff}	0.81
Number 3-GWt reactors per 125-ma acc.	10

A new nuclear future?

Irrespective of what nuclear experts may say in terms of "objective" information to the public, the main concerns of this same public regarding nuclear energy production are of two kinds:
(1) the ethical problem associated with the existence of very long-lived radioactive waste and
(2) the non-zero risk for a big reactor accident like that at Chernobyl.

These concerns are real and have to be considered seriously by the nuclear community. It may be speculated that nuclear power has no future if the physical origin of these basic concerns cannot be removed. The public demanded that the nuclear power enterprise should be more "human". By this is probably meant that human mistakes cannot be avoided and must therefore be acknowledged. With this in mind it is clear that in principle there should not be any radioactive waste of importance left with long half-lives. It should preferably be destroyed within one generation of human life. Also a reactor excursion or core melt down should not be possible.

It seems that ideas like the accelerator-driven concept could open *one* door—at least slightly—to this new and better nuclear world. The properties of the ATW-system just discussed may be summarized as follows:

1. "Unlimited" nuclear energy source.
2. Reacting system safe. No prompt criticality possible.
3. Limited cooling problems. No core melt down problem.
4. Long-lived radioactive residual products reduced by several orders of magnitude.
5. Always small amounts of actinides and fission products in reacting volume.
6. System operates at low pressure.

To this may be added that if the thorium-uranium cycle is used the risk for military abuse of the system is minimized.

If those nations using nuclear power, peaceful and military, were willing to mobilize an effort of research and development of the same relative magnitude as was done to produce the first nuclear weapons, it would help to solve the problems. It would be a great—and maybe necessary—service to future generations. It would perhaps be possible to make nuclear energy one of the cleanest, safest, most reliable and long-lasting energy sources on our globe.

The Future of Fusion

Professor Bo Lehnert

A review is given of the potentialities of fusion energy, the approaches to controlled fusion, the present state and perspectives of fusion research, and aspects of future possibilities and plans. Fusion research does not concern a single problem area but rather covers a complex of problems, ranging from basic plasma physics to technology and system studies.

Considerable progress has been made in all these areas. In the latest large tokamak experiments the "breakeven" parameter range of marginal balance between fusion power and power losses has now been reached and the first experimental reactor is planned to be ready for operation in 14 years' time.

Thus, it has already become possible to realize a power producing fusion reactor. However, such a reactor, being based on the current tokamak concept, is not likely to become technically or financially relevant. In a balanced global research programme, a broader approach including work on concept improvement becomes crucial to final success and for the full potential of fusion energy to be utilized.

Potentialities of fusion energy

Energy can be released by fusion of the nuclei of light elements. In nature fusion processes form the energy source in the interior of stars. The aim of controlled fusion research is to realize a technically and financially relevant energy source by utilizing such reactions.

Fusion has the potential of becoming a very large energy source, using several possible fuel types as follows:

- A mixture of the heavy hydrogen isotopes deuterium (D) and tritium (T) exhibits the highest reaction rate and will be used in a first generation of fusion reactors. The major part of the energy released is shared by emitted high-energy neutrons. The fuels of a DT-reactor, including lithium for the breeding of tritium, are so abundant in nature that DT fusion is essentially an inexhaustible source of energy, being at least comparable with that of the fusion breeder.

- In a second generation of fusion reactors, deuterium will be burnt directly. One liter of sea water is equivalent to 300 liters of gasoline for the DD-reaction. The neutron flux is smaller than in the DT-reactors, that is, more of the released energy is shared by electrically charged particles.

- In the remote future, advanced fuel reactions may be used like the deuterium-helium 3 and proton-boron reactions, with no neutron release at all. Helium 3 can be bred in a "primary" DD-reactor, and there are also large probable terrestrial reserves of this fuel in the earth's mantle, accessible from deep ocean hydro-thermal vents.

With respect to questions of environment and safety, the fusion reactor should also have a number of advantages.

- The fuels and the direct end product of fusion, that is, helium, are neither toxic nor radioactive and do not contribute to the greenhouse effect.

- The fusion reactor is characterized by inherent safety. A major feature is that the reaction zone contains only a small amount of fuel, required for some ten seconds of burn. Fuel is fed in as needed, as in fossil fuel plants. Critical accidents are impossible, since the reaction rate is self-limiting. The magnitude of a potential energy release from the reaction zone is small. In a fusion reactor the power density associated with the afterheat is much lower than in a fission reactor. Lithium fires can be avoided in a DT-reactor by using chemical compounds such as lithium ceramics.

- The first generation of DT-reactors will have a radioactive inventory arising from the fuel tritium, and from the radioactive materials produced by neutron activation of components in the reactor structure. Even so, the biological hazards of a DT-reactor are lower than those of a fission reactor of comparable power capacity. Moreover, the large development potential of the future fusion reactor should lead to further substantial improvements. Recently developed low activation materials (ferritic steel, silicon carbide) may reduce the neutron activation by a factor of hundred or more. Vanadium as a wall material would reduce neutron activation to zero.

- The DD-reaction and the advanced fuel reactions mentioned above reduce the emitted neutron flux, in some cases practically to zero.

Approaches to controlled fusion

So far, attempts to implement controlled fusion have been made along four lines of approach, as demonstrated in *figure 1*:

- Since the early 1950s, investigations have been performed on the confinement of hot plasma in a magnetic field ("magnetic bottle"). This approach appears at the present stage to be the most promising and will be the main subject below.

- Confinement by inertial forces can be achieved for small fuel pellets which are compressed to very high densities as a consequence of impinging laser or particle beams. Compression of DT-pellets up to 600 times solid density has been demonstrated. In other experiments 10^{13} fusion reactions have been produced, representing a released fusion energy amounting to 0.2 percent of the energy of the driver pulse emitted by a 10 kJ laser. As confirmed by experiments, theory predicts that a pulse energy of about 5 MJ is necessary for energy gain. Therefore particle beams appear to be a more efficient source for compression than lasers. Other problems are due to the Rayleigh-Taylor instability which can hamper efficient compression, and the technical and financial requirements of a system which has to endure about 10^{10} microexplosions with associated neutron bursts. Although inertial confinement fusion will not be discussed in greater detail here, it should be noted that this line of approach still has the possibility of becoming a successful alternative for controlled fusion.

Figure 1. The four approaches to controlled fusion.

HOT FUSION		COLD FUSION	
MAGNETIC CONFINEMENT	INERTIAL CONFINEMENT	MUON CATALYSIS	METAL CATALYSIS
Burning plasma, confined in a magnetic bottle	**Compression of small DT fuel pellets**	**Enhanced reaction rate through replacement of electrons by muons**	**Implantation of deuterium and tritium in the interatomic spacing of a metal**
Relatively low particle density	**High particle density**	**High particle density**	**High particle density**
Since the early 1950's	**Since the middle of the 1960's**	**Since the latter half of the 1970's**	**First attempts in 1926 New attempts in 1989**

- Substantial fusion rates could be obtained at room temperature, if the electrons which hold nuclei together in molecules were replaced by negatively charged elementary particles with larger masses. One such particle is the negative muon, an unstable particle with a mass 207 times that of an electron, and a lifetime of about one microsecond. Unfortunately, although the macroscopic effect is large enough to be detected, it seems unlikely that net energy can be produced competitively, as compared with the energy required to produce the muons.

- An alternative approach to achieving fusion at room temperature is based on the idea of forcing deuterium and tritium into the interior lattice of a metal such as palladium. However, to achieve useful fusion rates, this would require the realization of an interatomic spacing of about a factor of ten smaller than the normal one. So far there is also no clear evidence of any measurable fusion power production by this "cold fusion" method.

Basic conditions for magnetic fusion

There are two necessary conditions to be satisfied for magnetic fusion to result in a positive gain of energy:

- First, the plasma temperature T has to exceed an ignition temperature T_c which is about 3×10^7 K for the DT-reaction, and about 3×10^8 for the DD-reaction. This refers to the balance between the reaction rate and the bremsstrahlung loss in a clean plasma. Even small amounts of impurities, of the order of percent, can increase losses substantially and jeopardize this balance.

- Second, the product nt_E of the particle density n and the energy containment time t_E (cooling time) has to exceed a limit $(nt_E)_c$ for the total heat losses of the plasma to be covered by the fusion power production. The marginal value $(nt_E)_c$ is about 10^{20} s/m^3 for the DT-reaction, and about 10^{21} s/m^3 for the DD-reaction.

These conditions are necessary but not sufficient for a technically and financially relevant reactor to be realized. Thus, power production at an acceptable efficiency requires the values of T and nt_E to exceed T_c and $(nt_E)_c$ by sufficient margins. Also the beta value, defined as the ratio between the average energy densities of the plasma and of the confining magnetic field within the plasma volume, has to be high enough to secure an optimal energy balance and a desired power production in a reactor volume of acceptably large size.

Figure 2. The complex of problems in fusion research.

PROBLEMS IN FUSION RESEARCH

PLASMA PHYSICS	FUSION TECHNOLOGY	SYSTEM STUDIES
Plasma generation	Magnets with supports	Conceptual design
Plasma confinement	Materials and wall load	Operation reliability
Plasma stability	First wall, divertors	Repair and replacement
Plasma transport	Breeding blanket,shields	Safety and environment
Plasma heating	Vacuum System	Choice of power size
Radiation	Cooling systems	Choice of materials
Neutral gas interaction	Energy extraction	Economical efficiency
Wall interaction	Tritium regeneration	
Impurities	Radioactive vaste	
Alpha particle containment	Remote handling	
Fuelling and ash removal	Burn control	

The efficient transfer of heat to the plasma from the energetic alpha particles created by fusion is further necessary for sustaining a burning fusion plasma. Moreover, steady operation of the magnetically confined plasma is an important goal. Plasma-wall interaction and associated impurity release give rise to radiation losses and are significant factors in relation to fusion plasmas. This is also the case for fuelling and the removal of helium ash which would otherwise stop the fusion reaction after some time. Last but not least, a compact and efficient reactor leads to a high wall load which results in material, cooling and shielding problems due to the emitted neutron flux, impinging plasma particles, and radiation.

It is therefore evident that fusion research does not focus on a limited problem area, but involves an entire complex of problems in plasma physics, fusion technology and system studies which have to be matched to each other and solved as an entity *(figure 2)*.

Present state and perspectives of fusion research

Considerable progress has been made in fusion research since its inception in the early 1950s. Much of the basis of modern plasma physics has been developed within the frame work of this research, and experiments and theory have been brought closer together.

Numerous instabilities are now understood and can be controlled, and the analysis of plasma particle and heat transport has made progress. Several powerful plasma heating methods have been developed and implemented, such as those which are based on the injection of energetic neutral particle beams and imposed high-frequency plasma waves and oscillations. There is also an increased understanding of plasma-neutral gas and plasma-wall interaction, and the control of impurities has made progress by means of divertors.

Within the field of fusion technology, superconducting magnets have been designed and used in experiments, and new low-activation materials have been developed by which the induced radioactivity can be reduced by two orders of magnitude. The design of first wall elements, blankets, shields and cooling systems is also under way, and problems of remote handling are being tackled. Finally, a number of system studies have been conducted which predict the possibilities of constructing power-producing fusion reactors.

Magnetic bottles of tokamak type

In the field of fusion, a substantial part of the world's experimental resources have been devoted to research on the Tokamak confinement concept *(figure 3)*. The basic element of a tokamak is a strong toroidal magnetic field, whose field lines run in circles around the axis of symmetry. An electric current is induced along this field, to sustain and heat the plasma which is then confined in a resulting screw-shaped magnetic field configuration. The development of the experimental work with tokamaks since 1970 may be illustrated by the results of *figure 4*. The figure shows the ratio between the released DT fusion energy, calculated from measured data in hydrogen and deuterium plasmas on the one hand, and the measured plasma heat loss on the other. It will be seen that this ratio has been improved by more than a factor of 10^6 within 20 years, and it is now in a range approaching marginal energy balance ("breakeven"). A direct experimental confirmation of these results was achieved at the end of 1991 in the worlds's largest fusion experiment, the JET device *(figure 5)*, operated at Culham, England, by the European Community (Euratom). Here a DT mixture with a major amount of deuterium was used to produce 2 MW of fusion power during a period of 2 seconds at a plasma temperature of about 200 million degrees, with a value of nt_L equal to about 5 x 10^{19} s/m^3. The observed power production thereby agreed within an error of 15 percent with computed data, such as those of figure 4. Experiments with a 50/50 percent DT mixture should yield much more fusion power, but have yet not been conducted.

Figure 3. Outline of the principle of tokamak plasma confinement. A plasma current is induced along a strong toroidal magnetic field, the field lines of which form circular paths around the axis of symmetry.

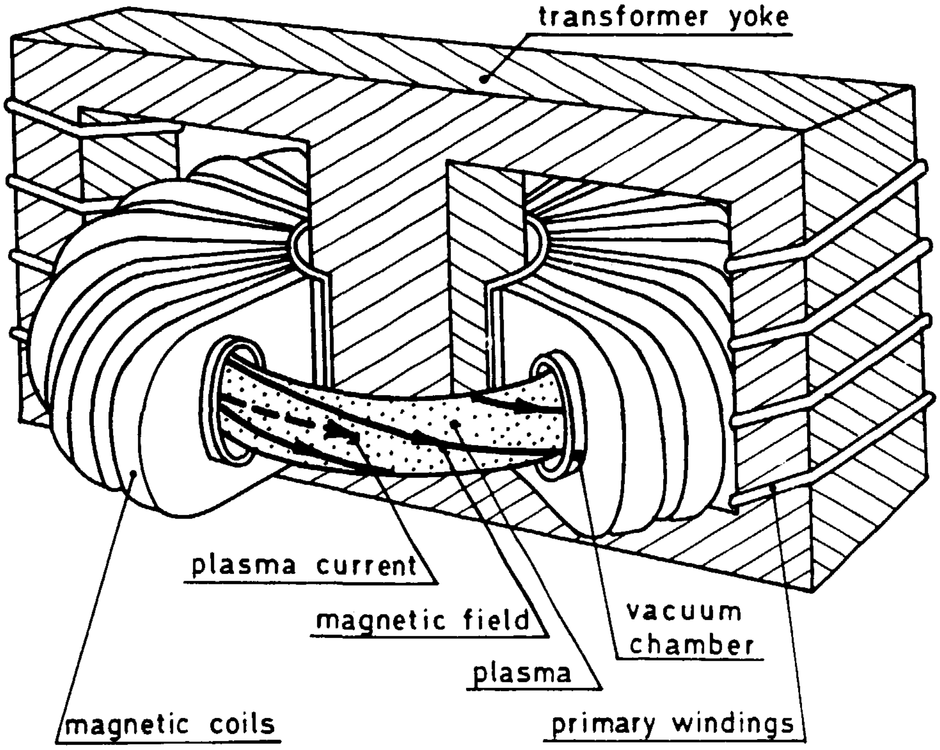


Figure 4. Ratio between estimated released fusion energy and measured plasma heat loss for a number of tokamak experiments during the period 1970 to 1990.

