Energy For Future Centuries
Will Fusion Be An Inexhaustible, Safe And Clean Energy Source?

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ABSTRACT

The current power consumption in different parts of the world and an estimate of the future energy needs of the world are given. The present energy supplies and prospects, the possible consequences of a continued massive fossil fuel consumption, and the potential of non-fossil candidates for long-term energy production are outlined. An introduction to possible fusion processes in future fusion reactors is given. The inexhaustibility, safety, environmental and economic aspects of magnetic fusion energy are discussed.

I. INTRODUCTION

Mankind is confronted with a continually rising world energy demand, which is a vital and precarious issue. Our energy future depends on a number of uncertainties of technological, environmental and political nature. Most of our energy is currently produced by burning fossil fuels. Negative side effects for the environment or depletion of fossil resources might force us in the future to switch to alternative energy sources.

The number of conceivable non-fossil candidates which in the long-term could substantially contribute to energy production is very limited : renewables, nuclear fission (breeders) and nuclear fusion. Fusion is the least developed of the three, but has particularly valuable environmental and safety advantages and disposes of virtually inexhaustible resources.

II. THE WORLD ENERGY PROBLEM

II.A. CURRENT AND FUTURE ENERGY NEEDS.

A brief overview of the current power consumption in different parts of the world is given in Table I.

The biggest consumers are Canada and Norway with about 13 kW per person, mostly because they dispose of cheap and abundant hydroelectric power. Power consumption in Japan and the European Union, is about half of that in the USA. With 6 billion people and a world average power consumption of about 2.1kW, the total amount of energy consumed currently amounts to about 2.1 kW × 6 billion people × 1 year ≅ 12 TWyr. A not too unrealistic estimate (see Appendix) of what might be needed in the future can be found with the following two assumptions :

(i) average power consumption per capita will rise from 2.1kW to about 3kW (i.e. about half of what is now already used in Europe and about one third of what is used in the USA), and

(ii) world population will rise to 10 billion in the next 50 years, as predicted by the UNO [1].

We thus find an estimated future energy need of 3 kW × 10 billion people × 1 year = 30 TWyr or about three times than what is already consumed now!

As a side remark, one could argue that a better energy efficiency in the future could lower this prediction. This is not as straightforward as it may seem. An interesting discussion in this respect, with many examples, can be found in [2].

How then are we going to satisfy this huge energy need? Can we continue to produce energy the way it is done now and what are the possible consequences?

COUNTRY	PER CAPITA CONSUMPTION (1995)
Canada	13200 W
Norway	13000 W
USA	11200 W
Japan	5700 W
Europe (West and East)	4800 W
Former Soviet Union	4000 W
China	990 W
India	370 W
Developing countries	100-1000 W
World	2100 W

Table I Per capita total primary power consumption for selected countries (average annual total primary power consumption per country divided by the number of its inhabitants) [3,4,4a,5].

II.B. CURRENT ENERGY SUPPLY AND FUTURE PROSPECTS

To answer the previous questions it is necessary to look at the present energy sources and supplies. Present proved recoverable reserves are given in Table II, together with an estimate of the period still available to use a specific source at the current rate of consumption.

One has to be careful with these numbers, however, as there lie huge political and economic interests behind them (for a frightening example, see [24]), which might lead to under- or overestimates depending on who is providing the data. In addition, large parts of the world are not yet prospected, and this could result in future updates of these numbers. Anyhow, from this table it follows that we can indeed go on as we do now for at least some decades. But is this really desirable ?

FUEL	PROVED RECOVERABLE RESERVES	YEARS OF USE AT THE CURRENT RATE OF CONSUMPTION
Coal	$1.0\ 10^{12}$ tons	270
Crude oil	$950\ 10^{9}$ barrels	40-50
Natural gas	$120\ 10^{12}$ m^3	60-70
Uranium	$2.0\ 10^{6}$ tons	40-50 (2400-3000)*

Table II Years of use of different fuels at the current rate of consumption [3,4,4a]
** if breeder technology is employed*

ENERGY SOURCE	CONTRIBUTION TO PRIMARY ENERGY PRODUCTION
Oil	40 %
Coal	27 %
Gas	21 %
Fission	6 %
Hydro-electricity	6 %

Table III Contribution of different energy sources to the primary energy production in the world [3].

As can be seen in Table III, about 90% of our energy is currently produced by burning fossil fuels This could pose serious problems in the future.

First, depletion of the world energy resources will inevitably lead to political instabilities in the world. The energy crisis of the 1970's, the 1991 Gulf war and the war in Chechenia are only small scale illustrations of what a real energy shortage could mean! Moreover, much better use could be made of the raw materials which are burned. They are invaluable for our chemical and pharmaceutical industry. From this point of view, our present energy production scheme causes irreplaceable basic chemicals to be lost forever on a gigantic scale.

