The path to fusion power

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Fusion is potentially an environmentally responsible and intrinsically safe source of essentially limitless power. It should be possible to build viable fusion power stations, and it looks as if the cost of fusion power will be reasonable. But time is needed to further develop the technology and to test in power station conditions the materials that would be used in their construction. Assuming no major adverse surprises, an orderly fusion development programme could lead to a prototype fusion power station putting electricity into the grid within 30 years, with commercial fusion power following some 10 or more years later. In the second half of the century, fusion could therefore be an important part of the portfolio of measures that are needed to cope with rising demand for energy in an environmentally responsible manner. In this paper, we describe the basics of fusion, its potential attractions, the status of fusion R&D, the remaining challenges and how they will be tackled at the International Tokamak Experimental Reactor and the proposed International Fusion Materials Irradiation Facility, and the timetable for the subsequent commercialization of fusion power.

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1. Introduction

Fusion powers the Sun and stars and is potentially an environmentally responsible and intrinsically safe source of essentially limitless energy on the Earth. Experiments at the Joint European Torus (JET) in the UK, which has produced 16 MW of fusion power, and at other facilities, have shown that fusion can be mastered on the Earth.

Fusion power is still being developed and will not be available as soon as we would like. We are confident that it will be possible to build viable fusion power stations, and it looks as if the cost of fusion power will be reasonable. But time is needed to further develop the technology in order to ensure that it would be reliable and economical and to test in power station conditions the materials that would be used in their construction.

Assuming no major surprises, an orderly fusion development programme—properly organized and funded—could lead to a prototype fusion power station putting electricity into the grid within 30 years, with commercial fusion power following some 10 or more years later. In the second half of the century, fusion could therefore be an important part of the portfolio of measures (improved

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efficiency, carbon capture and storage, increased use of renewables, improvements in the grid, smart metering, etc.) that are needed to cope with rising demand for energy in an environmentally responsible manner. The actual role that fusion plays will depend on environmental constraints/the cost of carbon and on the cost of alternatives; models suggest that the role will be very significant if any serious constraints are placed on carbon emissions—it is very hard to meet demand with carbon constrained, and the models exploit every means available in attempting to do so.

2. Fusion basics

Reactions between light atomic nuclei in which a heavier nucleus is formed with the release of energy are called fusion reactions. The reaction of primary interest as a source of power on the Earth involves two isotopes of hydrogen (deuterium and tritium) fusing to form helium and a neutron.

\[ \text{D} + \text{T} \rightarrow ^{4}\text{He} + n + \text{energy (17.6 MeV)}. \] (2.1)

Energy is liberated because helium-4 is very tightly bound: it takes the form of kinetic energy, shared 14.1 MeV/3.5 MeV between the neutron and the helium-4 nucleus (a chemical reaction typically releases approx. 1 eV (electron volt), which is the energy imparted to an electron when accelerated through 1 V).

To initiate the fusion reaction (2.1), a gas of deuterium and tritium must be heated to over 100 million °C (henceforth M°C)—10 times hotter than the core of the Sun. At a few thousand degrees, inter-atomic collisions knock the electrons out of the atoms to form a mixture of separated nuclei and electrons known as plasma. Being positively electrically charged, the rapidly moving deuterons and tritons suffer a mutual electric repulsion when they approach one another. However, as the temperature—and hence their speeds—rises, they come closer together before being pushed apart. When the temperature exceeds 100 M°C, the more energetic deuterons and tritons approach within the range of each other’s nuclear force and fusion can occur copiously.

There are three challenges. The first is to heat a large volume of deuterium (D) and tritium (T) gas to over 100 M°C, while preventing the very hot gas from being cooled (and polluted) by touching the walls. As described below, this has been achieved, using a ‘magnetic bottle’ known as a tokamak, although there is still plenty of scope for improving the conditions, in particular increasing the pressure without provoking instabilities, which is of key importance, given that the rate at which fusion occurs is proportional to square of the pressure at fixed temperature. The helium nuclei that are produced by fusion (being electrically charged) remain in the magnetic bottle, where (through collisions) their energy serves to help keep the D–T gas hot. The neutrons however are electrically neutral and escape into, and heat up, the walls: this heat is then used to drive turbines and generate electricity.

