European Review, Vol. 13, No. 3, 337–359 (2005) © Academia Europaea, Printed in the United Kingdom

Fusion power

CHRIS LLEWELLYN-SMITH and DAVID WARD

EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK

Fusion, which powers the sun and stars, is potentially an environmentally responsible and intrinsically safe source of essentially limitless energy on earth. The potential of fusion has been recognized for over 65 years, but mastering fusion on earth has proved to be an enormous scientific and technical challenge. It involves heating a large volume of dilute gas, containing equal parts of deuterium and tritium, to over 100M°C (M°C = one million degrees celsius) while preventing it from being cooled by touching the walls, from which it must be isolated using a 'magnetic bottle'. This has now been done, and the Joint European Torus (JET) – which is the world's leading fusion research facility – has produced 16 MW of fusion power. The next step, which is to build a power station sized device called ITER, will be taken by a global collaboration. ITER will be twice as big as JET in linear dimensions, and will integrate all the technologies needed in a fusion power station. ITER should produce at least 500 MW of fusion power, ten times more than needed to heat the gas, and confirm that it is possible to build a fusion power station. Time is, however, 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 will be used in its construction, which will have to stand up to intense bombardment by the neutrons that carry the energy out of the magnetic bottle. Up to now, fusion has not been developed with any sense of urgency: since devices called tokamaks emerged in 1969 as the best candidates for bottling hot gases, at least 15 years have been lost due to delays in decision making and inadequate funding. In view of the urgent need for new, large-scale, emission-free sources of energy, and given the fact that – assuming it can be made to work reliably – the economics of fusion power look reasonable, the time has come to develop fusion on the so-called Fast Track. This involves: building ITER and the essential International Fusion Materials Irradiation Facility in parallel, which will take ten years; using the results to finalize the design of a prototype fusion power station (generally called DEMO for Demonstrator); and then constructing DEMO, which will take another ten years. Assuming adequate funding, and that there are no major surprises, DEMO could be putting electricity into the grid within 30 years.

Introduction

World energy use is growing rapidly, and growth is needed to lift billions of people out of poverty. However, 80% of the world's energy is produced by burning fossil fuels, which will not last forever, causes debilitating pollution and drives potentially catastrophic climate change. New, clean, energy sources are therefore urgently needed. Fusion is one of very few options for large-scale, emission free, power production. It is looking promising, and we will argue that fusion power should now be developed as rapidly as reasonably possible.

Fusion powers the sun and stars. The Joint European Torus (JET), which is the world's leading fusion facility, has produced 16 MW of fusion power and shown that fusion can be mastered on earth. The advantages of fusion power are that it will be environmentally responsible and intrinsically safe, and the supplies of fuel are essentially limitless.

The main disadvantage of fusion power is, of course, that it is not yet available, and will not be available as soon as we would like. A fusion power station could be built, and it looks as if the cost of fusion power will be reasonable. However time is needed to develop further the technology in order to ensure that it would be reliable and economical, and to test in relevant conditions the materials that would be used in power station 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 10 to 15 years later.

This paper describes how fusion can be used to produce power, its advantages and disadvantages, the present state of fusion development, the steps and time that are needed to develop fusion power as a commercial reality, and fusion power's potential place in the future energy mix. The main text is self-contained, but we have included an Annex that provides (technical and other) details and elaborates some points in the text (for example, on alternative fusion devices and the energy challenge that makes the development of new energy sources so urgent). The final section of the Annex (section A7) addresses the frequently asked question – why has the development of fusion taken so long?

Fusion basics

Reactions between light atomic nuclei in which a heavier nucleus is formed with the release of energy are called fusion reactions. The most effective reaction for power production uses two isotopes of hydrogen, deuterium (D) and tritium (T), which can fuse to produce helium and a neutron, which carry large amounts of energy (see Annex A1 for details).

To initiate the fusion reaction, a gas of deuterium and tritium must be heated to over 100M°C – ten times hotter than the core of the sun, in order to allow the fuel particles to fuse rather than just bounce off each other's electrical charge. There are two challenges.

The first is to heat a large volume of D and T gas to over 100M°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 (from ТОроидальная КАмера с МАгнитными Катушками, meaning toroidal chamber with a magnetic coil). The helium nuclei that are produced by fusion (being electrically charged) remain in the 'bottle', where their energy serves to keep the 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 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.

Fusion fuel

The tiny amount of fuel that is needed is one of the attractions of fusion. The release of energy from a fusion reaction is 10 million times greater than from a typical chemical reaction, such as burning a fossil fuel. Correspondingly, while a 1 GW coal power station burns ten thousand tonnes per day of coal, a 1 GW fusion power station would burn only about 1 kg of D + 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 ~ 12 years, occurs only in tiny quantities naturally. But, as described below, it can be generated in situ in a fusion reactor by using neutrons from the fusion reaction impacting on lithium (see A1 for details).

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 litres of water, would (allowing for inefficiencies) produce 200,000 kW-hours of electricity – the same as 70 tonnes of coal: this is equal to the UK's current per capita electricity production for 30 years.

