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Energy for the Future *

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I. CONVENTIONAL ENERGY SOURCES AND THEIR SUPPLY SITUATION

The sun is supplying so much energy to our planet that, on the larger part of the surface of the earth, biological life of plants, animals and even mankind is possible. This is due to the climatological conditions in the lower atmosphere caused by the sun and due to the sunlight that causes so-called photosynthesis in green plants by which water and carbon dioxide, both available in practically unlimited quantities, are converted into hydrocarbons — vegetable materials, including wood. The major part of these organic materials decays again, after dying, into water and carbon dioxide, but a small fraction is used as food for animals and man. For many thousands of years, mankind has also been using wood, besides the energy of the sun, as an additional organic energy source for cooking, heating, etc. After dying, a very small fraction of the organic material was shut off from the oxygen of the atmosphere so fast that no decay could take place and fossilization of this organic material was possible. Our present-day fuels — coal, oil and natural gas — have been formed by fossilization and are now used by mankind on a large scale as additional energy.

Fig. 1 Ratio of additional energy to energy of the sun in 1860, 1972, and 2000

Year	1860	1972	2000
Ratio	$\frac{1}{1\,000\,000}$	$\frac{1}{10\,000}$	$\frac{1}{3000}$

The ratio of this additional energy to the energy the earth receives directly from the sun was, in 1860, about 1 : 1 000 000. Because of the "industrial revolution" starting in the last century, the present ratio is about one hundred times larger, namely 1 : 10 000. Even if in highly developed countries, as for example the U.S.A., no further increase in the energy consumption should take place, it can be expected that, because of the growth rate of the population in the world as well as the higher standard of living, at least in the developing countries, this ratio will increase again in the "magic year 2000" by a factor of three to about 1 : 3000. This last estimate is a very modest increase, if one realizes that at this moment the energy consumption per inhabitant in the U.S.A. is about 50 times higher than in India, so that some increase in the use of additional energy in the world is not only probable, but even desirable.

If we assume that the world is clever enough to reduce the energy consumption to such an extent that, after 2000, no further increase in energy consumption will be necessary, even then the reserves of fossil fuels are completely insufficient for the future of mankind. This can be easily understood if it is realized that we are consuming our fossile fuels one million times faster than they are formed in nature.

With only one graph this serious situation can be well illustrated. The consumption of oil up to 1972 is given in Fig. 2. For the total estimate of the oil stock, a consumption is assumed according to the bell-shaped curve in Fig. 2, as it is unrealistic to assume a steady increase of the exploitation of oil up to complete exhaustion, according to the dashed line, which would be desirable if there were no serious oil restrictions before exhaustion, and if only a modest increase of 4.8 % per year in the oil consumption was to take place. The essential conclusion is that oil should be replaced by other fuel in a few decades.

If also oil from shales and tar sands could be exploited, the oil stock might perhaps be doubled. Finally, if in addition the world coal stocks — 84 % of which are available in the U.S.S.R and the U.S.A., and only 16 % in the rest of the world — could be used for our energy needs and were not reserved for a transformation into more valuable chemical materials, an extension of the fossil fuel period by one or one-and-a-half centuries might be possible. It is a serious question for our society how far this outlook for the future is acceptable for mankind.

Furthermore the influence of a large-scale use of fossil fuels on the atmosphere cannot yet be precisely predicted. It has been observed that with the present energy production about 40 % of all carbon dioxide produced by fueling fossil materials is not recycled in our atmosphere, but has increased the carbon dioxide content of our atmosphere in the last few decades by about 7 %. As to how far this will change our climatological conditions is a controversial point of discussion in scientific circles.

Anyhow, the general conclusion is that other energy sources will be required for the future of our civilization, and on a much larger scale than available from estimated fossil fuel reserves only. Replacing only for example 25 % of our energy by non-fossil energy would not change the situation fundamentally.