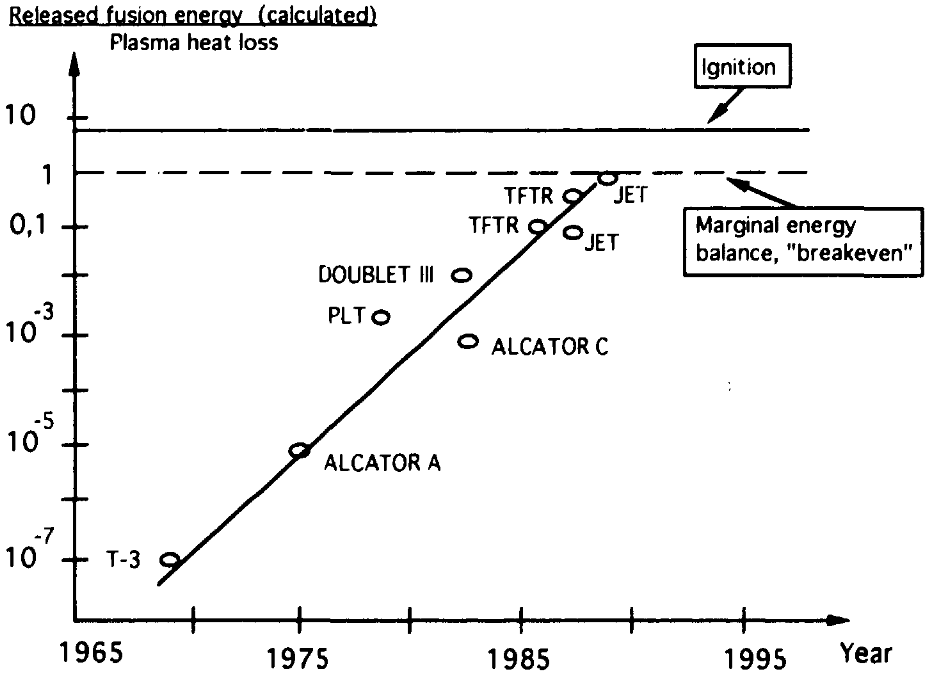
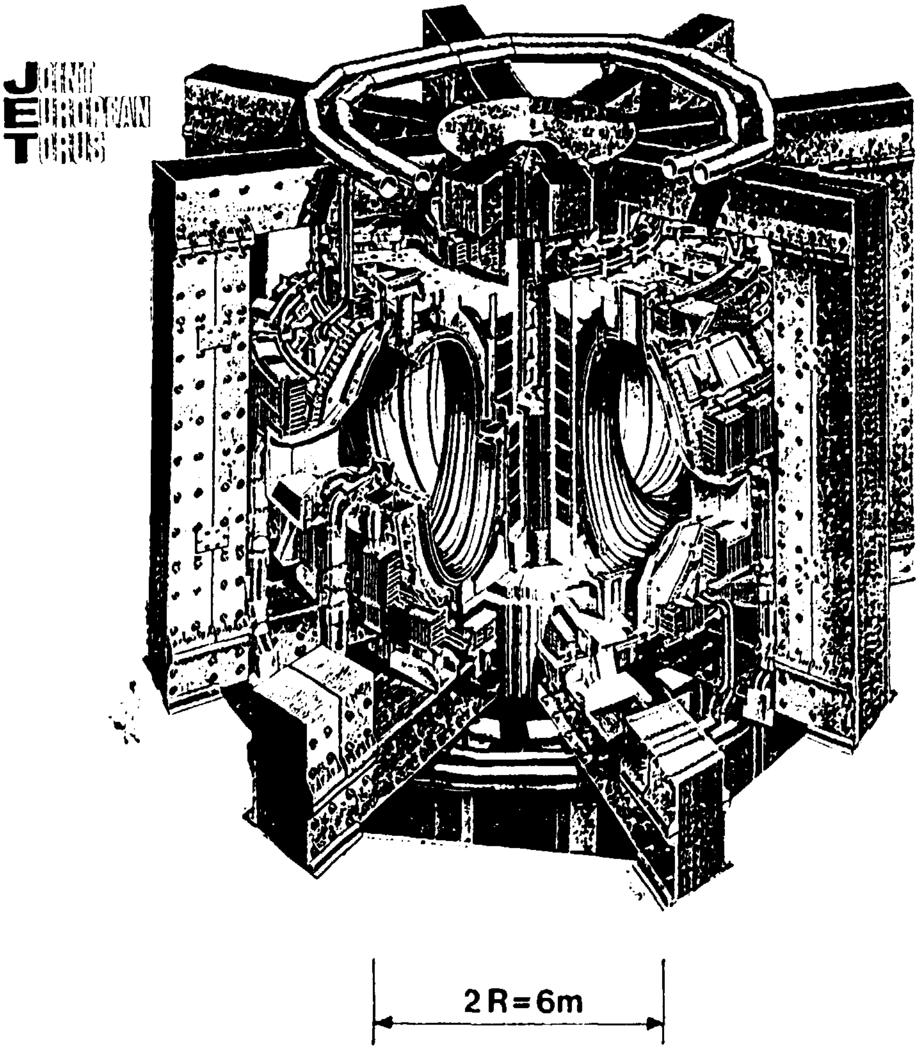
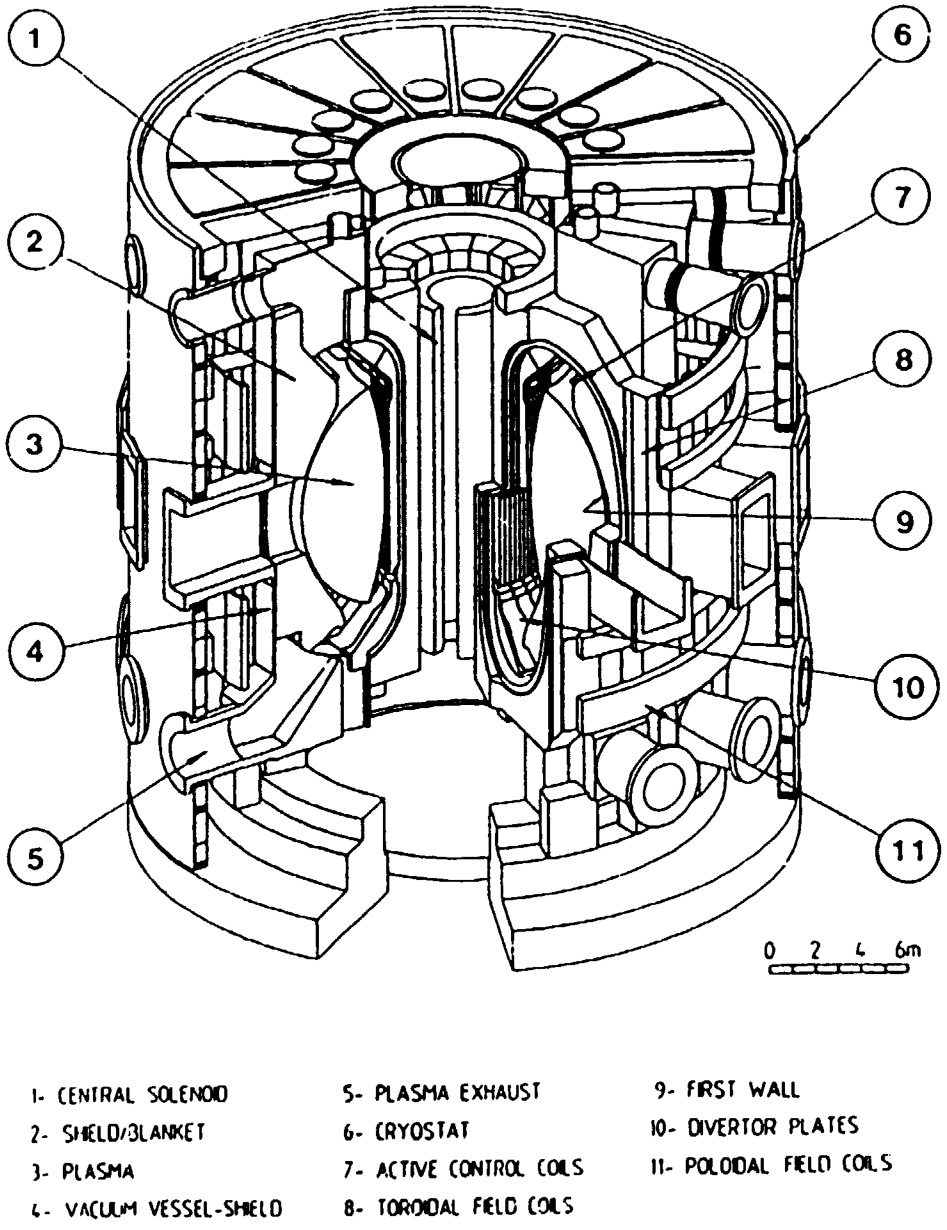


Figure 5. The JET (Joint European Torus) device at Culham, England.



As a next step in this development, an even larger project will be launched, the tokamak project ITER (International Thermonuclear Experimental Reactor) outlined in *figure 6.* The idea of this project was put forward by the International Fusion Research Council at the International Atomic Energy Agency in Vienna, and supported in its initial outline through the Geneva talks between Gorbachev and Reagan in 1985. Four parties, the European Community, Japan, USA and Russia, share the scientific and financial responsibility for this project. The device is designed for controlled ignition and extended burn of DT-plasmas and will demonstrate and perform integrated testing of the components required to utilize fusion power for practical purposes. A preliminary estimate of the capital cost of the ITER

Figure 6. Basic elements of the planned ITER (International Thermonuclear Experimental Reactor) device.



device is about USD 5,000 million. Three cooperative centers of design have been established at San Diego in the USA, Garching bei München in the EC and Naka in Japan. The first experiments are planned to start in 14 years' time. In the step represented by ITER, the role of industry has become more significant. Contacts have been made to establish closer cooperation between industry and the laboratories and research organizations, in particular in Japan, the EC and the USA.

For the present and the immediate future, the total world effort in fusion research will be supported by a budget of about USD 1,600 million per year.

After the experimental reactor project ITER, a further step in the more remote future would perhaps consist of a demonstration reactor, DEMO, with increased efficiency. Such a reactor might be based on an improved magnetic confinement concept which might turn out to be of non-tokamak type.

Concept improvement of magnetic confinement

The tokamak forms an important milestone on the road to the fusion reactor. It is clear that projects such as ITER have an outstanding role in studies of ignited and burning fusion plasmas, and are important to the development of full-scale reactor systems. Nevertheless, it is not clear that the tokamak concept in its present form will evolve into the best solution for a technically and financially efficient reactor. There are several problems to be tackled, of which the following should be mentioned:

- In tokamaks relatively low average beta values have so far been reached, that is, about 10 percent in the most successful cases. A high beta value promotes high power density and high fusion power to loss ratios, it minimizes the coil stresses, the coil power loss ratios and synchrotron radiation loss, it becomes a condition for the future use of advanced fuels, and it is advantageous in cases of a limited wall load.

- In tokamaks a strong toroidal magnetic field component is needed for stability. With respect to plasma equilibrium, this component acts as a kind of auxiliary field, making little or no contribution to the balance of the plasma pressure. A minimized or vanishing toroidal field therefore promotes the efficient use of the externally imposed total magnetic field, and it also leads to increased beta values and simplified technical constructions.

- Disruptions observed in tokamaks give rise to a release of magnetic energy stored in the plasma current configuration, and this becomes a particular threat to the operation of full-scale reactors at high plasma currents.

- Steady-state operation is necessary for an economical reactor, but has so far not been achieved in tokamaks. Several externally imposed current-drive mechanisms are under consideration, such as those based on beam injection and radio-frequency driven wave phenomena. For these mechanisms the necessary auxiliary energy input has to be included in the total efficiency. Current-drive by intrinsic "bootstrap" and diffusion-driven bootstrap-like mechanisms is likely to prove helpful. Such a current-drive becomes reinforced at high beta values for which there is a strong poloidal magnetic field component running in planes through the symmetry axis of *figure 3*.

To tackle these problems, research on magnetic concept improvement is being carried out at several national laboratories throughout the world. The work runs parallel with the research on tokamaks. The following approaches may briefly be mentioned:

- The Stellarator confinement concept is based on a screw-shaped magnetic field structure which is provided by an external magnetic coil system, thereby satisfying the plasma equilibrium conditions. This makes steady operation possible. Research is being done on this line of approach in Garching, Nagoya, Oak Ridge, Charkov, Madrid and Moscow.

- The Reversed Field Pinch concept is also characterized by a screw-shaped magnetic field, but the latter is in this case sustained by a dynamo mechanism driven by a plasma velocity pattern. The toroidal field component then becomes reversed in the outer plasma layers. The aim of this concept is to reach higher beta values. Research is being done in Padua, Madison and Stockholm.

- Field Reversed Configurations for pulsed plasma operation are developed in spherical-like geometry, where a combination of poloidal and toroidal fields produces a high shear, for which the field lines change their direction within adjacent plasma layers. This promotes stability and increases the beta value. Research is being done in Madison.

- The Extrap concept is based on a magnetic octupole field being imposed on a pinched plasma column, thereby forming a magnetic separatrix. The aim is to reach stable regimes at high beta values, where also bootstrap-like operation becomes reinforced. This concept has been developed in Stockholm with support from Euratom.

- Pulsed high-density Z-pinches are studied in the form of a straight plasma column having a narrow circular cross-section and no imposed external magnetic field. These pinches rely on kinetic large Larmor radius stabilization and aim at beta values of 100 percent. Research is being done at Imperial College, London.

- The Magnetic Mirror concept consists of a magnetic bottle with open field lines, that is, where these lines lead from the confined plasma out to a wall surface. Such a concept has a number of attractive features, including a high beta value and relative simplicity, but there are problems with the energy losses along the magnetic field. Research is being done in Novosibirsk and Tsukuba.

Concluding remarks about the future of fusion research

As based on present results and knowledge in fusion research, a fusion reactor could be designed and built at the present time, but such a reactor would be neither technically nor financially relevant. It would also be premature to think that present studies of fusion reactor systems give a final answer about the feasibility of fusion energy, because there is still great development potential with possibilities of new results and improvements.

The bottlenecks of future work may at present be identified as follows:

- As has been seen, the tokamak results represent important progress in the field of fusion research. Nevertheless, the tokamak concept has weak points and drawbacks, which make this concept questionable as a candidate for the final type (or types) of a technically feasible and financially efficient reactor. In a balanced global research programme, a broader approach including further work on concept improvement at the national laboratories, running in parallel with the ITER project, will be crucial to the final success of fusion research and development and for the full potential of fusion energy to be utilized.

- A speeded-up programme should therefore include strong and efficient efforts, both within the ITER project and at the national laboratories. Without the latter efforts, there is no adequate back-up and fall-back for ITER.

- The available scientific and technological competence among the staffs of the world's fusion laboratories is sufficient for an efficient research and development programme to be conducted. However, the present economic situation in the world is giving rise to restrictions which hamper this programme. With the present level of budgeting, the fusion reactor may become a reality first after the year 2050 or later. This schedule could be accelerated or delayed, depending on new results. It should further be noted that the planning and construction period of ITER forms a gap in experimental activities. For the fusion research programme not to lose momentum and qualified manpower, this gap has to be filled with continued and relevant plasma physical and fusion technological activities at the national laboratories, universities and other research centers.

- As a consequence of these circumstances, and with the aim of a successful and speeded-up broad programme, a substantial increase in funding is highly desirable. A three-fold increase of the yearly global budget for fusion to a level of about USD 4,000 million per year could result in a speedier arrival at the final goal, possibly around the year 2030.

Efficiency-Waste for Different Energy Sources, Future Outlook

Mr J.E. Naber and Mr H.J. Fijn van Draat

Introduction

The development of world energy use over time *(figure 1)* shows that mankind has become a consumer of copious amounts of energy. The consumption of commercial forms of energy—coal, oil, natural gas and electricity generated by hydropower or nuclear energy—has grown by a factor of 80 in 120 years, a timespan in which the world population has quadrupled.

Figure 1. World primary energy consumption

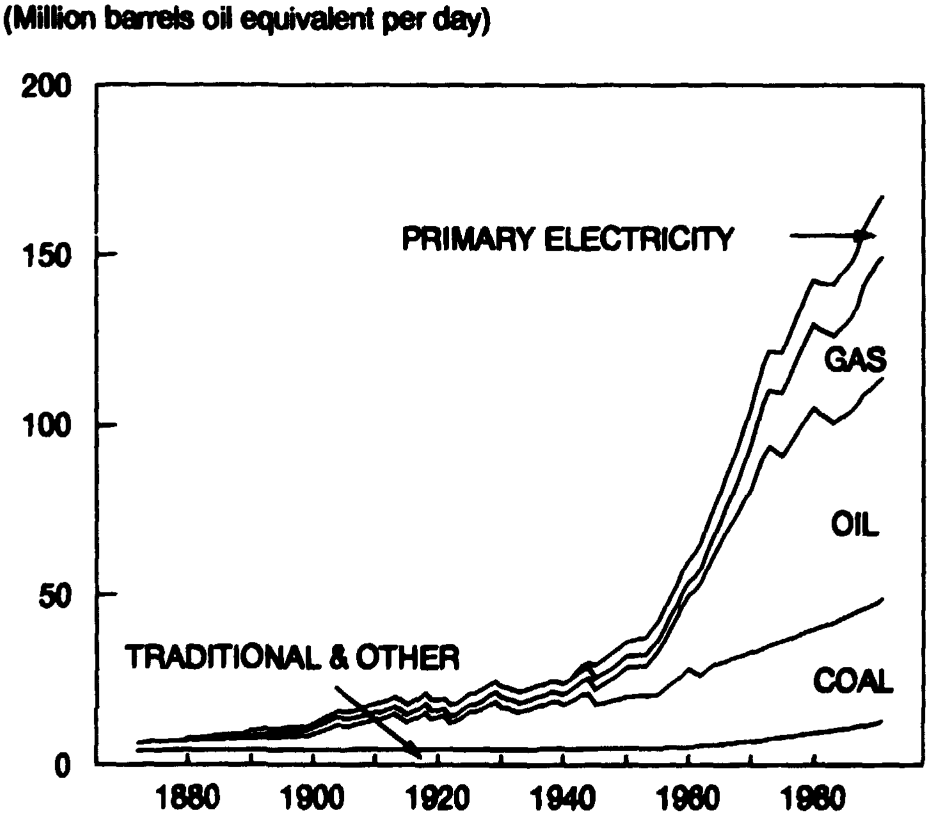
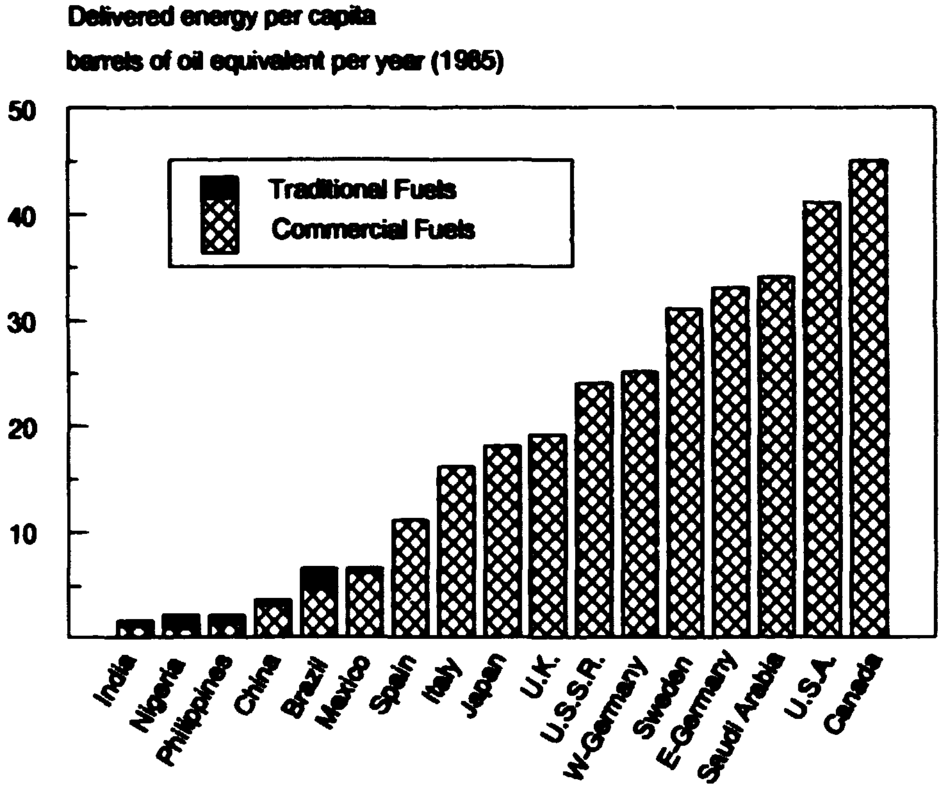


Figure 2. Energy use per capita in various countries



High energy consumption is part and parcel of modern life, at least for most people in the developed countries *(figure 2)*, and goes hand in hand with much that is seen as essential for a high quality of life. The manufacture of almost all goods and the provision of most services cannot dispense with energy. Energy is the "ultimate raw material".