Fusion power stations

Figure 1 shows the conceptual layout (not to scale) of a fusion power station. At the centre is a chamber (which will actually be toroidal – see later) with a

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

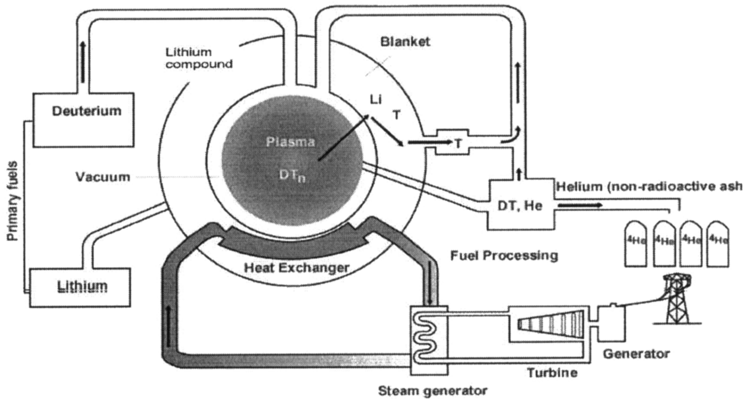

Figure 1. A fusion power station is conceptually similar to an existing thermal power station but with a different furnace and fuel. The figure is not to scale; in reality the fusion core would be a very much smaller part of the whole power station, and the 'blanket' would be ~ 1 m thick while the plasma (which, as explained later in the text, would be contained in a toroidal chamber) would occupy $\sim 1000\ \text{m}^3$.

volume $\sim 1000\ \text{m}^3$ containing a D-T plasma (as a gas is heated up, collisions between atoms and molecules, which move faster and faster as the temperature increases, knock off their electrons; at sufficiently high temperature, a gas therefore consists of dissociated electrons and nuclei – a state known as a plasma). D and T are fed into the core and heated to over 100M°C, a temperature routinely achieved at JET (see later). The neutrons produced by the fusion reaction escape the magnetic bottle and penetrate the surrounding structure, known as the blanket, which will be about 1 metre thick.

In the blanket, the neutrons interact with lithium to produce tritium, which is fed directly back to fuel the plant. Calculations show that it should be feasible to produce enough tritium for the plant, with a small excess to start up future plants. This vital part of the fuel system of a fusion power plant will be tested in ITER (the International Tokamak Experimental Reactor), which will be described below.

The neutrons will also heat up the blanket. This heat will be used to generate electricity, as indicated in Figure 1. Depending on the material choices for the power plant, different operating temperatures are envisaged (the 'thermodynamic efficiency', with which heat is turned into electricity, increases with temperature). These temperatures vary from around 400°C in so-called 'near-term' models that would use relatively ordinary steels, up to perhaps 1100°C in models that use more advanced materials such as silicon carbide.

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

Advantages and disadvantages

The advantages of fusion are

- essentially unlimited fuel;
- no production of CO_2 (or other greenhouse gases) or air pollution;
- major accidents are impossible;
- the 'internal' costs (i.e. costs of electricity generation) look reasonable – see the discussion of power plant studies below ('external' costs – impact on health, climate and the environment – will be essentially zero);
- it will meet a pressing need.

There is enough deuterium for millions of years of energy supply, and enough easily accessible lithium for several thousands of years.

A key fact is that, 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 ten postage stamps. Because the gas will be so dilute, there will be no possibility whatsoever of a runaway reaction. Furthermore, 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.

What are the potential hazards? First, although the main product of the fusion reaction, helium, is not radioactive, the blanket will become active when struck by the neutrons. However, the radioactivity decays with a half-life of the order of 10 years, and all the components could be recycled within 100 years. There is insufficient heat generation in the walls to lead to melting even in the event of complete failure of the cooling circuit.

Second, tritium is radioactive, but again the half-life is relatively short (12 years) and the hazard is not very great, particularly because so little fuel is used. In any case, it will be easy to design a reactor 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.

Like neutrons produced in fission reactors, or by neutron spallation, neutrons generated in fusion can, in principle, be used to generate fissile plutonium, which could be used to make nuclear weapons, as a product of collisions with the common isotope uranium-238 (or generate the fissile isotope uranium-235 in collisions with thorium). In order to do this, it would, however, be necessary to equip a fusion reactor with a special U-238/plutonium (or thorium/U-235) breeding blanket, which would be apparent by inspection. Furthermore, if even the tiniest trace of plutonium (or enriched U-235) was detected at or near a fusion reactor, and detection would be easy, it could only have been made deliberately.

A simple inspection system would therefore suffice to ensure that fusion reactors are not used to create material for nuclear weapons. (In contrast, nuclear fission reactors inevitably produce plutonium (or U-235 in a thorium-based breeder reactor) and it is therefore necessary to account for all the plutonium (or U-235) that might have been generated in order to be sure that none has been siphoned off to build weapons.)

Status of fusion research

The most promising magnetic configuration for confining ('bottling') fusion plasmas is a tokamak. Although there are alternatives that could have certain advantages (see Annex A2), the tokamak is the most developed system. The next large fusion device that will be built (ITER – see later) will be a tokamak, as almost certainly will be the first prototype power plant. In the early days of fusion research, however, a number of different magnetic configurations were considered, some of which are still used to produce hot plasmas for experimental purposes (see Annexes A2 and A7).

The basic layout of a tokamak is illustrated schematically in Figure 2 (see Annex A3 for a description of how a tokamak works). The hot fuel is contained in a toroidal chamber, surrounded by magnets. The combination of currents flowing in the magnets and in the fuel itself provides the magnetic bottle.

