INFORMATION FOR MEMBERS

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NUCLEAR FUSION

Since the first hydrogen bomb test showed that the sun's fusion energy processes could be reproduced on earth, governments and others have funded research into harnessing fusion to produce electricity. Over 30 years later, many national and international research efforts are about to be coordinated into a global project on nuclear fusion - the International Thermonuclear Experimental Reactor (ITER).

This Briefing Note examines the international progress towards power from nuclear fusion and its future prospects.

WHAT IS NUCLEAR FUSION?

Nuclear fusion powers the sun (see Box) - on earth, nuclear fusion is the process used in the 'hydrogen bomb'. In an H-bomb explosion, an atomic (fission) bomb initiates a fusion reaction in surrounding material (see POST Briefing Note 35) and energy is instantly and uncontrollably released. However, if the fusion reaction could be controlled - in effect creating a small 'sun' on the earth - then nuclear fusion could provide an effectively limitless supply of energy for peaceful purposes. This possibility has been actively pursued by many nations over the last 40 years.

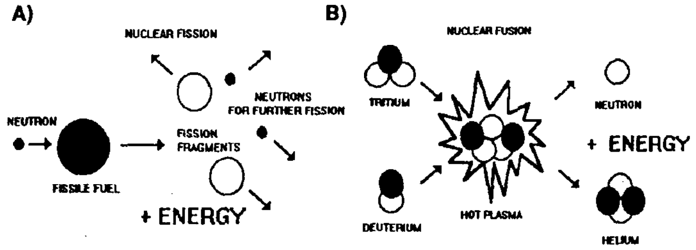
One way to induce nuclear fusion in the laboratory is to heat deuterium and tritium gas mixtures to very high temperatures (100 million °C - hotter than in the sun). At these temperatures, the gases break down into a *plasma* - a jumble of atomic nuclei and electrons. These very hot plasmas would melt all known materials and must therefore be suspended away from the walls of a containment vessel by large and precisely-designed magnetic fields. The commonest chamber shape used is a *torus* (a ring-doughnut shape).

In deuterium-tritium (D-T) fusion, energy is released in the form of energetic helium nuclei and neutrons. The helium nuclei remain in the torus and their energy can be used to maintain the plasma temperature, but the neutrons, carrying 80% of the fusion energy, are ejected from the plasma; in a practical reactor this energy would be captured in an outer 'blanket'.

NUCLEAR FISSION AND NUCLEAR FUSION

'Conventional' nuclear power - nuclear fission - uses mainly uranium. Some uranium nuclei are spontaneously fissile, i.e. they split into smaller fragments releasing energy in the process (see figure A). Nuclear particles released in a fission event cause further fission reactions in neighbouring uranium. A 'chain reaction' develops, liberating heat which is turned to steam to drive electricity-generating turbines.

In simple terms, nuclear fusion is the reverse of nuclear fission. If atomic nuclei are forced sufficiently close together, they fuse to form the nuclei of new elements (see figure B); in doing so, a vast amount of energy is liberated (two hydrogen nuclei fusing together generate 4 million times more energy than burning the equivalent amount of coal).



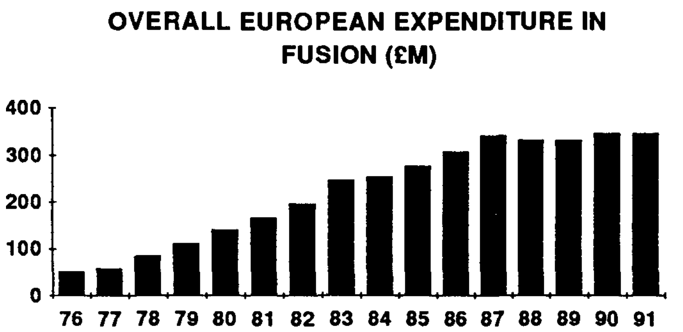
The sun, effectively a large ball of hydrogen, is powered by nuclear fusion. The sun's huge mass compresses together hydrogen nuclei at its centre where they fuse and irradiate energy. The hydrogen-hydrogen fusion process is very slow (fortunately, otherwise the sun would have long since burnt out), so to create useable fusion on earth, heavier versions (isotopes) of hydrogen are used which make the fusion process much quicker. These hydrogen isotopes are deuterium (D) and tritium (T). Deuterium is present in sea water (1 gram per 50 litres) but tritium does not occur naturally. A fusion reactor can however be designed to 'breed' tritium, so that deuterium/tritium fusion fuel is effectively inexhaustible.

