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FUSION AS A FUTURE POWER SOURCE: RECENT ACHIEVEMENTS AND PROSPECTS

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1.0 Introduction

Recent advances in high energy plasma physics show that nuclear fusion - the energy source of the sun and the stars [1] - may provide the corner-stone of a future sustainable energy system. Such power plants would be safe and environmentally friendly. In particular, one of the main problems of fission reactors, namely that of a possible uncontrollable nuclear reaction is banished; also the problem of radiotoxic waste is reduced by many orders of magnitude. Fusion reactors would have almost limitless supplies of fuel and could be sited anywhere in the world. Fusion is, however, still in the development stage and it is not expected that commercial power plants will start operation before the middle of this century.

The aim of the present paper is to present the current status of fusion research and to describe the steps ahead that will lead to power generation. First, we introduce the principle of nuclear fusion and explain how in a future power plant based on this principle the extremely hot ionised hydrogen gas ("plasma") is contained in a magnetic field cage ("magnetic confinement"). We then go on to describe the advances made in fusion research in the last few years and note that the so-called break-even point has almost been reached at the Joint European research facility JET in Culham, UK. Subsequently, the factors affecting the design of a future fusion power plant, its safety and environmental features as well as the possible costs of fusion power, are discussed. Finally, we consider the role which fusion might play in various energy scenarios in the second half of the century.

2.0 Principles of fusion

2.1 Mass turns into energy

According to our understanding of modern physics, matter is made of atoms [2]. Their constituents are positively charged nuclei surrounded by negatively charged electrons. Two light nuclei, when they approach each other, undergo, with a certain probability depending on their separation, a fusion reaction. Figure I depicts the reaction of heavy hydrogen and super-heavy hydrogen, deuterium and tritium (known as isotopes of hydrogen), to give helium (an α particle) and a sub-atomic particle, the neutron. Energy is gained in the process, which is carried away as kinetic energy by the helium atom and the neutron. At the same time, mass is lost: the combined mass of the products is lower than that of the reactants. Compared with a conventional (carbon) combustion process the energy gain is greater by six orders of magnitude! In principle numerous nuclei could be used as fuel in a fusion power plant. The advantage of deuterium and tritium is their high reaction probability.

The aim of fusion research is to design schemes in which light nuclei approach each other frequently down to such small separations that there is a high chance of numerous reactions taking place. Under normal conditions nuclei are separated at least by the so-called atomic radius which reflects the presence of the surrounding electron cloud. Under these conditions fusion does not take place. If the atoms are heated, the motion of the electrons and the nuclei will increase until the electrons have separated. A hot gas, where nuclei and electrons are no longer bound together, is called a plasma.

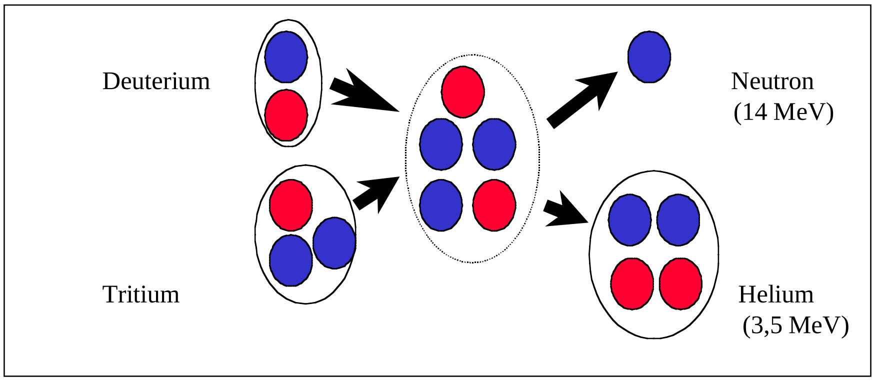

Figure I: Schematic of the fusion reaction in which deuterium and tritium form a helium atom and a neutron. Mass is lost in the reaction and energy gained.

Even in a plasma, however, the nuclei do not come close enough to react because of mutually repulsive forces. By heating the plasma to an even higher temperature – one speaks of a very hot plasma - the ions acquire an even higher velocity, or kinetic energy, and can then overcome the repulsive force. As an analogy, we can think of a fast ball rolling up a hill against the gravitational force. Clearly, the number of fusion reactions that take place will depend on the plasma temperature and plasma density.

The production of the plasma and its subsequent heating require of course energy. A successful fusion power plant requires that the power produced by the fusion reaction exceed the power required to produce and heat the plasma. The ratio of the power generated to that consumed (the fusion power amplification factor) is called the Q value. Initially, the plasma will be heated by various external sources, e.g. microwaves. With increasing temperature, however, the number of fusion reactions also increases and the fusion reaction itself heats the plasma due to the production of the energetic helium atoms (actually ions, or α particles). The kinetic energy of the helium nuclei exceeds the average kinetic energy of the nuclei of the fuel (deuterium and tritium) by orders of magnitudes. The energy is distributed to the fuel nuclei via collisions, as in a game of billiards. In fact, a point can be reached - termed ignition - when external heating is no longer necessary and the value of Q goes to infinity. In practice, however, power plant operation would probably correspond to a Q value of 20-40.

The state of a very hot plasma and its nearness to the ignition condition can be characterised by the product of temperature, density and the so-called energy confinement time. The latter value describes the ability of the plasma to maintain its high temperature; in other words, it is a measure for the degree of insulation of the plasma. Ignition can only be achieved if this “fusion triple product” exceeds a certain value.

2.2 Magnetic confinement fusion

The temperatures necessary to ignite a plasma are between 100-200 Mio °C. Obviously no solid material is able to confine a medium with such a high temperature. This dilemma is solved by the fact that in the plasma, all the particles carry an electrical charge and can thus be confined by a magnetic field. (The charged particles gyrate around the magnetic field lines.) It transpires that a doughnut-shaped configuration of the magnetic field “cage” is appropriate for this purpose, although the story is actually a little more complicated: the magnetic field lines not only have to be doughnut-shaped, they also need to have a helical twist. This scheme is referred to as magnetic confinement.

Different proposals were made to produce helically-wound doughnut-shaped magnetic field cages. The most successful approach has been the tokamak, first realised in Russia [3]. A sketch is shown in figure II. The magnetic field is the sum of the toroidal magnetic field produced by the coils shown and the magnetic field produced by a current in the plasma. The problem associated with the tokamak concept is driving the current in the plasma. The most important concept applied today is to place another magnetic coil in the centre of the tokamak (see figure II: solenoid magnet) and to ramp the current in this coil up or down. This will produce a varying magnetic field in the coil which in turn induces a voltage in the plasma (the principle of induction). This voltage can only be sustained for a limited time - one or two hours at the very most.