In view of the rapid growth of world energy use in the 20th century, it is no wonder that any further unchecked growth of fossil fuels consumption is being questioned in relation to the available reserves and also the costs and the potential environmental effects.

It will be shown that the recoverable reserves of oil and coal, although in principle finite, are sufficient to meet a much higher demand than the current one well into the second half of the 21st century. However, as a high proportion of these reserves can be recovered only at great cost—in money and potentially also to the environment—it makes more sense to curb wasted energy and to pursue enhanced energy efficiency. Technology for this purpose is available and can be further extended and improved. What is needed is the transfer and application of this technology.

Resources and consumption

Fossil fuels—oil, natural gas and coal—currently meet over 85 percent of the world energy demand. Some 20 years ago much concern was expressed about the imminent depletion of these resources. In actual fact, however, estimates of remaining proven reserves of oil in the world have increased in these twenty years by more than 50 percent and those of gas by more than 175 percent as a result of increased prospecting activity and advances in prospecting and production technologies *(figure 3)*.

The estimated "lifetime" of the reserves—the ratio of proven reserves to the current rate of consumption—is currently 40 years for oil, 60 years for natural gas, and 190 years for coal *(figure 4)*. These are global values; for oil the reserves and the consumption are unevenly spread. Over 75 percent of the reserves are in the OPEC countries, which consume about 10 percent of the world production of oil. As a result the lifetime for the oil reserves of the OPEC countries is over 100 years against only 11 years for the non-OPEC countries. This raises the issue of the security of world oil supplies.

Figure 3. Evolution of proven world oil and gas reserves

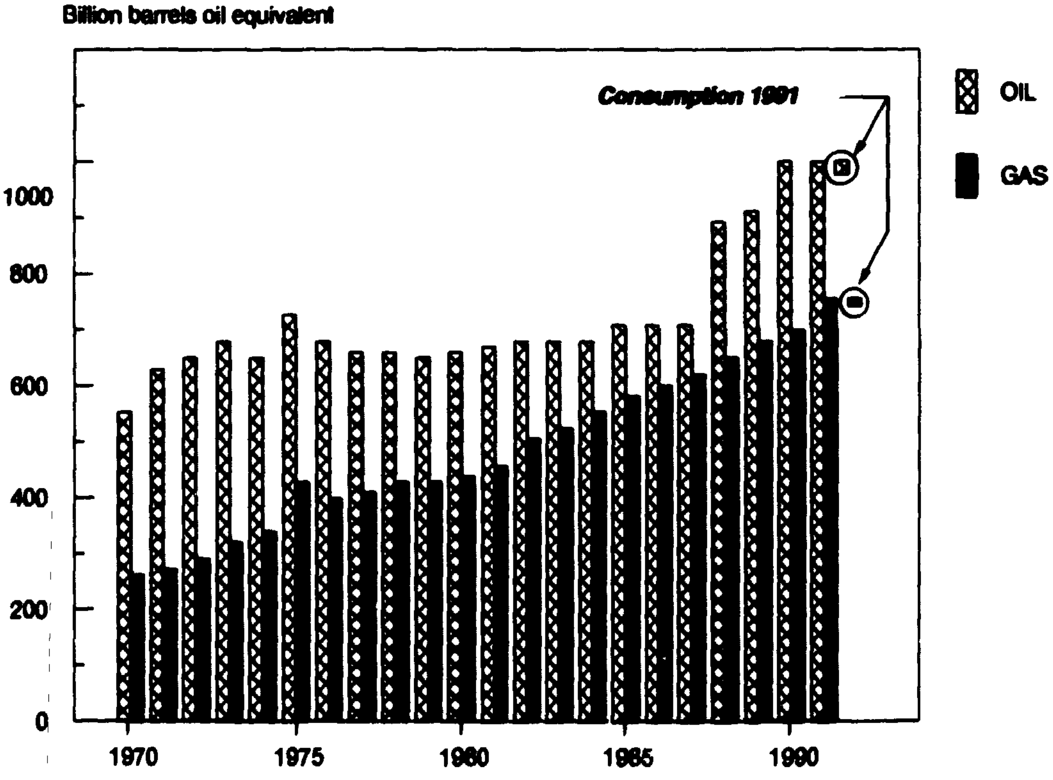


Figure 4. World fossil fuel reserves/consumption (1991)

	Proven reserves (10^9 b.o.e.)	Consumption in 1991 (10^9 b.o.e.)	Res./Cons. (years)
OIL	991	24	41
of which non-OPEC	240	21	11
GAS	780	13	60
COAL	4250	22	190

b.o.e.=barrels oil equivalent

Global average total energy consumption:
11 barrels (=1770 l) oil equivalent
per capita per year

The "lifetimes" given above are based on present-day proven, economically recoverable reserves and current rates of consumption. The latter are bound to grow, in view of the predicted growth of the world population (from 5.5 billion now to some 8 billion in 2025, predominantly in the developing countries) and the quite understandable aspirations of these countries to catch up in economic development, leading to higher energy demand. When considering a hypothetical situation of a (stationary) world population of 8 billion and a per capita primary energy consumption of 20 barrels of oil equivalent (b.o.e) per year (the current per capita consumption in Japan), the world energy consumption in this scenario would be 438 million b.o.e. per day compared to 168 million per day in 1991.

Additional oil reserves yet to be discovered in unexplored areas and enhanced recovery of oil from known oil fields are likely to double the recoverable reserves. Further there are huge proven reserves of unconventional oil (heavy oil in Venezuela: 700 billion barrels; tar sands in Canada: 1,000 billion barrels oil; higher grades of oil shales in the USA 1,500 billion barrels). For gas, the smaller fields and unexplored areas will provide additional reserves for the future. For coal, a quarter of the currently known reserves is assumed to be recoverable, albeit at (much) higher costs, owing to thinner seams, etc. In the high demand scenario, sketched above, the lifetime of the potentially recoverable fossil fuel reserves, assuming the same fuel mix as at present, is some 80 years for oil (including tar sands and shale oil), about 60 years for natural gas and over 150 years for coal *(figure 5)*. The costs of recovering fuels from these additional reserves could be high, ranging up to USD 50—60 per b.o.e. *(figure 6)*.

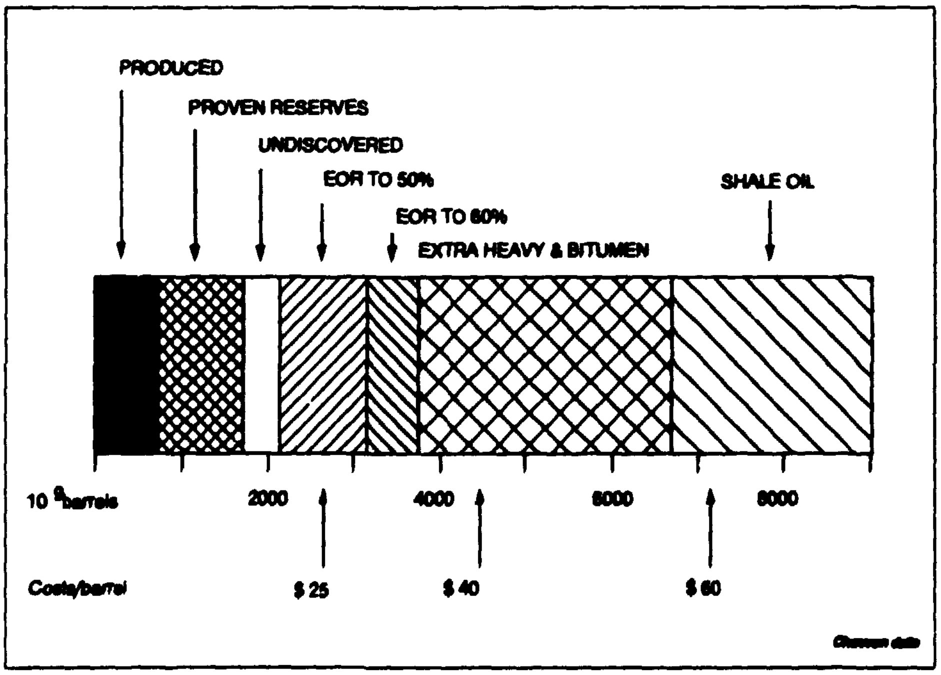
It would therefore be sensible from a financial point of view to weigh these high costs against the costs of using presently available energy sources more efficiently.

Figure 5. Lifetime of fossil fuel reserves in high demand situation

Hypothetical situation: - world population 8 billion (in year 2025 ?)
- per capita total energy consumption 20 b.o.e/year
(in 1991 this amounted to 11 b.o.e.)
- same fuel mix as in 1991

	Estimated recoverable reserves (10^9 b.o.e.)	Annual Consumption (10^9 b.o.e.)	Res./Cons. (years)
OIL	2000	63	> 63
SHALE OIL	1500		
TAR SANDS	1700		
TOTAL	> 5200		
GAS	> 2000	32	> 60
COAL	> 10,000	60	> 170

Figure 6. Estimated hydrocarbon resources and costs.

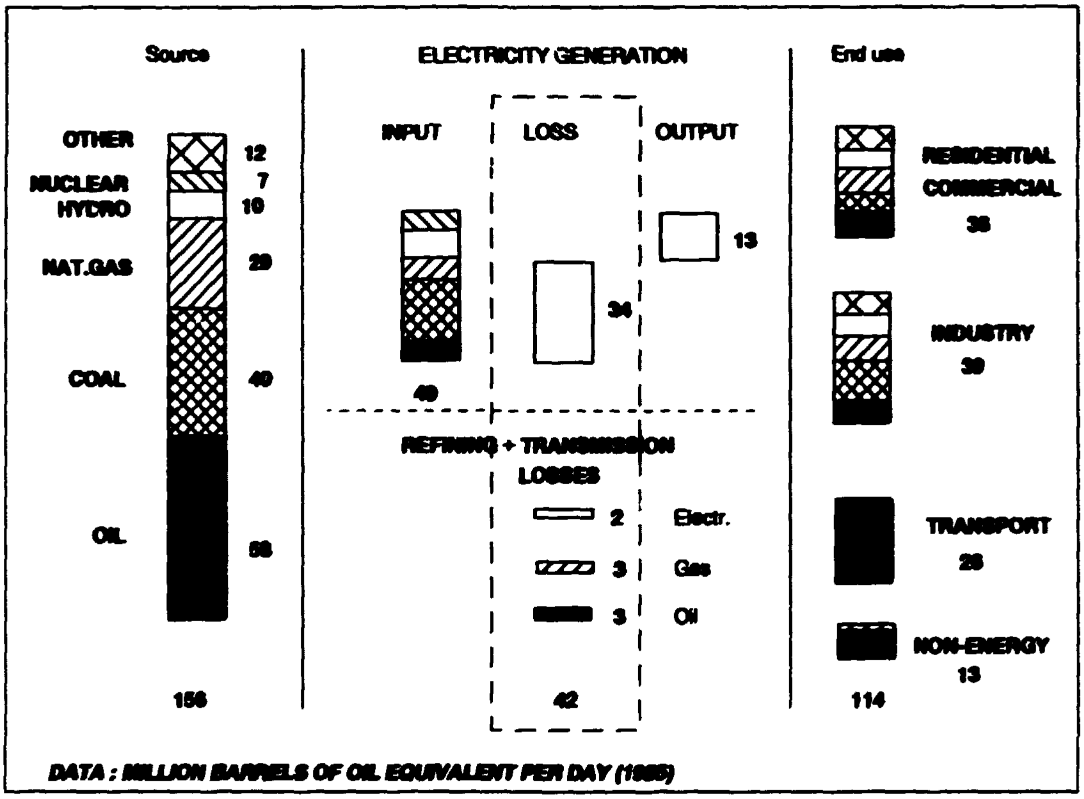


Chevron data

Potential for reducing losses in the production and conversion of primary energy streams

The magnitude of the world energy flows and the losses between production and end use are given in *figure 7*. In 1985, 42 million b.o.e. per day were lost, mainly (34 million bbl per day) in the upgrading of primary energy to electricity, but also 3 million b.o.e. per day in natural gas transport, 3 million bbl per day losses of oil and own use of refineries, and 2 million b.o.e. per day losses in electricity transmission.

Figure 7. World energy flows



Natural gas

Natural gas is a clean fuel with, in energy terms, the lowest carbon dioxide emission of all fossil fuels (50 percent of that of coal and 70 percent of that of oil). The current losses owing to venting and flaring (not included in figure 7) in exploration and the transport losses of natural gas are high. Conservative estimates amount to some 10 percent of the marketed gas which is equivalent to 3.5 million barrels of oil per day. This volume is roughly the same as the natural gas production of Western Europe, or more than five times the total energy consumption of Sweden!

As methane, the main component of natural gas, has some 60 times higher global warming potential than carbon dioxide, venting or losses of natural gas as such are potentially more serious from the environmental point of view than flaring or burning.

Technology is available to drastically curb these natural gas losses to below 0.1 percent; merely halving the natural gas losses would immediately provide a saving of 2 million b.o.e. per day.

Oil losses and refinery use

Oil losses during production, transport and refining are much lower. The aggregate losses are not precisely known, but are probably far below 1 percent or 0.6 million b.o.e. per day and are, by consequence, not easy to assess from differences in volume measurements. These losses as vapour or liquid spills are much more serious as local pollution than from a global point of view.

The energy required for the processing of oil in refineries (distillation of crude oil, cracking of heavy oil fractions, conversion processes, sulphur removal, etc.), amounts to about 5 percent of the crude oil processed. (1985: 3 million b.o.e. per day own use on 59 million bbl per day throughput).

Implementation of energy saving technology can be very effective: the specific (that is, per unit of product for the same processes) own energy use of the refineries of the Royal Dutch/Shell Group has been halved since 1960. Major factors in these improvements are enhanced heat recovery and better process control.

The increased conversion of heavy oil fractions and environmental requirements, however, may offset these improvements in total own energy use. The removal of sulphur from petroleum products, so as to reduce sulphur dioxide emissions in end use by one ton, requires additional energy with the extra emission of ten tons of carbon dioxide. Upgrading gasoline fractions, so as to achieve the required octane number without the use of additives containing lead, is also very energy intensive.

Electricity generation

A vast amount of energy is lost in the conversion of fuel into electric energy. In 1985, a world-wide energy loss equivalent of 34 million barrels of oil per day was incurred. In addition electricity transmission losses amounted to about two million b.o.e. per day. The global average for the net thermal efficiency of power generation and transmission in 1985 was only some 30 percent. This is far below the current capability of power generation technology, which ranges from 39 percent for conventional coal-fired power plants, to 43 percent for the (Shell) Coal Gasification Process (SCGP) in combination with steam and gas turbines, and 46 percent for natural-gas-fired combined cycle power plants. The high efficiency of the SCGP is achieved while simultaneously meeting very stringent emission requirements. It may be expected that efficiency can be further increased in future through improved technology, mainly by extending the temperature range of gas turbines by means of higher temperature resistant materials.

Cogeneration of electricity and heat, that is, using the waste heat of electricity generation processes for industrial, commercial or domestic purposes can increase the total thermal efficiency to some 80 percent, thus reducing energy waste in power generation by a factor of up to three. In the Netherlands cogeneration comprises 13 percent of the total electricity generating capacity installed, and this is estimated to grow towards some 25 percent to 30 percent by the year 2000. The scope for applying cogeneration depends, however, on the possibilies of balancing the variations in demand for power and heat. Seasonal factors in commercial and domestic heat demand are limiting the effect in actual practice. Industrial application of cogeneration is proving much more successful.

Enhancing the efficiency of the electricity generation process from the current global average of 31 percent to 39 percent (present state of technology for coal-fired plants) would yield a saving of 10 million b.o.e. per day primary energy. Implementation of cogeneration in 25 percent of electricity generation would give an additional saving of 4 million b.o.e. per day.

In view of the long lead times (5–10 years) and lifetimes (20–40 years) of the installations involved, these savings cannot be achieved overnight. High capital expenditure will be needed for scrapping old and inefficient power plants and for building new ones, employing state-of-the art technology. Although this may not seem economical at the moment in view of the current very low energy prices, it may show a very good return in the longer term.

Potential for enhancing the efficiency of energy end use

Energy consumption is, of course, not an end in itself but a means to obtain services such as a heated or cooled house or office, an illuminated working place, a distance travelled, a product, etc.

Here we consider the potential for obtaining the same service using less energy. As it is difficult to forecast future demand for these services, the effects of higher energy efficiency will be expressed as the amount of energy which would be saved in relation to current demand.

Private road transport

The future development of energy use for private road transport depends on the total distance covered (number of cars multiplied by mileage) and the fuel economy of the world car fleet.

