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# THE JET PROJECT AND ITS IMPACT ON NUCLEAR FUSION RESEARCH

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## INTRODUCTION

The Joint European Torus (JET), situated near Abingdon, UK, is the largest project in the co-ordinated programme of the European Atomic Energy Community (EURATOM). The EURATOM Fusion Programme is designed to lead ultimately to the construction of an energy producing reactor. Its strategy is based on the sequential construction of major apparatus such as JET, the Next European Torus (NET), and DEMO (a demonstration reactor), supported by medium sized specialized Tokamaks.

## BASIC PRINCIPLES

The basic principle of the fusion process is the fusing or joining together of light nuclei to form heavier ones and in so doing a small quantity of mass is converted into a large amount of energy. Fusion is the process occurring in the sun where light atoms, heated to temperatures of about 15M°C (~13keV) fuse together. The rate at which fusion occurs in the sun is relatively slow; for a fusion reactor on earth, a higher rate is required and hence much higher temperatures are needed - typically in the range of 100-200 M°C (10-20keV), which is 10 times greater than the temperature in the centre of the Sun. In addition, in a reactor, a high enough concentration (or density) of fuel must be maintained at these temperatures for sufficient periods. For a reactor, there are several possible fusion reactions, but the one that is easiest to achieve is that between the two isotopes of hydrogen - deuterium and tritium. Deuterium can be easily and cheaply obtained from water and tritium can be manufactured in a fusion reactor from the light metal lithium. The reactions involved are:

| | |
|---|---|
| Fusion Reaction | $D + T \rightarrow {}^4He + n$ |
| Tritium Breeding Reactions | ${}^6Li + n \rightarrow T + {}^3He$ |
| | ${}^7Li + n \rightarrow T + {}^4He + n$ |

The sun uses gravitation forces to hold the high temperature nuclei (or plasma) together but on earth this force would be much too small. Since plasma is made up of a mixture of charged particles (nuclei and electrons), magnetic fields can be used to contain the plasma. The most effective magnetic configuration used to hold the high temperature plasma is toroidal in shape. In a reactor, there must be sufficient fuel present and the energy losses must be kept low to ensure that more energy is released from the fusion reaction than is needed to heat the fuel and run the system. The effectiveness of the magnetic field in containing plasma and minimising losses can be measured by the time taken for the plasma to cool down. This is called the energy confinement time and needs to be between one and two seconds in a reactor - although the plasma will be contained for considerably longer times. The power output depends on the amount (or density) of fuel present, but there is a limit on the amount that can be held by the magnetic field. This needs to be only a few thousandths of a gram per cubic metre, but this is sufficient to yield vast amounts of energy. Thus a fusion reactor must produce very high temperature plasmas of sufficient density and long enough energy confinement time to generate a net output of power.

In a fusion reactor, the values of temperature, ($T_i$) density ($n_i$) and energy confinement time ($\tau_E$) must be such that the product ($n_i.\tau_E.T_i$) exceeds $5x10^{21}m^{-3}skeV$. Typical values for the parameters that must be attained simultaneously for a reactor are:

| | |
|---|---|
| Central ion temperature, $T_i$ | 10-20keV |
| Central ion density, $n_i$ | $2.5x10^{20}m^{-3}$ |
| Global energy confinement time, $\tau_E$ | 1 - 2s |

The principal advantages of fusion as a new energy source are, essentially:-

- it is a vast new energy source;
- fuels are plentiful and widely available and these avoid the environmental problems associated with the burning of fossil fuels;
- a fusion reactor will be an inherently safe system;
- there will be no radioactive waste from reaction products, although the reactor structure itself becomes radioactive.

## THE JET PROJECT

In Europe, there are several national fusion research laboratories which together form a well-integrated programme co-ordinated and partly funded by Euratom. During the early 1970s a consistent set of encouraging results emerged from a number of small-scale experiments around the world. It was then clear that to achieve near-reactor conditions much larger experiments were required which were likely to be beyond the resources of any individual country. In 1973, it was decided in Europe that one such large device would be built as a joint venture, the Joint European Torus (JET) and a Design Team was set up to prepare a design. Approval to proceed with the Project was given at the end of 1977. On 1st June 1978, the formal organisation for the Project - the JET Joint Undertaking - was set up. The Project Team is drawn from Euratom and the fourteen member nations - the twelve EEC countries, together with Switzerland and Sweden. Funding - currently at about 100M ECU per year - is provided 80% by Euratom, 10% by the U.K. as host country and the remaining 10% by members roughly in proportion to the size of their national fusion research programme. The construction of JET, its power supplies and buildings, were completed, on schedule and broadly to budget by mid-1983 and the research programme started.

