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THE FAST BREEDER AS A CORNERSTONE FOR FUTURE LARGE SUPPLIES OF ENERGY

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1. Introduction

The purpose of this paper is to put the development of the fast breeder and its deployment into the perspective of the current energy problem. This appears to be necessary as the early development stages of the fast breeder took place when the world looked quite different. Also, more and more there appears to be a widespread misinterpretation of its features and capabilities. But before we examine the fast breeder, it is appropriate to identify a few features of the general energy problem as we see it today.

2. The Phasing of the Energy Problem

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

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We distinguish the following three phases:

a) the short range phase - 1970 - 1985,

b) the medium range phase - 1980 - 1995, and

c) the long range phase - 1990 - 2050 (?).

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

a) The Short Range Phase (1970 - 1985)

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

The most obvious problem of this first phase is the supply of oil and gas, particularly in the United States. Consider, for instance, the problem of oil prospecting. According to M.K. Hubbert [1] the amount of oil discovered per foot of drilling in the U.S. has strongly declined since 1938 and is now only 35 barrels/foot. Further, Hubbert assumes that the discoveries up to 1965 represent about 82% of the prospective ultimate total. The situation for gas is qualitatively similar, but this is not the case for coal. Other factors inhibit the easy use of coal [2]. There is not much hope that new resources for oil and gas can be discovered easily, and an uncommonly large amount of capital would be required for such discoveries.

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

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

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

There are many existing regulations for the use of energy, import, taxes, rates. Quite often these regulations derived from a fragmented point of view. Suboptimizations were made when energy was not yet a comprehensive problem. An example is the import quotas for oil in the U.S. But also in the Federal Republic of Germany, for instance, it is only now that a comprehensive plan for dealing with energy as a whole is being devised. Additionally, regulations for the protection of the environment are now being added at an increasing rate. To some extent it was nuclear power that initiated an awareness for environmental problems. Of course one realizes that nuclear power fulfilled only a pilot function there; the environmental problems are much more general. Nevertheless, the complications in licensing nuclear power plants due to actions of environmental groups worsen the problem of sufficient supply of electrical power. Similarly, rigorous regulations for the emissions of pollutants of combustion engines tend to increase the consumption of gasoline. Regulations, therefore, probably have to be reconsidered from a comprehensive, systems point of view.

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

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

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

b) The Medium Range Phase (1980 - 1995)

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

Probably, also the problem of siting could be the subject for significant technological advancements. The scheme of having a serial production of nuclear power stations on floating platforms has to be mentioned here. This allows for cheaper fabrication under strict quality control provisions and it helps to ease the ever-increasing difficulties of choosing sites for power plants and other technical installations in crowded areas. But other developments on the general problem of siting must also be envisaged. Another goal for technological research and development could be abatement measures for the use of fossil fuels. Also special uses of solar power have to be mentioned. For instance, local space heatings in warmer climates fall under this category. Such special use of solar energy is taking place already today.

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

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

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

- One or two of the few existing options to have an almost infinite supply of energy have been identified and fully investigated for large scale implementation.
- The size of the global energy demand has been increased by at least a factor of ten. The developing nations are among those with the highest increase of energy consumption.
- Boundary and constraints for the global use of energy have been identified and modes for the production and use of energy that are consistent with such boundaries and constraints have been developed.
- The medium range phase of the energy problem has been used for a smooth transition into this long range phase of the energy problem.

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

3. Long Range Energy Demands

In the following we will deal with large amounts of energy. It is therefore useful to introduce the unit of $Q = 10^{18}$ BTU. In Table 1 the equivalent of Q in several units is given.

In Table 2 a few figures are given that characterize the consumption of energy. It should be noted that the world consumption of energy in 1970 is roughly 1/4 Q/year whereas the consumption for the year 2050 could be 6 Q/year. This is a factor of 25 larger than the value for 1970. The figure of 10^{10} for the population is an unsophisticated straightforward guess and can be heavily debated. It should be realized however that this figure does <u>not</u> imply exponential growth. A key figure, on the other hand, is the value of 20 kW/capita. This figure was introduced by Weinberg and Hammond [8] after having studied in somewhat greater detail future conditions of a civilized society. A breakdown of that figure is given in Table 3. Again it should be noted that also in the kW/capita figures no exponential growth of any kind has been assumed. The point that has to be made here is that we have to consider the life conditions of future decades when the population is high and recycling of resources and in particular water is probably necessary. In order better to understand such future life conditions sophisticated scenario writings and life style descriptions are required. But the argument goes further. Figure 2 [9] shows that at present the use of energy is non-uniformly distributed over the globe. Contrary to that, any consideration of asymptotic solutions of the energy problem must start from the assumptions that the provision of power per capita will be equal for all of the world population, and further, the actual value of that figure will correspond to the highest figure in question, i.e. the figure for the U.S. It is impossible that a non-proliferation of high power installations per capita can ever come into effect. Eventually the same comfort for all of the world population must be feasible and accessible, at least potentially, and that means that any asymptotic solution of the energy problem must be based on that assumption of equality. On the basis of these few conceptual considerations alone one can see that the demand of energy as compared with today's values will be significantly larger, at least 10 times but probably more.

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

The relevance of such considerations can be felt if Figure 3 is considered. It demonstrates the linearity between the energy use/capita and the gross national product/capita and the continued linearity if the recent increases in these figures are evaluated. There is debate today as to what extent this linearity is a necessity. Much work has to be done there.

4. Energy Resources

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

a) Fossil Fuel

Widely different figures for fossil fuel resources are being reported and discussed today. The reason for these discrepancies is the simple fact that it is difficult to define clearly an obvious upper limit for declaring deposits as resources. Earl Cook [10] makes the observation that there are three methods of forecasting the availability of resources. One is the economic method that simply projects historic trends and demand elasticities together with technological trends and concludes that if under such conditions one would look for fuel, it will be there. This was perhaps a reasonable approach in the past when the scale of energy production was small if compared with global yardsticks. Here we are concerned with a different order of magnitude of the energy problem. The next method is the geologic-analogy method which is supply oriented and not demand oriented as is the economic method. Extrapolations are made on the basis of geological considerations. The third method is the exploitation-history method of M.K. Hubbert [11] that takes into account the history of the production curve, the proved reserve curve and the curve of discovery per foot of exploratory drilling. The last two methods seem applicable for our considerations here.

