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XXIV-2

REMARKS ABOUT NUCLEAR AND SOLAR ENERGY

It is now generally agreed that conventional energy resources are not sufficient to cover the requirements of mankind in the long run. As far as a further increase of energy production on their basis is possible, more and more difficult problems arise: Destruction of the environment with hydroelectric power, increasing dependence on producing countries with fossil fuel, social drawbacks with mining, and pollution of air and water with combustion.

2. Many experts have come to the conclusion that fission power (nuclear power in the usual sense) cannot provide the long-term solution of the energy problem either. Admittedly, there is at present no acceptable alternative to the increasing use of fission power, at least for the most developed countries. So fission power is necessary, but it appears that it should be used as a stopgap only, maybe for a period of some decades. Every effort ought to be made to get away again from fission power as soon as possible.

3. One reason is the possibility for the military, paramilitary and criminal use of plutonium. The amounts of plutonium that will necessarily be produced in a rapidly expanding fission power programme are just staggering. For instance, Dr. Dixie Lee Ray, Chairman of the US Atomic Energy Commission, stated in January, 1974, that in her view the fission power capacity of the USA alone might reach 1.2 million megawatts by the year 2000. This involves, as is easily estimated, an annual production of roughly 500 tons of plutonium, corresponding to about 100.000 Hiroshima-size bombs. The destructive uses of plutonium will not be further discussed in this paper.

4. No less disquieting is the threat presented by radiation. This threat is partly independent of human ill-will. Among all substances of practical importance known to man, plutonium is the most terrible poison. The reason is the unfortunate coincidence that

a) Because of its chemical properties plutonium is concentrated within the body in very sensitive places, notably in bone marrow, and is firmly lodged there.

b) In its radioactive decay, plutonium emits particles with high "relative biological efficiency" (RBE), alpha particles.

c) The half-life of plutonium is long enough to make its disappearance by decay during the human life span unimportant.

d) The half-life of plutonium is, on the other hand, short enough to provide it with a high rate of emission of alpha-particles (high "specific activity").

For these reasons, the maximum permissible body burden of plutonium (to be exact: plutonium 239, which is the relevant isotope) has been fixed at a particularly low value by the International Commission for Radiation Protection. The value is 0.04 microcuries, which corresponds to only 0.6 micrograms (millionths of a gram). This is 1 part in 10^{15} of the amount of 500 tons envisaged as the annual production of the USA in the year 2000. No means are known to science or likely to be found by which plutonium once laid down within the body could be removed again to any appreciable extent. From the standpoint of radiation protection, plutonium is a product of the devil.

5. (Remarks for experts. In reactor operations, some other actinides, in addition to plutonium, are also generated. Atom by atom, they may be as dangerous as plutonium 239 from the health point of view. Though their quantity is much less than that of the plutonium, they must also be watched. On the other hand, uranium 233, which in the uranium-thorium cycle largely replaces plutonium 239, is, on account of both its nuclear and its chemical properties, less poisonous than plutonium 239.)

6. Concomitantly with the production of fission in the nuclear power stations, the plutonium is generated within the fuel elements. The risk of accidents to power stations, and also of intentional action against them, in an economy entirely or predominantly based on fission power is being debated in many quarters, and no contribution to this discussion is attempted here. In case of serious accidents, plutonium as well as fission products may be set free on a large scale.

7. (Be it also recalled parenthetically that the danger of pollution is particularly great in the case of breeder reactors, which are extremely difficult technically, and where the power density far exceeds that of reactors working with slow neutrons. Be it further recalled that breeder reactors are quite superfluous, as natural uranium is abundant. Though eventually lower grade ores than now will have to be exploited, the resulting difference in the price of electricity to the consumer is not great, as most of the price is for the production of the fuel from uranium oxide, and for the investment into the reactors, the generation plant and the distribution network.)

8. In the normal operation of any nuclear power station, the fuel elements must be removed after a time; the plutonium is (usually after dissolution of the fuel element) chemically separated, purified, converted into the desired chemical form, and shaped into new fuel elements. This is clearly a multi-stage process of great technical difficulty. During these stages plutonium cannot be entirely prevented from migrating into the environment. It would be unfounded optimism to assume that the amounts of plutonium that escape in the normal operation of separation plants are not important from the health point of view.