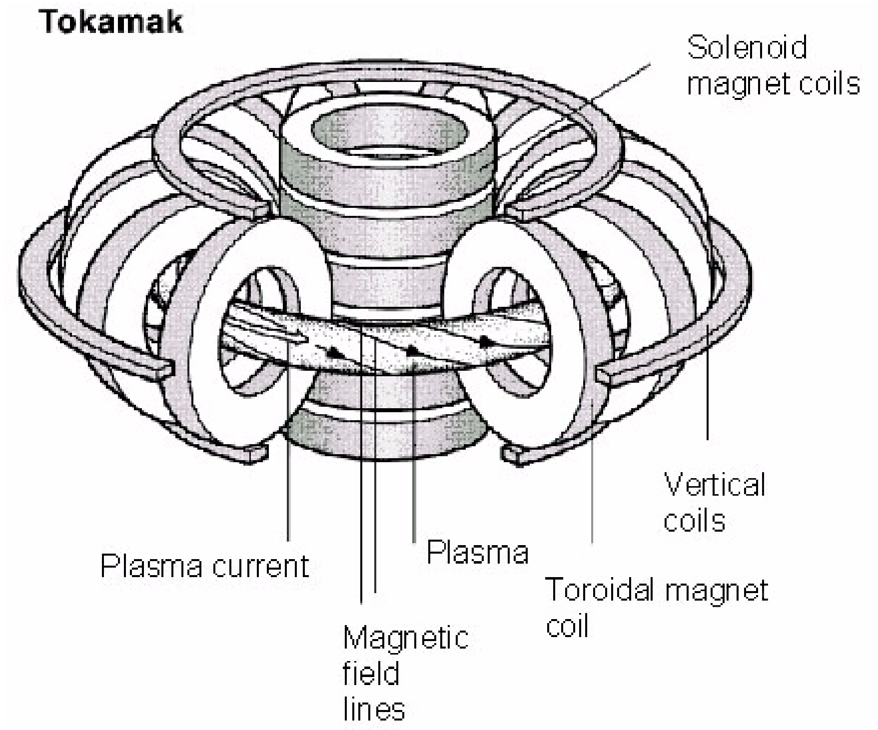

Figure II: The tokamak has so far been the most successful magnetic confinement scheme. The magnetic field cage - necessary to confine the charged particles - is produced by the superposition of a toroidal magnetic field and a poloidal magnetic field produced by a current in the plasma.

Base load electricity plants need of course to produce power under steady state conditions. Many current R&D activities are directed towards finding alternative ways of driving the current in the plasma (via microwave heating or particle beam injection) or to concentrate on the stellarator, successfully pursued in several countries, in particular Germany and Japan, in which no current is necessary.

2.3 Alternative path to fusion

Two alternatives to magnetic confinement are discussed briefly here: inertial confinement and muonic fusion.

In inertial confinement fusion a small pellet of deuterium and tritium fuel is compressed by so-called momentum conservation to extremely high density and temperature. (Densities of twenty times the density of lead and temperatures of 100 Mio ° C are envisaged.) The fuel pellet is encapsulated by an layer of another material and subject to extremely intense beams of laser radiation or high energy charged particles. The outer layer heats up and evaporates. The evaporation products move outwards, but the rest of the pellet is compressed inwards, due to momentum conservation. Inertial confinement is mainly investigated in the US and France and to a lesser extent in Japan, Britain and other European countries. Since such experiments can also be used to study the physics of nuclear weapon explosions, much of this research in the US is financed from the defence budget [4]. Inertial fusion is considerably less developed than magnetic confinement fusion with respect to the realisation of a power plant.

Muonic fusion, which seemed very promising in the beginning, is now only investigated in a few laboratories. The idea is to produce muons, which are the heavy sisters of the electron. The muon is injected into a deuterium-tritium gas mixture. There is a finite probability that the muon will be captured by a tritium or deuterium atom and form a deuterium-tritium molecule. Since the muon is very heavy, the dimensions of such a molecule are much smaller than those of a normal molecule with bound electrons. Therefore the nuclei will be much closer to each other and there is a greater likelihood that they will undergo a fusion reaction. The problem of this scheme is that the production of muons costs too much energy and that the muon will only “catalyse” about two hundred fusion reactions [5].

2.4 The possible design of a fusion power plant

The various features such as steam generator, turbine and current generator will be the same as in conventional nuclear or fossil-fuelled power plants. A flow chart of the energy and material flows in a fusion plant are depicted in figure III. The fuel - deuterium and tritium - is injected into the plasma in the form of a frozen pellet so that it will penetrate deeply into the centre. The neutrons leave the plasma and are stopped in the so-called blankets which are modules surrounding the plasma. The neutrons deposit all their kinetic energy as heat in the blanket. The blankets also contain lithium in order to breed fresh supplies of tritium via a nuclear reaction (see 4.2). The "ash" of the fusion reaction – helium – is removed via the divertor. This is the section of the containing vessel where the particles leaving the plasma hit the outer wall. The outer magnetic field lines of the tokamak are especially shaped so that they intersect the wall at special places, namely the divertor plates. Only a small fraction of the fuel is "burnt" so that deuterium and tritium are also found in the “exhaust” and can be re-cycled. The tritium produced in the blankets is extracted with a flushing gas - most likely helium - and delivered to the fuel cycle.

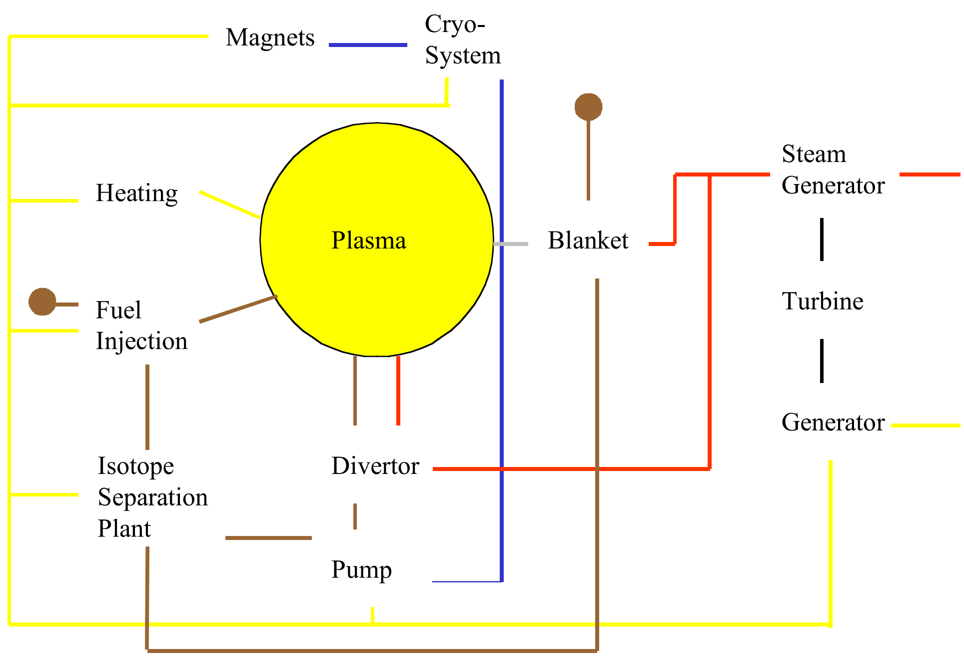

Figure III: Flow chart for a future fusion reactor: fuel (brown), electrical power (yellow), heat (red), neutron (grey), mechanical power (black) and cooled helium (blue).

The heat produced in the blanket and the divertor is transported via water or helium to the steam generator and used to produce electricity to feed to the grid. A small fraction is used to supply electricity to the various components in the plant itself. Electrical power is required mainly for the cryo-system which produces low temperature helium for the super-conducting magnets, the current in the magnets, the current drive and the plasma heating systems.

The reactor core is arranged in different layers like an onion. The inner region is the plasma, surrounded by first wall and blanket. All this is contained in the vacuum vessel. Outside the vacuum vessel are the coils for the magnetic field. Since the magnets operate at very low temperatures (superconductors), the whole core is inside a cryostat (see figure VII).