The second, and most worrisome problem are the possible consequences to our environment of the massive use of fossil fuels due to the inevitable release of gigantic quantities of CO_2 in our atmosphere. In 1993 alone, more than 22 10^9 tons of CO_2 were produced and released in the atmosphere [6]. This could still seem to be negligible, as it represents only a minor fraction of the total amount of CO_2 released into the atmosphere (and subsequently recycled) by nature. Nonetheless, measurements show a very steep increase of the CO_2 content in the atmosphere during the last few decades. This can clearly be seen in Fig. I, where the atmospheric concentration of CO_2 is shown as a function of time since the year 900. This graph - compiled from the analysis of air bubbles in the ice of the Antarctic and measurements at the Mauna Loa in Hawaii - shows that at least for the last thousand years this concentration remained at a level of about 280 ppm. Since the beginning of industrialisation (around 1800) it has risen to more than 360 ppm, i.e. an increase of about 25%, and this only during the last 200 years ! This is a very short time scale for such a change, and is the more frightening in the light of additional evidence indicating that the CO_2 concentration has remained at about 280 ppm for the last 160000 years [7] ! Carbon sequestration could perhaps help to reduce future increases in CO_2 in our atmosphere [7a], but is of no use to reduce the present levels.

What are the possible consequences of such a sudden change in the composition of the atmosphere?

CO_2 is a greenhouse gas, and a higher concentration of this gas will lead to an increased absorption of the infrared radiation re-emitted by the earth. There is general agreement among specialists that this will cause the average temperature on earth to rise [7,8]. What will happen to our environment if the average temperature increases ? This is a most difficult question. Our ecosystem is very complex, with much feedback and as such probably buffered against, and able to adapt to sudden changes. However, as is the case for buffers in chemistry, there are limits to the adaptability of our ecosystem and the question remains: what are these limits ? In which direction will the ecosystem evolve as soon as the stability thresholds are crossed?

First, a clear answer to these questions presently does not exist. This should not be a surprise, since our climate involves numerous feedback loops, many of which are possibly underestimated or even unknown in climate models. Second, and what makes things even more frightening, is that the time required by nature to remove an excess of CO_2 in the atmosphere is very long, as it is mainly determined by the slow exchange of carbon between surface waters and the deep ocean : it takes nature something on the order of 100 years to restore the atmosphere [7]. This means also that as soon as changes are visible in our climate, we will have to deal with these effects for at least 100 years, on the condition that all anthropogenic sources of CO_2 could be shut down immediately, otherwise it will be even longer. But even by shutting down all sources of CO_2 immediately (which will be nearly impossible to realise) we are not sure to be on the safe side : nobody can ascertain that with a restored atmosphere our environment will also be restored, because there is no guarantee that the whole ecosystem will return in a reversible way to the previous situation.

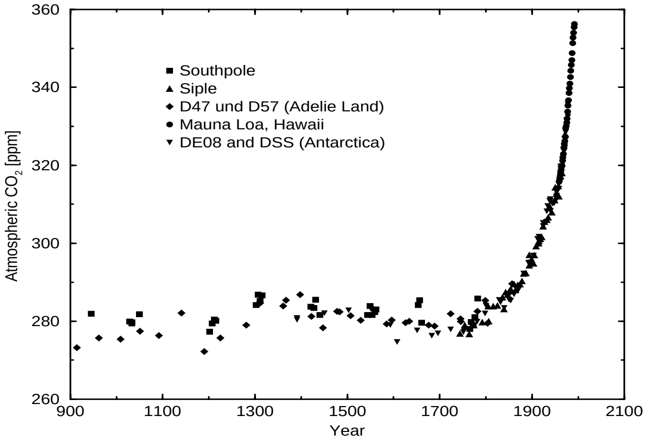

Fig. I Evolution of the CO_2 concentration in the atmosphere (in ppm) during the last 1000 years [9]

This is the most threatening consequence of our energy production scheme nowadays. We are conducting a possibly irreversible large-scale geophysics experiment. We have to remember that we have only one atmosphere and that it is irreplaceable, in other words, we are all "sitting in the test tube" ! The possibility of a global climatic change due to the emission of greenhouse gases poses dangers which are not well known, but might be very large. It cannot be excluded that certain parts of the world become no longer inhabitable in the future due to rising sea levels or desert formation; in addition, food-producing areas could shift, with hunger, poverty, migration of people, etc... as possible consequences. This would constitute a serious threat to peace and international security.

Is this the prospect we would like to offer our children and grandchildren?