In Table 4 we present information that was given by V.E. McKelvey and D.C. Duncan [12] and M.K. Hubbert [11]. The large difference between the lower and the upper limit in the case of the McKelvey-Duncan data and the data of M.K. Hubbert that are in between illustrate the above remarks. It should again be noted that the upper values are no limit in a physical sense. In the case of coal, for instance, the figure refers only to resources above a depth of 1800 m.

Oil resources are somewhere between 2 Q and 20 Q. It was outlined in the last chapter that consumption rates of a few Q/year must be anticipated in the not so distant future. The figures in Table 4 therefore indicate that such consumptions cannot be based on oil, it must be coal instead. There the resources are larger by a factor of ten or so. It is therefore indeed reasonably possible to make coal a cornerstone for the medium range phase of the energy problem. It could last for a few decades if simple-minded straightforward algebra would be applied. One has to think, however, about the conditions that would characterize such harvesting of coal at a large scale. It requires world-wide major operations. As we will see in the next chapter this leads into system problems--i.e. side effects that were secondary when the harvesting of resources were modest will become first order effects. For illustration the problems of surface mining could be mentioned. Similar remarks should be made also for the case of shale oil.

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

b) Uranium and Thorium Resources

The remarks on the difficulties of having meaningful estimates of fossil fuel resources apply equally to resources for nuclear fission reactors, i.e. uranium and thorium. There are many publications on this question. In the middle sixties the question of uranium reserves was heavily debated [13]. It should be realized, however, that all the figures on that time referred to known deposits or deposits that could be discovered with a high degree of certainty. Further, only uranium prices of up to $30/pound of U_3O_8 were considered. In order to appreciate this one has to realize what the ore costs per kWh relative to the busbar costs are for the various types of power plants. They are given in Table 5. An increase of ore prices from $10/pound to $30/pound would increase in case of a light water reactor the busbar costs by about 1 mill/kWh. Such considerations were setting the limits in the discussions of the sixties. However, in that time the main consideration was the commercial competition between nuclear and fossil power. In the context of today's energy considerations in general, and of this paper in particular, this is not the only valid viewpoint now. In Table 6 we have, therefore, also given estimates for higher uranium prices. At $100/pound the cost increase for electrical power from LWR would be at 5 mill/kWh and the resources would still be only a few hundred Q. These are quantities that are comparable to fossil resources. So far as fuel resources are concerned, present nuclear power plants do not differ from fossil fuel plants. But the picture is qualitatively different for the breeder reactor. Its near term importance is that increases in prices for uranium ores are practically not felt in the busbar costs of a breeder power station. Prices exceeding \$500/pound of U_3O_8 can be afforded. Vast amounts of resources therefore become accessible and those resources are better converted to energy by a factor of about 100. Table 6 therefore indicates that the energy resources accessible through the nuclear breeder reactor are practically unlimited; this is the long term importance of the breeder. M.K. Hubbert [11] gives the example for uranium deposits that become meaningfully accessible by breeder technology. In the U.S., the Chattanooga shale spreads out along the Western boarder of the Appalachian Mountains. This shale has a uranium rich stratum, which is 5 m thick and contains 60 g per ton. This is a value far below what is considered interesting under today's circumstances. The energy content of this shale per square meter would be equivalent to that of 2000 metric tons of coal, or the energy content of an area of 13 kilometer square would be equivalent to that of the world resources of crude oil ($2 \cdot 10^{12}$ barrel)!

The distribution of thorium on the various parts of the globe is different from that of uranium and this will have regional consequences. India, for example, has not much uranium but vast amounts of thorium. India therefore must look for special ways and means to exploit these resources. Altogether, however, the energy equivalent of the thorium resources only slightly exceeds that of the uranium resources. One is essentially correct if one assumes that these equivalents are equal. For further details we refer to McKelvey and Duncan [12]. Energy through the fission of the uranium and of the thorium atom by the use of the breeder reactor thus provides the first option for an almost unlimited supply of energy.

One has to realize that the development of the breeder reactor is far advanced. The most advanced version of the breeder reactor is the liquid metal fast breeder reactor. It is developed by the USSR, France, the UK, Germany together with Belgium and the Netherlands, the U.S., Japan, and Italy. But it shall be stressed especially that India, too, has her own fast breeder development. We will touch upon this later. Large scale developments like that of the fast breeder reactor have to pass three thresholds:

i) the threshold of scientific feasibility,
ii) the threshold of industrial feasibility, and
iii) the threshold of commercial feasibility.

At present large industrial prototype reactors in the 300 MWe class are being built or put into operation by the USSR, France, the UK, and Germany together with Belgium and the Netherlands. In the U.S. and Japan such construction is expected to come soon. That means that the second threshold, that of industrial feasibility, is now being passed. The commercial feasibility is expected for the middle eighties [15]. Further, the liquid metal cooled fast breeder reactor has back-ups. The helium cooled fast breeder provides such a back-up solution. Certain key problems of this reactor type are being investigated. But the thermal breeder [16] and especially the molten salt breeder as pursued by Oak Ridge Nat. Lab. in the U.S. back up the development of the liquid metal fast breeder reactor. The point that must be made here is this: already with the technology of the seventies and the eighties we have in the fast breeder reactor one industrially feasible option for a practically unlimited supply of energy, even if future energy consumption of a few Q/year must be envisaged sooner than expected. Figure 4 summarizes the situation for fossil fuel and nuclear fission reactors [9] and illustrates how one cannot have one single figure for energy resources.

c) Lithium and Deuterium Resources

Besides fission there is fusion as another form of nuclear power. It is known that fusion reactors have not yet passed the threshold of scientific feasibility, but it is not unlikely that this will happen in the next ten or fifteen years. Whatever the answer to the scientific and the other feasibilities might be, it is worthwhile to have a look at the fuel resources. By far the most probable scheme for fusion is the D-T reaction. This requires lithium as a fuel in addition to deuterium. It turns out that lithium is the limiting factor for the fuel supply. In fact, such a reactor is more precisely a fusion breeder [17] as lithium is bred into tritium similarly to the breeding of U-238 into Pu-239. If a technical fusion reactor is envisaged then it has been found that 1 MWd/gram of natural Li (7.4% Li-6 and 92.6% Li-7) can be produced [18]. That is the same amount as for uranium or thorium in fission reactors.

