Institute of Physics Report

Fusion as an Energy Source: Challenges and Opportunities

A report prepared for the Institute of Physics by W J Nuttall
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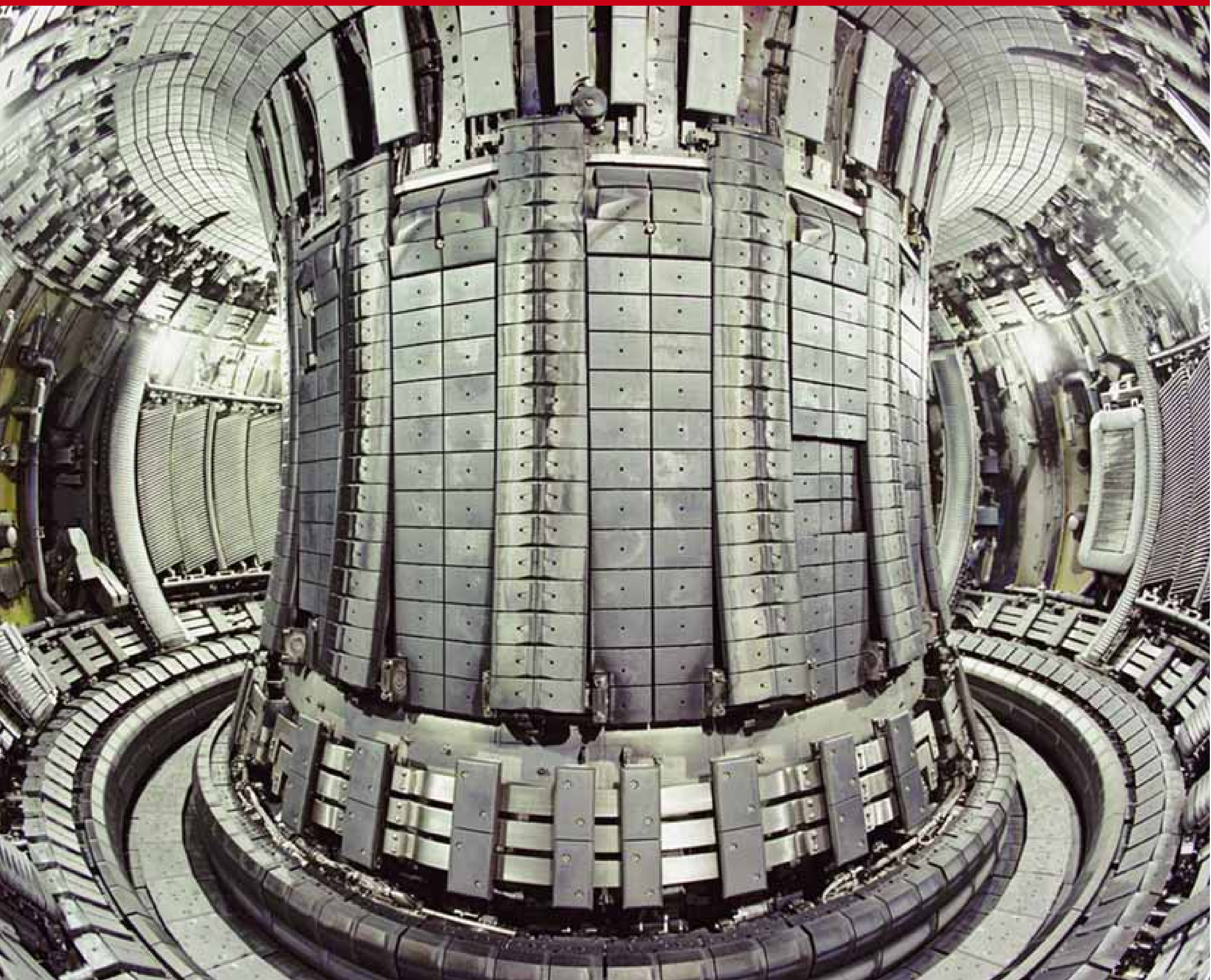

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1: Introduction

Life on Earth currently faces a threat on a truly global scale: climate change. A scientific consensus is emerging that civilisation must reduce its emissions of global warming gases by more than half in less than 50 years[1] if we are to stand a chance of achieving a global climate as stable as that of the past 10 000 or so years.

This pressing need comes at a time when fossil-fuel prices are high, albeit perhaps for short-term reasons, giving the world a window of opportunity in which to make a significant move away from environmentally harmful fossil-fuel combustion. Thus far, no country has managed to make significant cuts in greenhouse-gas emissions as a consequence of rising concern over global warming. In Europe, at least, political leaders have started to put in place policies that, if delivered, would have sufficient strength to have some impact on the problem. In January 2008 the EC president José Manuel Barroso released a major package of policies entitled "Climate Action".[2] The measures consolidated earlier plans for a 20% cut in EU greenhouse-gas emissions by 2020, even in the absence of any global deal that might see the EU target become a 30% cut.

To meet its primary energy needs each year, the world consumes energy roughly equivalent to 12 billion tonnes of oil. Of this, three-quarters comes from fossil fuels, all of which when combusted release carbon dioxide (CO_2); while around 6% is supplied by the very low CO_2-emitting technology of nuclear power.

All nuclear power stations in operation today rely on fission – the splitting of large atomic nuclei, in particular the very heavy elements uranium and plutonium. Most nuclear power stations are fuelled by uranium, and some plutonium is produced from uranium by the reactions.[3] However, fission is not the only type of nuclear reaction to release energy. An alternative approach to usable energy production depends on nuclear fusion. The basis of this is the release of energy when very light nuclei are brought together to form more stable heavier ones.

As with fission, fusion would be a source of usable heat-energy producing almost no CO_2 emissions. The only greenhouse-gas emissions produced would be those associated with the construction and manufacture of the power station, and the need for external energy inputs for start-up and operations. Fusion research holds out the promise of a clean, sustainable energy supply to contribute to the increasing needs of our civilisation.

In the history of fusion, governments have sometimes emphasised the scientific interest of fusion research. In the UK, however, the goal is clear: a fusion power station producing electricity for a competitive market. This is a substantial technical challenge but it seems that none of the technological elements is beyond reach.

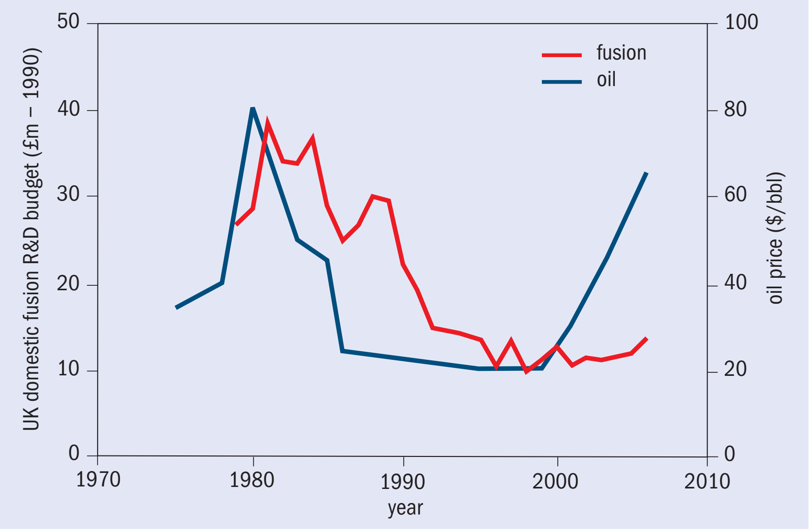


Figure 1: UK domestic fusion R&D budget and oil price from 1975 to 2005. Source: UKAEA Culham.

1.1: The funding landscape

Despite the growth in global concern about the increase in atmospheric CO_2 and average global temperatures since the 1980s, it is only in more recent years, with rapidly rising fossil-fuel prices, that support for fusion research has increased. There is a correlation between oil price and support for fusion research; figure 1 implies that there is a lag of a few years between a change in oil price and spending on the UK fusion programme.
Figure 2 shows the UK's investment in fusion research compared with international investment levels over a similar timescale. In all countries shown, fusion budgets had declined by the late 1990s, reflecting a period of inexpensive energy supplies. It is noteworthy that in the US, decreases in fusion research budgets occurred most strongly in the late 1970s, only increasing again modestly following the "second oil crisis", prompted by the 1979 Iranian revolution.