In this context, it seems nearly unavoidable to reduce or even stop burning fossil fuels and try to use other energy sources as soon as possible, to reduce the risk of such dramatic changes. It will be not easy to prove with certainty that the changes in our climate are due to man’s activities; but it seems not wise to use this as an excuse for delaying necessary actions. Why should we take the risk to wait until we are certain, because then it will be much too late ! There is compelling evidence for a warming of our planet in recent years : 4 out of the 10 hottest years of the last century occurred during the last decade and 1998 was an absolute record year with the highest global temperature of the last 1000 years [26]! Worrying signs of changes in our climate are the nearly world-wide reduction in the size of the glaciers, especially the tropical ones [27], the increasing anomaly index of the El Niño Southern Oscillation since 1980 [27a], the increase of the sea-level by 2mm/year [27b] and an increasing number of ‘strange’ events : storms with an extreme destructive power (e.g. hurricanes Andrew and Mitch, Christmas storm of 1999 in France), enormous mudslides and rivers becoming dangerous torrents after heavy rain (Brigg, Switzerland 1993, Fortezza, South Tirol 1998, Venezuela 1999, etc), the highest waterlevels of the century in the Rhine 1991 and 1993 and Oder 1997 (Germany), ice avalanches from glaciers which are literally ‘sliding’ out of the mountains in Switzerland and France (Gutzglacier 1996 and 1999 [27c], Grandes Jorasses 1996 and 1997 etc [27d]), the thinning and breaking away of ice shelves of several 1000 km^2 in the Antarctic (Larsen B and Wilkins ice shelve [27e]) (one has only to realise that this ice has been there for thousands of years), harbors in the polar region becoming now accessible for ships because of absence of ice due to a retrait of the polar ice cover (Churchill, Manitoba, Canada [27f]), an increase by a factor of 4 in the number of so-called 'exceptionally hot' days recorded in Southern Italy over the last 50 years [27g], the bleaching of corals in Florida and Australia resulting in the destruction of unique ecosystems, etc. It is difficult to believe that these events are totally unrelated to greenhouse effects! It may therefore already be too late to avoid any climatic changes at all (for a detailed discussion, see [7]), and it seems therefore not unlikely that environmental constraints will impose reductions on the use of fossil fuels well before the effects of resource limitations are felt.

However, a quick and drastic change in the current energy landscape may be very difficult to realise. First, except for fission, none of the possible alternatives is at present mature enough to replace burning of fossil fuels for large scale energy production (see Sect. II.C); but even fission is (i) unfortunately only short term with the current type of reactors, and (ii) has a low level of acceptance by the general public (too often advantages are not mentioned and disadvantages are overemphasized in public discussions). Second, energy research budgets have dramatically decreased over the last decade (e.g. in the OECD, by about 40% [28]). Third, steps are taken in a direction opposite to what one would expect as e.g. the recent liberalization of the electricity market in Europe : although beneficial for economy, it will certainly not help to reduce energy consumption ! Depending on how the electricity is produced, it seems unlikely that this will lead to a reduction in CO_2 emissions. In addition, an ideal opportunity seems to have been missed here, as one could have imposed (even a small fraction) of the total price reduction as an energy tax to fund energy research. Fourth, there are tremendous economic and political powers trying to maintain the current situation by all possible means, see e.g. the frightening report in Ref. [24].

What are then possible alternatives and what are their limitations?

II.C. LONG-TERM ENERGY SOURCES

The only long-term alternatives to burning fossil fuels are renewables, fission and fusion.

Although renewable energy resources in the world are large and inexhaustible, they have, unfortunately, only a limited potential, as illustrated in Table IV.

Natural obstacles met by renewables are low energy density and/or fluctuations in time, implying the need for storage, which reduces again the efficiency and leads to extra costs. The example of solar energy can illustrate this. The total global daily solar irradiation on a horizontal surface in Middle Europe is 1000-1100 kWh/(m^2yr) corresponding to a mean solar illumination in our regions of about 114 - 125W/m^2. At present only a small fraction - at best around 10-20% with photovoltaic cells of the current technology - can be extracted. This implies important land use and investments in materials, (even if the efficiency in the future would increase to 50%) and is a hidden and often overlooked problem in the discussion on renewables which could pose serious environmental constraints. [10].

Tabel IV compares the surfaces required to substitute <u>just one</u> modern nuclear or fossil electric power plant by renewable sources. To get the surfaces needed to produce <u>merely the electricity needs</u> of a given country by renewables, one has to multiply the numbers above by an appropriate factor. For the US this would be roughly 330, for Western Europe about 260. To hypothetically produce not only the electricity but the <u>total energy needs</u> for a given country by renewables, the surfaces needed will be even much larger. Energy losses due to conversion and reconversion processes accompanying storage, (necessary to overcome long periods of low sunshine or wind) would cause an additional doubling of the surfaces needed.