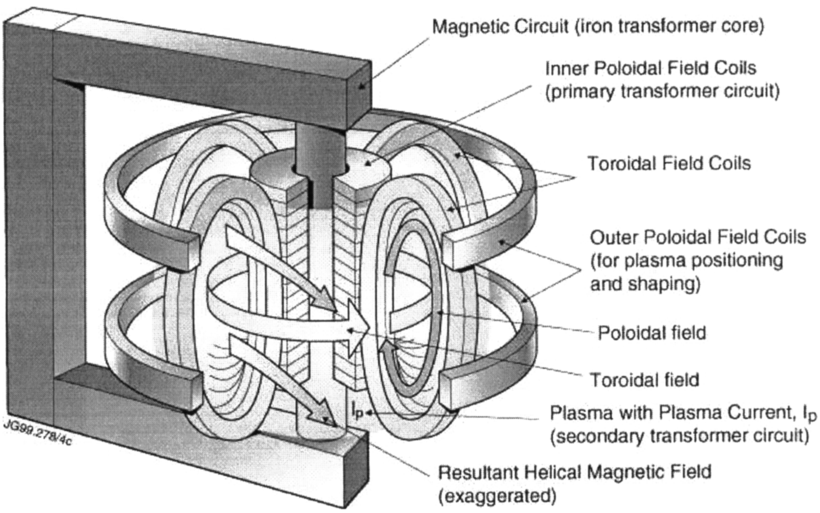

Figure 2. In a tokamak, the fusion fuel is held in a toroidal chamber surrounded by magnets. A current is induced in the fuel by transformer action and, together with the magnets, forms a helical magnetic structure that holds the hot fuel away from the wall (see Annex A3 for details).

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

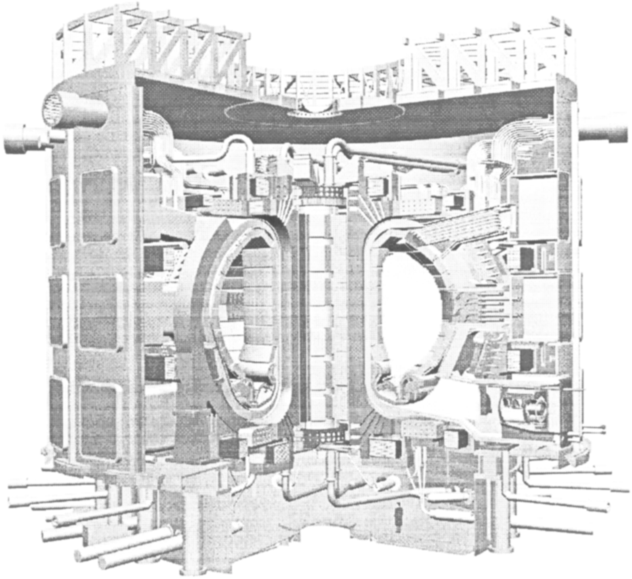

Figure 3. The ITER project, ready for construction, is designed to produce at least 500 MW of fusion power. It is similar in configuration to JET but twice as large (in each dimension).

Figure 3 shows a cutaway picture of ITER, an experimental device now ready for construction that will be about the size of (the core of) a fusion power station. The largest existing experimental fusion device is JET, which is about half the size (in linear dimensions) of ITER.

Tokamaks use a combination of magnets and a current flowing through the fuel (as in a fluorescent light) to hold the hot fuel away from the wall and provide thermal insulation. The current also heats the fuel up to 30M°C but additional heating methods are needed to push the temperatures up to the 100M°C required for fusion. The heating systems inject either microwaves, as in a microwave oven, or beams of very fast, energetic particles into the plasma. They serve the dual purpose of heating the fuel to the required temperature and maintaining the current flowing through the plasma.

Combining developments in heating, insulation and control, fusion research has made enormous progress over the last few decades, as summarized in Figure 4. Three parameters measure the progress:

(1) The plasma temperature (T), which must be above 100M°C.
(2) The plasma pressure (P).
(3) The 'energy confinement time' (τ_E) which measures how well insulated the fuel is against heat loss.

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

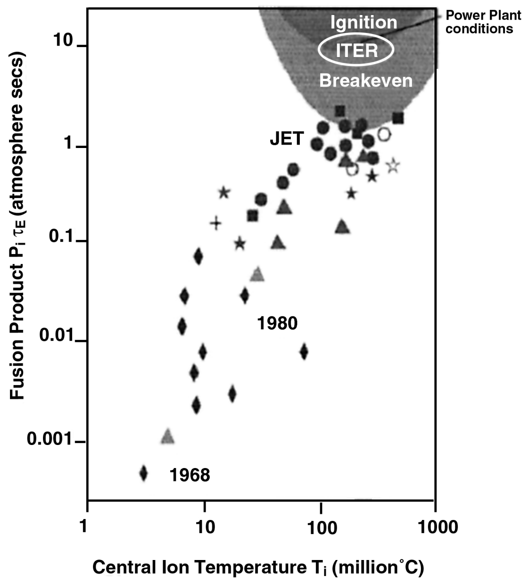

Figure 4. The progress in fusion has been substantial over recent decades from the low temperature, low energy gain points at the bottom left. Temperatures above 100M°C are now routinely achieved and an energy gain of around one has been reached. A power plant needs an energy gain above ten and this should be achieved in ITER.

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 ten or more in a fusion power station. The data points in the fusion performance plot (Figure 4) show results from different tokamaks. Semi-empirical scaling laws have been devised that interpolate rather accurately between results from machines with very different sizes, magnetic fields and plasma currents. These scaling laws give us confidence that ITER will perform as designed, and confirm that it is possible to build a fusion power station.