Heating the D-T gas mixture to 100 million °C requires a large amount of electricity to be fed to the reactor. To obtain useful power output, the fusion reactions must be sufficently intense and long-lasting to generate more power than that put in. Two 'figures of merit' are used to judge the success of scientific fusion experiments. The first is **'breakeven'**, where the energy generated in the plasma equals input power. The higher threshold needed for a reactor is termed **'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. Some of the output power, however, will be needed to drive the reactor's auxilliary electrical systems. Many formidable scientific and technological problems must be solved before ignition is achieved, and the earliest date envisaged for a fusion power station is the mid-21st century.

HISTORY OF FUSION RESEARCH

After World War II, all nuclear powers conducted their own programmes in controlled nuclear fusion. In the UK, an experiment named ZETA was set up in the '50s at the Atomic Energy Authority's laboratories at Harwell. In 1958, researchers thought they had observed nuclear fusion in ZETA, but later work disproved this. Around the world, controlled nuclear fusion was also proving elusive, and it became increasingly clear that the scientific problems were so great that no country was likely to overcome them alone. The UK and USA declassified

Figure 1



OVERALL EUROPEAN EXPENDITURE IN FUSION (£M)

most controlled nuclear fusion research in 1958 and, since then, many countries have collaborated.

In 1957, the (then) six EC countries signed a treaty establishing the European Atomic Energy Community, EURATOM and paving the way for collaborative research in nuclear power. The Community Fusion Programme began in 1959 and the UK became a member of EURATOM when it joined the EC in 1973. The UK funds fusion research both through its contribution to the EC and directly via the DTI (which subsumed the former Department of Energy in June 1992); all known European fusion research is integrated through EURATOM.

In 1968, Soviet scientists announced a breakthrough with a toroidal design (called a *Tokamak*) which achieved much improved plasma conditions than had been reached before and this stimulated many countries to take up the Tokamak idea. In W. Europe, design of a large Tokamak by a multinational team began in the early '70s and in 1978, the EC's Council of Ministers agreed that such an experimental device would be constructed under a 'Joint Undertaking' and staffed by EC nationals. The UK was chosen to host this Joint European Torus (JET) at the Atomic Energy Authority (AEA) site at Abingdon in Oxfordshire - JET is now the world's largest and most successful fusion experiment.

The members of the JET Joint Undertaking are EC States (through EURATOM) and Associate Partner countries in the EC's Fusion Programme (Sweden and Switzerland). In 1991, JET cost in total about £70M; 80% of JET's costs are met by EURATOM, which is a component of the Community budget to which all EC States contribute (UK contribution 17.5%). EURATOM also funds other fusion research in Member States, so that overall, the Community Fusion Programme amounts to roughly £150M p.a; some 1,750 professionals are directly engaged in the Programme. The total European fusion research budget (EC plus total expenditure in Member States) stands at about £350M p.a. (see **Figure 1**).

Table 1 APPROACHING POWER GENERATION BY FUSION

	Best Results Achieved(times away from ignition)
1970	25 000
1980	700
1983	100
1988	200
1989	10
1991	6 (at JET)

The UK's total spend on all fusion research for 1991/2 is ca. £42M p.a., made up from:

- the UK contribution via EURATOM for the support of JET (£9M);
- the national contribution of £8M to JET (10% of JET funding is shared between the JET partner governments and 10% met by the UK alone to offset the financial gain of hosting a major international facility[1]);
- the UK contribution to the remaining (non-JET) parts of EURATOM's fusion budget (£16M);
- the UK also contributes directly to the Community Fusion Programme via the AEA 'Contract of Association' with EURATOM (under these Contracts, EURATOM meets 25 or 45% of project costs). This work is undertaken in AEA laboratories on the JET site and since 1988 all AEA's fusion research has been in support of JET. In 1991/92, the cost of this work was about £8M.

In November 1991, JET achieved the world's first controlled release of nuclear fusion energy; the equivalent of about 1 million watts of energy for 2 seconds. The best plasma conditions achieved in JET are roughly those required for breakeven which is about 6 times away from ignition - **Table 1** shows the best results obtained around the world since 1970. JET is not physically big enough for ignition to be reached and all developed countries have now agreed to participate in building a larger facility known as the 'International Experimental Thermonuclear Reactor' - ITER. JET will continue in operation until 1996 undertaking experiments in support of ITER's design.