Here low figures for Li also have been reported [12]. This is obviously the case because formerly there was no incentive for adequate prospecting. But the amount of the lithium in the oceans alone is indicative: $2.7 \cdot 10^{11}$ which corresponds to $2.2 \cdot 10^{7}$ Q if all lithium could be extracted. If we again assume a factor of $\sim 3 \cdot 10^{-2}$ for extraction we obtain $\sim 7 \cdot 10^{5}$ Q.

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

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

d) Geothermal Sources

The use of geothermal sources for the supply of energy on a large scale is a comparatively new aspect. In the past only in Italy, New Zealand, and the U.S. have geothermal power stations been operated. The scale was modest, a few hundred MW at best. The expected lifetime of these stations is in the order of a few decades [11]. It was on this basis that this source had not attracted much attention when questions of energy on a large scale were under debate. More recently, however, the question has been reexamined. Donald E. White [19] has estimated that the world's ultimate geothermal capacity down to a depth of 10 km is roughly $4 \cdot 10^{20}$ Wsec. Not counting any conversion factors etc., this equals 0.4 Q. It is obvious that this is a negligible amount of energy in the context considered here.

However, there are also other voices. Recently R.W. Dose [20] has made the statement that by making more rigorous use of the existing geothermal sources in the U.S., sources with a lifetime of more than 1000 years and with 10^5 MW could possibly be explored. This would correspond to 3 Q in the U.S. and could therefore be crudely compared to the U.S. oil resources. Details for such estimates were not given.

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

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

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

e) Water and Tidal Power

Water and tidal power resources of the world are in the order of a few tenths of a Q [11]. Those power sources may be of regional interest but are definitely not an option for the large scale supply of energy.

f) Solar Power

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

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

Figure 5 gives the energy balance in somewhat greater detail. The heat balance is used in turn to drive the water cycle in the atmosphere by evaporation of rain water, to heat the ground and the lower part of the atmosphere, and to provide the power for biological processes.

The determining consideration for the exploitation of solar power on the surface of the globe is then obviously the question to what extent this energy balance may be distorted. This is of course an extremely complex systems problem. A straightforward estimate for the global average value for harnessing solar power may be 20 W/m^2.

It should be noted, however, that regionally considerably higher values could be acceptable. This will then be of regional significance accordingly. Here in this context we are interested in the question of global large scale energy supply. A value of 20 W/m^2 makes it obvious as we will see later that not the supply of power but land use is the determining factor for the collection of solar power on the surface of the globe.

But it is not necessarily so that solar power must be harvested on the surface of the globe, it could be harvested in outer space. A recent proposal of P.E. Glaser elaborates on that [21, 22].

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

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

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

From what has been said above it becomes clear that the fast breeder is the ultimate scheme for the option of obtaining nuclear energy from fission. It is the only option that is already viable and may therefore be significant not only for the long range aspects of the energy problem but also for the more near term aspects. Having established this perspective it may then be appropriate to look somewhat closer to some of the features of this fast breeder.

5. Plutonium

Plutonium is a necessary feature of all fission reactors that use uranium. Normal converter reactors rely on the fission of U-235. The fission neutrons that are not required to sustain the chain reaction either leak out of the reactor, become absorbed in the structural material of the core, or get absorbed in the U-238 of the fuel elements of these reactors. This leads after two β^- decays to the formation of Pu-239. If we leave aside the details of reactor physics it is sufficient to realize that a light water reactor produces roughly:

$$150 \text{ kg of Pu/1000 MWe} \cdot \text{year}$$

at a load factor of 0.7 [13]. The plutonium isototopic composition is roughly:

$$239 : 240 : 241 : 242 = 0.59 : 0.26 : 0.12 : 0.03.$$

This plutonium has to go somewhere. The reason for this is twofold:

a) it has to be used for economical reasons,

b) it has to be used for ecological reasons.

In the past it was mainly point (a) that had been considered. If only the here considered light water reactors exist the only place to use the plutonium are these light water reactors. In terms of criticality the value of plutonium is there only 0.7 of that of U-235; in terms of economy it is less than 0.5.

But attention must be given to point (b). The ecological reason is far more important. It is not considered to be a viable scheme to lay aside and store the produced plutonium one way or the other. One has to get rid of the plutonium to the largest possible extent by burning it. If only the light water reactor would be there the only place to burn the plutonium would be this light water reactor.

A further remark is this: Practically all commercial LWR start with a clean uranium core. This has sometimes given the wrong impression that only uranium comes into the picture there. But as mentioned before, after the first core is burnt up the plutonium is there and has to be burned.

Another possibility to burn the plutonium of light water reactors is the fast breeder reactor. If fueled with plutonium it can produce more plutonium than it burns. Under such conditions a fast breeder produces roughly:

240 kg of Pu/1000 MWe · year

at a load factor of 0.7 [13]. The plutonium isotopic composition is roughly:

239 : 240 : 241 : 242 = 0.69 : 0.25 : 0.04 : 0.02.

A few observations must be made here:

a) The difference between 150 kg/1000 MWe·year and 240 kg/1000 MWe·year is the salient feature that allows for breeding, that is, to have more plutonium produced than consumed.

b) The difference between 150 kg/1000 MWe·year and 240 kg/1000 MWe·year is insignificant in terms of ecological impact.

c) The plutonium breeding gain (production of plutonium minus consumption) is meant to go into the build-up of a fast breeder population. If this build-up comes to a halt, it is more than easy to operate the fast breeder such that the production equals the consumption, or if plutonium from the light water reactors is to be burned such that the production is smaller than the consumption.

d) The burning of plutonium in fast breeders is economically far more attractive than the burning of plutonium in LWR. The criticality value of plutonium in fast breeders is roughly twice that of plutonium in normal light water reactors. This makes the fast breeder a natural teammate of the light water reactor. The ecological necessity to

> burn the LWR plutonium becomes an economical asset if the fast breeder is there.