The objective of JET is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. This involves four main areas of work:

(i) to study various methods of heating plasma up to the thermonuclear regime;
(ii) to study the scaling of plasma behaviour as parameters approach the reactor range (that is to determine how the plasma temperature, density and confinement vary with dimensions, shape, magnetic field, plasma current etc., so that we can accurately define the parameters for a reactor);
(iii) to study the interaction of plasma with the vessel walls and how to continuously fuel and exhaust the plasma;
(iv) to study the production of alpha-particles generated in the fusion of deuterium and tritium atoms and the consequent heating of plasma by these alpha-particles.

## THE JET MACHINE

The plasma in JET is heated and contained in a very large toroidal or ring-shaped vessel known as a torus [1]. The plasma is confined away from the walls of the vessel by a complex set of magnetic fields. The detailed shape of the magnetic field is described as a Tokamak, a name used by the Russians who pioneered this particular form of magnetic device for high temperature plasma. There are many tokamaks in the world, principally in Europe, the United States, the Soviet Union and Japan, but JET is by far the largest and most powerful. The main dimensions of the machine are given in Table I.

**Table I: JET Parameters**

| Parameter | Design Values | Achieved Values |
|---|---|---|
| Plasma Major Radius ($R_o$) | 2.96m | 2.5 - 3.4m |
| Plasma Minor Radius (hor.)(a) | 1.25m | 0.8 - 1.2m |
| Plasma Minor Radius (vert.)(b) | 2.1m | 0.8 - 2.1m |
| Toroidal Field at $R_o$ | 3.45T | 3.45T |
| Plasma Current | 4.8MA | 7.0MA |
| Neutral Beam Power | 20MW | 21MW |
| ICRF Heating Power | 15MW | 18MW |

Plasma is heated in JET by a very large electric current - up to 7 Million amperes (MA) - together with two other additional heating methods. These are radio frequency (RF) heating (up to 20MW), and neutral beam (NB) injection heating (up to 21MW) which involves injecting beams of energetic atoms into the plasma. When the plasma is sufficiently hot and well confined abundant fusion reactions will take place turning the deuterium and tritium nuclei into helium nuclei (alpha-particles) and neutrons. The alpha-particles remain in the magnetic confinement region and their high energy continuous to heat new plasma to keep the reactions going.

Although this will not take place in JET, when sufficient reactions are taking place in a reactor the external heating systems can be turned off as the plasma will continue to heat itself. The neutrons will escape from the plasma and, in a reactor, will be slowed down in a surrounding blanket of moderator causing the blanket to heat up to a few hundred degrees Celsius. This heat will be removed to raise steam to drive turbines to generate electricity in the conventional way. By making the blanket of a lithium compound, the neutrons will also combine with lithium to produce tritium for fuelling the plasma.

A basic objective of JET is to study the self heating of plasmas by the alpha-particles, but the production of tritium and heating by neutrons will be the major objectives of the NET experimental device.

JET's plasma current is generated by a massive 2700 tonne transformer in which the plasma is the transformer's secondary winding. The magnetic confinement configuration is made by combining two magnetic fields, one produced by the plasma current itself and the other by a set of electromagnetic coils surrounding the torus. Finally a set of horizontal hoop coils encircling the apparatus ensures that the plasma remains centrally in the torus.

## JET RESULTS

JET is now about midway through its programme and results achieved in JET so far are most impressive [2]. The technical design specifications of JET have been achieved in all parameters and exceeded in several cases (see Table I). The plasma current of 7MA and the current duration of up to 30 seconds are world records and are over twice the values achieved in any other fusion experiment. The neutral beam injection system has been brought up to full power (21MW) exceeding the design value. In addition, the ICRF heating system has taken advantage of improvements in technology to increase its power level to ~18MW in the plasma. In combination, these heating systems have provided 35MW power to the plasma, and this is likely to increase in the near future.

