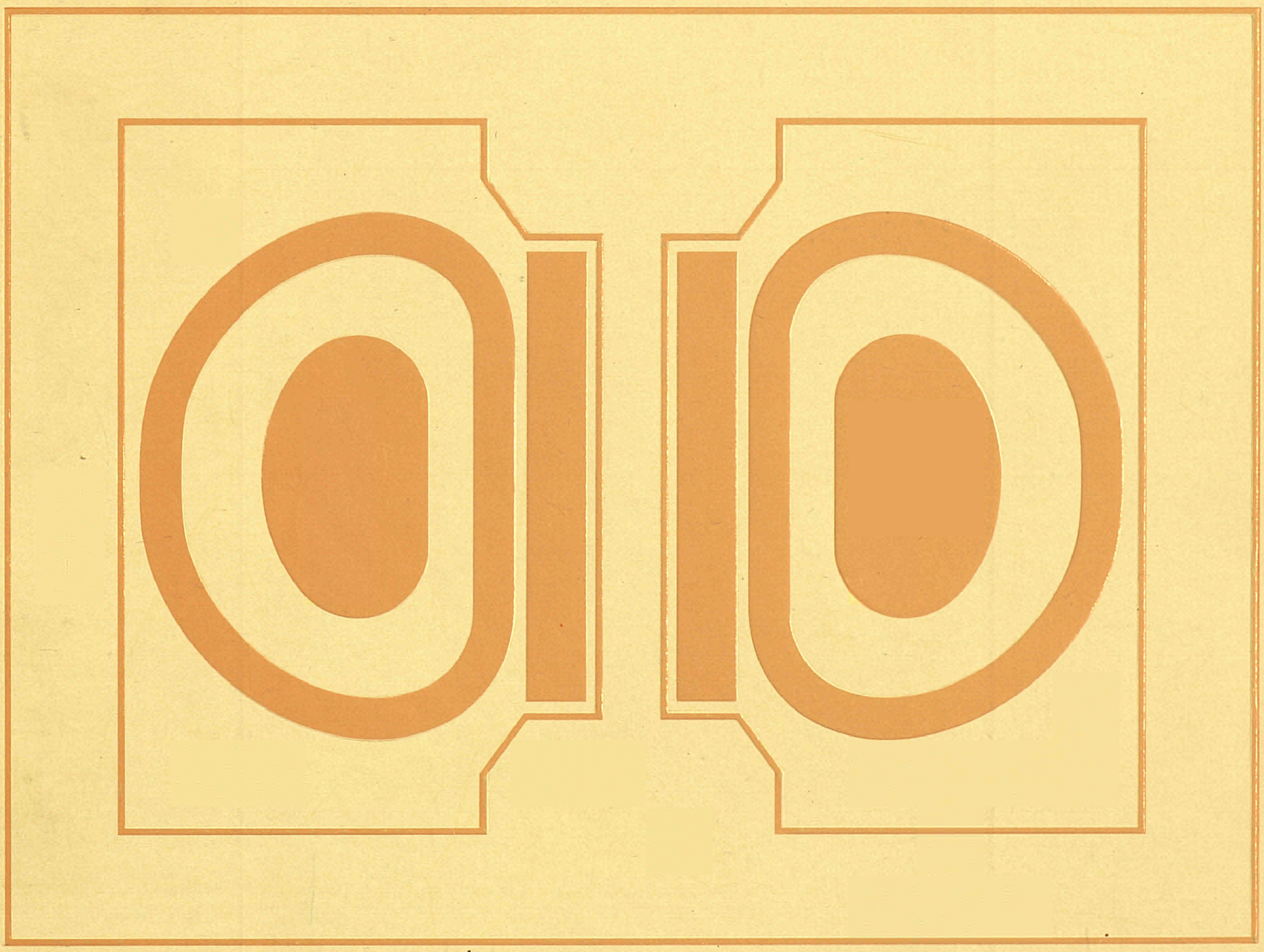
JOINT EUROPEAN TORUS

JET JOINT UNDERTAKING

ANNUAL REPORT 1987



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EUR-JET-AR10

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JULY 1988

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Page 44, The caption to Fig. 38 incorrectly identified D. Cribier as T. van Rentergem
The caption should read as follows:

Fig. 38 Participants at the JET Council meeting of June 1987. Standing (left to right): *J. T. Mendonça, G. W. O'Hara, A. Grau, G. Leman, M. Keilhacker, P. E. M. Vandenplas, D. Byrne, P. Zinsli, C. M. Braams, A. W. Plattenteich, H. von Bülow, P-H. Rebut, F. Troyon, A. Bracci, B. Deler, D. Cribier, W. M. Lomer, J. McMahon.* Seated (left to right): *V. Gonzalez, R. S. Pease, N. V. Nowlan, P. Fasella, Mlle L. Buyse, K. Pinkau, N. E. Busch, F. Chadwick, F. Prevot, C. Maisonnier.*

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Preface

1987 proved to be another successful year for JET from a scientific and technical point of view. Although the machine entered a planned shutdown midway through the second of four experimental phases, which lasted for the first six months of the year, the remaining experiment time proved to be very rewarding. During the shutdown, modifications and enhancements were made to many of the systems including changes to provide potential for operation with plasma currents up to 7MA with material limiters and up to 4MA in the magnetic limiter (X-point) configuration.

Operations were resumed at the end of June, as planned, with commissioning of the machine and the newly installed equipment, as the first priority. The success of these modifications was amply demonstrated during the first experiments and by the end of the year there was a clear shift to operations with even higher plasma currents. During this period, a number of technical restrictions were imposed to ensure that operations of the machine above the original design values were carried out with care and within conservative limits. By the end of the year, a maximum value for the plasma current of 6MA had been achieved with a flat-top duration of two seconds.

Significant scientific results were achieved in spite of commissioning requirements and of the exploratory nature of some of the experiments. Up to 16MW of power was coupled into the plasma using the upgraded ion cyclotron resonance heating system with eight water-cooled radio-frequency antennae. Operations with neutral beam injection heating, however, were rather disappointing when compared with the successes of the previous year. Even so, despite hardware failures a record input power of 22MW was deposited in the plasma with a combination of neutral beam and radio frequency heating in a material limiter discharge. This resulted in central ion and electron temperatures of 8.5keV (90 million degrees K) and 10keV (110 million degrees K), respectively. Similar values were also obtained during the quiescent period of a 'monster' sawtooth, whilst using only 15MW of combined heating power.

Although only limited experiments were carried out in the magnetic limiter mode, stable discharges were established for several seconds with a single null at a plasma current of 3.5MA and when neutral beam power above a certain threshold value was exceeded, transition to higher plasma confinement (H-mode) was re-established. Experiments showed a strong dependence of the threshold power needed for transition with the value of the toroidal magnetic field.

Initial experiments with the multi-pellet injection system, jointly developed in collaboration with the US Department of Energy under the Bilateral Agreement on Fusion Research, were succesful and densities well over $10^{20}m^{-3}$ have been achieved with decay times of several seconds.

The record value for the fusion product $(n_{i.}\tau_E\,.T_i)$ of $2\times10^{20}m^{-3}$skeV was again reached in 1987 but using only 6MW of neutral beam heating power compared with the 10MW used in the previous year. A significant improvement to the fusion product with radio frequency heating alone was also made, giving a value of $1.2\times10^{20}m^{-3}$skeV.

The scientific results achieved so far on JET are most encouraging as the stage has been reached where the plasma parameters—density, temperature and energy confinement time—are each within a factor of two or three of those needed for a fusion reactor. During 1987, considerable effort was devoted to the design, procurement and commissioning of equipment for installation during later planned shutdowns. These preparations are of the utmost importance as they will determine the future performance of JET and the potential for further increasing the value of the fusion product.

The temporary character of the Project has inevitably led to discussions among staff concerning their future. The Members are fully aware of the problems of JET as a temporary Project; they see JET in the context of the continuing European Fusion Programme and will make every effort so that the Project can continue to progress satisfactorily until the planned conclusion.

The results that have been achieved so far are a reflection of the dedication of those working on the Project and the assistance and co-operation received from the Associated Laboratories and Commission of the European Communities. I am convinced that, with the continuing commitment from all concerned, the Project can meet the many challenges that are likely to be encountered in the future and maintain its position at the forefront of world fusion research.

July 1988

K. Pinkau
Chairman of the JET Council

Introduction, Summary and Background

Introduction

The Joint European Torus is the largest project in the co-ordinated programme of the European Atomic Energy Community (EURATOM) which is aimed at proving the feasibility of using nuclear fusion as a source of energy.

The Statutes setting up the JET Project include a requirement for an Annual Report to be produced which

> '. . . shall show the current status of the Project, in particular with regard to timetables, cost, performance of the scientific programme and its position in the Euratom Fusion Programme and in the world-wide development of fusion research'.

This report is designed to meet this requirement and is intended to provide an overview of the scientific, technical and administrative status of the JET programme which is understandable to the average member of the public. Where appropriate, descriptive sections (in italics and boxed) are included to aid the reader in understanding particular technical terms used thoughout the Report.

A more detailed and comprehensive description of the technical and scientific aspects of the JET Project over the period covered by this report can be found in the 1987 JET Progress Report.

Report Summary

The Report is essentially divided into two parts:

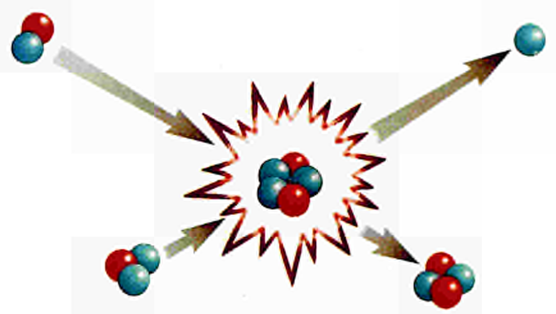
- the scientific and technical programme of the Project;
- the administration and organization of the Project.

The first part of the Report starts with this section which includes a brief general introduction, provides an overview of the planning of the Report and sets the background to the Project. This is followed by a section on JET and the Euratom and International Fusion Programmes which summarises the main features of the JET apparatus and its experimental programme and explains the position of the Project in the overall Euratom programme. In addition, it explains how JET relates to other large fusion devices throughout the world and holds a pre-eminent position in fusion research.

The next section reports on the technical status of the machine including: technical changes and achievements during 1987; details of the operational organisation of experiments and pulse statistics; and progress on enhancements in machine systems for future operation. This is followed by a section on the results of JET operations in 1987 which sets out the various operating conditions in terms of ohmic heating, radio-frequency (RF) heating, neutral beam (NB) heating and various combined scenarios in different magnetic field configurations; the overall global and

Nuclear Fusion

Energy is released when the nuclei of light elements fuse or join together to form heavier ones. The reaction of most interest, because it presents the least difficult path towards achieving reactor conditions, is that occurring between the two heavy isotopes of hydrogen – deuterium and tritium.



The deuterium-tritium reaction which yields an energetic neutron and a helium nucleus (alpha particle)

Most of the energy released in this reaction is carried by a high speed particle formed in the reaction called a neutron. The remaining energy is given to the alpha particle which is also produced in the reaction.
In a fusion reactor, the energy of the neutrons would be harnessed by capturing them in a jacket or blanket surrounding the reactor region. This would raise the temperature of the jacket enabling heat to be extracted so that steam could be raised and electricity generated in the conventional manner.

local behaviour observed; and the progress towards breakeven situations. In particular, the comparative performance between JET and other tokamaks, in terms of fusion product obtained, shows the substantial achievements made by JET since the start of operations in 1983. This section concludes with a discussion of future scientific prospects.

The final section of the first part of this Report describes the proposed future programme of JET which includes an extension until the end of 1992.

The second part of the Report explains the organisation and management of the Project and describes the administration of JET. In particular, this part sets out the budget situation; contractual arrangements during 1987; and details of the staff complement. This part concludes with a description of services provided by the Joint Safety Services and Public Relations Section.

Background

As early as 1971, discussions within the European fusion research programme were taking place on a proposal to build a large fusion device (tokamak) to extend the plasma parameters closer to those required in a reactor. In 1973, agreement was reached to set up an international design team which started work in the UK later that year and by the middle of 1975, the team had completed its design for a very large device.

On 30 May 1978 the Council of Ministers of the European Communities decided to build the Joint European Torus (JET) as the principal experiment and as a Joint Undertaking of the European Fusion Programme. To implement the Project, the JET Joint Undertaking was originally established for a duration of 12 years, beginning on 1 June 1978.

It was decided that the device would be built on a site adjacent to the Culham Laboratory, the nuclear fusion research laboratory of the United Kingdom Atomic Energy Authority (UKAEA), and that the UKAEA would act as Host Organisation to the Project. Fig. 1 shows the site of the JET Joint Undertaking at Culham near Oxford in the U.K.

The Members of the JET Joint Undertaking are Euratom, all its Associated Partners in the framework

Fig. 1 The site of the JET Joint Undertaking near Oxford in the United Kingdom

Fuels

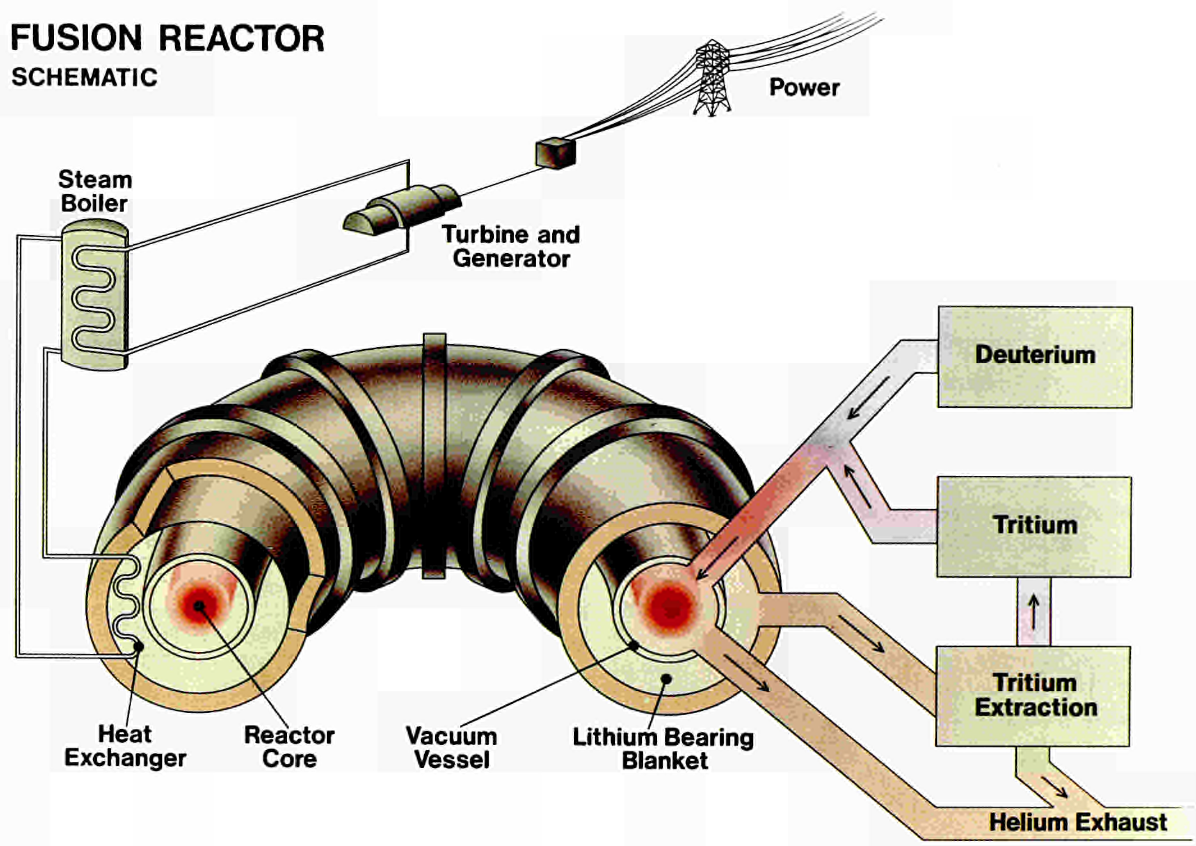
As deuterium is a readily separated component of water, there is a virtually inexhaustible supply in the oceans of the world. In contrast, tritium does not occur naturally in any significant quantities on the earth and must be manufactured. This can be achieved by using reactions that occur between neutrons formed in the fusion reactions and the light metal lithium.

Thus, although the fusion reactions occurring in a reactor will be between deuterium and tritium, the consummables will be deuterium and lithium.

Fusion Reaction $D+T \rightarrow {}^4He+n$

Tritium Breeding Reactions $^6Li+n \rightarrow T+{}^4He$
$^7Li+n \rightarrow T+{}^4He+n$

There are sufficient reserves of lithium available to enable fusion reactors to be run for several hundreds of years.



Schematic of a Fusion Reactor

In a fusion reactor a lithium compound would be incorporated within a blanket surrounding the reactor core so that the neutrons can be utilised for manufacturing tritium. The tritium produced would then be extracted for use in the reactor.

The blanket would also provide the means of utilising the energy carried away from the reactions by the neutrons. As the neutrons are slowed down within the blanket, its temperature would rise thus enabling steam to be raised so that electricity could be generated in the conventional manner.

Ultimately, it is hoped that the conditions would be reached to enable a reactor to be built utilising the deuterium—deuterium reactions below.

$$D + D \rightarrow {}^{3}He + n$$
$$D + D \rightarrow T + p$$

In this case there would be no need to manufacture tritium and a virtually inexhaustible reserve of energy would become available.

of the Fusion Programme including Sweden and Switzerland, together with Greece, Ireland, Luxembourg and Portugal, who have no Contract of Association with Euratom.

Eighty per cent of the expenditure of the Joint Undertaking is borne by Euratom, the UKAEA pay ten per cent with the remaining ten per cent shared between all Members having Contracts of Association with Euratom in proportion to the Euratom financial participation in the total costs of the Associations.

The Project Team is formed mainly by personnel from the Associated Institutions and from the Directorate General of the Commission responsible for Science Research and Development (DGXII).

Objectives of JET

The decision of the Council of Ministers states that the JET Joint Undertaking's mandate is to:

'construct, operate and exploit as part of the Euratom fusion programme and for the benefit of its participants in this programme, a large torus facility of tokamak-type and its auxiliary facilities in order to extend the parameter range applicable to controlled thermonuclear fusion experiments up to conditions close to those needed in a thermonuclear reactor'.

The essential objective of JET is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermonuclear reactor. These studies are aimed at defining the parameters, the size and the working conditions of a tokamak reactor. The realisation of this objective involves four main areas of work.

1) The study of scaling of plasma behaviour as parameters approach the reactor range.

2) The study of plasma-wall interaction in these conditions.

3) The study of plasma heating.

4) The study of alpha particle production, confinement and consequent plasma heating.

Two of the key technological issues in the subsequent development of a fusion reactor are faced for the first time in JET. These are the use of tritium and the application of remote maintenance and repair techniques.

Conditions for Fusion

Fusion reactions can only take place if the nuclei are brought in close proximity to one another. Difficulties arise because all nuclei carry a positive charge and therefore repel one another. By heating the gaseous fuels to very high temperatures, enough energy can be given to the nuclei for the repulsive force to be overcome sufficiently for them to fuse together. In the case of the deuterium-tritium reaction, temperatures in excess of 100 million degrees K are required—several times hotter than the centre of the sun.

To ensure a net energy gain it is essential in a reactor that more energy is released from the fusion reactions than is required to heat the fuels and run the system. The power output from a reactor will be dependent upon the square of the number density (n_i) of nuclei and the volume of gas.

Power losses must also be kept to a minimum acceptable level by holding the hot gases in thermal isolation from the material surroundings. The effectiveness of this confinement can be measured by the energy confinement time (τ_E) which can be viewed as the time taken for the system to cool down once all external forms of heating are switched off.

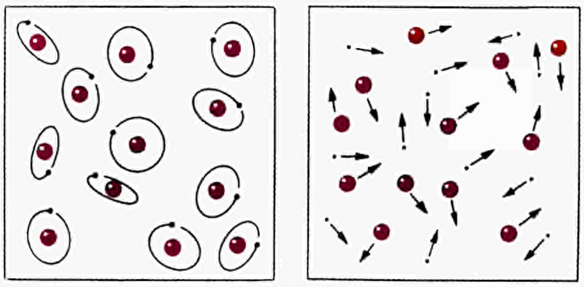
In a fusion reactor the values of temperature, density and energy confinement time must be such that their product ($n_i.\tau_E.T_i$), exceeds the figure of $5\times10^{21}\,m^{-3}\,s$ keV. *Typical values for the parameters that must be attained simultaneously for a reactor are:*

Central ion temperature T_i	10-20 keV
Central ion density n_i	$2.5\times10^{20}\,m^{-3}$
Global energy confinement time τ_E	$1-2\,s$

The temperature is expressed as the average energy of the nuclei with 1 keV approximately equal to 10 million degrees K.

Plasma

As the temperature of the fuel is increased, the atoms in the gas become ionised with the electrons, which normally orbit around the nuclei, stripped away to form a mixture of positively charged ions and negatively charged electrons. In this state the physical properties of a gas are very different from those under normal circumstances and a special name is given to this fourth state of matter—PLASMA.



Gas *Plasma*

The fact that a plasma is a mixture of charged particles means it can be controlled and influenced by magnetic fields. With a suitably shaped field it should be possible to confine the plasma with a high enough density and a sufficiently long energy confinement time to provide the conditions for a reactor.

The configuration that has so far proved to be most successful towards achieving reactor conditions and on which most data is available is the so called TOKAMAK, originally developed in the USSR.

JET and the Euratom and International Fusion Programmes

The Joint European Torus

JET uses the tokamak magnetic field configuration to maintain isolation between the hot plasma and the walls of the surrounding vacuum vessel. A diagram of the JET apparatus is shown in Fig. 2 and the principal design parameters are given in Table 1. The toroidal component of the magnetic field on JET is generated by 32 large D-shaped coils with copper windings, which are equally spaced around the machine. The primary winding (inner poloidal field coils) of the transformer, used to generate the plasma current for producing the poloidal component of the field, is situated at the centre of the machine. Coupling between the primary winding and the plasma, acting as the single turn secondary, is provided by the massive eight limbed transformer core. Around the outside of the machine, but within the confines of the transformer limbs, is the set of six field coils (outer poloidal field coils) used for shaping and stabilising the position of the plasma.

During operation large forces are produced due to interactions between the currents and magnetic fields. These forces are constrained by the mechanical structure which encloses the central components of the machine.

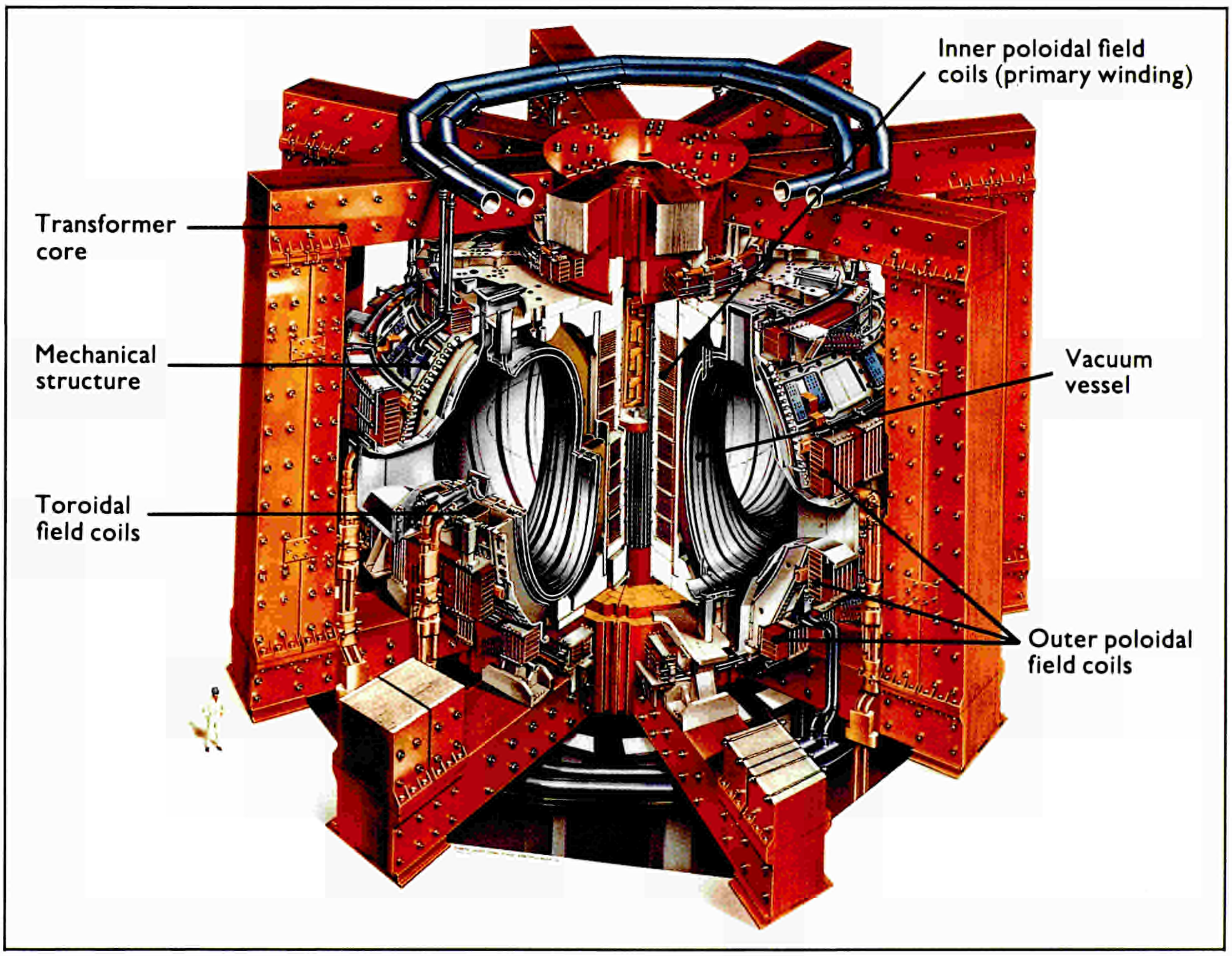
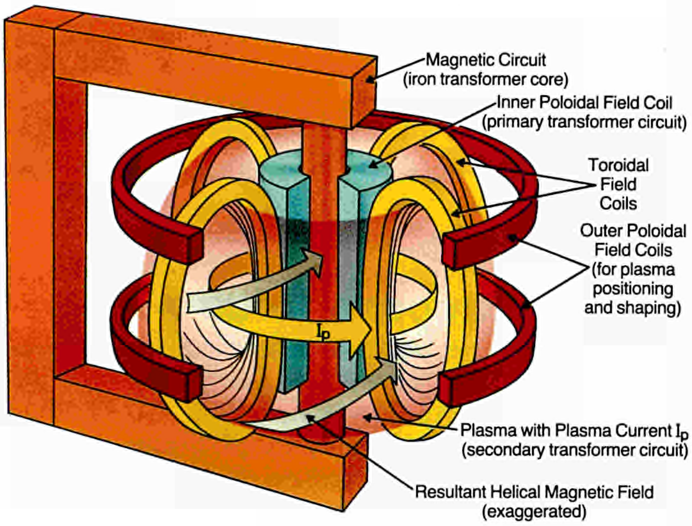


Fig. 2 Diagram of the JET Tokamak

The Tokamak

The tokamak magnetic field configuration is built up from three components. The first of these is produced by a set of coils around the minor circumference. These coils produce the toroidal magnetic field around the major axis of the machine. The second component (poloidal field) is produced by a large current caused to flow through the plasma by transformer action. The combination of these produces a helical magnetic field which keeps the plasma away from the vessel walls. The final component is generated by a set of hoop coils which is used to shape and stabilise the position of the plasma.