METHOD	INVESTMENT NEEDED FOR 1000MW,el. (typical size of a single modern electric power plant)
Photovoltaic panels	about 100 km^2 in Middle Europe (10% efficiency assumed)
Windmills	6660 mills of 150 kW (with rotor blades of 20m and at the average wind speed prevailing at the North Sea coast)
Biogas	60 million pigs or 800 million chickens
Bioalcohol	6200 km^2 of sugar beet 7400 km^2 of potatoes 16100 km^2 of corn 27200 km^2 of wheat
Bio-oil	24000 km^2 of rape-seed
Biomass	30000 km^2 of wood

Table IVIllustration of the limitations of renewable energy sources [calculated from data of Ref. 12] (assumed to be used for electricity generation; where necessary an overall efficiency of 40% for the thermal cycle is included; no compensation for losses due to storage is included for solar or wind power)

We would like to stress that we do not at all intend to imply that renewables are useless. The purpose of the comparison above is only to give an idea in simple terms of the vast requirements concerning materials and land use for renewable energy sources. It should be clear that they are not really 'alternative' energy sources to substitute fossil fuels for our modern society; they rather complement existing and future cleaner energy sources. It makes certainly sense to try to exploit their potential as much as is realistically possible, as every non-fossil energy source will be needed in the future. But one should bear in mind the limited prospects for this kind of energy [11].

Another option is given by nuclear energy : fission and fusion. In the case of <u>fission</u>, highly radioactive waste is produced, but the volume is rather low : only about $1m^3$ i.e. about 28 tons of irradiated fuel per GWyr. In addition, about 27 tons of the irradiated fuel can in principle be reprocessed and reused in other reactors [13] as it consists of a mixture of about 224 kg ^{235}U, 26400 kg ^{238}U and 170 kg of fissile Pu isotopes, the rest - fission products and non-fissile elements - must be disposed of. Hence, in the strict sense only 1 ton or about 50 dm^3 of highly active waste is produced per GWyr (the total volume after packaging for disposal becomes about $4m^3$). Moreover, the danger of this waste is known and new methods are being developed to store it in a safe way [14], or even to eliminate it by transmutation thereby producing energy [14a]. This is in sharp contrast with the large amount of waste produced by burning fossil fuels : gigatons of CO_2 spread around the world and nobody knows what will be the precise consequences ! With the present reactor types the lifetime of our uranium resources is rather short - about 50 years. Using breeder technology to transform non-fissile fuel into fissile elements, we could stretch our resources by a factor of about 60 [15, 16], although the safety and environmental problems are potentially more difficult to cope with. However, new reactor concepts, which rely on passive safety systems, could increase the acceptance by the general public [17].

METHOD	ANNUAL FUEL CONSUMPTION FOR 1000MW,el. (typical size of a single modern electric power plant)
Coal	2 700 000 tonnes
Oil	1 900 000 tonnes
Fission	28 tonnes of UO_2
Fusion	100 kg D and 150 kg T

Table V Fuel consumption for different energy production methods

The third option is nuclear <u>fusion</u>. It is the least developed of the three but it holds the promise of being a safe, inexhaustible and rather clean energy production method. As such it could become the best compromise between nature and the energy needs of mankind. Recent studies carried out for the European Commission [18] confirm this point of view. Energy quality criteria will become most important in the future : energy production must be not only economically, but also environmentally and socially acceptable.

<u>To reach this level, China has to build and to take into operation each month, and this during the next 50 years, at least one new electric power plant with a capacity of 1000 MW,el - fired by coal</u>. Note that this huge installation rate is not a theoretical possibility, an average rate of 1500 MW,el/month has been realised already in China during the period 1995-1997 [3,18c] !

III. NUCLEAR FUSION AS AN ENERGY SOURCE FOR THE FUTURE.

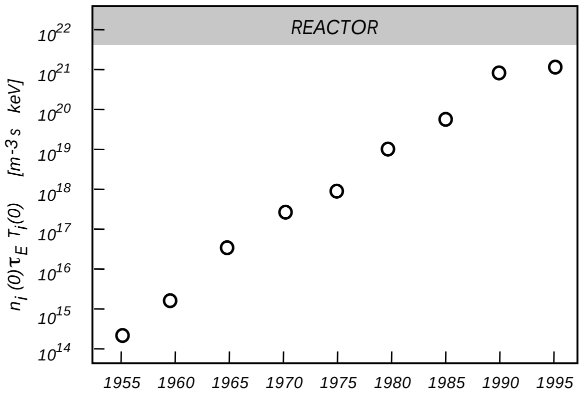

Fig. II Evolution of the value for the fusion triple product since the beginning of fusion research [after 21a]