3.0 Status of Fusion Research

3.1 Plasma physics: "break-even" at JET

Progress on the path to ignition in magnetic confinement fusion research is best characterised by the improvement in the triple product. As described above, the triple product is the product of plasma temperature, plasma density and energy confinement time. Figure IV depicts the increase of the triple product by five orders of magnitude in the last three decades. Only a factor 5-6 remains to be overcome before ignition is reached. The first promising results were achieved in the Russian tokamak T3, following which tokamaks were constructed in many countries at the beginning of the seventies. Construction of the Joint European Torus (JET) started the end of the seventies. It went into operation in 1983 and remains the largest fusion device in the world.

The major physics issues in the world-wide fusion program centres are: improvement of the energy confinement time, plasma stability, particle and power exhaust, and α particle (helium nuclei) heating.

The energy confinement time depends strongly on the plasma dimensions. Larger machines will have longer confinement times. The confinement time is - as mentioned above - a measure of the heat insulation of the plasma core and it is clear that a larger plasma insulates the core better than a smaller plasma. Improvements have also been made by establishing new plasma modes, i. e. stable states corresponding to particular sets of the various parameters that characterise the plasma. Increased understanding of the underlying physics and many experimental studies have led to the discovery of new plasma modes, such as the so-called H-mode in 1982 [6].

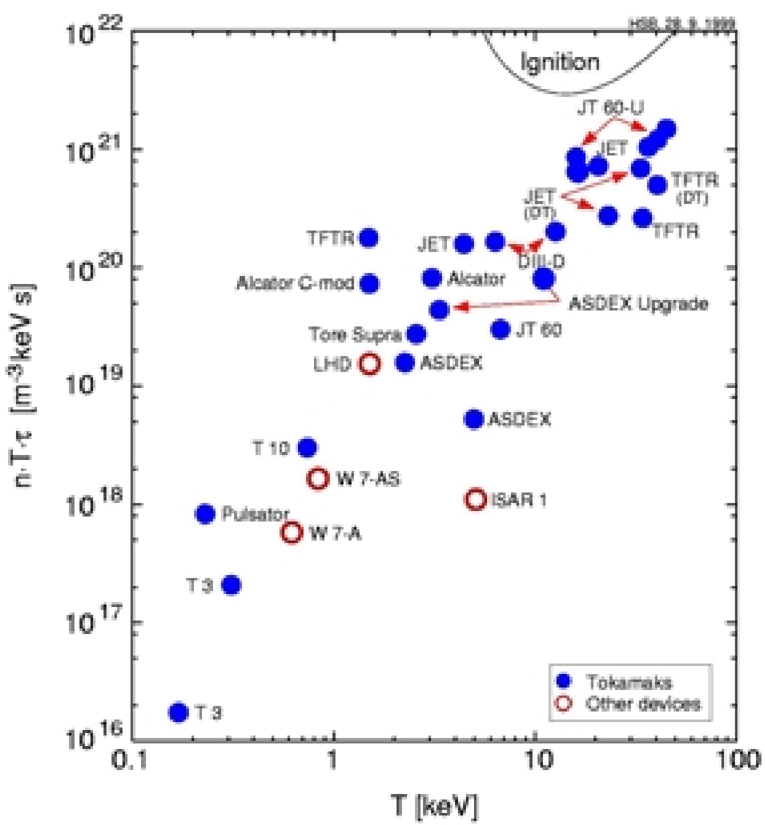

Figure IV: The development of the triple product of plasma temperature, plasma density and energy confinement time in the last three decades. The temperature 1 keV is equivalent to 11 Mio. K.

Establishing the H-mode improves the energy confinement time by a factor of two. Attention now turns increasingly towards advanced plasma scenarios which are characterised by an internal transport barrier [7]. Plasma stability is a matter of particular importance for the economics of fusion. The figure of merit is the ratio of the plasma pressure to the pressure of the magnetic field. This ratio is very small in current machines. If this value is exceeded, the plasma becomes unstable and collapses in a so-called disruption. Limits also exist for the plasma density, although these are generally soft and considerable improvements may be expected in future. Major improvements are expected from active measures to shape the plasma by special control mechanisms [8].

The particle and power exhaust seemed to a major problem for several years. As mentioned above, a viable solution for the power exhaust is the divertor concept [9]: with the help of additional magnets the stream of plasma particles leaving the core is directed to the divertor plates. These plates are made from special material, either carbon fibre composites (CFC) or tungsten. Special cooling schemes have been designed for the plates which have to withstand heat loads of the order of 10 MW/m^2.

Experimentally it has also been demonstrated that the residence time of helium in the plasma poses no severe problem [10] and the helium "ash" can be transported efficiently to the divertor to be removed from the system.

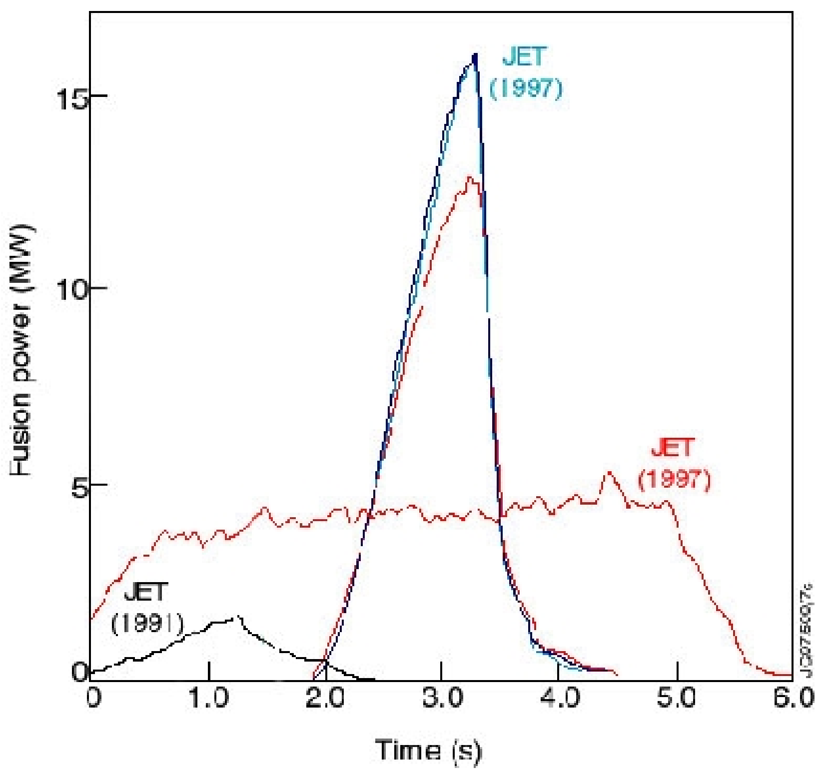

Figure V: Fusion energy production in the Joint European Torus (JET)[11].

At JET, experiments with deuterium and tritium have led to considerable power production [11]. 16.1 MW fusion power were produced for about a second and about 4 MW for a few seconds (see figure V). The fusion reaction produced for a short period nearly as much energy (65%) as was delivered to the system in the form of external heating, corresponding to Q = 0.65. While this is an outstanding result in itself, it also demonstrated the principle of alpha-particle heating as described above.