The use of transformer action for producing the large plasma current means that the JET machine operates in a pulsed mode. Pulses can be produced at a maximum rate of about one every ten minutes, with each one lasting up to 30s. The plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96m and a D-shaped cross-section of 4.2m by 2.5m. The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gram.

The construction phase of the Project, from 1978 to 1983, was completed successfully within the prescribed five year period and within 8% of the projected cost of 184.6MioECU at January 1977 values.

Table 1
Main Design Parameters of JET

Plasma minor radius:	
horizontal	1.25m
vertical	2.10m
Plasma major radius	2.96m
Flat top pulse length	20s
Weight of the iron core	2800t
Toroidal field coil power (peak on 13s rise)	380MW
Toroidal magnetic field at plasma centre	3.45T
Plasma current:	
circular plasma	3.2MA
D-shape plasma	4.8MA
Volt-seconds available to drive plasma current	34Vs
Additional heating power	25MW

Heating

Initial production and heating of the plasma is produced by the large electric current (ohmic heating) used to generate the poloidal magnetic field.

The heating effect of this current is reduced as the plasma gets hotter as its electrical resistance decreases with increasing temperature. It is therefore necessary to provide additional means of heating if the temperatures needed for a reactor are to be reached.

Two additional heating methods are in general use:

(1) Neutral Beam Heating. In this method, a beam of charged hydrogen or deuterium ions is accelerated to high energies and directed towards the plasma. As charged particles cannot cross the magnetic field confining the plasma, the beam must be neutralised. The resulting neutral atoms cross the magnetic field and give up their energy through collisions to the plasma, thereby raising its temperature.

(2) Radio Frequency Heating. Energy can be absorbed by the plasma from high power radio-frequency waves. The frequency of operation is chosen to be close to that at which the ions or electrons orbit or gyrate in the magnetic field.

The first plasma pulse was achieved on 25 June 1983 with a plasma current of 17 000 A lasting for about one tenth of a second. The JET Tokamak is shown in Fig.3 just prior to the start of operation in June 1983. This first phase of operation was carried out using only the large plasma current to heat the gas. In 1985, the first additional heating system, employing radio-frequency heating, came into operation and during 1986 reached its full design capability with 12 MW of output power from the generators. The first neutral beam heating system was brought into operation in 1986, with up to 10 MW of power injected into the torus.

So far, experiments have been carried out using hydrogen or deuterium plasmas. In the final stage of the programme it is planned to operate with deuterium-tritium plasmas so that abundant fusion reactions occur. The alpha particles liberated from the reactions should then produce significant heating of the plasma. During this phase of operation the machine structure will become radioactive to such an extent that all repairs and maintenance will have to be carried out using remote handling systems.

Research and Training Programme for Euratom in the Field of Controlled Thermonuclear Fusion

(Euratom Fusion Programme)

Under the Euratom Treaty, the Community research programme in the field of controlled thermonuclear fusion is adopted by the Council of Ministers for periods not exceeding five years. In accordance with the decision of the Council, the programme is part of a long-term co-operative project embracing all the work carried out in the Member States on nuclear fusion. It is designed to lead in due course to the joint construction of power-producing prototype fusion reactors, with a view to their industrial production and marketing. Periodically, a new multi-annual programme is adopted which overlaps the previous one. The current programme, for the period 1985-89, was adopted by the Council on 12 March 1985.

The programme is implemented principally by means of Contracts of Association between Euratom and

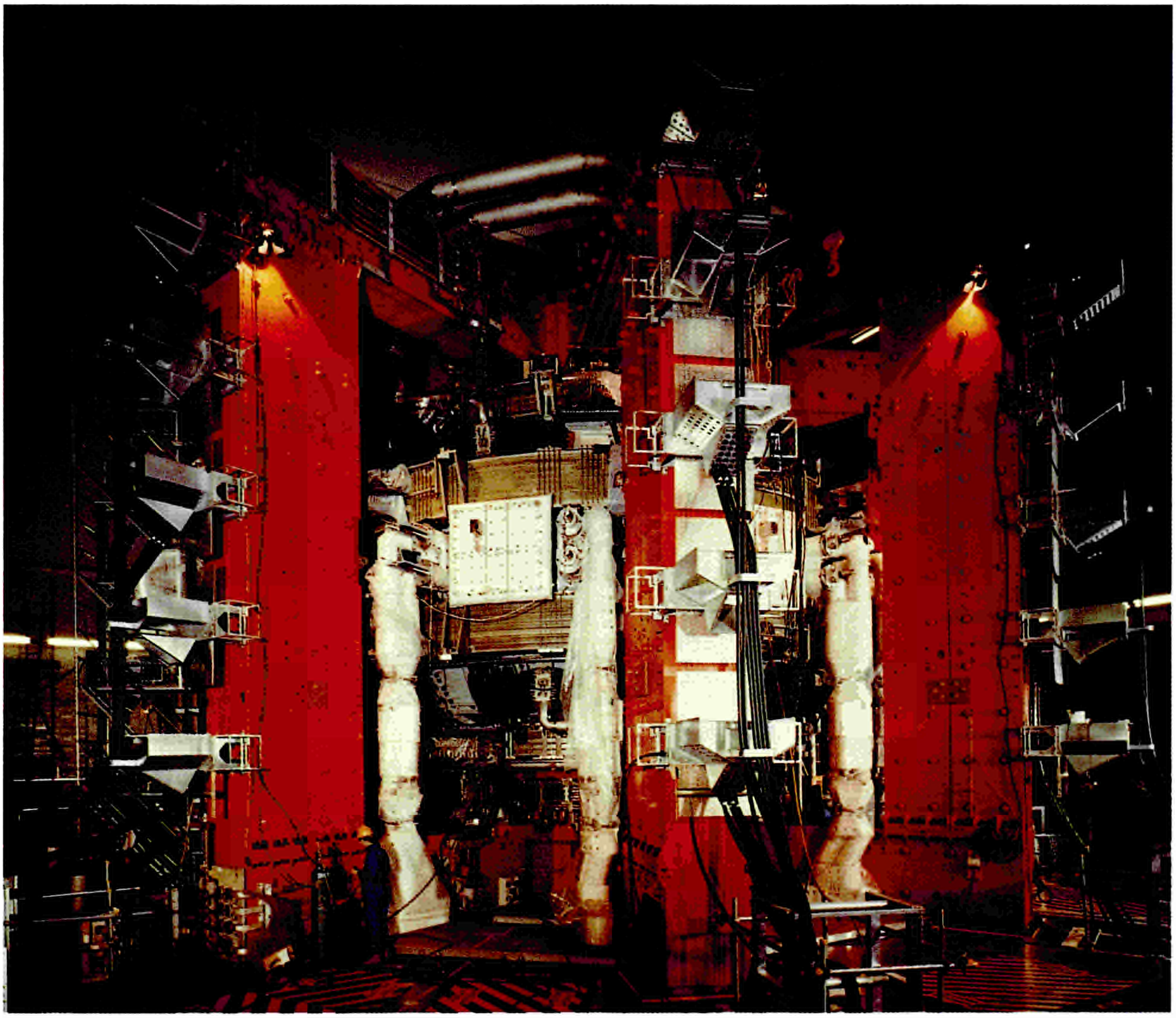


Fig. 3 The JET Tokamak prior to the start of operation in 1983

organisations within the Member States that are active in the field, by the JET Joint Undertaking and by the NET (Next European Torus) Team at IPP, Garching, F.R.G. Part of the programme of the Joint Research Centre at Ispra, Italy, is devoted to fusion technology.

In 1976, Sweden, and in 1978 Switzerland, at their request, joined the Community fusion programme. Greece joined the JET Joint Undertaking in 1983 and on 5 June 1987, Portugal and Spain also became members. The locations of fusion research laboratories involved in the Euratom fusion programme are shown in Fig.4.

The strategic assumptions underlying the Euratom fusion programme which were recommended in 1981 by the 'European Fusion Review Panel' and endorsed by the Council of Ministers are:

- The need to pursue a substantial programme following the tokamak route towards a demonstration fusion reactor (DEMO);
- The completion of the first stage of the programme, which is the JET Project with its extensions, and programmes carried out in support of the tokamak confinement system;
- A reasonable effort within available resources on alternative confinement systems with reactor potential;
- The concept of a single step, NET, between JET and DEMO and an increasing activity towards the development of the technology required in this context, guided by conceptual studies.

The scientific and technical achievements of the European Fusion Programme places Europe in the forefront of world fusion research. JET, which is the leading fusion experiment in the world, has made formidable progress towards the demonstration of the scientific feasibility of fusion. A substantial contribution towards this success has been due to research carried out in the Associated Laboratories such as the discovery of the H-mode and development of plasma heating systems.

Large International Tokamaks

There are now three large tokamaks operating in the world: TFTR, at Princeton in the USA, started operating in December 1982; JET which followed in June 1983; the Japanese machine, JT-60, which became operational in April 1985. The three projects have complementary aspects. For example, JET and TFTR are designed to operate with deuterium and tritium plasmas. JET has the largest plasma diameter, volume and current, but lowest toroidal magnetic field of the three large machines. JT-60 has a form of divertor and in addition has the potential for the highest additional heating into the plasma. Fig. 5 illustrates the relative sizes of these three tokamaks and their major operating parameters.

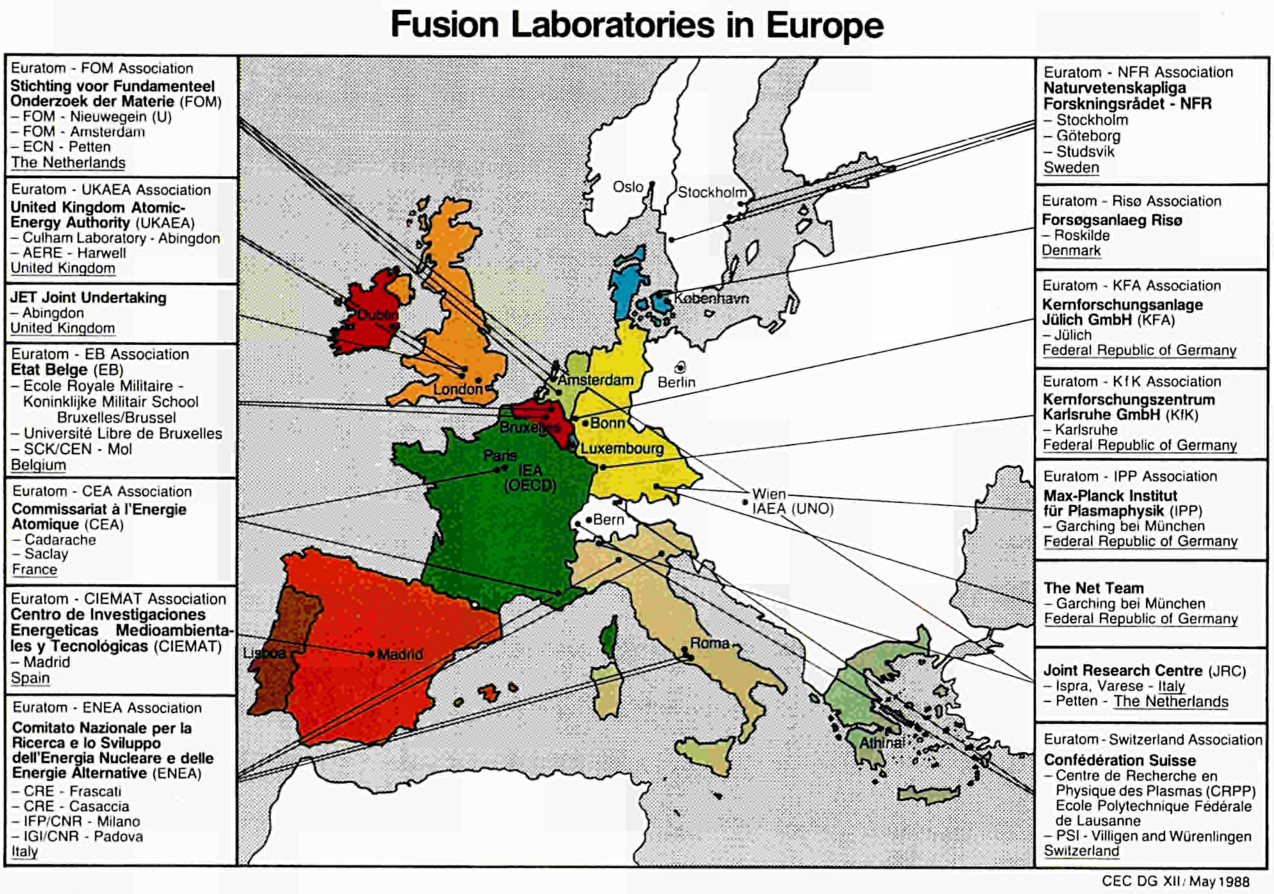


Fig. 4 Location of organisations associated with the Euratom fusion programme

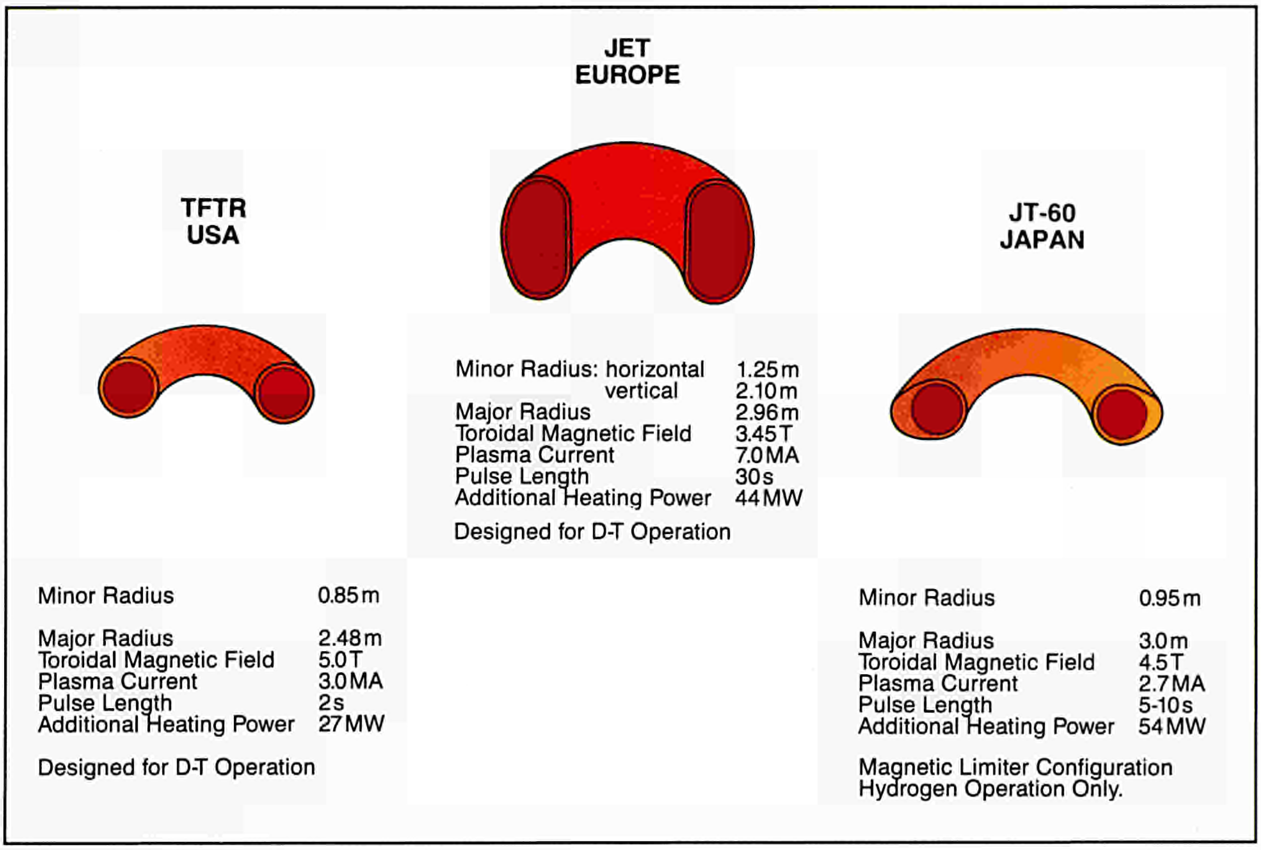


Fig. 5 The operating parameters of the three large tokamaks

In terms of fusion product achieved, both JET and TFTR have obtained a fusion product ($n_i.\tau_E.T_i$) of $2\times10^{20}m^{-3}$ s keV. JET however, achieved this value of fusion product under conditions directly relevant for a reactor.

JET is a flexible device which can adapt to different combinations of heating in various limiter and magnetic configurations. High confinement times (H-mode) have been achieved in the X-point (separatrix) configuration in JET and have kept JET clearly in the forefront of world fusion research.

An agreement was signed in 1986, for the exchange of information between the three large tokamak groups.

Present research is concentrated towards proving scientific feasibility and approaching the conditions that will be needed in a reactor. After the successful completion of this stage the need will still remain for large programmes to develop suitable technology and prove the economic viability of a reactor system. The long-term nature of these research programmes, means that a fully developed commercial system is unlikely to become available until well into the next century.

Technical Status of JET

Introduction

In this chapter the present technical status of JET is described. The first section outlines details of the development and improvements made to the system in 1987, especially those made in the major shutdown which took place during the first half of the year. Machine operations in the remainder of the year are summarised in the second section and the final section gives details of continuing technical developments on equipment for installation in the future.

Technical Achievements

The first part of 1987 was devoted to a major shutdown with machine operations restarting again in June. During the shutdown period major modifications and enhancements were made to a number of the machine systems and the success of these was amply demonstrated during the subsequent operating period. The plasma start-up conditions were greatly improved which has allowed the use of larger premagnetisation currents and has enabled 5MA plasma currents to be obtained with 10s flat tops. By using the newly installed Poloidal Field Booster Amplifier (PFX), plasma currents of 6MA have already been obtained with a 2s flat-top period. A comparison between the current-pulse distributions for 1986 and 1987 is shown in Fig. 6. These successes have been very encouraging but operations of the machine above the original design rated values are carried out with great care and a number of technical restrictions have been imposed so that it is operated within conservative limits. These limitations are being studied and tests or design modifications planned so that progress can be maintained during 1988.

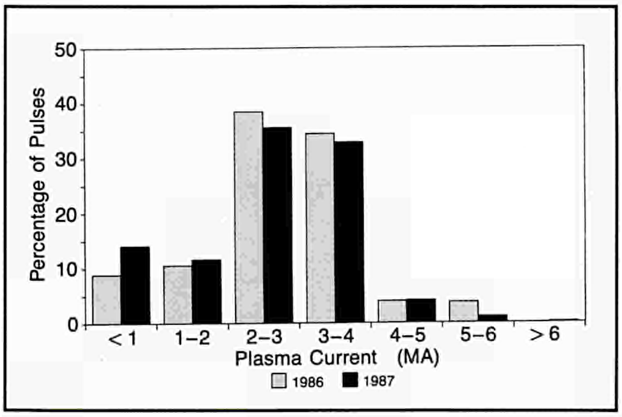


Fig. 6 Comparison of current-pulse distributions for 1986 and 1987

Modifications to the Poloidal Field Coil System

Major modification were made to the central poloidal field coil system to permit plasma currents up to 7MA with material limiters and up to 4MA in the X-point mode of operation. To facilitate these requirements two subcoils were added, bringing the total to 10, so that stray magnetic fields could be reduced and the breakdown of the gas and plasma start-up improved. Additional bus-bars were also connected to the six centre subcoils so that these could be controlled separately from those at the ends. This modification gives a greater flux swing capability and allows improved flexibility in controlling the plasma shape.

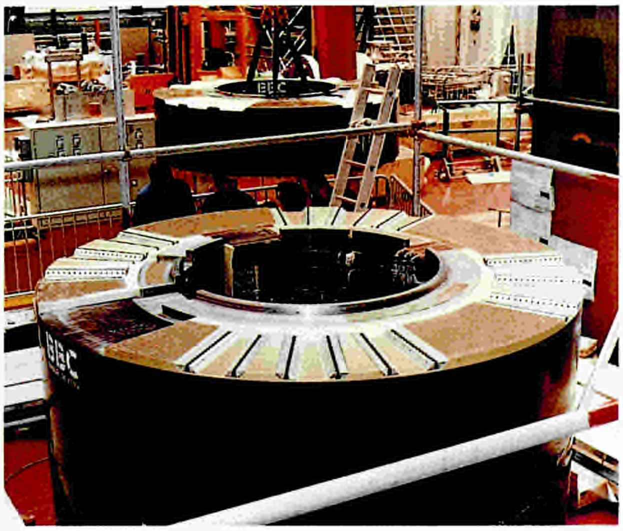


Fig. 7 Spring mechanism and keyways fitted to the inner poloidal field coils

When the central field coils were removed for these modifications, it was found that the keys, which locate and prevent relative rotation between sub-coils, were fractured. To prevent any reoccurence of this problem, the number of keys has been increased and spring mechanisms fitted so that the coils return to their starting position after each pulse. Figure 7 shows this new arrangement of keys.

Power Supplies

Major enhancements have been made to the power supplies for the poloidal field coils to allow operation at higher plasma currents both in material limiter and magnetic limiter(X-point) modes. The new additions to the poloidal field circuit, Fig. 8, together with their associated safety interlock and control systems, that have been successfully brought into operation are:

- a switching network to control the rate of rise of the plasma current;
- the PFX power supply for controlling the current in the six centre sub-coils of the central poloidal field coil;
- the temporary booster amplifier for the poloidal vertical field current. This system is currently operating with a 2.8 kV booster which will be replaced by a 10 kV unit early in 1988.

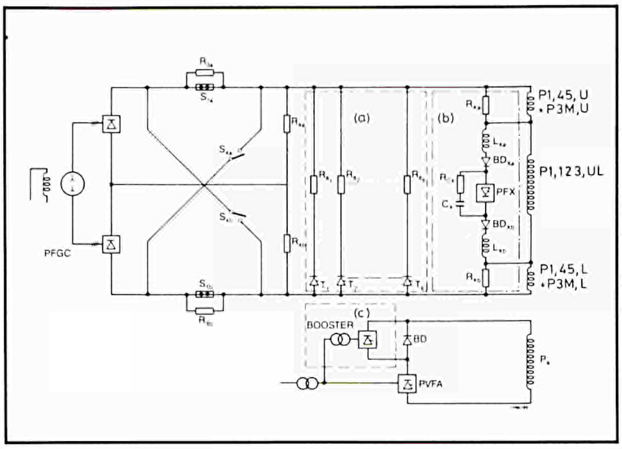


Fig. 8 New additions to the poloidal field circuit

Power Supplies

The electric power to the JET device during an experimental pulse is counted in hundreds of megawatts.

An agreement with the Central Electricity Generating Board (CEGB) allows up to 575 MW of pulse power to be taken directly from the 400 kV grid which after transformation down to 33 kV is fed to the JET loads through a system of circuit breakers.

Two flywheel generators are used to provide the peak power for the toroidal magnetic field coils and ohmic heating circuit. Each of the generators has a rotor 9 m in diameter weighing 775 tonnes. Between pulses, 8.8 MW pony motors are used to increase the speed of rotation. When power is required for a JET pulse, the rotor windings are energised and the rotational energy of the flywheel is converted into electrical energy. On slowing down from the maximum speed of 225 rpm to half speed, the generators can each delivery 2.6 GJ of energy with a peak power output of 400 MW.

Operation with this modified circuit at well above 4 MA in the X-point mode had been considered but has now been abandoned as it would require replacement of an outer poloidal field coil as well as requiring strengthening of the upper support structure for the toroidal field coils. A new scheme has been proposed in which 7 MA X-point operation could be achieved by driving the top and bottom outer poloidal field coils out of balance. This scheme would remove the need for a new coil and would have the advantage of transferring additional stresses to a less critical region.

As the 400 kV supply system has been developed to its full capacity, effort has been devoted to extending the AC auxiliary power system to cope with additional requirements. Figure 9 shows the outdoor AC-DC high voltage power supplies for neutral beam and radio frequency heating systems. By the end of the shutdown, over 100 km of new cable, involving forty different types, had been laid.

Fig. 9 Outdoor high voltage power supplies for neutral beam and radio frequency heating systems

In Vessel Components

The eight discrete graphite limiters were removed from the interior of the vacuum vessel and replaced by two toroidal belt limiters. The assembly of these components included the installation of pipework inside the vessel for water cooling which required the use, for the first time, of remote handling tools specially developed for cutting and welding. The belt limiters were assembled with a maximum deviation of ±1mm from the true circle. This provided an evenly distributed power loading from the plasma in the toroidal direction and, after adjustment of the plasma position, between the upper and lower belts. The belt limiter and other newly installed components are shown in Fig. 10.

Over half of the interior surface was covered with graphite tiles during the shutdown. This included forty belts of tiles covering the U-joints and bellows as well as a ring of carbon fibre reinforced graphite (CFC) tiles around the equatorial plane. Operational experience with the new CFC tiles has shown that even severe power loading has not resulted in any failure of these tiles although severe erosion has been observed. However, small modifications will have to be made to the surface shape of the inner wall to increase the power handling capabilities needed for a loading of up to 40MW for 10s.

Containment of Forces Acting on the Vacuum Vessel

Considerable effort has been devoted to estimating the forces that would act on the vacuum vessel during operations with increased plasma currents. Events which generate large forces on the vacuum vessel are radial plasma disruptions and vertical instabilities.

The results of calculations for disruptions show that large radial displacements of the inboard wall and of the vertical upper and lower ports of the vessel would be caused. It has therefore been decided to strengthen the vessel against these forces and at the end of 1987, a design was being prepared involving the welding of reinforcing rings to the inside of the vessel at the inboard wall.

Vertical instabilities of the plasma result in vertical forces on the vacuum vessel which depend, in a complex way, on the plasma current, configuration of the vertical and shaping fields and also the toroidal field. Tests have enabled more accurate scaling laws to be used to extrapolate the intensity of vertical forces at higher plasma currents. A radial force can be generated due to the vertical instabilities not being truly vertical, which could result in large radial displacements of the vertical ports. Hydraulic dampers will be connected to reduce the movement of these ports so that equipment connected to them is not damaged.