The huge flux of very energetic neutrons and heat (in the form of electromagnetic radiation and plasma particles) can damage the container. The second challenge is to make a container with walls sufficiently robust to stand up, day-in day-out for several years, to this neutron bombardment and heat flux. Fusion power stations will be very complex and the third challenge is to make them work reliably.
3. Fusion fuel

The tiny amount of fuel that is needed is one of the attractions of fusion. The release of energy from a D–T fusion reaction is 10 million times greater than that from a typical chemical reaction, such as occurs in burning a fossil fuel. Correspondingly, while a 1 GW coal power station burns 10 000 tonnes (10 train loads) per day of coal, a 1 GW fusion power station would burn only approximately 1 kg of D\textsubscript{2}T per day.

Deuterium is stable and in one in every 3350 molecules of ordinary water, one of the hydrogen atoms is replaced by a deuterium atom. Deuterium can be easily, and cheaply, extracted from water. Tritium, which is unstable and decays with a half-life of approximately 12 years, occurs only in tiny quantities naturally. But, as described below, it can be generated \textit{in situ} in a fusion reactor by using neutrons from the fusion reaction impacting on lithium to produce tritium in the reaction

\[
\text{Neutron} + \text{Lithium} \rightarrow \text{Helium} + \text{Tritium.} \quad (3.1)
\]

The raw fuels of a fusion reactor would therefore be lithium and water. Lithium is a common metal, which is in daily use in mobile phone and laptop batteries. Used to fuel a fusion power station, the lithium in one laptop battery, complemented by deuterium extracted from 45 l of water, would (allowing for inefficiencies) produce 200 000 kW h of electricity—the same as 70 tonnes of coal; this is equal to the UK’s current per capita electricity production for 30 years.

4. Fusion power stations

Figure 1 shows the conceptual layout (not to scale) of a fusion power station. At the centre is a D–T plasma with a volume of 1000–3000 m\textsuperscript{3} (actually contained in a ‘toroidal’ (doughnut shaped) chamber, described later). D and T are fed into
the core and heated to over 100 M°C, a temperature routinely achieved at JET, as described below. The neutrons produced by the fusion reaction (2.1) escape the magnetic bottle and penetrate the surrounding structure, known as the blanket, which will be approximately 1 m thick.

In the blanket, the neutrons encounter lithium and produce tritium through reaction (3.1). There are various competing reaction channels, which do not produce tritium directly, but some of them produce additional neutrons that can then produce tritium (the production of additional neutrons can be enhanced, e.g. by adding beryllium or lead). The upshot is that, on paper at least, it is possible to design fusion reactors that would produce enough tritium for their own use plus a small surplus to start up new plants; this will be tested at the International Tokamak Experimental Reactor (ITER), as described below.

The neutrons will also heat up the blanket to around 400°C in so-called ‘near-term’ power plant models that would use relatively ordinary materials, and up to perhaps 1100°C in models that use advanced materials such as silicon carbide. The heat will be extracted through a primary cooling circuit, which could contain water or helium, that in turn will heat water in a secondary circuit which will drive turbines.

(a) Advantages and disadvantages

The attractions of fusion are

— essentially unlimited fuel,
— no CO₂ or air pollution,
— intrinsic safety,
— ‘internal’ costs (i.e. costs of generation) expected to be reasonable provided reasonable availability can be achieved (e.g. 75%)—see the discussion of power plant studies below (‘external’ costs—impact on health, climate and the environment—will be essentially zero), and
— it will help meet a vital need.

There is enough deuterium for millions of years, and easily mined lithium for several thousand years (if/when it becomes scarce on land, lithium could be extracted from water, which contains 100 times as much lithium as uranium).