In 1985, the world outside the former Centrally Planned Economies counted some 350 million cars consuming 9.5 million barrels of gasoline or gasoil per day. The number of cars is expected to grow further, possibly to about 600 million in the year 2010, while the distance annually covered per car is not expected to decrease significantly. Will this inevitably lead to a near doubling of fuel consumption by 2010?

The global average fuel economy of the existing car fleet in 1985 was only some 20 mpg (miles per gallon) or 7 km/l, whereas the average new car in 1985 showed much better fuel economy: 30 mpg *(figure 8)*.

Figure 8. Fuel efficiencies in cars and aircraft

Private road transport (commercially avalble cars 1985)	
Total global fuel consumption :	9.5 million barrels per day
Average fleet fuel efficiency :	20 miles per gallon
Average new car fuel efficiency :	30 miles per gallon
Fuel saving by changing to new cars:	3.2 million barrels per day
Fuel efficiency best new cars 1992 :	50 miles per gallon
Fuel efficiency best new cars 1998 :	60+ miles per gallon
Aviation (commercial aircraft)	
Total global fuel consumption, 1985:	2.4 million barrels per day
Average fleet fuels eff. 1985:	231 ton.km/barrel
Best new aircraft fuel eff. 1987 : (Boeing 757-200)	316 ton.km/barrel
Fuel saving by chaging to new aircr.:	0.6 million barrels per day

Further major improvements in fuel economy are feasible. Fuel economy enhancement in the USA achieved since the first energy crisis (1973), stimulated by the Corporate Average Fuel Economy (CAFE) standard, has yielded a gasoline saving of over 2 million barrels per day (about 30 percent of US gasoline consumption). Improvement of the design and electronic control of the engine (that is, "lean burn") and transmission, weight reduction of the vehicle through down-sizing and utilization of new materials (composites, plastics) can raise the fuel economy higher still.

Several present-day commercial 4-passenger car models achieve 50 mpg (18 km/l) on the road. This is already 2.5 times better than the average world car fleet fuel economy in 1985 and would, if globally applied, constitute a fuel saving of some 6 million barrels per day.

There is scope for yet further enhancing fuel economy and a target of 60 mpg (21 km/l) for a commercial 4-passenger car by the end of this decennium would not seem unrealistic.

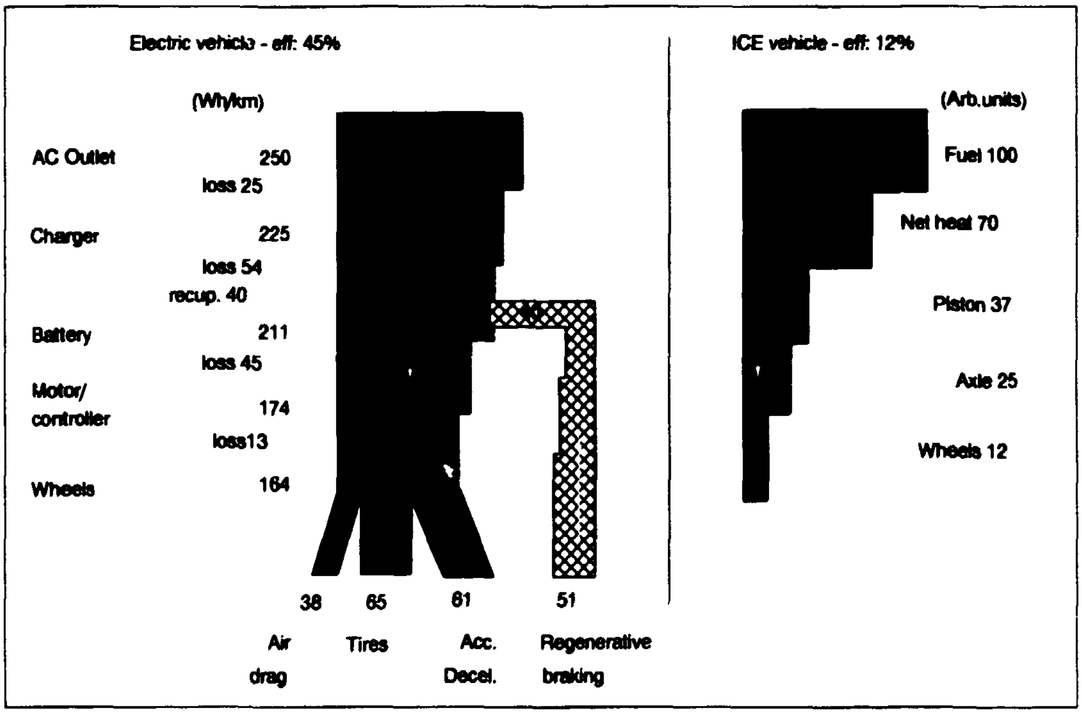
Assuming the average fuel economy in 2010 to be at the level of several present-day standard types of commercial vehicles (50 mpg) the vast increase in number of cars from 350 million to about 600 million, would result not in an increase but in a decrease of the total fuel consumption from 9.5 million barrels per day in 1985 to less than 7 million barrels per day in 2010).

Whether these potential savings will be realized, depends not only on technology but to a large extent on motorists' choices of vehicle and driving style and the "scrap rate" of older cars as well. Governments can exert a substantial influence here, as demonstrated in the case of the USA CAFE mandatory efficiency standard.

Switching over from gasoline or gasoil powered internal combustion engines to electric vehicles will not in itself result in energy saving.

Present-day state-of-the-art electric vehicles are effectively utilising only some 45 percent of the electric energy taken from the grid for charging the batteries, even when they apply regenerative braking *(figure 9)*. This electric energy constitutes on average only some 30 percent of the primary energy used for power generation. The overall efficiency "from well to wheel" of electric vehicles therefore amounts to some 12 percent, which is comparable to that of cars equipped with internal combustion engines under similar driving conditions (at 30 mpg).

Figure 9. Electric and internal combustion engine vehicle efficiencies



The absence of *local* environmental effects is, of course, the driving force behind the possible introduction of electric vehicles. Such effects are transferred to the power plants which are likely to be better equipped for emission control. The total carbon dioxide emission of present-day internal combustion engine cars and electric vehicles in combination with coal-fired power plants are, however, comparable.

Aviation

Air traffic is a rapidly expanding sector, possibly tripling in the coming twenty years. What are the prospects for increasing energy efficiency in this sector, with consumed 2.4 million barrels per day in 1985?

As in the case of cars, present-day types of commercial aircraft are far more fuel-efficient than the older ones. As an example, the 1987 Boeing 757 has only half the specific fuel consumption of the 1973 Boeing 707. Replacing the 1985 fleet by the most fuel-efficient commercially available aircraft would, other things being equal, give a fuel saving of some 25 percent or 0.6 million barrels per day (figure 8).

There are many possibilities for further fuel saving: both in aircraft and engine design (for example, weight saving, improved wing and body design, better electronic engine control and in particular improved engines such as the Ultra High Bypass engine) and in operating practices (load factor, air traffic control).

Residential/commercial

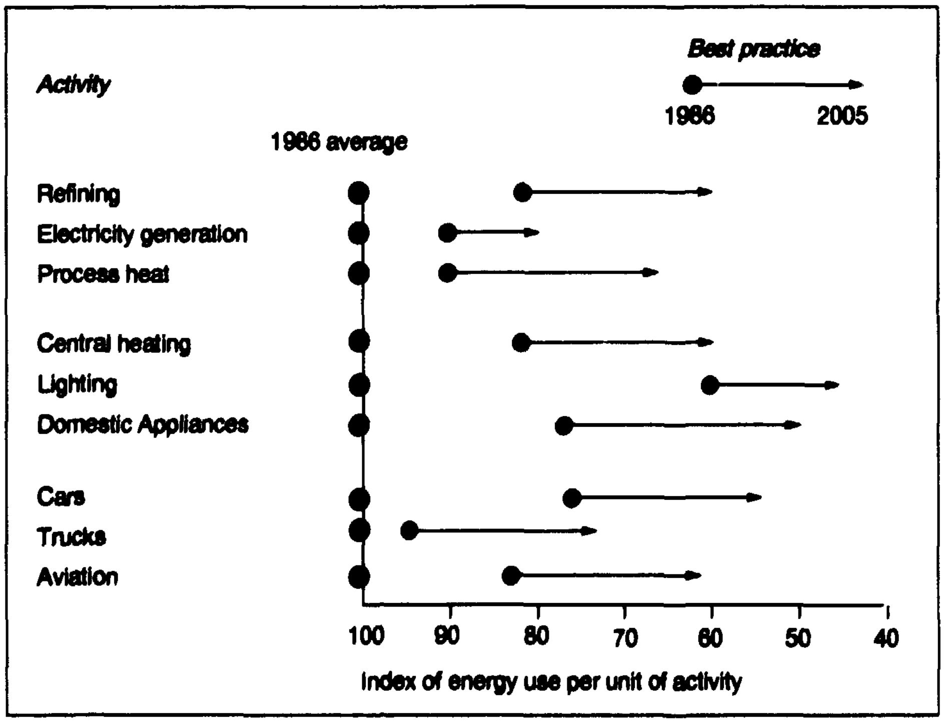
Residential and commercial end use of energy for purposes such as space and water heating, air-conditioning, refrigerating, cooking, lighting, etc., amounted to 36 million b.o.e. per day in 1985, or 36 percent of total end use of energy.

For almost any application, there is a wide margin between the fuel efficiency of the average equipment installed in 1985 and the average best new equipment available.

Replacing the average 1985 refrigerator, freezer, air-conditioner, lighting, etc., by the most energy efficient commercially available equipment of 1985 would have reduced the energy consumption in these applications by 25–40 percent *(cf. figure 10).*

Even for most heating equipment an improvement of energy efficiency by some 20–40 percent is possible, just by using the best available equipment. In addition dramatic reductions in heating requirements

Figure 10. Potential energy efficiency improvements (OECD countries)



can be achieved by the proper thermal insulation of houses and buildings.

As an illustration: the space heating requirements of the average US house is about three times higher than for the average insulated house, and ten times higher than for a state-of-the-art insulated house.

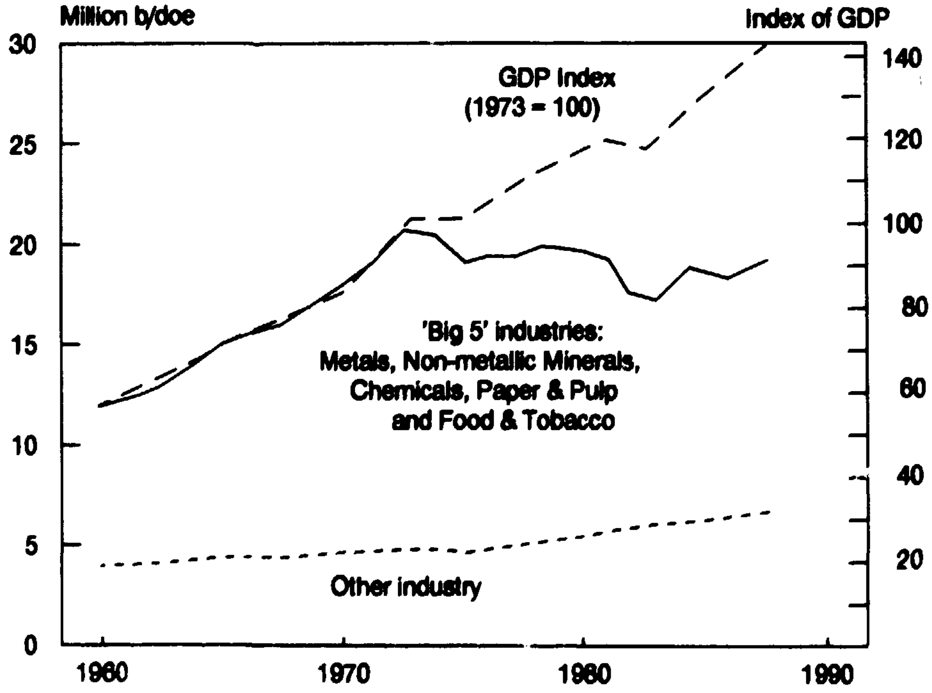
Although the great diversity of the energy applications in the residential and commercial sectors makes it difficult to accurately assess the potential for energy saving, it would seem that savings in the order of 25–30 percent are possible by replacing old equipment with present-day commercially available appliances. The global energy saving would then be approximately 10 million barrels per day.

There is clearly scope for the further enhancement of energy efficiency in future by technological improvement, for example, heat pumps instead of heating equipment, the wide-spread application of fluorescent lamps instead of incandescent lighting, etc.

Industry

The efficiency of energy use has markedly increased since 1973, in particular in large energy consuming industries (*figure 11*). This has for the greater part been realised by genuine energy saving, achieved by

Figure 11. Industrial energy demand (OECD, including petrochemical feeds)



improved energy recuperation, better process control, etc. As a result the energy intensity (that is, the amount of energy used for a certain production volume) has decreased. Both financial reasons and technical aspects have induced industry to pursue energy efficiency. In energy intensive industries, the energy cost is an important factor in total production costs. For competitive reasons, these types of industries had no other option than to cut back on energy use. In addition large scale industrial installations are often better suited for energy efficiency improvements than the great variety of small scale equipment encountered in light industry.

In view of the fact that the easiest energy savings have already been realized in industry, the prospects for further large-scale energy saving in industry are not as good as for private road tranport or residential energy use. Nevertheless, further increase of energy efficiency is possible by incremental technology: many small steps, potentially resulting in significant improvements.

Biomass as a source of primary energy

So far we have mainly discussed fossil fuels as a source of primary energy. (144 out of 168 million b.o.e. per day or over 85 percent in 1991).

Fossil fuel reserves will be depleted in the very long run and their use is inevitably coupled with the emission of carbon dioxide. A potentially sustainable source of energy which does not give rise to a net carbon dioxide emission is biomass.

The net global product of plant photosynthesis is estimated at 120 billion tons of dry product, containing some 60×10^9 ton of carbon per year. This is equivalent to 1,000 million b.o.e. per day, or some six times current world energy production.

Biomass is estimated to currently contribute some 10 percent of the world's primary energy input, but in many cases its use (fuel wood gathering, charcoal production) is very inefficient and has negative ecological effects.

Biomass, however, has the potential of becoming a significant sustainable source of primary energy. Studies have indicated that well chosen biomass crops in combination with advanced gasifier/power generation installations are technologically feasible and could even be commercially feasible under certain reasonable (no carbon) tax systems. To give an example, an afforestation programme totalling 100 million hectares (a little more than double the area of Sweden, or less than 1 percent of the world land area) would be capable of sustainably supplying more than 30 percent of the current global electricity demand. Implementing such a programme would save some 13 million b.o.e. of fossil fuels per day. From the energy efficiency point of view, this approach is to be preferred to current systems for the direct conversion of biomass into liquid fuels (for example, fermentation to ethanol or the use of vegetable oil as a fuel, see also *figure 12*).

Figure 12. Financial aspects of biofuel options

		Wheat Ethanol	RME	SRC
Cost of feed	US $/t	140	713	60
Processing cost	US $/t feed	123	160	
Byproduct values	US $/t feed	72	40	
Biofuel yield	t/t feed	0,33	1	
Biofuel costs	US $/t	580	833	60
Market value	US $/t	176	162	50
Yearly support needed	US $/ha	1090	1075	160

*** Costs exclude subsidies.**
*** Rotterdam sport prices 19-03-1992.**
*** Short Rotation Crop (SRC) wood value based on competitive power generation by gasification/gas turbine vis a vis power from coal.**

Summary and Conclusions

Fossil fuel resources are sufficient to enable further growth of energy use for the foreseeable future. Recovery of fossil fuels will however become increasingly costly in financial terms and may present increasing environmental challenges.

The combustion of fossil fuels is related to the emission of carbon dioxide. At the moment it is not known whether the increased carbon dioxide content of the atmosphere will give rise to a significantly enhanced greenhouse effect; current climatic models are giving conflicting results. It would seem prudent to curb waste of energy and to adopt energy-saving measures, in particular in cases where this is already financially viable.

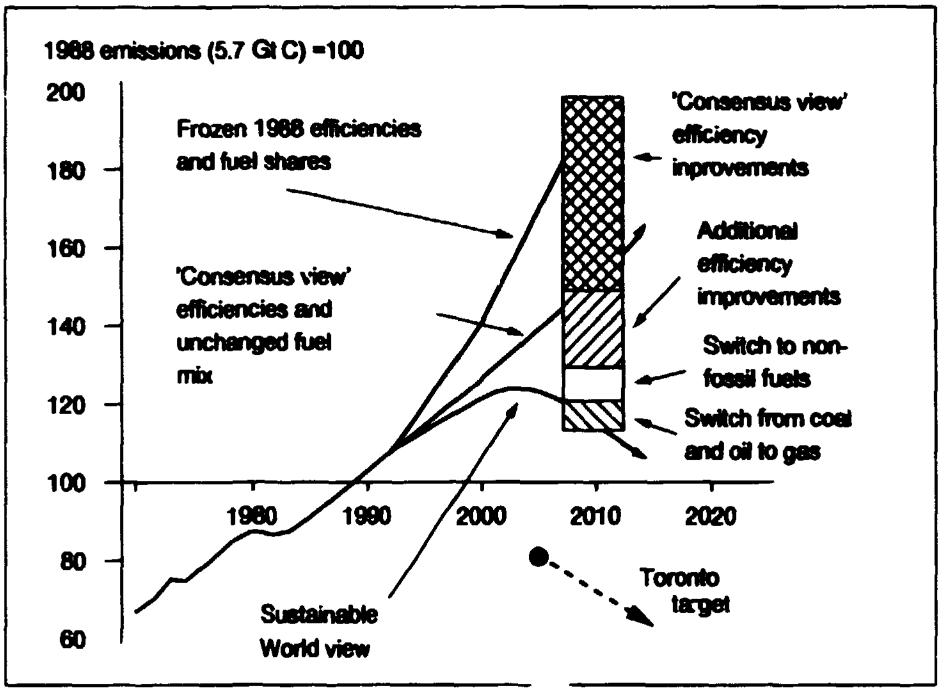
Most current new energy-consuming equipment has much higher energy efficiency than old equipment. The mere replacement of old, energy inefficient cars, aircraft, domestic equipment, etc., by average new commercially available equipment would result in a total energy saving end use in the order of 20 million b.o.e. per day or some 20 percent of the current delivered energy *(figure 13)*. In addition an amount of energy in the order of 10 million b.o.e per day could be saved by applying state-of-the art technology in the generation of electricity. These savings, together constituting some 20 percent of the total energy demand, would make it possible to achieve the Toronto target for global carbon dioxide emission *(figure 14)*.