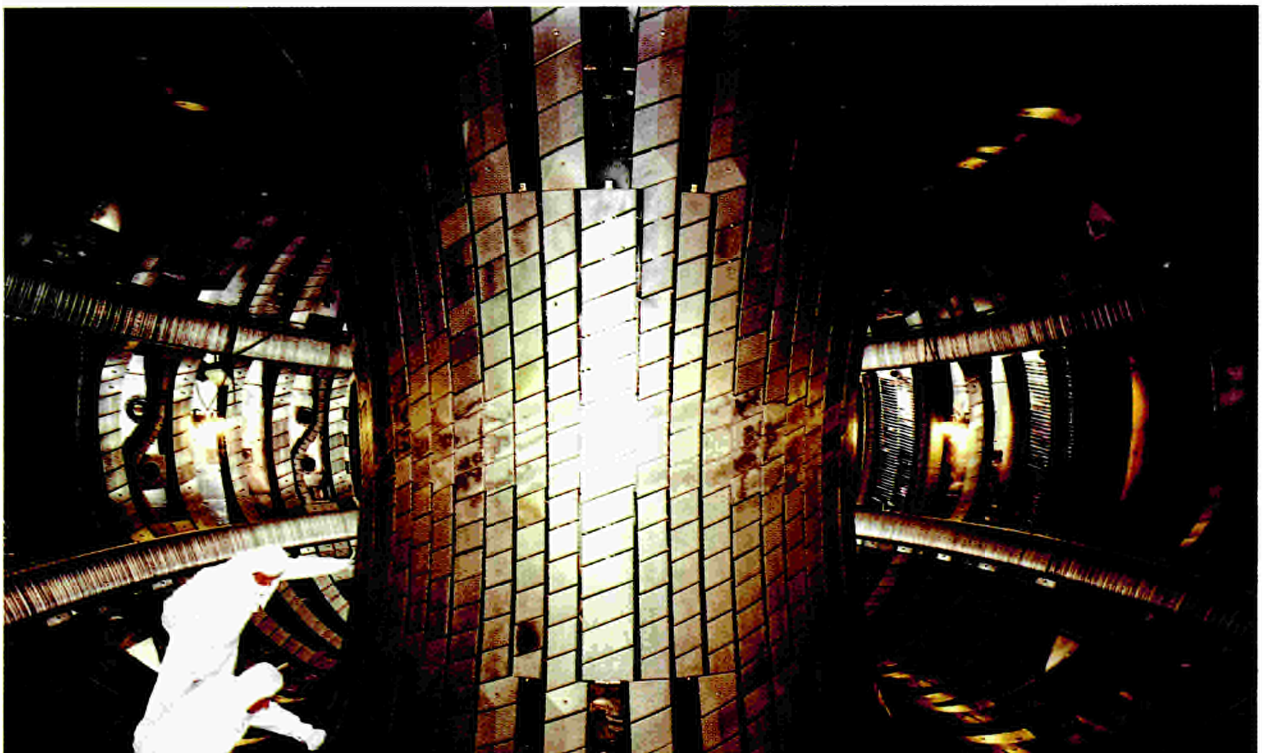


Fig. 10 Interior of the JET vacuum vessel

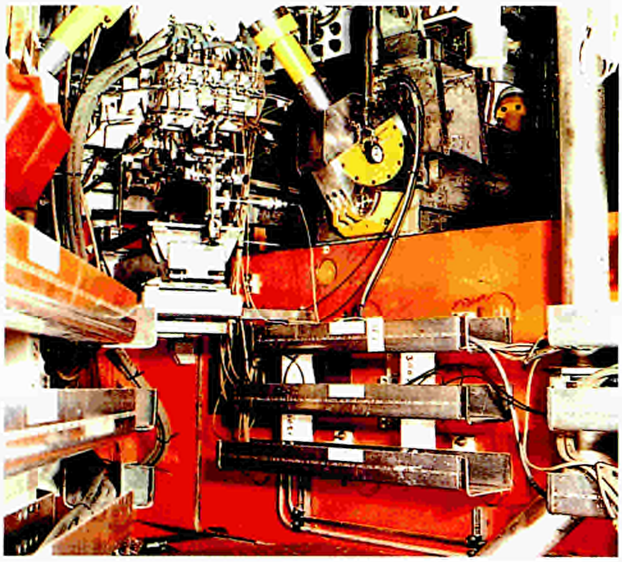


Fig. 11 Vacuum vessel supports

The vacuum vessel supports, which are shown in Fig. 11, were installed during the 1987 shutdown to cope with these forces but did not behave as expected. This was partly due to the inertial brakes not locking early enough. This was circumvented by decreasing the stiffness of the springs controlling the inertial brakes. An additional problem was friction in the bearings which caused some of the brakes to lock while the vessel was being heated up or cooled down. Friction was also present due to overheating and clearances being overtight in the spherical bearings connecting the brakes to the ports. The problem was solved by fitting new bearings based on a PTFE material and by controlling the temperature at the ports. It has also been decided to fit all brakes with active locking devices to ensure they all lock during plasma operation. These will be installed in 1988.

Neutral Beam Heating

During the shutdown, improvements and modifications were made to the neutral beam system at Octant No. 8 which has been in use since the beginning of 1986 and to the second unit scheduled to come into operation at the end of 1987. The second system is shown in Fig. 12 installed at Octant No. 4 of the torus. On two occasions after the start of operations, a water leak developed in the second stage of the neutralisers on the first neutral beam system. These failures were due to a delamination of the electrodeposited copper and were not associated with beam operations. All of these components are being replaced with new neutralisers using a different manufacturing technique.

After re-commissioning, a different fault occurred when one of the ignitron crowbars suffered a failure prior to a beam pulse. This resulted in only six power systems being available out of a full complement of eight. Considerable effort was expended in adding extra protection and six beams were brought into operation again in December. During subsequent operations, H-mode confinement in single-null X-point discharges was again established. Operation of all eight sources is expected by the middle of 1988 after the repair of the damaged power supply.

The second neutral beam system was in the final stages of commissioning at the end of 1987 with eight beam sources operating and beam extraction obtained from four of them. Beam injection into the machine is now scheduled for early in the new year.

An active magnetic shield has been planned for the neutral beam injector systems as operations at high plasma currents will lead to unacceptably large stray fields. This system consists of coils, with horizontal and vertical axis, fitted within the existing material shielding. Magnetic probes monitor the stray field from the tokamak and control the current in the coils via a feedback loop. A set of new power supplies for this system has been designed and is under procurement.

Neutral Beam Heating

The two JET neutral beam systems have been designed for long (~ 10s) beam pulses. They have the unique feature that each injector consists of eight beam sources in a single integrated beamline system connected to the torus. The first beam sources have been designed to operate at accelerating voltages up to 80kV and later on these will be substituted with units capable of operating up to 140kV.

Each system is connected to the torus by a long narrow duct through which 10MW of power can be directed.

Fig. 12 The second of the neutral beam injection systems

Radio Frequency Heating

Eight water cooled antennae for the radio frequency heating system have been installed between the two toroidal belt limiters. These antennae have been

Radio Frequency Heating

Ion Cyclotron Resonance Heating (ICRH) has been chosen for JET and the wide operating frequency band (25-55 MHz) allows the system to be operated with the various mixes of ion species required in the different phases of the scientific programme and to choose the location where the heating in the plasma occurs.

The ICRH system has been designed in eight identical modular units. Each unit is composed of a tandem amplifier chain, a network of coaxial transmission lines and matching elements and finally an antenna located in the vacuum vessel on the outer wall. Ultimately, the eight RF generators will produce a maximum output power of 32MW.

constructed with a newly designed central conductor to allow operation with both monopole and toroidal dipole configurations. Plasma protection is provided by columns of graphite tiles along the vertical sides of each antenna, with each tile located between nickel fins for good radiative heat transfer to the water-cooled manifold. Two of the water cooled antennae installed on the interior of the vacuum vessel can be seen in Fig. 10. Installations of the antennae were carried out with the help of the remote handling boom to demonstrate the feasibility of this kind of operation.

The 3MW output tetrodes in the generators are being replaced with 4MW items and by the end of 1987, five units had been converted. The upgrading of the generators, shown in Fig. 13, is expected to be completed by the end of 1988.

Operating the eight antennae at a single frequency, using the generators in a 'master/slave' configuration, has improved reliability as this has removed generator trips due to fluctuations in the reflected power caused by beats when nearby antennae are operated at close, but not identical, frequencies. To date, 16MW of power into the plasma has been achieved with both monopole and dipole phasings. This value is slightly in excess of the original design value of 15MW and with upgraded output tetrodes, as well as the installation of additional DC power supplies, should increase the power capability to 20MW.

Pellet Injection

Under the collaborative agreement between the US Department of Energy (DoE) and JET, a multi pellet injector has been installed, commissioned and operated.

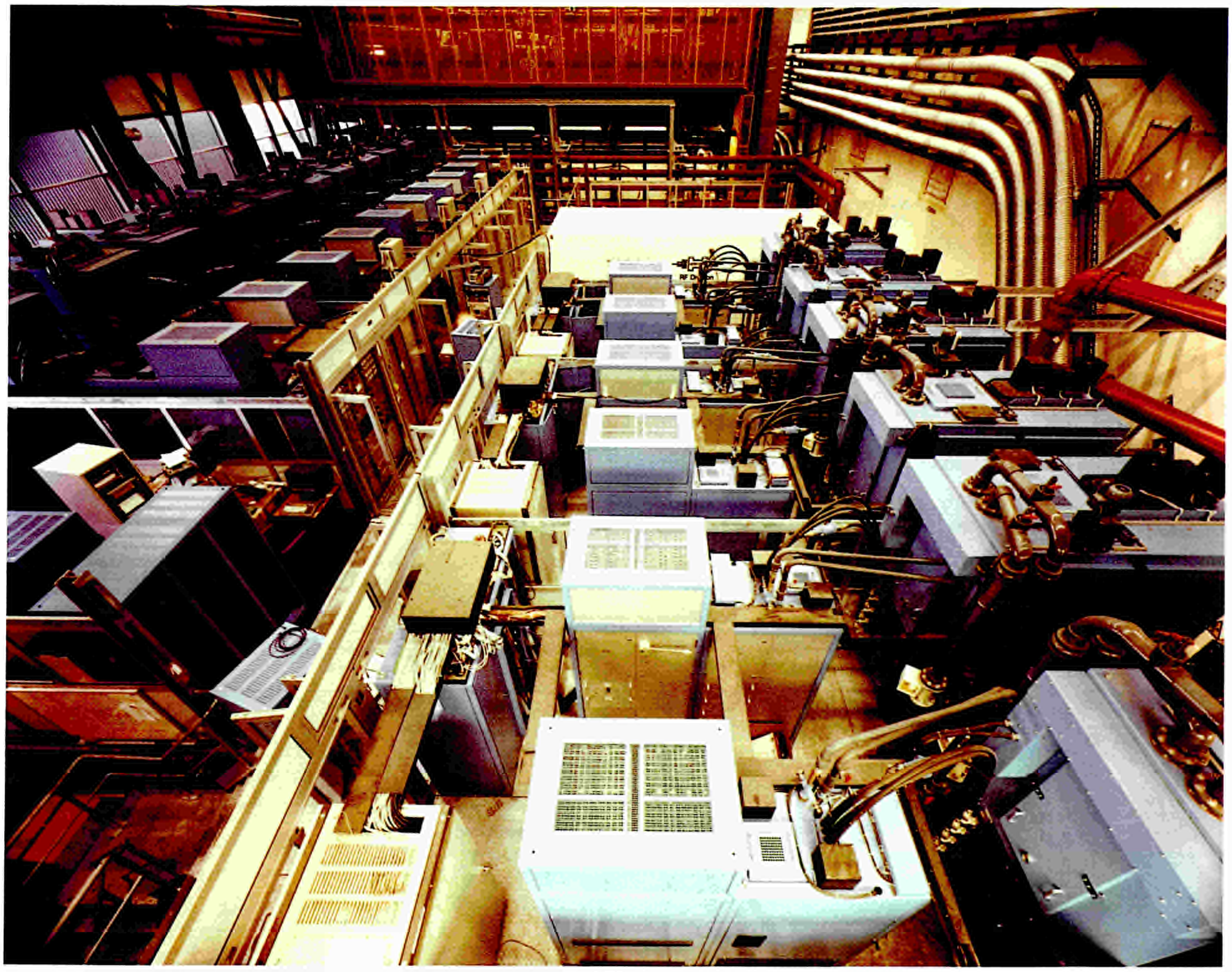


Fig. 13 The generators for the radio frequency heating system

The system, shown in Fig. 14, consists of the pellet launcher, interface with the JET machine and the respective controls. The launcher, which was provided by the DoE and built by Oak Ridge National Laboratory (ORNL) in USA, delivers pellets with diameters of 2.7, 4 and 6mm from the different barrels at repetition frequencies of several per second from each. The system was delivered in the early part of the year and is scheduled to operate in JET until the end of 1989. Despite the care taken in detailing the specifications, considerable effort was needed to interface the two systems into one unit. The complete system is now being operated from JET's machine control room and during the operational phase in 1987 delivered multiple pellets of all three sizes to the plasma.

Diagnostics

The location of the diagnostic systems, whose installation is now nearing completion, is shown in Fig. 15 and their status at the end of 1987 is shown in Table 2. Many of these systems operate automatically with minimal supervision from scientific staff. The measurements obtained are accurate and reliable and provide important information on the behaviour of the plasma.

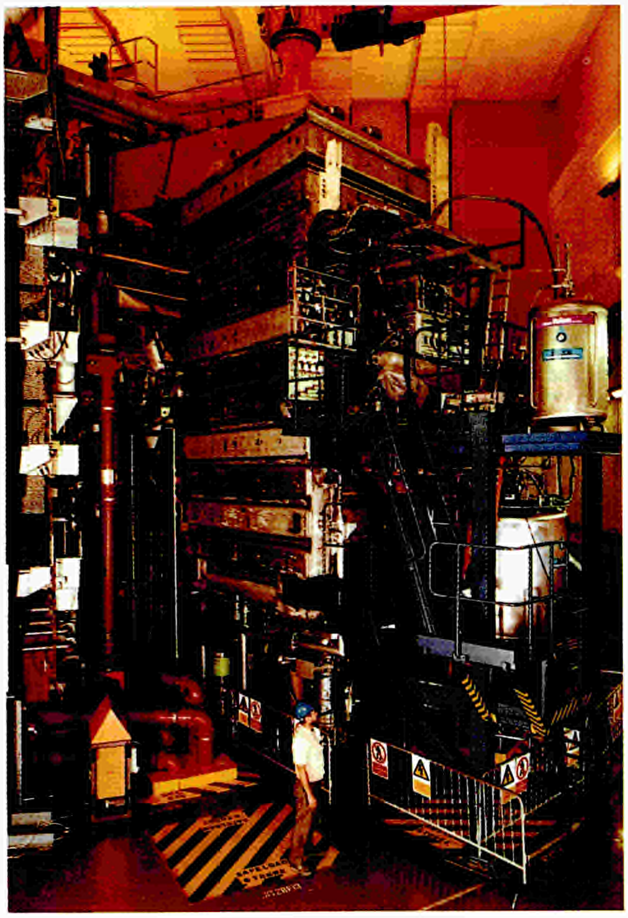


Fig. 14 The multi-pellet injector and interface ►

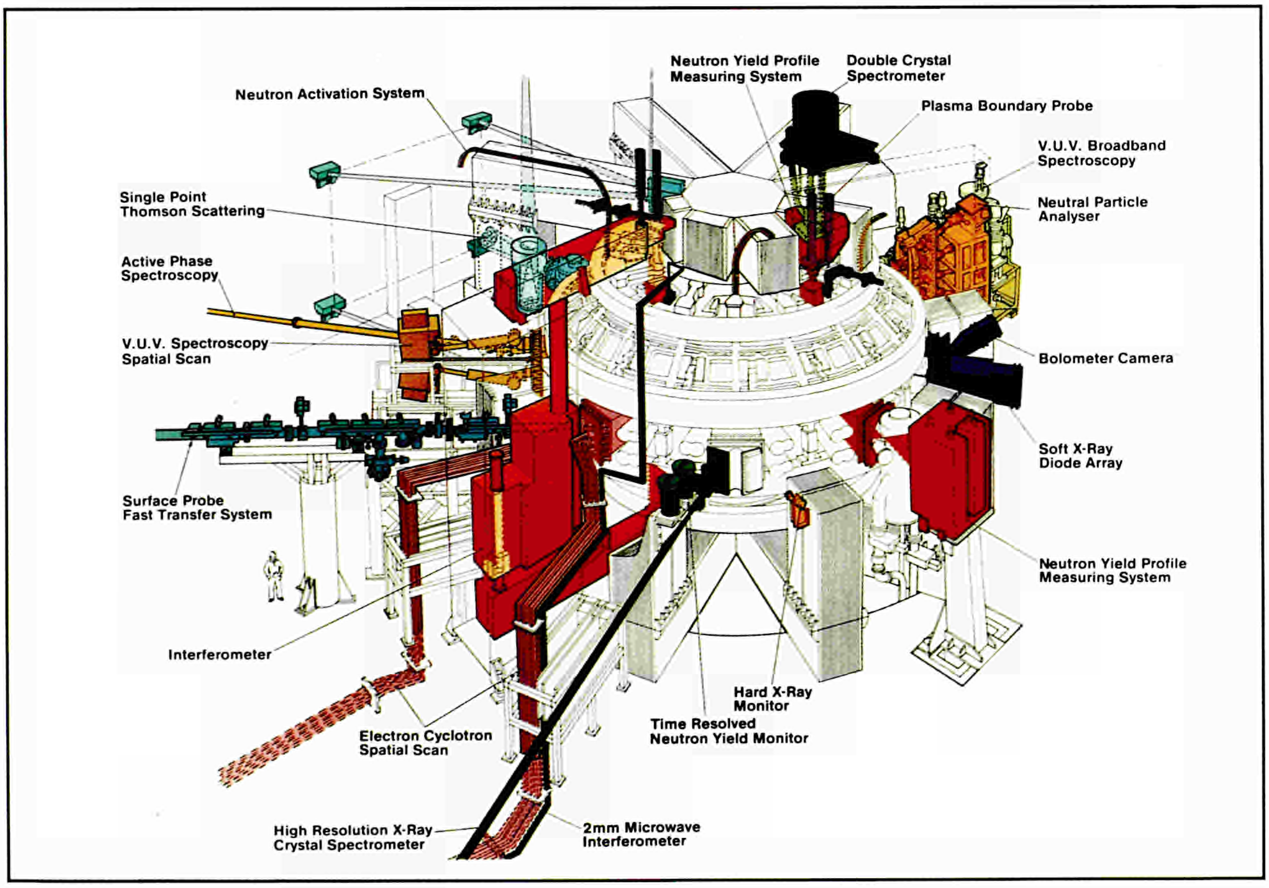


Fig. 15 Location of the JET diagnostic systems

Table 2
Status of the JET Diagnostics Systems, December 1987

System	Diagnostic	Purpose	Institution	Status (Dec. '87)	Compatibility with tritium	Level of automation
KB1	Bolometer Array	Time and space resolved total radiated power	IPP Garching	Operational	Yes	Semi-automatic
KC1	Magnetic Diagnostics	Plasma current, loop volts, plasma position, shape of flux surfaces, diamagnetic loop, fast MHD	JET	Operational	Yes	Fully automatic
KE1	Single Point Thomson Scattering	T_e and n_e at one point several times	Risø	Operational	Yes	Fully automatic
KE3	Lidar Thomson Scattering	T_e and n_e profiles	JET and Stuttgart University	Operational	Yes	Fully automatic
KG1	Multichannel Far Infrared Interferometer	$\int n_e ds$ on 6 vertical chords and 2 horizontal chords	CEA Fontenay-aux-Roses	Operational	Yes	Semi-automatic
KG2	Single Channel Microwave Interferometer	$\int n_e ds$ on 1 vertical chord	JET and FOM Rijnhuizen	Operational	Yes	Fully automatic
KG3	Microwave Reflectometer	n_e profiles and fluctuations	JET	(1) Prototype system operational (2) Multichannel system in commissioning.	Yes	(1) Not automatic (2) Will be fully automatic
KG4	Polarimeter	$\int n_e B_p ds$ on 6 vertical chords	CEA Fontenay-aux Roses	Operational	Yes	Semi-automatic
KH1	Hard X-ray Monitors	Runaway electrons and disruptions	JET	Operational	Yes	Fully automatic
KH2	X-ray Pulse Height Spectrometer	Plasma purity monitor and T_e on axis	JET	Operational	Yes	Semi-automatic
KJ1	Soft X-ray Diode Arrays	MHD instabilities and location of rational surfaces	IPP Garching	Operational	No	Semi-automatic
KK1	Electron Cyclotron Emission Spatial Scan	T_e (r,t) with scan time of a few milliseconds	NPL, UKAEA Culham and JET	Operational	Yes	Fully automatic
KK2	Electron Cyclotron Emission Fast System	T_e (r,t) on microsecond time scale	FOM, Rijnhuizen	Operational	Yes	Fully automatic
KK3	Electron Cyclotron Emmission Heterodyne	T_e(r,t) with high spatial resolution	JET	Operational	Yes	Not yet implemented
KL1	Limiter surface temperature	Monitor of hot spots on limiter, walls and RF antennae	JET and KFA Jülich	Operational	No	Fully automatic
KL3	Infrared belt limiter viewing	Temperature of belt limiters	JET	Commissioning	No	Will be fully automatic
KM1	2.4MeV Neutron Spectrometer		UKAEA Harwell	Commissioning	Not applicable	Semi-automatic
KM3	2.4MeV Time-of-Flight Neutron Spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	NEBESD, Studsvik	Operational	Not applicable	Fully automatic
KM4	2.4MeV Spherical Ionisation Chamber		KFA Jülich	Commissioning	Yes	Will be fully automatic
KM2	14MeV Neutron Spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	Under Construction	Yes	Not yet installed
KM5	14MeV Time-of-Flight Neutron Spectrometer		SERC, Gothenberg		Yes	Not yet installed
KM7	Time-resolved neutron yield monitor	Triton burning studies	JET and UKAEA Harwell	Operational	Not applicable	Fully automatic
KN1	Time Resolved Neutron Yield Monitor	Time resolved neutron flux	UKAEA Harwell	Operational	Yes	Fully automatic
KN2	Neutron Activation	Absolute fluxes of neutrons	UKAEA Harwell	Operational	Yes	Semi-automatic
KN3	Neutron Yield Profile Measuring System	Space and time resolved profile of neutron flux	UKAEA Harwell	Operational	Yes	Fully automatic
KN4	Delayed Neutron Activation	Absolute fluxes of neutrons	Mol	Commissioning	Yes	Fully automatic
KP2	Fusion Product Detectors	Charged particles produced by fusion reactions	JET	Operational	No	Semi-automatic
KR1	Neutral Particle Analyser Array	Ion distribution function, $T_i(r)$	ENEA Frascati	Operational	Yes, after modification	Semi-automatic
KR2	Active Phase NPA	Ion distribution function, $T_i(r)$	ENEA Frascati	Under study	Yes	Fully automatic
KS1	Active Phase Spectroscopy	Impurity behaviour in active conditions	IPP Garching	Operational early '88	Yes	Not yet implemented
KS2	Spatial Scan X-ray Crystal Spectroscopy	Space and time resolved impurity density profiles	IPP Garching	Operational	No	Not yet implemented
KS3	H-alpha and Visible Light Monitors	Ionisation rate, Z_{eff}, Impurity fluxes	JET	Operational	Yes	Semi-automatic
KS4	Charge Exchange Recombination Spectroscopy (using heating beam)	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Operational	Yes	No
KT3	Active phase CX spectroscopy		JET	Under construction	Yes	Not yet implemented
KT1	VUV Spectroscopy Spatial Scan	Time and space resolved impurity densities	CEA Fontenay-aux-Roses	Operational	No	Semi-automatic
KT2	VUV Broadband Spectroscopy	Impurity survey	UKAEA Culham	Operational	No	Fully automatic
KT4	Grazing Incidence Spectoscopy	Impurity survey	UKAEA Culham	Operational	No	Semi-automatic
KX1	High Resolution X-ray Crystal Spectroscopy	Ion temperature by line broadening	ENEA Frascati	Operational	Yes	Fully automatic
KY1	Surface Analysis Station	Plasma wall and limiter interactions including release of hydrogen isotope recycling	IPP Garching	Operational	Yes	
KY2	Surface Probe Fast Transfer System		UKAEA Culham	Operational	Yes	Automated, but not usually operated unattended
KY3	Plasma Boundary Probes	Vertical probe drives for electrical and surface collecting probes	JET, UKAEA Culham and IPP Garching	Operational	No Under study	
KY4	Fixed Langmuir Probes (X-point and belt limiter)	Edge parameters	JET	Operational	Yes	Semi-automatic
KZ1	Pellet Injector Diagnostic	Particle transport, fuelling	IPP Garching	Operational	Yes	Not automatic
KZ3	Laser Injected Trace Elements	Particle transport, T_i	JET	Under construction	Yes, after mocification	Not yet implemented

Boundary Measurements

The magnetic measurement system has continued to work routinely and reliably. Front end processing has been adapted to allow for operation with plasma currents up to 7 MA and special pick-up coils have been installed near the X-point region to provide much better resolution in this area.

The number of boundary probes has been substantially increased so that plasma parameters can be measured in nearly all of the important areas. An extensive experimental data set of boundary measurements has been compiled showing the scaling with the main plasma parameters. A fast-moving Langmuir probe has been delivered, which has been designed to cross the boundary and reach about 5 cm inside the main plasma, to provide a scan within 200 ms.

Samples of limiters, protection tiles and small, well prepared long-term samples have been retrieved from the vessel each time it is opened. Surface analysis has been performed in-house with ion-beam and Auger techniques as well as in external laboratories.

A new system for monitoring the limiters, based on a cooled infra-red array working at a wavelength of 3-5 μm, has been delivered and is awaiting installation.

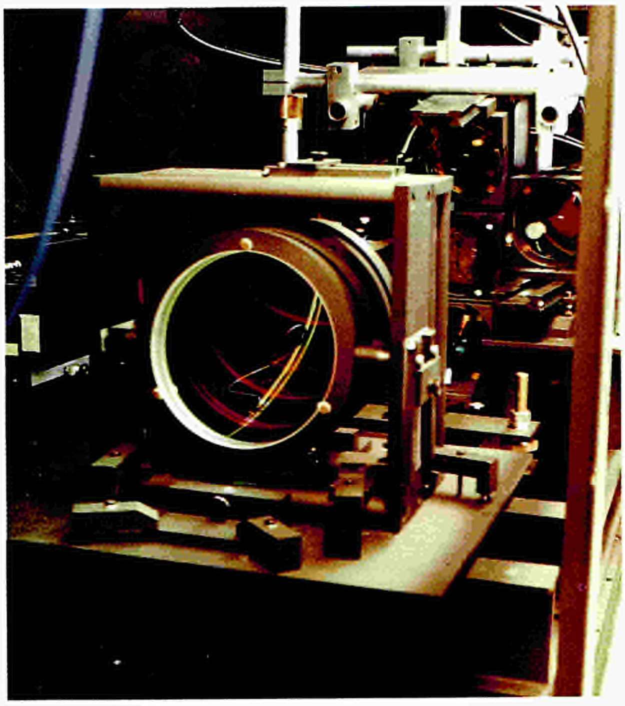


Fig. 16 The Spectrometer for the LIDAR Thomson scattering diagnostic. In front is the edge filter stack to give the spectral dispersion and behind, the imaging lenses for the yellow, red and green channels

Temperature and Density Measurements

The electron cyclotron emission (ECE) systems have been operated routinely during the year. The electron temperature data, provided by these systems, has been used in a wide variety of plasma physics studies. In addition, the heterodyne radiometer has provided electron temperature measurements at eight locations with very good spatial and temporal resolution.

The single point Thomson scattering system has been operated regularly during the year and the data provided used in the overall assessment of JET plasmas and for validation of electron temperature measured by ECE systems. During the shutdown, the system was completed and now comprises six spectral channels covering the wavelength range 400 μm – 800 μm. Considerable progress has been made with the LIDAR Thomson scattering system which allows spatially resolved measurements of electron temperature and density to be made. The system has been in operation since the shutdown and good agreement has been found with results from other diagnostics. The spectrometer for the LIDAR system is shown in Fig. 16.

The microwave transmission interferometer has been used for electron density measurements and for plasma control purposes. Progress has been made with the multichannel reflectometer which will probe the plasma at twelve frequencies so that density layers in the range from 0.4 to $8 \times 10^{19} m^{-3}$ can be investigated. During 1987, construction and installation of sufficient components were completed for two channels of this diagnostic to be brought into operation.

Neutron Measurements

Regular use has been made of the neutron yield monitors for measuring the flux of neutrons emanating from the plasma. In addition, they have been used in an extensive study of photoneutron emission which accompanies most major disruptions.

After an initial evaluation of the performance of the neutron profile monitor, substantial improvements were made during the 1987 shutdown and this diagnostic is now providing reliable data on a routine basis.