So far, plasma temperatures up to 250M°C (23keV) have been reached and the plasma densities (up to $\sim 1.8\times10^{20}m^{-3}$) and energy confinement times (up to 1.5s) are within the range required in a reactor (see Table II). Although these values have been achieved in individual experiments, they have not all been reached simultaneously. There are two regimes of energy confinement observed in a special magnetic configuration (the X-point configuration). One of these, a higher confinement regime (called the H-mode) has energy confinement times about twice the lower values (called the L-mode). In both regimes, confinement degradation occurs in that the plasma thermal energy does not increase proportionally to the heating power. Therefore considerably more power is needed to increase the plasma temperature and energy. This problem is presently being investigated.

Fig.1 presents a plot of the fusion product ($n_i.\tau_E.T_i$) versus central ion temperature $T_i$ for a series of experimental devices developed over the last 20 years. It is seen that considerable progress has been achieved in 20 years and JET has now reached a fusion

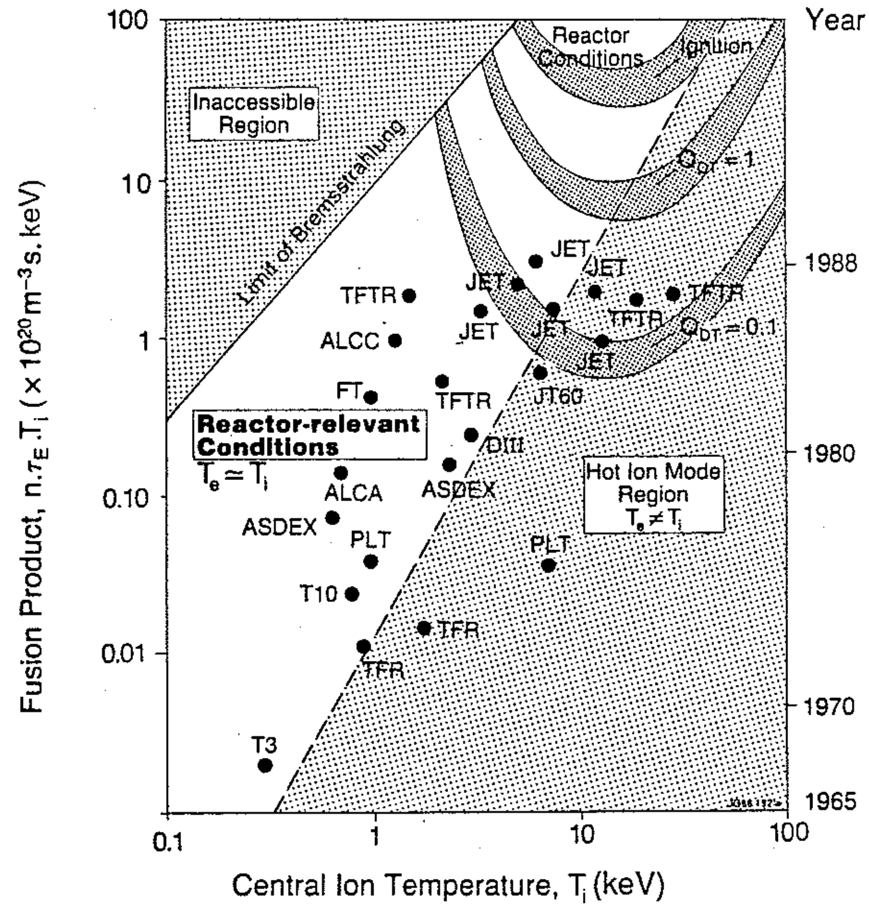


Fig.1: Plot of fusion product ($n_i.\tau_E.T_i$) versus central ion temperature $T_i$ for a series of experimental devices

product value of $3 \times 10^{20} m^{-3} skeV$, which is only about a factor of 20 below the value of $5 \times 10^{21} m^{-3} skeV$ required in a reactor. In particular,JET has shown that plasmas of thermonuclear grade may be contained in a controlled way in a terrestrial device. These latest results put JET on the top of the fusion league table - a position it is likely to maintain for the rest of its operating life.