Figure 13. Potential fossil fuel savings

Order of magnitude of potential energy savings achievable by changing over from average existing equipment to new, commercially available, energy efficient equipment and technology (1985):

	Million b.o.e./day
Natural Gas production and transport: (halving flaring, venting and leakage)	2
Electricity generation	10
Cogeneration	4
Cars	3
Aircraft	.6
Residential	10
Total of these savings	~ 30
Afforestation of 100 million ha for electricity generation and substitution of fossil fuels by energy crops	13
Total potential savings on fossil fuels	~ 43 (25% of world demand)

Figure 14. World carbon dioxide emission scenarios



Utilizing a relatively modest part (1 percent) of the world land area for rapidly growing trees and using the wood for burning or gasification in electricity generation would save some 13 million b.o.e. per day of fossil fuel. This would buy more time to ultimately change over to additional sustainable energy sources during the course of the 21st century.

There is therefore considerable scope for reducing the tension between increasing energy demand and resource availability and environmental effects, by using currently available more energy-efficient technology. Significant further scope may well be provided by additional technological developments.

What Will Endure of 20th Century Biology?

Professor Manfred Eigen

Quo vadis humanitas?

We find ourselves in the last decade of this century; no previous century has had such a profound effect on human life. Perhaps no century has produced such a level of apprehension and fear, anchoring them in the consciousness of man. One has become mistrustful. When a discovery becomes known nowadays, the first question is not, "Of what use will it be to mankind?", as in earlier times, but, "What damage will it cause, and how will it diminish our well-being and health?". Our present state of well-being is bestowed upon us mainly due to scientific knowledge; this has brought life expectancy up to 75 years, approaching the biologically natural age limit. At the beginning of this century, life expectancy was a mere 50 years and at the beginning of the previous century it was only about 40 years. In developing countries, the curve of life expectancy is also rising, although it lags about 50 years behind ours; meanwhile, our life expectancy is approaching an upper limit. Yet, as never before, we peer apprehensively into the future. This despite the fact that in the political sector, some of the gravest and most grotesque developments instigated by humanity in this century appear to be in the process of rectification. It is unlikely to be decided in this last decade whether these changes are really for the better.

This decade not only brings the century to a close, it ushers in a new millennium. We feel impelled to reflect on the way we have come and on the road ahead. Our predicament becomes conscious in the question: "Will humanity even survive to the end of the coming millennium?" Of the thirty or so generations that span a thousand years, we already have direct experience of two or three. These thirty generations may be listed spaciously on a printed page; but, nonetheless, a thousand years defies our comprehension. What indeed could Charlemagne have predicted about our times? Proper experience of the past is essential for any extrapolation to the future but, even then, what is really new remains a surprise. In basic research, the situation is no different. New insight can open up whole continents of new opportunities. Moreover, all the things that shape our daily life depend essentially on discoveries and insight from the most recent past. All that we can really say about the future is almost a truism: changes in our way of life will be yet more radical in the coming millennium than they have been in that which is drawing to a close.

The world population is currently growing hyperbolically. How does hyperbolic differ from the exponential growth that is usually referred to in publications on this subject? Well, the latter involves successive doublings at equal intervals of time; with hyperbolic growth, these intervals become steadily shorter. A constant percentage rate of birth already yields exponential population growth, but, over and above this, an increasing percentage of people reach sexual maturity as a result of improved hygiene and medical care of infants and children in developing countries. The most recent doubling of the world population took only 27 years. There are now 5.5 billion of us on earth. If things continue according to the hyperbolic law, which has accurately described the increase of the past 100 years, there will be 12 billion people in 2020 and in 2040 the growth curve will tend asymptotically to infinity! I can see myself being quoted in the media: "Scientist prophesies growth catastrophe in the year 2040." Steady on now: the only prediction that I can make with certainty is that this will not take place; it cannot, since the resources of the earth are limited. We do not know where the coming century will lead us. Nevertheless, the really uncanny aspect of our predicament is not this fatalistic nescience. Much more disconcerting is the fact that we cannot derive anything from the present growth behaviour, not even in principle. Near such a singularity, even the smallest fluctuations can be amplified and come to have an enormous effect. Catastrophes, on a small scale or even of a global character, will limit the growth of world population. Such catastrophes are certainly not new to us. We know too that we stand helpless before them in their path. There is something amiss with our ethics, which is still matched to an epoch where human survival (or that of smaller demographic units) had to be secured through numerous offspring.

You may wish to interject that the population of industrial nations long ago reached equilibrium. In some countries it is even declining. Nonetheless, our population density is so great that, if it were to spread to the entire land mass, there would be a population of 30 to 40 billion people. According to a study by Roger Revell, that would be about the maximum number that could be maintained by mobilizing all conceivable planetary resources. An increase in food harvests over the entire earth to the local maximum when he wrote (corresponding to the corn harvest of the state of Iowa in the USA for instance), would be necessary just to barely feed such a population. There could be no prospect of general prosperity. The number calculated by Revell allows perhaps for a few regions of ample production, but in most regions there would be a catastrophic deficit. In this analysis, I have not even mentioned the environmental problems that are already getting out of control. Neither has mention been made of bottlenecks in the exploitation of resources and in energy production, nor of sanitation or medical emergencies.

This must suffice for an introduction. I wanted to describe the backdrop before which humanity's development will be played out. We should not lose sight of it when considering the future of science and our associated expectations, fears and hopes.

Turning now to the main topic, I will begin my disposition by taking stock of the current situation.

The biology of the 20th century

One is indeed justified in proclaiming the second half of this century as the era of molecular biology, analogously to the first half as the age of atomic physics. In fact it was physicists who first took up the analysis of the concept of life, even if this initially led in the wrong direction. Pascual Jordan's *Physics and the secret of organic life* from the year 1945 and most notably Erwin Schrödinger's 1944 book *What is life*, published in England, are characteristic examples. Schrödinger's text was epoch-making, not because it offered a useful approach to an understanding of the phenomenon of life, but because it inspired new directions of thought. Much of Schrödinger's prophetic content had long since been resolved by biochemists, but no one had previously so openly delved for basic principles. Nonetheless, it was not pure theoreticians who initiated the turn of the tide in biology and established the new science of molecular biology. They stood helpless in the face of the complexity of living things. Rather it was physicists who began to experiment in a radically new way, using our basic knowledge of the chemical nature of life processes as a springboard. There was Max Delbrück, a theoretical physicist of the Göttingen school who, inspired by Nils Bohr's complementary principle, decided to investigate the molecular details of inheritance. This was the foundation of phage genetics. And then there was Linus Pauling, a physicist of Sommerfeld's school who sought a deeper understanding of the nature of proteins, the molecular executive of living cells. He discovered in the process essential structural elements, forming figuratively a seam between chemistry and biology. Most conspicuously, there was Francis Crick, a technical physicist who had been involved in problems of radar during the war, who together with James Watson in 1953 reconstructed the double helical structure of DNA from X-ray reflections. In the process, and this is what really made the discovery important, he concluded how genetic information could be stored and transferred from generation to generation. In Cambridge there was also Max Perutz, working in the Cavendish Laboratory under Sir Lawrence Bragg, whose method of X-ray interference patterns he applied to such complex molecules as the red blood cell dye, haemoglobin, elucidating together with John Kendrew for the first time the detailed design of a biomolecular machine. That was the birth of molecular biology.

Today we have a broad appreciation of the molecular design of living cells, including detailed mechanisms of the molecular processes lying at the basis of cell functions. We know about perturbations and breakdowns of such functions, as expressed in the most diverse sets of clinical symptoms; how parasites in the form of bacteria, fungi and viruses destroy the life cycle of an organism. Indeed, we can even go so far in regulating these life processes as to permanently alter their genetic program. Increasingly, the currently more chemically oriented pharmaceutical industry is exploiting our detailed knowledge of molecular biology and the associated technical opportunities. It is basic research, paramountly, that has irrevocably embraced the so-called recombinant DNA technology. What would we know about the molecular structures of the immune system, or about oncogenes or AIDS without this technology?

But I don't wish to bombard you with a quasi-alphabetical list of all the highlights of molecular biology, nor to confront you with a list of the names of those, from Avery, Luria and Delbrück to Neher and Sackmann, who excelled in creating them. Neither in my account do I want to deal with the biology of the first half of this century more specifically, other than to say that it was not just a completion of the grand concepts of the 19th century, of the ideas of Charles Darwin and Gregor Mendel, the insights of Louis Pasteur, Robert Koch, Emil von Behring and Paul Ehrlich. The first half-century established primarily a chemical foundation, through the work of Otto Warburg, Otto Meyerhof, his students Hans Krebs and Fritz Lipmann and many others, upon which the molecular biology of the second half-century could develop. I would much rather focus on the fundamental questions of biology. Answering them has only entered the realms of possibility through the compilation of detailed molecular knowledge in the 20th century. In doing so, we will cross the threshold into the 21st century and cast a glance into the future. Many questions that we can formulate today will only find a satisfactory answer in the coming century.

What is life?

Not only is this a difficult question, perhaps it is not even the right question. Things we denote as "living" have too heterogenous characteristics and capabilities for a common definition to give even an inkling of the variety contained within this term. It is precisely this fullness, variety and complexity that is one of the essential characteristics of life. Possibly it will not take very much longer until we know "everything" about the *E. coli* bacterium, perhaps even about the fruitfly *Drosophila*. But what will we then know about humans?

It is certainly then more sensible to ask: how does a living system differ from one that is not alive? When and how did this transition take place during the history of our planet or of the universe as a whole?

As a chemist I am often asked: what is the difference between a coupled chemical system albeit arbitrarily complex, and a living system in which we again find nothing other than an abundance of chemical reactions. The answer is that all reactions in a living system follow a controlled program operated from an information centre. The aim of this reaction program is the self-reproduction of all components of the system, including the duplication of the program itself, or more precisely of its material carrier. Each reproduction may be coupled with a minor modification of the program. The competitive growth of all modified systems enables a selective evaluation of their efficiency: "To be or not to be, that is the question."

There are three essential characteristics in this behaviour which are found in all living systems yet known:

1 Self-reproduction—without which the information would be lost after each generation.

2 Mutation—without which the information is "unchangeable" and hence cannot even arise.

3 Metabolism—without which the system would regress to equilibrium, from which no further change is possible (as Erwin Schrödinger already rightly diagnosed in 1944).

A system that shows these properties is predestined to selection. I mean that selection is not an additional component to be activated from outside. It would be meaningless to ask who does the selecting. Selection is an inherent form of self-organization and as such, as we know today, a direct, physical consequence of error-prone self-reproduction far from equilibrium. Equilibration would only select the most stable structure. Selection—an alternative category incompatible with equilibrium—chose instead a sufficiently stable structure which is optimally adapted for certain functions which ensure the preservation and growth of the organism. Evolution on the basis of natural selection entails the generation of information.

In order to fix information structurally, defined classes of symbols are required, like the letters of an alphabet or the binary symbols of a computer code. Additionally, we need the connecting relations between symbols forming words and the syntax rules which combine words into sentences. Facilities to read the sequences of symbols are admittedly also necessary and, ultimately, information is only that which may be understood and evaluated. The ability to deal with information in our language is coupled with the existence of a central nervous system.

What form does this take in the case of molecules? Information storage in molecules is subject to the same prerequisite that the information be "readable" and may be evaluated. Only with nucleic acids did molecules learn to read. Complementary interaction, an inherently specific association between two matching pairs of nucleic acid building blocks, underlies this ability of nucleic acids. So the basis of molecular information processing is base pairing, as discovered by Watson and Crick. This at first purely chemical interaction enables the transcending of chemistry, for the chemical building blocks act primarily as information symbols. Evolution, first molecular, then cellular and finally organismic, was only possible through reproduction and selection. It no longer selected according to purely chemical criteria but according to the functional encoding of information. Man differs from *E. coli* bacteria not in a more efficient chemistry but in greater information content (in fact a thousand times more than a *coli* bacterium). This information codes for sophisticated functions and makes complex behaviour possible.

The formation of a subcellular information processing system occurred 3.8±0.5 billion years ago, as we can reconstruct today from comparative studies on the adaptors of the genetic code. Accordingly, life probably began on earth and not just somewhere in the universe.

It is not older, but also not much younger than our planet. This means that life arose as soon as conditions were suitable. There were already single celled organisms at least 3.5 billion years ago. Admittedly, the path to the true masterpieces of evolution, to the multicellular plants, insects, fish, birds and mammals, was a long and difficult one. It took all of 3 billion years. Mankind entered the stage in this magnificent drama only one million years ago.

Molecular biology has confirmed Darwin's fundamental idea through its ability to disclose what the genomes of living organisms have in common. Information, in this case genetic information, is formed by way of successive selection. Darwin proposed his principle for the evolution of autonomous living things. An extrapolation to precellular systems, to answer the question "How did the first life forms arise? From where did the first autonomous cell come?", seemed to him to be too daring a step. Once he did express a speculative "if" and qualified it immediately with "oh, what a big if!". The exciting realization today is that selection is already active at the molecular level, with replicable molecules like RNA and DNA, and so is amenable to a derivation on the basis of the physico-chemical properties of molecules. This closes a gap which yawned between biology on the one side and physics and chemistry on the other. This does not imply that biology may be reduced to physics and chemistry in the conventional sense. It simply confirms that there is a continuity between physics, chemistry and biology. The physics of living systems has its own characteristic regularities. It is a physics of information production.

The new theory of self-organization goes far beyond Darwin in detail and answers questions that had to remain open or were even paradoxical in his time. Darwin's legacy is a testimony of the 19th century.

Ludwig Boltzmann once said (in 1886): "If you ask me earnestly whether this century will be called the iron century, or the century of steam or of electricity, I must answer without hesitation, it will be called the century in which the mechanisms of nature were encaptured, the century of Darwin." Surely Boltzmann hid his light a little under a bushel there in paying tribute to Darwin. Only today is it apparent that the reduction of living phenomena to a mechanical conception of nature is only one side of the story. The natural laws underlying selection and evolution overthrow any purely causal-mechanical conception of nature and describe a world with an open, indeterminable future. This change of paradigm, perhaps the only one in natural science which deserves the title, is not limited to biology. It has extended to the whole of physics over the past few decades and will work out its consequences over a far longer period. While learning how information can arise, we build a bridge between nature and mind.

How is (biological) information generated?

Since the middle of this century, we have been in possession of a theory bearing the name information theory. Its founder, Claude Shannon, however, pointed out from the beginning, that it is not a theory dealing with information itself but rather with the communication of information. The information as such is excluded from consideration, it is treated as given, one sequence of symbols amongst many alternatives which must be maintained during transmission, irrespective of its semantic content or value. Information in this theory only features as a complexity measure. A string made up of two symbols, for example one and zero, of length N has 2^N possible alternative sequences. Even for relatively short sequences of length N about 300 (occupying a paragraph on less than half a printed page), the number of alternative paragraphs is larger than the number of atoms in the universe. Only a dynamic theory of selection can account for the difference between meaningful and meaningless sequences, by means of criteria which evaluate their semantic or phenotypic content. In order to enable an evolutionary optimization of this content, it must be reproduced with a finite error rate. Indeed there is an error threshold, immediately beneath which evolution is optimal, but above which the information falls victim to an error catastrophe. It vaporizes just as if at a material phase transition.

A modification of the Darwinian world view is already apparent here. Natural selection is not simply an interplay between random mutation and deterministic, necessarily consistent selection. With such a large number of alternatives, the successful guesses for advantageous mutants would occur much too seldom. Today, this interplay of chance and necessity can be simulated readily on a computer. A process running according to this scheme is found to progress much too slowly. If natural selection had proceeded according to this scheme we would not exist.

In reality, molecular evolution near the error threshold involves an extremely broad spectrum of mutants. The best adapted (fittest) type, the wild type, that plays such a major role in Darwin's theory, is only present in relatively small numbers compared with the total population at the molecular level. However, the large number of mutants do indeed cluster about the best adapted type, so that the mean "consensus" sequence does represent the entire population. Molecular biologists have learnt how to determine such sequences. Cloning experiments have revealed that the wild type does in fact correspond to the mean of a spectrum of myriad alternative sequences. In essence, this population is composed of only those mutants that can be efficiently reproduced. This theoretical result has been confirmed experimentally for virus populations. Since there are many billions of more or less mutated copies in such a molecular or viral distribution, which is fully stable below the error threshold, it is as if dice were being cast in a billion channels in parallel. If a better adapted mutant is found, the previous distribution is no longer below the error threshold. It becomes unstable and its information content vaporises only to condense in the vicinity of a new wild type. Despite the continuity of the underlying molecular processes, we see that evolution proceeds via discrete jumps. Selection proves so efficient because it is a property of the whole population, representing a massively parallel sequence of events. If one wanted to simulate this process, one would need a new kind of parallel computer. To perform such a simulation on a serial computer would involve impractical demands on time and money. Nature demonstrates what form the computer of the future must take. Our brain is such a parallel computer with many billions of nerve cells, each one of which is connected with some 1,000 to 10,000 neighboring cells via synapses. Our immune system, too, is a cellular network of this order of complexity.