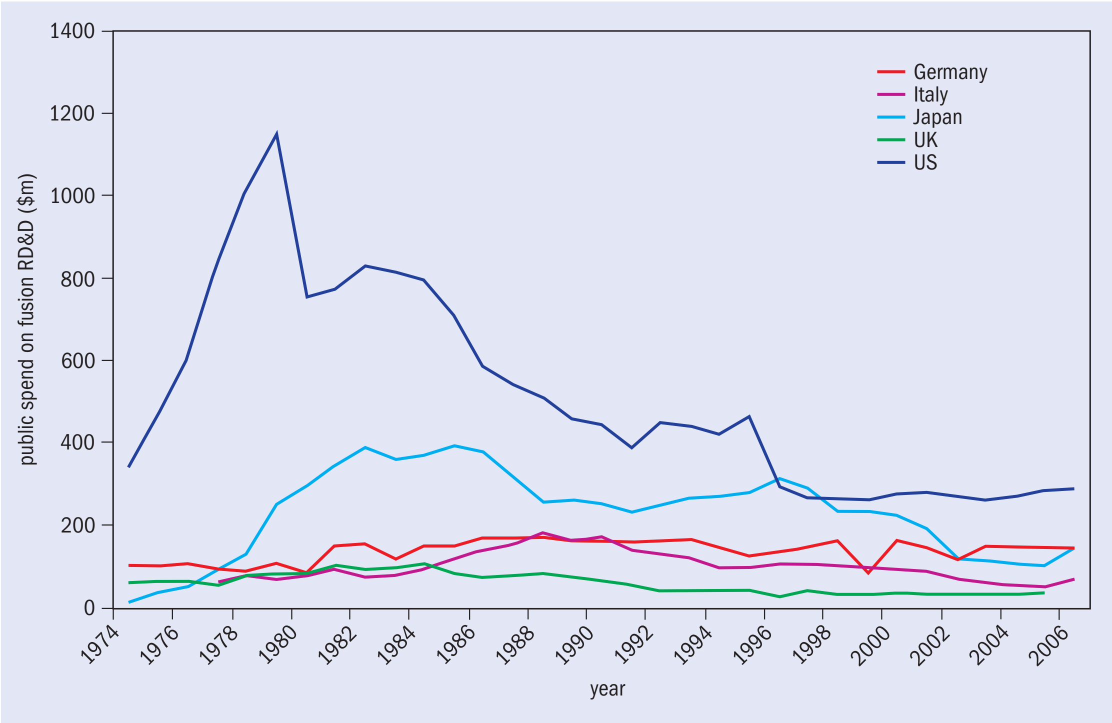
1.2: The benefits of fusion as an energy source

In principle, fusion has several key benefits over conventional approaches to nuclear power based on fission:

- **The fuel for fusion is abundantly available**. Two isotopes of hydrogen are well suited for fusion: deuterium and tritium. Deuterium is available from seawater (and can be extracted by electrolysis) and it is expected that tritium can be produced within a fusion power station from small quantities of lithium.[4] Lithium has a range of commercial uses, including, importantly, in modern batteries. Despite increasing demand, lithium supplies remain

1 engineers.ihs.com/news/eu-en-greenhouse-gases-5-07.htm.
2 *Climate Action: Energy for a Changing World,* ec.europa.eu/energy/climate_actions/index_en.htm.
3 IOP 2004 *The Future of Fission Power: Evolution or Revolution?*
4 A Klix *et al.* 2005.

Figure 2: Public spend on fusion RD&D, international comparison from 1974 to 2006. Source: International Energy Agency, see www.iea.org/textbase/stats/rd.asp.



abundant. The long-term fuel security of fusion would appear to exceed that of fission power and hence far exceed that of fossil-fuel energy. A fusion station would use about 100 kg of deuterium and 3 tonnes of lithium to produce the same amount of energy as a coal-fuelled power using 3 million tonnes of fuel.[5]

- **Fusion has a low environmental impact**. Whereas fission stations produce spent fuel with half-lives of thousands of years, the only radioactive wastes produced from a fusion station would be from the intermediate fuel, tritium, and any radioactivity generated in structural materials. The radioactivity of tritium is short-lived, with a half-life of around 12 years, and if chosen appropriately the structural materials have a half-life of around 100 years.
- **Fusion is inherently safer than fission in that it does not rely on a critical mass of fuel**. This means that there are only small amounts of fuel in the reaction zone, making nuclear meltdown impossible.
- **Fusion power stations would present no opportunity for terrorists to cause widespread harm (no greater than a typical fossil-fuelled station) owing to the intrinsic safety of the technology**. Fusion in a tokamak relies on a continuous supply of fuel, without which the process soon dies away. Furthermore, the process is only sustained via careful use of the controlling magnetic fields. While the magnets contain some limited stored energy, the fusion reactor does not. This is in contrast with other low-carbon electricity sources, fission and conventional hydropower, which require the safe control of large amounts of stored energy, even when not operating.
- **As with fission, fusion power stations would provide energy at a constant rate, making them suitable for base-load electricity supply**. Fusion electricity will be similar to fission electricity in its cost structure; a power station will require complex and expensive engineering, while fuel costs will be negligible in comparison. Staffing levels will be roughly constant whether or not the plant is generating. As such, the majority of costs will be capital costs and almost all will be fixed. The marginal cost of electricity generation will be very small.
- **Fusion power stations would not produce fissile materials and make no use of uranium and plutonium, the elements associated with nuclear weapons**. This reduces proliferation concerns associated with these elements, although fusion is not completely free from proliferation risks.[6]

5 Typical annual values, see R Pitts *et al.* 2006.
6 See section 6.

2: What is fusion? The basic physics

Nuclear reactions are different from chemical reactions in that they involve the protons and neutrons in the nucleus, rather than electrons. Like chemical reactions, nuclear reactions can involve either a net absorption or a net release of energy. To achieve a release of energy in a fusion reaction, smaller, less stable nuclei must be joined together to form a more stable nucleus. Elements on the far left of the curve in figure 3 release energy by fusion, while elements on the far right release energy via fission.

The energy released arises from the difference between the nuclear binding energies of the initial and final components. In the conventional approach to fusion, no fundamental nuclear particles are created or destroyed. The energy associated with binding the initial components is greater than that associated with the reaction products, and it is this energy difference that is released during fusion. Interestingly, these small differences in binding energy are reflected in the observable masses of the various reaction components; via Albert Einstein's famous equation describing the equivalence of mass and energy: $E=mc^2$. This states that energy = mass × (speed of light)^2. That is, the components after the reaction actually weigh less than those before the reaction and the mass difference is released as energy. Einstein's equation gives an indication of the scale of the proportionality between mass and energy, and it explains why very small changes of mass in nuclear fuel can release a great deal of usable energy.

Fusion occurs inside the Sun at 15 million °C, and at more than 100 million °C in manufactured experimental reactors.[7] It is interesting to note that, despite the temperatures involved, the pressure inside a fusion tokamak will actually be quite low, similar to atmospheric pressure. This is a consequence of the small amounts of fusion fuel involved. Fusion reactors use specific isotopes of hydrogen as fuel because these can react at a useful rate for power production, allowing a fast reaction at more easily achievable temperatures. Most reactors use deuterium and tritium. As shown in figure 4, all of these atoms have a single proton but, while hydrogen has no neutrons, deuterium has one and tritium has two.

In preparation for fusion, these isotopes are heated so that they become a plasma. This is an ionised gas consisting of free electrons and nuclei not bound into atoms, and it is a distinct state of matter, along with solids, liquids and gases. This allows the atomic nuclei to be separated out. Since the deuterium and tritium ions, like any atomic nuclei, are positively charged, they repel each other strongly with an electrostatic force. For fusion to occur, this repulsion must be overcome, forcing these lighter nuclei close enough together for long enough to bring them into collision. This involves confining the plasma at very high temperatures, and at the same time isolating it from the walls of the container to prevent impurities. Plasma stability remains an active area of fusion physics research. The fusion plasma must be confined and kept clean for the longest possible sustained fusion reaction – ideally in an operating power station for several hours.[8]

There are two conventional ways of achieving this in a fusion power station. In magnetic confinement approaches to fusion (MCF), magnetic fields hold the plasma in isolation while very high temperatures, corresponding to very high speeds for the nuclei, create the necessary collisions. MCF, in the form of a tokamak reactor, is the most common approach to fusion

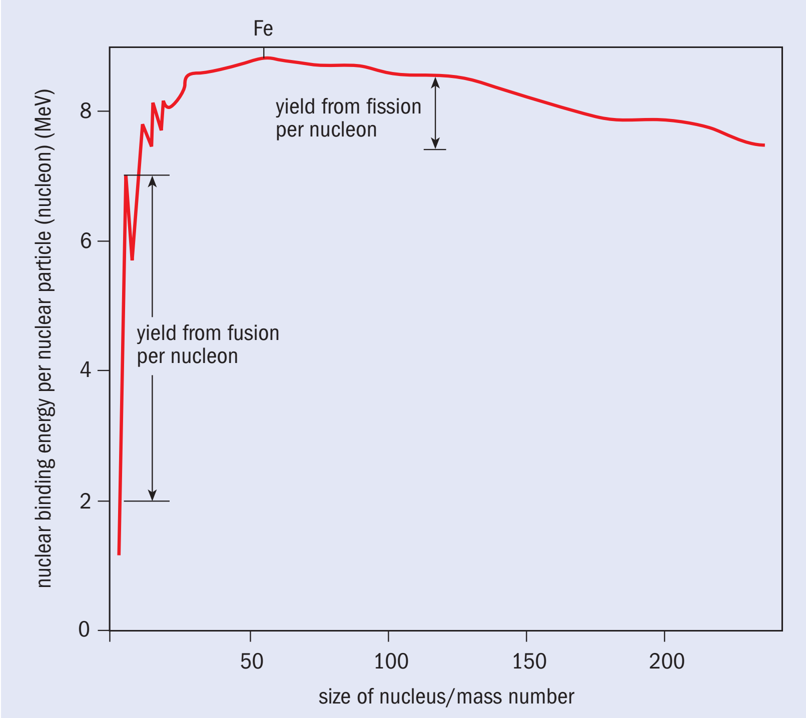


Figure 3: The relationship between binding energy and mass number of elements.