Next steps – ITER and IFMIF

Two intermediate facilities are necessary (which can and should be built in parallel) before the construction of a demonstration fusion power station, fully equipped with turbines etc, that will supply power to the grid. These are:

1. ITER (the International Tokamak Experimental Reactor)

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

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

power, with an input of ~50 MW, and show that the already-obtained plasma performance can be reproduced with much higher fusion power. Improvements with the potential to improve the economic competitiveness of fusion will also be sought – a key goal is to 'bottle' plasmas at higher pressures without leaks (see Annex A4).

ITER will use superconducting magnets, which will allow operation for tens of minutes at a time, and will also contain test blanket modules that, for the first time, will test features that will be necessary in power stations, such as the in situ generation and recovery of tritium. Prototypes of all key ITER components have been fabricated by industry and tested. Construction of ITER, which will cost €4.5 billion, through a consortium of the European Union, Japan, Russia, USA, China and South Korea, will begin once a choice has been made between candidate sites in France and Japan.

2. *IFMIF (the International Fusion Materials Irradiation Facility)*

The structural materials close to the plasma in a fusion power station will be subjected to continuous bombardment of neutrons (see Annex A5 for details). This will be a very hostile environment and, even though tests so far show that appropriately chosen materials may be reliable, it is only by reproducing the real environment of a power station that this can be fully explored.

The only way (other than building a power station) to reproduce the fusion environment, is to construct an accelerator-based test facility, which has become known as IFMIF (International Fusion Materials Irradiation Facility), and will cost ~€800 million. IFMIF will consist of two deuteron accelerators that will be focused on a liquid lithium target to produce neutrons with energies and intensities matching those generated in fusion. Some ten years will be needed to finalize the design and construct and bring IFMIF into operation. As we shall see, IFMIF (with ITER) is on the critical path to fusion, but unfortunately there are no immediate plans to start construction, although there is increasing recognition of its importance.

Power plant studies

A Power Plant Conceptual Study has recently been completed under the auspices of the European Fusion Development Agreement. This study provided important input to developing the critical path analysis of fusion development described below.

Four models A–D were studied as examples of a spectrum of possibilities, covering the range of scientific, technological and material possibilities. The designs range from a water-cooled plant made of steel (Model A) through to a

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

helium-cooled plant that incorporates silicon carbide to allow high coolant temperatures, up to 1000°C (Model D).

The cost of fusion-generated electricity is dependent primarily on the capital cost of the power station (of which about half would be for fusion-related components; the other items are conventional – see Figure 1). This decreases across the range of power plant concepts, primarily as a result of the improved thermodynamic efficiency, which allows devices that produce less fusion power and are therefore physically smaller, to produce the same electrical output. The cost of electricity found in this study decreases from a range of €0.05–0.09 per kWhr for Model A (depending on the level of maturity of the technology) to €0.03–0.05 per kWhr for Model D (these costs assume power stations operating for 75% of the time). Even the first cost could be competitive in a future electricity market if there was a significant carbon tax.

The power plant study shows that economically acceptable fusion power stations, with major safety and environmental advantages, are accessible on a 'fast track' through ITER with material testing at IFMIF, provided there are no unpleasant surprises.

The route to fusion power

A group at Culham has recently completed a critical path analysis of the development of fusion power, and a plan and possible timetable for the completion of the first prototype fusion power station, which has become known as DEMO (for Demonstrator). The results will be used to (i) prioritize future research and development, and (ii) motivate support for, and drive forward, the rapid development of fusion power.

Using technical targets derived from power plant conceptual studies (including the dependence of the cost of electricity on power station parameters), the study began by identifying issues that still need to be resolved, and then considered whether they will be resolved by existing devices, ITER or IFMIF. The next step was to estimate when information that is still needed to finalize the design of DEMO will become available. Assuming 'just in time' provision of the necessary information from ITER and IFMIF, this leads to the construction timetable for DEMO shown in Figure 5. The first commercial fusion power stations would follow some 15 years later after the beginning of DEMO phase 1 operation. This is not the place to elaborate further on this schedule, but three points should be made:

(1) It should be stressed that this model is a technically feasible plan, *not* a prediction. Meeting the timetable will require a change of focus in the fusion community to a project orientated 'industrial', approach,

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

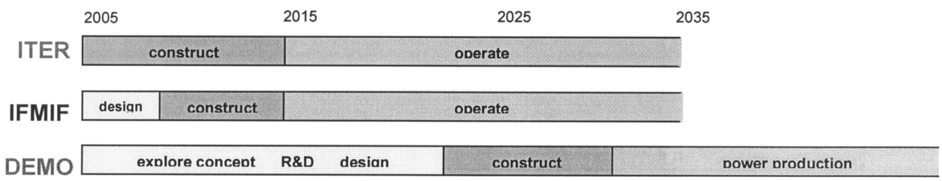

Figure 5. Possible timetable for the construction of a prototype fusion power station (DEMO), assuming the design is finalized on the basis of 'just in time' flow of information from ITER and IFMIF.

accompanied of course by the necessary political backing and funding.

(2) The timetable reflects an orderly, relatively low risk, approach. It could be speeded up if greater risks were taken, e.g. starting DEMO construction before in situ tritium generation and recovery have been demonstrated.

(3) Reduced risks and faster development could be achieved through the use of other devices run in parallel to the main programme. These could be devices similar to ITER, IFMIF or DEMO, or other, smaller, devices targeting earlier attainment of specific strategic information.