At the end of the 20th century, we are conscious that in many different branches of biology analagous questions are being formulated. These can be commonly phrased as "How is information generated?" This is true for the process of evolution at the molecular level, for the process of differentiation at the cellular level and equally for the process of thought in a network of nerve cells. Still more exciting is the appreciation that nature apparently uses similar fundamental principles in quite different technical implementations in molecular genetics, the immune system and the central nervous system. The 90s were designated in the USA as the decade of brain research. The legacy of biological research in this century will be a deep understanding of information creating processes in the living world. Perhaps this entails an answer to the question "What is life?".

Only, "the devil is in the nuts and bolts". Very soon, we will know the construction plans of many living organisms, and we will know how these have been found in the course of evolution. The historical roots, however, are still completely shrouded in mist. The schoolmen early asked the question, what came first—the chicken or the egg, or, in modern terms, proteins or nucleic acids, function or information. The RNA world, containing as it does a genetic legislative and a functional executive, may offer a way out of this dilemma. I must admit that we do not (yet) know how the first RNA molecules "entered the world". From an historical perspective, the proteins should have come "first", but historical precedence is not necessarily identical with causal precedence. Evolutionary optimization requires self-reproducing information storage and we only know nucleic acids to be capable of this role. So RNA, or a precursor, would have been necessary to set the merry-go-round of evolution in motion.

We are now in a position to observe in laboratory experiments the process of information generation in systems that contain both components: proteins (as enzymes) and nucleic acids (as information storage). Viruses are outstanding model systems. Viruses cannot however have formed a pre-biotic world. They need a host cell to survive, with whose help they have evolved, that is, probably only post-biotically.

The accumulation of knowledge about the process of information generation which we have achieved in the past 20 years is already beginning to bear fruit. Using laboratory methods, we will be able to produce new kinds of natural medicines and drugs. These skills are not restricted to the molecular level. In the same manner, we will understand the ontogenic level of living organisms and be able, for example, to intervene to heal tumors by causing them to degenerate. We will learn to know and to model our nervous system and its mode of operation. Artificial life and thinking computers will no longer be relegated to science fiction. It is scarcely possible to assess the impact all this will have on our lives.

But—there will be limits, both natural and normative. We will have to determine parts of our knowledge we may apply, those parts that we will have to apply despite an awareness of possible side effects and those aspects that we must not meddle with, let alone apply. A blind frenzy of application is just as dangerous as a strict prohibition. We, the whole community of man, must find out rationally what should or should not be done, what must be done and what must not. Precisely in this context is where I see the biggest unresolved problem which will occupy us in the coming century.

What problems remain unresolved at the end of this century?

Some problems have been raised above; but even if I constructed a restricted list of only those problems which we can precisely define, it would be unmanageably lengthy. So I can only proceed by examples and I have chosen two problems from the heart of my own branch of research: one scientific problem with a great impact on society and a second problem where society has a great impact on science.

One problem which has not been solved despite the most intensive research is AIDS. What is AIDS? The word is an acronym for Aquired Immune Deficiency Syndrome. The disease is initiated by a virus or, to put it more cautiously, is causally linked with a viral infection. The question as to whether the virus is both necessary and sufficient for the outbreak of disease symptoms is currently under vigorous debate. There are two known subtypes of the human immune deficiency virus: HIV-1 and HIV-2. In addition, a larger number of monkey viruses have meanwhile been isolated that, while showing no pathogenic effect in their natural hosts, do so on transmission to other populations of monkeys. The US Center for Disease Control has established that on average ten years pass between viral infection and the outbreak of disease symptoms. More precisely, one finds that after ten years about 50 percent of those infected show disease symptoms which quickly lead to a complete paralysis of the immune system. The disease AIDS then always results in death, mostly due to an infection by a pathogen with which the immune system would normally have easily dealt. Many patients die of pneumonia, precipitated by a bacteria (*Mycobacterium tuberculosis*) which is latent in nearly every second person. During the symptom-free period, the AIDS virus itself is only present in a very small population in the organism. The latter produces antibodies in large quantities, with whose help the presence of the virus is detected in AIDS tests. In the USA, the number of registered cases of AIDS has now climbed to well over 100,000. Worldwide, the number of people infected with the AIDS virus is estimated to be nearly 10 million, with a concentration of cases in Central and West Africa and in S.E. Asia. No lasting therapy is known.

Where does AIDS come from? How old is the virus? When did it first appear in the human population? To answer these questions, the wildest hypotheses have been expressed. The ultimate was the claim that the virus was "composed" in a US army laboratory and escaped by accident into the ecosphere. This is pure nonsense! Sequence analysis of the genes of this virus resolve its evolutionary history, or at least quantitatively constrain it. And these are the results:

- Both human subtypes, HIV-1 and HIV-2, as well as the currently known monkey viruses have a common ancestor that can be dated to about 1,000 years ago.

- All HIV and SIV sequences show matching positions (about 20 percent) and clear homologies in these to other retroviruses, of mammals. The AIDS pathogen is thus the progeny of an old family of viruses whose origin reaches back many millions of years.

- The majority of the variable positions have a mean substitution time of approximately 1,000 years. The special behaviour of the retrovirus, especially its pathogenicity, can change radically in such a period of time. Thus, plagues like AIDS may come and go. They may prove more pathogenic for some species and less so for others.

- A smaller population (about 10 percent) of the positions prove to be hypervariable with a mean substitution time of about 30 years. This is, nonetheless enough positions to generate an enormous number of different mutant combinations. Among these, escape mutants are repeatedly found that are not suppressed by the immune defense. In the end, this exhausts the immune system and is probably the main reason for the pathogenicity of the virus.

- The AIDS virus certainly did not appear in the USA, Europe or Japan before the sixties. In Africa, related forms may be dated back to the previous century. During the last hundred years, horizontal transmission between monkeys and man may be seen. The focal point of HIV-1 lies in Central Africa and that of HIV-2 in West Africa; HIV-1 and HIV-2 separated, like most species-specific monkey viruses, many hundreds of years ago.

The high pathogeneticity of the virus has three causes:

1 Since HIV is a retrovirus, its genome is integrated in the genetic program of the host cell following infections. Once a cell is infected it can no longer free itself of the viral information. At most it can suppress its expression.

2 The target of the virus is the immune system itself, whose control centre is paralysed by the virus.

3 Because of its high mutation rate, which incidentally is right at the error threshold, the virus consists of a widely dispersed mutant spectrum containing a large number of escape mutants.

The virus evolves without pause under the selection pressure exerted by the host's immune system. The infected individual is thereby unprotected against every normally harmless parasite.

The difficulty in fighting the virus lies in its great adaptive potential. The virus manages to give the host's defence mechanisms the slip with the help of "side-stepping" mutants. Since the viral strategy is now known, there is some prospect of finding an antiviral strategy that takes account of the side-stepping behaviour, leaving the virus no chance of surviving. To seek out such a strategy we need not only genetic technology but also animal experiments. Whatever our position on these, the reality is ten million HIV-infected people, of whom the majority will develop AIDS symptoms by the turn of the century. Hardly any of these will survive—unless we have found an effective therapy by then.

The second problem has exactly the reverse polarity, directed from society to science. For several years now, we have had a gene law in Germany. Indeed it is the toughest in the whole world. It has begun to cause paralysis in research and industrial development. On the other hand, we should credit the fact that worldwide there have not yet been any mishaps or very serious accidents. Recent proposals even go so far as to require the prior proof of the absolute safety of a procedure. But what is "absolute safety"? Even now, before any application of a procedure, every conceivable test is carried out and a long probationary period is adhered to. Nowadays the demand is being made to exclude things which are not yet known. This would bring research to a complete standstill and as a consequence make the development of new medicines impossible. (Proposals for animal protection laws also lead in this direction). I will now give an example. Before the beginning of the 60s, spinal paralysis of children, poliomyelitis, was a terrible plague in our latitudes. It manifested itself in both isolated cases and world wide epidemics claiming many victims and many lifelong handicaps. In 1950 alone, 30,000 cases were recorded in the USA Today, such cases have almost completely disappeared thanks to a rigorous program of prophylactic vaccination. Only in developing countries, and here largely because of an inadequate inoculation program, is poliomyelitis still a serious problem. The pathogen is a virus, a so-called picorna virus. There are at present two vaccines, either a mixture of killed virus (Salk vaccine) or a so-called "attenuated" virus (Sabin vaccine) that is a mutant, no longer pathogenic, of the wild type that nonetheless evokes an immune reaction which is stronger than that of the killed virus. It is especially thanks to this orally dispensable vaccine, with its ease of use and great effectiveness, that the virus could be almost completely eradicated in the western world. Occasionally, instances of the illness are observed, but their course is relatively mild.

This was all very well. All the more unexpected was it, when the RNA sequence of one of the Sabin vaccines (B-type) became known a few years ago. It turned out that essentially a two-error mutant of a pathogenic wild type was involved. Such a mutant can revert to the wild type inside 48 hours. Apparently this period is long enough to initiate an effective response by the immune system. Since mutations are random events, occasionally more rapid back mutation is possible and this may be the cause of the isolated occurrences of the disease. In the case of AIDS, such a vaccination program would certainly set off a disastrous epidemic.

What is the difference between the polio virus and the AIDS virus? Both their genomes consist of a single RNA molecule. The mutation rates prove to be of a similar magnitude in both cases. With the help of a new method of comparative sequence analysis, called statistical geometry, we found out that there is a vast heterogeneity in the fixation of mutations in the different codon positions in the gene which codes for the surface proteins of the virus. Each protein building block is determined by a codon containing three positions. The first two determine the specific type of amino acid to be incoporated in the translation, while exchanges in the last position yield mostly synonymous amino acids, that is, producing no effect on the amino acid sequence of the translated protein. With the AIDS virus, all three codon positions are substituted at an equally high mutation rate, thereby creating a large spectrum of different protein molecules (some of which escape from the immune response). However, in the case of the polio virus, almost the only mutations that are fixed are those in the third codon position. At least, virtually all of the different, widely spread mutants that have been found differ only at the third codon positions. These substitutions are so numerous, that there is almost complete substitution, while the first and second codon positions remain almost unchanged in all mutants. This means that the proteins on the surface of the polio virus scarcely change. There are hence no escape mutants. The immune system can "get its eye in", that is, an effective immune defense is built up within a short period.

But now to the moral of the story: had one known that the attenuated virus was such a close relative of the pathogenic wild type, there would surely have been the gravest scruples about allowing such a vaccine. According to the current view, this would certainly not be possible since it has become common to produce such mutants through directed mutagenesis, that is, by genetic egineering. One would now be "circulating a genetically manipulated pathogenic agent". At any rate, we could not exclude with our current state of knowledge a risk that is in fact a real one, as shown by the occasional incidences of the disease after oral vaccination. Nothing was known of all this when the Sabin vaccine was introduced. One proceeded, quite legitimitately, by empirically testing the attenuated virus. There was then absolutely no other alternative.

However, a genetically engineered mutant is no different from one arising naturally. In one case, we manipulate and *we know what happens.* In the other, nature manipulates by itself and we don't know what comes out but can only test empirically what happens. One method is branded evil, the other accepted as natural, although it is always easier to control a risk by *conscious* action than by unconscious tinkering. Reading the text of our gene law, one repeatedly meets such nonsense; one wishes to exclude every risk 100 percent while accepting other imponderables without consideration. For example, research work that could one day serve to ward off a danger is totally suppressed. In the case of polio, one would certainly have avoided the not quite risk-free path of genetic manipulation and that would have de facto meant the death of many children. The sabin vaccine saved them, because one trusted nature blindly and thereby accepted unconsciously the inherent risk.

In this context, the question must be raised: how far should the indifferent majority of society give in to the ideological arguments of an emotionally aroused minority against the advice of specialists? What is, ultimately, freedom of research, as guaranteed in our constitution? I wish by no means to interpret freedom as a total lack of restraint. We can neither do all that we know nor should we do all that we are able. What other way is there to make decisions if not rationally? In the case of Hiroshima, there was insufficient military and political sense, and in the case of Chernobyl, there was too little technical sense. Knowledge cannot be "undiscovered". We must learn to live with it. For this purpose, a sensible legal structure is required that should be *internationally* binding. Over and above this, there is an ethical duty to employ available knowledge for the benefit of mankind, whether it be to reduce the suffering of individuals or to ensure the health and nourishment of the world population. I return to the scenario of the future of mankind which I described in my introduction. An environmentally just safeguarding of food production for a multi-billion strong world population, an adequate system of sanitary and medical care for such "masses of people": these are things only possible today if all available knowledge is applied. This includes a genetically engineered breeding of new organisms for food as well as the use of nuclear technology for electricity production.

The future: the study of mankind is man!

We live in a society that shies away from risk. Will it come to the point that society, for this very reason, closes the door on science and especially on basic research. It would not surprise me even now to see on the rear window of a car, belching blue-grey exhaust, the sticker "Basic research—no thank you!". What some members of the animal protection movement are engaged in is pitched at least down at this level. The opponents of atomic power are happy that electricity flows from the wall plugs at home. We can do nothing useful without taking on risks at the same time. Failing to do anything can be the greater evil in the long run. We must learn to weigh odds, and slogans are not very helpful in this.

When I speak of the future of biological research, it will be of increasing problems of risk evaluation, of responsibility and ethics that we must debate. For the central object of biological research is man and his environment, "his" meaning relative to man. Consequently, the results of research are relevant to everyone.

I do not want to attempt to construct scenarios for the coming century, let alone for the coming millennium. According to Friedrich Dürrenmatt, problems are only fully thought out "when one has imagined the worst possible turn of events". Indeed, futurologists are liable to paint only the rosiest possibility.

We will be able to explore the genetic nature of man far better than we have ever dreamed for there will be machines that will be able to read the three billion letters of human inheritance inside a month. This will, in particular, enable comparative studies to be made. In the same way, we will determine the genetic sequence of very many other life forms and then be able to unravel our own evolutionary origin. We will fathom the human brain and build computers that far exceed the brain in particular tasks. I do not believe that we will ever possess a computer that even approximates the human brain in all its capacities, but a connected brain and computer will demonstrate "superhuman" capabilities. We will not be able to crystallize an homunculus, but robots will be invested with powers hitherto met only in the biological realm. Whether we call this "Artificial Life" or not is only a matter of taste. We will be able to cure cancer, because we are uncovering more and more of its causes. Furthermore, for heart disease, we will be in a position to make earlier diagnosis allowing medical assistance to come in time. Nevertheless, in the long run it will be immaterial from which illness we die, because even in the future I expect our age to hardly exceed 100 years. We need not actually worry whether the cities of the future will have a glass dome and an artifical atmosphere. But we certainly should ask ourselves today: where will we obtain all the energy that will be needed one day to maintain a recycling economy? Keeping air and water clean is a task bound up with high entropy production. A timely provision for the future is essential here. Admittedly, there will be many novel discoveries and inventions that defy our imagination now. It is just for this reason that every detailed scenario for the future will be wrong. We are in the same position as Charlemagne would be if his contemporaries had asked him about the world of the 20th century.

Despite this, one prognosis is reasonably certain: whether the course of humanity takes the worst or the best possible turn will depend on whether man finally learns what he has failed to learn in the five millennia of his cultural history, namely, to act rationally and sensibly in the interests of humanity and to work out well-defined rules of conduct. The latter are analagous to a genetic program and must be established as binding for all.

Man stands on the highest rung of the ladder of evolution. I say this, not because I can't imagine any creature more perfect, but because with man evolution has reached a new platform, accessible to no other organism, from which evolution must proceed in a radically new fashion. Operating on the basis of selection, evolution requires the continuous mutagenic reproduction of information, laid down like printers' type in our genes. New avenues of communication have opened up between cells with the formation of cellular structures and networks. These were originally mediated by chemical signals that are collected by specific receptors and ultimately mediated by electrical signals that are received by synapses and relayed to the next cell. By this means, a correlated overall behaviour of the differentiated cell system could develop, preprogrammed in the genome only in its layout. It is selection that ensures that this layout operates to the advantage of the whole organism. This is incompatible with single cells or organs working against one another. Such antagonism can only take the form of diseased degenerations like cancer. In the central nervous system, this intercellular communication has developed into an inner language that controls our behaviour, emotions, disposition and feelings. Even this facility has become genetically anchored and has been selected so that it is not directed against the species. This is the way in which man arose in the course of evolution and this genetically programmed, individualistic and species-specific behavior is inherently egoistic, set on competition and self-assertion. In places where instead it appears altruistic, it rather serves in the long run the advantage of the species or clan, which, in its turn, has an advantageous effect in some way on the individual.

Man has, by this means, developed a specific faculty, distinct from that of other primates, that allows him to achieve a formalizing of the inner language coded primarily in nerve cell discharges. This formalization not only facilitated the communication between members of the species, it also formed the basis of our ability to think, to record results for the benefit of mankind and to bequeath them to following generations by setting them down in writing. This implies a new plane of information transfer, similar to the primary plane of genetic information which added a totally new quality to chemistry. On the plane of the human mind, a new form of evolution can take place: the cultural evolution of humanity.

