# NUCLEAR FUSION UPDATE

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Postnote 40 (1993) examined international progress towards power from nuclear fusion and its future prospects. Recent years have seen technical developments but also continued debate and uncertainty over whether fusion will ever be economic as an energy source.

***This briefing describes recent developments in this area, looks at how the prospects for future energy supply from fusion have changed and examines the issues that arise.***

## BACKGROUND

Technical aspects of using nuclear fusion as a means of generating energy were given in POSTnote 40 (see **Box 1** for a summary). Research in this area has progressed through international collaboration for many years because the problems posed by harnessing fusion are too great to be addressed by individual countries. The UK is involved in fusion research through its own programme at Culham and as host to the European Atomic Energy Community's (EURATOM) Joint European Torus (JET), an experiment also sited at the UK Atomic Energy Authority (UKAEA) in Oxfordshire. JET's principal objectives were to:

- enable the essential requirements of a tokamak (Box 1) reactor to be defined by creating and studying plasma in near-reactor conditions.
- pioneer key technologies that will be essential for fusion reactors (e.g. the use of tritium as a fuel and remote handling techniques).

JET has been scientifically successful and has accomplished these goals in recent years but funding ends in 1999 and the key question facing international collaborators is what happens next. After negotiations in the 1980s, the big four fusion collaborators (USSR, US, EU and Japan) agreed to design and build a bigger experimental fusion reactor known as ITER (International Thermonuclear Experimental Reactor) under the auspices of the International Atomic Energy Agency (IAEA). This was seen as the middle phase in a three-step programme leading to the first experimental fusion power station (DEMO) in 2025-2050 (**Figure 1**). ITER was originally intended to allow detailed study of ignited plasmas (Box 1) and to develop technology (materials for the inner walls, fuelling requirements, tritium 'breeding', etc.) to build a fusion power station. As discussed below, the recent effective withdrawal of the US from the project, along with concerns over costs, have led to a re-evaluation of the ITER design.

### BOX 1 TECHNICAL ASPECTS OF NUCLEAR FUSION

**Harnessing Fusion for Energy**

**Nuclear fusion** occurs when atomic nuclei are forced sufficiently close together that they fuse to form the nuclei of new elements, releasing energy in the process. The sun is powered by nuclear fusion (its huge mass compresses hydrogen nuclei together at its centre where they fuse and irradiate energy), but the process is too slow to form the basis of a commercial reactor. In an H-bomb explosion, an atomic (fission) bomb initiates a fusion reaction in surrounding material (see POSTnote 35) and energy is instantly and uncontrollably released. The goal of fusion research is to achieve a happy medium between these two extremes and to devise a way of producing controllable fusion reactions to generate electricity.

**Fusion Reactors**

To create useable fusion on earth, two isotopes of hydrogen are used - **deuterium** (D, naturally present in seawater) and **tritium** (T, which does not occur naturally but which can be 'bred' in a fusion reactor). This D-T fusion fuel can be used to induce nuclear fusion in the laboratory if it is heated to very high temperatures (100 million ˚C - hotter than in the sun). At these temperatures, the D-T gases break down into a **plasma** - a jumble of atomic nuclei and electrons. These plasmas can melt all known materials and must thus be suspended away from the walls of a **containment vessel** by precisely-designed **magnetic fields**. The commonest design is the **tokamak**, which uses a torus chamber (shaped like a ring-doughnut). In a D-T fusion reactor, energy is released in the form of energetic helium nuclei (which remain within the torus and help maintain plasma temperature) and neutrons (which are ejected from the plasma). These neutrons carry most (80%) of the fusion energy and would be captured in a commercial reactor in an **outer (toroidal) blanket** and used to generate electricity (and to breed T for refuelling purposes).

Heating the D-T gas mixture to 100 million °C requires a large amount of electricity to be fed into the reactor. To obtain useful power output, the fusion reactions must be sufficiently intense and long-lasting to generate more power than that put in. Two criteria are used to evaluate scientific fusion experiments:

- **Breakeven** - where the energy generated in the plasma equals the input power.
- **Ignition** - where the plasma generates so much energy that, with appropriate refuelling, it becomes self-sustaining and no power is required to feed the plasma.

