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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 $\alpha$ 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.

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*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.

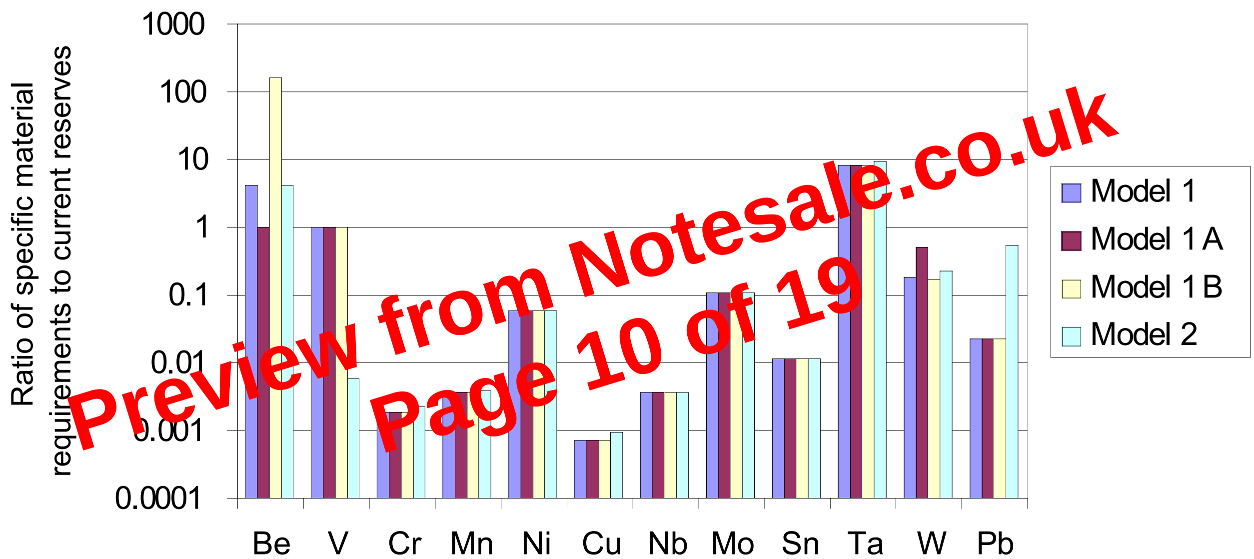


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*Figure VIII: The picture shows the ratio of specific materials necessary to construct 1000 fusion plants (for various plant models) normalised to current reserves of this material.*

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

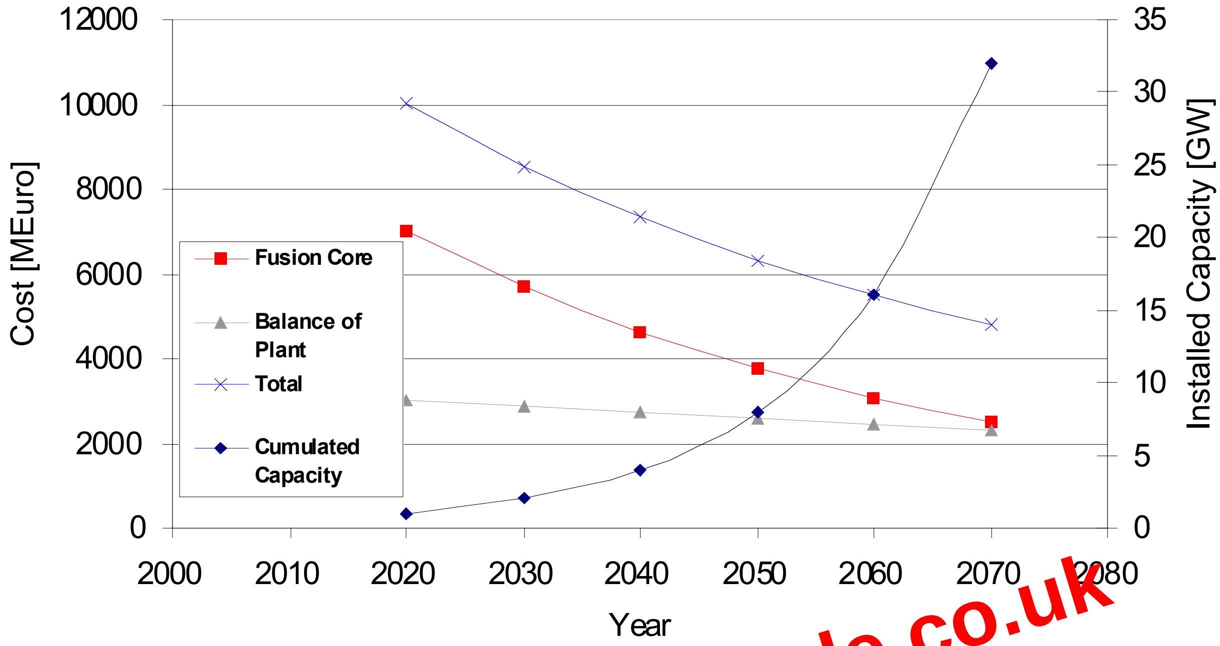


*Figure IX: Learning curves for fusion power plants [29].*

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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”.