3.2 Development of fusion technology

Fusion gives rise to complex technologies and still demands progress in various fields such as superconducting magnets, high heat load materials, materials able to withstand high neutron flux, remote handling devices and plasma heating techniques.

The next step in the international fusion programme, ITER (= International Thermonuclear Experimental Reactor) will demonstrate the viability of fusion as an energy source. A special programme was therefore launched in 1994 (Engineering Design Activity, or ITER-EDA) to assess the key technologies [13]. Seven tasks were set up in world-wide collaboration to design, construct and test these components. They encompass construction and testing of a solenoid magnet module, a toroidal field magnet, a divertor cassette, a blanket module, a sector of the vacuum vessel, remote handling devices for the divertor cassettes and the blanket module. With the exception of the toroidal magnet, where tests will start soon (spring 2001) all the tasks have been successfully completed. In case of the solenoid magnet performance exceeded expectations [12]. Remote handling proved to operate satisfactorily [13]. Divertor concepts were developed that could withstand heat loads of more than 10 MW/m^2 and had lifetimes expected for regular ITER operation [14].

Figure VI: Photograph of a the prototype sector of the vacuum vessel for ITER (Photo ITER).

Materials for fusion devices need to fulfil two objectives: (i) they should retain their mechanical properties even after irradiation with intense neutron fluxes and (ii) neutron-induced activation should not lead to the production of long-lived radioactive waste. A number of materials have been identified as candidates for future fusion power plants [15]. Experimental data are unfortunately lacking, since no existing neutron source is able to produce neutron fluxes of the intensity and spectrum expected in fusion plants [16].

4.0 Path to a Fusion Power Plant

The European fusion strategy has always been reactor-oriented. Via two major steps (ITER and subsequently the demonstration reactor DEMO) the programme is intended to provide the scientific and technological basis to build and operate economically viable fusion power plants by the middle of the 21st century. The first step has three major parts: construction and operation of ITER, development of fusion technologies including advanced materials and improvement of the magnetic confinement scheme.

ITER is a collaboration involving the European community, Japan and the Russian Federation. In the ITER Conceptual Design Activity (CDA) and the original Engineering Design Activity (EDA) the US was the fourth partner. The CDA phase began in April 1988 and was completed in December 1990. The EDA phase lasted from 1994 to 1998. In the current extension of the ITER-EDA the design is being modified to produce a lower cost, lower performance version. The so-called ITER-FEAT may not reach ignition but will be characterised by Q value of at least 10. The design modifications do not change the major objectives of ITER, namely the prove that fusion can deliver considerably more power than is required by the external heating and that the complex technology can be mastered.

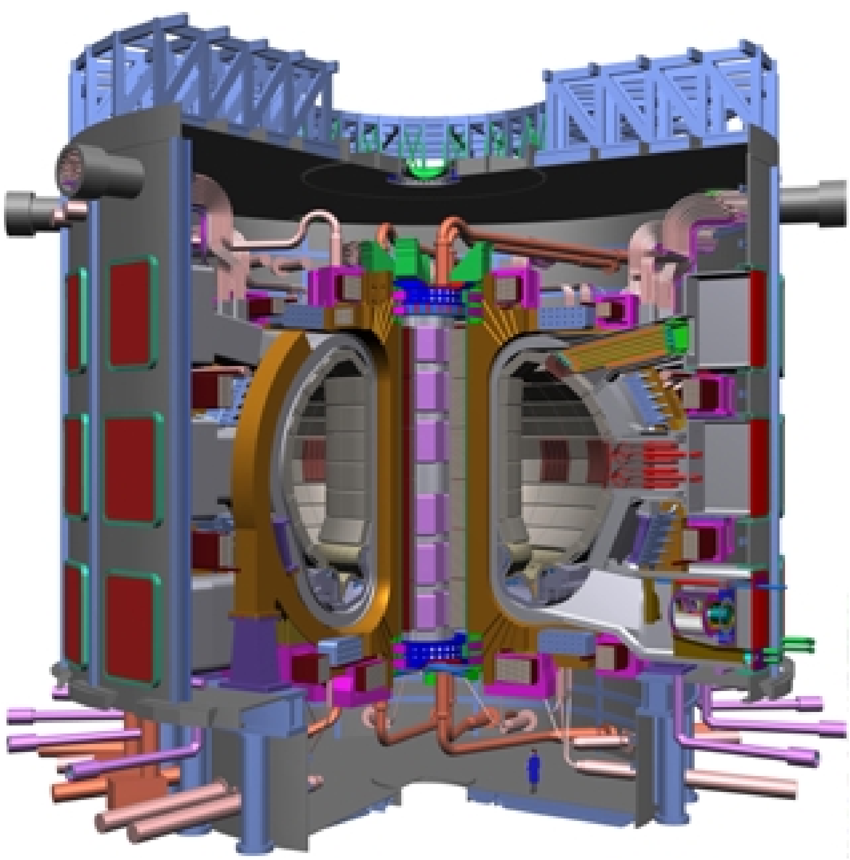

Figure VII: Sketch of the ITER-FEAT Experiment (photo ITER).

Further improvements of the magnetic confinement scheme are necessary. The pulsed mode of the conventional tokamak is not feasible for a power plant. Two lines of improvements are followed. The first is called the "advanced tokamak" in which – amongst others - techniques are developed to replace the inductive current drive. Many existing machines have already investigated such scenarios. The second approach is to (substantially) modify the magnetic field cage so that only external magnetic fields are required and an induced plasma current becomes unnecessary, as in the stellarator. Two large stellarator projects are now being pursued: the LHD stellarator in Japan went into operation in 1998; the

WENDELSTEIN 7-X stellarator in Germany is expected to start operation in 2006. A smaller stellarator is in operation in Spain.

The development of fusion materials requires the construction of an intense neutron source. A world-wide collaboration under the auspices of the International Energy Agency (IEA) in Paris has been launched to design the International Fusion Material Irradiation Facility (IFMIF). The conceptual design report was produced at the end of 1996.

All these activities, i.e. ITER, advanced concepts and technological development will form the basis for DEMO, the detailed design of which can be started after ITER has operated for about five years.

5.0 Characterisation of fusion as power source

5.1 Fusion plant models

A number of detailed system studies have been performed in the last thirty years in order to study the possible design of future fusion plants [17]. On the basis of these studies it is possible to analyse economic and environmental impact. The detailed design work on ITER adds useful complementary material.

5.2 Fuel and material availability, energy requirements

One of the main motivations from the very beginning of fusion research has been that fusion can be considered as a practically unlimited source of energy. The argument is based on the abundance of the fusion fuels - lithium and deuterium - and the very small quantities required [18]. A 1 GWe fusion power plant would require annually 110 kg deuterium and 380 kg lithium consumption.

Deuterium is a hydrogen isotope. In terrestrial hydrogen sources, such as sea water, deuterium makes up one part in 6700. Given the above annual consumption rates it can be shown that fusion could continue to supply energy for many millions of years. The oceans have a total mass of $1.4 * 10^{21}$ kg and therefore contain $4.6 * 10^{16}$ kg of deuterium; moreover, there is already a mature technology for extracting the deuterium. One of the main applications is the production of heavy water for heavy water-moderated fission reactors. Existing plants can produce up to 250 t/a of heavy water which means a production of 50 t/a of deuterium. This would be enough to supply deuterium for 500 fusion plants each with 1 GWe capacity. Obviously deuterium supply places no burden on the extensive use of fusion. What about tritium? As we have mentioned above, tritium, also a hydrogen isotope, will be bred from lithium using the high flux of fusion neutrons. Lithium is found in nature in two different isotopes ^{6}Li (7.4 %) and ^{7}Li (92.6 %). The two nuclear reactions

$$^6\text{Li} + n \rightarrow T + {}^4\text{He} + 4.8 \text{ MeV}$$

$$^7\text{Li} + n \rightarrow T + {}^4\text{He} + n - 2.5 \text{ MeV}$$

are relevant Since the second reaction is endothermic only neutrons with an energy higher than the threshold can initiate this process. In most blanket concepts the reaction with ^{6}Li dominates, but in order to reach a breeding ratio exceeding unity the ^{7}Li content might be essential.