The need for fusion and its potential place fusion in the future energy mix

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 magnitude of this challenge is enormous (see Annex A6). 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 requires major breakthroughs); nuclear fission; and fusion.

We believe that, with so few horses in the race, we cannot afford *not* to back fusion.

What role could fusion play in the future energy mix? It turns out that the economics of fusion power improve with the electrical power output (P_e): the cost of electricity varies roughly as $(P_e)^{-0.4}$. The minimum viable output may be above

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

1 GW, depending on what electricity cost is acceptable. Fusion power stations will therefore be large and best suited for powering large cities and countries with good electric grids. This is not a serious limitation: the installed electricity generating capacity in western Europe ~ 1 GW per million people, and much of the world's population lives in cities of over a million people. In this sense, fusion could complement renewable power sources, which typically produce small outputs and are most suitable as smaller scale sources of local power in places with poor grid connections.

The relatively large output of a fusion power station, combined with the fact that the costs will be dominated by capital, with rather small operating costs, raises the question of possible uses of off-peak fusion-generated electricity, which could be produced at low marginal cost. There are two possibilities (both of which have also been considered for nuclear fission). One is to use fusion reactors to generate hydrogen: by electrolysis off-site (where the hydrogen is going to be used); by high temperature electrolysis on-site; or by on-site high temperature catalytic cracking of water, that requires temperatures of 900°C or more, which may be achieved in fusion power stations that use advanced materials. The other is to use off-peak power produced near coasts for desalination.

Concluding remarks

The development of fusion has taken much longer than originally hoped, partly because the scientific and technical challenges were very much greater than anticipated, and partly because it has not been pursued with any great urgency, as discussed in Annex A7. However, given the remarkable progress that has been achieved in recent decades, and the urgent need for new environmentally responsible, large-scale sources of energy, we believe that the time has now come to develop fusion as quickly as reasonably possible.

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 of Figure 5, which would require adequate funding of a properly focused and managed programme, and that there are no major surprises. However, given (i) the magnitude of the energy challenge, (ii) that fusion is one of very few candidates for large scale CO_2-free generation of baseload power, and (iii) the relatively small investment that is needed compared to the \$3 trillion p.a. scale of the energy market, we are absolutely convinced that accelerated/fast track development of fusion would be fully justified.

In 1973, when asked 'When will fusion be available?', the great Russian fusion pioneer Lev Artsimovich replied 'Fusion will be ready when society needs it'. The need is already very clear to us. We fervently hope that fusion will be available before the 'energy challenge' has developed into an energy crisis.

Acknowledgement

This work was funded by the UK Engineering and Physical Sciences Research Council and Euratom.

Further reading

General information on fusion can be found in the recent book, *Fusion, the Energy of the Universe*, G. McCracken and P. Stott (Elsevier, 2005), ISBN 0-12-481851-X, and in *La Fusion Nucléaire*, J, Weisse (Presse Universitairs de France, 2003), ISBN 2-13-053309-4 or on our website: www.fusion.org.uk

The EU studies of fusion power plant concepts are summarized in *A Conceptual Study of Commercial Fusion Power Plants*, D. Maisonnier *et al.*, EFDA-RP-RE-5.0 (2004). The analysis of the development path for fusion is given in *Accelerated Development of Fusion Power* by I. Cook *et al.*, February 2005, UKAEA FUS 521, available at http://www.fusion.org.uk/techdocs/ukaea-fus-521.pdf

About the Authors

Chris Llewellyn-Smith is Director of UKAEA Culham Division, which operates JET on behalf of Euratom and houses the UK's fusion research programme. He spent the first part of his career as a theoretical high energy physicist, before becoming Chairman of Oxford Physics, Director General of CERN (1994–98), and President and Provost of University College London. He is a Fellow of the Royal Society and a Member of the Academia Europaea. His scientific contributions and leadership have been recognized by awards and honours in seven countries in three continents. He has also spoken widely and written on science policy and energy issues.

David Ward is a fusion scientist at UKAEA Culham. Having first worked on theory and experiments at JET, he now plays a leading role in pan-European fusion power station design studies, and studies of the socio-economics of fusion.

Annex

A1. *The D-T fusion reaction and tritium generation*

The fusion reaction of primary interest as a source of power on earth is

$$D + T \rightarrow {}^{4}He + n + \text{energy (17.6 MeV)}$$

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

Here

D = a deuteron, the nucleus of deuterium ('heavy hydrogen') which consists of a proton and a neutron;
T = a triton, the nucleus of tritium ('super heavy hydrogen') which consists of a proton and two neutrons;
^{4}He = the nucleus of ordinary helium-4, which consists of two protons and two neutrons;
MeV = million electron volts: 1 electron volt [eV] is the energy imparted to an electron when it is accelerated through an electrical potential of 1 volt (a chemical reaction typically releases a few eV).
n = a neutron.

Energy is released because the constituent protons and neutrons are much more tightly bound together in helium-4 than in D and T (i.e. a huge amount of energy is needed to pull the constituents of helium apart, and the same amount of energy must be liberated when they are put together). The energy takes the form of kinetic energy (energy of motion) shared 14.1 MeV/3.5 MeV between the neutron and the ^{4}He nucleus

To initiate fusion, a D-T gas must be heated. At temperatures of a few thousand degrees C, the energy imparted by inter-atomic collisions knocks the electrons out of the atoms to form a mixture of separated nuclei and electrons known as a 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 100M°C (at which point the kinetic energy of the deuterons and tritons is around 10 keV), the nuclei approach within the range of the nuclear force and fusion begins.