9. In practice, some plutonium also remains mixed with the fission products after their extraction from the irradiated fuel elements. A complete removal of the plutonium from the fission products would be intolerably expensive. It is well known that no safe method for the permanent disposal of the fission products, themselves very dangerous, has been found as yet. The fate of the plutonium mixed with the fission products is as uncertain as that of the fission products. Further, there is the problem of what is to happen to abandoned, and still radioactive, power stations.

10. Thus we are faced with the danger of increasing contamination of the surface of the Earth with the most poisonous substance known. As a radioactive substance, plutonium is entirely indestructible, and will take tens of thousands of years to decay spontaneously to an important extent. It is probably possible to keep down sufficiently the release of plutonium in the routine operation of power stations, and it may also be possible to deal with larger amounts of plutonium set free in isolated accidents to power stations or separation plants, e.g., by evacuating and fencing off stretches of land, and/or by treating such land chemically. But to deal with the plutonium set free again and again through leakage or accidents in a world economy wholly based on plutonium is a problem of an altogether different order of magnitude. This applies even more as the political stability of the world over hundreds of thousands of years can hardly be taken for granted.

11. Three alternatives to fission power for the long-term solution of our energy problem have been proposed: fusion power, geothermal power and solar power. In this paper, we shall consider only solar power.

12. The rate of the energy flow from the Sun to the Earth is tremendous: 1.7×10^{14} kilowatts = 1.7×10^{11} megawatts = 1.7×10^{8} gigawatts, i.e., 170 billion (European) kw. This corresponds, if evenly spread, to 40,000 kw per person on Earth, while now the power consumption in the

most developed countries is of the order of 10 kw only. Of course, this primitive calculation does not indicate practical possibilities, but only shows the orders of magnitude involved.

13. The Second Law of Thermodynamics tells us to what extent an existing amount of energy can be utilized in the best case. It shows, e.g., that the energy contained in some sources, notably the heat content of the oceans, is of such a low potential that it can do only very little work. It is therefore practically useless economically, and must remain so. Solar energy is not of that kind. The energy of the solar rays has essentially the potential of the energy of their source, i.e., of the visible parts of the Sun with a temperature the order of 6000 degrees Kelvin. Therefore devices for the use of solar energy can basically use the temperature difference between the Sun and the Earth. Consequently, they can in principle work with an efficiency like that of a hypothetical heat engine that works with steam of 6000 degrees and the corresponding pressure. The consequence is that - always in principle - by far the greater part of the energy of the solar rays is available.

14. Existing devices for the utilization of solar energy generally use one of two methods. First, the rays produce low-temperature heat for domestic heating, cooking and steam raising, or, in a few highly specialized applications, high-temperature heat for the treatment of materials. Secondly, solar cells, as used in astronautics, convert solar energy with high efficiency into useful electric energy without intermediate production of heat. Applied research and development work with all such devices ought to be very much accelerated. However, in the present paper a third possibility will be emphasized.

15. We are referring to photochemical action. The most obvious example is the photolysis of water. E.g., a quantum of green light (wave length 500 nanometres, where the solar irradiance curve has its maximum) has an energy of 57 kilocalories per einstein (mole of light quanta) = 237 kilojoules/einstein. The free energy needed to split, under standard conditions, one mole of water into one mole of hydrogen gas and one half of a mole of oxygen gas is also 57 kilocalories. Thus in principle 1 quantum of green light is sufficient for the photolysis of 1 molecule of water. Light with larger quanta (blue light) is even better. While yellow and red light, on the other hand, have not enough energy in each quantum, the energy of several quanta can, of course, be piled together. Though no process is now known that can photolyze water on a large scale by irradiation with visible light, it must be emphasized that no law of

Nature is opposed to the existence of a process of this kind. Therefore its discovery may be only a question of research and development. Some pioneering work in this field was done by Eugene Rabinowitch, Farringdon Daniels and others (see Daniels, Biophysical Journal, 1972). No real success has so far been achieved, but this is not surprising as the means and man-years so far invested have been pitifully small.