However, there lies the key problem. Humanity is not something like a multicellular organism in which every cell leads its individual life but is committed by the genetic legislature to the common good of the cell community. Cultural information is not inherited by the individual, just as little as is socially acceptable behavior. Despite the cultural evolution of humanity, which has lasted now for thousands of years, people still engage in war and no less cruelly than ever. We delude ourselves if we believe that socially acceptable behavior is something natural and asocial behavior, in contrast, something pathological. It is the norm only in the original sense of the Latin word *norma,* meaning rule or regulation.

We find ourselves in a genuine dilemma, for all previous attempts to subject individual freedom to dictates, degenerating the individual to the status of a cell without will in a centrally controlled organic whole, have only harmed human society in the long run and have even resulted in the annihilation of parts of humanity. These experiments have failed, partly because the new organism was not the whole of humanity but only a certain grouping, representing special interests which often violated basic human rights. Partly they have failed because the "leading cells", the "brain cells" of this large organism, were mostly self-obsessed or egoistic human cripples, primarily concerned with exercising power. Incomparable suffering was the result.

Ideologies cannot replace reason. All political groupings that advocate party discipline should come to appreciate this. Of course, they stand for ideals that have a valid basis, whether they call themselves socialists—who wouldn't be for a social conscience?—or Greens—who wouldn't like to keep the environment clean?—or Christians—who would wish for a world without mercy or charity? This holds equally for those who want to place the freedom of the individual above everything else. Each of these motives, raised alone to a pedestal of doctrine, is directed against our common sense, in which, incidentally, not only our intellect but also our limbic system, our feelings and emotions are involved. Even in the future, we will by no means be able to delegate our judgement to a computer.

One glance at the current state of the world is apt to make us pessimistic. The first half of this century has dealt us two of the most shocking wars. And what lessons have we learnt? Nothing will change if we do not base our decisions on reason accepting humanity as a moral imperative. The future of mankind will not be decided at the genetic level. We need a binding system of ethics for all people. Here evolution, an evolution from the individual to humanity, awaits its consummation.

The Human Genome Project—Promise or Threat?

Professor Ulf Pettersson

By the year 2005, the human genome is expected to be characterized in all its details. This grand scientific enterprise is called the human GENOME-project or the HUGO-project (HUGO = HUman Genome Organisation). The results will provide a blueprint of the human body and they will be of immense importance for all future biomedical research.

Mapping the human genome is not new science. The mapping of human genes started in the 1960s when the first methods for gene localization were disclosed. Gene mappers have in the past been working on their favourite genes and knowledge about our genome has accumulated incrementally. In fact the human genome would be mapped and sequenced even without the GENOME-project. The new idea is to co-ordinate a worldwide effort, to increase the pace and to ascertain that the work is completed, using state-of-the-art methods.

The human genome resembles a teleprinter tape; it is a linear text without headlines or punctuation marks comprising some 3,000 million letters (nucleotides, represented by the letters A,C,G, and T). The text is subdivided into a number of smaller 'volumes' which the geneticists call *chromosomes*. The purpose of the human GENOME-project is to map each chromosome and eventually to determine the identity of all the 3,000 million letters that comprise the whole human genome. To accomplish the goal of having everything sequenced by year 2005 the collective world wide sequencing effort must on the average generate about 1 million nucleotides per working day. By today's standards this is an astonishing accomplishment. To grasp the width of the undertaking an historical comparison might be appropriate. The first nucleic acid to be fully sequenced was a small molecule comprising some 80 letters. This sequencing task took one team several years to complete and it rendered the person responsible for the project a Nobel prize in 1968.

To facilitate the mapping, landmarks ('markers') are first identified along each chromosome with an average spacing of some million letters (nucleotides). This is accomplished by constructing a so-called genetic map utilizing what are known as markers (a marker is a position in the genome where chromosomes from different individuals exhibit differences). This first goal has been reached—a crude genetic map has already been presented with markers spaced less than 10 million nucleotides apart in most chromosomal regions and denser maps are being constructed with new sets of markers, which will soon reach a spacing of one marker per 100,000–1,000,000 base pairs. The work has recently been speeded up by the discovery of highly informative so-called microsatellite markers, that is, markers representing regions in the genome which exhibit an exceptionally high degree of variability among individuals.

Parallel with the establishment of genetic maps so called physical maps are being constructed. A piece of DNA can be physically located on a chromosome by a microscopic method called *in situ hybridisation.* However, to construct physical maps at the DNA-level it is necessary to isolate fragments of DNA that represent a given chromosomal region. The physical maps can then be expanded so that they finally cover whole chromosomes. The construction of physical maps has recently been greatly facilitated by the development of what are known as YAC-vectors (YAC = Yeast Artificial Chromosome). YAC-vectors are DNA-carriers which allow very large pieces of human DNA to be introduced and maintained in yeast. Artificial yeast chromosomes have been constructed which carry single pieces of human DNA, amounting to more than 1 million nucleotides in size. By isolating sets of YACs which contain neighboring DNA segments it is possible to construct so called *contigs*, that is, collections of YACs which cover a significant portion of a human chromosome. The immense power of the YAC-technology has recently been demonstrated by building complete YAC-based maps of the human chromosomes Y and 21. Some recent results indicate that it will most likely possible to construct complete physical maps of all the human chromosomes from YAC-libraries. Thus the first complete physical map of the entire human genome might already be available within another year.

Once contig-maps are available, large-scale sequencing can begin. The sequencing technology currently in use, was invented in the 1970s by Maxam and Gilbert and by Sanger. Most of the steps involved in this technology were automated in the 1980s. Current automated sequencers have the capacity to produce sequences amounting to some 10,000 base pairs per day and the preparatory work is facilitated by robots which can handle large numbers of sequencing reactions. Today considerable resources are being devoted to the improvement of sequencing technology and breakthroughs can be expected in the future which may change our perspective on sequencing completely. New sequencing methods, based on microscopy, nucleic acid hybridization, or enzymatic degradation of DNA, are currently being considered in different laboratories. If a breakthrough does occur with regard to any of these approaches we could be faced with a situation in which whole human chromosomes could be sequenced in weeks or days. DNA-sequencing is in fact likely to become a routine method in clinical medicine in not too distant a future.

The GENOME-project will result in an enormously complex text which, if printed, would occupy more than 100 meters of book shelves. It is, however, most unlikely that the text ever will be printed in its entirety. Instead the results will be stored in databases with which scientists all over the world can communicate.

A problem with a sequencing project of this scale is that its routine character will make it enormously boring. Many scientists will be attracted to the regions containing interesting genes but when it comes to other less immedately attractive regions of the genome there will be limited interest. It can be anticipated that much of the work will be carried out by companies which specialize in DNA-sequence analysis. Another problem is that about 90 percent of the human genome, like all mammalian genomes, apparently contains junk which will probably generate data that is of little or no biological significance.

The question of whose genome should be sequenced has attracted some attention. In practice, however, this question is of little significance since the error frequency in sequence determination is likely to exceed the sequence variability in most regions of the genome. For practical reasons it seems likely that the DNA whose sequence will be determined is the DNA that was used to construct the best YAC-libraries, since those libraries are already being used by many workers in the field.

The cost of the GENOME-project is calculated to amount to approximately 1 dollar per base pair or roughly SEK 20,000 million for the entire project. This is certainly a large amount of money. However, considering the expected significance of the results it is in my opinion quite reasonable. After all, more money is spent annually in Sweden on advertising and SEK 20,000 million would only suffice to purchase a small number of advanced military aircraft.

The idea of sequencing the complete human genome has been subjected to quite severe criticism. Besides the ethical objections, as discussed below, several other concerns have been raised in connection with the project. A serious objection relates to the cost of the project and the fear that other types of highly significant biomedical research will suffer. It has therefore been emphasised that countries which initiate genome programs should finance these with 'fresh' money and this appears to have been the case in most of the countries which today support large genome programs.

Another objection is that it would be better to concentrate the sequencing efforts on the 100,000 genes which are present in the human genome and ignore the remaining 90 percent which appears to be mostly junk. It has, however, been argued that it will be difficult to know for sure when all the genes are identified, and once the sequencing technology is fully automated it might be nearly as easy to sequence the whole genome as to first select the relevant parts and then sequence only these. Besides, for future work in human genetics it will be of value to have access to the whole sequence without any missing pieces. This particular issue is still, however, subject to debate and recent success in sequencing cDNA clones (that is, clones containing sequences which originate from genes) has provided encouragement to those who advocate a concentration of the sequencing effort on expressed sequences (genes). Judging from the current pace of cDNA sequencing, it seems that more than 50 percent of all human genes might be identified and partly sequenced within another year. It has also been argued that one should sequence the genomes of *Drosophila* or the Mouse before the human sequence is undertaken, since the former can be subjected to experimentation. This is a relevant argument. However, there are good reasons to give priority to the human sequence as it is likely to provide immediate medical benefits. Besides it is for obvious reasons much easier to obtain funding for work on human rather than on animal genomes. Nevertheless it has been decided that, parallel to the work on the human genome, genomes of model organisms like, *Drosophila* (fruit fly), Mouse, *Arabidopsis* (a plant), Yeast, and *E. coli* should be mapped and sequenced.

As the nucleotide sequence of the human genome is being established, it will become important to understand the meaning of the complex instructions that are hidden in our genes. The interpretation of the sequence data will be a much more complex and time-consuming task than the actual mapping and sequencing. The interpretation of the sequence is assisted by computers that help to identify the genes (the 'exons') among the junk DNA. Computers can also help us to make predictions about the functions of many of our genes. Our genome encodes some 100,000 different proteins. However, these are not all unique but rather comprise families of related proteins. Computer analysis will help identify 'motifs' in these proteins which will provide information about possible functional relationships. Immunological methods will also help to establish the location of the different gene products in the body. Moreover, transgenic animals in which genes corresponding to human equivalents have been 'knocked out' will be very helpful for delineating functional relationships.

Is the GENOME-project really worth the effort? The greatest value of having access to a complete genome map and genomic sequence is that it will once and for all provide a manual for how the human body works. This will be a handbook, listing all the protein constituents occurring in a human being between conception and death. Such a handbook will assist biomedical scientists in their efforts to understand the molecular basis of human diseases. Once all components in a living cell are identified this will allow a much more sophisticated understanding of how different cells in the human body interact. Knowledge about the different cellular components and about the interplay between cells will permit the design of new types of drugs. Partly due to results from the GENOME-project, pharmacology will in future to a much greater extent be based on natural components derived from the body. Production methods based on gene technology will allow these to be produced on a large scale. This will in many cases allow a much more precisely targeted and efficient treatment of disease, mitigating or avoiding the side of effects of many drugs in use today.

An immediate result of the GENOME-project will be that many of the 4,500 known inherited monogenic disorders will be traced at the DNA level. This knowledge will allow more precise diagnosis, open possibilities for prenatal and carrier diagnosis and in many cases permit prevention or treatment. Also polygenic and multifactorial diseases, that is, diseases which are caused by several cooperating genes or by a combination of genetic and environmental factors, exemplified by coronary heart disease, high blood pressure, diabetes, etc., will be understood at the genetic level when knowledge about our genes increases. This will allow better preventive measures once we know the significance of the genetic factors.

Early in the history of the GENOME-project, it was recognised that it poses complicated ethical, social and legal issues. Many laymen express deep concern about the ramifications of the GENOME-project, sensing that we are approaching forbidden ground when we look into what is nothing less than the blueprint of a human being. Knowledge about our genes will provide an insight into the genetic basis underlying differences between individuals. All human beings, with the exception of monozygotic twins, have a unique genetic make up. The results of the GENOME-project will not immediately tell us anything about genetic differences between individuals, since the sequence will be derived from very few individuals and since the sequencing error frequency is likely to mask the true differences. However, as more knowledge is accumulated about genes from different individuals we are bound to obtain insight into the genetic basis not only of diseases but also of the normal genetic variation that is observed between individuals. In a disturbing future scenario, we may be able to make accurate predictions about the future life of an individual based on the interpretation of genetic constitutions. This could lead to determinism and resignation among those who have been less fortunate in the genetic lottery. I believe, however, that this scenario is exaggerated. We must keep in mind that an individual is the result of interplay between genetic and environmental factors. In addition, the genetic complexity of man is likely to be so great that it will be impossible to make any reasonable predictions, except in case of diseases or traits which are predetermined by one or only a few genes.

Nevertheless, the fact that we can learn about genetic factors which do influence our health is a cause for concern. There is always the risk that the information will be used for discriminatory purposes. For instance, knowledge about an individual's genetic constitution is of obvious interest to insurance companies or employers in order to identify individuals at risk of developing diseases. Another difficult problem concerns serious diseases for which there is no cure or which cannot be influenced by a change in life style. Is it meaningful to know that one will contract a life-threatening disease in the distant future if there is nothing we can do to prevent the disease from breaking out? Many of us would probably answer no.

The use of genetic tests in a prenatal setting will always be associated with ethical complications. A question that needs to be addressed is whether the pregnant woman herself should be given the free choice to request prenatal diagnosis or if society should impose restrictions to avoid the abortion of foetuses with minor defects. It is important that society undertakes a serious discussion of these complicated matters. An ethical monitoring of the genome project is important and most national GENOME-programs have allocated resources for studies of the ethical, social and legal issues that are thought to be connected with these programs. One of the main tasks of the international organisation HUGO is in fact to address the ethical issues related to GENOME-research.

It is an urgent responsibility of the scientists who are engaged in GENOME-research to participate actively in the public debate. It should, however, be emphasized that the ethical problems that are likely to arise as a consequence of GENOME-research are not new ones. We are already faced with them when using the limited set of genetic tests that can be offered today. We should learn from past experience, and I am convinced that mankind will be able to handle the problems in a way that is acceptable to most of us. It is my firm conviction that the benefits of the GENOME-project are enormous and that there is a clear positive balance between benefits and feared complications.

Ethical Controversies of Future Biotechnology

Professor Erling Norrby

Ethical considerations related to tinkering with the human genome have already been considered by professor Ulf Pettersson (p. 136). In this contribution, ethical problems connected with other applications of the new genetic techniques will be discussed. Thus I employ a restricted interpretation of the term biotechnology, which may be excused by the fact that most current advances in this realm reflect the introduction of powerful new methodology to identify, modify and transfer genetic material. From the start I must emphasize that my professional background is that of a researcher devoted to studies of viruses—I am not an ethicist. Still, my responsibility for a number of years as chairman of the Swedish Recombinant-DNA Committee, among other things, has fostered an interest in ethical value assessments. The subjective remarks that follow are made in good faith.

These reflections will be divided to first give some remarks on the evolution of science, in particular biological science, and then to consider applications of the new technology to animals, plants and microorganisms. Finally, some general ethical considerations taking their point of departure in anthropocentric evaluations as applied to the diverse and abundant applications of the new gene technology will be considered.

The evolution of science

Science in its modern sense is a young branch on the tree of civilization. After the period of romantic enlightenment, science began to emerge as a hypothetico-deductive enterprise, first in physics and chemistry and then in biology and medicine. The industrial-technical revolution began in the 19th century and more recently accelerated developments have originated in advances in electronics and computer science.

During the last four decades, we have been witnessing a biological revolution. Interestingly, this revolution brought with it an important new quality which was not associated with preceding physico-chemical developments. This qualitative difference derives from the fact that only biology reflects an evolutionary process. The dramatic development of the branch of biology that we call molecular genetics dates back only to the discovery of the double helical structure of DNA by Watson and Crick in 1953. Since then, we have come a long way in our understanding of the structure and expression of genetic material. The gradual accumulation of knowledge of the structures of the genomes (the sum of the genetic material) of ever more complex live entities, with the eventual characterization of the whole human genome in the HUGO project as discussed in a separate presentation, will provide radically new perspectives on functional homologies and evolutionary relationships.

According to the Finnish philosopher von Wright, we live in a period of increased "biologization" of modern science and society. This development may according to von Wright pose some inherent problems, since as he proposes, modern science in general has relinquished its claim to be a source of values. This view is arguable, at least with respect to the biological sciences. We are, in fact, by the use of modern genetic techniques obtaining an insight into the evolution of life itself. Not only does this insight fill us with awe and admiration, but it also emphasizes the interdependence of different species. The importance of genetic plurality and the intricate ecological balance in nature are starting to be highlighted on a molecular level. The results of our analyses will by necessity have a major impact on our value orientation.

The transgene world—applications of new gene technology to animals, plants and microorganisms

It would be appropriate to preface these words with the truistic statement that since the initiative for performing the genetic modifications to be discussed comes from man, their purpose is to serve man. There exist manifold applications of the new gene technology to animals, plants and microorganisms. In the following, only some selected examples will be given. In animals *(table 1)* attempts have been made to improve the products of animal husbandry. One obvious approach is to amplify the expression of the growth hormone gene. In highly inbred farm animals, the aim is to further increase in size of a stock of animals already selected for this property. Transfection of the growth hormone gene to pigs did in fact lead to a certain increase in size of animals and also to production of somewhat leaner meat. However, there were also drawbacks with the gene treatment. The animals showed an increased susceptibility to infections and also had reduced

Table 1. The application of new gene technology to animals and animal cells

1. Improvement of animal health and animal husbandry
2. Production of pharmaceuticals in animals. Genetic farming—bioreactors
3. Experimental studies—chimeric animals—transgenic animals—gene "knock-out" animals
4. Production of homologous or heterologous proteins in cultural animal cells

fertility. Another goal is to improve the immune resistance of animals and to promote better utilization of food by use of gene technology. These applications are still at an early stage. Possibly more needs to be learnt so that a balanced perhaps multigene transfer approach may be taken to reach these goals. A special use of transgene animals is for so called genetic farming, also referred to as bioreactor application. In this case the transgene animal is directed to synthesize a selected heterologous protein of pharmaceutical importance, for example, the blood clotting factor VIII, for secretion into milk. The advantage of this approach is that large amounts of the selected protein can become available and what remains is to isolate the product from milk by some simplified purification procedure.