The reaction that will be used to generate tritium in a fusion reactor's blanket is

$$\text{Neutron} + \text{Lithium} \rightarrow \text{Helium} + \text{Tritium}.$$

This reaction occurs with both Lithium-6 and the more abundant Lithium-7. Some enhancement of the Lithium-6 content is desirable as the reaction occurs with higher probability and liberates additional heat, whereas the reaction with Lithium-7 absorbs heat. There are competing reactions, which do not produce tritium, but they include reactions in which additional neutrons are generated, which can then also produce tritium. The upshot is, that on paper at least, it is possible to design reactors that would produce enough tritium for their own use plus a small surplus to start up new power plants.

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

A2. *Confining fusion plasmas: early ideas and alternative configurations*

It is now generally accepted that, apart perhaps from spherical tokamaks and stellarators, which are described below, the conventional tokamak (described in the main text and Annex A3) is the best candidate configuration for at least the first fusion power stations. Many other possible ways of confining hot plasmas were, however, considered in the 1950s and 1960s, and experiments with other configurations produced (and are still producing today) a wealth of important information about the behaviour of plasmas. These alternative configurations include: linear devices in which high temperatures and relatively high densities are created for short times by 'pinch' effects ('Z pinch', 'theta pinch'); linear devices which contain hot plasmas for relatively long periods using a 'magnetic mirror' that reflects some (but not all) of the plasma particles as they approach the ends; and toroidal devices, dominated by the magnetic field generated by the current in the plasma and the pinch that it produces. The first fusion-orientated plasma experiments (in the UK) involved 'pinches' in a toroid (generated by an induced current in the plasma, as in a tokamak). They were followed in the 1950s by the very ambitious ZETA project at Harwell in the UK (the historically important impact of false expectations raised by early ZETA results is described in Annex A7). ZETA was conceived as a toroidal pinch device but, while it was under construction, Roy Bickerton proposed adding a toroidal magnetic field to stabilize the plasma, as in a tokamak. This was done, but the maximum field strength was not sufficiently large relative to the field generated by the current in the plasma to reach the stable, quiescent tokamak regime. Meanwhile, in 1950, Tamm and Sakaharov in the USSR had invented the tokamak, in which the externally imposed (toroidal) magnetic field is much bigger than that generated by the current in the plasma. The first tokamak was built in the late 1950s at the Kurchatov Institute in Moscow.

Today, the only really serious alternatives to conventional (JET/ITER-like) tokamaks for commercial production of fusion power are:

(1) *Stellarators*, which were invented at Princeton by Lyman Spitzer in the early 1950s. In a tokamak, the plasma is confined by a helical magnetic field, which is a combination of the field produced by the toroidal field coils, and a 'poloidal' field produced by the current flowing in the plasma. In a stellarator, a confining helical field is produced entirely by external coils, without an internal current. The challenge of keeping a current flowing continuously in the plasma is therefore avoided, but the price to be paid is the much greater complexity of the magnet system. This price may be too high if, as is currently widely believed, continuous currents can be driven through the plasmas in conventional tokamaks. There is nevertheless

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

a good case for developing stellarators as an insurance policy, in case steady state operation of large tokamaks proves impossible, and for the additional insights that they provide into the behaviour of fusion plasmas. A device called W7X, which is currently under construction in Germany, will be the world's most advanced stellarator when it comes into operation around 2010.

(2) *Spherical tokamaks*, which were pioneered in the UK (the Mega Amp Spherical Tokamak – MAST – at Culham and NSTX at Princeton are the world's most advanced spherical tokamaks). Spherical tokamaks have much smaller inner radii, relative to their outer radii, than conventional tokamaks. It turns out that, as a result, it is possible to obtain the same pressure as in a conventional tokamak with a much smaller current in the toroidal field coils, and therefore to use conventional (non-superconducting) coils. This opens the possibility of fusion power stations based on spherical tokamaks that could be smaller, cheaper, simpler and more reliable than superconducting devices. Spherical tokamaks are at a much earlier stage of development than conventional tokamaks, and there are major challenges to be met to establish their viability as potential power sources, e.g. dealing with the higher heat loads that results from the more compact configuration; starting up the plasma given that a power-generating spherical tokamak will not have space for a neutron shielded inner poloidal field coil. Nevertheless, spherical tokamaks look very promising, and meanwhile are providing data that contribute to understanding the physics of tokamaks generally as they provide a long 'lever arm' for studying plasma behaviour as a function of the tokamak's aspect ratio. Spherical tokamaks also appear to be a promising candidate for constructing a compact Component Test Facility (CTF) in which prototype components of a power station could be tested in power station conditions.

A3. *Tokamaks*

Tokamaks work as follows (see Figure 2).

- The air is pumped out of the toroidal (doughnut-shaped) chamber.
- An electrical current is switched on in coils that surround the toroidal chamber, thereby generating a magnetic field.
- A small amount of gas (hydrogen or deuterium in most experiments; deuterium and tritium in some experiments at JET and in an actual fusion reactor) is injected into the vacuum chamber.

- 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 (~5 MA in JET) through the gas, which acts as the secondary.
- The electric current heats the gas, and turns it into a 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.
- 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 very 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, tokamaks are equipped with 'diagnostic' devices that measure the magnetic field, electron and ion temperatures and densities, the plasma pressure position and shape, neutron and photon production, impurities etc, and monitor the development of instabilities

A4. *Plasma Physics Issues*

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:

(1) Demonstrating that large amounts of fusion power (10 times the input power) can be produced in a controlled way, without provoking uncontrolled instabilities, over-heating 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.

