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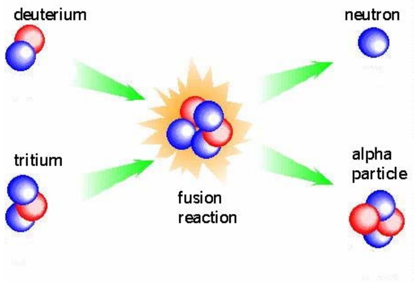
NUCLEAR FUSION

There is growing interest in using nuclear fusion for generating electricity in the future. The fuel it would use is abundant and it produces no greenhouse gases. International negotiations are under way to construct the next major experimental fusion reactor (ITER) and the US has recently decided to re-enter these discussions. Questions remain over issues such as the economic viability and environmental impact of fusion power and the timescales for its commercialisation. This note discusses such issues and updates POST's previous briefings on fusion research[1].

What is fusion?

Fusion occurs when light atomic nuclei are forced close enough together that they combine to form heavier nuclei, releasing energy in the process. This process powers the sun and stars. Fusion is essentially the reverse of fission, where heavy nuclei break into lighter fragments - the principle behind today's nuclear power plants. The easiest fusion reaction to recreate in the laboratory is that of deuterium (D) and tritium (T), which are heavy forms of hydrogen. This produces an alpha particle and a neutron, as shown below. The fusion of one kilogram of D-T fuel releases thousands of times more energy than burning one kilogram of coal and has no associated greenhouse gas emissions. The fuel supply is abundant - deuterium occurs naturally in seawater and tritium could be 'bred' within a fusion reactor, from lithium, which is also naturally abundant.



Sustaining fusion under laboratory conditions presents many technological challenges. For D-T fusion to occur, the fuel must be heated to ~100 million °C. At such temperatures it is in the form of a gaseous plasma of nuclei and electrons. This hot plasma must be confined to avoid damaging its containment vessel. Currently the most advanced confinement technique is *magnetic confinement*, where magnetic fields suspend the plasma within a large containment vessel. The most common apparatus is the **tokamak** - a doughnut (torus) shaped magnetic chamber.

Large amounts of energy are needed to maintain the high temperatures required for fusion[2]. However, if the energy generated from fusion were to exceed the amount put in, there would be a net energy output. The ultimate aim of fusion research is to harness this energy to meet future energy demands. To gauge the performance of fusion experiments, three conditions can be defined: breakeven, 'burning' plasma and ignition (see box above). Of these, only breakeven has been demonstrated to date.

Milestones in fusion research

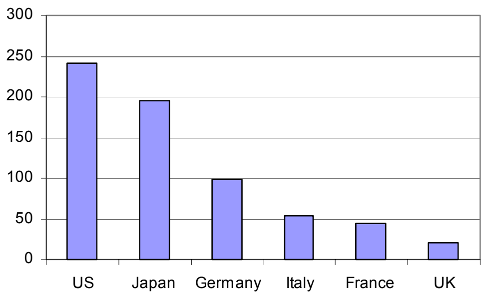
- **Breakeven**: when the total output power equals the total input power. The ratio of these two quantities is known as 'Q'. Breakeven was demonstrated at the JET experiment in the UK in 1997.
- **Ignition** (yet to be demonstrated): when the plasma generates so much energy that no input power is required (i.e. when Q is very large).
- **'Burning' Plasma** (yet to be demonstrated): an intermediate stage where the plasma mainly heats itself, as a result of alpha particles from the fusion reaction colliding with other nuclei, rather than being predominantly heated externally. 'Burning' plasma is achieved when Q exceeds 5.

According to current thinking any future commercial fusion reactors would need to achieve a 'burning' plasma with Q of at least 30 but would not need to achieve ignition. In a reactor using D-T fuel, energy would be extracted from the plasma by capturing neutrons from the fusion reaction and using their heat to generate electricity by conventional means such as steam turbines. The neutrons would be captured by a 'blanket' lining the walls of the containment vessel, made of a suitable material (see page 3).

Fusion research in the UK
This is centred at the UK Atomic Energy Authority (UKAEA) research facility at Culham in Oxfordshire, which is host to the JET (Joint European Torus) experiment and also to three other experimental tokamaks. Following a fusion policy review in 2000-2001, UK fusion research is now administered by the Engineering and Physical Sciences Research Council rather than by the DTI Nuclear Industries Directorate. Recently the UK government has shown renewed interest in the development of commercial fusion reactors and is promoting a 'fast track' approach to fusion (see below).