Three neutron spectrometers are currently in operation and can be regarded as a single unit as their different characteristics provide some three orders of magnitude range of neutron intensity. Measurements have been made of the confinement and slowing down of 1 MeV tritons emitted from the $D + D \rightarrow T + p$ reaction by observing the 14 MeV neutrons from the $D + T \rightarrow n + {}^4He$ reactions induced by the fast tritons. Two approaches have been used, the first involving the neutron activation system to measure the ratio of 14 MeV to 2.5 MeV neutrons while the second measures the instantaneous emission strength of 14 MeV neutrons during a brief period of neutral beam heating using deuterium atoms.

Gamma Ray Studies

Gamma rays are emitted as a result of all light particle fusion reactions. This has been particularly useful as it provides a means of monitoring the 16 MeV gamma rays emitted from the ${}^3He + D$ reaction when ${}^3He$ is the minority species during radio frequency heating. These measurements have been used to demonstrate the generation of about 10 kW of fusion power during machine operation.

Remote Handling

During the shutdown, the articulated boom was used extensively for installing the belt limiters, Fig. 17, and new radio frequency antennae. Generally the boom was operated under manual control but some experiments were carried out using the 'teach-repeat' mode. A real-time 3-D computer generated display of the articulated boom, Fig. 18, has been successfully commissioned and connected to it. A similar system for ex-vessel remote handling work is now being defined.

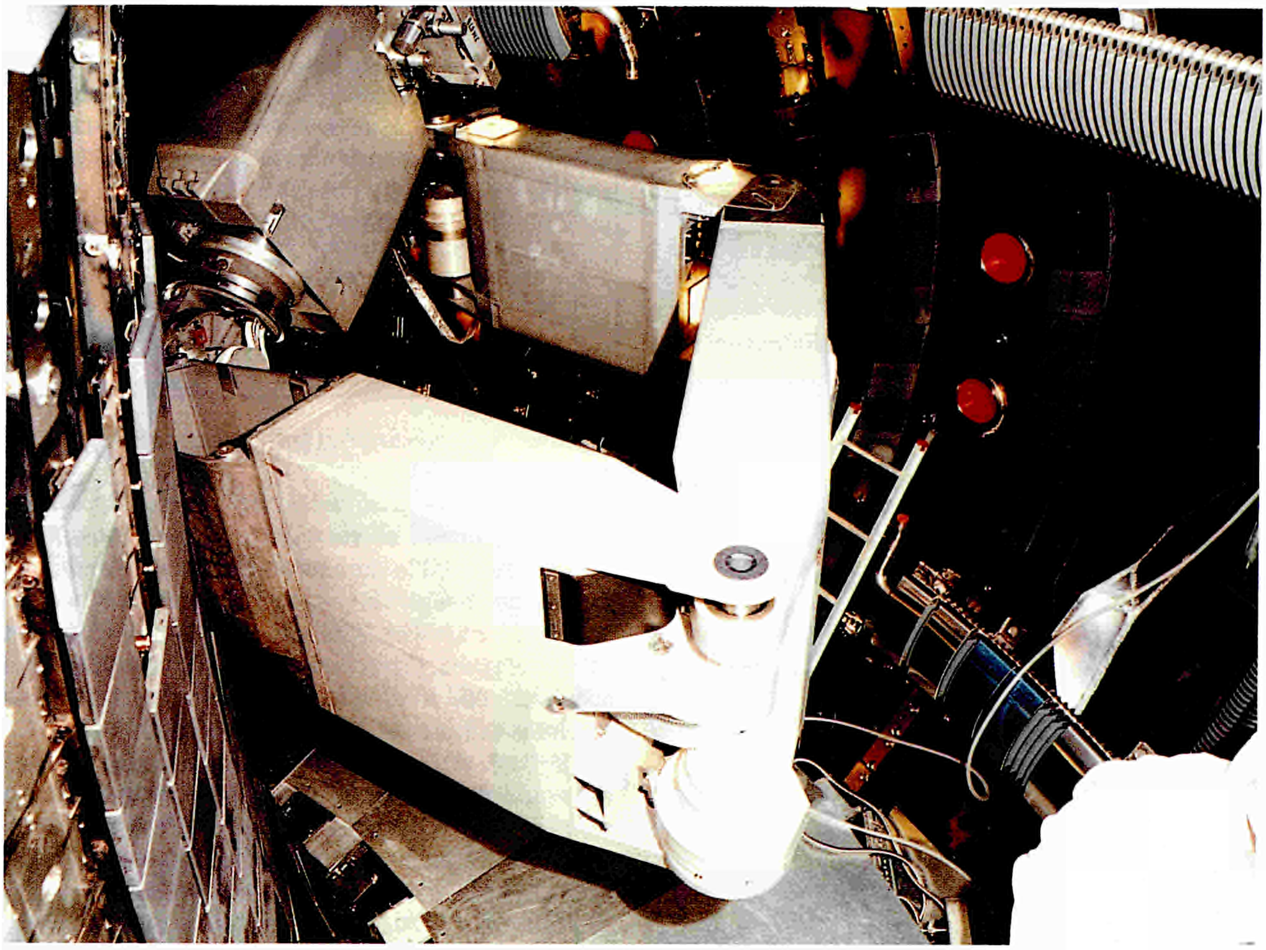


Fig. 17 The articulated boom being used to install a section of a belt limiter

A new boom extension, with the relevant controls, has been procured and is being commissioned. This will be used initially on a turret truck for trials on mock-ups and, later, on the telescopic transporter (TARM) mounted on the crane. The low-level transporter was used, under manual control, to install vacuum pumps during the shutdown and the additional equipment for conversion to a fully remote-controlled unit has been specified.

The first of the two mascot servomanipulators was delivered in mid-1987 and the second unit has been completed ready for delivery in its basic configuration. Over 200 vacuum seal welds were performed using automatic remote handling compatible welding tools and no leaks were experienced from these during subsequent operation. Improvements have been made to the in-vessel inspection system with the provision of a continuous lighting capability.

The TARM, to be used for remote maintenance on the exterior of the machine, has been ordered and is due for completion in early 1989. It will consist of a 17m telescopic mast attached to the overhead crane with an articulated end section. Rotary actuators with improved stiffness have been developed for use on the boom and

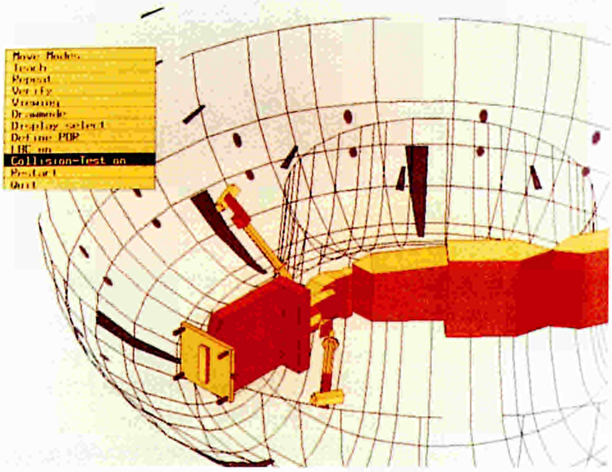


Fig. 18 Computer generated display of the articulated boom

TARM and a prototype has been manufactured.

Work on the remote handling control room has started and a prototype workstation tested with respect to the articulated boom and control of the welding power pack which can be operated fully remotely up to 100m from its power supply. The first phase of the closed circuit TV system has been installed and commissioned. This system will allow images and sound to be selected for display on any of the workstation and control room monitors. Installation of cameras and associated equipment will be carried out in the Torus Hall and other remote handling operational areas during 1988.

Control and Data Management

A major achievement in 1987 was the establishment of a JET Mainframe Data Processing Centre based on an IBM 3090/200E computer with one vector facility and some 70 Gigabytes of disc storage and a further 240 Gigabytes of IBM Mass Storage. The complex is housed at UKAEA Harwell and operated for JET by a team under contract from that Laboratory. The computer, shown in Fig. 19, is also connected to the Harwell CRAY 2 machine.

The transfer of the complete JET workload, including about 60 Gigabytes of data from the Harwell IBM 3084Q, which was previously used by JET, to the new computer was achieved within a month of delivery of the mainframe and with no interruption to normal service. The improvement in the computing service has been dramatic. Good interactive response is now provided for scientific and technical users as well as for those using the JET computer aided design systems. Prompt execution of the intershot analysis is provided together with a rapid turn-around of the batch work-load.

Fig. 19 The new JET mainframe IBM Computer located at Harwell

Control and Data Acquisition

Due to the high number of components and their distribution throughout a large site, the operation and commissioning of JET is supported by a centralised Control and Data Acquisition System (CODAS). This system is based on a network of Norsk Data minicomputers interfaced to the experiment through CAMAC instrumentation (including front end microprocessors) and signal conditioning modules. The various components have been logically grouped into subsystems with each one controlled and monitored by a computer. After a pulse all the information from the subsystem is merged together into a single file on the storage and analysis computer. This file is then sent to Harwell for detailed analysis. A summary of information from the JET pulses is held in the JET Survey Data Bank.

A review has been carried out of the data link between the JET computer at Harwell and the site at Culham. This has resulted in the choice of a system using three 2 megabaud British Telecom lines. Tests on the CODAS interface for use with this link have been successful and a transfer speed, in test mode, of 187 kBytes/s has been achieved. The final version of the software for the system is expected to be ready early in 1988.

The basic architecture of the control computers has been modified which has provided an improvement in the rate of data collection from 14 to 47 kBytes/s. The computer for controlling the pellet launcher has now been included into the operational system and work is continuing on the development of the control systems for tritium handling and lower hybrid current drive.

JET Computations

The data resulting from routine processing of the JET pulse file are stored in the Processed Pulse File (PPF) data base system. This contains some 3 Mbytes of data from each of 8600 pulses and is the source of information for almost all subsequent analysis. The JET Survey Data Bank gives a summary of the data from more than 7700 plasma pulses characterised by about 200000 time traces. For comparison with theoretical predictions, data banks with well checked and validated plasma data (including spatial and temporal dependencies) for a few selected discharges are being prepared.

Activities, in which important advances have been made during 1987, are detailed in the JET Progress Report. Among these are:

- Continuing improvements on transport codes for predicting the performance in new operating ranges and comparison with measurements from past discharges. Recent developments have been aimed at making existing codes more user friendly and for facilitating their use in special applications.

● Numerical modelling has included the heat and particle fluxes in the boundary layer of the plasma. This model includes the belt limiters and has been used to study the performance of the proposed pump limiters. A simplified model of the power deposition during radio frequency heating has also been developed.
● The transport code model, which model the temperature profiles best, reproduces their steady state and time evolution and has been used to predict the performance of 'next-step' devices.
● A wide range of problems relevant to JET have been studied analytically. Included amongst these are: the stability of monster sawteeth which may be due to energetic trapped ions produced by radio frequency heating; particle loss from the so-called 'snake' which sometimes occurs after pellet injection; the effect of energetic ions produced by additional heating; and problems relevant to ion cyclotron heating.

Summary of Machine Operation

The first period of operation in 1987 (weeks 20 to 33) were spent in commissioning the systems modified during the shutdown and the significant advantages of the modified central poloidal field coil assembly and the additional switching network in the ohmic heating circuit were rapidly demonstrated. The eight RF antennae and multi-pellet injector were also successfully brought into operation. However, there were some problems with the new vessel restraints and two water leaks in the neutralisers on one of the neutral beam heating systems delayed commissioning of these units.

There was a total of 133.5 operating days in 1987, during the period from June to December. About 50 % of these days were devoted to experimental operation, with 20 % allocated to each of ohmic and radio frequency heating, and about 10 % for combined neutral beam and radio frequency heating experiments. The allocation of time to different activities of the programme is shown in Fig. 20.

The organisation of operational time remained largely the same as that in 1986 except that commissioning was carried out in double-shift operation in an attempt to recover lost time. The total number of pulses achieved in 1987 was 2889 compared with 4902 in the previous year bringing the total number of pulses to 14113, see Fig. 21. Even though many of these pulses were for commissioning, the relative number of tokamak pulses continued to increase.

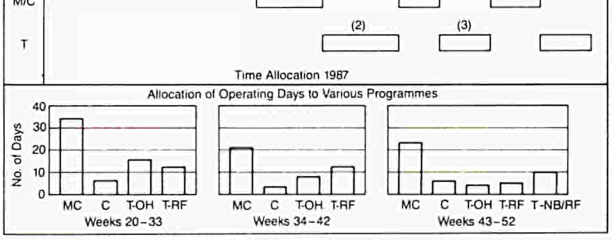


Fig. 20 Allocation line time to different activites in 1987
S = Shutdown,
M/C = Machine Commissioning
T = Tokamak Operation

> **Prediction, Interpretation and Analysis**
>
> *The prediction of performance by computer simulation, the interpretation of data, and the application of analytic plasma theory are of major importance in gaining an understanding of plasma behaviour in JET.*
>
> ● *Prediction work continuously checks the measured behaviour against the different computational models, and provides a basis for long term programme planning:*
>
> ● *Interpretation plays a key role in the assessment of plasma performance, and hence in optimisation studies and programme planning.*
>
> ● *A major role of analytic theory is to compare the observed behaviour against that expected from existing analysis, and to modify the latter when there is divergence.*
>
> *A central task is to provide a quantitative model of tokamak plasmas with the ultimate objective of including all the important effects observed in JET and other tokamaks. It is preferable to understand each effect theoretically, but in some cases it may be necessary to rely on an empirical description.*
>
> *For carrying out these tasks it is important that JET data is held in a readily accessible and understandable form.*

During the next seven weeks (weeks 34 to 42) some interruptions to operation were caused by in-vessel work and again by imperfect functioning of the vessel restraints. However, the belt limiters and RF antennae screens and other in-vessel components were cooled down successfully and the poloidal field circuit was successfully reconfigured to provide the additional radial position control that is needed for the higher plasma energies associated with increased heating power. Although the performance of both ohmic and radio frequency heating has been extended, neutral beam heating was further delayed by power supply problems.

About half of the operating time in weeks 43 to 52 was devoted to commissioning of the PFX amplifier and its controls. The large degree of operational flexibility introduced by this system and its ability to provide different current distributions in the central primary winding was rapidly demonstrated. Further advances were made with ohmic heating of 6MA full aperture plasmas, 3.5MA single X-point plasmas and with radio frequency heating. During this period repairs to the neutral beam injector system were completed and the unit was again brought into operation. Half of the tokamak plasma programme during this period was devoted to combined neutral beam and radio frequency heating experiments.

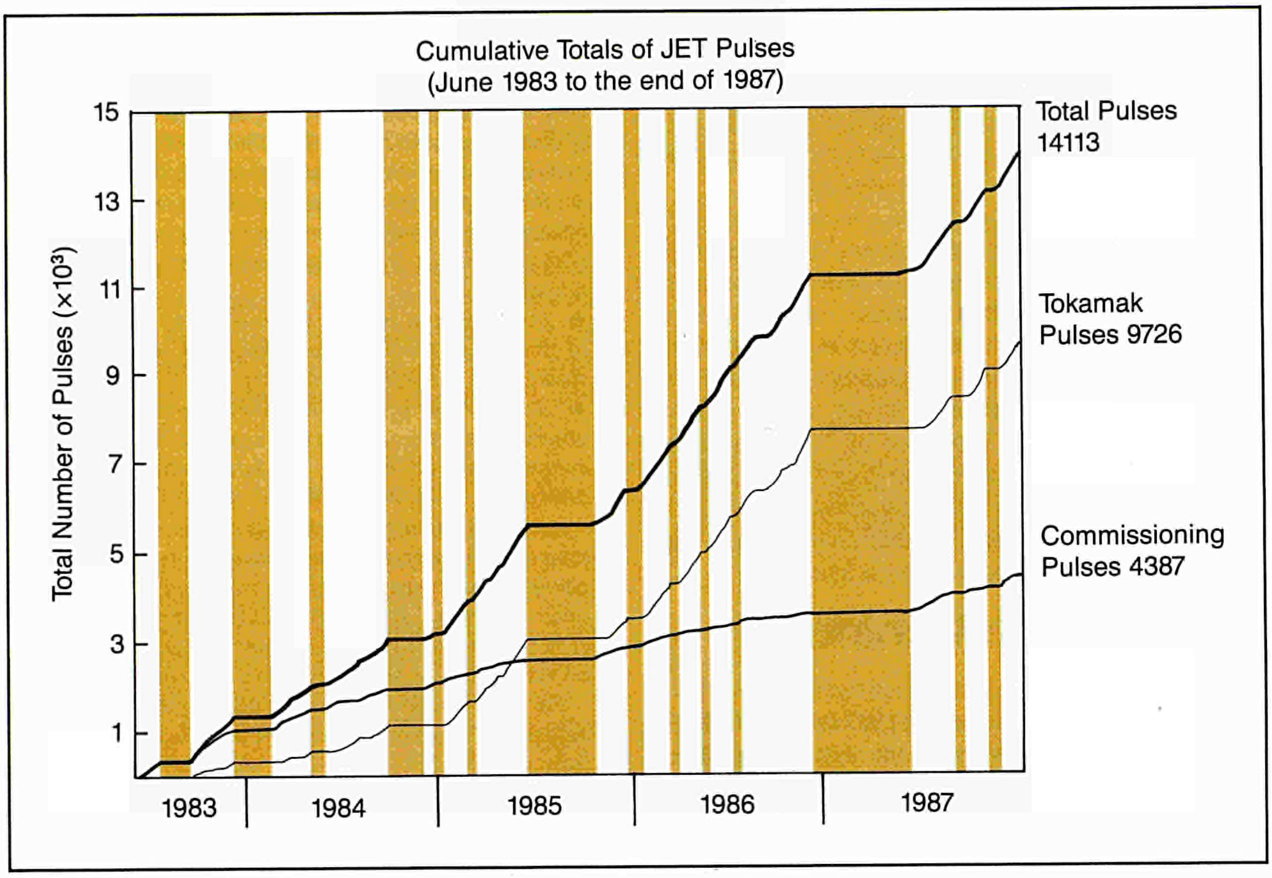


Fig. 21 Cumulative total of JET pulses

Technical Developments for Future Operations

Considerable effort has been devoted during the past year to the design and procurement of equipment for installation on the machine during future major shutdowns. Reference should be made to the section on the Future Programme of JET to relate these technical developments to the overall JET programme.

Study of the New Extended Operating Conditions

Modifications carried out to the poloidal field coil system during the shutdown, are in line with the planned increases in plasma current up to 7MA in limiter mode and 4MA for X-point operation. As this enhancement represents a considerable extension to the original design parameters, a major design review was started in 1986 and continued through 1987 to determine the safe operating limits for major machine components and identify any changes that are needed. By the end of 1987 the analysis of the JET coils had been completed. The prototype toroidal field coil has been tested by subjecting it to 20000 cycles at the full design value of transverse load and will be subjected to progressively higher forces to establish its ultimate strength.

The poloidal field coil system must carry increased currents and progressively more complex mathematical models are being developed to analyse this situation. A problem of thermal stress has already been identified and a modified cooling system will be installed in 1988. The analysis of the vacuum vessel has uncovered some potential structural difficulties that could occur due to disruptions at high plasma currents. Design changes are being considered so that these problems can be overcome.

It has recently been proposed that a further increase in plasma current, up to 7MA with single null X-point, should be possible using a particular coil configuration. The predicted magnetic flux for operation with a single null configuration at 7MA plasma current is shown in Fig. 22. An analysis is underway to determine the shear stresses on the toroidal field coils and the forces produced on the vacuum vessel in case of accidental loss of control of the vertical position of the plasma.

Disruption Stabilisation System

On JET, it is proposed to stabilize disruptions by utilising a system with magnetic feedback. Perturbations, which usually precede a disruption, will be detected by pick-up coils. The signal from these will be used to drive large saddle coils via a feedback circuit. The saddle coils, mounted on the interior of the vacuum vessel, will produce magnetic field peturbations to cancel out those due to the growing instability.

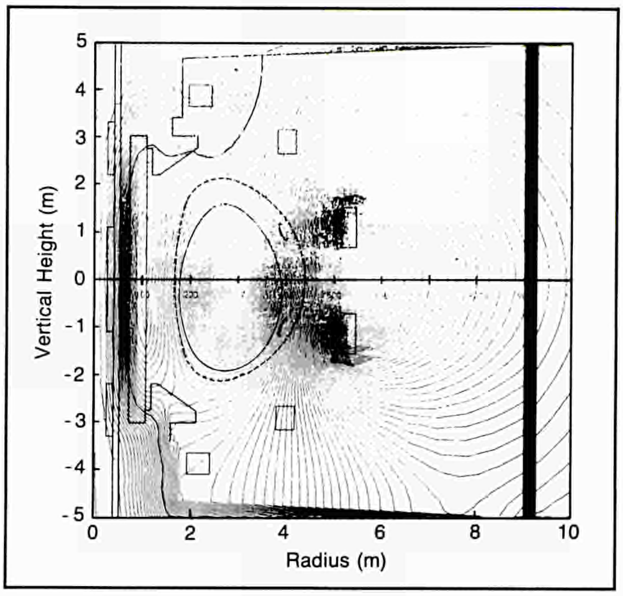


Fig. 22 The calculated flux for a single null configuration at 7MA plasma current

There are many constraints on the size of the saddle coils and their locations within the vacuum vessel, which are shown in Fig. 23. They must be located so that they do not impose restrictions on the operation of JET with X-point or limiter discharges, as well as minimising their impact on the diagnostic systems. These will be arranged four above and four below the horizontal centre line with each one spanning two octants. Each of the coils will consist of three turns, each with a cross section of 20 × 70mm, fabricated from Inconel 600. The coils will be insulated from the vessel walls with alumina balls and supported from the rigid sectors by clamps.

Prefabrication of the coils will be in several parts and they will be mounted inside the vessel during the 1988 shutdown. Connections to the coils will be made by busbars via insulating feedthroughs on existing ports of the vacuum vessel. Detailed design of the coils is complete and tenders are being sought for the construction contract.

The main requirements for the feedback amplifier have been established and various schemes to meet these are being considered. The power supply for driving the coils is being designed as a modular system so that low power experiments can start with only part delivery of the power supply.

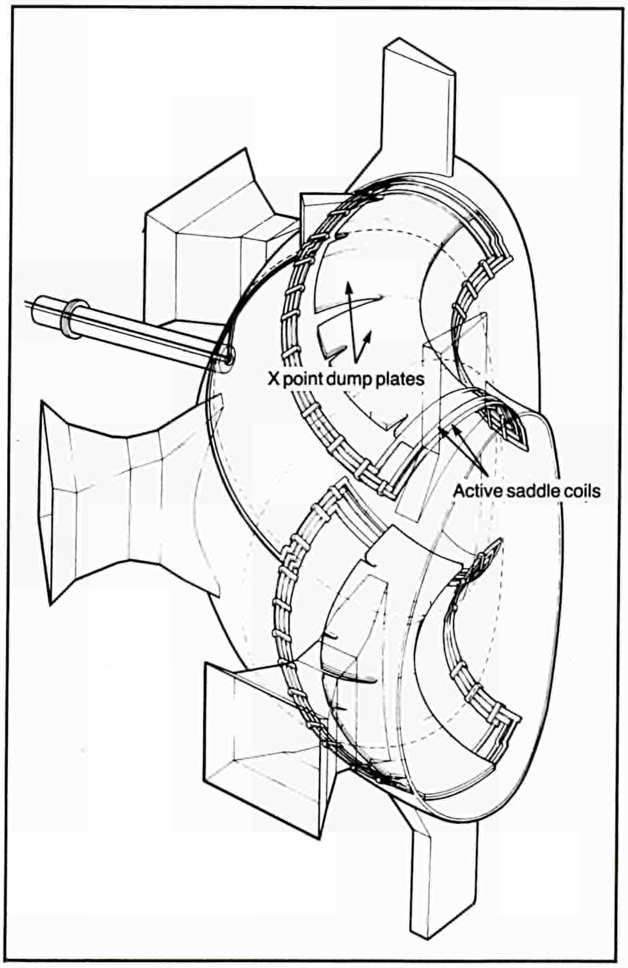


Fig. 23 Location of saddle coils within the torus

Lower Hybrid Current Drive

Ultimately, Lower Hybrid Current Drive (LHCD) will be the main method of decoupling the plasma current and temperature profiles in JET. This programme is aimed at installing a prototype launcher with a nominal power of 2MW during the 1988 shutdown and installation of the full size launcher for the 12MW system in the 1990 shutdown.

The radio frequency power will be coupled to the plasma through a single large horizontal port by a multijunction phased waveguide array shown diagramatically in Fig. 24. This allows a good match to the power source over a wide range of plasma conditions and provides for flexibility in the relative position of the grill to the plasma surface.

The conceptual design of various subsystems has been completed and the first stage of manufacturing contracts has been released. High power tests on the first klystrons have been carried out and power outputs up to 680kW for 10s have been obtained with a well

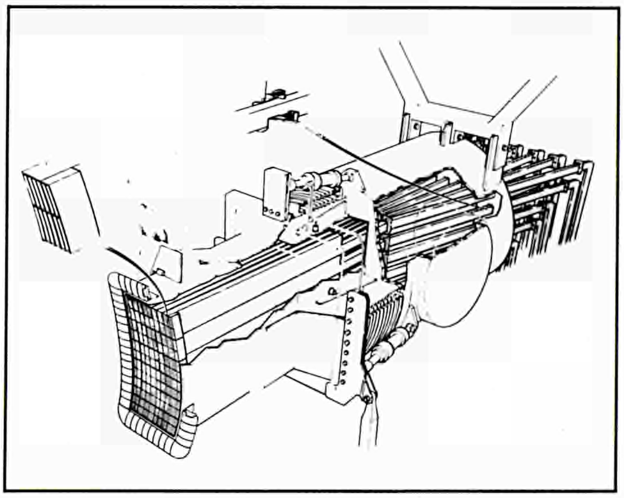


Fig. 24 The multi-junction phased waveguide array for LHCD

matched load. Some of the high power tests on components for the waveguide transmission line have been performed and low power testing of the main microwave components has been completed.

The testbed for this system will be installed and ready for use early in 1988. The design for the LHCD power supplies has been completed and orders placed for the main power supply and for the crowbars needed for klystron protection. Delivery of the five power supplies, one for the testbed and four for the actual system, will start at the end of 1988.

High Speed Pellet Injector

Successful experiments have been carried out using a pellet cryostat from Centre d'Etudes Nucleaires Grenoble (CENG), France, coupled to a two stage gun at the Ernst Mach Institut Freiburg (EMI), Federal Republic of Germany. In these experiments, it was found that velocities up to 2.7 km s^{-1} could be reached but that it was unlikely that this could be improved due to heavy erosion of the pellets. However, considerably higher velocities, up to 3.8 km s^{-1}, have been achieved by surrounding the deuterium pellet with a sabot (casing). Experiments have been carried out with a split sabot and it has been demonstrated that the two halves can be separated from the solid deuterium pellet by internal pressure build-up. This would take place outside the barrel and the halves would subsequently be dumped into a conical target with a central hole through which the deuterium pellet can pass and enter the plasma.

An extrapolation has been made to define a prototype gun, which will be a two stage gas driven piston device capable of delivering up to 6 mm diameter pellets, with velocities of 4 to 5 km s^{-1} at a rate of one per discharge. The gun will be tested during the first half of 1988 and later coupled to the low speed multi-pellet injector on the torus.

Pump Limiter

When the initial design for a pumped limiter was considered, there were large uncertainties about the characteristics of the plasma boundary with a belt limiter. Therefore, it was proposed initially that a prototype pump limiter would be installed with reduced performance and then, from operating experience, any necessary changes incorporated for the final phase of operation. Since the initial proposal, a number of new developments, such as X-point operation, have taken place. The head for the pump limiter has therefore been redesigned to cope with higher power densities to allow operation with various configurations.