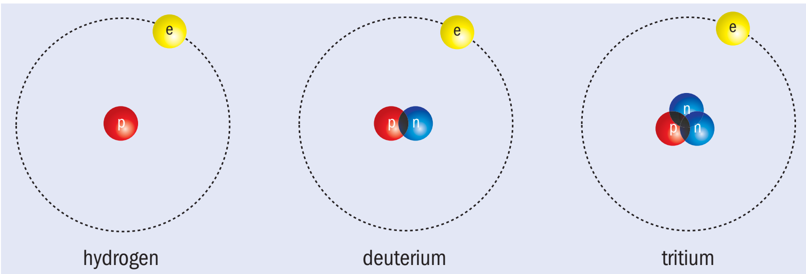


Figure 4: Hydrogen, deuterium and tritium.

7 J Bahcall 2005.
8 R Pitts *et al.* 2006.

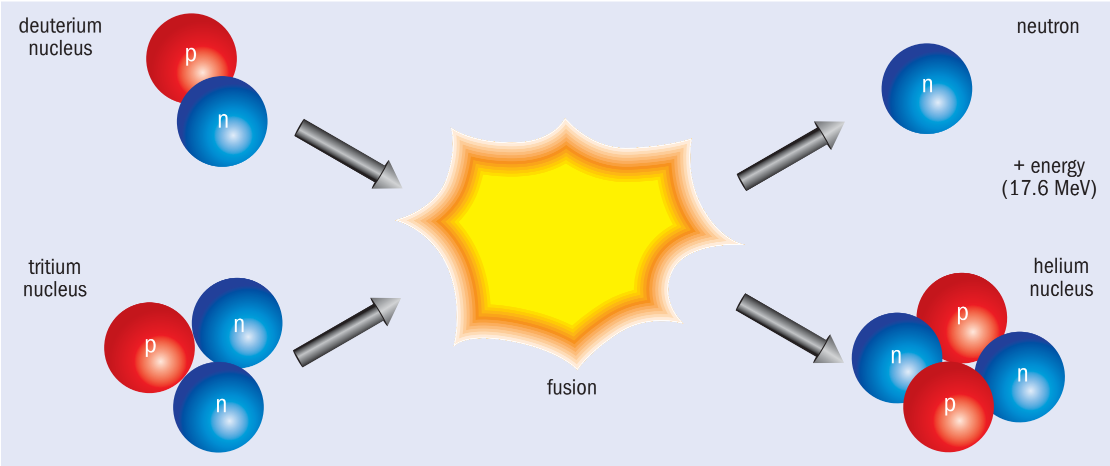


Figure 5: The fusion reaction of deuterium and tritium.

power and magnetically confined fusion energy (MCE). In inertial confinement approaches to fusion research and to fusion energy (ICF and ICE), very high pressure is applied very quickly, initiating a short fusion pulse. Inertial confinement can be achieved using high-powered lasers. The majority of this report deals with MCE, as this approach will more probably yield a usable energy source before ICE does.

Figure 5 illustrates the fusion reaction between deuterium and tritium, releasing a helium nucleus and a single neutron, as well as 17.6 MeV (2.82×10^{-12} J) of energy. The original energy of convergence is negligible in comparison. The released energy is taken up by the two new particles in inverse proportion to their masses. That is, a fifth is taken up by the kinetic energy of the helium nucleus and four-fifths by the kinetic energy of the neutron. As an electrically neutral particle, the neutron is unaffected by any magnetic fields. These fast neutrons are emitted in all directions and are the primary means by which energy leaves the fusion reactor.

Many of these neutrons would leave the reactor on its outer edge and come to rest in a component known as "the blanket". This contains material designed to slow down the fast neutrons and in doing so become heated. This heat is, in turn, transferred to a medium such as high-pressure helium or steam. This hot, high-pressure gas can be used to drive an electricity-generating turbine. Some modules of the power-station blanket would include lithium, which reacts with the fast neutrons to generate tritium, one of the two fuels required for the reaction. In this way a fusion power station could produce one component of its own fuel *in situ*.

Unlike the neutron, the helium nucleus is charged, so in MCF it becomes trapped by the magnetic fields holding the plasma in place. This allows energy to be retained in the plasma, helping to maintain high temperatures. If this internal heating effect is sufficient to sustain the required temperature at the correct density, the plasma is said to ignite and the reactor to operate in ignition mode.

However, once the helium nucleus has transferred its energy to the plasma, it becomes something of a problem. As a heavy ion it acts to dilute and cool the plasma, thereby inhibiting the reactions. It becomes helium ash, and power-station designs incorporate sophisticated devices known as divertors to extract this residue. Divertors and the associated plasma geometry present significant technical challenges. One key challenge is the choice of high-temperature durable materials for the divertor target.[9] In an eventual power station the divertor would be subject to intense particle bombardment and reliability will be key to its commercial success.

2.1: Tokamaks: a technical explanation

The tokamak addresses a key challenge for fusion – sustained operations and plasma stability. The conventional design for an MCF reactor is shown in figure 6. The plasma is contained in a toroidal vessel and held in isolation from the walls by a helical magnetic field from a set of D-shaped toroidal field coils (blue). The process starts with the high-vacuum reactor vessel being charged with a small amount of deuterium and tritium gas, which is then ionised and the electrons are removed.

The voltage applied to the primary circuit (red) is swept slowly from a large positive to a large negative value. In near-term research machines, such a sweep might last for about a minute. In a commercial MCE power station, such a sweep would last far longer, perhaps even hours. This magnetises the iron core (orange), generating a field that induces a current in the plasma (analogous to the secondary coil of a conventional electric transformer). Positively and negatively charged components are not bound together in a plasma, so the changing field induces a current of two components: positive nuclei moving in one direction round the torus and negative electrons moving in the opposite direction. The key advantage of this geometric arrangement is the fact that the plasma particles do not follow smooth circular paths round the ring. While the transformer action gives rise to a poloidal magnetic field, the coils create a toroidal magnetic field. The combination of these fields results in the plasma particles following a helical path

9 R Pitts *et al.* 2006.

round the torus (black). This helical motion is key to the stability of a tokamak plasma.

At the start of a voltage sweep the plasma is cold and viscous. Much of the applied electrical energy is converted into plasma heat because of friction effects. However, such resistive heating alone is insufficient. In modern tokamaks, heat is also transferred to the plasma in a range of other ways, including resonant radio frequency energy (not unlike the operation of a domestic microwave oven) and high-energy beams of neutral particles, such as hydrogen atoms (the motion of which is unaffected by the magnetic fields of the tokamak, at least prior to ionisation).

Tokamak plasma physics is benchmarked according to a few key indicators; an important one is the pressure ratio, β. This is the ratio of the pressure in the plasma to the "magnetic pressure", or energy density, which is proportional to the square of the applied magnetic field. Generally those considering fusion power concepts are attracted to high-β designs because of their more efficient use of the magnetic field.

Inductively driven tokamaks are pulsed machines. Fundamentally this arises because the plasma current is driven by transformer action, and the primary circuit necessarily only has a limited voltage swing. This transformer action provides the initial heating and sets up the plasma current. Once the voltage sweep is finished, the plasma current starts to decay because of resistive losses. However, this plasma current can be sustained via directed heating, and also as a result of complex secondary effects, such as the so-called "bootstrap current". These additional sources may be sufficient to allow a power station to operate in a near-continuous, rather than pulsed, mode. At present, most fusion proponents look to tokamak operations lasting several hours in a long pulse mode, with only limited time required to reset for the next pulse.