(2) 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

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

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 electricity.

(3) 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' (see Annex A3), from radio-frequency waves and particle beams, boosted by a self generated ('bootstrap') current; however, this must be optimized to minimize the cost in terms of the power needed.

A5. *Materials issues*

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 a $\sim 2.5\,\mathrm{MWm^{-2}}$ 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, but occasionally they do not and this weakens the material. On the basis of experience of neutron-induced damage in fast breeder reactors, it seems that materials can be found that would meet the target of a useful lifetime of around five years before the materials would have to be replaced. 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 (though which impurities and the helium 'ash' produced in D-T fusion are exhausted) will be subjected to additional fluxes of $500\,\mathrm{kWm^{-2}}$ and $10\,\mathrm{MWm^{-2}}$ 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 and intensity as those that will be experienced in a fusion power station, is by constructing an accelerator-based test facility that has become known as IFMIF (International Fusion Materials Irradiation Facility). Further modelling and proxy experiments (e.g. using fission and neutrons produced 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 ~30% 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 ~€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 an 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, respectively, 0.1, 0.5 and 6 litres.

A6. *The energy challenge*

Present trends suggest that energy use will increase 60% by 2030, largely as a consequence of a very rapid increase in per capita energy consumption in India and China, from currently very low levels, which is accompanying their welcome rapid economic growth. Adequate energy sources are necessary for development. The International Energy Agency has produced a plot of the Human Development Index (HDI) (which combines life expectancy at birth, adult literacy and school enrolment, and gross national product per capita at purchasing power parity) against per capita energy consumption. It shows HDI increasing rapidly with energy consumption up to about 3 tonnes of oil equivalent per capita (toe pc) pa, above which point there is no evident correlation between HDI and energy. To bring all countries below 3 toe pc pa up to 3 (assuming consumption remains constant for those that already consume 3 or more) would require the world's energy consumption to be doubled at constant population, or increased by a factor of 2.6 with the world population of 8.1 billion predicted in 2030.

Meeting future demand while striving to reduce the use of fossil fuels, or mitigate their environmental impact, is an enormous challenge. The world's remaining fossil fuels will be used sooner or later. We must seek to slow down the rate at which they are burned (by improving efficiency and deploying alternatives) in order to reduce carbon dioxide production, and buy time to further develop alternatives and – if possible – develop ways to capture and store carbon dioxide safely at an affordable cost.

Increasing efficiency must be a priority, although it will ameliorate rather than solve the problem. Up to a certain level, the capital costs of driving down energy use by increasing efficiency are probably no more than the cost of providing the corresponding increase in supply. But the former costs would be borne by end users. Governments must devise and implement ways to ensure that investment in efficiency replaces investment in increased supply when possible.

Renewables must be developed and deployed when and where appropriate. But the only alternatives to fossil fuels that are capable, in principle, of meeting a large fraction of energy demand are

- solar: but major breakthroughs are needed to bring down the cost, and (given that the distribution of sunlight is not temporally or geographically well matched to energy demand) major breakthroughs are also needed in storage and transport of energy if solar power is to play a major role;
- nuclear fission: but nuclear power faces political problems in many countries, which will become more acute if there is a large increase, as it would require widespread deployment of fast breeder reactors. Work is needed to improve further and advertise the excellent safety features of modern reactors, and ways to improve waste storage and reduce proliferation risks must be sought;
- fusion.

A7. *Fusion development from the 1930s to today*

The basic features of nuclear fusion were quickly understood following the discovery of the neutron and deuteron in 1932. The series of reactions by which the sun burns hydrogen were identified in 1936, and Bethe published a detailed analysis of the two major reaction chains in 1939. A number of people had speculated about the use of D-T fusion as a terrestrial energy source in the late 1930s, and it was discussed at Los Alamos during the Second World War.

Following the war, during which several nuclear piles had been built in the USA for experimental purposes and for plutonium production, the primary goal of applied nuclear research was to develop nuclear fission power. Nevertheless, some fusion research began in the UK in 1946 at a small level and was soon followed by work in the USSR and USA.

In considering why it has subsequently taken 60 years to reach the present stage of fusion development, two phases can be distinguished:

(1) *The childhood of fusion*, which lasted from 1946 to 1969, when the tokamak emerged as the clear front-runner among various competing devices. This time was needed to learn more about the physics of plasmas and identify the most promising method for confining hot plasmas. It might have been speeded up somewhat had fusion not been classified, for reasons described below, from around 1950 to 1958.

The complexity of plasma physics, to which little attention had previously been paid, was greatly underestimated. In the 1962 words of the great Russian fusion pioneer Lev Artsimovich: 'It is now clear that our original beliefs that the doors into the desired region of ultra-high temperatures would open smoothly at the first powerful pressure exerted by the creative energy of physicists, have proved as unfounded as the sinner's hope of entering Paradise without passing through Purgatory', although he added 'And yet there can be scarcely any doubt that the problem of controlled fusion will eventually be solved'. Furthermore, it was at first not understood that 'the problem of raising a gas to a sufficient temperature for thermonuclear reactions to occur, though difficult, is trivial compared with that of devising a system in which there is a net power yield' in the (1957) words of John Lawson, who had derived the criterion for 'break even' (i.e. a net power yield).