16. In fact, the photolysis of water is the central bioenergetic achievement of the plants. As shown first by Cornelius van Niel in the nineteen thirties, the essence of plant photosynthesis is the chlorophyll-sensitized photochemical splitting of water into oxygen and hydrogen. The oxygen is discarded, and has formed the atmosphere, which now supports respiration and consequently all higher forms of life. The hydrogen is normally not set free as such by the plants, but is used immediately to convert (reduce) carbon dioxide from the atmosphere to carbohydrates and all the other plant components.

17. This achievement of the green plants has been characterized in powerful words by Boltzmann in 1886, although in his time he could not know anything about detailed mechanisms: "Hence the general struggle for existence of the organisms is not a struggle for the elements, nor for energy, which in the form of heat, unfortunately inconvertibly, is present in abundance in every body, but a struggle for entropy (more exactly, in the terms of Schrödinger, negative entropy. E.B.), which becomes available through the transition from the hot Sun to the cold Earth. To exploit this transition as fully as possible, the plants spread out the immeasurable areas of their leaves and force the Sun's energy in a manner as yet unexplained, before it sinks down to the temperature level of the Earth, to carry out chemical syntheses, of which one has no inkling as yet in our laboratories".

18. It would be the task of solar energy research to learn from the green plant how to photolyze water. The hydrogen would not directly be used by man to reduce carbon compounds, but would be diverted and applied separately. "Hydrogen economies" have been discussed in recent years, mostly in connection with nuclear energy. Hydrogen is to be used as a fuel, preferably through fuel cells, as a metallurgical reductant, and as a chemical raw material.

19. (Parenthetically, attention may be drawn to the rather direct use of hydrogen for the biosynthesis of feeding matter by means of "hydrogen bacteria" (Knallgas bacteria). These are nonphotosynthetic

organisms, which obtain energy for their life processes and for the reduction of carbon dioxide through the combustion of hydrogen, of course at ambient temperature. Such bacteria are studied, e.g., by H.G.Schlegel in Göttingen.)

20. It will take a long time and strenuous efforts to develop the technology of water photolysis. For encouragement, it may be pointed out that Nature did not succeed in one jump either. The green plants were preceded by photosynthetic bacteria, many kinds of which still survive. They are more primitive than the plants. They do not succeed in exploiting water as a source of hydrogen. Rather, the bacteria use organic or inorganic compounds in which the hydrogen is less firmly bound, notably sulphides. Plants succeed, where bacteria fail, by adding up the energy of two light quanta for each reductive step. For experts: To reduce 1 molecule of pyridine nucleotide, which in turn serves as reductant for carbon dioxide.

Paragraphs 21 and 22 contain admittedly no arguments in favour of the technical use of solar power, but they may be of interest nevertheless.

21. Solar energy is a far more natural kind of energy for man than fission energy (or geothermal, or fusion energy). There would be no fission power if the only nuclide that can be used to start it, uranium 235, did not exist on Earth. It still does exist merely as the result of the "cosmic accident" that its half-life (0.7 giga-years) is relatively long compared to the age of the elements, at least 4.7 giga-years. But no fission energy was ever exploited by organisms until 1942, and therefore no adaptation to it could take place. In contrast, the life of man and his ancestors has always been based on the utilization of the rays from the Sun.

22. The successive stages, by which living matter learned to exploit solar energy more and more efficiently, are about the following (see Broda, Progr. Biophys. Mol. Biol., Vol.21, and Broda, The Evolution of Bioenergetic Processes, Pergamon Press, to be published).

A. A "prebiotic soup" (solution of organics and other compounds) was formed through ultraviolet irradiation of the atmo- and hydrosphere (Oparin, Haldane).

B. Eobionts and primitive organisms arose and lived by the fermentation of the photoproducts. At a certain stage, the energy began to be used in the form of adenosine triphosphate, ATP.