Lithium can be found in:

- salt brines, in concentrations ranging from 0.015 % to 0.2 %
- minerals: spodumene, petalite, eucrypotite, amblygonite, lepidolite.; the concentration varies between 0.6 % and 2.1 %.
- sea water; the concentration in sea water is 0.173 mg/l (Li^+).

The land-based reserves are given in table I according to two different sources.

Table I: Land reserves of Lithium.

Material	Current Production	Reserve [19]	Reserve base [19]	Reserve [20]
Lithium	15,000 t	3,400,000 t	9,400,000 t	1,106,000 t

While the annual consumption of lithium in a fusion plant is low, the lithium inventories in the blankets are much larger [21, 23]. At least a couple of hundred tons of lithium are necessary to build a blanket. It is expected that most of the lithium can be recovered and re-used, although radioactive impurities such as tritium will complicate the handling. No detailed concept for recovering lithium has been developed so far. The lithium supply is, however, a minor problem in the context of the construction of the whole plant: lithium can be purchased today for around 17 Euro/kg and the blanket containing 146 t of lithium needs to be replaced five times in the life of a fusion plant, which would amount to only 12 MEuro. Beside the land-based resources there is a total amount of $2.24 * 10^{11}$ t lithium in sea water. Techniques to extract lithium from sea water have already been investigated [25]. The associated energy consumption has also been investigated [26]. The ultimate lithium resources in sea water are thus practically unlimited.

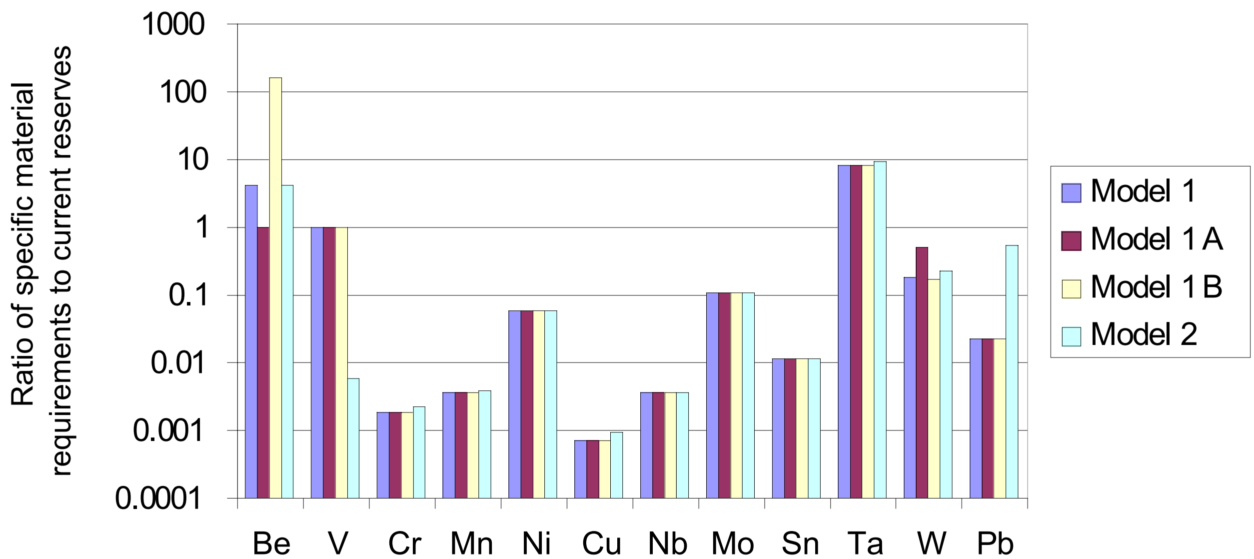

Figure VIII: The picture shows the ratio of specific materials necessary to construct 1000 fusion plants (for various plant models) normalised to current reserves of this material.

Besides fuel numerous other materials will be necessary in order to construct and operate a fusion power plant [21, 22]. A first idea of the availability of these materials is sketched in figure VIII. The material required to build 1000 1 GWe fusion power plants are divided by the known reserves of these materials. Beryllium and tantalum seem to pose problems, but this is because these materials are hardly used today and the proven reserves are probably much smaller than the actual resources.

The energy necessary to produce, transport and manufacture all the materials to build a fusion plant add up, in a conservative model, to 3.15 TWh [27,28]. The energy pay back time, the time necessary for the plant to deliver the same amount of energy necessary for its construction, is roughly half a year and thus comparable with conventional power plants.

5.3 Cost of electricity

Basis for the cost estimates of fusion power is a plant of 1 GWe capacity based on the tokamak concept. Conceptually the plant can be divided up between the fusion core - the heat source - and the rest consisting of turbines, generators, switchboards. The assumptions in the underlying physics and technology seem well with reach based on current achievements. If progress in fusion technology is faster, it might of course lead to considerably lower costs.

Most of the components of the fusion power core are unique for fusion. The basis for the cost estimates of these components is (i) existing experience with operating fusion experiments, (ii) the experience with designing ITER [30] and (iii) numerous system studies. The ITER experience is of particular importance because it combines system studies and real manufacturing experience. As mentioned earlier, part of the ITER activities to date have been the design, construction and testing of central components of the experiment. The following discussion is based on [29,31,32].

Magnets make up 30 % of the investment costs of the fusion core for a prototype and another big item are the buildings. The rest splits up into numerous items. Blanket and divertor make up 14 % and 3 %, respectively, although these items will have to be replaced regularly. The divertor will be replaced every second year, the blanket every fifth year. Two possible technological developments should be mentioned which might lead in the long run to cost reductions. The pressure of the magnetic field has to balance the pressure of the plasma. For specific physical reasons, however, the magnetic pressure needs to much higher than the plasma pressure in current installations. Progress in plasma physics could reduce this ratio in future and thus reduce the size and cost of the magnets. Also a
lower replacement frequency of blanket and divertor due to the development of advanced materials might lead to a further reduction.

Cost of electricity (COE) is the sum of the capital costs for the fusion core (39 %) and the rest of the plant (23 %), the costs for the replacement of divertor and blanket during operation (30 %), fuel, operation, maintenance and decommissioning (8 %). An annual load factor of 75 %, an operating lifetime of 30 years and an real interest rate (corrected for inflation) of 5 % are also assumed. The investment costs for DEMO are expected to be roughly 10000 Euro/kW (1995) [29] giving an expected COE of 165 mEuro/kWh.

Collective construction and operation experience are expected to lead to considerable cost reduction due to accumulated learning processes [33]. Learning curves describe the correlation between the cost reductions and the cumulated installed capacity. The slope of the curve - the so-called progress ratio - gives the cost reduction for a doubling of the capacity. A progress ratio of 0.8 is assumed for the novel components in the fusion core. This ratio is well within the values generally experienced in industry; possible physics progress is also included. Figure IX shows the expected cost development with time.