A key safety feature is that there is not enough energy inside the plant to drive a major accident and not much fuel available to be released to the environment if an accident did occur. Although it will occupy a large volume, the amount of tritium and deuterium in a fusion reactor will be tiny: the weight of the hot fuel in the core will be about the same as 20 postage stamps. Since the gas will be so dilute, there will be no possibility whatsoever of a dangerous runaway reaction. Furthermore, fusion must be continuously fuelled and is easily stopped—indeed, if anything untoward should occur that changed the conditions appreciably, the fusion ‘fire’ would go out.

What are the hazards? First, although the products of fusion (helium and neutrons) are not radioactive, the blanket will become activated when struck by the neutrons. However, the radioactivity decays away with half-lives of order 10 years, and all the components could be recycled within 100 years. Should the cooling circuit fail completely, radioactivity in the walls would continue to generate heat, but the temperature would peak well below the temperature at which the structure could melt.
Second, tritium is radioactive, but again the half-life is relatively short (12 years) and the possible hazard is not very great. In any case, it will be easy to design reactors, so that even in the worst imaginable accidents or incidents (such as earthquakes or aircraft crashes) only a small percentage of the tritium inventory could be released and evacuation of the neighbouring population would not be necessary.

5. Status of fusion research

The most promising magnetic configuration for confining (‘bottling’) fusion plasmas is called a tokamak (a contraction of a Russian phrase meaning toroidal chamber with a magnetic coil). The basic layout of a tokamak is shown in figure 2. An understanding of how tokamaks work is not needed to follow the rest of this paper, but the following brief summary is given for readers who are interested.

— A small amount of gas (hydrogen or deuterium in most experiments, whose goal is to understand and control the behaviour of hot plasmas; deuterium and tritium in some experiments at JET and in an actual fusion reactor) is injected into the toroidal (doughnut shaped) vacuum chamber after the magnetic field coils have been switched on.

— A current is discharged through a coil wound around the column at the centre, which acts as the primary of a transformer. This drives an electric current (approx. 5 MA in JET) through the gas, which acts as the secondary.

— The electric current heats the gas and turns it into plasma. It also produces a magnetic field which, combined with the magnetic field produced by the external coils, serves to ‘confine’ the plasma, i.e. hold it away from the walls and provide very good thermal insulation.
— The current induced by transformer action can only heat the plasma to about one-third of the temperature needed for copious fusion to occur. Additional heating power must therefore be supplied by mechanisms that serve also to drive the current (which is essential for plasma confinement) thereby keeping it flowing.

— This additional heating and ‘current drive’ can be provided by injecting either microwaves (rather as in a microwave oven) or beams of fast energetic neutral particles, produced by banks of small accelerators, which transfer energy to the plasma through collisions, or both. Many MWs of heating power can be supplied by these means.

In addition to heating and current drive systems, experimental tokamaks are equipped with ‘diagnostic’ devices that measure the magnetic field, electron and ion temperatures and densities, the plasma position and shape, neutron and photon production, impurities, etc., and monitor the development of instabilities.

Three following parameters control the fusion reaction rate.

(i) The plasma temperature \((T)\), which as already stated must be above \(100 \text{ M}^8\text{C}\).
(ii) The plasma pressure \((P)\); the reaction rate is approximately proportional to \(P^2\).
(iii) The ‘energy confinement time’ \((\tau_E)\) defined by

\[
\tau_E = \frac{\text{energy in the plasma}}{\text{power supplied to heat the plasma}},
\]

where \(\tau_E\) measures how well the magnetic field insulates the plasma. It is obvious that the larger \(\tau_E\), the more effective a fusion reactor will be as a net source of power.

It turns out that the ‘fusion product’ \(P\) (in atmospheres) \(\times \tau_E\) (in seconds) determines the energy gain of the fusion device, and this must be 10 or more in a fusion power station. The ‘fusion performance plot’ (figure 3) of \(P\tau_E\) versus \(T\), which shows data points from different tokamaks, indicates the substantial progress towards power station conditions that has been achieved in recent decades.

Semi-empirical scaling laws have been devised that interpolate rather accurately between the results from machines with very different sizes, magnetic fields and plasma currents. The scaling law for confinement time is shown in figure 4. This figure makes us rather confident that the power station-sized device called ITER, which (see below) will be constructed in the near future, will perform as advertized. ITER should confirm that it is possible to build a fusion power station (provided that, meanwhile, work on the materials that will be used to construct a power station proceeds apace, as described below).