The techniques for establishing experimental animals with a defined genetic alteration have been developed extensively during the last years. Mosaic animals were described a number of years ago, but they do not rely on selected transfer of genetic material. The technique of establishing transgenic animals has gradually become more refined. Foreign genes can now be introduced in targeted positions and under conditions that permit their accurate induction and expression. The more recently established gene 'knock-out' technique provides an important supplement to the armamentarium for evaluating the role of individual genes under in vivo conditions. It can be predicted that during the forthcoming decade an avalanche of new information will accumulate. A number of unexpected findings can be anticipated, such as the dispensability of conserved genes highlighting a more complex orchestration of physiological phenomena with parallel and alternate pathways for a particular activity. Models for complicated disease processes in man are now reproduced in animals. One example is the recently described mouse model for the congenital disease cystic fibrosis.

Finally, animal cells can be used in a dispersed form for cell culture, which can then be used as 'work-horses' for production of selected heterologous proteins. Thus a certain cell line from hamsters, CHO cells, is being used for production of growth factors and viral vaccine components. The advantage of the eukaryotic cell cultures as compared to yeast cells and prokaryotic cells is that they can provide a complete post-translation processing of proteins.

Plants provide excellent opportunities for targeted genetic changes (*table 2*). Extensive earlier breeding efforts have led to the highly selected monocultures used in agriculture today. The new transgenic techniques, however, potentially offer the introduction of new qualities, in some cases reflecting abnormal crossing of species barriers. Many examples can be given. Plants to which the gene for the coat protein of tobacco mosaic virus was transfected became resistant to infection with this virus. Genetically modified tomatoes showed markedly improved storing properties. The introduction of herbicide resistance has been debated, since it makes the user dependent on a particular herbicide. It has been demonstrated, however, that successful modification of this kind can be achieved. In contrast, it has not been possible as yet to transfer capacity for nitrogen fixation to plants not normally endowed with this property. This presumably reflects the fact that nitrogen fixation is dependent on a complex multigenic system. Encouraging results have been obtained in attempts to improve both quantitative and qualitative nutritional properties of plants. Finally, plants might also be used for production of heterologous protein. When the tobacco industry is eventually phased out, it could be attractive to use tobacco plants for the large scale production of selected proteins. In one study antibodies were produced in plants. They were appropriately referred to as plantibodies.

Table 2. The application of new gene technology to plants

1. Better resistance to
   - stress
   - temperature variations
   - infection
   - storage
   - herbicides
2. Acquisition of new properties—N_2-fixation
   - improved nutritional value
   - improved photosynthesis
3. Production of heterologous proteins

In the world of microorganisms exchanges of genetic material across species barriers occur extensively. One means for such transfers is provided by the packages of wandering parasitic genes we call bacteriophages. In one hitherto unique case it has been found that a microorganism called Crown gall bacterium can transfer its genetic material into plant cells and programme these cells to uncontrolled division. At this stage no other example of genetic transfer between different kingdoms of live entities is known, but this may merely reflect limitations in our current state of knowledge.

Microorganisms are generally excellently amenable to genetic manipulation, partly because of the limited size of their genome *(table 3)*. Only a few examples will be cited here. Infection of man with microorganisms represents an invasion of foreign genetic material. With the new technique called polymerase chain reaction (PCR) such material can now be identified even when occurring only in minimal amounts. Radically new techniques for diagnoses of infections based on identification of microbic-specific genetic material are becoming available. A precise finger-printing of strains of organisms can now be made. In the field of vaccines there are means of establishing stable attenuated strains, of experiencing selected microbial protein intracellularly by viral vectors or extracellularly by prokaryot vectors and also to produce components for subunit vaccines in the laboratory. A host of other heterologous proteins can also be produced in bacteria. As examples, human growth hormone and Fab fragments of human antibodies may be mentioned. By use of recombinant DNA produced growth hormone it was possible to avoid contamination with prion

Table 3. The application of new gene technology to microorganisms

1. New diagnostic reagents
2. New live vaccines, vector-borne component vaccines, subunit non-replicating vaccines
3. Production of heterologous proteins
4. Improved fermentation
5. Biological weapons
6. Miscellaneous
   - frost protection of plants
   - insecticides
   - degrading of oil
   - cleaning waste fluid
   - heavy metal extraction, etc.

agents responsible for degenerative brain disease, which caus serious problem when pituitory gland extracted material was use From the ethical perspective, this is an example of a situation where i is a moral responsibility to apply the recombinant DNA technology. The technique of production of antibody Fab fragments is currently being established and offers unique opportunities. In future, it will be possible to produce at will antibodies with desired specificity and host species characteristics without immunization. Eventually, this technique will substitute for the monoclonal antibody technique which has hitherto been the method of choice for refined characterization of antigens and immunogens.

Also, when it comes to very traditional microbiological, biotechnological procedures such as baking, brewing and cheese production, improvements can be made by directed genetic modification of the microorganisms employed. Similarly and regrettably, it is also possible to take a more "effective" approach to the development of biological weapons. The only way of ensuring against such an unethical use of gene technology is to enact binding conventions and find efficient means for on-site inspections by external specialists.

Other examples of applications of new gene technology to microorganisms focus on the amplification of preexisting and unique properties of these organisms. Thus bacteria may be used for degrading oil, cleaning waste fluids, extracting heavy metals, etc.

The ecological position of man as a species

The calling of conferences of the present kind, focusing on man and future technology, highlights that we are curious about our ecological role and the particular responsibilities deriving from the unique qualities bestowed on man as a species. In a series of brief interviews carried out in Sweden by a professor of theology, Anders Jeffner, laymen were asked whether they felt that man as a species ranked higher than animals. In about 60 percent of the responses, the answer was negative. This remarkable result may reflect either that the question was inappropriately framed or that wide-ranging future discussions on the implications for society of prevailing concepts are required. Obviously 60 percent of the Swedish population are not vegetarians and probably few have given a thought in this context to the fact that we wear shoes of leather. What then does this answer reflect? Could it be that the majority of people feel that man as a species has his influence too far outside his allotted niche in the ecological equilibrium?

To make the problem more complex, one needs to consider that laymen show different emotional relations to animals of different species. A devastating epidemic among foxes in Sweden stirred much less public involvement than a corresponding epidemic among seals. There is a trivial reason for this irrational behaviour. As pointed out by the Harvard teacher Stephen Jay Gold, the artist creating Mickey Mouse, during the first 50 years of life of this character, transferred him from an adult into a more juvenile character. Thus animals that have certain cardinal features of a young human being promptly stir positive emotional reactions in us, a phenomenon referred to as neoteny, first pointed out by Konrad Lorenz. In fact, to apply a non-anthropocentric view on animals in a vertebro-(animalo)cratic way is essentially impossible. Where do you draw the line? Are you allowed to kill a mosquito?

Let us take another perspective of man's position in nature and go back to the dawn of human civilization. When man settled down and took up collective habitation, exploiting the benefits of agriculture, an irrevocable step was taken towards ecological domination of the globe. This domination has progressively increased, partly as a consequence of population increase, but also as a result of technical progress. It is worth emphasizing that a continued unrestrained increase in world population will stretch the limit of our Earth as a provider within 50 years. What is it that makes the position of man unique? In a famous speech on human dignity, the Renaissance humanist Pico della Mirandola stated that the Creator did not give man a fixed position in the order of matters but that man is the only species that is endowed with qualities that allow him to make choices. Expressed differently, man is the only species that contemplates actions and considers the consequences of actions that are proposed. It it obvious that we never have and never will deny ourselves the use of this ability. In a similar vein, Kant has emphasized the unique role of man as a species with a capacity for—and inherently connected hereto a responsibility for—taking responsibility. We are the only living moral entity.

The value assessment problem

This problem has been discussed for centuries. In this presentation, only some superficial comments will be made. Just recently another verbose report has been presented by a Committee appointed by the Swedish Government to analyse the need for legislative intervention in the field of gene technology. In this report it is concluded that nature has a value of its own, but that this does not deny man a right to change nature (we have already been doing this for thousands of years!) Such changes, however, can only be made with due consideration for a doctrine for the care of Nature. According to this doctrine, man should "prevent serious and irreversible upsetting of balances in basic formation of the natural ecosystem". It is difficult to draw precise conclusions from this statement. For example, what is meant by natural? Nature was never stable. There was an ice age in Scandinavia about 10,000 years ago and there may be another ice age in this part of the world in about 5,000 years. In the field of medicine, we are drastically changing the gene pool. People with diabetes and high infection susceptibility can now live a long life and reproduce. With the use of vaccines we have eradicated smallpox, a threat to human civilization for thousands of years, and we are on the verge of actively and irreversibly eliminating the smallpox virus as a species. However, first we want to have a complete read-out of its genetic program. The hallmark of our ecosystem is unpredictable dynamics.

The communication problem

It is worth reiterating that the only way of guaranteeing the appropriate use of new knowledge generated by a process of unrestrained research is open communication. Thus there must be means whereby the often very involved themes of modern science can be transformed into information that is understandable by laymen and their elected representatives, the politicians. In this process, the various massmedia shoulder a considerable responsibility. Regrettably, the tradition is that new information with a stamp of controversy or general negativism sells better than balanced positive information.

Modern science—not least, biological science—generates an amazing amount of exciting new information, but this information is enjoyed by only a limited number of people. For these, the richness of the information flow allows exciting intellectual excursions, but the same information in a transmuted version could be used for the day-to-day enrichment of the knowledge of the population at large. When shall we see science news sections in the daily newspapers that match the ever-expanding reporting of financial happenings? It should be emphasized that it is increasing knowledge in the population as a whole that gives us rights as individuals and as parts of a collective to contribute to the structuring of future civilization. This process has been referred to as the "democratization of knowledge".

One example of the occasional deceptiveness of modern journalism is the following: During the Swedish general election in 1988, problems relating to pollution of our environment developed into a central issue.

The discussion was boosted by an epidemic among seals on the west coast of Sweden. Election posters depicted seals looking with their emotion-rich eyes (neoteny again!) at us voters to ask why we were spoiling their marine habitat. Through the mass media we quickly learnt to appreciate the sequence of assumed interrelated causal factors: pollution of the environment, immunosuppression, viral infection. However, this description at the time it was presented lacked a factual basis. The truth of the matter was that the seal population was afflicted by an epidemic caused by an agent like the measles virus and the animals were taken ill regardless of any predisposing factor. What we were witnessing was a normal fluctuation in the population of a species. Three lessons may be derived from this example. Firstly, the critical scrutiny of facts should be ranked very high in the ethics of journalism. If unfounded statements are made about crucial problems, the results will be self-defeating, besides the fact that the medium involved will be discredited. Secondly, questions of ecological balance are highly complex and are understood only to a limited extent. Whereas we must carefully evaluate the effects of our civilization on the regional and global environment, we must also be careful not to make imperative or impulsive extrapolations from isolated findings. The issues at stake are much too complex and much too important to permit non-critical evaluations. Thirdly, the ultimate victims of biased journalism are politicians, since they may be forced to represent opinions that are not in accord with present knowledge or reason.

Epilogue

This chapter has highlighted some examples of the dramatic evolution of biotechnology, stemming from the powerful and revolutionizing techniques of modern genetics. Also more general aspects of science and man were discussed. The new techniques of genetics are indeed opening Pandora's box. Immense possibilities now become available to improve human health and the condition of human civilization. In most cases, the new genetic techniques mean a pronounced improvement in the precision and controllability of induced changes as compared with traditional, more empirical methods. In a number of cases transgene modifications of a kind never exemplified in nature are being exploited. Clearly, case-to-case evaluation of potential risks of application will have to be made and misuse has to be legislated against, for example, in the case of application development of biological warfare. On the whole, though, it is clear that huge benefits can be reaped at the same time as mature reflection and judgment should restrain misuse and contain any upsetting of the ecological balance.

Some Reflections on Large Technical Systems and Their Impact on Society —a Summary

Professor Arne Engström

The realization of large technical or societal enterprises and systems is often a long-term project reckoned from the time of their inception to their functional completion. A decision to build a large installation for use in research in physics, for example a large accelerator, is taken at a time when the existing systems of social values and the economic situation in the community are in accord with the project. After a long period of construction, sometimes as long as ten years, the installation is complete and operational. However, during the construction period, the societal value system may well have undergone considerable change, and the newly completed enterprise has to operate in a new and different value system, which sometimes leads to controversies and disruptions in public opinion. The time constant of the construction or organizational process simply does not tally with that of the opinion-forming process. Thus there arises a mismatching of time constants. Hard core technological innovation does not always coincide with changes in societal value systems.

I experienced this dilemma when a project in Big Science was processed in Sweden. When the idea of building the large storage rings at CERN was presented, the Swedish scientific community supported the project. After it had started and was nearing completion, the matter of financing became a burning issue for the Swedish government's Science Advisory Council on which I served as scientific advisor to the government. When it became apparent that a substantial portion of the Swedish science budget would have to be allocated to this major international science project, different sectors of the Swedish scientific community reacted, first hesitantly and then with protests. In the end it turned out that a majority of the Swedish scientific community was opposed to participation in the CERN expansion program. Many people argued that participation would lead to less funding for national science programs.

When a final decision from the government was called for, the Minister for Science and Education, Mr Olof Palme, had a tough decision before him. Should he follow the dissenting opinion in the Swedish scientific community or should he support Big Science in its international forum?

Sweden finally adhered to the international undertaking. The critical turning point was a telephone call from Mr Willy Brandt in Germany to Olof Palme in which Brandt argued convincingly that the European countries should make a concerted effort to put European Big Science in the forefront, and that this could only be achieved through international cooperation.

Before making any further comments on the intricate mechanisms involved in the start-up and management of major systems and in the creation of official and public support for technical systems, I would like to diversify into a field where the timing processes seemed to be well matched, at least after some initial difficulties. As an example I have chosen an environmental issue concerning the protection of the marine environment from pollution owing to deliberate dumping of waste and toxic substances at sea.

The dumping at sea of toxic waste generated by modern industrial society increased continuously during the post-war period, as it was a cheap way to dispose of toxic industrial by-products. Special vessels were constructed for large-scale dumping. When scientists discovered, among other findings, traces of chlorinated hydrocarbons at various places in the oceans, the idea of an international convention to prohibit the dumping of waste in the sea emerged in the late 1960s.

The launching and implementation of such a convention constitutes a major technical and political enterprise, where a number of national and international processes with different time constants must be harmonized. I was closely involved in the preparatory work for the UN conference on the environment which took place in 1972. Some of the tasks involved preparing the ground for, among other things, conventions to protect the marine environment. An enterprise of this nature is interesting because it shows the complex time mechanisms involved. My personal recollection of the creation of the co-called London Dumping Convention (LDC) is as follows:

After some countries had put forward proposals, a one-day meeting of the countries which were interested was arranged in order to discuss the dumping of waste at sea. This meeting was held at the International

Coffee House in London in 1969. The round table in the session hall was decorated with the flags of the nations who produced, sold, bought and perhaps drank coffee. Our proposal for an international convention met with little support and the meeting ended in complete discord.

I had pleaded for some kind of arrangement to protect the seas from pollution, but these ideas received support only from a few quarters. Naturally, I was disappointed, but inspired by the atmosphere of the coffee house and its history I did not give up hope. I recollected the London of three hundred years earlier, when coffee houses were enormously popular. They were referred to as the "penny universities". In fact, they became so popular that King Charles II tried to have them closed down.

In a decree dated December 29, 1675, the closing down was motivated in the following way: "as well for that many tradesmen and others do herein misspend much of their time, which might and probably would be employed in and about their lawful calling and affairs; but also for that in such diverse, false, malicious and scandalous reports are devised and spread abroad".

The reaction to this decree was overwhelming, and after two weeks the coffee houses were re-opened. In one particular coffee house, sailors and merchants gathered and the proprietor kept records of ships at sea and in dock. In this coffee house, run by Edward Lloyd, the Lloyd's Insurance Company was created in 1698.

History repeated itself, and at further meetings in London, Reykjavik, Montreal, Stockholm and London the London Dumping Convention was finally ratified.

The establishment of international conventions which have economic consequences is an interesting process in its own right. There are several, if I may call them "heavy" systems, which must comply with the basic ideas behind a convention. Examples of such large systems are developments in science and technology, acceptance by the public, the environmental movement and not least the global economic situation. Each of these systems changes and evolves at a different rate, and there is often a mismatch of time constants. If the mismatch is too great it becomes difficult to etablish new joint enterprises. But around the year 1970 we were fortunate in that, in spite of the Cold War, the forces of the large systems (which I mentioned) were pulling in the same direction and at the same rate. This is borne out by the fact that in a relatively short space of time it was possible to conclude a number of different treaties aimed at the protection of the seas.

Now, a treaty such as the London Dumping Convention, has a life of its own. It is not hard to predict that such an organization, like any living organism, will in time follow the logarithmic S-shaped growth curve. Naturally, the time constants in such curves vary tremendously, but over time they are in principle alike. This means that once a convention is ratified, it is necessary to plan for its modernization and the inclusion of new significant developments in science and technology. Other aspects must also be taken into consideration in order to prevent stagnation and organizational geriatric problems.

This analogous reasoning is also applicable to large technological systems.

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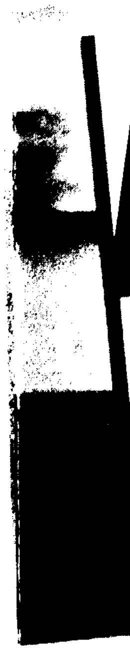

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