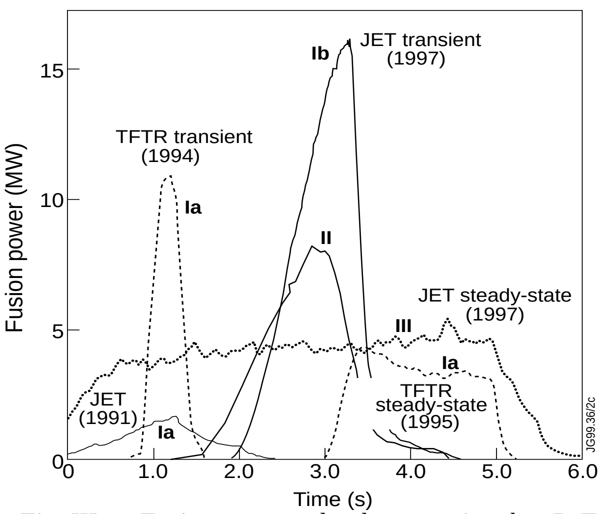

Fig. III Fusion power development in the D-T campaigns of JET (full and dotted lines) and TFTR (dashed lines), in different regimes: (Ia) Hot-Ion Mode in limiter plasma (Ib) Hot-ion H-Mode, (II) Optimized shear and (III) Steady-state ELMY-H Modes [21b].

The development of nuclear fusion as an energy source is one of the most complex scientific and technical tasks ever undertaken for non-military purposes and will still span several human generations. There exist presently two approaches to realise nuclear fusion on earth : inertial and magnetic fusion. Inertial fusion consists of micro-explosions of small fuel pellets by means of powerful lasers or particle beams. Confinement of the fuel is based on the inertia of the pellet fuel mass, which resists the natural expansion when it is heated to thermonuclear fusion temperatures. Magnetic fusion uses magnetic fields to confine the fuel. The European fusion effort is concentrated on the latter and hence we will briefly review only this method here. The interested reader can find a wealth of additional information in the references [18, 19, 20, 21].

A fantastic progress has been obtained in magnetic fusion. Three generations of tokamaks with doubling of characteristic dimensions at each step led to a 10000 times higher value of the fusion triple product (density times temperature times confinement time) in the last 30 years. Since the start of controlled fusion research, a 10 millionfold improvement in the fusion triple product has been obtained verging to reactor conditions, as illustrated in Fig. II.

Since 1991 several megawatts of fusion power have been released in a controlled way in deuterium-tritium experiments in JET (Joint European Torus, Culham, UK) and TFTR (Tokamak Fusion Test Reactor, Princeton, USA). Peak values of about 16 MW have been obtained on JET in 1997 corresponding to Q_{DT} values (i.e. the ratio of the power released from deuterium-tritium fusion reactions to the power applied to heat the fuel) of more than 0.6; in a stationary way fusion powers of more than 4 MW have been obtained for more than 5 s on JET. A comparison of high performance D-T pulses is given in Fig. III. Break-even in deuterium-tritium experiments, i.e. $Q_{DT} = 1$, is expected at JET in the coming years.

Alternative, non-tokamak magnetic fusion approaches (stellarators, reversed field pinches) may offer economic and operational benefits. However, these approaches are more than one generation behind the tokamak line.

III.A. NUCLEAR FUSION PROCESSES AND FUTURE FUSION REACTORS

The least difficult fusion reaction to initiate on earth is that between the hydrogen isotopes D and T :

$$D + T \rightarrow {}^{4}He\ (3.5MeV) + n\ (14.1MeV)$$

in which D stands for deuterium (the stable isotope of hydrogen with a nucleus consisting of one proton and one neutron) and T for tritium (the radioactive hydrogen isotope with a nucleus of 2 neutrons and 1 proton, see Section III.B). To produce sufficient fusion reactions, the temperature of the plasma has to be on the order of 100 to 200 million C for this reaction.

A first generation of future fusion reactors would be based on this reaction. The reaction products are thus an _-particle (helium nucleus) and a very energetic neutron. Twenty percent of the energy is taken by the _-particles which are confined, owing to their charge, and deliver their energy to the background plasma. In this way they compensate for losses and might make the reaction self-sustaining. The kinetic energy of the fast neutrons will be converted into heat in a blanket and then into electricity using conventional technology (steam). About one million times more energy is released from a fusion reaction in comparison with a chemical one (MeV's instead of eV's for the latter). This is the reason why so little fuel can produce so much energy : when burnt in a fusion reactor, the deuterium contained in 1 l of water (about 33 mg) will produce as much energy as burning 260 l of gasoline.

The D-T reaction is not the only possibility for controlled fusion. Other conceivable reactions are :

$$D + D \rightarrow {}^3He\ (0.82MeV) + n\ (2.45MeV)$$

$$D + D \rightarrow T\ (1.01MeV) + H\ (3.02MeV)$$

$$D + {}^3He \rightarrow {}^4He\ (3.6MeV) + H\ (14.7MeV)$$

These are more difficult to achieve and have a much lower power density than the D-T reaction [21, 25] but show even more benign environmental features. The D-D reaction would eliminate the need for tritium and produce neutrons with lower energies which are therefore easier to absorb and shield. A reactor based on the D-^{3}He reaction would proceed with very low neutron production (some neutrons would be produced in competing but much less occurring D-D reactions) with minor radioactivity produced in the reactor structures. This reaction also releases its total energy in the form of charged particles, enabling in principle the possibility of direct energy conversion to electrical energy. However, the prospects for these 'advanced' fuels are still too speculative and only the D-T reaction has immediate future prospects.