Tokamaks require several sets of magnetic coils. Physically the largest coils are the toroidal field coils – superconducting magnets (blue in figure 6). The magnetic fields required for a tokamak are very large, yet space around and within the machine is at a premium. These constraints lead to the need for superconducting magnets in all future large-scale tokamaks. The International Thermonuclear Experimental Reactor (ITER) will use some of the largest superconducting magnets in the world.[10] Superconductors have the property of zero electrical resistance at low temperatures, which allows large currents to flow through ITER's electromagnets with very high efficiency.

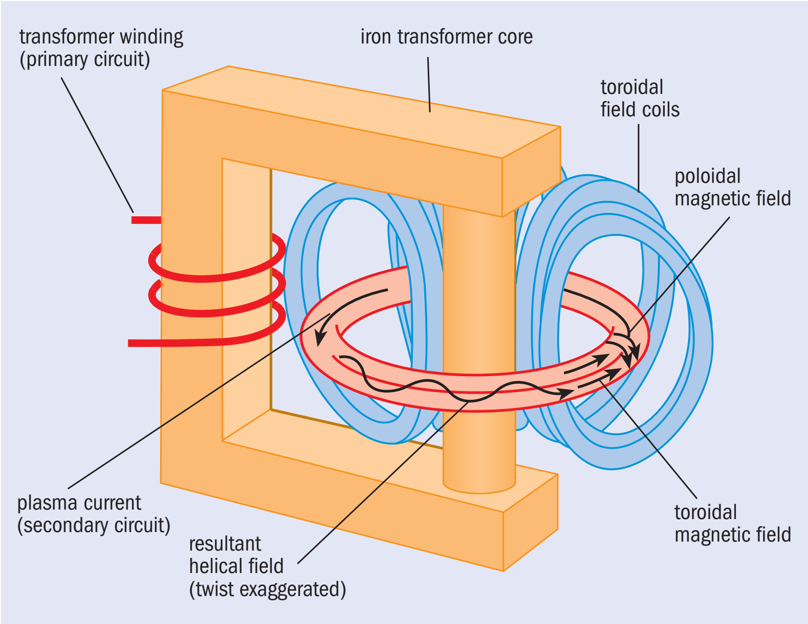


Figure 6: Schematic of a tokamak. Source: EFDA JET.

10 See section 3.

3: The quest for fusion: a history

The first fusion experiments were conducted at the University of Cambridge, UK, during the 1930s, but it wasn't until the following decade that fusion's potential as an energy source was realised. Fusion research for energy generation has had a turbulent and complex history.

The 1950s saw misplaced optimism with the operation in the UK of the Harwell Laboratory's Zero-Energy Thermonuclear Assembly (ZETA)[11] – a stabilised toroidal pinch machine. It had a toroidal shape but the region of plasma physics interest was restricted to a particular toroidal segment – the "pinch", where the plasma was magnetically squeezed to increase its "magnetic density".

Throughout the early years of fusion research, plasma stability in MCF systems presented an ongoing difficulty. While some in Britain were calling for an end to fusion-energy research, a breakthrough came in 1968 from the Kurchatov Institute in the Soviet Union. A new approach known as the tokamak was found to work very well in the form of the T3 machine, which was based on a 1951 concept from Igor Tamm and Andrei Sakharov.

In the 1970s the construction of big fusion-research machines was approved, including a European collaboration to build the biggest machine to date – the Joint European Torus (JET). In the 1980s, Soviet general secretary Mikhael Gorbachev proposed to US president Ronald Reagan that the superpowers might collaborate to build ITER. In the 1990s, however, policy-makers' enthusiasm for grand energy research projects wavered against a background of sustained low oil prices. A key step was taken in November 2006 when a much-revised ITER plan was finally agreed as a seven-party international collaboration.

3.1: Achievements of the large tokamaks

While much good research has been conducted on small tokamaks, it is three large tokamaks that have done the most to help to make fusion energy a viable prospect. They are:

- Japan Atomic Energy Research Institute Tokamak-60 (JT-60) in Naka, Japan, 1985 to present;
- Tokamak Fusion Test Reactor in Princeton, New Jersey, US, 1982–1997;
- JET in Culham, Oxfordshire, UK, 1984 to present.

Together these three machines have demonstrated the scientific fundamentals of fusion power production. For instance, researchers at JT-60 demonstrated that even once the initial driving transformer sweep has ended, it should be possible to continue to operate the tokamak by means of an external current drive – an important step towards continuous electricity generation.

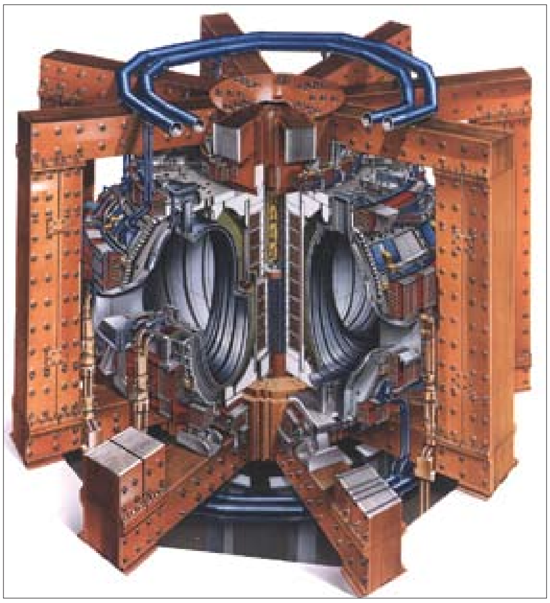
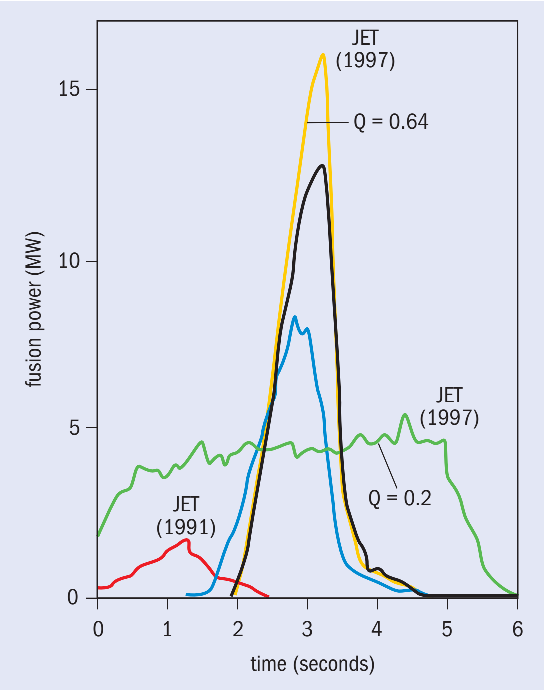


Figure 7: The JET tokamak. Source: EDFA-JET.

A greater challenge than maintained high plasma temperature is plasma confinement. Much work has been undertaken to understand the diffusion of plasmas in tokamak fields. Key considerations are high-energy particle collisions and plasma turbulence. Another critical topic specifically for the tokamak is continuous operation. Sustained plasma motion and confinement might be maintainable as a consequence of the bootstrap current – an important effect predicted theoretically in the early 1970s and first observed by Michael Zarnstorff in 1984 at the University of Wisconsin-Madison. The bootstrap current was not anticipated when tokamaks were first proposed, but it could be of great importance in achieving continuous electricity generation. If the bootstrap current is insufficient, plasma motion may also be enhanced, for example via directed neutral beam injection or resonant frequency electromagnetic waves.[12] JET has achieved the highest level of fusion energy production (figure 8). In 1997, JET briefly produced 64% of the amount of energy being fed into the plasma (denoted by $Q = 0.64$). This refers to the total energy released by the reaction, four-fifths of which is taken up by the emitted neutrons, providing the heat for electricity generation. Only when the plasma reactions release five times the amount of energy that is put in ($Q > 5$) is the internal heating power greater than the supplied power. Clearly a power station needs to produce vastly more energy than it consumes (e.g. $Q \sim 50$). Originally it was anticipated that a fusion power station might operate without ongoing supplied power, in ignition mode ($Q = \infty$). Increas-

11 C M Braams and P E Stott 2002, section 4.2.
12 See section 2.1.



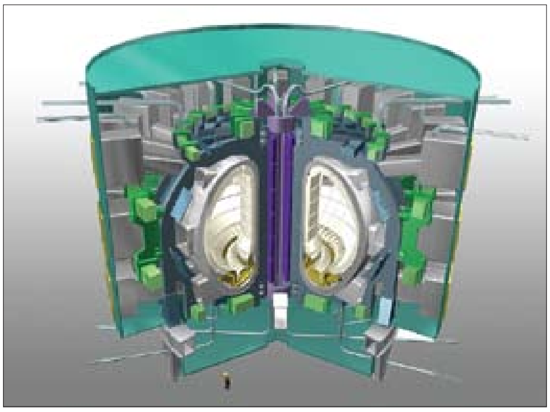


Figure 8 (left): Record-breaking deuterium-tritium fusion energy production at the JET facility. Source: EDFA-JET.