With both the LWR and the fast breeder, therefore, there has to be a fuel cycle that has large amounts of plutonium in it. In view of the ecological dangers of plutonium this creates a problem. Roughly the equivalent of 0.5% of the plutonium inventory goes yearly into the waste if present day technology of the fuel cycle, and in particular of reprocessing, is applied. This poses what one may call a systems problem because it appears when a large scale fast breeder propulation is operated as a system. We will return to this problem later in the paper. Another systems problem is nuclear material safeguards. That also will be dealt with later.

Earlier we have seen that a fast breeder based economy can, with today's technology, already provide energy on a large scale for practically unlimited periods. The price that has to be paid for this almost unlimited benefit is systems problems. There are more systems problems than safeguards or just keeping the plutonium away from the ecosphere. The proper question which must now be posed is: what are the alternatives and <u>what are the systems problems of these alternatives?</u> Before we address ourselves to that question, a few words must be said about fast reactor safety.

6. Fast Breeder Safety

One basic physics characteristic of fast breeders is their short neutron lifetime--they use fast neutrons. The short neutron lifetime has often been used as an argument against fast breeders (see for instance [23], [24]). But a short neutron lifetime is a safety problem only if the power/temperature coefficient is positive. In that case the short neutron lifetime leads to very high energy productions before the device disassembles. However, contrary to a widespread belief, in case of a negative power/temperature coefficient it is rather the opposite that is true (other things being equal). The negative power coefficient leads to sharply limited, smaller power bursts, until the delayed neutrons and/or the mechanical movement of the core determine the time behaviour [25]. The energy production until shutdown by mechanical movement is very limited this way. This elementary feature was the reason for the effort of the fast breeder development groups in the early sixties to prove that the Doppler coefficient (the power coefficient) was indeed negative. The most important demonstration for that was the SEFOR reactor experiment [26]. All the fast breeder reactors that are now under construction or under consideration have this inherent Doppler stability characteristic. This separates fast breeders principally from nuclear explosive devices.

But one must also look into the absolute size of the mechanical energy coming from such a bounded excursion. The safety report of the German fast breeder demonstration plant SNR 300 [27] has 150 MWsec of mechanical work ($\int pdV$) as a reference value, and the "Deutsche Reaktorsicherheitskommission" (the German counterpart to the Advisory Committe on Reactor Safeguards in the U.S.) has accepted this figure as the basis for the tank design [28] and the more recently specified 370 MWsec (mech) as the basis for the design of the primary cell. On the side of the ACRS such acceptance has not yet taken place, but it is expected that the figure will be similar. The experience of the past few years shows that this figure went down as one looked closer and closer into the details of the problem. Some scientific investigators today consider even lower figures [29]. More theoretical and experimental work is going on to establish a high level of confidence for this. But it should be noted that fast breeders can be designed to withstand mechanical energy releases even substantially in excess of 150 MWsec (370 MWsec). Whatever the appropriate evaluation of the bounded excursion comes out to be, one must realize that such an amount of mechanical work is not large enough to consider fast breeders a reactor safety class of their own. They simply line up with other reactors.

7. The Fusion and the Fission Breeder

The questions on the alternative of fast breeders lead into systems problems--i.e. problems that arise if a certain technological approach is implemented on a truly large scale. It cannot be claimed that the study of systems problems of the four major options mentioned earlier have attracted the necessary attention. Even the much more limited task to compare the fast fission breeder with the fusion breeder remains largely to be done. Only recently Ch. Starr of Los Angeles and the author of this paper have made a first approach to that end [17]. In the following paragraphs a few such comparisons shall be given.

The first comparison one can make concerns waste disposal. During the last few years the fusion community has undertaken a number of engineering design studies [30, 31]. All of these design studies use niobium as a structural material. This leads into the problem of neutron activation. After a certain fluence such activated material has to be replaced and the problem of waste disposal therefore also arises with the fusion breeder. Table 7 reports on the radioactive inventory of a fusion breeder after shut down; Table 8 reports on such inventory for the fission reactors--both the LWR and the fast breeder. This leads into annual discharges that are reported in Table 9. Due to the activation characteristics of Nb the amount of Curies/W(th) is larger in the case of fusion than in the case of fission.

The claim here is not that this is a general result. It only so happens that the first engineering design that was presented by the fusion community has Nb as a structural material. This need not be so; other structural materials, e.g. Vd, may be feasible. Nor shall it be implied that a Curie of Nb is in all aspects equal to a Curie of plutonium. The point rather is that realistic designs together with at least virtual large scale implementation lead into problems that tend to be overlooked in the beginning.

In the case of fusion it was argued that the elementary process is clean and therefore the reactor would be clean. It turns out that at least in the more detailed engineering study of a D-T reactor that uses Nb as a structural material this is not the case.

Another system problem is the diversion of nuclear material, as has been mentioned earlier. The negotiations for the Non-Proliferation Treaty (NPT) and its connected international safeguards system for nuclear materials helped to establish a few categories that are helpful here. Accordingly, one has to distinguish between the timely detection of a diversion of nuclear material and the protection of such nuclear material, and both detection and protection must be considered on the governmental level and the level of small "private" groups. Following Ralph Lapp

[34] we will call such a group "Group X." The Non-Proliferation Treaty was concerned with the governmental level. It was possible to develop successfully an international safeguards system which is now under implementation on a world-wide basis [35]. Along with it went a remarkable amount of systems analysis [36]. The safeguards system of the International Atomic Energy Agency (IAEA) is explicitly aimed at the:

> timely detection of diversion of significant quantities of nuclear material from peaceful nuclear activities to the manufacture of nuclear weapons or of other nuclear explosive devices or for purposes unknown, and deterrence of such diversion by the risk or early detection [35].

It sharply reduces the probability of having a clandestine diversion not only on the governmental level but also on the level of Group X. To that extent the safeguard problem can be considered taken care of. After the Non-Proliferation Treaty and when international material safeguards were based on a semi-quantitative, rational, and objective basis, it was also possible to specify the requirement and features for safeguards aimed at the protection of nuclear material. The IAEA has issued first guidelines for that [37]. For the case of the U.S. H. Kouts has given greater details for the steps that are considered necessary [38]. Table 10 clarifies the here described situation.

So we are dealing now with the protection against actions of Group X. (Note: This is an universal problem; the distinction between nuclear weapon states and non-nuclear weapon states is meaningless here.) The remaining problem should be seen in the context of other existing safeguard measures. For example the careful accounting of nuclear material now implemented on a world-wide basis and aimed at the detection of diversion eliminates the aspect of the clandestine diversion. It is open attack that we now have to consider here.