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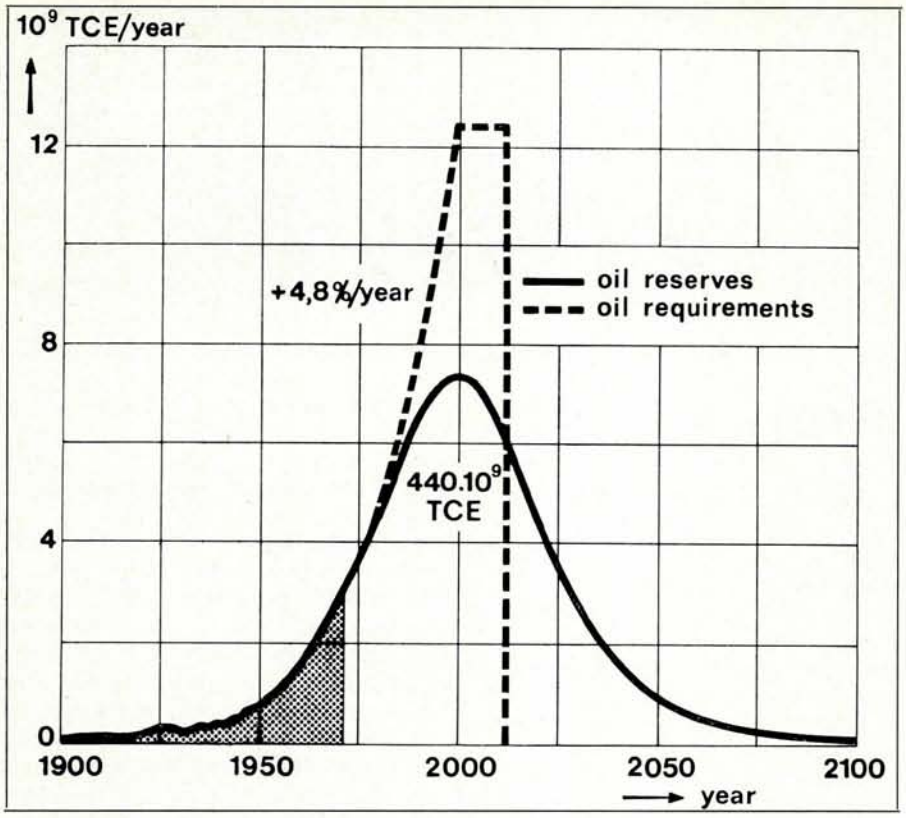

Fig. 2 Graph of the estimated oil reserves in the world (continuous line) and the oil requirements (dashed line) in Tons Coal Equivalent (TCE)

II. NUCLEAR ENERGY SOURCES

The conclusion of the first section concerning the availability of fossil fuel is that it is of the utmost importance that in the second half of this century nuclear energy will also become available for our future energy requirements.

It is known that, until now, only fission energy has been developed, in so far as it is technically possible to use the fission process for energy production. How far also fusion energy can be used in the future is still problematic. Therefore, in this section, only fission energy will be discussed.

Very well known, however, are the objections in our society to nuclear energy. As these objections are more emotional and political than technical and scientific, I think it is of real importance to discuss a few of the most urgent questions concerning nuclear energy.

In my opinion, the three most important questions are :

1. What is the supply position of nuclear energy ?
2. Are nuclear reactors safe enough for their surroundings ?
3. Is it possible to store the radioactive waste products in a safe way ?

1. Supply position of nuclear raw materials

As is well known, natural uranium and thorium are the raw materials for nuclear energy production. However, only 0.7 % of the uranium atoms (U 235), as they are found in nature, can be fissioned immediately, since the other 99.3 % of the uranium atoms (U 238) and 100 % of the thorium atoms (Th 232) need to be transformed into new, fissionable atoms, using a process that can take place efficiently only in so-called breeder reactors. In fact, U 238 is then transformed into Pu 239 and Th 232 into U 233.

Although in practically all nuclear reactors transformation can take place for a certain small fraction, so that in presently used light water reactors only 1-2 % of all natural uranium atoms are ultimately fissioned, in future breeder reactors it will be possible to fission 30-70 % of all uranium or thorium atoms.

This difference of a factor of 30 between the present light water nonbreeding reactors — with 1-2 % utilization of the raw materials — means even more than a 30-fold increase in energy production for the same amount of raw materials. If with the same amount of raw materials 30 times more energy can be produced, it is, in principle, also acceptable to use 30 times more expensive raw materials. For uranium this means, for example, that very low grade sources, like the uranium content of the oceans, can be exploited. The consequence would be that, if the additional energy consumption in the world could, after the year 2000, be kept constant at 30×10^9 TCE/year (the present-day world consumption is about 10×10^9 TCE/year), then energy could be supplied for a further 2000 years with 1 % of the uranium content of the oceans.

The conclusion is that with nuclear energy and breeders the future additional energy requirements of mankind can be met.