ITER

Following agreement between Presidents Reagan and Gorbachev for joint research on fusion energy, discussion on international collaboration expanded to include the USA, the (then) USSR, the EC and Japan. These would collaborate as four partners with equal status, financial contribution, access to results, etc.

The conceptual design of ITER began in 1987 under the auspices of the International Atomic Energy Agency (IAEA). In June 1992, the four partners signed an agreement to move towards a reactor proper. The ITER organisation will operate separately from the IAEA or any national agencies.

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[1] Since JET's inception in 1973, UK firms have won over 50% of contracts for services, plant, etc. and half of JET's 400 total staff are foreign nationals who spend some of their income in the local economy. This net financial gain will be somewhat offset by decommissioning costs for JET which will depend on the future experimental programme.

Work on a full design, scheduled to last six years, has just started, with each of the four partners making equal contributions of about $40M annually towards a grand total of $1,000M. EC funding will come from the Community budget which means that the UK contribution will be $7M p.a. during this phase. The design project is split between teams in the USA, Japan and a European team in Germany. In the spirit of international cooperation, a Russian manages the US site, an American the team in Germany, and a (non-UK) EC national leads the effort in Japan. Less senior levels are just beginning to be filled. No country 'quotas' are to be applied - appointments will be made solely on merit.

The overall ITER project is to be headed by an EC national (the ex-director of JET) and will be overseen by a multinational Council, formally based in Moscow, chaired by a Russian and co-chaired by a Japanese. The Council will be aided by 2 Committees, one for technical advice chaired by an American, one for management led by the Japanese co-chair of ITER Council. Despite the apparent complexity of these arrangements, the partners agreed them in less than 9 months.

ITER is seen as the penultimate experiment to a demonstration fusion power station scheduled for construction early in the next century. ITER is expected to cost $5,000M to build and the whole research and development programme $30,000M; its missions are twofold:

- **Scientific**. To develop a high-power capability equivalent to 1,000 Megawatts - the size of a large power station today - for 'burn' times up to one hour; and a detailed study of ignited plasmas.
- **Engineering**. Definition of materials for the inner torus walls, fuelling requirements, and tritium 'breeding' in the toroidal blanket.

The scientific phase will precede and help to define the engineering objectives. Experiments in ITER are scheduled to start in 2005, though it is as yet undecided where the reactor will be sited. Japan has already offered to host ITER but the USA, France or Germany may bid strongly for the facility.

ISSUES

The Pros and Cons of Fusion Technology

Supporters of fusion energy stress its potential attractiveness from several viewpoints and an evaluation carried out for the EC in 1990 ('Colombo' report) supported fusion and the European effort strongly, though calling for increased emphasis on engineering and other aspects and recommended a further review before 1995. Some of the perceived advantages of fusion have been challenged in a review by the European Parliament's Science and Technology Assessment (STOA) project.

Fuel Availability. One attraction is that fuel is essentially unlimited. Deuterium is available from the sea whereas tritium can be created artificially (see Box).

Safety. Because the conditions for fusion are so extreme and difficult to produce, any abnormality or malfunction puts the plasma out so that the reactor rapidly 'fails safe'. Additionally, only a small amount of fuel would be present in a fusion reactor at any one time (enough for a minute or so of operation), which means that in the worst case of rupture of the torus, very little radioactive material would be released. The danger of reactor runaway as experienced at Chernobyl is thus absent with fusion.

Another advantage of fusion is that the radioactive tritium fuel is created on site obviating transportation hazards. Tritium is used in H-bombs, so there are considerations concerning the proliferation of nuclear weapons. However, the tritium would only be of use to a party already possessing fission atomic weapons. Fusion reactors are therefore likely to pose less of a proliferation risk than fission reactors.

Environmental Factors. One environmental benefit is that a fusion reactor would produce very little carbon dioxide (CO_2) in operation relative to fossil fuels (as with current fission nuclear power). Fusion reactors would not be free of radioactive waste but the waste they produce should be easier to dispose of than current waste from fission reactors. This is principally because fusion reactors will not generate the long-lived and highly radioactive waste related to the spent fuel rods of fission reactors (see POST Briefing Note 5). Of the fusion fuels, deuterium is inert but tritium is a radioactive gas which permeates readily through materials and forms tritiated water which is toxic and corrosive. Progress has been made in learning how to handle tritium at JET and elsewhere, but further research is needed on tritium and tritiated waste.