In major parts of the nuclear fuel cycle the fuel is highly inaccessible or self-defending. Fresh fuel elements for LWR that have 3% U-235--which is the case in all the LWR of today--is meaningless; further enriching is extremely difficult if not impossible. Irradiated fuel elements that contain Pu that has built up during irradiation in the reactor are strongly defending themselves as they are highly radioactive. The transport casks for irradiated fuel elements are bulky and heavy, and moreover, it is very expensive if not impossible for Group X to handle such material. Attention must instead be directed toward the part of the fuel cycle from the reprocessing into the fuel fabrication. Up to now there has been only very little reprocessing and under special circumstances. Only when the commercial fuel cycle develops fully, this problem comes into the picture. One must also realize that plutonium in the commercial fuel cycle is always dirty plutonium, that is Pu with a high Pu-240 content. The isotopic compositions of Table 8 indicate that. The fuel cycle of fast breeders provides for mixing of the Pu coming from the core and the blanket, and that is a question of accounting and regulation. It can be taken care of by already existing means. As everyone knows the efficiency of an explosive device that uses such dirty Pu is sharply reduced. This perspective must be kept in mind. It narrows down the concern considerably but does not completely eliminate it.

It will be necessary to protect certain open parts of the fuel cycle along the lines described above. Containment and surveillance measures for the buildings in question and the transport devices are the principal options for taking the appropriate steps. The adoption of the international safeguards system prompted a number of appropriate containment designs which have already been studied [39, 40]. These efforts are now considerably increasing. The author feels that this problem can be handled. It requires additional action but is less formidable than it appears at the first look.

Concern has been expressed not only about the fast breeder but also about the fusion breeder [41]. If Group X is sufficiently sophisticated the diversion of tritium together with plutonium may also be considered attractive. It is difficult, though, to evaluate this aspect in the necessary depth, but one cannot simply put it aside.

Further, during the negotiation of the Non-Proliferation Treaty, an article of S.T. Cohen [42] raised major concern both in political circles and in the press [43]. This concern was with the clean H-bomb. The point was that the achievement of getting a fusion reactor to operate may also make way for the neutron bomb which develops only very little blast and gives off energy by fast neutrons. These concerns may be farfetched as all the fusion reactor development work is mainly directed towards obtaining long containment times. But it is difficult today to predict what the future will look like when the fusion reactor becomes physically and technically feasible. We cannot exclude the clean H-bomb now, because any device for initiating a thermonuclear reaction might be used as an initiator for a clean H-bomb. So it may be possible that fusion reactors also have to encounter the full impact of safeguards. One possible approach could be to include Li, H^2, and H^3 under the materials to be safeguarded. It is probably premature to go into the details of these questions as neither the fusion reactor nor the clean fusion bomb is already there. But it is obvious that it is fusion that has to live up to the standards of safeguards of fission, not the opposite.

8. The Task of Systems Analysis in the Case of Energy Systems

It should be noted that the safeguards problem exemplifies what has to be classified as systems problem. It comes up if nuclear power is implemented on a large scale and was originally considered to be a rather secondary point. But when the scale of implementation becomes really large, such secondary concerns may well become first order concerns. This stems from the fact that the large scale implementation leads to a heavy interweaving that must be studied by a systems analysis effort. In the case of the energy systems considered here, it is possible to spell out what the task of such systems problems is. There appear to be the following subtasks:

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

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

- the atmosphere
- the hydrosphere
- the ecosphere
- the sociosphere.

c) It is then necessary to identify and evaluate alternatives, options for large scale implementation. There seem to be the following options for large scale energy supply:

- energy by nuclear fission
- energy by nuclear fusion
- solar power
- energy from geothermal sources.

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

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

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

It is also plain that the challenge posed by such system problems is global. The effort to meet such challenges must therefore be also global and that means international. The very fact that the safeguards problem was taken care of by the International Atomic Energy Agency is a good proof for that. But there is more of that kind. About a year ago the International Institute for Applied Systems Analysis was founded and is now being built up at Laxenburg near Vienna. The idea is precisely to meet the global challenges of systems problems. Therefore the energy problem is being studied there [44], but also other system problems like the ones connected to water, towns, and ecology. Information, management, health, and other fields with systems implications are also being studied at IIASA.

But this conference here at New Delhi is also such an international effort. The special point of view at this conference is the energy problems as they appear to India and other countries in similar positions.

10. The Rationale of the Indian Fast Breeder Development

India is having her own fast breeder development. The Indian fossil fuel reserves are small [45]. This is true in an absolute sense. But it is even more true in view of the large population of India. She has $500 \cdot 10^6$ people. With a per capita level that eventually has to approach the level that is applied in countries like the U.S. and others--i.e. 20 kW/capita--this leads to 1/3 Q. This is roughly the present energy consumption of the whole globe. The argument here is the order of magnitude, not factors. It is therefore only natural that under the leadership of the late Dr. Bhaba and also the late Dr. Sarabhai India became strongly interested in nuclear energy as this is within a foreseeable time scale a viable option to overcome the energy problems of India once and for all. For a country like India it is natural to follow the line of natural uranium reactors. They have a number of advantages for India: no enriched uranium is necessary, and the technology can be mastered by India alone. The Bhaba Research Center at Trombay near Bombay is a proof for that. India's uranium resources are not large but are sufficient to build up a first generation of nuclear reactors. This reactor type allows also for the partial use of the thorium resources of India which are indeed extensive. To make full use of the thorium resources is a task that is best fulfilled by a fast breeder. Thorium is not a fissionable material; it is a fertile material, and only fast breeders convert such fertile material to a larger extent into fissionable material than the fissionable material is consumed. The fast breeder makes India's large thorium resources therefore fully accessible. And technically it makes good sense to go from natural uranium heavy water reactors to fast breeders. For some time those fast breeders will use the plutonium that is produced in these heavy water reactors. Later it is not a major problem to use instead of plutonium the U-233 that is bred out of thorium. It is therefore fully consistent with her general situation if India pursues her own fast breeder project at Madras.