The redesign takes advantage of the high heat conductivity of compressed annealed pyrolitic graphite for the leading edge. Inertial cooling would be used during a discharge so that complicated, expensive and failure prone structures could be eliminated.

Negotiations were carried out during 1987 between the US Department of Energy and JET to implement an agreement for collaboration on the pump limiter.

In Vessel Components

Divertor dump plates will be installed at the top and bottom of the machine for use during high current X-point operations. The water cooled support structure will be covered with 24 mm thick tiles of carbon reinforced graphite tiles. Prototype dump plates have already been manufactured and series production has started.

For the last few years, preparations have been made to use beryllium as an alternative to graphite. The graphite belt limiter tiles would be exchanged for beryllium and the remaining surfaces covered with a layer of beryllium, deposited by evaporation techniques. Beryllium could be used as soon as it is deemed necessary, as the belt limiter tiles have been manufactured and are now available. Evaporation tests have been carried out using nickel, and beryllium tests are proposed as soon as it is decided to introduce this material to the torus.

Tritium Handling

The JET programme requires that the Active Gas Handling System should be ready for final commissioning by the middle of 1990 so that deuterium-tritium operation can begin in 1991.

The multi-column system that is needed in cryogenic distillation for isotope separation, has been identified as the time critical item and a design and procurement contract had been placed. Design of the cryogenic forevacuum system and the main part of the impurity processing system has been finalised and tender action will take place early in 1988. Prototype tests were conducted on components of the forevacuum system and further tests will be carried out on components with improved analytic equipment to establish whether the impurity content can be reduced to the required very low level.

A consulting contract has been negotiated with CEA, France, for assistance in the design and commissioning of the chromatographic isotope separation system.

The basic principles of the documentation necessary to justify operational safety have been agreed with the UKAEA Safety and Reliability Directorate (SRD). A procedure has been established for the assessment of the compatibility of the torus systems with tritium operation and assessments have been made on a number of diagnostics and other torus systems. Close contact has been maintained between UKAEA Culham Laboratory, SRD and HM Inspectorate of Pollution (HMIP) to ensure that the relevant external organisations have an opportunity to comment on JET's proposals before they are finalised.

SRD have accepted the Preliminary Safety Analysis Report in principle and this has cleared the way for the preparation of second stage reports.

The Results of JET Operations in 1987

Resumé

The overall objective of the JET Project is to study plasma in conditions and with dimensions close to those that would be needed in a fusion reactor. The central values of temperature, density and energy confinement time needed for a reactor operating with deuterium and tritium must be such that their product, $(n_i.\tau_E.T_i)$ exceeds the figure of $5\times10^{21}m^{-3}$ skeV. Typical values for these parameters, which must be attained simultaneously in a reactor, are given in Table 3.

Using purely ohmic heating, ion and electron temperatures of 3keV and 4keV respectively have been achieved on JET with a plasma density of $4.2\times10^{19}m^{-3}$ and energy confinement time exceeding 0.8s. These values were obtained simultaneously during one discharge and result in a fusion product of $1\times10^{20}m^{-3}$ skeV.

Higher peak values of electron and ion temperature have been reached using radio frequency heating, neutral beam injection heating and a combination of these two methods. However, the substantial increases in temperature were associated with a drop in the energy confinement times to 0.5s and below. Thus, gains in plasma temperature have been offset by the degradation in energy confinement time and the fusion product obtained in the above situations have not shown the full gains anticipated over conditions with ohmic heating only.

A substantial increase in the value for the fusion product has been achieved, however, by operating with the magnetic limiter (X-point) configuration in JET. In 1986, a value of $2\times10^{20}m^{-3}$ skeV was obtained using 10MW of neutral beam injection heating and this was repeated in 1987 but using only 6MW of power from the same heating method.

Table 3
Typical Reactor Parameters

Central Ion Temperature T_i	10 – 20keV
Central Ion Density n_i	$2.5\times10^{20}m^{-3}$
Global Energy Confinement Time τ_E	1 – 2s
Fusion Product $(n_i.\tau_E.T_i)$	5×10^{21} m^{-3}skeV

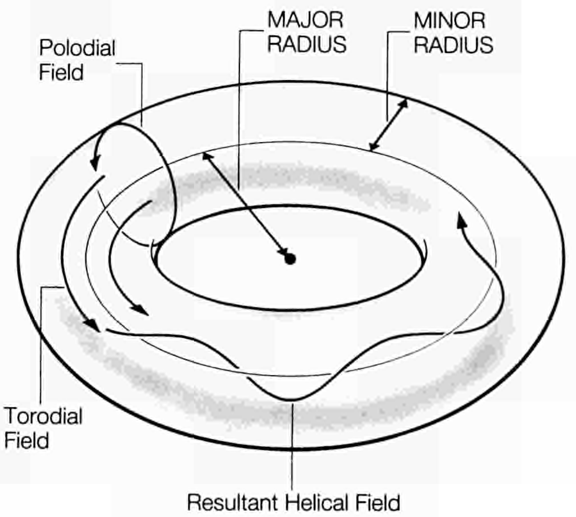
Magnetic Field Configuration

The toroidal and poloidal magnetic fields combine to form helical magnetic field lines which define a set of magnetic surfaces. As the strengths of the magnetic fields vary across the minor cross-section of the machine, the pitch of the field lines varies and usually decreases with increasing minor radius.

The number of turns a field line must traverse around the major direction of the torus, before closing on itself, is denoted by the safety factor q. Of special importance are the positions where q is the ratio of small integers as these regions are specially sensitive to perturbations. Instabilities arising from these perturbations can result in enhanced energy losses.

In addition, the maximum plasma pressure which can be maintained by a given magnetic field is dependent on the value of the plasma current. The effectiveness with which the magnetic field confines the plasma is given by β which is defined as the ratio of plasma pressure to the magnetic field pressure.

JET can be operated with an elongated plasma cross-section rather than circular. This enables larger plasma currents to be carried for a given value of magnetic field, major radius and horizontal minor radius, as well as producing larger values of β.



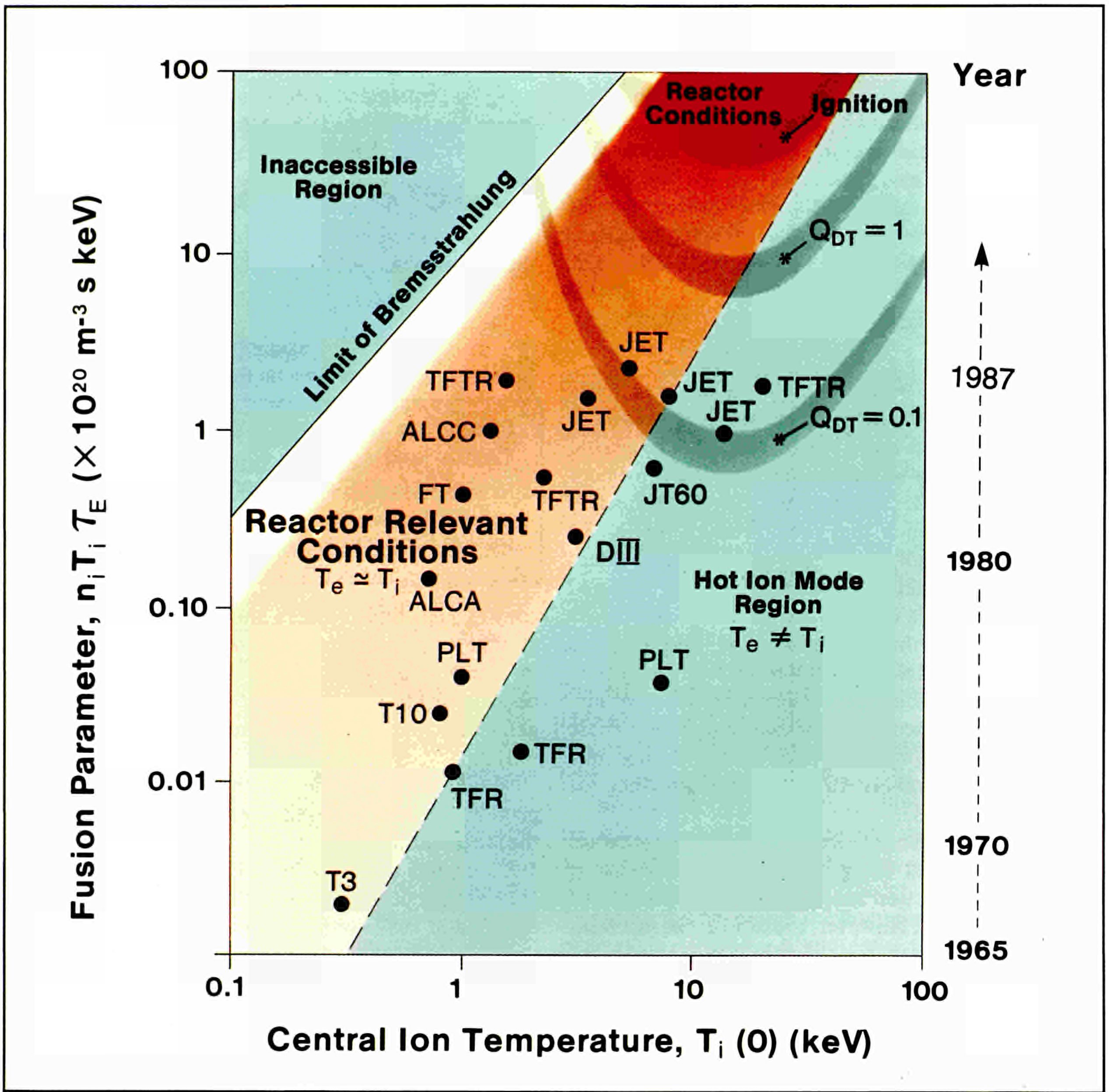


Fig. 25 The comparative performance between JET and other tokamaks is given in terms of the fusion product and temperature of the ions. Although a large range of values is covered, not all of the region indicated on the figure can be considered as relevant to those needed for a reactor.

The Bremsstrahlung limit represents the maximum value of the fusion product that can be obtained if the energy losses from the plasma were due only to this type of radiation. Any additional energy losses will further increase the size of region which is inaccessible.

Some of the results from JET and other tokamaks fall within the region to the right of the figure. Within this area, the collisional processes between electrons and ions are not sufficient to enable energy to be transferred between each other, ie, the electron and ion temperatures are very different.

In a reactor, most of the energy carried by the alpha particles produced in the fusion reactions would be transferred to the electrons. The ions receive their energy from the electrons and their temperature cannot be significantly different. The central section of the figure, where the electron and ion temperatures are approximately equal, therefore represents the region leading most directly to reaction conditions. The three bands represent different values of the ratio of fusion power to input power, Q_{DT}, if a deuterium-tritium mixture were used. JET has achieved results above the band representing $Q_{DT}=0.1$, which would result in the fusion power liberated being about one tenth of the input power in a D-T plasma. The bands above this represent breakeven, where $Q_{DT}=1$, and ignition where the alpha-particle heating would be sufficient to maintain the density and temperature needed in a reactor. In the presence of high energy neutral beams, interactions between the particles in the beams and the background plasma would result in the fusion rate and value of Q_{DT} being significantly increased above the level shown in the figure.

Considerably higher individual values of temperature, density and energy confinement have been obtained, but not simultaneously during one discharge. These include peak ion temperatures in excess of 14 keV, energy confinement times of over one second and densities of $1.2 \times 10^{20} m^{-3}$.

Breakeven

This condition is reached when the power produced from fusion reactions is equal to that necessary for maintaining the required plasma temperature and density.

The highest value of the fusion product that has so far been attained would need to be increased by about a factor of 25 to reach the conditions needed in a reactor. A factor of five increase would bring the conditions in JET to breakeven. In Fig. 25, the increases in performance that have been achieved on JET and other tokamaks since 1965 are shown.

Ignition

Ignition of a mixture of deuterium and tritium would be reached if the power produced by the alpha particles (20% of the total thermo-nuclear power) released from the fusion reactions is sufficient for maintaining the temperature of the plasma.

As the global energy confinement time scales favourably with plasma current in discharges with both magnetic and material limiters, the modifications carried out in 1987, to increase the plasma current in both of these modes of operation, give confidence that the breakeven condition should be approached when JET is operated with both deuterium and tritium together.

Experimental Programme

The strategy of JET is to optimise the fusion product by building up a high density and high temperature plasma in the centre of the discharge, while still maintaining an acceptably high confinement time. These conditions would mean that sufficient alpha particles would be produced with deuterium-tritium operation for their confinement and subsequent heating of the plasma to be studied.

The overall scientific programme of JET is divided into four phases as shown in Fig. 26. The Ohmic Heating, Phase I, was completed in September 1984 and Phase II—Additional Heating Studies started early in 1985. By December 1986, the first part of this phase, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the start of the second part of the additional heating studies, Phase IIB, in June 1987. The general objective of this phase, from mid-1987 until mid-1988, is to explore the most promising regimes for energy confinement and high fusion yield and to optimise conditions with full additional heating power in the plasma. Experiments would be carried out with plasma currents up to 7 MA in the limiter mode and up to 4 MA in the X-point mode and with increased radio frequency heating power up to 20 MW and neutral beam injection power operating up to 20 MW at 80 keV. The ultimate objective is to achieve full performance with all systems operating simultaneously.

The programme objectives for the operational period of 1987 were divided into four main areas:

- Experiments to move towards full performance conditions in the material limiter configuration by gradually increasing plasma current, from above 5 MA towards 7 MA, and with the use of full additional neutral beam injection and radio frequency heating. This would enable the performance of the belt limiters to be assessed

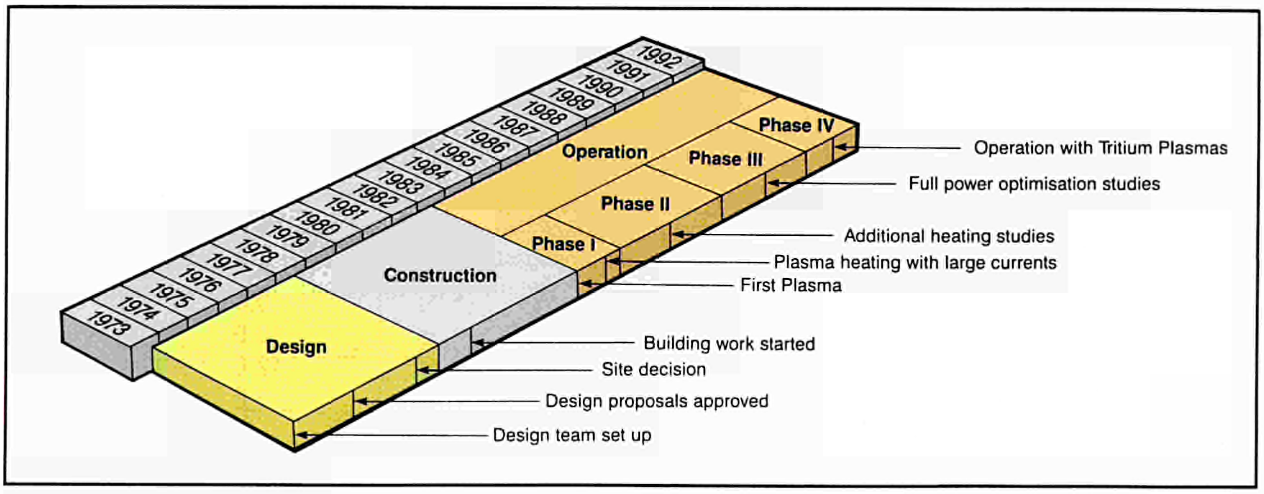


Fig. 26 The overall JET Programme

and improve plasma confinement at high temperatures with high elongation, full-bore plasmas;

- Experiments in the magnetic limiter (X-point) configuration, at plasma currents exceeding 3MA and with high additional heating, to explore the high confinement (H-mode) regime of operation;
- Experiments to produce dense core plasmas by injecting solid hydrogen and deuterium pellets as well as investigating the possibility of sustaining these with centralised heating, using radio frequency and neutral beam injection heating, and of tailoring the profiles for optimum fusion products;
- Experiments to obtain high fusion yields including high ion and electron temperature regimes involving a dominant non-thermal yield.

The machine started operation again at the end of June. The first priority was to recommission the machine in its new configuration and to commission the new equipment with plasma under operating conditions and to optimise its performance.

The main scientific results achieved during the second half of 1987 are summarized in the following paragraphs.

Summary of Scientific Results

Plasma currents in excess of 4MA were quickly re-established after the start of operation in mid-June. There was steady progress towards higher current operation with longer flat-tops as well as progressively increased additional heating power. Improved diagnostics were brought into operation; in particular, the LIDAR system to measure electron temperature and density profiles; the polarimeter to allow deduction of the radial profile of the safety factor, q; and the spatial scan crystal spectrometer to measure the spatial distribution of impurities. Experiments were performed in the four main programme areas mentioned above, involving operation in both material limiter and magnetic limiter configuration in various additional heating and pellet injection scenarios. An overview of the 1987 operation giving the percentage of time devoted to each major research area is shown in Table 4 and a summary of parameters achieved by the end of 1987 is shown in Table 5.

Table 4
Percentage Operating Time Devoted to Major Research Areas

Topic	Percentage of Operating Time
Ohmic Heating	19
RF Heating	25
Combined Heating (RF + NB)	5
X-point Studies	7
Pellet Injection	4
Diagnostic and Systems Commissioning	14
Machine Commissioning	26

Table 5
Summary of main JET Parameters
(Not necessarily in the same plasma pulse)

Toroidal field	B_t (T)	≤	3.4	
Plasma current	I_p (MA)	≤	5.0	6.0
Duration of max. I_p	t_p (s)	≤	10.0	2.0
Plasma major radius	R_0 (m)	≤	3.0	
Horizontal minor radius	a (m)	≤	1.2	
Vertical minor radius	b (m)	≤	2.0	
Elongation	b/a	≤	1.7	
Safety factor at	q_{cyl}	≥	1.5	
plasma boundary	q_ψ	≥	2.1	
Input ICRF power	P_{RF} (MW)	≤	18.0	
Input NBI power	P_{NB} (MW)	≤	9.0	
Total input power	P_{TOT} (MW)	≤	18.0	
Stored plasma energy	W_p (MJ)	≤	6.5	
Volume average electron density	n_e (10^{20}m^{-3})	≤	0.6	
Central electron temperature	T_e (keV)	≤	10.0	
Central ion temperature	T_i (keV)	≤	12.0	
Global energy conf. time	τ_E (s)	≤	1.0	
Fusion performance parameter (simultaneous $n_i.\tau_E.T_i$)	$n_i.\tau_E.T_i$ (10^{20}m^{-3}s keV)	≤	2.0	

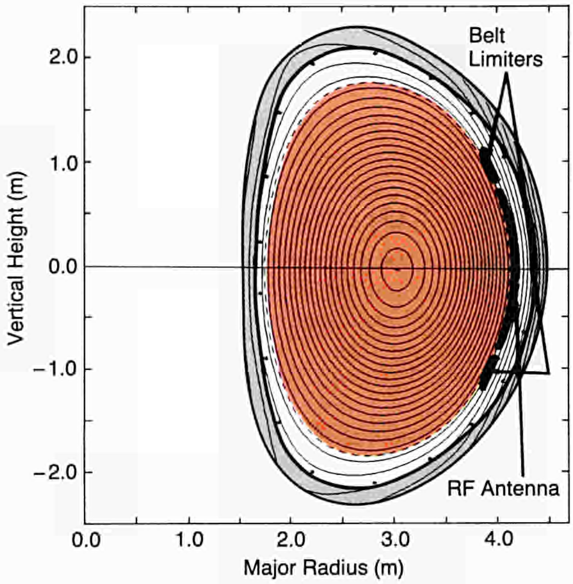
Operating Modes

Under normal operating conditions the magnetic surfaces are nested inside each other. The edge of the plasma is defined by the magnetic surface which intersects the limiter. The only magnetic field lines intersecting the walls of the chamber are those beyond the region bounded by the limiters as shown in the diagram on the left. This is termed limiter operation.

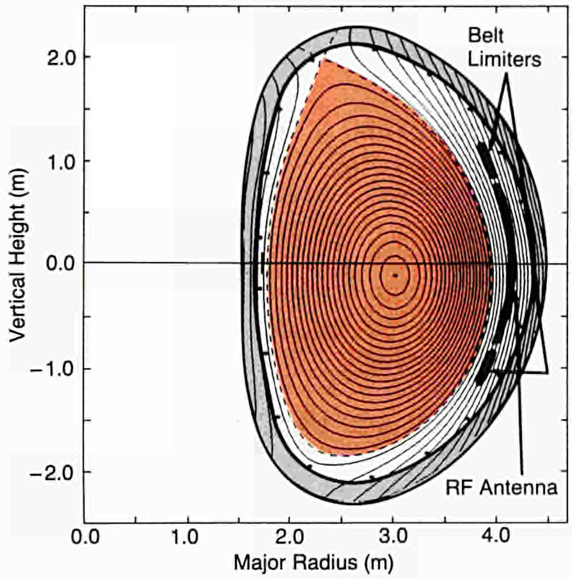
The magnetic field configuration on JET can be modified so that one of the closed surfaces near the limiter is opened up so that it intersects with the vacuum vessel wall. In this configuration, the magnetic separatrix is moved to within the vacuum chamber. This so called X-point configuration can be operated with the two nulls of the separatrix within the vacuum chamber (double null) or with only one inside (single null) as shown in the diagram on the right.

During X-point operation with additional heating, the plasma can behave, with respect to confinement, as though its edge were bounded by limiters. This is called the Low(L)-mode. Under certain circumstances, the plasma can be induced to behave in a different manner which produces better plasma confinement. This is termed High(H)-mode.

Limiter Operation



X-point Operation



The main results of particular investigations and studies are described below within the areas of Density Effects, Temperature Improvements, Energy Confinement Studies and Other Material Effects.

Density Effects

Density and Current Limits due to Disruptions

Disruptions pose a major problem for tokamak research as they limit the density and current range in which stable operation can be achieved. A diagram of the stable operating regime can be constructed by mapping the normalised current $1/q$ ($\propto I_p/B_t$) (where q is the safety factor, I_p the plasma current and B_t the toroidal field) against the normalised density $\bar{n}\,R/B_t$, (where $\bar{n}$ is the average density and R the major radius) as shown in Fig.27. In ohmically heated plasmas, the density limit is dependent on plasma purity and is given by:

$$n_{c(OH)}(\mathrm{m}^{-3}) = 1.2\times10^{20}B_t(T)/qR(\mathrm{m}).$$

There is only a slight increase to this limit with radio frequency heated discharges, possibly because the beneficial effect of the extra power is cancelled by an increase in the level of impurities. With neutral beam

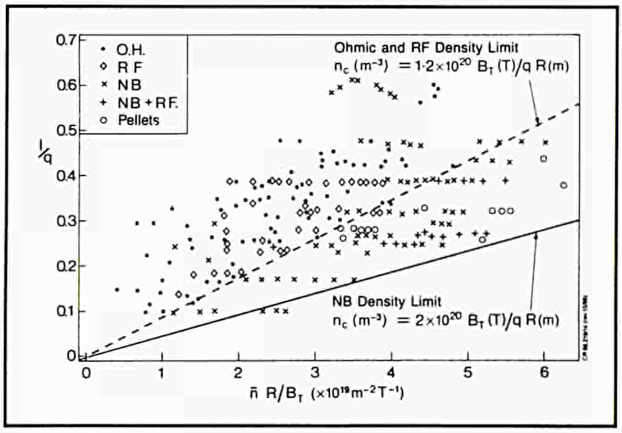


Fig. 27 The normalised current (1/q) plotted against normalised density ($\bar{n}$ R/B)

heated plasmas, the limit is increased substantially, as shown in Fig.27 to:

$$n_{c(NB)}(\mathrm{m}^{-3}) = 2.0\times10^{20}B_t(T)/qR(\mathrm{m}).$$

Switching off the neutral beam heating at high density causes the plasma to disrupt, which indicates that power input plays an important role in the disruption mechanism. Experiments using pellet injection have also enabled the ohmic heating density limit to be exceeded.

Density limit disruptions are always preceded by an increase in the radiation from impurities at the plasma edge which causes the contraction of the electron temperature profile. This is followed by the growth of magnetic instabilities and the plasma becomes disruptively unstable. Both observations and theoretical considerations show that the central plasma density can be increased by deep refuelling, possibly by using high-speed pellet or neutral beam injection.

> **Disruptions**
>
> *There is a maximum value of density which can be contained with a given plasma current. If this value is exceeded a disruption occurs when the plasma confinement is suddenly destroyed and the plasma current falls to zero in a short period of time. Under these conditions high mechanical and thermal stresses are produced on the machine structure. Disruptions are thought to be caused by instabilities mostly developing on the surface where $q=2$.*

Operation is also restricted at high normalised currents, where $1/q$ ($\propto I_p/B_t$) is less than ~ 0.6. Experiments have shown that the 'low-q' boundary is precisely given by $q_\psi=2$ when q_ψ is the actual field line safety factor at the plasma boundary. This is caused by the $q_\psi=2$ surface, on which the disruptive instability mostly occur, coinciding with the boundary of the plasma. Thus, there is an upper limit on the operating plasma current at a given toroidal field.

Pellet Injection

Initial experiments have been carried out with a multi-pellet injector jointly installed and operated by JET and the US Department of Energy under the Bilateral Agreement on Fusion Research. The launcher can deliver 2.7, 4 and 5mm diameter pellets, with their length approximately equal to their diameter, from three different barrels in parallel. The pellets can be injected at a maximum frequency of several per second with nominal speeds up to 1500m.s^{-1}. The injection of pellets into the plasma started during the second half of 1987, but the investigation is in an early stage and only a few features have been studied so far.

Peaked density profiles have been achieved in ohmically heated discharges with central densities well over 10^{20}m^{-3} using 2.7 and 4mm diameter deuterium pellets. The decay time of the density is in the several seconds range, Fig.28, and some plasmas have shown no sign of sawtoothing for several seconds after injection. Is is planned to use these plasmas as high density low Z_{eff} targets for auxiliary heating. However, attempts to heat the centre of the plasma using radio frequency heating have been troubled by the frequent occurrence of instabilities and a consequential rapid pump-out of density. Although this leads to broad density profiles, the maximum density is still in the highest range that has been achieved so far in JET. A density build up, produced by injecting a string of 10 pellets into the plasma as early as 1.5s into the plasma current ramp up, as shown in Fig.29, has produced a relatively clean high density plasma that appears remarkably tolerant to pellet disturbances.

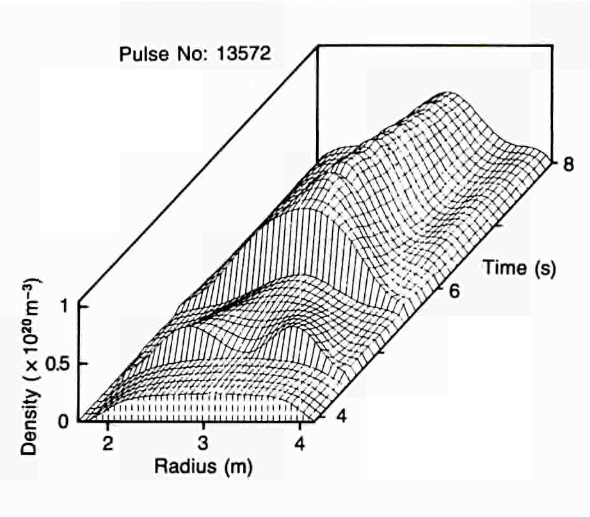


Fig. 28 Density profile with pellet injection

> **Density Control**
>
> *Increasing the density can be achieved by introducing additional gas into the vacuum vessel, by the injection of energetic neutral atoms (neutral beam heating) and by pellet injection*
>
> *Increasing the input power to the plasma through additional heating raises the electron density limit. However, problems can occur when this heating power is switched off if the electron density is too high. To overcome this problem, the plasma is moved, prior to the switch off point, so that it bears on the carbon tiles covering the inner wall. The tiles have been found, unexpectedly, to provide a pumping mechanism for removing particles so that the density can be reduced below the critical limit.*

Although it is too early to draw any definite conclusions on the role of multi-pellet injection on JET, promising and interesting features have been observed. The high values of peak and average density achieved as well as the production of clean plasmas are encouraging results.