2. Safety of nuclear reactors

The safety of nuclear reactors requires much more attention than the safety of conventional power plants. This is due to the fact that the waste products of nuclear reactors are radioactive, whereas in conventional fossil power stations the annoying waste products are gaseous carbon dioxide, some sulphur dioxide and oxides of nitrogen. Although, as was already mentioned, carbon dioxide might in the long run effect a change in the atmospheric conditions on a worldwide scale, the radioactive waste of nuclear reactors causes already, after a short operation, a potential hazard for the immediate surroundings of the reactor installation.

Only if safe containment of the fission products can be guaranteed is safe production of nuclear energy possible. A safe containment can be guaranteed by a three-fold containment, if the third containment is, in fact, independent of the first and second.

In a present-day fast breeder reactor, the first containment of the fission products is the canning of the fuel elements. The second is the reactor system proper. The third system is the gastight reactor building. To guarantee a safe containment means, therefore, that if the first containment fails, either due to fuel element faults or to failures of the reactor system, no possibility should exist that the reactor containment building also fails. This means that the energy release of the reactor should be shut off so quickly by the mechanical control system of the reactor that no thermal decomposition of the gastight building can occur. In fact, this means that the control system has to be split off into more than two independent shut-off systems.

In thermal breeders with liquid fuels, the system is so different that the three containments are also different. The fission products in a liquid fuel reactor are in the circulating fuel, that means in the reactor system as a whole. Therefore two independent containments surrounding the reactor system are provided. To control the reactor in order to avoid an energy excursion is relatively simple. The reactor has a so-called prompt negative temperature coefficient of nuclear reactivity. This means that if the heat extraction is stopped, the energy production also stops, since the temperature in the system cannot rise. A rupture of the reactor system should also stop the nuclear energy production as every other distribution of the fuel between the reactor core and the surrounding would stop the reactor according to the physical conditions.

Of course a leak from the reactor system proper would require a very high leaktightness of the reactor containment, and for that reason the containment surrounding the reactor system is doubled.

3. Storage of radioactive waste products

The waste products produced by the fission process are practically all radioactive, with so-called decay constants between a few seconds and thirty years. The decay constant is defined as the time in which half of a special fission product is transformed into another less or non-radioactive fission product. Twenty half-life times, that means twenty times reducing the radioactivity by a factor 2, therefore reduces the radioactivity in total by a factor 2^{20}, which means one million. This is sufficiently small to be ignored in comparison with the original radioactivity. Storage times of fission products up to $20 \times 30 = 600$ years are thus sufficient for a complete decay of all fission products.

The consequence of this physical phenomenon, the decay of radioactive material, is, therefore, that "safe" storage of a few hundred years is required. A "safe" storage means a storage place where it will be impossible to have any contact either with the surface of the earth or with ground water during the required storage time.

Geological formations acceptable for such a storage are large, several-hundred-metres-thick salt formations, if these formations have not yet been used by mankind for other purposes such as salt mining, storage of oil, etc. As such salt formations are millions of years old and apparently have not been leached out during that time, it is certain that such salt layers have had no contact with water layers after their formation.

One of the most interesting methods to dispose fission products in salt formations has been suggested, for example, by the Euratom laboratories in Ispra, Italy.

After a few years of operation of a nuclear reactor, the fission products are separated in a reprocessing plant from the valuable, but hazardous, fissile and fertile nuclear fuels. If this separation can be carried out with an efficiency of exactly 100 % and not with the present-day 99 to 99.5 % efficiency, then, as mentioned, a storage time of the waste products a few hundred years will be sufficient. By loading fission product containers with so many radioactive materials that the decay heat can raise the temperature of the container surface up to the melting point of the salt, the container placed through a bore-hole on top of the salt formation will melt its way into the salt formation. By filling the container not only with long-living fission products, but also with a certain amount of short-living fission products, heat production and the temperature of the container surface would decrease with time as would the melt-down process in the salt formation. Therefore, it is possible to use such conditions that the container melts in the salt formation, but never reaches the bottom.

As, however, at least for the time being, the separation of the waste products from the fissile or fertile so-called transuranic materials such as plutonium is not exactly 100 % efficient, a more complicated situation exists.

The most annoying properties of several transuranic materials are, firstly, α-radioactivity, which in several respects is much more dangerous than β-and γ-radioactivity of fission products, and, secondly, the fact that several transuranic materials have half-life decay times about 1000 times longer than for the longest decay times of fission products. It is my opinion that storage times of a geological length of half-a-million years that would result from the example mentioned, are not very acceptable.