11. Final Remarks

The purpose of this paper was to show the potential of the fast breeder reactor as a tool of providing practically unlimited amounts of energy for very long time periods. The perspective for that is the general energy problem which has been explained in this paper. A large scale fast breeder economy will have system problems, and a few of them have been mentioned here. There are other options to provide great amounts of energy and the question is: are these other options feasible and more so: what are their system problems? This paper elaborated on the option of having fusion breeders. If technically implemented, fusion breeders could well have problems of a similar nature and size. In the case of geothermal or solar power the system problems have still to be identified. A strong systems analysis effort is therefore advocated. This could perhaps then answer, at least partially, the question of the alternatives to the fast breeder and of a minimization of system effects.

It appears to the author that the fast breeder continues to be attractive as a cornerstone of future energy economies, not only of countries that are already highly developed but also for a country like India. Her own effort in the field of fast breeders points to that.

Note: Parts of this paper are closely related to the author's paper on Energy Systems [46] and that of the author and Ch. Starr [17].

Fig.1 The Phasing of the Energy Problem

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

Fig. 2 Growth in Energy Demand

Source : Ch. Starr [9]

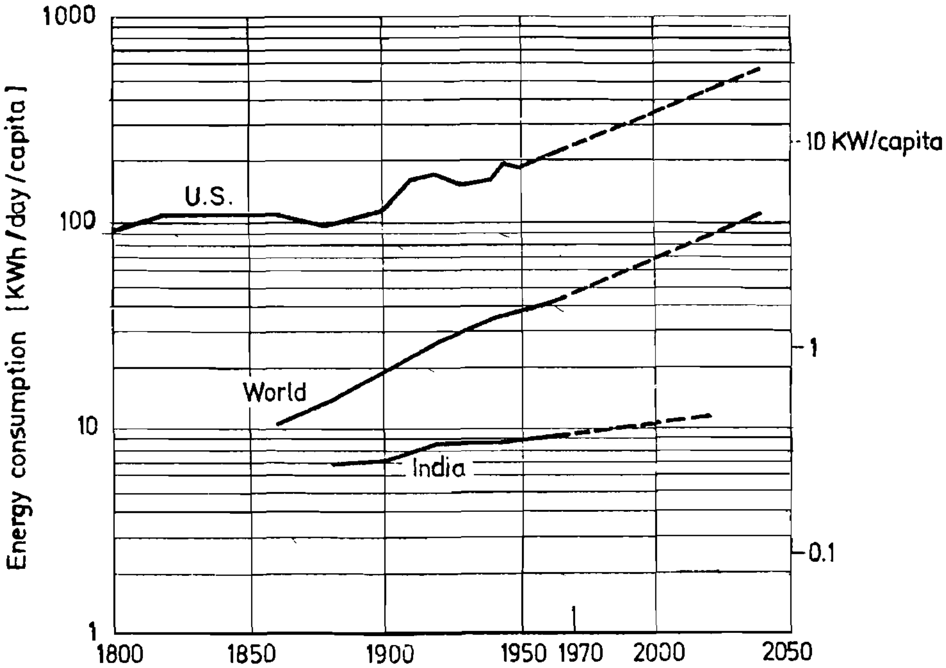

Fig. 3 Commercial Energy use and Gross National Product

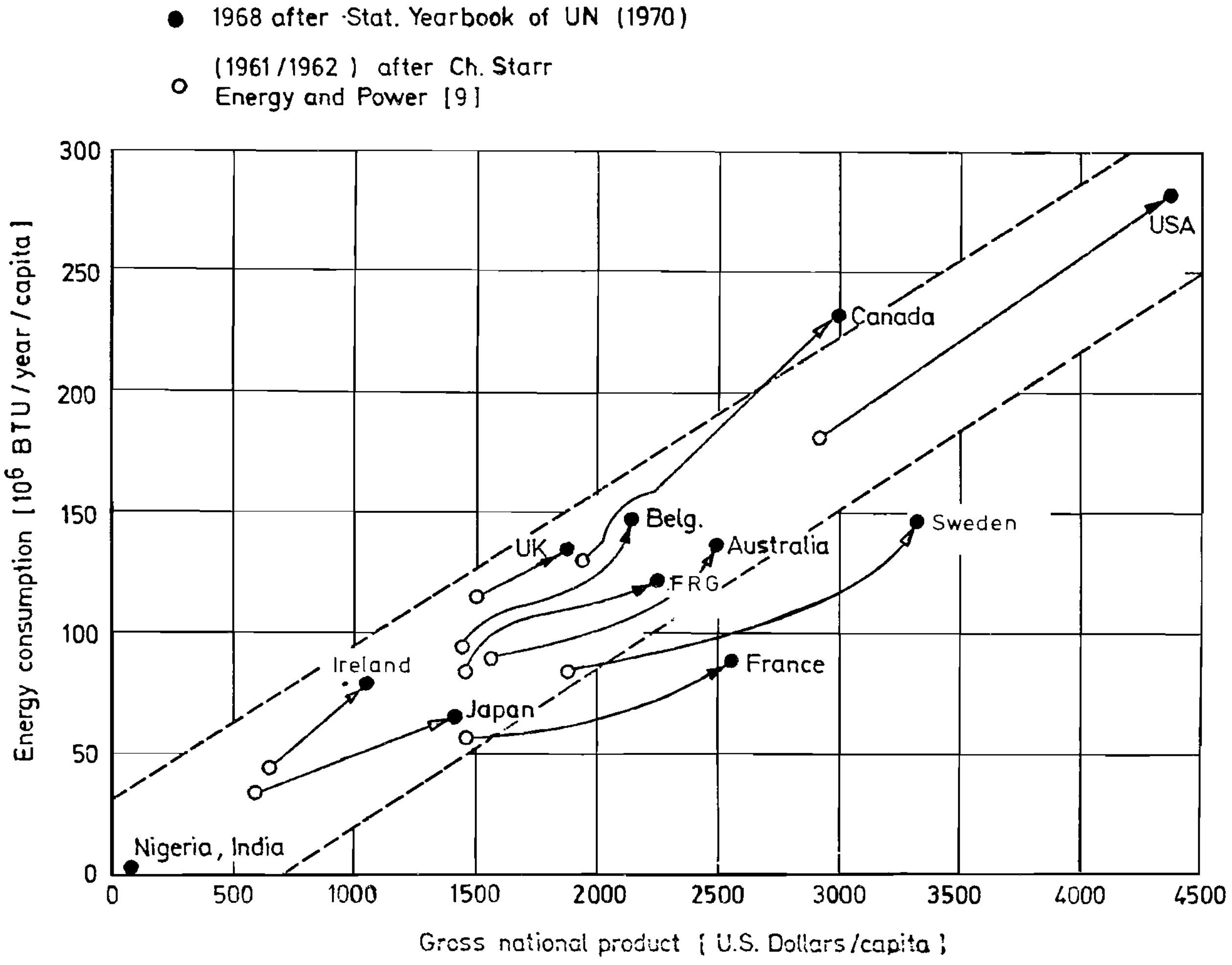

Fig. 4 Comparative Fuel Costs

Source : Ch. Starr [9]