Temperature Improvements

Sawtooth Oscillations

Sawtooth oscillations of the central values of temperature and density occur in almost all JET discharges. In the central plasma region this periodic process shows a slow rise in electron temperature and then a fast drop within a central region inside the so-called inversion radius, which is close to the $q=1$ surface. This temperature drop is associated with an

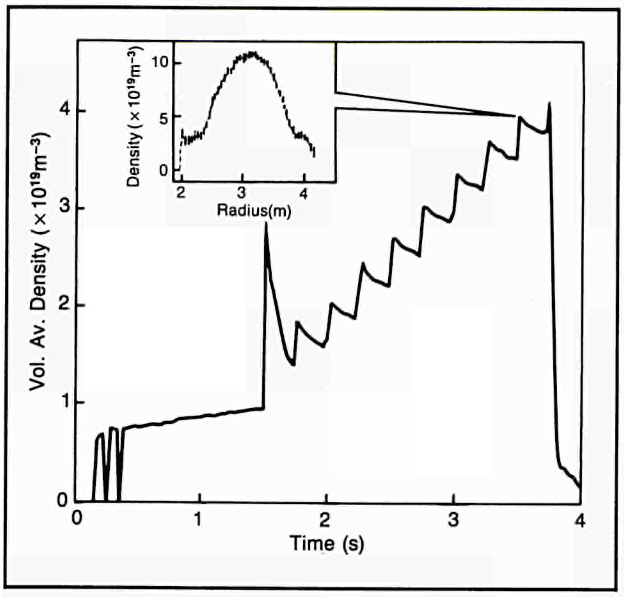


Fig. 29 Density build-up resulting from the injection of a string of ten pellets into the plasma

internal disruptive instability which produces enhanced heat transport within the central region. This is due to a large scale convective motion and results in a flattening of the temperature profile up to the inversion radius. The presence of sawteeth oscillations, therefore, limits the maximum temperature that can be reached in the centre of the plasma and creates a source of energy loss from the central region.

Sawteeth

Perturbations on the $q = 1$ magnetic surface can result in the formation of large fluctuations in the central temperature and density. These fluctuations have been termed 'sawteeth'. They are also associated with the expulsion of energetic ions from the central region of the plasma. Understanding this process is important as the alpha-particles produced from deuterium-tritium fusion reactions might be lost before they can produce any effective heating of the plasma.

If additional power is deposited in the centre of the plasma, especially with radio frequency heating, the sawteeth may develop large amplitudes, with up to a doubling of the electron temperature and with longer periods up to 0.6s. Ultra-long sawteeth, nicknamed 'monsters', with durations up to 2.8s have also been observed. Monsters are actually a prolonged stabilization of the sawteeth oscillations and have been observed at plasma currents up to 5MA in discharges with radio frequency heating and in combination with neutral beam injection heating, see Fig. 30. During these periods, the central electron temperature can reach high values, with peaked profiles, as shown in Fig. 31, usually accompanied by a rise in the ion temperature and an improvement in thermonuclear reactivity. The long quiescent periods have enabled the assessment of the transport properties of plasma free from sawteeth, and have permitted an analysis of the benefits of sawtooth stabilisation in the near ignition regime. While a small improvement in confinement time has been observed, with τ_E increasing by up to 20%, the major advantage is an increase in the fusion product due to the peaked temperature profiles which occur. This regime has been observed under a wide range of plasma condition on JET: $2.1 \leq B_t \leq 3.4$T, $1.5 \leq I_p \leq 5.0$MA, $3.4 \leq q \leq 8.4$ and $\bar{n}_e \leq 4 \times 10^{19}$m^{-3} and there is some evidence that it may be reached by using neutral beam injection heating alone.

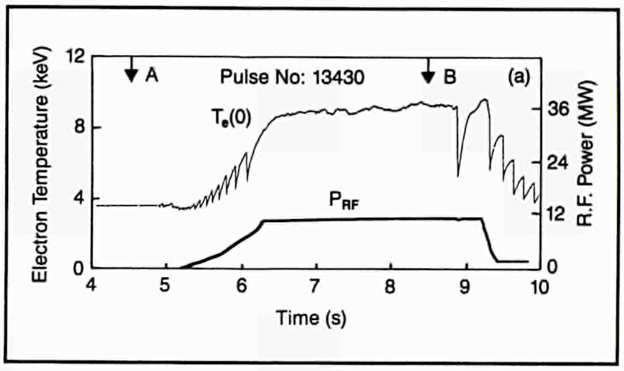


Fig. 30 Electron temperature during a monster sawtooth

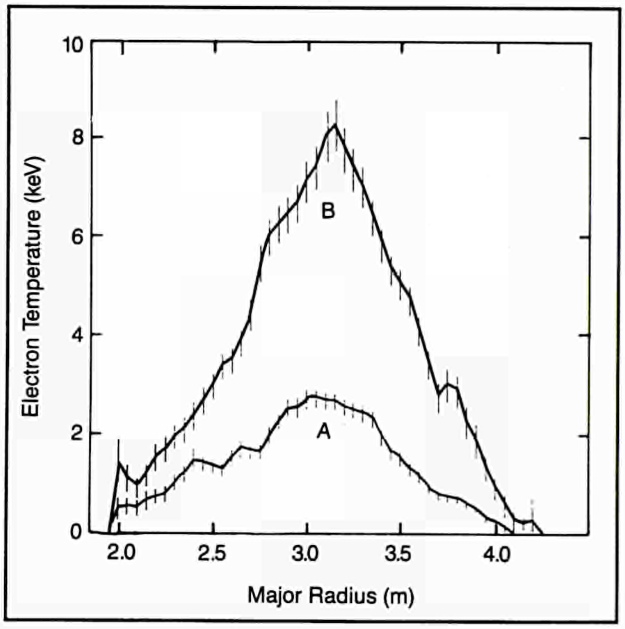


Fig. 31 Comparison of electron temperature profiles before and during a monster sawtooth

Radio Frequency Heating

With the upgraded ion cyclotron resonance frequency (ICRF) heating system, up to 16MW of power has been coupled into the plasma for 2s. This was achieved using eight antennae in both monopole and dipole modes of operation. The facility for switching between modes on successive pulses has enabled the identification of operations in the dipole mode as beneficial as it releases fewer impurities from the screen into the plasma.

ICRF heating studies have been carried out using both hydrogen and ^3He minority ions, usually with the minority ion cyclotron resonance on-axis for optimum efficiency. The energy given to the minority ions is then redistributed through collisions with the ions and electrons in the bulk plasma thus raising the temperature. In such experiments, during relatively quescient periods occurring with monster sawteeth, heating of the ions in the bulk plasma, using ^3He as the minority ions, has yielded temperatures on-axis of 8keV in ^4He plasmas and 7keV in deuterium plasmas. In both cases electron temperatures up to 10keV were reached, although there was a degradation in the energy confinement time with additional heating.

Current Profile Control

The highest current density exists at the centre of the plasma as this is the hottest region and the electrical resistivity decreases as the temperature increases. Without the sawteeth, which occur on the $q=1$ surface, this high current density region would be squeezed or pinched inwards. Selective heating outside of the central region would remove the $q=1$ surface from the plasma and so avoid the onset of the sawteeth. Another way is to decouple the plasma current and temperature profiles. On JET, it is intended that an electric current, additional to that generated by transformer action, should be produced by neutral beams and by radio-frequency power at 3.7GHz.

With a radio frequency heating input power of 16MW, a stored energy in the plasma of 6MJ has been produced and a fusion rate from D-D reactions of $1.4\times10^{15}s^{-1}$. In these discharges, a significant fraction of the stored energy comes from the minority ions which are expected to produce a high fusion yield in (D) T heating schemes.

By modulating the ICRF power, experiments have been carried out to study the radio frequency power deposition profiles. These have confirmed that power is mainly deposited in a narrow central region of the plasma, extending radially about 0.6m, when the applied frequency closely matches the magnetic field region of the resonant ion species. Measurements of the modulated global energy content showed that at least 85% of the radio frequency power was utilized for plasma heating and that almost all of the modulated component resided in perpendicular energy, in agreement with calculations.

Neutral Beam Injection Heating

Nineteen eighty seven proved to be rather disappointing in terms of neutral beam injection heating, when compared with the successful first year of operation in 1986. During the major shutdown, a considerable amount of work on planned improvements and modifications to both the neutral beam system was successfully completed. Two significantly new experimental results were obtained during 1987, in spite of three hardware failures which occurred during commissioning. H-mode confinement in the magnetic limiter (X-point) configuration was re-established and the power threshold for the transition from low (L) to high (H) mode of confinement was studied over a limited range of values of the toroidal magnetic field. In addition, in the material limiter configuration, combined neutral beam injection and radio frequency heating, with a total power of 22MW, resulted in central electron temperature values of 10keV and central ion temperatures of 8.5keV. During the quiescent periods of monster sawteeth, comparable temperatures were obtained with about 15MW of combined neutral beam injection and radio frequency heating.

Energy Confinement

The global energy confinement time of JET in all plasma configurations, is defined as:

$$\tau_E = W_k / \left[P_t - \frac{dW_k}{dt} \right]$$

where W_k is the kinetic energy and P_t is total input power to the plasma without subtracting radiation losses. The values of τ_E reported are quasi-stationary.

Material Limiter Configuration

The energy confinement time on JET falls with increasing heating power, as seen in a number of other experiments and this effect is independent of the type of heating, whether neutral beam injection, radio frequency or a combination of the two methods. The way in which the energy confinement time falls with increasing heating power is shown in Fig.32. The rate of increase in kinetic energy with power input, $\Delta W_k/\Delta P_t$, appears to reach a limit of between 0.1 and 0.3MJ/MW at high powers. This indicates that there is a lower limit to the energy confinement time in JET of between 0.1 and 0.3s. Only a weak dependence on plasma density has been found for the energy confinement time but there is a favourable scaling with plasma current.

The global energy confinement time results can be fitted by a simple power law relationship. However, measurements of the radial propagation of heat pulses following sawtooth crashes, strongly supports a linear offset relationship between plasma kinetic energy and power input which takes the form:

$$W_k(P_t) = W(0) + \tau_{inc} P_t$$

The best fit in the case of limiter or inner wall discharges on JET gives:

$$W(0) = 0.225\, n^{0.6}\, I_p^{0.5}\, B_t^{0.4}$$

with an incremental confinement time of $\tau_{inc} = 0.05\, I_p$. The units are W(MJ), $n(\times 10^{-19}m^{-3})$, I(MA), B(T), and τ_{inc} (s).

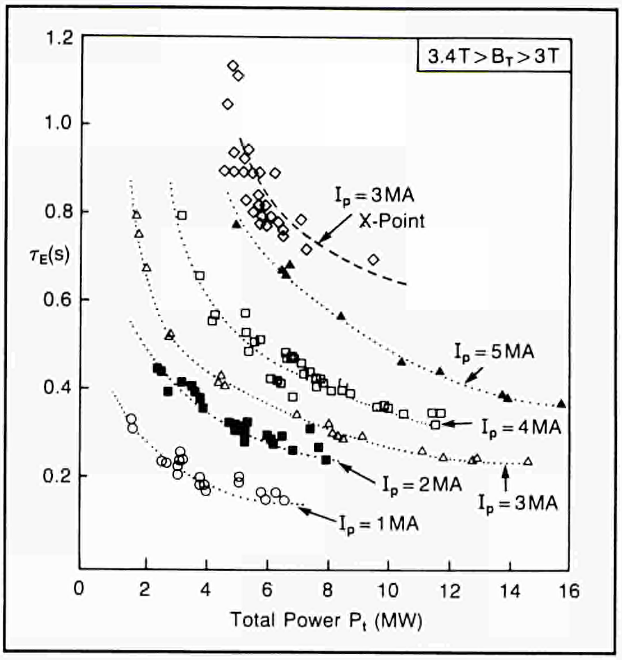


Fig. 32 Energy confinement time versus input power for various plasma currents and configurations

Magnetic Limiter Configuration

With magnetic separatrix operation (X-point), the plasma is detached from both the limiter and inner wall and recycling occurs in an open divertor region near the X-point. Stable discharges with a magnetic separatrix have been maintained in JET for several seconds at plasma currents up to 3.5MA with the single null configuration. Operations in this configuration have been undertaken to compare the global confinement characteristics with those with limiter discharges, as well as to study the conditions for the creation of a high density, highly radiative, cool plasma region near the X-point which is capable of screening and isolating the bulk plasma.

With neutral beam injection heating above a certain threshold value, which is dependent upon the toroidal magnetic field, a transition occurs to enhanced plasma confinement (H-mode), particularly in single-null operation. Fundamental characteristics include a rise in the plasma density and energy content as well as an increase in electron temperature near the separatrix, which produces a pedestal in the temperature profile, and a flat density profile with a steep gradient near the separatrix. The global energy confinement time in the H-mode exceeds that obtained with limiter discharges by more than a factor of two, as also shown in Fig. 32.

Due to technical problems, only limited neutral beams injection heating experiments could be performed until late in 1987 and then only heating powers up to 6MW were available during X-point discharges. However, the results of 1986 were reproduced as soon as the neutral beam power exceeded the threshold values for transition to the H-mode in X-point discharges. Experiments with a wider range of toroidal magnetic field, confirmed a strong dependence on the threshold power, P_{th}, and indicated a scaling of $P_{th} = 0.6\ B_T^{2.5}$, Fig. 33, with only a weak dependence on plasma current. Confinement times up to $\tau_E = 0.75$s have been obtained with neutral beam injection power of 6MW.

A preliminary analysis of the H-mode confinement times obtained in 1987, shows only a weak dependence on toroidal magnetic field between 1.8 and 2.4T. The confinement times obtained in 1987 are slightly less than the 1986 values, partly due to the new belt limiters reducing the cross-section of the single-null X-point plasmas by about 10%. It is not clear, without a more detailed analysis of existing data and without an extension of H-mode results to a higher power levels, whether the confinement time degrades with increasing heating power. Increased heating levels, up to 15-20MW with neutral beam injection heating and 20MW of radio frequency heating, should be available early in 1988.

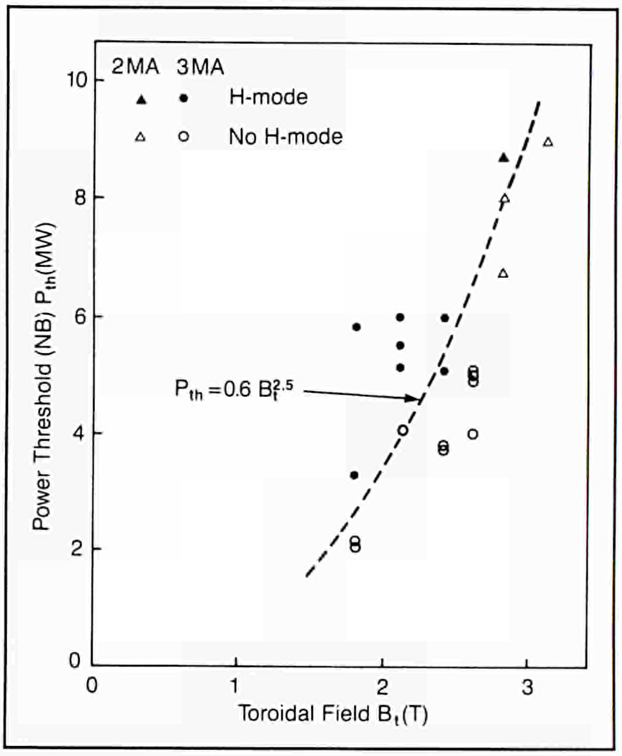


Fig. 33 Power threshold versus toroidal field for the transition to H-mode

Pronounced changes have been seen in the density profiles between the L and H-mode phases. Following the transition to H-mode, the plasma density profile is flat or even slightly hollow. However, the electron temperature profile shows a general increase in temperature at the on-set of the H-mode but with no dramatic change in shape. The temperature profile also stays roughly the same throughout the H-mode phases whereas the density increases by up to a factor of three.

The radial distance between the separatrix and belt limiters affects not only the duration of the first H-mode period but also that of the subsequent changes between the two modes. The total duration of L and H-mode periods has been limited by the length of the neutral beam pulses. When these are increased, the length of the L and H-mode train should be limited finally by the accumulation of impurities in the centre of the plasma.

So far, attempts to achieve the H-mode using radio frequency heating alone have not been successful during limited experiments but further experiments will be carried out during 1988.

Other Material Studies

Impurities

Impurities present a major problem in tokamak plasmas as they can have detrimental effects which cause:

- reductions in the number of effective ions in the plasma available for productive fusion reactions;
- large power losses from the plasma by radiation;
- reductions in the density limit at which major disruptions occur.

The main impurities in JET plasmas are carbon, oxygen and nickel with chlorine occasionally observed. The nickel concentration, $C_{Ni} = n_{Ni}/n_e$, depends significantly on the previous history of radio frequency heating and is usually $\leq 10^{-5}$ during operation with ohmic heating alone. During radio frequency heating, nickel is released from the antennae screens and is subsequently deposited on the protection tiles and limiters. After high power radio frequency heating, nickel concentrations of $C_{Ni} \approx 10^{-3}$ were measured during ohmic heating phases with this value increasing several times during the radio frequency heating. Oxygen concentrations, $C_O = n_O/n_e$, have been between 0.5 and 1 % in deuterium plasmas. In helium plasmas, this was reduced by about a factor of ten due to lower oxygen influxes from the walls and limiters which is a clear indication of a chemical production mechanism. Carbon appears to be produced by physical sputtering and had a concentration of several percent in both deuterium and helium discharges, with a tendency to increase during additional heating.

The parameter which provides a measure of the impurity content of a plasma is the effective ion charge, Z_{eff}, which is the average charge carried by an ion in the plasma. The global impurity content is measured routinely throughout each pulse by measuring the radial profile of Z_{eff}. During the ohmic heating phase, Z_{eff} is peaked on axis. Whilst the precise value of Z_{eff} is sensitive to previous machine operation, in general, it decreases with increasing density, see Fig. 34, and increases with current. During the application of radio frequency heating power (≥ 5 MW) there is a gradual rise in Z_{eff} and the profile becomes flatter due to increased impurity production at the plasma edge, caused by power loading on the antennae. The injection of neutral beams of deuterium or pellets reduces the value of Z_{eff}. With neutral beam injection heating, the profile of Z_{eff} is essentially unchanged as, even though the beam increases the deuterium source on axis by over two orders of magnitude, recycling at the plasma edge dominates the global particle balance. However, when pellet injection penetration to the axis is achieved, the Z_{eff} profile becomes flatter with prompt reductions of Z_{eff} at the centre, by factors up to three due to the abrupt dilution of the impurities in the core. Values for Z_{eff} of about two are common for discharges in a well conditioned vacuum vessel. Since carbon and oxygen are the most important impurities, this implies that, at the centre of the plasma, the ratio of n_O/n_e is ~0.5. However, following pellet injection, the central values of Z_{eff} of ≤ 1.3 have been achieved, and the ratio n_O/n_e is ~0.9.

Impurities

Impurities released from interactions between the plasma and material surfaces can have major effects on plasma behaviour by causing:

(a) increased radiation losses;

(b) dilution of the number of ions available in the plasma between which fusion reactions can occur.

A measure of the overall impurity level is given by Z_{eff} which is defined as the average charge carried by the nuclei in the plasma. A pure hydrogen plasma would have $Z_{eff} = 1$ and any impurities would cause this value to be increased. In JET Z_{eff} is generally in the range from 2-3.

Major energy losses can result from two radiation processes:

1) Bremsstrahlung Radiation - Radiation is emitted when electrons are accelerated in the electric field of an ion. The amount of radiation emitted increases with Z_{eff}. Bremsstrahlung radiation imposes a fundamental limit to the minimum plasma temperature that must be attained in a fusion reactor;

2) Line Radiation—Heavy impurities will not be fully ionised even in the centre of the plasma and energy can therefore be lost through line radiation.

Considerable effort is made to keep the level of impurities in the JET plasma to a minimum. The vacuum vessel is baked at 300 °C to remove gas particles trapped on the vessel walls which might be released by plasma bombardment.

Interactions between the plasma and vacuum vessel walls would result in the release of heavy metal impurities. To reduce this possibility, the edge of the plasma is defined by limiters. These are panels protruding from the vessel walls and covered with a material such as carbon, which has a relatively low electric charge on the nucleus. Prior to some experimental pulses, a glow-discharge is operated in methane so that the walls become carbonised. This reduces the level of heavy impurities released from the walls.

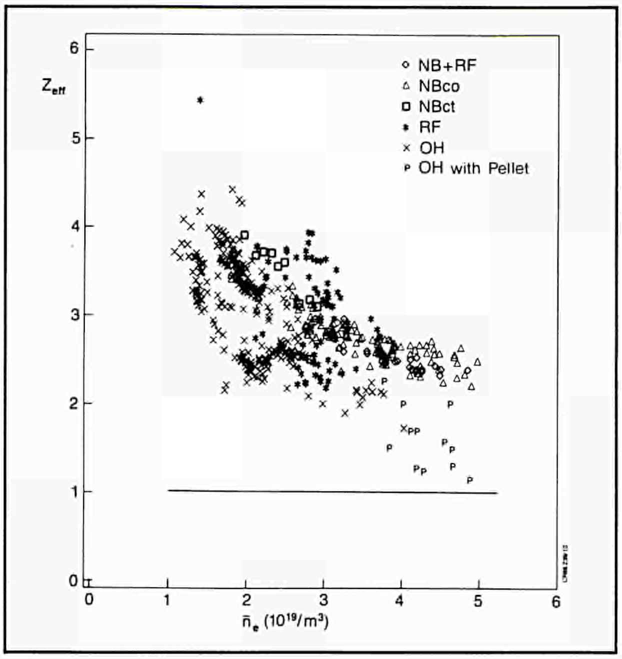


Fig.34 Effective charge (Z_{eff}) versus average density ($\bar{n}_e$) for various plasma regimes

Plasma Boundary Phenomena

The plasma boundary layer, defined by the material or magnetic (X-point) limiters, is relevant to:

- the release and transport of impurities in the plasma;
- recycling, retention and transport of hydrogen isotopes in the plasma;
- the energy confinement properties of the core plasma.

Analysis of measurements in the boundary have shown that the edge density and temperature scale consistently with the average density of the plasma and the total input power. The edge density increases as the square of the line average density, while the edge temperature decreases with the square of increasing density but increases with the input power. During radio frequency heating the boundary layer broadens and the temperature in the boundary generally increases. With neutral beam injection heating the increase in density more than compensates for the increased input power, Fig.35, and the edge temperature generally decreases. When the belt limiters were installed, the edge temperature and density were much less consistent for given discharge conditions than with the previous discrete limiter configuration. However, probes at various toroidal locations showed good toroidal symmetry and that in the vertical direction was readily obtained using the feedback control of the vertical position of the plasma.

Recycling of the plasma at the walls has been studied under a variety of conditions. It has been shown that pumping occurs at all surfaces including the belt limiter, inner bumper limiter and X-point protection tiles and that there was no significant change in the pumping rate when the wall temperature was changed from 150°C to 300°C. Measurements of outgassing after a normal discharge, indicate that a large fraction, of between 70 and 90% of the gas introduced, remains trapped in the vessel indefinitely. The only explanation for this at present is that there is co-deposition of carbon and hydrogen isotopes on some surfaces which leads to permanent trapping. This has not yet been verified quantitatively but in the tritium phase of operation could have repercussions on the tritium inventory and amount released in the vessel.

During X-point operations, measurements have been made of plasma parameters in the divertor. The electron density varies from about $3\times10^{18}m^{-3}$ in ohmically heated discharges up to about $1\times10^{20}m^{-3}$ with high power heating. The corresponding electron temperature values are from 30 to 70eV with ohmic heating with an even wider range of temperatures occurring during additional heating. Power fluxes, up to 40MW m^{-2}, have been inferred from the probe measurements. Observations suggest that the termination of the H-mode may be associated with the establishment of a very cold divertor plasma, perhaps with insufficient power being fed into the boundary layer to prevent a thermal collapse of the divertor plasma. There is evidence that recycling neutrals can be ionized close to the divertor target tiles, in high recycling conditions, or can escape from the diverted plasma and enter the confined plasma which would be detrimental to confinement.

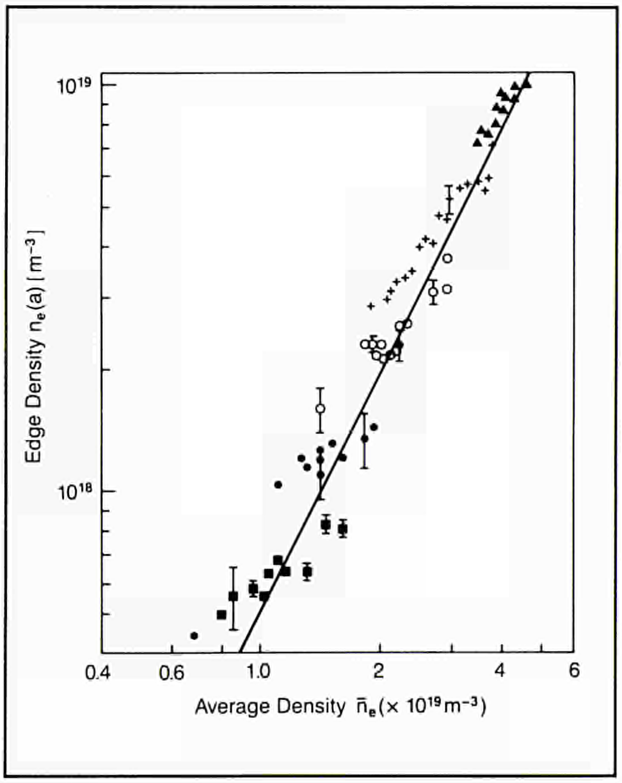


Fig.35 Increase in electron density at the edge with increasing average plasma density

Progress Towards Breakeven

A record value of the fusion product $(n_i.\tau_E.T_i)$ of $2\times10^{20}m^{-3}skeV$ was achieved in 1986 with 10MW of neutral beam heating during X-point operation in the H-mode. In addition, for limiter discharges, the values of the fusion product obtained were similar for ohmic heating, radio frequency heating, neutral beam injection heating and combinations of these methods. This was a result of the gains made in the values of temperature and density being offset by the degradation in energy confinement time.

During 1987, with magnetic limiter operation in the H-mode, this same maximum value of fusion product of $2\times10^{20}m^{-3}skeV$ was repeated. In this case, however this was achieved with only ~6MW of neutral beam heating with a 3MA plasma current, following optimization of the various plasma parameters. However, a significant improvement was made in the fusion product with radio frequency heating alone. A value of $1.2\times10^{20}m^{-3}skeV$ ($n_i=3.8\times10^{19}$, $T_i=8keV$ and $\tau_E=0.4s$) was reached using ^3He minority heating with an input power of 16MW into a 3.5MA deuterium plasma. The maximum values of the fusion product and the corresponding values of plasma temperature, density and energy confinement time are given in Table 6 for different operating scenarios.