## TECHNICAL DEVELOPMENTS

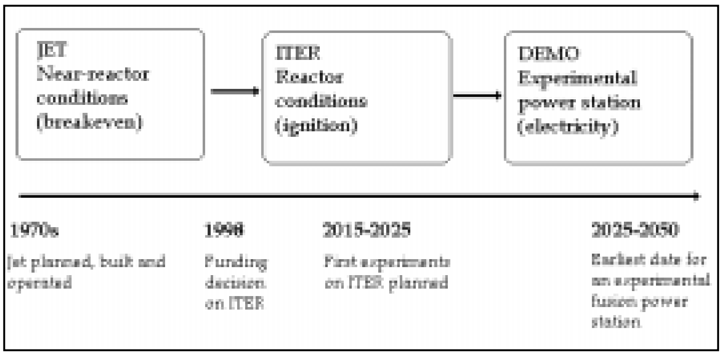
### *JET*

Work on JET is split into four main areas of study:

- plasma heating;
- plasma behaviour as parameters approach those that would be needed in a 'commercial' reactor;
- plasma-wall interactions under such conditions;
- helium production, confinement and subsequent use for plasma heating.

In a preliminary experiment in November 1991, using a D-T fuel mix (see Box 1), JET achieved the world's first controlled release of nuclear fusion energy; the equivalent of about 1 million watts (MW) of energy for 2

### FIGURE 1



seconds. Steady improvements in each of the areas above have resulted in experiments in 1997 using various D-T fuel mixes which have yielded world records for:

- **fusion power production** - 16.1MW (for slightly less than 1 second) compared with the previous record of 11MW (for 0.4 seconds) achieved by a US experimental reactor;
- **fusion energy output** (22MJ);

The best plasma conditions achieved in JET are roughly those required for **breakeven**, where the amount of fusion energy released by the reactor matches that needed to heat the plasma in the first place. Scientists estimate that these conditions would have to be scaled up by a factor of ~6 for **ignition** (Box 1) to occur, although JET is not physically big enough to produce and contain such a plasma. Indeed, this was originally one of the main aims for building the bigger ITER reactor. The main thrust of the remaining work carried out at JET will be to provide further data of direct relevance to ITER, as well as to continue developing ITER-relevant technologies such as remote operation/maintenance and tritium handling.

## *ITER*

Design of the proposed new reactor began in 1992, when the four international collaborators (Russian Federation, US, EU and Japan) agreed a six year, $1B ITER engineering design activity (EDA). This involved work at JET and elsewhere to develop key technological areas relevant to ITER such as magnetic field coil design, inner wall structure, shield design, development of remote handling technologies, specification of operating limits, etc. The EDA culminated in a Final Design Report in December 1997 which proposed that ITER should be a tokamak design, substantially larger than JET (8.1m in radius compared with JET's 2.96m) costing in the region of $7-11B (£4.3-6.9B).

## *Other Routes to Fusion*

Conventional wisdom in fusion research has supported the tokamak reactor as the most promising approach since the early 1970s when plans for JET were being drawn up. Indeed, this is still the current consensus view, although recent years have seen considerable progress being made on other types of designs. Alternatives (see **Box 2**) fall into two main categories - those using magnets to contain the plasma and those using lasers. The former come in many different shapes and sizes, and vary principally in the geometry and nature of the magnetic fields used to contain the plasma (see Box 2), although none is as technically highly developed as conventional tokamak devices such as JET. It is also possible to induce fusion using lasers (Box 2). Such approaches do not require magnetic containment, but are limited by the fact that lasers are not currently powerful enough to achieve breakeven.

### BOX 2 ALTERNATIVE FUSION REACTOR DESIGNS

**Magnetic containment**

**Conventional tokamaks** (CTs) are based on an original Soviet design, where a plasma is contained within a ring-doughnut (torus) shaped chamber by a combination of two magnetic fields. One of these is created by intense electric currents induced in the plasma itself (which also serve to heat it), and the other by external magnetic coils. The result is a helical magnetic field that keeps the plasma away from the walls. CTs (JET and the proposed ITER) are the most studied reactor design.

**Spherical tokamaks** (STs) work on a similar principle to tokamaks, but have a different geometry (like a football with a hole through the middle). Among the potential advantages are that STs are a simpler design that requires lower power external magnetic fields to stabilise the plasma. Another potentially important advantage is that tests on the START (Small Tight Aspect Ratio Tokamak) at Culham (UK) suggest that STs may not be so prone to the plasma disruptions that have hampered the development of CTs. In addition to the UK reactors (START, which will soon be succeeded by the new MAST - Mega Amp Spherical Tokamak) which are supported by the DTI, UKAEA and EURATOM, countries such as Australia, Brazil, Italy, Japan, Russia and the US are also pursuing research on STs.

**Reverse Field Pinch** - another magnetic containment scheme for use in torus vessels. In this arrangement most of the magnetic field needed for containment is generated in the plasma itself. One potential advantage is that such an arrangement may be capable of igniting a plasma without the need for further heating.