C. Visible light was exploited by photosynthetic bacteria first to obtain energy (ATP) for their metabolism. NB. Bacteria also use infrared rays. This capability has, for reasons unknown, been lost by the (later) plants.

D. Photosynthetic bacteria learned to increase body mass through assimilation of carbon dioxide. External reductants, mostly hydrogen sulphide, were applied, and the energy was again supplied through photosynthetically made ATP.

E. Plants substituted as reductant the hydrogen of water for hydrogen of hydrogen sulphide. Water is all-present, but because of its unfavourable electrochemical potential two quanta in succession must be invested for each act of reduction. The first plants were, about 3 gigayears ago, the blue-green algae. They still thrive.

F. The oxygen set free by the plants made respiration (full combustion of organic fuel) possible. Very much ATP is made in respiration, and all higher organisms employ respiration. The machinery for respiration probably developed directly from that for photosynthesis.

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ADDENDUM TO REMARKS ABOUT NUCLEAR AND SOLAR ENERGY.

I

In my paper, Baden XXIV-2, I have argued against long-term reliance on fission energy and, especially, against the fast breeder. The basis of the argument is that unlimited expansion of fission energy means unlimited expansion of production of plutonium, i.e., a substance that is both a nuclear explosive and an indestructible poison of tremendous potency. The fast breeder, specifically designed for the conversion of uranium (U) into plutonium (Pu), has been characterized by many previous authors as particularly dangerous and also, in view of the large amounts of U in the Earth's crust, as unnecessary. Since my paper was written, further data, some of them quite recent, have become available.

II

The case against the fast breeder is based on the conviction that no shortage of U need be anticipated for a very long period, provided a quite moderate increase in the price of nuclear energy is accepted. Therefore, a large-scale utilization of U 238, via Pu, is not needed. The relative smallness of the increase in the energy price, which is caused even by a large increase in U price is, of course, due to the fact that raw U contributed little to the total cost of nuclear energy. This applies especially to those consumers that obtain electricity through an elaborate and expensive network.

Handy figures have now been supplied by Lewis (1). The basic assumptions are: Price of natural U oxide (U_3O_8) 8 $/lb.; fixed charges on working capital 10%/year; plant capacity factor 80%. In these conditions, a 2,5fold increase in U price (to 20 $/lb. oxide) would involve - in the most unfavourable case (light water reactor without Pu recycling) - an additional cost, at the outlet of the power station, of about 0,9 mills/kwh (at a price of 8 - 10 mills; see below). The variants of the high temperature gas cooled reactor (HTGR) and of the heavy water moderated reactors (CANDU and SGHWR) are much less sensitive to the price of raw U. E.g., for CANDU, Lewis gives as additional cost 0,3 - 0,6 mills/kwh. With a basic price of 6 mills/kwh (2) this would imply a rise of only 5 - 10% directly at the power station, and much less elsewhere.

In a survey by IAEA (3) it is stated that a rise to 30 $/lb. oxide would still only mean an increase by 1,3 mills/kwh in light water reactors, for which in the study an energy price of 8 - 10 mills/kwh is given. Even at 100 $/lb. oxide the cost increase with light water reactors would be only 5 mills/kwh (4).

Clearly other factors (for instance: political, monetary, fiscal) will generally affect the energy price to a far higher extent. Consequently, from the point of view of price, a utilization of poorer ores can very well be afforded, and breeding is unnecessary.

III

The known reserves of rich ores (less than 10 $/lb. oxide) are increasing rather rapidly. E.g., they rose by 34% alone between 1970 and 1973 (5). But how large are the reserves of poorer ores? The fact is that nobody knows, as no systematic search for them has ever been made, and so they have been found incidentally only (3,6). Characteristically, in a detailed survey of the OECD ores containing U oxide at more than 15 $/lb. are not even listed (5).