Understanding of fusion plasmas has made steady progress in the last two decades, and there have been two especially important positive developments.

— The discovery (following a prediction made at Culham) of a self-generated (‘bootstrap’) electrical current in the hot plasma, with the consequences that (i) much less external power will be needed to keep the electric current in the plasma (that generates part of the essential magnetic field) flowing than previously thought and (ii) achieving steady-state operation will be less of a challenge.

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Figure 3. Selected results from different tokamaks demonstrate substantial progress over recent decades from the low temperature, low energy gain points at the bottom left. Temperatures above 100 M°C are now routinely achieved and an energy gain of around one has been reached. A power plant needs an energy gain above 10 to be viable and this should be achieved in ITER.

Figure 4. Confinement times (in seconds) measured at a range of very different tokamaks are well described by a semi-empirical scaling law that ‘predicts’ the confinement time as a function of the tokamak’s size, magnetic field and plasma current (and other parameters). The prediction for ITER is shown.
The serendipitous discovery (in a fusion experiment at Garching in Germany) of a ‘high confinement’ plasma mode of operation that allows higher pressure, and hence higher fusion power, with a given magnetic field.

6. Next steps: International Tokamak Experimental Reactor and International Fusion Materials Irradiation Facility

Two intermediate facilities, called ITER and IFMIF, are necessary (which, see below, can and should be built in parallel) before the construction of a prototype fusion power station, fully equipped with turbines, etc., that will supply power to the grid.

The International Tokamak Experimental Reactor (ITER). ITER, which is shown in figure 5, will be approximately twice the size of JET in linear dimensions and will operate with a higher magnetic field and current flowing through the plasma. The aim of ITER is to demonstrate integrated physics and engineering on the scale of a power station. The design goal is to produce at least 500 MW of fusion power, with an input of approximately 50 MW.

JET can only operate for up to 1 min because the toroidal coils that produce the major component of the magnetic field are made of copper and heat up. This would not be acceptable in a fusion power station, and ITER will be equipped with superconducting coils, that will allow indefinite operation if the plasma current can be kept flowing (the design goal is above 10 min). Superconducting tokamaks already exist, and others are under construction, but superconducting
coils have not so far been used in really large tokamaks capable of using tritium. ITER will also contain test blanket modules that, for the first time, will test features which will be necessary in power stations, such as the *in situ* generation and recovery of tritium.

A major goal of ITER is to show that existing plasma performance can be reproduced with much higher fusion power than can be produced in existing devices. Developments with the potential to improve the economic competitiveness of fusion power will also be sought (in experiments at existing machines as well as ITER). The main goals are as follows.

(i) Demonstrating that large amounts of fusion power (10 times the input power) can be produced in a controlled way, without provoking uncontrolled instabilities, overheating the surrounding materials or compromising the purity of the fusion fuel. These issues are successfully managed in existing devices but will become much harder at higher power levels produced for longer times. ITER is designed to tolerate this but it remains a big challenge.

(ii) Finding ways of pushing the plasma pressure to higher values (the rate at which fusion occurs, and produces power, is proportional to the square of the pressure) without provoking uncontrollable instabilities. This would allow a power plant to operate either at higher power density or with reduced strength magnets, in either case lowering the expected cost of fusion-generated electricity.

(iii) Demonstrating that continuous (‘steady-state’) operation, which is economically and technically highly desirable if not essential, can be achieved without expending too much power. There is optimism that the plasma current can be kept flowing indefinitely by current drive, from radio-frequency waves and particle beams, boosted by the self-generated (bootstrap) current; however, this must be optimized to minimize the cost in terms of the power needed.

Prototypes of all key ITER components have been fabricated by industry and tested. ITER, which will cost €4.5 billion, will be funded and built by a consortium of the European Union, Japan, Russia, USA, China, South Korea and possibly India. Construction will begin, at Cadarache in France, once planning permission—which is being sought at the time of writing—is granted.