These experiments are currently being carried out in hydrogen or deuterium plasmas and plans for using the tritium are scheduled to come into operation in 1991. The forward programme up to 1992 include a number of these enhancements and innovations intended to enable JET to create abundant fusion reactions and thereby achieve its objective of producing "plasmas of dimensions and parameters close to those in a fusion reactor".

## Table II: JET Results

| | Best Achieved | Achieved Simultaneously | Reactor Values |
|---|---|---|---|
| Temperature,T | | | |
| (M°C) | 250 | 70 | 120 -240 |
| (keV) | 23 | 6 | 10 - 20 |
| Energy Confinement Time, $\tau_E$ (s) | 1.5 | 0.9 | 1 - 2 |
| Density, n, ($\times 10^{20} m^{-3}$) | 1.8 | 0.5 | 2 - 3 |

## IMPACT ON NEXT STEP

Plasma temperature, density and confinement values already achieved, but not simultaneously, are individually close to the requirements of NET. In addition, JET results on scaling of these parameters have allowed some of the requirements of a reactor to be specified. In particular, the next step Tokamak must be about 2.5 times the linear dimensions of JET, have a plasma current of 25-30MA, and an output of several GW. The plasma must be maintained for very long times, such as 1 hour, rather than the 20-30 second bursts presently used in JET. Sufficient knowledge now exists to design such a device, but a number of plasma engineering problems remain to be solved.

These relate mainly to the interaction of the plasma with the vessel walls - eg, control of impurities, fuelling and exhaust. JET has the capability of studying these problems and will be doing so in the second half of its programme. JET will operate with deuterium/tritium plasmas, rather than pure deuterium ones, so that the production of alpha-particles in a true thermonuclear plasma can be studied. This will require a tritium fuelling system and, since JET will become radioactive, remote handling equipment will be used.

There are several teams working on designs for a Next Step. These include NET (Next European Torus) and ITER (International Thermonuclear Experimental Reactor), involving groups from the US, USSR, Japan and Europe. The results from JET are very important from a reactor point of view. Both design teams are taking JET results into account and are adopting the same design philosophy as JET, that is a large non-circular cross-section and a large plasma current.

Based largely on JET results, the present studies to define ITER, NET or any other next step Tokamak clearly emphasize the need for obtaining additional information not only on impurity control and plasma-wall interaction but also on modes of operation, such as those avoiding plasma disruptions and enhance confinement regimes.By virtue of its size, its already demonstrated plasma performance and its long pulse capability, JET is in the best position to address these problems in the basic geometry considered for a Next Step.

## CONCLUSIONS

In summary:

(a) JET is a successful example of European collaboration involving fourteen countries;
(b) This advanced technology machine was constructed on time and broadly to budget;
(c) On the technical side, JET has met all its design parameters and in many cases, has substantially exceeded the values. In particular, it has reached a record plasma current of 7MA;
(d) On the scientific side, JET has achieved plasmas with ion temperatures of 250M°C (23keV) and simultaneously ion and electron temperatures have exceeded 12M°C (10keV). In addition, JET has reached record plasma energy confinement times in excess of 1s;
(e) Individually, the parameters required for a fusion reactor had been achieved, and simultaneously the fusion product is within a factor of 20 of the reactor value. JET overall performance is closer than any other machine to required reactor conditions;
(f) JET has successfully achieved and contained plasmas of thermonuclear grade;
(g) JET technical and scientific achievements give confidence that a fully ignited experimental reactor could be built, as soon as control of particles is achieved;
(h) JET results show that a Tokamak with a plasma current of 30MA in a machine of 2-3 times the size of JET is required to produce ignition;
(i) Energy confinement would no longer be the dominant problem. However, scientific difficulties remain in the areas of:
    - plasma wall interactions and impurities
    - plasma fuelling and exhaust
    - quasi-continuous operation
(j) JET is the largest and most powerful fusion experiment in the world. It has the capability for studying these reactor relevant problems and providing important information required in designing and planning the Next Step device;
(k) JET results will continue to be of crucial importance in the development of Fusion research.

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# APPENDIX 1.

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