**Stellarators** - the chief difference between a stellarator and a CT design is that no current is induced within the plasma, so the magnetic fields used for containment are all provided directly by externally placed magnetic coils. Stellarators are effectively steady state systems and thus avoid problems such as thermal and mechanical cycling, current drive and plasma disruption inherent in CTs. The down-side is that the externally generated magnetic fields are extremely complex and difficult to achieve. Such systems are less developed than CTs, with most expertise being in Germany and Japan.

**Non-magnetic Confinement**

Another approach to fusion is to implode the plasma so quickly that the inertia of the converging particles causes fusion. To date, the most practical scheme developed uses tiny pellets of fuel bombarded on all sides by ultra high power lasers. Such systems have the advantage that they do not require magnetic containment and are thus technologically simpler than the devices described above. The current generation of lasers is not powerful enough to allow breakeven to be achieved, although the US Department of Energy (USDOE) is investing over $1B in constructing a National Ignition Facility with the aim of reaching ignition and achieving a moderate energy gain within 10 years.

# ISSUES

## Recent Developments

Much has happened since ITER was originally conceived in the late 1980s. For instance, the global political climate (characterised by the spirit of *glasnost* when the agreement was signed) has changed significantly with the collapse of the Soviet Union, and the prevailing economic circumstances in the Russian Federation now preclude these countries from making significant financial contributions to ITER. Elsewhere, recent years have seen an economic downturn in Japan and concerns over monetary union within the EU. Such factors have led to a re-evaluation of the original ITER proposals. Three of the partners (EU, Japan and the Russian Federation) signed a three year extension to ITER EDA in July 1998 to:

- review possible locations for the construction of ITER. Sites have already been offered in Canada, Italy and Japan, while the Russian Federation are currently considering whether to propose a site.
- consider changes to the original design in order to reduce the costs.

At the same time, the US Department of Energy (USDOE) announced that American participation in any further ITER design work had been suspended, although the US did sign a 1 year extension (until July 1999) to allow completion of ITER-related research work and to provide "*an orderly closeout of our design activities*". This effective withdrawal from the ITER programme reflects Congress's belief that the US should pursue low-cost approaches to fusion by conducting further research into small-scale (magnetic containment and laser-induced) devices rather than committing to the building of a large reactor. **These recent developments mean that the original ITER design will now almost certainly not be built, since the costs (£4.3-6.9B) are too great for the three remaining partners.** This effectively leaves the ITER collaborators with three main options - to discontinue research on fusion, to conduct research on smaller scale devices (possibly in collaboration with the US) or to continue with a lower cost version of ITER.

## Proceeding with Fusion?

There are a number of pros and cons (**Box 3**) associated with using fusion to generate power. Weighing these potential advantages (e.g. ready availability of fuel, relative safety, low $CO_2$ emissions) and disadvantages (e.g. high costs, long development times) is virtually impossible at such an early stage in the development process, given the uncertainties about the economics of fusion power, the amount of radioactive waste generated, etc. Advocates of continuing with fusion research argue that it is an attractive option given the Kyoto agreements to reduce greenhouse gases and in view of predictions of increasing energy demand in the face of dwindling fossil fuel reserves. Others however, question the timescales, pointing out that fusion will not deliver any electricity until 2025-2050, while the Kyoto agreements need to be met by 2008-2012. They also question the energy demand scenarios underpinning the original case for fusion research, particularly the assumption that future economic growth is linked to rising energy consumption. Given uncertainties over future energy demands and the imperative to reduce greenhouse gas emissions, they see a greater role for the development of energy efficiency and renewable energy sources. The UK government spent ~£16.6M in 1997/98 on fusion research and ~£11.1M on renewable energy.

### BOX 3 PROS AND CONS OF POWER FROM FUSION

**Potential Advantages**

- Fuel availability (deuterium is naturally abundant and tritium can be manufactured in fusion reactors).
- Safety - in the event of failure, the plasma rapidly 'fails-safe'. The potential for radioactive releases is also low since only small amounts of radioactive material are present in the chamber at any one time.
- Low $CO_2$ production - fusion reactors will produce little $CO_2$ compared with fossil fuels.
- Spins-offs - fusion research has spawned various industrial applications (vacuum systems, cryogenic technology, magnets/superconductors, remote handling, plasma control, advanced materials, etc) and more are expected.