Figure 9 (right): ITER cryostat and tokamak. Source: ITER.

ingly, however, this is recognised as neither essential nor even desirable for reasons of plasma control.

3.2: The International Thermonuclear Experimental Reactor

ITER ("the way" in Latin) is an experimental tokamak reactor that is due to be built between 2009 and 2018. The project is a collaboration between the EU, China, India, Japan, Russia, South Korea and the US, although current US participation is shaky, with only $10.7 m (£5.4 m)[13] having been appropriated for ITER in the 2008 federal budget, rather than the expected $160 m (£81.0 m).[14]

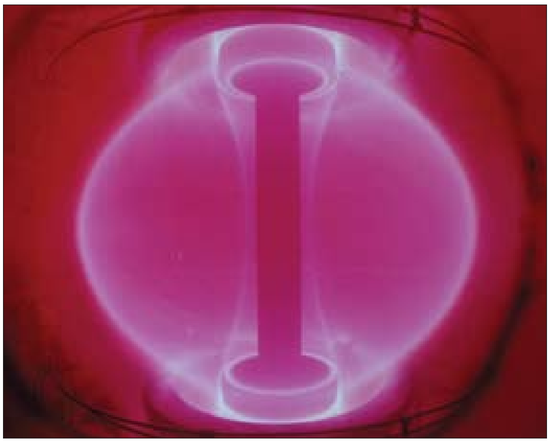
ITER is to be the next step on the main trajectory towards a fusion power station, combining fusion science and technology. ITER will cost at least €10 bn (£7.9 bn) over its 30-year lifetime. Roughly half of this will be used to build the machine and half to operate and decommission it. Following intense international competition, the global partners agreed to locate the machine at Cadarache in southern France.

While the earliest plans imagined that ITER should achieve ignition, this ambition has been scaled back (from aiming to achieve an infinite Q value, ignition, to a level of at least Q = 10), recognising that power stations would be unlikely to operate in ignition mode.

The goal for ITER is to produce roughly 500 MW of thermal energy[15] (a similar power rating to that of a modular natural-gas-fuelled combined-cycle gas turbine for power production) in long pulses of at least 400 seconds. The reactor is experimental; there is no intention of using ITER as a power station. Preparatory site works began in 2007, and most of the design and negotiation challenges have now been met.

13 Based on 2008 exchange rates.
14 *ibid.*
15 C Llewelyn Smith and D Ward 2005.

4: Unconventional approaches to magnetic confinement



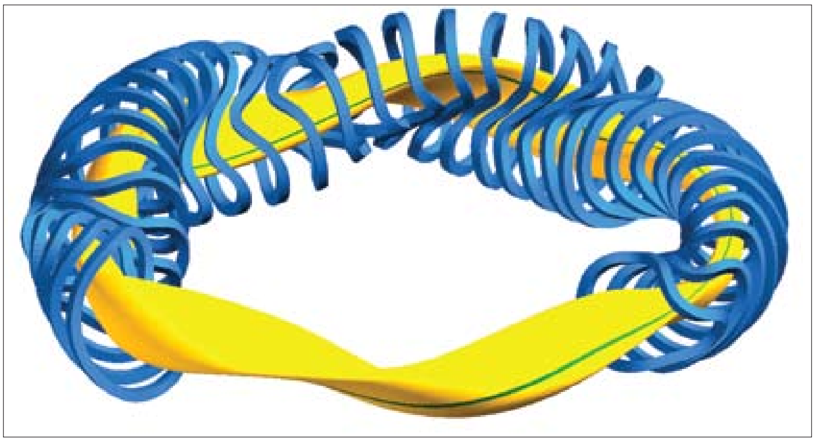


Figure 10 (left): Hot plasma from the MAST fusion experiment. Source: UKAEA Culham.

Figure 11 (right): Schematic arrangement of a magnetic field coil system for the Wendelstein 7-X stellarator under construction in Greifswald, Germany. Source: Max Planck Institute.

While there is a clear and coherent path from the early Russian T3 machine, through the big tokamaks of the 1970s, towards ITER and an eventual fusion power station, this sequence is not the only interesting and potentially energy relevant tokamak research.

One research thread has been that of low-cost tokamaks, intended primarily for scientific, rather than energy, purposes. Perhaps the most radical of such proposals is the Ignitor concept from Bruno Coppi and colleagues at Massachusetts Institute of Technology (MIT) and the Italian National Agency for New Technologies, Energy and the Environment (ENEA).[16]

This design aims to achieve ignition as cheaply as possible. Perhaps most important is that the project avoids some of the more complicated technology of other fusion reactors by not employing a divertor to extract the helium ash, because the machine is intended from the outset only to perform pulsed experiments. Coppi points to the high levels of inherent plasma cleanliness in the Ignitor concept as being a key positive attribute of that particular low-cost approach. At present, while components of Ignitor have been manufactured, the machine is far from complete.

4.1: Spherical tokamaks

Another radical and highly successful concept is Martin Peng's spherical tokamak (ST), which was demonstrated for the first time in the UK by the Spherical Tight Aspect Ratio Tokamak (START). The Culham Science Centre team built START in its spare time using second-hand equipment, and in 1998 smashed the world record with a high value for the key plasma-physics benchmark – the pressure ratio β.[17] Since the success of START, impressive achievements have been made with second-generation STs, with Globus-M in Russia, the National Spherical Torus Experiment at Princeton in the US, and in the UK with the Mega Amp Spherical Tokamak (MAST), which has been running since 1999.

The ST is topologically identical to the torus of the conventional tokamaks because the sphere has a hole running through it. The term spherical refers to the outer shape only.

Princeton Plasma Physics Laboratory reports that ST plasma configuration "may have several advantages, a major one being the ability to confine a higher plasma pressure for a given magnetic field strength. Since the amount of fusion power produced is proportional to the square of the plasma pressure, the use of spherically shaped plasmas could allow the development of smaller, more economical fusion reactors."[18]

In addition to a very high pressure ratio, STs also have the advantage of a very large bootstrap current compared with conventional tori. This suggests the possibility that sustained operations would be achieved more easily in an ST than in more conventional approaches. Despite these opportunities, it must be emphasised that STs are far less developed than conventional tori such as ITER, which remain the technology on track for the first commercial deployment of fusion.

4.2: Beyond tokamaks: the stellarator

Before the breakthrough that gave us the tokamak, there was one other candidate expected to achieve a sustained MCF plasma. This was known as the stellarator, and in the 1960s the US was a world leader in this area. In a stellarator, unlike in a tokamak, the field coils alone provide an induced helicity to the plasma. There is no transformer action with a sweeping driving current, so the machine operates in a steady-state mode, with plasma confinement arising solely from the geometry of the external magnetic field. Studies done in Japan and Europe have shown that stellarators achieve distinctly higher plasma densities than tokamaks and do not suffer from current-driven instabilities and plasma disruptions like the toka-

16 R Herman 1990.
17 www.pppl.gov/projects/pages/nstx.html.
18 See section 2.1.

mak. The confinement is observed to be similar to that of equal-sized tokamaks.

As figure 11 illustrates, the stellarator requires field coils of an extremely complex configuration. Despite the benefits provided by computer-aided design, stellarators remain difficult machines to manufacture. The most impressive attempt under way is in Greifswald, Germany, where the 30 m^3 Wendelstein 7-X stellarator is under development, with the first plasma operation scheduled for 2014.[19]

19 J-H Feist *et al.* 2007.

5: Why is fusion development so slow?