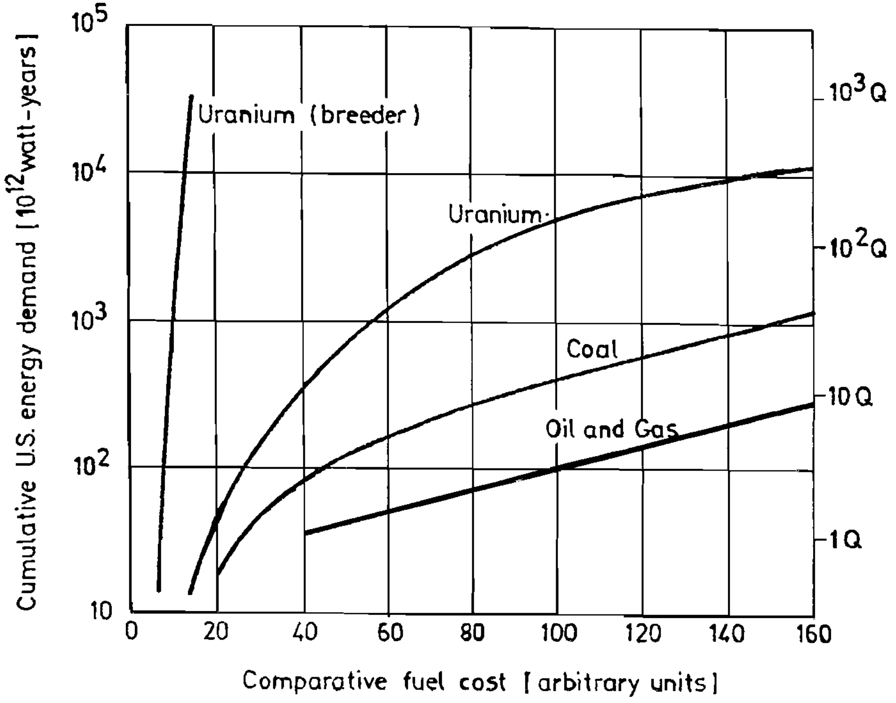

Fig. 5 Distribution of Solar Power Input

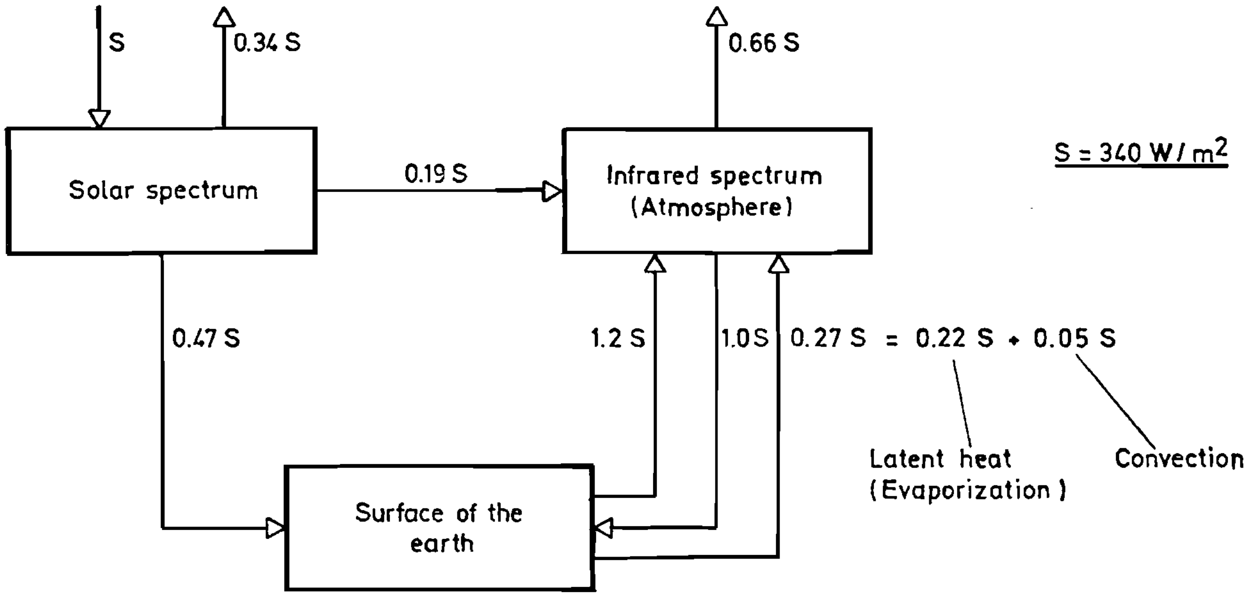

Table 1 Energy Equivalence

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

Table 2 Energy Consumption

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

Table 3 Energy Budget for a Steady - State Civilization *

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

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

Table 4 Energy Content of the World Supply of Fossil Fuel

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

	According to V.E. Mc Kelvey and D.C. Duncan [12]		According to M.K. Hubbert [11]	
	Known recoverable	undiscovered and/ or marginal	eventually recoverable	°/₀
Coal	17.3	320	192	88.8
Crude oil	1.73	23	11.1	5.2
Nat. gas	1.95	20	10.1	4.7
Nat. gas liquids	0.21	3.2		
• Tar - sand oil	0.23	6.3	1.7	0.8
Shale oil	0.87	77	1.1	0.5
Total	22.5 Q	450 Q	216 Q	