**Potential Disadvantages**

- **High cost** of fusion research - JET represents a capital investment of around £450M and had an annual budget of nearly £60M in 1997 (80% from EURATOM, 10% from UKAEA as host organisation and 10% from members who have contracts of association with EURATOM). UK spending on fusion research (including contributions to JET) under the Fusion Programme has fluctuated in recent years, but was estimated at around £16.6M in 1997/98. Any commitment to start building even the lower cost version of ITER (see text) would significantly increase UK spend in fusion, and the UK will also soon face costs associated with decommissioning JET (the extent of these will vary according to the programme chosen).
- **Long development times** - even if construction of ITER started tomorrow and the project was a technical success, it would be 2025 at the earliest before the first fusion-derived electricity was generated (by DEMO).
- **Technical uncertainties** - the majority view is that results at JET confirm scientists' faith in the *physics* of the tokamak design, but that the main challenges encountered will be on the *engineering* side. For instance, most radioactive waste from fusion reactors will be due to radioactivity being induced in the materials of the reactor itself (through neutron bombardment), and development of low activity materials is seen as a key engineering challenge facing ITER.

## Research on Smaller-Scale Devices

The US government's decision to withdraw from ITER reflects its determination to pursue "*low-cost approaches*" to magnetically contained fusion and to establish "*a new international arrangement encompassing this and other fusion science areas*". This new approach will involve continuing smaller-scale research into the various different reactor designs (outlined in Box 2) in parallel with the development of other promising routes to fusion (notably laser generated fusion). In this way, the relative merits of the different approaches (most of which are 10-20 years behind tokamaks in development terms) can be compared before choosing one or more designs to scale up. USDOE is thus currently reviewing its fusion research programme and preparing draft arrangements that it hopes will form the basis of future international fusion research.

This approach is partly guided by concerns over the high costs of ITER. It also reflects a reluctance to start building the reactor on the grounds that this would represent a long-term commitment to the tokamak, a design which the US sees as not necessarily the best, merely the best studied (a point of view not shared by the remaining ITER partners, who see the project as a technology-proving step relevant to all types of magnetic containment devices). A final feature of the new programme is that it increases the emphasis on laser induced fusion, an area where the US has a very strong research base.

## A Lower Cost Version of ITER?

The three remaining ITER parties have reaffirmed their commitment to proceeding with scale up of the tokamak design to prove the technology at a larger scale. To this end, they have signed up to an extended design phase to produce plans for a lower-cost ITER, and see considerable scope for cost saving by reducing the technical objectives of the original design. Rather than trying to achieve ignition, the new objective is to demonstrate a net energy gain. To do this, the new ITER will 'only' have to sustain plasma burns for relatively short periods of time, in the region of thousands of seconds, and this means that the design will be both simpler and smaller than the original. For instance, current proposals are to reduce the external radius from 8.1m to around 6m, with associated savings in the size of the magnetic coils required, the dimensions of the vacuum vessel, etc. In this way, it is hoped that the current proposals for a Reduced Technical Objectives/Reduced Cost Option will cut the costs from the original level of £4.3-6.9B to around £3-4B.

While this approach has been guided primarily by cost cutting, it also reflects a current debate in fusion research concerning the necessity of plasma ignition. This had been regarded as a prerequisite for commercial fusion power plants, which have been envisaged as continuous processes needing constant refueling and exhausting of waste products. However in more recent years, results at JET and elsewhere have suggested that a 'driven reactor' capable of sustaining quasi-continuous plasma burns might be a more practical route to commercial power generation.

## Overview

International collaboration on fusion research faces an uncertain future in the wake of the US withdrawal from ITER. Some see this as the ideal opportunity for the UK to reassess its participation in fusion research, arguing that such a review should address fundamental questions such as the likely future need for fusion power, as well as its potential cost-effectiveness and technological feasibility compared with other carbon-free energy approaches (e.g. energy efficiency, renewables).

A similar exercise in the US preceded withdrawal from ITER and led to a decision to focus on developing the various different approaches to fusion (outlined in Box 2). This involves smaller-scale research on magnetic containment and laser induced approaches, to assess the most promising for scale-up at some point in the future. It has the advantage of avoiding the expense of building a large-scale ITER facility in the near future. Research into the feasibility of fusion with lasers is already carried out in the UK at the Rutherford Appleton Laboratory (RAL), and the programme has well established links with the major laser fusion projects in the US, Japan and France. Proponents of this route argue that a relatively modest increase in RAL's funding would leave the UK well placed to make a substantial contribution to an international laser fusion programme. However, critics of this approach see the emphasis on laser induced fusion as a step backwards, arguing that refocusing on the basic science will delay development of nuclear fusion as a commercial technology.

A lower-cost (£3-4B) version of ITER is still the option favoured by the remaining three partners, although it remains to be seen whether the money can actually be found to realise this design. The partners view this as the essential technology-proving step required to maintain the momentum of international fusion research, whereas US reluctance to go down this route is based on doubts over whether tokamak reactors will ultimately prove to be the best design. However, the ITER partners see the project as augmenting (rather than replacing) research conducted at the national level on different reactor designs and emphasise that the technological lessons learned from ITER should be applicable to any magnetic containment fusion approach.