UK public funding of fusion research consists of ~£14M (million) p.a. domestic expenditure and ~£23.5M p.a. contribution to the EU fusion programme. It is difficult to make accurate comparisons of expenditure on different forms of energy R&D, because of difficulties in standardising how the figures are calculated. Nevertheless, a recent government report indicates that in 2000-2001, ~£10M was spent on renewable energy R&D, compared with ~£14M domestic expenditure on fusion[3]. The graph below shows that UK fusion funding is still lower than in many countries.

2001 Domestic fusion R&D budgets (in millions of $US)



Source: International Energy Agency; UKAEA

Overview of fusion research
Significant progress has been made since fusion research began in the 1950s. The UK has its own research programme (see box above) but international collaboration plays a key role. The main focus of international research is the tokamak design. The fusion community envisages that a series of experimental devices (see box opposite), each with a higher power output, will lead ultimately to commercial electricity production. They are:

- JET, the largest existing tokamak facility, located at Culham in Oxfordshire.
- ITER, the next major experimental tokamak. Decisions are currently being made on where it will be located.
- DEMO, a demonstration/prototype fusion power plant, for which no formal collaboration yet exists.

Timescales
Both ITER and DEMO would take ~10 years to build and would run for ~20 years. Facilities would also be needed to test possible structural materials (see page 3). Fusion researchers originally envisaged that a separate prototype power plant would be needed after DEMO. However, a group of experts convened by the EU Council of Ministers and chaired by the UK Government's Chief Scientific Adviser recently argued that this stage could be omitted. They proposed that commercial reactors could follow on directly from DEMO, if materials testing for future plants were carried out in parallel with ITER rather than after. This 'fast-track' approach is intended to reduce the timescale over which commercial reactors could be realised (see page 4). According to the expert group, the fast-track approach would need additional funding in the short term but could save costs in the long term by omitting one generation of device.

Experimental Fusion Devices
JET (Joint European Torus) is a tokamak with a radius of 3m (metres). It has been operated by the UKAEA since an original 'joint undertaking' between the EU, Sweden and Switzerland ended in 1999. JET achieved the world's first controlled release of fusion energy in 1991 and approached breakeven in 1997. JET's physical size limits any further increases in power output. Its operation has been extended until 2004 to carry out tests in preparation for ITER.

ITER (International Thermonuclear Experimental Reactor) is yet to be built. It has a proposed radius of 6m and is intended to be the first demonstration of a 'burning' plasma, which should mainly heat itself rather than require external heating (see page 1). When ITER was first proposed in 1985 as a collaboration between the USSR, US, Japan and the EU, it was to have a radius of 8m and was intended to achieve ignition. However, the US withdrew in 1999 and the design was scaled down to its current form. Current estimated costs are €5-6 billion, roughly half the original costs. The US recently announced that it would be rejoining ITER (see below).

Scientific and technical objectives of ITER
ITER is intended to further understanding of many aspects of plasma behaviour, particularly issues such as plasma stability, which are of key importance to the feasibility of any future commercial fusion reactors. It will test technologies for future reactors, such as superconducting magnets and remote handling of radioactive components. Specific technologies for DEMO will also be tested such as the 'blanket' surrounding the containment vessel, which will be used to extract heat and generate tritium fuel required for the fusion reaction.

ITER negotiations and schedule
The design phase of ITER is now complete. Negotiations are taking place to establish ITER as a legal entity and to decide on issues such as how costs will be shared and where ITER will be located. There are four candidate sites: Japan, France, Spain and Canada. Site inspections have begun and a decision is expected by Autumn 2003.

On 30 January 2003, the US announced its decision to rejoin ITER negotiations. The US contribution towards ITER's construction costs is expected to be around 10% - the minimum required for full ITER participation. China has also recently applied to join the collaboration. Note that it may not be straightforward for a party to withdraw from ITER once the international agreement has been ratified. The precise terms are not yet finalised, but it is likely that parties may be required to commit for several years before they can withdraw and that the host party will not have the option of withdrawal.

DEMO (demonstration/prototype power plant)
No formal collaboration yet exists for DEMO, but conceptual designs for fusion power plants are being developed in the US and the EU. Results from experiments at Culham indicate that spherical tokamaks may have advantages over conventional ('doughnut-shaped') tokamaks like JET and ITER.