In the radio frequency heated plasma, which produced the highest fusion product, nearly 16MW of power produced a plasma stored energy in excess of 6MJ and fusion rate for D-D reactions of $1.4\times10^{15}s^{-1}$. In this discharge, a significant fraction of the stored energy resulted from the minority ions which are expected to produce high fusion yield in (D)T heating schemes. However, the maximum neutron yield obtained so far is that of $3\times10^{15}s^{-1}$ produced previously with neutral beam heating. This resulted mainly from D-D reactions occurring between the deuterium particles in the heating beams and the background plasma. The best ratio of fusion power to input power obtained was $Q_{DD}=3.5\times10^{-4}$ which is equivalent to $Q_{DT}\sim0.2$, if tritium were introduced into the machine under these condition. This would correspond to a fusion power production of above 1MW. This enhanced reaction rate is due to interactions between the neutral heating beams and the plasma.

Prospects

During 1987, operation concentrated on recommissioning existing systems and on bringing the newly installed systems into operation under full operating conditions. During the first half of 1988, the second neutral beam box should be ready for operation, and then the two units should provide 20MW of power. In addition, all eight generators of the radio frequency heating system should be upgraded to a total power of 32MW which should provide about 24MW into the plasma. This should make available a total additional heating power of 44MW. In addition, operations should be possible with 7MA plasma currents in the material limiter configuration and over 4MA in the magnetic limiter mode. Additional high grade carbon tiles will be fitted to the X-point dump plates to permit higher powers to be used in this configuration. All

Table 6
Maximum Values of the Fusion Product (Dec 1987)
$\langle n_i.\tau_E.T_i\rangle$

Experimental Programme	Peak Density n_i ($\times10^{19}m^{-3}$)	Energy Confinement Time τ_E (s)	Ion Temperature T_i (keV)	Fusion Product $\langle n_i\tau_E T_i\rangle$ ($\times10^{20}m^{-3}skeV$)
Ohmic (4.6MW)	4.2	0.8	3.0	1.0
ICRF (16MW)	3.8	0.4	8.0	1.2
NBI (6MW) High n_i	4.4	0.4	4.0	0.7
NBI (6MW) Low n_i	1.5	0.4	10.0	0.6
Combined NBI + RF (15MW)	4.0	0.35	7.5	1.0
X-point (NB – 10MW)	5.0	0.65	6.0	2.0
X-point (NB – 6MW)	5.0	0.75	5.5	2.0

these enhancements should enable improved plasma parameters to be obtained as well as higher fusion products.

Present results give confidence that alpha particle production will be significant when a deuterium-tritium plasma is used in JET as, with the envisaged increases in plasma current, the equivalent Q_{DT} should be close to a value of unity in both configurations. This would correspond to the production of several tens of megajoules of thermonuclear energy during a JET pulse. In these conditions, about one-half of the fusion power would come from beam plasma reactions. Further improvements, outlined in the section on Future Programme, are aimed at increasing the thermonuclear output.

Future Programme of JET

Introduction

The initial JET objectives remain unchanged and the same four areas of work are still the focus of the Project's activities. The study of energy confinement and its degradation with additional heating is covered by areas one and three. The study of different low atomic number (low-Z) materials, edge effects, exhaust and fuelling is covered by area two. The study of α-particles, area four, must clearly wait until area two and three have been successfully addressed, as α-particles will need to be produced in sufficient quantities for their effect on the plasma to be observed.

The aims of the Project clearly state that JET is an experimental device and that, to achieve its objectives, the latest developments in tokamak physics must be allowed to influence its programme. The experimental results currently achieved in JET and in other tokamaks, notably those of the European programme, together with the latest developments in tokamak physics, show that the sought after increase in the fusion product could not be achieved without making additions to the original JET programme.

While present achievements show that the first three objectives of JET are being actively addressed and substantial progress is being made, the programme can now be summarised as a strategy to optimise the fusion product ($n_i.\tau_E.T_i$). For the energy confinement time, τ_E, this involves maintaining, with full additional heating, the values that have already been reached with ohmic heating alone, which means avoiding energy confinement degradation. For the density and ion temperature, it means increasing their central values to such an extent that operation with deuterium and tritium would produce α-particles in sufficient quantity to be able to analyse their effects on the plasma.

Objectives of JET

The essential objective of JET is to obtain and study plasma in conditions and with dimensions approaching those needed in a thermonuclear reactor. These studies will be aimed at:

1. *The study of scaling of plasma behaviour as parameters approach the reactor range.*
2. *The study of plasma-wall interactions in these conditions.*
3. *The study of plasma heating.*
4. *The study of α-particle production, confinement and consequent plasma heating.*

New and Enhanced Systems

Through the following methods, additions to JET aim to build up a high density and high temperature plasma in the centre of the discharge, where α-particles could be observed, while maintaining an acceptably high global energy confinement time:

- Decoupling the temperature profile from the current density profile;
- Increasing the density of deuterium and tritium ions in the central region to between 1 and $2\times10^{20}m^{-3}$;
- Reducing the edge density by pumping;
- Achieving high central temperatures 12–15 keV;
- Increasing the plasma current in two main configurations.

(*a*) with a magnetic separatrix (X-point operation) up to 4MA;

(*b*) with low-*Z* material limiters at higher currents up to 7MA.

Progress on the development of these systems is outlined in the section describing the 'Technical Status of JET'.

It is intended that the aims outlined above should be obtained by using the following:

Control of Current Density Profile

The strong correlation between the temperature profiles and the current density existing in an ohmically heated tokamak could be removed by using non-inductive current drive mechanisms so that flatter current profiles can be obtained. This would keep the safety factor q above unity everywhere in the plasma, and thus avoid (or considerably reduce) the sawtooth phenomena, achieve high temperatures and eventually improve confinement.

The main method of controlling the current profile in JET will be by driving 1 – 5MA current, dependent upon density, in the outer half radius of the plasma by using 12MW of lower hybrid current drive (LHCD) power at 3.7GHz. The system envisaged could be upgraded to 17MW dependent upon testing of components.

Control of Density

A high speed multi-pellet injector will be used to increase the central density well above present levels by injecting hydrogen pellets into the plasma. To achieve deep density refuelling, pellet speeds in excess of $5 \mathrm{km\,s^{-1}}$ will be needed. This system will only be introduced if successful development takes place outside JET.

The increase in central density needs to be obtained without increasing that at the edge of the plasma. A particle exhaust system is therefore required to control the edge density. It is not clear whether wall pumping, which is the main mechanism presently used, can be utilised as most of the pumped particles remain within the vessel walls. As an alternative, pumped limiters are being developed.

Control of Disruptions

In tokamaks, major plasma disruptions impose limits on the plasma density. This not only strongly affects the overall performance of the plasma but also determines the operational limits of the device, as the mechanical and thermal stresses reach their peak values during a disruption. It is proposed to control disruptions in JET by:

- Minimising the radiation cooling at the plasma boundary by using low-Z materials for the first wall facing the plasma. Carbon, which has already been used, is planned to be replaced later with beryllium which has the additional advantage of gettering oxygen;
- Stabilising the magnetic oscillations present at the onset of a disruption with magnetic perturbations produced from a set of internal saddle coils using feedback control.

Increasing the Central Plasma Temperature

High central plasma temperatures (~12 – 15keV) should be achieved by a combination of additional heating from:

- On-axis ion cyclotron resonance frequency (ICRF) heating using upgraded radio frequency (RF) generators with eight antennae in the torus, which should produce at least 30MW power in the plasma;
- Two neutral beam (NB) injectors providing at least 10MW of 140keV neutral particles in the plasma.

In addition, 10MW of lower hybrid current drive power at 3.7GHz will be dissipated in the outer plasma region, which should assist in raising the whole temperature profile.

Increasing the Plasma Current

To assist improvements in the confinement time, the plasma current is being increased in two main modes of operation: from 5 to 7MA in the material limiter mode and from 3 to 4MA in X-point operation. These experiments, which correspond to a considerable extension to the original design parameters, are making full use of the inbuilt capability of the JET machine and of the new reinforced supports for the vacuum vessel. The extension means that modifications and enhancements have had to be made to the magnets and their electrical power supplies, as well as provision for additional protection of dump plates in the vacuum vessel to absorb the energy of the plasma reaching the wall in the vicinity of the X-points. Additional studies are underway to determine the possibility of operating with plasma current up to 7MA in the X-point mode of operation.

The Proposed JET Programme

The additions mentioned above, together with the ambitious JET programme on additional heating and the preparation for the tritium phase of operation (remote handling maintenance and tritium recycling system), could clearly not be completed by the end of 1990. A new programme has therefore been prepared which is supported by the JET Council and awaits the approval of the Council of Ministers.

Figure 36 shows this new programme which is two years and seven months longer than that originally envisaged and which should still be considered provisional for the reasons outlined above. One major shutdown every eighteen months is planned to allow all the necessary modifications to be made for the following operational period. It is now envisaged that the tritium phase will last for fifteen months. During this period, a few thousand discharges would be performed to study α-particle production, confinement and heating of the plasma.

The figure showing the new JET plan also includes the various phases in the JET programme. Phase I, the Ohmic Heating Phase, was completed in September 1984, and Phase IIA was completed in December 1986. The remaining phases are as follows:

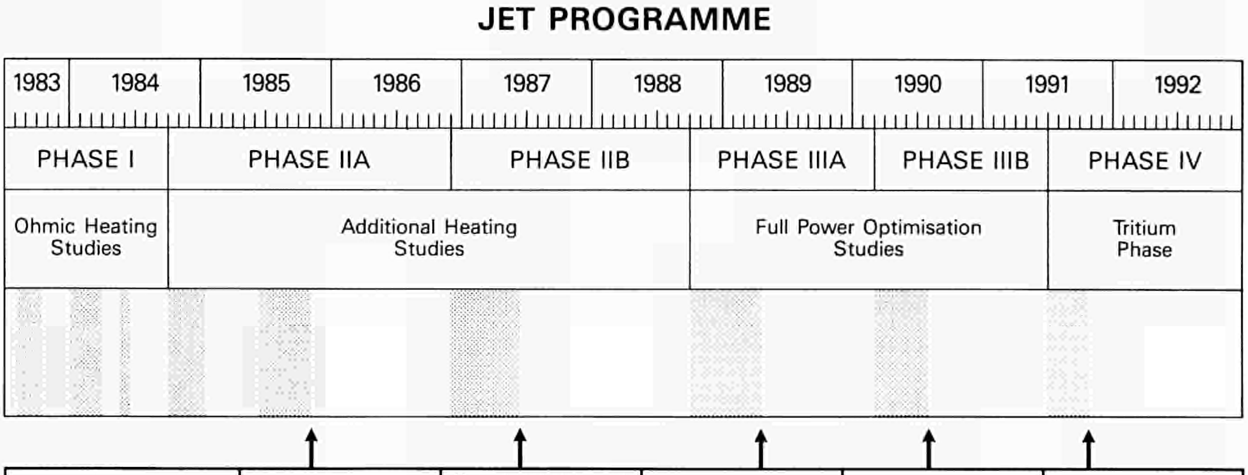
Phase IIB (mid-1987—mid-1988)

The general objective of this phase is to explore the most promising regimes for energy confinement (currents up to 7MA in the limiter mode, 4MA in the X-point mode) and for high fusion yield (high T_e and T_i regimes including also significant non-thermal fusion yield) at increased ICRF power (20MW) and neutral beam heating power (20MW at 80kV). The ultimate objective is to achieve full performance with the simultaneous operation of all systems.

Phase IIIA (mid-1988—end of 1989)

During the shutdown at the beginning of this phase, the following items should be installed:

- Prototype single shot high speed pellet injector;



Ohmic Systems	5MA	Vessel restraints and improved volt-seconds for 7MA operation			
Separatrix		Additional P1 Coils	Cooled separatrix dump plates		
Limiters	Eight carbon mid-plane limiters	Carbon belt limiters	Beryllium belt limiters		
Pellets	Single pellet injector	ORNL multiple pellet injector ($1.5 km s^{-1}$)	Prototype high speed pellet injector ($>3 km s^{-1}$)	[Multiple high speed pellet injector]*	
Pump limiters				Adjustable pump limiter	
NBI	First NBI line (80kV)	Second NBI line (2×80kV)	One line modified to 140kV	Second line modified to 140kV	
ICRH	Three A_0 antennae	Eight A_1 antennae			
LHCD			Prototype system	Full system	
Disruption control			Saddle coils		
Tritium and Remote handling				Tritium plant and main RH modifications	Final modifications

*To proceed if successful development takes place outside JET

CR86.2 (rev 24/2/88)–Ro1540. H1 P CR86.2

Fig. 36 The proposed future JET Programme

- Conversion of one neutral injector to 140keV;
- Beryllium belt limiter;
- Final modifications to the electro-magnetic system for X-point operation and cooled separatrix dump plates;
- Testbed for lower hybrid current drive and prototype module;
- Disruption control system using internal saddle coils.

The main aims of this phase will be to consolidate the operation of JET at full performances with long pulses (>10s) at full additional heating power (20MW of ICRF heating, 10MW of NB heating at 80kV, and 7.5MW of NB heating at 140kV). The effect on confinement of controlling the current and density profiles, using pellet injection and current drive by ICRF heating, NB injection and LHCD in quasi stationary states, will be established. The use of beryllium as a low-*Z* wall and limiter material represents an option in the programme. The potential benefit expected from this, is a reduction of the impurity level by gettering oxygen, to allow good confinement over an extended range of parameters.

Phase IIIB (early 1990—mid 1991)

After the shutdown at the beginning of this phase the following systems should be operational:

- Final lower hybrid current drive system for profile control;
- Adjustable pump limiter;
- Both neutral injectors at 140keV;
- All remote handling systems required for the active phase;
- Multiple pellet injector system (if successful development takes place outside JET);
- Diagnostic systems required for the active phase.

The comissioning of the tritium plant should also take place during this phase.

The main aims of this phase will be to reach maximum performance with deuterium plasmas and to establish operating regimes to be used in the tritium phase (limiter, X-point, non-thermal, or any other modes of operation which have proved successful). These regimes will also be modified and enhanced by the plasma control systems (acting on current profile, density profile, impurities and disruptions) at their full capacity.

During this phase, the machine will be upgraded to the status compatible with full radioactive operation (i.e. remote handling systems tested, tritium compatibility of systems completed, shielding requirements implemented, tritium plant commissioned, neutral beam and pellet injectors upgraded for tritium beam and pellet injection).

Phase IV D-T Phase (mid 1991—end of 1992)

Deuterium-tritium (D-T) operation should begin when the conditions achieved in deuterium alone suggest that significant α-particle heating would be achieved in D-T.

The main aim of this phase is to operate JET with D-T plasmas. In the light of present knowledge, all the currently planned new equipment will be needed to bring the performance to a level justifying the introduction of tritium in the torus. There will be two main areas of development during this phase.

(*a*) Establishment of Tritium Operation.
The characteristics of D-T plasmas will be studied, including their confinement properties and impurity content. An important element will be the control of the composition of the core plasma using tritium neutral beam injection and/or pellets. New scenarios will be explored leading to the optimisation of ICRF and NB heating for D-T plasmas.

(*b*) High Fusion Yields and the Detection of α-Particle Heating.
The study and optimisation of intensely heated D-T plasmas will be required both for the maximisation of the fusion yield and for the database for future devices. It is anticipated that current and density profile control will play important roles.

The main questions to be studied should be:

- Are the α-particles confined?
- Do the α-particles behave as expected?
- What kind of confinement degradation does the α-particle heating cause?

The answer to this last question will directly influence the size of a reactor.

The Members and Organisation of JET

Members

The JET Joint Undertaking has the following Members:

- The European Atomic Energy Community (EURATOM);
- The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas of the École Royale Militaire') and on behalf of the Université Libre de Bruxelles' ('Service de Chimie-Physique II de l'ULB'); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studiecentrum voor Kernenergie' (SCK);
- The Centro de Investigaciones Energeticas Medioambientales y Tecnologicas (CIEMAT), Spain;
- The Commissariat à l'Énergie Atomique (CEA), France;
- The Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy;
- The Hellenic Republic, Greece;
- The Forskningscenter Risø (Risø), Denmark;
- The Grand Duchy of Luxembourg, Luxembourg;
- The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal;
- Ireland;
- The Kernforschungsanlage Jülich GmbH (KFA), Federal Republic of Germany;
- The Max-Planck-Gesellschaft zur Förderung der Wissenschaften eV—Institut für Plasmaphysik (IPP), Federal Republic of Germany.
- The Swedish Natural Science Research Council (NFR), Sweden;
- The Swiss Confederation, Switzerland;
- The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands;
- The United Kingdom Atomic Energy Authority (UKAEA), Host Organisation;

Management

The JET Joint Undertaking is governed by Statutes which were adopted by the Council of the European Communities on 30 May 1978. The organs of the Joint Undertaking are the JET Council and the Director of the Project. The JET Council is assisted by the JET Executive Committee and is advised by the JET Scientific Council, see Fig. 37.

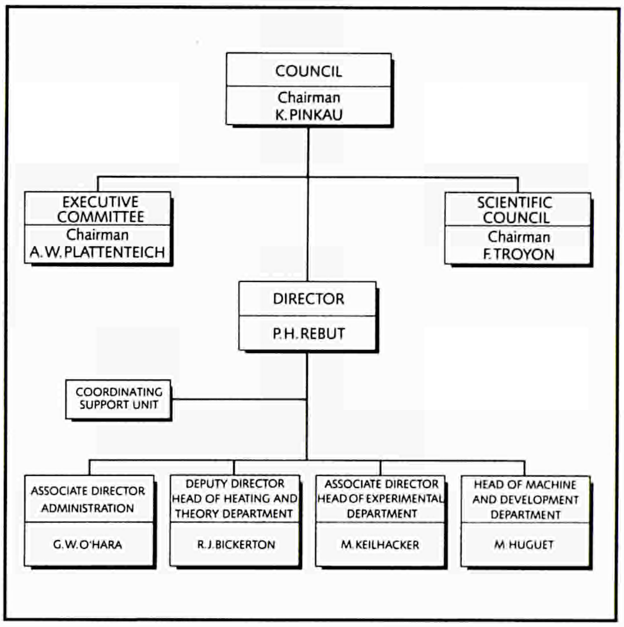


Fig. 37 Organisation of the JET Joint Undertaking

JET Council

Each member of the Joint Undertaking is represented on the JET Council, which is required to meet at least twice yearly. The Council is responsible for the management of the Joint Undertaking and also for:

- The nomination of the Director and Senior Staff of the Project with a view to their appointment by the Commission or the Host Organisation as appropriate;
- The approval of the annual budget, including staffing, as well as the Project Development Plan and the Project Cost Estimates;
- Ensuring the collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project, including the establishment of rules on the operation and exploitation of JET.

Three meetings of the JET Council were helding during 26 – 27 March, 18 – 19 June and 22 – 23 October. The membership of the JET Council is shown in Appendix I. Fig. 38 shows the participants who attended

Fig. 38. Participants at the JET Council meeting of June 1987. Standing (left to right) J. T. Mendonça, G. W. O'Hara, A. Grau, G. Leman, M. Keilhacker, P. E. M. Vandenplas, D. Byrne, P. Zinsli, C. M. Braams. A. W. Plattenteich, H. von Bülow, P-H. Rebut, F. Troyon, A. Bracci, B. Deler, T. van Rentergem, W. M. Lomer, J. Mcmahon. Seated)left to right) V. Gonzalez, R. S. Pease, N. V. Nowlan, P. Fasella, Mille. L. Buyse, K. Pinkau, N. E. Busch, F. Chadwick, F. Prevot, C. Maisonnier.

the JET Council meeting in June 1987.

JET Executive Committee

The JET Executive Committee is required to meet at least six times a year. Its functions include:

- Advising the JET Council and the Director of the Project on the status of the Project on the basis of regular reports;
- Commenting and making recommendations to the JET Council on the Project Cost Estimates and the Draft Budget, including the establishment of staff, drawn up by the Director of the Project;
- Approving, in accordance with the rules on the award of contracts established by the JET Council, the tendering procedure and the award of contracts;
- Promoting and developing collaboration between the Associated Laboratories and the Joint Undertaking in the execution of the Project.

The membership of JET Executive Committee is shown in Appendix II. The Committee met seven times during the year on 5 – 6 February, 5 – 6 March, 14 – 15 May, 16 – 17 July, 24 – 25 September, 5 – 6 November and 10 – 11 December.

JET Scientific Council

The JET Statutes confer the following functions on the JET Scientific Council:

- Upon the request of the JET Council, to advise on scientific and technical matters, including proposals involving a significant change in the design of JET, its exploitation, and its long-term scientific implications;
- To perform such other tasks as the JET Council may request it to undertake.

The membership of the JET Scientific Council is shown in Appendix III. The Scientific Council met three times during the year on 26 – 27 February, 3 June and 6 - 8 October.

The main work of the JET Scientific Council in 1987 was to assess and report to the JET Council on:

- the scientific priorities at JET in the light of certain elements of the JET experimental programme (namely, X-point operation, lower hybrid current drive for current profile control, pump limiter for plasma exhaust, feedback control of disruptions, the use of beryllium as material for the belt limiter, the use of tritium in the neutral beam and pellet injectors); the status of tokamak research; and the resources available to the project and the time factors involved.

Host Organisation

The United Kingdom Atomic Energy Authority, as the Host Organisation for the JET Joint Undertaking, has made available to the Joint Undertaking, the land, buildings, goods and services required for the implementation of the Project. The details of such support, as well as the procedures for co-operation between the Joint Undertaking and the Host Organisation, are covered by a 'Support Agreement' between both parties. In addition to providing staff to the JET team, the Host Organisation provides support staff and services, at proven cost, to meet the requirements of the JET Project.

Project Team Structure

The Director of the Project

The Director of the Project, Dr P-H. Rebut, is the chief executive of the Joint Undertaking and its legal representative. He is responsible to the JET Council for the execution of the Project Development Plan, which specifies the programme, and for the execution of all elements of the Project. The Project Development Plan covers the whole term of the Joint Undertaking and is regularly updated. The Director is also required to provide the JET Scientific Council and other subsidiary bodies with all information necessary for the performance of their functions.

Internal Organisation

The internal organisation of the Project consists of four Departments and the Coordinating Staff Unit. The four Departments are:

- Heating and Theory Department;
- Experimental Department;
- Machine and Development Department;
- Administration Department.

The overall Project Structure is shown in Fig. 37.

Directorate

The Heads of the Departments report to the Director of the Project and together with the Director form the JET Directorate. Various special functions are carried out by the Director's Office. The Internal Audit Office monitors the financial activities and provides advice of accounting and control procedures as well as maintaining links with the Court of Auditors. The Project Control Office is responsible for financial planning and for the preparation of the Project Development Plan and Project Cost Estimates. The Secretariat provides Secretarial Services to the JET Council and to the Executive Committee and also to the JET Project Board.

In addition there are two groups, one containing Scientific Assistants who assist and advise the Director on scientific aspects of JET operation and future development. The other group contains the Technical Assistant who assists and advises the Director on organisational and technical matters related to JET operation and who also acts as JET Publications Officer.

Heating and Theory Department

The Heating and Theory Department is responsible for heating the plasma, the theory of tokamak physics, the organisation of experimental data and the day to day operation of the machine. The main functions of the Department are:

- following the theory of tokamak physics;
- heating of the plasma and analysis of its effects;
- centralising the interpretation of experimental results and investigating their coherence;
- organising data acquisition and computers;
- preparing and co-ordinating operation of the machine across the different Departments.

The Department is composed of two groups (Machine Operations Group and Physics Operation Group) and four Divisions:

(1) Control and Data Acquisition System Division (CODAS), which is responsible for the implementation, upgrading and operation of the computer-based control and data acquisition systems;

(2) Neutral Beam Heating Division, which is responsible for the construction, installation, commissioning and operation of the neutral injection system, including development towards full power operation of the device. The Division also participates in studies of the physics of neutral beam heating;

(3) Radio Frequency Heating Division, which is responsible for the design, construction, commissioning and operating the RF heating system during the different stages of its development to full power. The Division also participates in studies of the physics of RF heating;

(4) Theory Division, which is responsible for prediction by computer simulation of JET performance, interpretation of JET data and the application of analytic plasma theory to gain an understanding of JET physics.

Experimental Department

The main functions of the Department relate to the measurement and validation of plasma parameters. The major tasks are:

- to conceive and define a set of coherent measurements;
- to be responsible for the construction of necessary diagnostics;
- to be responsible for the operation of the diagnostics and the quality of measurements and the definition of the plasma parameter;
- to play a major role in the interpretation of data.

The Department consists of two Groups (Diagnostics Engineering Group and Data Processing and Analysis Group) and two Divisions:

(1) Experimental Division One (ED1), which is responsible for specification, procurement and operation of approximately half of the diagnostic systems. ED1 undertakes electrical measurements, electron temperature measurements, surface and limiter physics and neutron diagnostics;

(2) Experimental Division Two (ED2), which is responsible for specification, procurement and operation of the other half of the diagnostic systems. ED2 undertakes all spectroscopic diagnostics, bolometry, interferometry, the soft X-ray array and neutral particle analysis.

Machine and Development Department

The Machine and Development Department is responsible for the performance capability of the machine as well as for equipment for the active phase, together with enhancements directly related to it (excluding heating) and the integration of any new elements on to the machine. In addition, the Department, which is composed of three divisions, is responsible for maintenance and operation of the coil systems, structural components and machine instrumentation. The three Divisions are:

(1) Magnet and Power Supplies Division, which is responsible for the design, installation, operation, maintenance and modification of all power supply equipment needed by the Project;

(2) First Wall Division, which is responsible for the vital area of plasma wall interactions. Its main tasks include the provision and maintenance inside the vacuum vessel of conditions leading to high quality plasma discharges. The Division develops, designs, procures and installs first wall systems and components, such as limiters, wall protections, internal pumping devices and pellet injection systems. The area of responsibility encompasses the vacuum vessel as a whole, together with its associated systems, such as pumping, bake-out and gas introduction;

(3) Fusion Technology Division, which is responsible for the design and development of remote handling methods and tools to cope with the requirements of the JET device, and for maintenance, inspection and repairs. Tasks also include the design and construction of facilities for handling of tritium.

Administration Department

The Administration Department is responsible for providing Contracts, Finance and Personnel services to the Project.

Coordinating Staff Unit

The Coordinating Staff Unit is responsible for the provision of engineering services to the whole project and for the implementation of specific coordinating tasks at the Project level.

It comprises four groups:

- the Technical Services Group;
- the Planning Group;
- the Drawing Office;
- the Quality Assurance Group.

The Administration of JET

Introduction

The three main aspects of JET's administration—Finance, Contracts and Personnel—are discussed in this section as well as the work of the Joint Safety Services and Joint Public Relations Section.

Finance

The budgets for 1987 were approved at 93.06 Mio ECU for Commitments and 104.37 Mio ECU for both Income and Payments Budgets. The Commitments and Payments Budget each subdivide into two phases of the Project—Extension to Full Performance and the Operational Phase; further subdivisions distinguish between investment, operating and personnel costs. The Basic Performance Phase was closed at the end of 1986.

Commitments (Tables 7 and 8)

Of the total appropriations in 1987 of 123.51 Mio ECU (including 30.45 Mio ECU brought forward from previous years) 102.41 Mio ECU was committed and the balance 21.10 Mio ECU was available for carry forward to 1988.