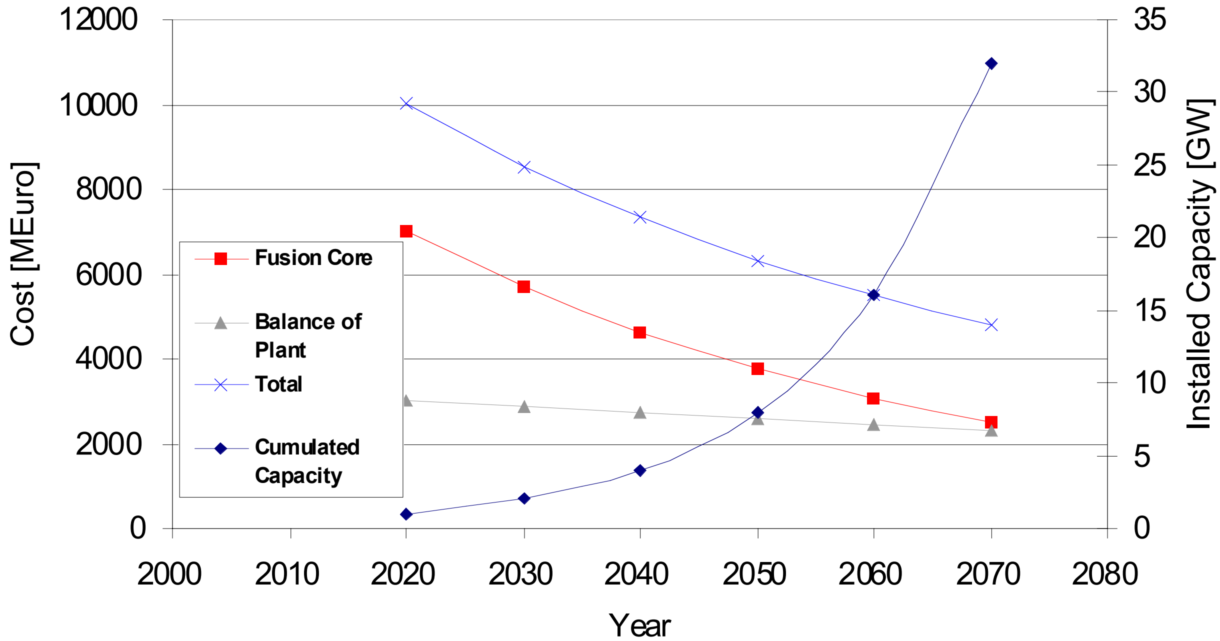

Figure IX: Learning curves for fusion power plants [29].

Further cost reductions can be achieved by scaling up the plant size or by siting two or more plants at the same site. When fusion is a mature and proven technology in 2100, costs are expected to be in the range described in table II.

Table II: Cost of electricity for different fusion plant models.

Plant capacity [GWe]	Number of plants at the site	Study	Cost of electricity [mEuro/kWh]
1	1	Knight [32]	96
1	1	Knight [32]	71
1	1	Gilli [29]	87
1,5	2	Gilli [29]	67

Studies performed in the US and in Japan arrive at even lower investment and electricity costs[34].

The underlying assumptions do not violate any physical principles but assume tremendous progress in technology.

5.4 Environmental and safety characteristics (external costs)

5.4.1 Effluents in normal operation

A fusion power plant is a nuclear device with large inventories of radioactive materials. The safe confinement of these inventories and the minimisation of releases during normal operation, possible accidents, decommissioning and storage of waste are major objectives in the fusion power plant design. Besides tritium the other source of the radioactivity in the plant is the intense flux of fusion neutrons penetrating into the material surrounding the plasma and causing “activation”.

Three confinement barriers are foreseen: vacuum vessel, cryostat and outer building. Small fractions of the radioactive materials are released during normal operation. The amounts depend strongly on design characteristics such as cooling medium, choice of structural materials and blanket design. The releases during normal operation for two different plant models are summarised in table III. A detailed analysis is presented in [35].

Table III: Doses to the public due to normal operation effluents for two different fusion plant models.

	Model 1	Model 2
Doses to the most exposed public from gaseous effluents [μSv/y]	0.28	0.003
Doses to the most exposed public from liquid effluents [μSv/y]	0.95	0.11

The expected doses to the public stay well below internationally recommended limits [36].

5.4.2 Possible accidents

Detailed accident analyses have been performed within the framework of system studies [35] and in even more detail for ITER [37]. Although ITER is not in all aspects comparable to a later power reactor many of the characteristics are similar. Different methods (bottom-up and top-down) are applied to guarantee a complete list of the accident sequences. Reactivity excursions are for several reasons not possible in a fusion power plant. Therefore, the most severe accidents are all related to failures of the cooling system. These failures can be caused either by power failures or ruptures in cooling pipes or both. As an example of one of the most severe accident sequences, a total loss of coolant accident, should be described. Shortly after the accident the fusion reaction will come to a halt. This happens because the walls surrounding the plasma are no longer cooled and their temperature increases. Impurities, evaporated from the hot walls, enter the plasma. The larger impurity content in the plasma disturbs its energy balance and more energy is radiated, thus cooling down the plasma. Fusion reactions are extinguished. With no more fusion reactions, only the decay heat of the activation products in the structural materials and the blanket produce heat. Detailed calculations show that the heat produced will be dissipated by heat radiation to the inner walls of the cryostat. Temperatures in the structural materials will stay well below the melting temperature and keep the confinement barriers intact. During such an accident sequence not more than 1 PBq of tritium would be released. Doses for the population would stay in the range of 1 mSv [35,38].

As a worst case scenario it was assumed that the complete vulnerable tritium inventory (roughly 1 kg) of the fusion plant is released at ground level. The initiator of such an accident could only be very energetic outside events such as an aeroplane crash on the plant. Even if the worst weather conditions are assumed, only a very small area, most likely within the perimeter of the site, would have to be evacuated[38].

5.4.3 Waste

All the radioactive material produced in a fusion plant is neutron-induced. A detailed analysis of the amount and composition of the fusion power waste was performed in [35,38]. Time evolution of the radiotoxicity of the waste is shown in figure X. The plant model assumed is based on available materials. The picture shows a rapid decrease in radiotoxicity once the plant is shut down. The time evolution of the fusion waste is compared with the time evolution of the waste from a PWR fission plant and with the radiotoxicity of ash in a coal-fired power plant. The radiotoxicity of the waste of fission plants hardly changes on the time scale of a few hundred years and stays at a high level. Fusion approaches rapidly the radiotoxicity of the coal ash. It is a fair conclusion to say that the radiotoxicity of fusion waste does not place a major burden on future generations.