Developments in materials research

Many structural materials in a fusion reactor, particularly those facing the plasma, would be exposed to extreme conditions such as high temperatures and intense neutron bombardment. This could lead to mechanical degradation or to *activation*, where impurities in materials become radioactive due to neutron exposure. Materials could also be contaminated by radioactive tritium. They would therefore have to meet several criteria:

- During operation, they should ensure minimal exposure of workers and the general public to radiation.
- When removed from the reactor, they would constitute radioactive waste. They would therefore have to be chosen to minimise both the volume and total radioactivity of waste generated.

It is hard to satisfy these criteria simultaneously and there is no 'ideal' material. Research is currently underway to develop 'low activation' materials with optimised response to neutron bombardment. There are three main candidates, none of which is yet ready for use in a power plant - these are vanadium alloys, silicon carbide (SiC) and certain types of steel. Of these, steel is the closest to application, and SiC the furthest.

Materials testing facilities

There is wide consensus that if commercial fusion is ever to be realised, development of suitable structural materials is essential and will require a dedicated testing facility, although some materials testing can be carried out at ITER. An outline design exists for an International Fusion Materials Irradiation Facility, costing ~€600 million, for testing the behaviour of small quantities of candidate materials. No collaborators have yet offered to host it, but plans are expected to accelerate once the site has been chosen for ITER. Some researchers have suggested that a further facility, capable of testing whole components, will be needed before DEMO comes into operation. However, there are no formal plans for this yet.

Issues

The practicability of any future fusion plants will depend on their safety, environmental impact and economic viability. EU working groups, on Safety and Environmental Aspects of Fusion Power (SEAFP)[4] and Socio-Economic Research on Fusion (SERF)[5], have looked at these issues. However, there are inevitably many uncertainties in their predictions, as the studies rely on a range of assumptions about future power plant designs and future structural materials.

Safety and environmental issues

Safety

Fusion is inherently safer than fission because there is no risk of an uncontrolled chain reaction, as can occur in the core of today's fission reactors if safety mechanisms fail. At any given time, there would be enough fuel in the reactor vessel to keep the plasma burning only for a few minutes, since fuel is constantly injected. The SEAFP study showed that during normal running, the amount of radioactive material released into the environment would be less than 1/1000 of the natural background radiation. However, a serious incident could result in release of part of the plant's radioactive material, principally tritium[6], into the environment. The study concluded that an accident due to an internal event (e.g. loss of coolant) could result in a maximum dose to a member of the public of a few millisievert (mSv) - roughly equivalent to the annual natural background radiation dose and below the recommended evacuation threshold of 50 mSv.
The consequences of an external event (e.g. sabotage, earthquakes) may be more significant but have not been studied in detail. Preliminary studies show that in a worst-case scenario, the maximum dose to a member of the public in a small area close to the plant, could be ~400 mSv – eight times the recommended evacuation threshold. Although the SEAFP study pointed out that people within this area would be at a greater threat from the event itself than from associated radiation, there are no detailed estimates of doses outside this area. Some analysts[7] believe that evacuation over a few square kilometres might be necessary in this eventuality.

Radioactive waste

Fusion reactors would give rise to radioactive waste, largely through structural materials becoming 'activated' (see box on left) or contaminated with radioactive tritium. These materials would constitute waste when removed from the reactor (at the end of the component or the plant's lifetime). The type and amount of waste will affect both the economic viability and public acceptance of future plants. Current studies indicate that if suitable materials were developed, the radioactivity of waste from a fusion reactor would decay faster than waste from today's fission reactors. It would therefore be less hazardous, in the long term. However, the total volume of waste from fusion would be comparable with fission, and a fraction of it could require long term management. The nature and volume of this waste would depend on the materials used, the reactor design and the waste management strategy. Fusion programmes propose two main methods of minimising the amount of waste requiring long term management:

- Recycling some radioactive waste within the nuclear industry. Material might need treatment before re-use, which could give rise to further waste streams. There is no guarantee that recycling would be economic – this would depend on unknown factors such as the cost of waste disposal, the cost of new raw materials and how long the material would have to be stored before it decayed to acceptable levels of radioactivity (see below) - this could be several decades.
- 'Clearance' of some radioactive waste, i.e. freeing it from regulatory control. Cleared materials would be disposed of as non-radioactive waste, or recycled outside the nuclear industry ('free release'). These activities already take place with waste from fission reactors, but to a limited extent. Free release of radioactive material is a controversial issue. Environmental groups say that even if doses from individual products are trivial, the combined exposure could be significant and hard to monitor. However, proponents argue that clearance limits could be set such that the combined exposure was not significant, thereby avoiding the need to monitor. Controversy remains over what constitutes a 'significant' radiation dose.