III.B. INEXHAUSTIBLE ENERGY SOURCE ?

The most obvious advantage of fusion is the virtual inexhaustibility of the fuels which are cheap and widely accessible. Table VI summarises the presently estimated reserves.

Deuterium, a non-radioactive isotope of hydrogen is extremely plentiful as it can be obtained from ordinary water (about 33 g from 1 ton) with cheap extraction techniques using conventional technology. Complete burning of deuterons and the first generation fusion products (T and ^{3}He) results in the overall equation :

$$6D \rightarrow 2\,{}^4He + 2H + 2n + 43.3\ MeV$$

providing 350 10^{15} J/ton D. The deuterium content of the oceans is estimated at 4.6 10^{13} tons [15], thus equivalent to about 5×10^{11} TWyr.

Tritium is the radioactive isotope of hydrogen. It decays to ^{3}He by emission of an electron :

$$T \rightarrow {}^3He + e^- + 18.7\ keV$$

with the rather short half-life of 12.3 years. The quantities available in nature are not sufficient for technical applications. The neutrons produced in the fusion reactions will be used to breed it by bombarding a blanket around the burn chamber containing a lithium compound, according to :

$${}^6Li + n \rightarrow {}^4He\ (2.05MeV) + T\ (2.73MeV)$$

$${}^7Li + n \rightarrow {}^4He + T + n - 2.47\ MeV$$

Thus the real consumables in the D-T fusion process are D and Li, while T is an intermediate fuel.

Lithium, like deuterium, is a widely available element. There are two isotopes ^{6}Li and ^{7}Li, which occur naturally (7.5% and 92.5% respectively). ^{6}Li is the most useful isotope as it reacts with neutrons in the lower energy range ($E < 1MeV$). Model calculations [18] show that the burnup of ^{7}Li in a future fusion reactor would be negligible and thus only ^{6}Li is relevant to resource considerations. Per ^{6}Li atom, one T atom is formed, with an extra energy of 4.78 MeV. Including the energy released in D-T fusion reactions, 22.38 MeV is released per ^{6}Li atom. The energy content of natural Li is therefore about 27 10^{15} J/ton. Estimated reserves of natural Li are 11 million tons in known ore deposits in the earth and 200 billion tons dissolved in sea water [18d], equivalent to about 9 10^3 and 1.7 10^8 TWyr. The amount of energy needed to extract Li is negligible compared to the energy released in thermonuclear reactions.

FUSION FUEL	ENERGY CONTENT (TWyr)	YEARS OF USE TO SUPPLY WORLD ELECTRICITY NEEDS (AT 1995 LEVELS)
D	5×10^{11}	150 billion yr
Li (known reserves)	9×10^3	3000 year
Li (in sea water)	1.7×10^8	60 million yr

Table VI Estimated reserves of fusion fuels.

Since only one neutron is produced in each fusion reaction and since each new tritium nucleus to be bred from Li requires one neutron, it is necessary to provide a small additional neutron source, to balance losses in the breeding blanket. A possible suitable neutron multiplier is beryllium, using the (n,2n) reaction:

$$^{9}Be + n \rightarrow 2\,^{4}He + 2n - 1.57\ \text{MeV}$$

Another question related to inexhaustibility is if we dispose of enough suitable materials (e.g. structural and superconducting materials for the magnets) for a large scale use of fusion energy over many centuries. Also here there seem to be no significant constraints [18].

III.C. SAFETY ASPECTS

• Inherent and passive safety

- Can Chernobyl-type accidents occur?

First, the amount of fuel available at each instant is sufficient for only a few tens of seconds, in sharp contrast with a fission reactor where fuel for several years of operation is stored in the reactor core. Second, fusion reactions take place at extremely high temperatures and the fusion process is not based on a neutron multiplication reaction. With any malfunction or incorrect handling the reactions will stop. An uncontrolled burn (nuclear runaway) of the fusion fuel is therefore excluded on physical grounds. Even in case of a total loss of active cooling, the low residual heating excludes melting of the reactor structure [18].

• Radioactivity

The basic fuels (D and Li) as well as the direct end product (He) of the fusion reaction are not radioactive. However, a fusion reactor will require radiation shielding since it has a radioactive inventory consisting of (i) tritium and waste contaminated by tritium and (ii) reactor materials activated by the neutrons of the fusion reaction. Studies [18-20] indicate, however, that an adequate choice of the latter can minimise the induced radioactivity such that recycling should become possible after some decades to a century. Thus, radioactivity does not have to be inherent to nuclear fusion, in contrast to nuclear fission where the fission reaction itself leads to dangerous long-lived radioactive products.