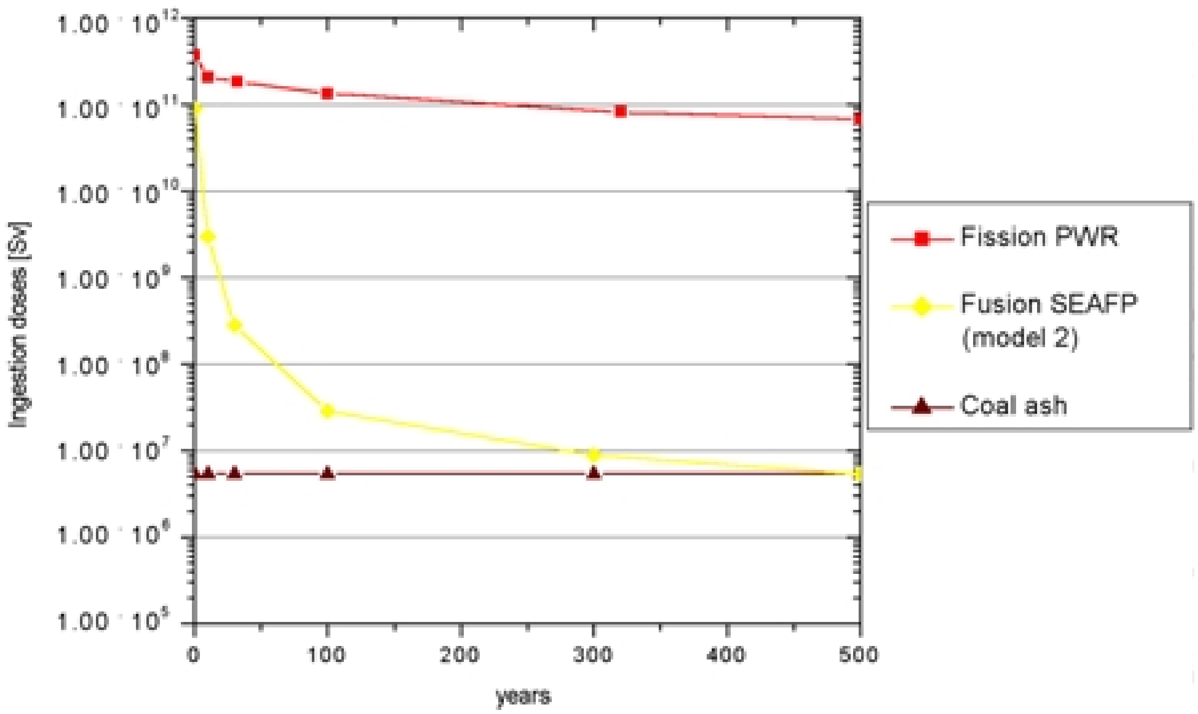

Figure X: Development of radiotoxicity for a fusion plant, a fission plant and the ash of a coal plant. It is assumed that all the plants produce the same quantity of electricity. The volume of coal ash is of course 2-3 orders of magnitude greater than that of fusion or fission waste.

The impact on the population is rather low. Doses below 60 µSv/y are expected in the case the fusion waste stored in typical waste repositories like Konrad in Germany or SFR or SFL in Sweden. The value represents a rather conservative estimate.

5.4.4 External costs

Comparisons between competing technologies on an economic basis is mainly based on cost arguments. Comparison on the basis of environmental performance or safety issues is often more interesting. It is tempting therefore to look for a scale which also covers these aspects. One promising approach in this direction is the concept of "external costs" or “externalities” [39]. All the damage and problems not contributing to the market price are reflected in the “external costs” which are normally borne by society as a whole. Examples of externalities are the damages to public health, to agriculture or to the ecosystem.

A methodology for the assessment of the environmental externalities of the fusion fuel cycle has been developed within the ExternE project [40]. The method used is a bottom up, site specific and marginal approach, i.e. it considers extra effects due to a new activity at the site studied. Quantification of impacts is achieved through damage functions or impact pathway analysis. The whole fuel and life cycle of the plant is considered.

The hypothetical plant under investigation is sited at Lauffen in Germany on the river Neckar. Two different fusion plant models are considered. Most characteristics of these models are taken from the European fusion safety study SEAFP [35]. The first model utilises a vanadium alloy for the structural materials and helium as coolant (Model 1). The second model has a water-cooled blanket and martensitic steel as structural material (Model 2). The parts of the plant not included in the above-mentioned study are taken from the ITER design and from data for a fission plant.

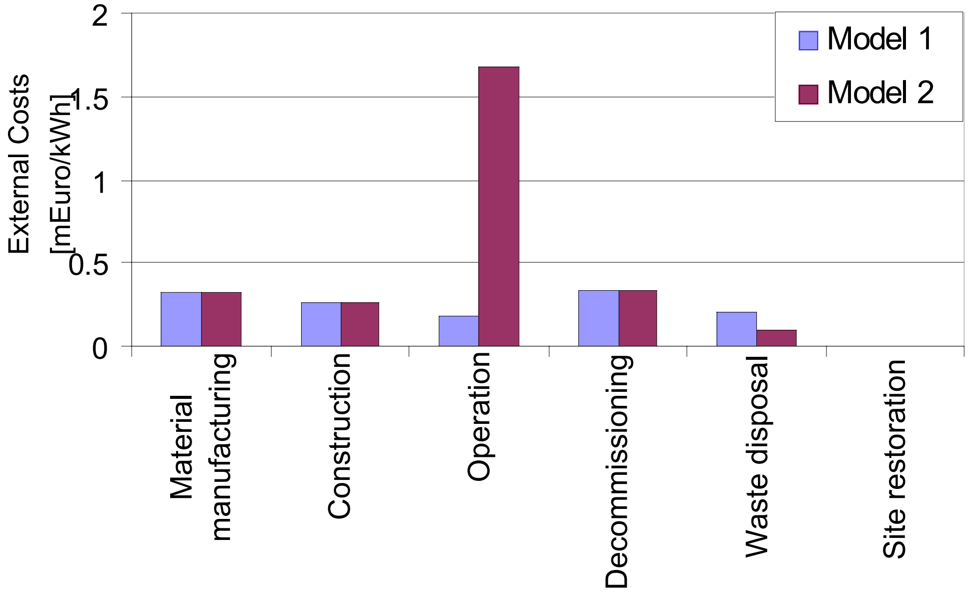

Figure XI: External costs of fusion [41].

The results (Figure XI) indicate that the external costs of fusion do not exceed those of renewable energy sources. A major factor in the external costs of plant model 2 are the ^{14}C isotopes released during normal operation which enter the world-wide carbon cycle. Nevertheless, the individual doses related to theses emissions are orders of magnitude below the natural background radiation. For all models a considerable fraction of the external costs is due to material manufacturing, occupational accidents during construction and decommissioning.

5.5 The possible role of fusion in a future energy system

5.5.1 The global dimension

What is the possible impact of fusion on future energy systems? What role could fusion play to mitigate greenhouse gas emissions? First, a general answer can be given which reflects well-known patterns of technological change. For a good review article on this question, see [42]. Technological change is described by two phases, the first being that of invention. In case of fusion, invention would be the point in time when the first commercial power plant goes into operation. The second phase, in which numerous power plants would be constructed in many different places, is represented by the time of diffusion. It usually follows very general patterns, which can be described by an S-shaped curve, starting with a smooth increase in market share, followed by a robust growth and finally a smooth approach to a saturation level.