The radioactivity of any waste would have to fall below established threshold levels before these options were possible. However, regulations vary significantly between countries. For example, in the UK, the threshold below which radioactive material can be freed from regulatory control is currently more stringent than that recommended by the European Commission.

Nuclear weapons proliferation

Fusion reactors pose less of a proliferation threat than fission reactors, which handle large quantities of fissile materials (uranium or plutonium) that can be used to fabricate nuclear weapons. Although fusion reactors could be modified to generate such materials, this design option is not currently being pursued. Clandestine activities would be hard to conceal, since modifications would be easy to detect. In principle tritium from fusion reactors could be used to make advanced nuclear weapons, but only within the framework of an advanced nuclear weapons programme. It would therefore be of limited use to 'rogue' states or sub-state terrorist groups.

Economic issues

Economic viability of fusion power

The economic viability of fusion power will hinge on whether it can compete with other potential future energy sources. This is hard to predict, as many unknowns are involved, e.g. future technological advances, market structures and regulation. Estimates of the direct cost of fusion electricity are also highly sensitive to plant availability - the amount of time a plant is shut for maintenance or component replacement. The direct cost of fusion electricity, estimated by the SERF study, may be at the high end of the estimated range for other technologies such as fission, fossil fuels and renewables, largely due to the high capital investment costs for fusion plants. Some analysts say fusion power would be of limited use to developing countries because it would involve high capital costs as well as an advanced infrastructure and skills base.

The cost of fusion research

It is hard to estimate the total cost of commercialising fusion power. The EU alone invests ~€200 million p.a. in fusion research and development (R&D)[8] and several decades of further R&D may be needed before commercial fusion reactors become available (see below). There is some controversy over the funding of fusion research – some critics say this money would be better invested in other forms of energy R&D, while proponents say the long term benefits of fusion power justify the investment.

Timescale for development of commercial reactors.

Given a 'fast-track' approach, current estimates are that the earliest demonstration of electricity from fusion could take place at DEMO in 30 years' time. Thus, should fusion ever prove to be commercially viable, construction of the first commercial reactors could begin ~40 years from now, according to fusion researchers. However, this will depend on many factors. For example, if the design of a fusion power plant differs significantly from ITER, an intermediate experimental facility may still be needed between ITER and DEMO. It is also possible that new scientific phenomena may be observed at ITER which need to be understood before commercial fusion power can become a reality. Importantly, since fusion research relies on international collaboration, timescales depend on the smooth running of political negotiations and on how well international activities are co-ordinated. Finally, if fusion reactors were to come into operation, it could still be decades before fusion captured a significant share of the energy market.

The UK and ITER

The UK will play a leading role in ITER by contributing expertise acquired as a result of hosting JET. There are some concerns that it will be difficult to maintain a skills base in the period between the end of JET in 2004 and the start of ITER 10-15 years later. There are also concerns that EU staff may be deterred from working on ITER if it is built outside the EU. It is not yet known whether UK fusion funding will increase once construction of ITER begins.

Overview

- ITER is the next major step in international fusion research. Decisions are currently being made on where it should be built.
- Fusion researchers say the earliest demonstration of electricity from fusion could take place in 30 year's time at a demonstration reactor. Any commercial fusion reactors would not be available before 2050.
- Key advantages of fusion power would be an abundant fuel supply and the absence of greenhouse gas emissions. Disadvantages include potentially large volumes of radioactive waste and high capital investment costs. Development of suitable materials is essential if commercial fusion is ever to be realised.

Endnotes

1 See postnotes 120 and 40 for more background information.
2 For example, demonstrations of fusion power at JET use typical heating powers of ~20 MW, sustained for several seconds.
3 Department of Trade and Industry*, Report of the Chief Scientific Adviser's Energy Research Review Group*, February 2002.
4 Cook et al. "Safety and Environmental Impact of Fusion", *European Fusion Development Agreement (EFDA) Report*, 2001 .
5 Information by the EFDA leader, "Socio-economic aspects of fusion power" , *EFDA Report*, 2001.
6 Tritium can form tritium oxide, which poses a health hazard if absorbed by the human body.
7 A.M. Bradshaw, "Answers to selected fusion questions", Bundestag Committee on Education, Research and Technology Assessment, 2001.
8 Compared to ~€ 250 million investment in non-nuclear energy R&D. Figures taken from the EU Framework V programme 1998-2002.

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