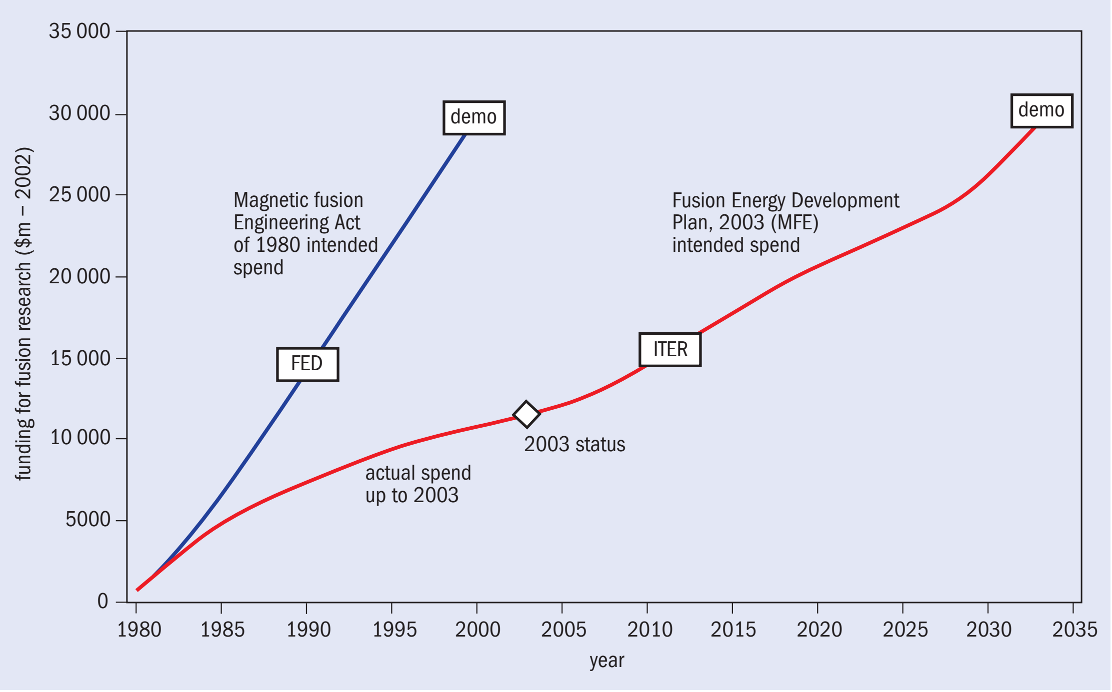


Figure 12: The goal of fusion energy recedes if research is under-supported. Source: DOE Princeton University Plasma Physics Laboratory.

In public policy terms, the greatest challenge facing fusion is the pervasive perception that fusion as a power source is an ever-receding goal. This view is not without foundation. On 18 April 1967, then UK minister of technology Tony Benn noted in his diary that Soviet nuclear scientist Lev Andreevich Artsimovich had said to him: "Well, 10 years ago we said it would take us 20 years to make fusion work and we still say that it will take 20 years to make fusion work, so we haven't altered our view in any way."[20] Such insights might lead us to the view that things have actually got worse, not better.

In the fusion research laboratories an alternative view is presented. It is argued that the crucial measure is not time but effort. If sufficient resources had been provided and sustained then some of the earlier promises would have been fulfilled.

A 1976 report from the US Energy Research and Development Administration presented a set of scenarios for the then future development of MCE. The costs presented (US dollars in 1976) range from about $15 bn to $20 bn[21] (£8.3 bn to £11.1 bn).[22] Researchers at Princeton Plasma Physics Laboratory have considered US support for fusion since 1980 (figure 12). If all had gone well, the original 1980 estimate of $30 bn (£12.9 bn)[23] might have been sufficient to achieve demonstration fusion by the year 2000. In fact, federal research funding was supplied at a far slower rate than originally anticipated in the Magnetic Fusion Engineering Act of 1980. As a consequence the prospect of a demonstration of commercial fusion power production receded to the year 2035. The simple message from the fusion research community is that if we work less than half as hard, it will take us more than twice as long. These voices assert that if fusion is to address pressing energy policy challenges, it will need resources that constitute a significant proportion of the energy budget. At present, Europe devotes less than 0.5% of its total energy spend to related R&D, and fusion research is merely a small part of that total. To make significant adjustments to Europe's energy system to address policy goals, much more R&D will be needed, not only in fusion but also in other areas.

5.1: A strategy for the 21st century

Scientific fusion research has had many successes, and it is often said that no fundamental scientific challenges remain, only engineering ones. Such statements can, however, give a false impression. While the fusion reaction is well understood, many physics questions remain, such as those regarding plasma-burn control and robust fusion materials.

Various "fast-track" approaches are being pushed by fusion laboratories to bring forward the time when fusion energy will be a viable option. Central to the fast track is a strong emphasis on materials testing. Originally ITER was, in part, intended to provide a source of fast neutrons for materials testing.[24] The necessary materials research would only start once ITER had demonstrated

20 T Benn 1996.
21 The 1976 ERDA report is most accessible as a reprint: S O Dean, Fusion power by magnetic confinement program plan *Journal of Fusion Energy* **17 4** 263–287.
22 Based on the 1976 12 month average exchange rate.
23 Based on the 1980 12 month average exchange rate.
24 V Barabash 2004.

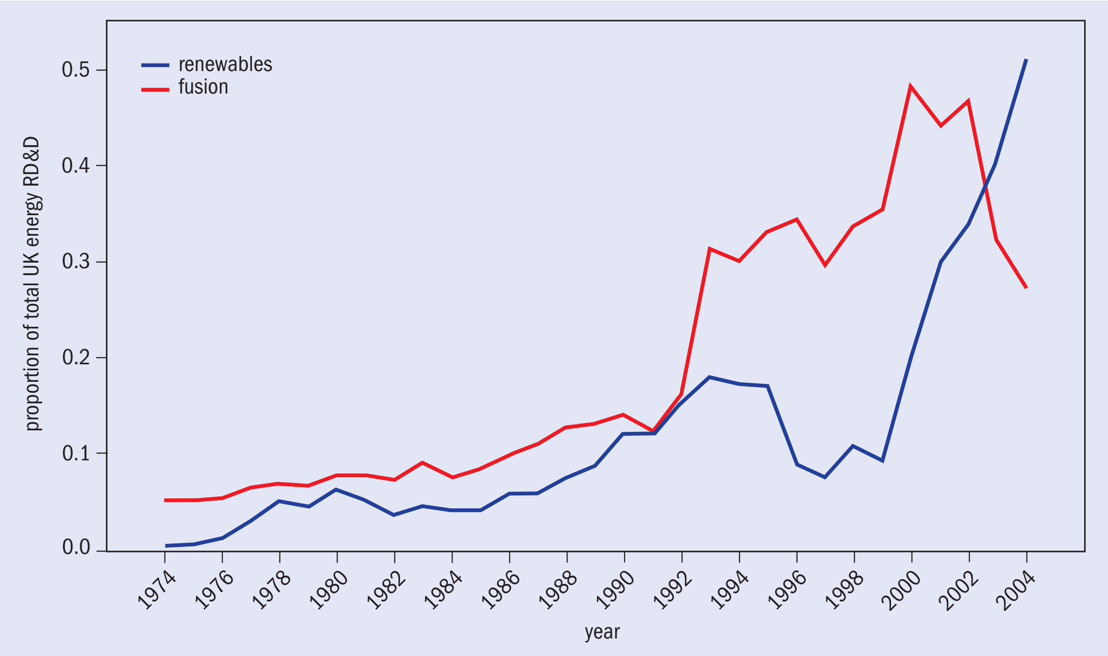


Figure 13: Proportion of UK public spending on fusion in comparison with renewables RD&D. Source: International Energy Agency (see www.iea.org/textbase/stats/rd.asp).

the fundamental fusion physics. Now, however, it is recognised that other experimental demands will mean that ITER will not deliver the sustained high neutron fluxes required. Furthermore, waiting until the scheduled start of ITER in 2018 would cause an unhelpful delay in materials research. As a consequence, the fast track includes the International Fusion Material Irradiation Facility (IFMIF), which was conceived in 1996. The Japanese are taking the lead on the engineering design of IFMIF in Rokkasho, but no site has been proposed in Japan, or elsewhere, for the facility. IFMIF would allow rapid progress on important materials-science research essential for fusion power stations, but at present the IFMIF facility is yet to be funded.

In addition to IFMIF, the fast track envisages only one step between the ITER experimental facility and a first commercial power station. That intermediate step is the Demonstration Power Plant (DEMO), which is intended to produce 250% of the heat of ITER – a thermal output consistent with the demands of an actual fusion power station. It is conventional to speak in terms of a single DEMO power station following the ITER research project, although it is probable that there would be several in different parts of the world such as in the US, Europe, Japan, and perhaps China or India. In some countries the DEMO stage is expected to be led by private corporations with public subsidy or other forms of initial support.

Conventionally it has been intended that DEMO should follow ITER and build on the research undertaken with that machine. Increasingly, however, individuals such as Chris Llewellyn Smith, director of the UK Atomic Energy Authority (UKAEA) Culham Division, have been advocating a prompt start to the construction of DEMO, in advance of completion of the ITER machine.

5.2: Historical, current and future costs

Fusion research is controversial in science and technology public-policy circles, not because of its technical merits or otherwise but because of its cost. For some it is the great white elephant of energy research budgets with ever more good public money being sent to follow investments gone bad. For others, the history of fusion is one of consistent underfunding punctuated by relatively short bursts of proper research support when oil prices peak.