The International Fusion Materials Irradiation Facility (IFMIF). Those ‘structural’ materials, from which fusion power stations will be built, that are close to the plasma will be subjected to many years of continuous bombardment by an approximately 2.5 MWm$^{-2}$ flux of 14 MeV neutrons. This neutron bombardment will, on average, displace each atom in nearby parts of the blanket and supporting structures from its equilibrium position some 30 times a year. Displaced atoms normally return to their original configuration (when thermal vibrations bring displaced atoms together with vacancies). It is possible however that the vacancies and displaced atoms may migrate differently, in which case accumulations at grain boundaries can produce swelling or embrittlement and weaken the material.

It had been thought that only exotic materials (such as silicon carbide composite ceramics) could survive fusion neutron damage for long periods. The discovery during
the 1990s, in tests at fission reactors, that special (body-centred cubic) steels can probably survive in fusion reactor conditions for around 5 years before they would have to be replaced was therefore a very positive and welcome surprise.

The much higher energy fusion neutrons will however initiate nuclear reactions that can produce helium inside the structural materials, and there is a concern that the helium could accumulate and further weaken them. The so-called plasma-facing materials and a component called the divertor (through which impurities and the helium ‘ash’ produced in D–T fusion are exhausted) will be subjected to additional fluxes of 500 kWm\(^{-2}\) and 10 MWm\(^{-2}\), respectively, in the form of plasma particles and electromagnetic radiation. Special solutions are required and have been proposed for these areas, but they need further development and testing in reactor conditions.

Various materials are known that may be able to remain robust under such bombardments (it is in any case foreseen that the most strongly affected components will be replaced periodically). However, before a fusion reactor can be licensed and built, it will be necessary to test the materials for many years in power station conditions. The only way to produce neutrons at the same rate, and with essentially the same distributions of energies as those that will be experienced in a fusion power station, is by constructing an accelerator-based test facility known as IFMIF. Further modelling and proxy experiments (e.g. using neutrons produced in fission and/or by spallation sources) can help identification of suitable candidate materials. But they cannot substitute for IFMIF, and neither will testing in ITER be sufficient, because (i) the neutron flux will only be approximately 30% of that in an actual fusion power station, in which the fusion power will be several GWs and (ii) as an experimental device, ITER will only operate for at most a few hours a day, while IFMIF will operate round the clock day-in day-out.

IFMIF, which will cost approximately €800 million, will consist of two 5 MW accelerators that will accelerate deuterons to 40 MeV (very non-trivial devices). The two beams will hit a liquid lithium target that will produce neutrons, stripped out of the deuterons, with a spread of energies and intensity close to that generated in a fusion reactor. These neutrons will provide estimated displacement rates (in steel) of 50, 20 and 1 displacements per atom per year over volumes of 0.1, 0.5 and 6 litres, respectively.

The priority at IFMIF will be to fully test the relatively conventional materials that are likely to be used in early fusion power plants, but it is very important also to push forward the development of advanced materials (such as SiC composites) that would allow higher blanket temperatures and hence greater efficiency in generating electricity.

7. Power plant studies

A power plant conceptual study has recently been completed under the auspices of the European Fusion Development Agreement (EFDA). This study provided important results on the viability of fusion power and inputs to the critical path analysis of fusion development described below.

Four models (A–D) were studied as examples of a spectrum of possibilities. Systems codes were used to vary the designs, subject to assigned plasma physics and technology rules and limitations, in order to produce an economic optimum.

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The resulting parameterization of the cost of fusion-generated electricity as a function of the design parameters should be used in future to prioritize research and development objectives.

The near-term models (A and B) are based on modest extrapolations of the relatively conservative design plasma performance of ITER. Models C and D assume progressive improvements in performance, especially in plasma shaping, stability and protection of the ‘divertor’, through which helium ash and impurities will be exhausted. Likewise, while model A is based on a conservative choice of materials, models B–D would use increasingly advanced materials and operate at increasingly higher temperatures (which would improve the ‘thermodynamic efficiency’ with which they turn fusion power into electricity).