Although, as discussed in the main text, fusion is today not considered to be a potential proliferation risk, around 1950 (in a fit of unfounded optimism about the prospects of rapid development) fusion research was classified in the USA, UK and Russia, on the grounds that fusion neutrons might be used to make fissile materials. It was soon realized, however, that classification made little sense given that large amounts of fissile material were already being produced, relatively easily, by fission reactors. After a gradual thaw, fusion came out of the closet at the Atoms for Peace conference in Geneva in 1958. Since then, there has been complete and open exchange of information between scientists worldwide working on magnetic confinement fusion. (The same is not true of work on the very different subject of inertial confinement, which involves creating very hot, extremely high-density plasmas, as in H-bombs. The interesting properties and physics of these very high-density plasmas have little in common with those of the low-density plasmas used in magnetic fusion. There are major challenges to be surmounted before inertial confinement could be a viable power source.)

The tokamak only emerged as clearly the most promising of many candidates for confining hot plasmas in 1969, when a British group confirmed that the T3 device at the Kurchatov Institute in Russia, which had a volume of less than 1 m^3, had achieved temperatures $\sim$ 10M°C.

(2) *The adolescence of fusion*, which lasted from 1970 to today, from T3 (with a volume of less than 1 m^3) through JET (volume 100 m^3) to a firm decision to construct ITER (volume 1000 m^3).

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

> Had there been a real will to develop fusion rapidly, backed by adequate funding, these developments could have been advanced by up to 15 years.

Although in the early 1970s many felt that more needed to be known about tokamaks before building a really big device, a Design Phase Agreement for a Joint European Torus, with the goal of producing real fusion power in a volume $\sim 100\ m^3$, had come into force by the end of 1973. Spurred by the oil crisis, a ‘fast track’ programme was envisaged leading quickly to a reactor scale device (now ITER), followed by a Demonstrator (DEMO) early in this century. This logical progression has so far been followed, but at a much slower pace due to delays in decision making and because the perceived urgency diminished as oil prices dropped, and fusion funding was cut.

Two years were lost in choosing a site for JET, which finally came into operation at Culham near Oxford in the UK in 1983. A proposal to construct ITER as a world project, with the idea that it might as a by-product serve to alleviate cold war tensions, was put to Ronald Reagan by Mikhail Gorbachev at a summit in 1985. Design work – by a US, Russian, European and Japanese team – started in 1988. By 1990, sufficient results were available from JET and other tokamaks to provide a basis for deciding to build ITER, which – allowing time for detailed design work and construction – could then have come into operation in not much over ten years. But development of fusion no longer seemed urgent following the fall of oil prices in the 1980s, and the fall of the Berlin wall removed the political motivation.

Large cuts were by then being made in fusion R&D budgets worldwide (the reduction of UK fusion funding by a factor of three in real terms from the mid 1980s to late 1990s was one of the most extreme cases). In any case, fusion has never been funded at anything like the level of fission development. In the UK, for example, fusion funding at its peak (in real terms) was less than a twentieth of funding for fission development.

The time that fusion development has taken is therefore easy to understand retrospectively. But the old joke that fusion seems always to be 50 years away clearly has some truth in it, although the end may now be in sight. Fusion scientists, especially in the UK, are particularly sensitive to this joke as a result of the enormous publicity generated by suggestions in 1957–58 that thermonuclear fusion might have been observed in a device called ZETA. This false claim has dogged the image of fusion for nearly 50 years.

ZETA, which for many years was the world’s largest fusion experiment (see Annex A2), was a toroidal device (with a volume of $\sim 10\ m^3$) with many features in common with a tokamak, that began operation at Harwell in the UK in the second half of 1957. Neutrons were soon observed. The question arose whether

https://doi.org/10.1017/S1062798705000499 Published online by Cambridge University Press

they were due to thermonuclear fusion, or other collisions of particles accelerated by the electromagnetic fields. Rumours that thermonuclear fusion had been observed reached the press, although the ZETA scientists were very cautious. They realized that it was very unlikely that the temperature was high enough to initiate fusion, and recalled Kurchatov's warning that neutrons can easily be generated in other ways, delivered during a speech at Harwell in 1956, in which he partly lifted the veil of secrecy on Russian work.

The press, however, which wanted a national triumph at a time of perceived western scientific humiliation, following the launch of the first Sputnik in October 1957, announced success under banner headlines such as 'Britain wins the H-race'. A press conference was arranged in late January 1958 at the Harwell laboratory, where a public relations success was desperately needed following the UK's first serious nuclear accident, a fire in the plutonium production plant at Windscale. The Press Release concluded by saying that 'there are good reasons to think that (the neutrons) come from thermonuclear reactions', but that this 'had not yet been definitely established'. Unfortunately, the Director of Harwell, Sir John Cockroft, stated that he personally was '90% certain' that a thermonuclear reaction had been achieved.

Subsequent Harwell publicity stated that 'the most optimistic estimate of the time needed before a practicable "fusion station" can be constructed is ten years; and it may take as long as fifty years. Sir John Cockroft has given his estimate as "twenty years plus" '. Many people over 60 in the UK remember the ecstatic headlines, such as 'A SUN OF OUR OWN – and it's made in Britain', and the subsequent disillusionment following an announcement in June 1958 that the neutrons did not have a thermonuclear origin. This incident seeded undue public scepticism about subsequent progress in fusion, and also made generations of fusion scientists very cautious when announcing advances. In fact, ZETA fulfilled its design goals and produced many very important results, although the scientists and engineers involved have had to put up with a public perception of failure.