Fusion research is “big science”, but for most countries it is big science with a purpose – commercial energy production. The fusion community’s ambition to yield a sustainable energy source for the late 21st century prompts one to consider the costs of fusion research against those of other proposed energy technologies.

At the EU level the bulk of research support for fusion is handled via the Framework Programmes. In the Seventh Framework Programme (2007–2013), EURATOM has a budget of approximately €2.7 bn, whereas European co-operation in (non-nuclear) energy matters receives €2.35 bn.[25] Of the EURATOM budget, roughly 85% is for fusion research.[26] In these terms fusion can appear to be expensive, taking the lion’s share of the pie. The pie, however, is not static. For instance, the EU budget for energy and transport networks has risen by 92.5% between 2007 and 2008.[27] It seems probable, as has occurred before, that as public-policy concern for energy rises, fusion budgets will recede in relative importance while growing in absolute terms.

It is also important to stress that most fusion research occurs at an international (e.g. European or global) scale. As such, the costs specified for this kind of research can appear to be very large when compared with more conventional national research programmes in energy.

25 Council of the European Union press release, 16887/06 (Presse 366), www.consilium.europa.eu/ueDocs/cms_Data/docs/pressData/en/misc/92236.pdf.
26 Note that the EC also supports the Joint Research Centre, much of which relates to non-nuclear energy.
27 EU Budget 2008 flier. Available at http://ec.europa.eu/budget/library/publications/budget_in_fig/dep_eu_budg_2008_en.pdf.

Looking at energy research spending in the UK allows a cross-comparison of fusion research support with renewables (figure 13). Broadly, the funding levels are similar, with fusion having secured greater support during the 1990s when energy was inexpensive globally. Now that energy prices have started to rise significantly and climate change becomes a more pressing concern, support for renewables research is rising fast, outstripping that available to fusion.

Tokamak research involves co-operation and negotiation between some of the world's leading high-technology economies. Fusion research includes activity at the Universidad Nacional Autónoma de México and at the University of Malaya in Kuala Lumpur, Malaysia. China has shown an impressive ability to develop its fusion research capacity, starting with the use of donated second-hand fusion experiments such as the German Asdex and the Russian T7 tokamaks. China currently has a world-leading position with its impressive and operational mega-ampere superconducting tokamak EAST, formerly known as HT-7U, which started its experimental programme in September 2006.

Another country rapidly accelerating its fusion research base is South Korea. In September 2007, South Korea finished construction of a new experimental tokamak known as KSTAR. This machine will be the first in the world to make use of advanced superconducting magnet technology based on niobium-3-tin (Nb_3Sn) conductors. Similar technology is planned for ITER. The KSTAR team encountered and successfully overcame some difficulties testing the large superconducting toroidal field coils.[28] Such technical difficulties are to be expected in any large, complex, high-technology project. Lessons learned from smaller machines, such as KSTAR, can help to minimise the technical risks to be faced by ITER, but they cannot be eliminated entirely.

5.3: Commercial fusion before fusion electricity: faster than fast track?

While most fusion research is dedicated to electricity generation through the orthodox approaches described here, there is also a separate fusion research community that addresses the issue of nuclear weapons reliability. However, these two relatively well funded communities are not the entirety of energy-related fusion research, and occasionally radical ideas emerge from outside these large fusion laboratories. Frequently these external proposals seek to make use of fusion energy on timescales that are even shorter than the fast track of MCE. Most of these ideas focus on a direct use of the heat of fast neutrons produced by tokamak fusion, rather than using it to make electricity.

There are also some, such as Wallace Manheimer of the US Naval Research Laboratory, who seek to link fusion to fission-based nuclear power. Manheimer has advocated the construction of fission–fusion hybrids, in which fast neutrons released through fusion prompt fission reactions in the blanket for boosted energy production. This technique might be used to produce fissile uranium-233 fuels for conventional fission reactors from abundant thorium;[29] or fusion's fast neutrons might be used to transmute existing fission wastes into more benign and shorter-lived isotopes.

Leslie Bromberg and colleagues at the Plasma Science and Fusion Center at MIT are interested in the role of an MCF facility as a fuel source for a fleet of relatively conventional fission power stations. Such a fusion facility would not produce commercial electricity, hydrogen or process heat; it would instead produce nuclear fuel for fission power stations. In the future, the commercialisation of fusion might involve much more than simply the sale of clean electricity.

Researchers from General Atomics in San Diego have long suggested that fusion-process heat might be used to produce hydrogen via high-temperature catalytic chemistry. This could be a highly efficient route to hydrogen production that does not involve electricity production or electrolysis. One possible supply-chain for hydrogen would make use of liquid tanker shipments rather than gas-pipeline networks. In collaboration with Richard Clarke of Culham Science Centre and Bartek Glowacki of the Department of Materials Science and Metallurgy at the University of Cambridge, the author of this report has proposed that a fusion reactor for liquid-hydrogen production might make use of that same liquid-hydrogen product to cool the magnets of the fusion device. This approach seeks to free fusion reactors from the cost of large amounts of helium as a consumable for the cryogenics system. The idea is known as Fusion Island.

28 K Kim *et al.* 2005.
29 The subject of current research at MIT.

6: Fusion – another way?

6.1: Inertial confinement fusion energy

While the major current approaches to fusion are all MCF based, ICF could also present opportunities for fusion energy.

In a thermonuclear weapon, fusion materials are compressed using radiation emitted by a first-stage fission reaction. In ICF, similar but much smaller pulsed compression is employed on a (relatively) tiny fuel pellet. Inevitably, therefore, ICE would produce pulsed power. In a potential power station this would involve releasing energy in a series of millions of tiny controlled explosions, not unlike the millions of explosions that occur in an internal combustion car engine. Such an ICE power station might pulse at around five times a second. The major approach to ICF uses very-high-intensity converging laser beams to compress and heat a millimetre-sized fusion fuel pellet. Significant experimental facilities, dedicated partly to assessing nuclear weapons reliability, are under construction in the US and France. These are also likely to advance progress towards commercial ICF energy production. It is expected that the US Department of Energy installation will demonstrate ignition in around 2020. Even with such developments it remains probable that MCF will be the quicker route to commercial usable fusion energy.

In September 2007, EU scientists recommended support for a British-led High Power Laser Energy Research Facility (HiPER). This completely civilian enterprise will build on military advances in ICF from the US and elsewhere. A £500 m research programme is expected for HiPER over seven years.

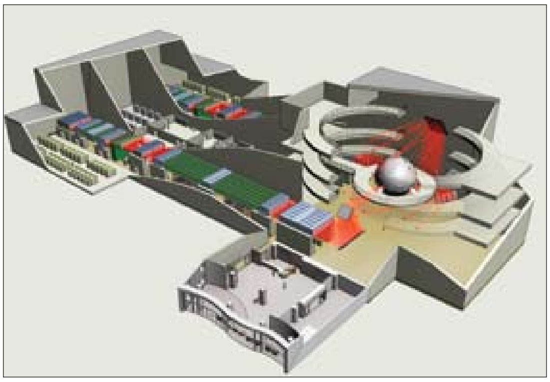


Figure 14: Early representation of the EU's HiPER. Source: HiPER (see www.hiper-laser.org).

6.2: Plasma pinch

Another possibility, taking ideas from both MCF and ICF, is the plasma pinch. The most developed concept is the Z-pinch, which achieves fusion in a similar way to ICF. A fuel pellet of cryogenically frozen deuterium and tritium is compressed by a uniform radiation pressure, which is achieved by rapidly creating, vaporising and pinching a plasma of ionised metal atoms rather than by the direct use of laser beams.

The heavy ionised metal plasma arises from the passage of an enormous current through a small high-precision wire cage known as a hohlraum. When the pinched metal ions collide at high energy, X-rays are produced that should in principle be sufficient to compress a pellet of fuel into a fusing plasma. If Z-pinch machines could be developed for electricity production, they would have the following advantages over conventional ICE systems: the pulse rate would be more manageable at once every 10 seconds rather than several times a second; the energy production process would be more efficient; and the energy produced per pulse would be larger. The drawbacks compared with more conventional ICE approaches would be that each fuel pellet assembly would be a more complex manufactured item and that the hohlraum in Z-pinch would be far larger than its ICE equivalent. Lastly, it is important to stress that Z-pinch for energy production is farther from commercialisation than conventional ICE and hence much further from commercialisation than MCE approaches based on ITER.

6.3: Cold fusion?