A proposal that eliminates these problems but that still requires more quantitative physical knowledge both of fission products and of transuranic materials has been made by The Netherlands Government to Euratom. This proposal is to burn out, by physical means, the transuranic atoms left over in the fission products waste after a preliminary separation of the bulk of the transuranic elements. Without discussing any details — which go too far for this introduction — it seems possible to burn out the small amounts of the dangerous transuranics left over in the fission products by using very fast neutrons which are produced in the centre of fast breeder reactors. By capturing fast neutrons, transuranic elements are easily fissioned, so the dangerous transuranic materials are transformed into less dangerous fission products.

Although for large-scale storage systems, the methods just mentioned are necessary, for the present-day, small-scale nuclear energy production, storage in well-contained tanks is sufficiently acceptable for the development area of nuclear energy.

The conclusion of this second section is, therefore, that uranium and thorium can supply, in a sufficiently safe way, the energy needed for the future of our civilization.

III. ENERGY FROM NUCLEAR FISSION

Although it has been explained that nuclear fission can supply sufficient energy to mankind in an acceptably safe way, nuclear fission is at present used only for electricity production.

Today, however, only about 25 % of all primary fuel is used for electricity production. As the efficiency of the conversion of fossil to electric energy is between 30 and 40 %, no more than 8 % of all primary fuel is now delivered to the customers in the form of electric energy. At the same time, therefore, 75 % of all fossil fuel is delivered directly to customers. This means a ratio of about 1 : 10 between electric and fossil energy.

It is to be expected that this ratio will decrease both because of special electric applications and because of a general trend to use high-grade energy. It seems unlikely, however, that this ratio will decrease below 1 : 3, or 1 : 2.

When it is produced, electricity in itself is a most efficient energy carrier and, with respect to the environment at the place of consumption, completely clean. However, in two respects electricity is not so ideal. It cannot be stored in the form of electric energy (that means it must be produced promptly on request) and, compared with oil or natural gas, it is an order of magnitude more expensive to transport in bulk. And large bulk transport of electricity seems to be unavoidable, if the cooling water problems of the very large nuclear power complexes to be used in the future have to be solved by placing them on the sea coasts.

Therefore, it has been suggested from different sides that hydrogen gas be used as a carrier second to electricity. First of all, hydrogen is as clean as electricity if it is burned with air to water. Only at very high temperatures would it produce some poisonous nitrogen oxides. Secondly, the transport of hydrogen is only slightly more expensive than the transport of natural gas, and, therefore, much cheaper than the transport of electricity. Thirdly, it can be produced from water, everywhere available. Finally, it can be stored, for example, in empty natural gas fields.

The production of large amounts of cheap hydrogen from water is still a problem to be investigated thoroughly.

The electrolysis of water is well-known. This means starting to produce electricity, and then using the well-known, high-pressure electrolytic decomposition of water. The total efficiency of these two processes together is only 25-30 %. With these known technologies it seems possible to produce economically acceptable hydrogen, but only with the excess electrical production capacity above the load factor of the system and with the available installed reserve capacity.

A more promising but not yet available method for real bulk production of hydrogen would be the decomposition of water by chemical means at intermediate high temperatures. These processes are being investigated on a small scale both in Europe and in the U.S.A.

Water can be decomposed spontaneously at very high temperatures above 2500°C. However, we have no sufficiently heat-resistant materials available for this process. Therefore, the possibility of decomposing water has been investigated not in one step at 2500°C, but in a few successive steps at intermediate temperatures not higher than 800-900 °C. For such processes high temperature breeder reactors can be used, in principle. Although economicaly and technically acceptable reactions with respect to temperature, corrosion, etc. have not yet been developed, it seems very attractive, and therefore of the greatest importance for the future of our energy supply that this long term research should be stimulated.

It should be realized how important it is that the introduction of a new energy carrier — hydrogen — can already be started in the near future within certain limits with the well-known electrochemical process, and can be extended step-by-step according to smaller or greater successes with purely chemical processes.

If large-scale hydrogen production should become possible, which means also that large-scale hydrogen transport would be necessary, transport of liquid hydrogen could become economically attractive and could then be combined with the transport of electricity at liquid-hydrogen temperatures. This would mean a reduction of the electric resistance in aluminium at room temperature by a factor one hundred, so that combined bulk transport of hydrogen and electricity in cables — and not ultra-high-voltage overhead electric lines — would become a technical and economical possibility.

Sufficient energy for mankind in the clean form of electricity and hydrogen produced by abundant nuclear materials, available everywhere in the world, will be a worthwhile challenge for mankind to develop.