The tritium cycle is internally closed, and the total tritium inventory in the fusion power plant will be on the order of a few kg, of which only about 200 grams could be released in an accident. Special permeation barriers will have to be used to inhibit discharge into the environment of tritium diffusing through materials at high temperature [18]. As tritium is chemically equivalent to hydrogen, it can replace normal hydrogen in water and all kinds of hydrocarbons. It could thus contaminate the food chain when released in the atmosphere. The absorption of tritium contaminated food and water by living organisms is a potential hazard. However, possible damage is reduced owing to the short biological half-life of tritium in the body of about 10 days.

• Links to nuclear weaponry?

The operation of pure (i.e. non-hybrid) fusion reactors (see Section III.E) is not accompanied by the production of fissile materials required for nuclear weapons. Only a significant modification of the fusion reactor - the introduction of a special breeding section containing fertile material - would make the production of weapons grade fissile materials possible. However, according to the conclusion of experts (see e.g. [22]), the presence of such a section (in an environment where none at all should be present) could be easily discovered by qualified inspectors. This is in sharp contrast to a fission reactor where production of these materials occurs in the reactor core itself and where in addition a delicate balance has to be made of large inventories of ingoing and outcoming nuclear material to discover any possible diversion of fissile material.

• Other non-nuclear risks

Reactor designers will have to minimise non-nuclear risks such as Li-fires, release of chemical toxins like Be, sudden loss of vacuum or cooling liquids, etc... But none of the possible issues currently appear to be sufficiently serious to weigh importantly in societal discussions about the attractiveness of fusion compared to other energy systems.

III.D. ENVIRONMENTAL ASPECTS

• Environmental pollution?

The primary fuels (D and Li) and the direct end product (He) are not radioactive, do not pollute the atmosphere, and do not contribute to the greenhouse effect or the destruction of the ozone layer. Helium is in addition chemically inert and very useful in industry. There are no problems with mining (Li) and fuel transportation. There also exist no ecological, geophysical and land-use problems such as those associated with biomass energy, hydropower and solar energy.

Measures for tritium containment and detritiation of substances contaminated with tritium will have to be taken. During normal operation the dose for the public in the neighbourhood of the plant will only be a fraction of the dose due to natural radioactivity.

• Dangerous waste?

An important advantage of fusion is the absence of direct radioactive reaction products, in contrast to fission, where radioactive waste is unavoidable since the products of the energy releasing nuclear reaction are radioactive.

Adequate disposal of radioactive waste is especially difficult if the products are volatile, corrosive or long-lived. The neutron-activated structural materials of a fusion reactor would not pose such problems and because of their high melting point and their low decay heat, will not necessitate active cooling during decommissioning, transport or disposal. Recent studies [18] show that over their life time, fusion reactors would generate, by component replacement and decommissioning, activated material similar in volume to that of fission reactors but qualitatively different in that the long-term radiotoxicity is considerably lower (no radioactive spent fuel).

Fusion could be made even more attractive by the use of advanced structural materials with low activation as e.g. vanadium alloys or silicon carbides. These materials offer in principle the prospect of recycling after about 100 years after shutdown of the reactor as the radioactivity would fall to levels comparable to the those of the ashes from coal-fired plants [18] (which contain always small amounts of thorium and other actinides). It is not yet clear that they will meet a number f technical specifications with regard to thermo-mechanical properties and the ability to withstand a high neutron flux and further research is necessary to clarify these points [23]. But even if existing structural materials like stainless steel are used, the induced radioactivity in a fusion reactor is still about 10 times less than in a fission reactor of comparable power [15, 20].

III.E. ECONOMIC ASPECTS

- Economic viability of future fusion plants?

It is obviously difficult to estimate with any useful precision the cost of a system which will only be put into service several decades from now. In comparing with other energy sources, environmental and safety-related advantages and the virtual inexhaustibility of the fuel sources should be taken into account, as well as the evolution of the cost of electricity based on (exhaustible) resources. Present studies, embodying many uncertainties, produce cost estimates, which are close to those of present power plants. Investment costs (reactor chamber, blanket, magnets, percentage of recirculating power,...) will probably be higher, but the fuel is cheap and abundant. Fusion is likely to be a centralised energy source. On the basis of present knowledge, technologically sophisticated power plants will probably have an electrical output larger than 1GW to be economic. The fast neutrons produced in the D-T reaction could be used to produce fissile material in fusion-hybrid breeder reactors [21]. This complementary role for fusion might improve system economics compared with pure fusion systems; however, it would increase societal concerns related to safety, environment and weaponry.