The "market" share of different primary energy sources in the past 150 years has always developed according to this pattern. In the nineteenth century wood was replaced by coal. In the first half of the 20th century oil started to replace coal and now natural gas begins to replace oil. Extrapolation of the current trend would mean that gas would become the most important primary energy carrier in the first half of the 21st century [43]. This would mean that fusion can only hold a considerable market share by the end of this century since the invention phase is expected to happen around 2050. Therefore fusion can not play a role as greenhouse gas mitigation technology before that time. Second, it means that even without further incentives the primary energy carrier natural gas, which has a specific lower CO_2 emission than coal and oil and which can be converted at least to electricity with very high efficiencies (nearly 60 % today, roughly 70% in the foreseeable future), would in any case lead to a specific reduction of greenhouse gas emissions. In comparison with coal this combined advantage would produce roughly a factor of three lower CO_2 emissions per kiloWatthour delivered. If all coal-fired plants were to be replaced by very efficient gas-fired plants the electricity demand could triple without increase in emissions. Third, the time when the share of natural gas will pass its maximum roughly coincides with the “invention” (the technological and economic proof of principle) of fusion.

Another very important point is of course the future development of energy usage and, in particular, the electricity demand. Scenarios made by the International Institute of Applied System Analysis (IIASA) and the World Energy Council (WEC) describe various possible paths into the future [44]. Of the scenarios labelled A, B and C, A is a high growth scenario, B an average growth scenario and C an ecologically driven scenario. Even in the C scenario electricity consumption will increase considerably even after 2050, leaving enough space for fusion, even without replacing older technologies. It must be noted that, given the long lead-time, alternative low-GHG electricity generating techniques might compete for the same potential market as fusion. While predicting winners or losers is obviously a very long shot, continued R&D is an absolute necessity for all of them.

5.5.2 Fusion in Western Europe

In the framework of socio-economic studies on fusion (SERF), which have been conducted by the European Commission and the Fusion Associations, a study was carried out on the possible impact of fusion on the future West-European energy market, on the assumption that fusion is commercially available in the year 2050. The scenario horizon is based the complete 21st century. The scenarios were performed with the programme package MARKAL [45]. Details of the analysis can be found in [29].

Two different scenarios were explored which differ in the discount rates, level of energy demand, availability of fossil fuels and energy price projections. The first scenario is called Market Drive (MD): interest rates on power generation investments are 8%, interest rates on end-use investments are higher. 15 % of the world resources of fossil fuels are available to Western Europe and a rapid increase in the oil price is expected. The second scenario is called Rational Perspective (RP): discount rates are 5 % across the whole energy sector, but only 10,5 % of the world fossil fuel resources are available to Western-Europe. The oil price increases more slowly. Energy demand is higher in scenario Market Drive. Both scenarios assume that the capacity of nuclear fission never exceeds the current level. Fission is expected to phase out at 2100.

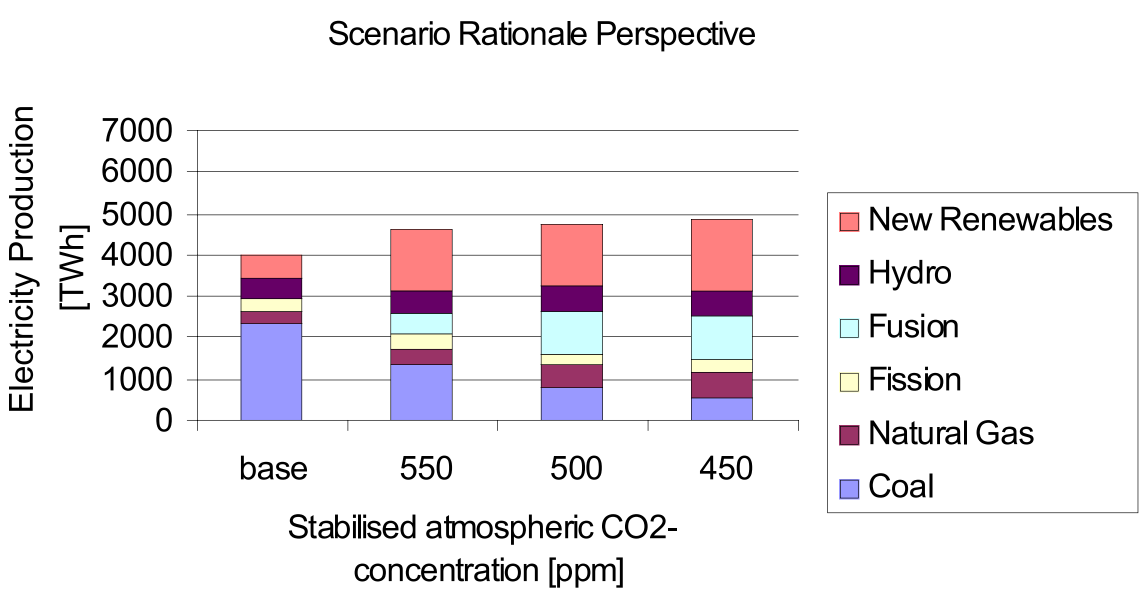

Figure XII: The possible role of fusion in 2100 in the European electricity market [29].

The demand for energy increases in the two scenarios. In Market Drive it more than doubles in relation to the 1990 value and in Rationale Perspective it increases by more than 50 %. Steady increases in efficiency keep the overall primary energy demand roughly constant over the whole scenario horizon. The demand for electrical energy increases in both scenarios roughly by a factor two.

The development of energy supply and conversion technologies, especially further progress in economic performance and efficiencies, is based upon detailed assessments of the literature and on the studies by Fusion Associations, and have been, where appropriate, guided by learning curves. The increase in efficiency or the decrease in costs are time-dependent. A detailed description of the supply technologies can be found in [46]. Another important point is the future development of fuel prices. An increase in the oil price to $25/bbl (RP) or 29,5/bbl (MD) in 2100 is expected. The gas price is strongly tied to the oil price. The price for hard coal is considerably flat over the whole period investigated. In both scenarios neither new renewables nor fusion will win considerable market shares until the year 2100. Fossil fuels remain the most important primary energy sources. Two shifts in the use of fossil fuels can be identified. The use of gas increases considerably until the middle of the 21^{st} century when the easily accessible natural gas reserves are exhausted and its price has substantially increased. Coal will then win again a market share and advance to the most important primary energy carrier at the end of the 21^{st} century. The picture change drastically, however, if future CO_2 emissions are to be restricted in order to reduce the risk of climate changes. These cases are constructed in such a way that the global emissions would lead in the long term to a stabilisation of the CO_2 concentration in the atmosphere. Different values for the stabilisation concentration are assumed. Western Europe would be allowed to produce 10 % of these global emissions. The time-dependent allowed emissions are constraints in the optimisation. If these constraints are applied to the scenarios, the energy mix changes considerable. The share of the electricity supply technologies in 2100 is shown in figure XII. Fusion and new renewables such as wind and solar win considerable market shares. The conclusion can be summarised as follows: fusion can win shares in the electricity market if (i) the further use of fission is limited and (ii) if greenhouse gas emissions are constrained.

Similar studies have been performed in Japan [47] and the US [48].

6.0 Summary

Fusion research has made considerable progress in the last three decades. More than 16 MW fusion power have been produced in the joint European experiment JET at a Q value (fusion power amplification factor) of 0.65.

Technologies for the next step in the international fusion programme (ITER) have already been improved by intense engineering R&D and the construction and test of prototypes. The ITER experiment still awaits approval. Sites in France, Canada and Japan are, however, being discussed. ITER is intended to demonstrate the proof of principle for magnetic confinement fusion as a future energy source.

Detailed investigations on the safety, environmental and socio-economic aspects of fusion have been performed. Fusion - if fully developed in 2050 - will fit into a sustainable energy system and be able to supply electricity for millennia to come at economically acceptable costs.

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