Table 7
Commitment Appropriations for 1987

	Mio ECU
1987 Commitments Budget	93.06
Uncommitted amounts available from 1986	30.45
	123.51
Commitments made during the year	102.41
Balance uncommitted in 1987 available for use in 1988	21.10

Table 8
Commitments and Payments for 1987

Budget Heading	Commitments		Payments	
	Budget Appropriations Mio ECU	Out-turn Mio ECU	Budget Appropriations Mio ECU	Out-turn Mio ECU
Phase 2 — Extension to Full Performance				
Title 1 — Project Investments	20.88	13.24	23.22	21.63
Phase 3 — Operational				
Title 1 — Project Investments	21.60	12.62	6.72	6.68
Title 2 — Operating Costs	43.09	41.98	56.27	56.00
Title 3 — Personnel Costs	37.94	34.57	30.42	30.10
TOTAL Phase 3	102.63	89.17	93.41	92.78
Project Total—all phases	123.51	102.41	116.63	114.41

The details of the commitment appropriations available and of the amounts committed in each Phase during the year shown in Table 8 are summarised as follows:-

- In the extension to Full Performance Phase of the Project, 13.24 Mio ECU was committed leaving commitment appropriations not utilised at 31 December 1987 of 7.64 Mio ECU to be carried forward to 1988.
- In the Operational Phase, 89.17 Mio ECU was committed leaving a balance of 13.46 Mio ECU to be carried forward to 1988.

Income and Payments (Table 9)

The actual income for 1987 was 101.06 Mio ECU to which was added 3.05 Mio ECU available appropriations brought forward from previous years giving a total of 104.11 Mio ECU; this total compares with the 1987 Income Budget of 104.37 Mio ECU; the shortfall of 0.26 Mio ECU has been matched by an equivalent reduction of the Payments Budget. Of the total available payments appropriations for 1987 of 116.37 Mio ECU, payments made were 114.41 Mio ECU, and transfers to the Special Reserve Account to meet commitments outstanding at 31 December 1987 were 1.84 Mio ECU, leaving a balance of 0.12 Mio ECU to be carried forward for offset against Members' future contributions. More detailed comments are given in the following paragraphs (Payments by Phase are summarised in Table 8).

Table 9
Income and Payments for 1987

	Mio ECU		
Income			
Budget for 1987		104.37	
Income received during 1987			
(i) Members Contributions	99.82		
(ii) Bank Interest	1.20		
(iii) Miscellaneous	0.04		
(iv) Unused payments appropriations brought forward from 1986	3.05		
Total Income		104.11	
Shortfall of budgeted income			−0.26
Payments			
Budget for 1987		104.37	
Reduction of the payments budget due to shortfall of income		0.26	0.26
Adjusted payments budget 1987		104.11	
Add amounts available in the Reserve Account to meet outstanding commitments at 31 December 1986		12.26	
Total available appropriations		116.37	
Actual Payments for 1987		114.41	
Unutilized appropriations carried forward at 31 December 1987			1.96
			1.96
Attributable as follows:			
(i) Reserve at 31 December 1987 to meet oustanding commitments at that date			1.84
(ii) Carried forward for reduction of Members' future contributions			0.12
			1.96

1. Contributions from Members

The budget for Members' contributions was 99.82 Mio ECU funded as follows:-

- 80% from the general budget of the European Atomic Energy Community (Euratom);
- 10% from the United Kingdom Atomic Energy Authority as Host Organisation;
- 10% from members who have Contracts of Association with Euratom in proportion to the previous year's contribution from Euratom towards the cost of their Association Contracts. Table 10 gives the provisional percentage contribution from Members for 1987. CIEMAT, (Spain), who became a Member of JET in 1987, is not shown in the Table as Euratom participation figures are not yet available for this country which joined the EEC on 1 January 1986.

Table 10
Provisional percentage contributions to JET for 1987 based on the Euratom participation in Associations' contracts for 1984.

Member	%
Euratom	80.0000
Belgium	0.1401
CEA, France	2.3010
ENEA, Italy	1.0298
Risø, Denmark	0.0835
Luxembourg	0.0039
KFA, FRG	0.8068
IPP, FRG	2.6358
KFK, FRG	0.5276
NFR, Sweden	0.1578
Switzerland	0.4236
FOM, Netherlands	0.4390
UKAEA	11.4511
	100.0000

2. Bank Interest

Income is normally received on a quarterly basis in respect of Members' contribution and intermittently in respect of other items. The Project, therefore, has funds which are not immediately required for the discharge of its commitments; these funds are placed on deposit account at market interest rate; during 1987 earned interest amounted to 1.20 Mio ECU.

3. Unused Payment Appropriations and Excess Income from Earlier Years

3.05 Mio ECU of unused payment appropriations and excess income arising in previous years and held for reduction of Members' future contributions was transferred to income in 1987.

Summary

Table 11 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1987, which have yet to be audited. The final audited accounts will be published in due course.

Table 11
Summary of Financial Transactions at 31 December 1987

	Mio ECU
Cumulative commitments	803.1
Cumulative payments	752.1
Current commitments	51.0
Of which carried forward on reserve account	1.8
Amount available from 1986 and 1987 due to be set off against future contributions from Members	0.7

Contracts

The trend towards service and smaller supply contracts that has been evident since 1984 has continued. This is reflected in the substantial rise in the number of minor contracts and the decline in the total of major contracts.

Minor Contracts

Minor contracts are those with a value of less than 50,000 ECU. The volume of these handled by the Contracts Service increased from 8049 in 1986 to 8579 in 1987, an increase of 7%. Many of these minor contracts fall within the small value order system which provides swifter processing of small requisitions (other than amendments to existing orders) below 750 ECU. The number of orders processed in this way totalled 5179 representing 60% of all minor contracts placed, while their aggregate value of 1 332 792 ECU amounted to 2% of the total value of all minor contracts placed.

Major Contracts

Major contracts are those which have a value greater than 50000 ECU. The number of these contracts placed fell from 166 in 1986 to 144 in 1987. This 13% decrease reflects the continued progress of the Operational Phase and the completion of many of the major supply contracts. Even so the value of the major contracts placed in 1987 represents 67% of the total value of all orders for the year.

Many of the larger contracts involve advance and retention payments for which bank guarantees are required by JET. The total value of guarantees held at 31 December 1987 was 5.7 Mio ECU.

Import and Export Services

The Contracts Service is also responsible for the import and export of JET goods. Each consignment must be closely monitored en route as JET is exempt from custom duties and VAT on its goods under privileges granted by the Host Country.

The total number of imports handled in 1987 was 1265, representing an increase of 14% over the 1986 figure. The 442 exports for 1987 represents a decrease of 8% compared to 1986. There were also 913 issues of goods to UK firms during 1987, an increase of 43% on the 1986 figure. The total value of issues to all countries during the year was 6.3 MioECU.

Details of all transport transactions are held on a Transport System database. Insurance for all consignments is arranged by the Contracts Service except for imports against major contracts which are insured by the suppliers. All insurance policy claims are handled within the service.

Administration of Contracts

The computerised system for requisitions operates satisfactorily. In addition to allocating contract numbers, the data input is absorbed into the databases of both the Contracts and Finance Services. Data are also retained on the distribution of contracts between countries which is shown in Table 12. Included in these figures are all contracts with a value of 10 000ECU and above placed prior to 1984, together with all contracts placed during the period 1984-87, regardless of value.

To ensure that suppliers from all member countries are considered, the Contracts Service carries out tendering procedures before placing large contracts. In 1987 there were 139 new tender actions for work expected to exceed 25 000ECU in value.

Contracts Service has also established a Register of Suppliers which is a computerised database covering 475 different categories of supply and 2580 suppliers. This register is used extensively in the tendering process as it contains suppliers from all member countries. Information from the register is also available to all JET technical officers. A completely revised Catalogue of Suppliers was issued to divisions and departments in September 1987.

Table 12
Allocation of JET Contracts
(position as at 31 December 1987)

Country	Total of ECU Values	% of Total
UK	266727877	49.01
Germany	115382676	21.21
France	51827753	9.53
Italy	34462986	6.33
Switzerland	32705083	6.01
Netherlands	9592333	1.76
Denmark	8889363	1.63
Belgium	6509412	1.20
Sweden	5373815	0.99
Ireland	354014	0.07
Others	12275550	2.26
Totals	544100862	100.00

Personnel

The activities of the Personnel Service were influenced by the major review of all posts in the project which was stipulated at the start of the Operation Phase in 1983; the ruling of the European Court disallowing the case brought by the UKAEA team members against the JET statutes; and the absence of agreement by the Council of Ministers to a revision of the Fusion Programme.

No decision has been taken by the Council of Ministers on a revision to the Fusion Programme which includes the allocation of 21 additional temporary Euratom posts to JET. In an attempt to ensure that the Project would achieve its 1987 objectives, the JET Council allowed the project to increase temporarily the number of contract staff working on the project with the same number as the 'frozen' Euratom 1987 posts in addition to an increase in contract posts in the project which it had already approved. The composition of the allocation of posts for 1987 is shown in Table 13. Fig.39 shows the composition of team staff by nationality.

Table 13
Distribution of Posts

Team Posts:	
Temporary EURATOM staff	170
UKAEA staff	260
DG XII Fusion Programme staff	19
	449
Contract Posts	231
Total	680

Recruitment

Despite the shortfall in new Euratom complement posts, the 1986 achievement of filling all Euratom positions in the team could not be maintained. This was due mainly to a somewhat larger number of staff leaving the Project

Table 14
Post Filled Against Complement
(position as at 31 December 1987)

	Complement	In Post
Team Posts:		
Temporary EURATOM staff	170	153
UKAEA staff	260	209
DGXII Fusion Programme Staff	19	10
	449	372
Contract Personnel	231	259*
Total	680	631

**This includes additional contract personnel used up to the number of vacant team posts, as authorised by the JET Council, pending the filling of these posts with Team members.*

than in previous years, and the non-availability of suitable candidates from the Associated Laboratories. The same picture was true as far as the UKAEA complement posts were concerned. As a result the number of contract personnel working at JET increased by a further 30 during the year. Table 14 illustrates the filling of posts against the approved complements.

Euratom Staff

In 1987, 14 newly appointed Euratom staff joined the team, of which six had previously worked for a JET partner. During the same period 16 staff members left (eight returned to employment with a JET partner). During the year 3 DG XII staff members left the project (two returned to Brussels and one retired), and one joined, leaving a shortfall of nine in the DG XII complement.

The number of Euratom staff in post at the end of the year was 163 including ten from DG XII.

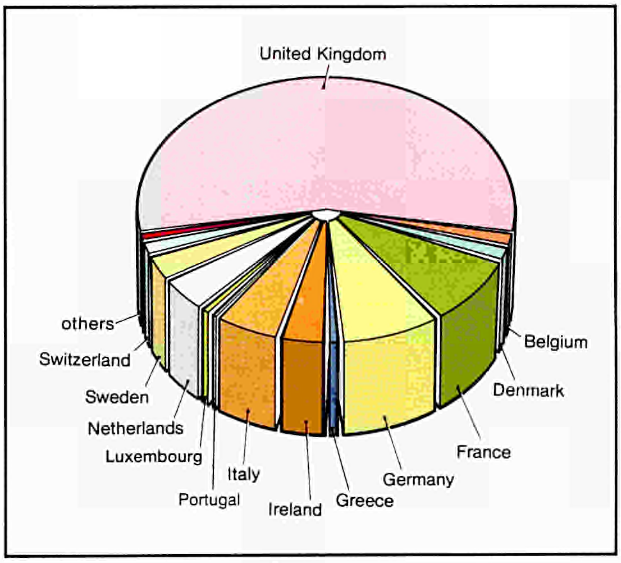


Fig. 39 Project team staff by nationality

UKAEA Staff

During the year 13 new staff were seconded to JET by the UKAEA (eight were already employed by the UKAEA before being selected) offset however by the departure of 20 UKAEA staff from the Project of which only four returned to the Authority). The number of UKAEA staff in post at the end of the year was 209.

Review of Posts

All contracts and assignment letters stipulated that all team positions in the JET organisation should be reviewed during the first five years of the Operational Phase. A complete re-assessment of all team posts was carried out during the spring and summer of 1987. As a result of this review eight positions were identified as not being required beyond June 1988 and the holders and partners were informed accordingly.

Retention of Experience

In recognition of the fact that the JET Project has a limited life span and that it is most desirable that staff who have gained essential experience on the Project should be encouraged to remain until it terminates, the UKAEA approved the introduction of a Retention of Experience Allowance to certain staff assigned by the Authority to the JET Project. The allowance, which is payable to the eligible staff in post every 31 December, will increase exponentially up to the end of 1991, subject to an overriding upper limit of 15% of the staff member's salary. The first payment of the allowance took place in December 1987 to 174 eligible UKAEA staff members in the JET Project team.

Assigned Associate Staff

Assigned Associate Staff (AAS) are scientific or technical staff of the Associated Laboratories, assigned to JET for limited periods of between one month and two years (renewable). The scheme came into operation towards the end of 1981 and to date about 240 staff from the Associated Laboratories have been assigned to JET in this way. While at JET the Associated Laboratory continues to pay the assignee his/her home salary and JET pays a monthly expatriation allowance directly to the assignee.

During 1987, 66 staff from the Associated Laboratories (other than the UKAEA) were assigned to JET under the scheme. The total contribution was about 38 man years, including an estimated contribution of 12 man-years by staff assigned from the UKAEA. This compared with 42 man-years in 1986, 30 in 1985, 23 in 1984 and eight in 1983. Tables 15 and 16 show respectively the contribution by the partners during 1987 and the deployment of AAS within the Project.

Table 15
Contribution made by Associated Laboratories during 1987

Associated Laboratory	Man-Years
UKAEA (Great Britain)	*12.00
IPP (The Federal Republic of Germany)	6.92
CEA (France)	5.52
ENEA (Italy)	3.60
FOM (The Netherlands)	2.90
NFR (Sweden)	2.02
ERM (Belgium)	1.50
CIEMAT (Spain)	1.13
CRPP (Switzerland)	1.06
JNICT (Portugal)	0.67
Risø (Denmark)	0.54
CNR (Italy)	0.29
KFA (Federal Republic of Germany)	0.29
Total	38.44

**The UKAEA contribution is estimated.*

Table 16
Assigned Associated Staff within the Project

Division	Man-Years
Experimental Division I	16.67
Experimental Division II	11.76
Radio Frequency Heating Division	4.77
Theory Division	3.15
Fusion Technology Division	1.50
Neutral Beam Heating Division	0.17
Heating and Theory Department	0.42
Total	41.77

Visiting Scientists

During 1987 the number of Visiting Scientists working at JET increased to twelve, in comparison to eight in 1986. Two came from Australia, the United States and the USSR, with one each coming from China, India, Brazil, Japan, Poland and Italy.

In response to an increased demand for Visiting Scientist placements the JET Council agreed that up to 15 such appointments could run concurrently, an increase of five.

Consultants

Thirteen Consultants were appointed during the year compared with four in 1986. The areas of work in which they provided specialist advice included remote handling, data interpretation, tritium systems and additional heating.

Exchange of Personnel

Towards the end of 1986 an IEA Implementing Agreement for Co-operation on Existing Large Tokamak Facilities (JET, JT-60 and TFTR) was entered into. A programme for exchange of scientific personnel between the JET, JAERI (Japan Atomic Energy Research Institute) and PPPL (Princeton Plasma Physics Laboratory) was established.

During the year 12 JET staff members have been attached for up to 3 months to the projects in the USA and Japan (5 to JAERI and 7 to PPPL). In return four members of the TFTR team joined the JET Project as did eight staff from JT-60.

Students

During the year 87 students (less than 50% UK nationals) from 13 different countries were employed for a total of 285 man-months, in experimental, computing, engineering and administrative work. More than half the students stayed on average five months.

Fellowships

Of the five applicants selected during 1986, four had joined the Project by Spring 1987. A further five candidates were identified at the Selection Committee convened in April, and by the Autumn four of these had also joined the Project. Placements have been obtained in all of the three scientific Departments.

Shift Work

During the shutdown apart from the technician team the only regular shift work undertaken was by a few team staff who were required to supervise contractors on the in-vessel work.

Double shift working was reintroduced in May to accelerate the recommissioning and with the commencement of operations in June the machine was operated from 0630 to 2230 hours, Monday to Friday. The shifts on Monday being for commissioning and the remaining eight shifts for operations.

The basic operation of the machine systems has required the manning of 27 posts per shift by staff from the Heating and Theory Department and the Machine and Development Department, the Experimental Department has manned approximately eight posts for the basic operation of the experiments with additional posts being manned depending on the requirements of the scientific programme.

In total 210 staff have been required to work on a casual shift basis to man these posts, plus the 12 shift technicians who have worked continuous shifts seven days per week.

Overtime

Recorded overtime this year has shown an increase of 40% and has averaged 700 hours per week which represents the equivalent of an additional 19 man years. This has resulted from the major shutdown during which the working week was extended to six days and overtime increased to a peak of 930 hours per week during the final two months of the shutdown.

After the commencement of operations the level gradually reduced until by the end of the year it had returned to an average of 500 hours per week as in the previous year. 70% of the total overtime was worked by staff in the Heating and Theory Department and the Machine and Development Department.

This recorded overtime represents the additional hours worked mainly by the non-professional team and contract staff who are eligible to claim remuneration or compensatory leave. Over the year, out of the average of 182 non-professional team staff in post, 152 have been required to undertake overtime working. This increase in the level of overtime has created difficulties for some staff who have been unable to take compensatory leave accrued or their full annual leave allowance.

On-call

The on-call duties during the shutdown were reduced to the minimum with full on-call provision being provided for essential services only. The remaining systems were reintroduced from May onwards as recommissioning began and by July, 11 sub-systems of the Torus had staff rostered for on-call provision. This involved a total of 57 staff being required to undertake these duties with each working an average of 10 weeks of on-call duty per year. Those staff eligible received the allowance towards the cost of having to provide telephone facilities.

Staff Training

During 1987, 53 staff were recalled by their parent Associations to undertake short periods of training, and 10 staff were allowed to pursue part-time courses in furtherance of their long-term career development.

The one-day JET Induction programme continued throughout the year; a total of 58 staff attending the five sessions held. Under the language training scheme, 21 staff from non-English speaking countries received English tuition and 112 staff took lessons in other European languages. During the year courses in written English were introduced and attended by 12 staff.

The Joint Safety Services held a number of courses throughout the year, attended by 61 staff. These included two radiological safety courses. Specific industrial training was organised for ·59 of the staff, with 11 attending the Presentation Skills course which were also introduced during the year.

Conferences

During the year about 115 JET attendances were recorded. The major events included the 14th European Conference on Controlled Fusion and Plasma Physics, Madrid, Spain, the 2nd European Fusion Theory Meeting in Varenna, Italy, the 29th Annual Meeting of the American Physical Society in San Diego, USA and the 12th Symposium on Fusion Engineering in Monterey, USA.

Liaison with JET Partners

Contact between JET and the Associated Laboratories was maintained relating to such matters as recruitment of staff and their re-employment at the end of their secondment to JET.

The annual staff reports required by partners in respect of their staff in the JET team were provided by the Project during the year.

Staff Representation

Six official meetings were held during the year between JET management and the Staff Representative Committee at which a wide range of topics concerning working conditions were discussed.

Safety

Organisation and Procedures

The JET Director is responsible for safety and is required by the JET Statutes to undertake all organisational measures to meet relevant safety requirements. In fact JET does more than meet all the requirements of relevant UK legislation. Under the Host Support Agreement, JET has agreed to comply with the safety regulations of the host organisation with particular reference to radiological safety standards. In addition, JET has developed special access control and fire detection schemes. The Joint Safety Service provides support to both JET and Culham Laboratory and there is a continuing consultation between the two organisations through this service and the JET-UKAEA Liaison Committee.

Safety in 1987

The successful operation of the JET device led, as expected, to a low level activation of the vacuum vessel. This resulted in it being classified at the start of the 1986/87 shutdown as a radiation controlled area under the Ionising Radiations Regulations 1985. Radiation dose rates generated by the activation of the vacuum vessel were monitored and found to fall by approximately a factor of three during the shutdown period. As a result of this decay, the radiation dose rates in the vacuum vessel were lower at the end of the year than at the beginning.

The access and dose control system was extended to cover entry to the vacuum vessel and to provide radiation dose control information during the shut-down. Access to the torus was made via the torus access cabin and all members of staff and contractors who work inside the vessel or enter under a formal scheme of work are classified radiation workers, and all are closely monitored. The radiation doses received by staff during the 26 week shutdown were small: the collective dose accrued amounted to 19 man mSv. All individual doses for the shut-down period and the remainder of the year were well below both the UK statutory limits and the more restrictive JET dose control targets (classified persons, 5 mSv/year—all other staff, 1 mSv/year). No radiological hazard due to JET machine operations existed outside the shielded torus hall and basement at any time during the year.

A fire took place in a cubicle containing high voltage and control equipment leading to the dispersion of several hundred grams of mercury in an area associated with the neutral beam power supplies. Since the area was unoccupied, no members of staff were affected by this incident. Considerable effort was expended by JET and contract staff in decontaminating the affected areas.

The Tritium Safety Assessment Panel studied the safety of the design for the active gas handling plant and of the proposed tritium operating system, and the safe disposal of radioactive waste. The panel continues to ensure that all statutory requirements for holding and discharging radioactive materials are met. Formal arrangements for liaison between JET, the UKAEA Safety and Reliability Directorate and Culham Laboratory have been made to facilitate a proper approach to tritium operations.

The JET Safety Working Group has continued to review all aspects of safety and to implement improvements both to equipment and documentation paying particular attention to the means of controlling the proposed use of beryllium on site.

Public Relations

Throughout 1987 public and scientific interest in the Project remained at a high level and a record number of visitors were shown around the JET Project. Over half of the 9000 visitors, who came to JET in 1987, visited during the Open Days held on 19-20 September. Many groups of visitors, ranging from local schools and organisations to delegates from the International Conference on Phenomena in Ionised Gases (ICPIG XVIII-Swansea) and the Space '87 Conference held in Brighton, also toured the JET facilities throughout the year.

Notable visitors to the Project included Signor Boris Biancheri, Italian Ambassador to the UK, Lord Plumb of Coleshill, President of the European Parliament, The Rt Hon Roy Jenkins, MP, and Dame Jennifer Jenkins, several Members of the European Parliament, as well as senior officials from the UK Cabinet Office and Foreign and Commonwealth Office.

A major event was the Scientific and Technological Options Assessment (STOA) Fusion Workshop, which was held at JET in November under the auspices of the European Parliament. The Workshop brought together Members of the European Parliament, representatives from the European Fusion Programme Directorate (DG XII), Brussels, invited experts and senior members of the JET Management. The meeting was held to clarify the various scientific, technical, economic, political and environmental issues likely to be relevant to the future of fusion research.

The media continued to show a great deal of interest in the Project and over thirty journalists, including a group of ten Brussels-based German correspondents and others from Japan and the USA, received briefings at JET. Four radio broadcasts were recorded for national and local programmes and six European TV crews filmed on site. A meeting of the members of the JET Information Network, who disseminate information about the project within the member countries, was held at JET on 6 March.

Seventeen lectures on the JET Project and fusion research in general were given to outside bodies during the year and JET participated in seven European exhibitions, including 'Physique 87', organised by the Société Française de Physique in Paris and 'Eurofest', held in Brussels to mark the 30th anniversary of the European Community.

Appendix I
The JET Council

Member	Representative	
The European Atomic Energy Community (EURATOM)	*P. Fasella* *(Vice-chairman)* *C. Maisonnier*	
The Belgian State, acting for its own part (Laboratoire de Physique des Plasmas of the École Royale Militaire) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the ULB)	*P. E. M. Vandenplas* *Mlle L. Buyse* *T. Van Rentergem*	 *(Jan-June)* *(from June)*
The Centro de Investigaciones Energeticas Medioambientales y Tecnalogicas (CIEMAT), Spain (Member since 5 June 1987)	*J. L. Alvarez-Rivas* *G. Madrid-Gonzalez*	
The Commissariat à l'Énergie Atomique (CEA), France	*J. Horowitz* *(Chairman)* *D. Cribier* *F. Prevot*	*(Jan-June)* *(from June)*
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy The Consiglio Nazionale delle Ricerche (CNR), Italy	*A. Bracci* *P. Longo*	
The Hellenic Republic (Greece)	*A. Katsanos*	
The Forskningscenter Risø (Risø), Denmark	*H. von Bülow* *N. E. Busch* *H. Bjerrum Møller*	 *(Jan-July)* *(from Aug)*
The Grand Duchy of Luxembourg (Luxembourg)	*J. Hoffmann* *P. Gramegna* *J. P. Zens*	 *(Jan-Oct)* *(from Oct)*
The Junta Nacional de Investigação Cientîfica e Tecnológica (JNICT), Portugal (Member from 5 June 1987)	*J. T. Mendonça* *New nomination awaited*	*(to Oct)*
Ireland	*N. V. Nowlan* *D. Byrne*	*(Jan-June)*
The Kernforschungsanlage Jülich GmbH, Federal Republic of Germany (KFA)	*A. W. Plattenteich*	
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	*K. Pinkau* *(Chairman from June)*	
The Swedish Energy Research Commission (SERC) From July changed to Swedish Natural Science Research Council (NFR)	*G. Leman* *S. Bergström*	
The Swiss Confederation	*F. Troyon* *P. Zinsli*	
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	*C. M. Braams* *K. H. Chang*	*(Jan-Oct)*
The United Kingdom Atomic Energy Authority (UKAEA)	*F. Chadwick* *M. A. W. Baker* *R. S. Pease* *D. Sweetman*	*(Jan-June)* *(from June)* *(Jan-Oct)* *(from Oct)*

Secretary J. McMahon, JET Joint Undertaking.

Appendix II

The JET Executive Committee

Member	Representative
The European Atomic Energy Community (EURATOM)	*C. Maisonnier (Vice-chairman)* *K. Melchinger*
The Belgian State, acting for its own part (Laboratoire de Physique des Plasmas of the École Royale Militaire) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the ULB)	*R. Vanhaelewyn*
The Centro de Investigaciones Energeticas Medioambientales y Tecnalogicas (CIEMAT), Spain (Member since 5 June 1987)	*F. Manero (from 5 June)* *(observer to 5 June)*
The Commissariat à l'Énergie Atomique (CEA), France	*C. Gourdon* *J. C. Saey*
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	*R. Andreani* *M. Samuelli*
The Hellenic Republic (Greece)	*A. Theofilou*
The Forskningscenter Risø (Risø), Denmark	*F. Øster (to December)* *V. O. Jensen*
The Grand Duchy of Luxembourg (Luxembourg)	*R. Becker*
The Junta Nacional de Investigação Cientîfica e Tecnológica (JNICT), Portugal. Member since 5 June 1987. (Member from 5 June 1987)	*Mrs M. E. Manso (from 5 June)* *(observer to 5 June)*
Ireland	*N. V. Nowlan* *F. G. Burrows*
The Kernforschungsanlage Jülich GmbH, Federal Republic of Germany (KFA)	*V. Hertling* *A. W. Plattenteich (Chairman)*
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	*M. Kaufmann*
The Swedish Energy Research Commission (SERC) From July changed to Swedish Natural Science Research Countil (NFR)	*E. Hellstrand*
The Swiss Confederation	*A. Heym* *P. Zinsli*
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	*H. Roelofs* *L. T. M. Ornstein*
The United Kingdom Atomic Energy Authority (UKAEA)	*D. M. Levey* *W. M. Lomer*

Secretary J. McMahon, JET Joint Undertaking.

Appendix III
The JET Scientific Council

Members appointed by the JET Council:

F Troyon (Chairman)
EURATOM-SUISSE Association
Centre de Recherches en Physique des Plasmas
Ecole Polytechnique Fédérale
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K Lackner
EURATOM-IPP Association
Max-Planck-Institut für Plasmaphysik
D-8046 Garching bei München
Federal Republic of Germany

A Messiaen
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Laboratorie de Physique des Plasmas
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D Palumbo
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D C Robinson (Secretary)
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A Samain
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S Segre
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Staff Secretary M. L. Watkins, JET Joint Undertaking