The power plant study shows that the cost of fusion-generated electricity decreases with the electrical power output ($P_e$) approximately as $P_e^{0.4}$. It was assumed that the maximum output acceptable to the grid would be 1.5 GW. Given the increase of temperature and hence thermodynamic efficiency, the size and gross fusion power needed to produce $P_e = 1.5$ GW decreases from models A (with fusion power 5.0 GW) to D (fusion power 2.5 GW). The estimated cost of electricity, which is dominated by the capital cost, also decreases with size from 9 eurocents/kWh for an early model A to 5 eurocents/kWh for an early model D (these costs would decrease as the technology matures). Even the first cost would be competitive with other generating costs if there was a significant carbon tax, which now effectively exists in Europe with the Emissions Trading Scheme. If acceptable and necessary, larger plants (with $P_e > 1.5$ GW) would be more cost effective.

The power plant study shows that economically acceptable fusion power stations, with major safety and environmental advantages, seem to be accessible through ITER with material testing, if possible in parallel, at IFMIF (but without major material advances).

The above discussion assumes that the first prototype fusion power station will be based on a conventional (ITER/JET-like) tokamak. This will almost certainly be the case, unless ITER produces major adverse surprises. Alternative magnetic confinement configurations (‘spherical tokamaks’; ‘stellarators’) are however under development that have certain theoretical advantages and could form the basis for later prototypes and actual fusion power stations. Meanwhile, they provide additional insights into the behaviour of plasmas and fusion technology which feed into the mainstream, conventional tokamak line.

8. Fast track studies

A detailed study of the time that will be needed to develop fusion was carried out by UKAEA Culham in 2004. It was assumed that construction of ITER and IFMIF both begin in the immediate future. The information that will be needed to finalize the design of the first prototype fusion power station, which has become known as DEMO (for demonstrator), was identified and estimates were made of when this information will be provided by ITER and IFMIF. Assuming just in time provision of the necessary information, this led to the construction timetable for DEMO shown in figure 6. Commercial fusion power stations would follow some 10 or more years after DEMO comes into operation.
The Culham fast track timetable reflects an orderly, relatively low-risk, approach. It could be speeded up if greater financial risks were taken, e.g. by starting DEMO construction before \textit{in situ} tritium generation and recovery have been demonstrated. The risks could be reduced—and the timetable perhaps speeded up—by the parallel construction of multiple machines at each stage.

Figure 6 assumes, overoptimistically, that ITER and IFMIF would both be approved in 2004. In fact the ITER treaty will not be signed until the end of 2006, and IFMIF is not yet approved—although a €150 million development and prototyping stage, funded by the European Union and Japan, will begin in 2007 (some delay in IFMIF construction might however be tolerable without compromising the end date). It should be stressed generally that the fast track model is a technically feasible plan, \textit{not} a prediction. Meeting the timetable will require a change of focus in the fusion community to a project-oriented ‘industrial’ approach, accompanied of course by the necessary funding and political backing.

9. Concluding remarks

The world faces an enormous energy challenge, as a result of rising energy use, and the fact that burning fossil fuels (which currently provide 80% of primary energy) is driving potentially catastrophic climate change and, when not managed carefully, producing debilitating pollution. The response must be a cocktail of measures: we must strive to use energy more efficiently, and renewables should play a role where appropriate. But there are in principle only four ways of meeting a large fraction of world energy demand: continuing use of fossil fuels (as long as they last); solar power (but realizing its potential as a source of base-load power requires major breakthroughs in costs and in storage of energy); nuclear fission; and fusion.

With so few horses in the race, we cannot afford \textit{not} to back fusion. Given the remarkable progress that has been achieved in recent decades, we are confident that fusion will be used as a commercial power source in the long term. We are less confident that fusion will be available commercially on the time-scale outlined above, which would require adequate funding of a properly focused and managed programme, and that there are no major adverse surprises. However, given the magnitude of the energy challenge and the relatively small investment that is needed on the ($4.5 trillion pa) scale of the energy market, we are absolutely convinced that accelerated/fast track development of fusion would be fully justified.

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