- Cost of fusion research?

Public expenditure on fusion research in the European Community is presently about 500 million Euro per year. Every comparison has unavoidably its disadvantages, but in the case of fusion – being an important possible option for our energy future, generating electricity – it seems fair to compare this number to (i) the present cost of electricity in Europe and (ii) to the investments in other energy systems under development.

Concerning (i): The total electricity bill spent in 1997 in the European Community by end users can be estimated as the product of the net consumption times an average electricity price or roughly 2150 GWh × 0.1 Euro/kWh = 215 billion Euro [18c]. The fusion effort in Europe is thus equivalent to about 0.4% of the yearly European electricity bill. Alternatively one can calculate the cost of fusion research per European citizen: with about 390 million Europeans, the fusion effort comes down to about 1.2 Euro for every European per year.

Concerning (ii): All funds for fusion research are and have to be public, due to the long period still needed before a fusion reactor can become a commercially available system. These public funds are very well known. For the other energy sources (especially wind and solar), it is not so easy to get a complete picture of the money spent on research as several private companies are contributing with own research investments. In addition, subsidies or tax reductions may be applied to promote these systems, which should be included in the public expenditure on the system. To illustrate these points and to show that the public expenditure on energy research for the other sources is certainly not less than for fusion, we take the case of Germany. Total investments in fusion research for 1999 are about 300 million DM. This number should be compared to the cost alone of subsidising electricity generated by solar and wind in Germany, which is estimated at something between 1.5 billion DM/year and 4 billion DM/year [29].

IV. CONCLUSIONS

In a most profound sense, mankind's quality of life depends on an acceptable response to the continually rising demand for energy. To be able to satisfy our future energy needs, we therefore have to invest in all viable energy options, compatible with our environment.

Fusion is one of these options and is characterised by exclusive properties, some of which represent distinct advantages over the other major energy sources. They can be grouped around three aspects :

- Fuel : abundant supply of cheap fuels (D and Li); they are non-radioactive, and their extraction does not cause any significant ecological problem.

- Safety : fusion reactors offer inherent, passive safety. They are not based on a neutron multiplication reaction and do not contain a large supply of fuel in their core. An uncontrolled burn of the Chernobyl type is excluded.

- Environment : Fusion reactions produce energy and no direct radioactive waste with all its problems. However, in current fusion reactor concepts there is radioactivity from two sources. First, from tritium, which is bred locally from lithium, but consumed directly. Second, by activation of reactor structures by neutrons. Future reactor concepts might strongly limit this radioactivity. Anyhow, by carefully choosing structural materials, the radioactive wastes will not constitute a burden for many generations. In addition there is no production of combustion gases as is the case for power plants burning fossil fuels. Hence, there is no contribution to the greenhouse effect, to acid rain and to the destruction of the ozone layer.

There should be no illusions about the technical difficulty or the time required bringing even the D-T reaction to a commercially viable system. However, there is no indication up to now to doubt that finally fusion could be made practical and successful. History has repeatedly proven that major technological projects (not hampered by scientific limits) have finally reached a breakthrough. Who would have believed 80 years ago (when flying was already an exciting reality) that highly sophisticated planes would provide transport of passengers across the Atlantic on a large scale and at prices far below those by ship ?

Given the potential advantages of nuclear fusion compared to the risks and dangers of all other alternatives for base load electricity generation and given its potential contribution to long-term sustainable world development, is it not our duty towards future generations to continue the fusion effort without delay and with full commitment ?

APPENDIX:

Present and future energy needs.

Presently, the Far East (with 60% of the world population) consumes about 25% of the energy in the world, with an annual growth of about 5% over the last 10 years [3]. The rest of the world has an annual growth of 1.5%. A cautious extrapolation of these numbers can perhaps be made as follows. If we assume that (i) the growth in the Far East will not remain at the current high level but drop to only half of what it is now, (ii) the annual growth in the rest of the world will also drop (to e.g. 1% annually) then - supposing the world population would remain at its present 5.7 billion level - we may expect a 50 to 100% increase in the world energy consumption in the coming 20-30 years, as outlined in Table VII. The explosive growth of the world population, however, could in the best case outweigh possible overestimates in the growth numbers assumed in Table VII, but could also make the situation much worse. This estimate could therefore well be only a lower bound, and it is possibly not too unrealistic to expect a threefold increase in the world energy consumption around 2030.

	Present Primary Energy Consumption (TWyr)	Average Annual Growth		Primary Energy Consumption in 20-30 years (TWyr)
		Present	Assumed in extrapolation	
Far East	3.2	5%	2.5%	5 - 7
Rest of world	8.8	1.5%	1.0%	11 - 13
Total	12	-	-	16 - 20

Table VII Extrapolation of the present primary energy consumption to within 20-30 years, omitting the effect of a growing world population.

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