Table 5 Busbar Cost Sensitivity to Ore / Fuel Costs

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

Table 6 Uranium Resources

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

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

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

a.) US $ values of the late sixtees

b.) assuming a conversion factor of 1 short ton of $U_3O_8 \simeq 7\times 10^{11}$ BTU

c.) assuming a conversion factor of 1 short ton of $U_3O_8 \simeq 7\times 10^{13}$ BTU (1 short ton = 907 kg)

d.) making reference to note d.) of table 4 in [12]

e.) not necessarily consistent with [12]

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

g.) it has been estimated that the extraction of uranium from the sea could be done at 25 $ / pound of U_3O_8 [14]

Table 7

Radioactive Inventory of a Fusion Reactor after Shut-down

	10^3 sec ≈ 20 min Ci / Wth	10^7 sec ≈ 4 months Ci / Wth	10^8 sec ≈ 3 years Ci / Wth	10^{10} sec ≈ 300 years Ci / Wth	10^{11} sec ≈ 3000 years Ci / Wth
H^3	$2 \cdot 10^{-2}$	$2 \cdot 10^{-2}$	$1.7 \cdot 10^{-2}$	–	–
Nb^{94m}	0.17	–	–	–	–
Nb^{95}	1.1	0.11	–	–	–
Nb^{95m}	1.1	–	–	–	–
Nb^{92m}	0.3	–	–	–	–
Nb^{93m}	0.4	0.4	0.33	–	–
Nb^{94}	$0.7 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$	$0.7 \cdot 10^{-3}$	$\approx 0.7 \cdot 10^{-3}$
Nb total	3.07	0.51	0.32	$0.7 \cdot 10^{-3}$	$\approx 0.7 \cdot 10^{-3}$

Note: x) The Nb activities refer to 20 years reactor operation, 10 year values are lower by an insignificant factor except for the case of Nb^{94}. There the factor is roughly 2.

x) Figures are consistent with ORNL-TM-3094 /32/

Table 8

Radioactive Inventory of a Fission Reactor after Shut - down

		10^3 sec ≈ 20 min Ci/Wth	10^7 sec ≈ 4 months Ci/Wth	10^8 sec ≈ 3 years Ci/Wth	10^{10} sec ≈ 300 years Ci/Wth	10^{11} sec ≈ 3000 years Ci/Wth
I^{131}	U	$0.30 \cdot 10^{-1}$	$0.14 \cdot 10^{-5}$			
	LWR	$0.30 \cdot 10^{-1}$	$0.14 \cdot 10^{-5}$			
	LMFBR	$0.30 \cdot 10^{-1}$	$0.14 \cdot 10^{-5}$			
Sr^{90}	U	$0.45 \cdot 10^{-2}$	$0.45 \cdot 10^{-2}$	$0.42 \cdot 10^{-2}$	$1.8 \cdot 10^{-6}$	
	LWR	$0.36 \cdot 10^{-2}$	$0.36 \cdot 10^{-2}$	$0.34 \cdot 10^{-2}$	$1.5 \cdot 10^{-6}$	
	LMFBR	$0.10 \cdot 10^{-2}$	$0.10 \cdot 10^{-2}$	$0.09 \cdot 10^{-2}$	$0.4 \cdot 10^{-6}$	
total fission products	U	2.5	0.18	$0.29 \cdot 10^{-1}$	$0.2 \cdot 10^{-4}$	$0.9 \cdot 10^{-6}$
	LWR	2.5	0.18	$0.28 \cdot 10^{-1}$	$0.2 \cdot 10^{-4}$	$0.9 \cdot 10^{-6}$
	LMFBR	2.3	0.17	$0.18 \cdot 10^{-1}$	$0.15 \cdot 10^{-4}$	$0.6 \cdot 10^{-6}$
Pu^{241}	LWR	$0.39 \cdot 10^{-2}$	$0.39 \cdot 10^{-2}$	$0.33_5 \cdot 10^{-2}$		
	LMFBR	$0.73 \cdot 10^{-2}$	$0.73 \cdot 10^{-2}$	$0.62 \cdot 10^{-2}$		
ΣPu 239 - 242	LWR	$0.39 \cdot 10^{-2}$	$0.39 \cdot 10^{-2}$	$0.33_8 \cdot 10^{-2}$	$0.28 \cdot 10^{-4}$	$0.23 \cdot 10^{-4}$
	LMFBR	$0.75 \cdot 10^{-2}$	$0.75 \cdot 10^{-2}$	$0.64 \cdot 10^{-2}$	$1.7 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$
ground total	LWR	2.5	0.18	$0.31 \cdot 10^{-1}$	$0.50 \cdot 10^{-4}$	$0.23 \cdot 10^{-4}$
	LMFBR	2.3	0.17	$0.25 \cdot 10^{-1}$	$1.8 \cdot 10^{-4}$	$1.4 \cdot 10^{-4}$

Note: U means only thermal fissions from U^{235}

LWR means a LWR with an U: Pu power ratio of 0.7 : 0.3, and Pu 239 : 240 : 241 : 242 = 0.59 : 0.26 : 0.12 : 0.03, and 1 MW th/kg fiss. mat. as the rating.

LMFBR means a LMFBR with Pu as fuel in natural uranium, and Pu 239 : 240 : 241 : 242 = 0.69 : 0.25 : 0.04 : 0.02, and 1 MW th/kg fiss. mat. as the rating.

All fission products, including isomeres and daughters, have been considered.

Figures are consistent with KFK - Report 1797/ 33 /.

Table 9

Annual Discharge Activity for Disposal

	10^8 sec ≈ 3 years Ci/MWth·year	10^{10} sec ≈ 300 years Ci/MWth·year	10^{11} sec ≈ 3000 years Ci/MWth·year
Nb^{93m} (1)	$1.7 \cdot 10^4$	$0.5 \cdot 10^{-2}$	—
Nb^{94} (1)	35	35	35
total of fission products (LWR) (2)	10^4	6	0.3
0.5% of Σ Pu/year (LMFBR) (2)	35	1	0.4

Note: (1) Figures are consistent with Table 7 and 20 years of residence time of Nb in the fusion reactor.

(2) Figures are consistent with Table 8 and a 3 years residence time of the fuel in a fission reactor.

Table 10

Classes of Diversion of Nuclear Material

	detection	protection
governmental level	NPT, taken care of	NPT, taken care of by timely detection
Group X	NPT, taken care of	the problem here considered

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