Most waste from fusion reactors will be due to radioactivity being induced in the materials of the reactor itself (steel, etc.). However, there is considerable uncertainty over the amounts which might be generated, and some experts believe that the actual quantity of intermediate level waste could be more than in a fission reactor. Much depends on what materials will ultimately be developed for the torus. The development of low-activity materials will be one of the keys to the future environmental acceptability of nuclear fusion.

Technical Prospects

The 1991 experiment at JET (Table 1) was widely hailed as a major scientific achievement and has led to optimism about the practicality of fusion. However, neither JET nor ITER are designed to create electricity and it will be well into the next century before the feasibility of a nuclear fusion power station can be tested. In view of the scientific uncertainty, the costs of fusion-based electricity can only be speculated but current estimates (including decommissioning) are from 1-2 times the cost of electricity produced from nuclear fission.

Results at JET lead scientists to believe that the *physics* of magnetically-confined nuclear fusion have essentially been proved. However, there are profound *engineering* problems to be faced in a practical reactor. For example, the inner toroidal walls will be subject to intense nuclear bombardment. The structural behaviour of materials under these conditions is still a matter for research, and new materials may need to be developed to avoid excessive maintenance and shutdown of the reactor. Intense radioactivity surrounding the reactor means that all maintenance must be performed by robots working at very fine tolerances in a hostile radioactive environment Such problems are being addressed but other engineering problems exist for which no solution is yet in sight.

Is ITER the Best Option?

The advantages of the ITER programme are that costs and risks are shared between nations; indeed it is doubtful whether any nation on its own could provide the scientific and engineering resource for the ITER project. However, such a wide and long-term collaboration involves some compromise with national competitiveness and security, and aspects of technology transfer and ownership of intellectual property rights have not yet been clarified.

The country hosting ITER may enjoy considerable economic and technological benefits (though also eventually incurring decommissioning costs which could be substantial). The UK bid to host JET was agreed on the understanding that it would not host JET's successor. Through JET, the UK has acquired considerable scientific, engineering and industrial skills which it is in the UK's interest to see applied to ITER's construction. As ITER will be sited abroad, some see a need for active DTI involvement to maximise the benefits to the UK of particiation in ITER.

Other Routes to Fusion. Although the recent agreement on ITER shows that there is consensus that the Tokamak is a promising approach to creating fusion, other approaches are possible. One is the so-called 'stellarator', where very complex magnetic fields confine the plasma. Stellarator systems are much less developed than Tokamaks; most expertise is in Germany and Japan.

It is also possible to induce fusion without any magnets. In Japan and the USA, experiments are in progress where ultra-high-power lasers irradiate a small pellet of D-T fuel causing the pellet to implode and the nuclei to fuse. Current lasers are not powerful enough for breakeven to be reached, though feasibility has been demonstrated in trials where the lasers were replaced by small atomic bombs.

The USA believes that the technique is sufficiently promising to merit work in parallel with magnet confinement but the implications of laser-induced fusion for nuclear and laser weaponry limit scope for international collaboration. Some believe laser-induced fusion is technologically simpler and has a greater chance of success than magnetically-confined plasmas because the H-bomb proves the implosion route to fusion.

Future UK Policy

Other Energy Sources. Cost estimates of fusion-generated electricity, together with the large capital outlay envisaged for each fusion reactor, lead some to doubt the commercial viability of fusion and question whether research should continue to be supported. However, concerns over global warming lead many to believe that non-fossil fuels will increasingly have to be used for energy production if 'greenhouse gases' are to be reduced. Some see it as important not to preclude fusion as a potential option for creating energy without contributing to global warming. ITER meets this need and, currently, each EC Member's financial contribution to ITER is modest, though it will inevitably increase as the project matures, and total European expenditure on fusion could double by the year 2000.

However, on a short-term view, prospects for **economic** fusion power generation appear no more and probably less favourable than for 'breeder' fission reactors, where the UK (and Germany) intend to stop research on commercial grounds. If the UK and other governments take the view that there is insufficient need to continue breeder research, some see a similar rationale applying to fusion. DTI has not expressed a view on the fusion programme since the decision on terminating 'breeder' research was announced, but supporters of continued research would point out that there are so many unknowns in forecasting world economies, energy supply/demand, etc. to 2050 and beyond, that a case for stopping fusion research now on the basis of projected costs would be difficult to sustain, particularly in view of the highly integrated nature of the international research effort.

FURTHER READING

Additional details and background information are available from POST, 2 Little Smith St., London SW1P 3DL, tel: (071)-222-2688.

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