In 1989 two electrochemists, Stanley Pons and Martin Fleischmann, observed unusual phenomena that, they reported, suggested fusion in a simple table-top apparatus. Some researchers, including Peter Hagelstein of MIT, continue to search for fundamental new physics in such experiments. If cold fusion releases energy, as Hagelstein and others continue to report, then it does so without the production of large numbers of high-energy neutrons or other emitted reaction products. That would mean that the physics involved must differ fundamentally from that observed in a conventional "hot fusion" process. Any cold fusion reaction would involve the emitted nuclear energy coupling directly with the atomic lattice of the electrodes in the table-top cell: such speculative new physics has been termed condensed-matter nuclear science. The orthodox view of cold fusion is that such phenomena do not exist. In response the proponents continue to suggest that such phenomena are merely difficult to generate.

7: Six challenges for fusion

7.1: Planned availability

Large capital costs with a small marginal cost of electricity-generation force fusion power towards base-load supply. D Ladra and co-workers have reported: "to be competitive, fusion power stations should have high availability, preferably exceeding 80%, with very few unplanned shutdowns".[30] The 80% target, now routinely achieved by fission technology, will be a stretch for any planned fusion power station.

The requirement for continuous power at high availability is particularly demanding for the tokamak's essentially pulsed output, albeit possibly operating in very-long-pulse mode. Although researchers suggest that plasma motion and stability can be maintained for many hours after the initiating voltage sweep, there is a significant availability difference between long-pulse operations and a truly continuous operation. Much consideration has been given to the challenge of continuous operation.[31] In extremis, multiple tokamaks in a single power station would be a possibility. For instance, two pulsed tokamaks operating out of phase with each other might raise steam to drive a single turbogenerator set for continuous electricity production.

7.2: Reliability

An even greater challenge than availability is the need to achieve very high levels of reliability. That is, unscheduled and unanticipated interruptions to power generation must be avoided. A fusion-based electricity company in a modern competitive electricity market will need to enter into long-term bilateral contracts with electricity suppliers to provide the necessary business stability.

A rule of thumb for plasma stability in tokamaks is: the bigger the machine, the better. Also, the engineering of a fusion power station is likely to face significant economies of scale, further favouring large machines of at least 1.5 GW electrical output. If such a machine were to be forced to shut down unexpectedly then there would be significant penalties in the electricity market. In addition, intervention would be required to ensure the supply-demand balance. This represents a potential pressure on the system operator (i.e. the National Grid in the UK). If a power station were to fail during a high-demand period, even if the cause of the problem was minor, the station might not be able to restart because the system operator would not be able to spare the large amounts of power required to restart the fusion process. This issue is relatively easy to address, with on-site generation and/or energy storage such as flywheels, which can already deliver many hundreds of megawatts on JET. Such items would provide the restart power but would represent a significant capital cost for the MCE power station and in a conventional concept would only be used intermittently.

7.3: Structural integrity

As a consequence of its basis as a transformer driven by a single sweep of the primary, a tokamak is inherently a pulsed device. A power station will operate with very long pulses, but during its life it will still be subject to many tens of thousands of pulses. Given the very large magnetic fields associated with plasma confinement and drive, each pulse will place significant magnetic stresses on the structure of the power station. The station must withstand repeated cycling of these structural loads.

Much of a station's structure, such as the blanket, will be at high temperatures at which conventional steels cease to have good tensile properties, and this will make the structural strength of the machine an even greater challenge.

Lastly, some of the structural components could be exposed to significant neutron fluxes. Each fast neutron impact can cause microstructural defects in engineering materials.

A tokamak power station is a major structural engineering challenge, in terms not of whether it can be built, but of whether it can survive years of reliable operation.

7.4: Helium supply

While the fuels for fusion power are abundant and easily obtained, this does not mean that a fusion power station would be free from energy security risks. Central to such risks must be the long-term availability of affordable helium used for tokamak pumping, purging and, above all, cooling superconducting magnets. While helium could in principle be obtained from the atmosphere at great cost, and while it is also possible that economically viable helium gas wells could be developed, the reality today is that all commercial helium is obtained as a by-product of the natural-gas industry. That industry is expanding and, as it moves towards liquefied production and supply, the economics of helium production are favoured. While it is likely that abundant helium will be available in the short term, the natural-gas industry is a fundamentally unsustainable process of resource depletion. These issues are considered by a joint UKAEA, Linde-BOC and University of Cambridge research project considering global helium resources.[32] Helium availability and cost are potentially serious issues for the large-scale deployment of fusion energy systems. A move to liquid hydrogen for superconductiv-

30 D Ladra *et al.* 2001.
31 H S Bosch *et al.* 1996.
32 Z Cai *et al.* 2007.

ity would eliminate the jeopardy, possibly extant, in an over-reliance on helium.

7.5: High-temperature plasma-facing materials – the divertor

Components directly facing the very hot fusion plasma include the first wall of the blanket on the outer edge of the torus and the divertor, which is usually placed round the bottom of the torus. In all MCF the plasma must at some point touch the vacuum vessel. This could be using a device dedicated to that purpose (a limiter), but more conventionally that role is played by the divertor. As a result of contact with the vacuum vessel, the tiles of the divertor will glow white hot. It is expected that these tiles will need frequent replacement and, given that the tokamak vessel will be a highly radioactive environment, this will need to be done robotically. At JET, much effort has gone into such remote handling. Nevertheless, divertor component reliability and replacement represent key challenges for a fusion power station.

7.6: Problematic materials

It is often rightly stressed that, if properly developed, a fusion power programme need not lead to a legacy of long-lived radioactive waste. The waste of the fusion process is harmless helium gas in small quantities. The main issue of concern for waste is the radioactivation of the tokamak. It is possible to manufacture the device from materials known only to activate into short-lived radioisotopes. As such we can be confident that a fusion power station would leave a negligible radioactive legacy 100 years after shutdown.

A more controversial matter is whether fusion energy would represent a proliferation hazard. There is agreement on the benefits of fusion making no use of fissile isotopes such as uranium-235 or plutonium-239, which are required for fission weapons, but beyond that opinion is divided. The remaining issues fall into two broad classes: tritium and fast neutrons.

7.6.1: Tritium

Tritium is an intensely radioactive gas with a half-life of 12.3 years, and it is an essential fuel for a fusion power station. Despite its radioactive hazards it has numerous conventional industrial applications. It is also a material of interest to the nuclear weapons community, particularly in the context of boosted fission weapons.[33]

Even in a scenario of nuclear weapons proliferation it is possible that tritium might remain as a material of only modest concern because the spread of thermonuclear fusion-boosted weapons might be prevented purely via the prevention of the spread of basic nuclear weapons technology. Such long-standing proliferation prevention methods rely on safeguards against the spread of special nuclear materials – essentially plutonium and highly enriched uranium.[34] Without such materials, fission weapons and boosted fission weapons cannot exist.

At present, tritium is not a material controlled by strong international safeguards. It has numerous industrial applications and is difficult to inventory because it tends to be absorbed into metals and other structures. If nuclear proliferation grows as an international concern then it seems likely that tritium controls would increase in the coming years, possibly affecting the fusion research community in all countries.

7.6.2: Fast neutrons

Deuterium-tritium fusion is a source of high-energy neutrons. Some assert that these represent a proliferation risk because they can convert mundane materials (benign fertile actinide elements), such as thorium and depleted uranium (neither of which are subject to any controls and both of which are difficult to detect), into the special nuclear materials (fissile isotopes) of proliferation concern. Such a breeder capacity would require special engineering of the tokamak, including additional cooling, shielding and a reprocessing capability. It would not be possible to establish such infrastructures at a station that was subject to rigorous international inspections. The additional equipment required, and the fissile materials produced, would be easily detected and current International Atomic Energy Agency (IAEA) safeguards should be sufficient to prevent illicit production of any fissile materials at a fusion facility. It is important to stress that there are much easier ways for proliferators to seek to make fissile isotopes than via the misuse of a future fusion facility. Nevertheless, as a source of high-energy fast neutrons, fusion energy applications will surely need to be monitored.

33 Federation of American Scientists *Special Weapons Primer Tritium Production*, see www.fas.org/nuke/intro/nuke/tritium.htm.
34 After the first Gulf War in the early 1990s, the IAEA Safeguards were extended to include fuel-cycle research and specified manufacturing activities, such as heavy-water manufacture, see www.hse.gov.uk/nuclear/safeguards/what.htm.

8: Conclusions

In the last 10 years the pace of development for fusion as an energy source has noticeably quickened. ITER has been agreed, the fast track has been accepted, and energy and climate sustainability have moved to centre stage. As a consequence, the fusion community is starting to look forward collectively to the day that fusion energy becomes a commercial reality. The best years for fusion physics are still to come.

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Fusion as an Energy Source: Challenges and Opportunities

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