However, the reserves are sure to be very large. Generally, reserves of elements in the Earth's crust are, as pointed out by Weinberg, about inversely proportional to the square of the concentration. Further, we shall assume, quite conservatively (6), that the cost of recovery indicates the inverse concentration. In this case, oxide at, e.g., 30 $ comes from ores 3,75 times poorer than oxide at 8 $, and the reserves are therefore expected to be 14 times larger - certainly sufficient to take us far into the 21st century, i.e., to a period where alternative sources of energy, notably solar energy, can replace fission energy.

Probably a ceiling to the possible price of raw U is for a long time set by the ocean. The seas are thought to contain $4,5 \cdot 10^9$ tons of U (1). This corresponds, with 1% utilization, to 10^{18} kwh (thermal). With a final world population of $15 \cdot 10^9$ and an energy consumption per head of 20 kw (thermal) - a common, but very far-reaching assumption - the marine U would cover all needs of mankind for 300 years. (Needless to say that here no particular level of the population or energy consumption per head is advocated.) Concerning the recovery cost of marine U, we are on less secure ground. Häfele (4) quotes 25 $/lb. oxide (7). However that may be, clearly from the point of view of the reserves breeding is again not required.

IV.

If breeding is not needed, the question arises whether for the peaceful utilization of nuclear energy spent fuel elements need be worked up at all. Nowadays, of course, much of the Pu extracted is, as far as it does not serve breeding, earmarked for nuclear warfare, but this is a different story. Instead of working up the spent fuel elements, the fuel elements could be stored as such. In the reactors, they would be replaced by new fuel elements containing virgin U. This would be enriched with U 235 or not, depending on the system.

It appears that at least with the existing price structure the economics of nuclear energy are quite insensitive to the decision whether Pu is recycled or not. Extracted Pu has in fact so far not been employed for recycling (6). That recycling has little effect, has also been pointed out in the OECD study (5).

Some figures: In a recent study of Electricité de France about light water reactors (8) the value of recovered U + Pu is given as 0,17 centimes/kwh only, compared to the value of the initial charge of enriched U of 0,71 c/kwh and to the price of the new fuel, in the form of the ready-made fuel element, of 1,05 c/kwh. These figures show at the same time that recovery of U from the spent fuel element is not an important economic consideration either. 0,17 c (French) = 0,3 - 0,4 mills (US).

An even more striking illustration for the lack of importance of recycling is provided by the CANDU reactors where the spent fuel elements are just stored in water-filled bays of large capacity (9). At that stage the value is very small, and there is at present no intention to extract Pu (or, obviously, U. E.B.) (9).

V.

It may be concluded from the consideration both of existing reserves and of economics that there is no need to work up spent fuel elements, neither for breeding nor for recycling. Nonrecovery of Pu would mean that the difficult procedure of chemical separation would be dispensed with. Moreover, the problems of fuel element transport and of waste disposal would be much facilitated. In this way, the dangers of injection of Pu into the biosphere and of illegal utilization as explosive would be much reduced.

The possibility of a world-wide adoption of Pu nonrecovery ought not to be construed as an argument against the urgency of work on safe energy sources, notably solar energy. Nevertheless, this adoption would ease the situation, and provide more time for a solution of the world energy problem that is in the long run satisfactory. Of course, it is fully realized that Pu nonrecovery can be envisaged only as far as the threat of nuclear warfare can be removed. Ultimately, this is again a political question.

References.

(1) W.B.Lewis, Naturwissenschaften 60, 501 (1973). G.T.Seaborg is quoted as the original author of these data.

(2) e.g., W.B.Lewis, University of Guelph, 26th Feb., 1974

(3) J.A.Lane, R.Krymm, N.Raisic, J.T.Roberts, World Power Conference 1974

(4) W.Häfele, Bull. IAEA 16, 17 (1974)

(5) Uranium. Ressources, production at demande. OCDE, Paris, 1973

(6) D.J.Rose, Science 184, 351 (1974)

(7) The original paper is by R.V.Davies et al., Nature 203, 1110 (1964)

(8) Reproduced in Kerntechnik 16, 283 (1974)

(9) W.B.Lewis, Personal communication; see G.R.Fanjoy and A.S.Bain, Nucl. Eng. Intern. 15, 514 (1970)