JOINT EUROPEAN TORUS JET

JET JOINT UNDERTAKING

ANNUAL REPORT 1986

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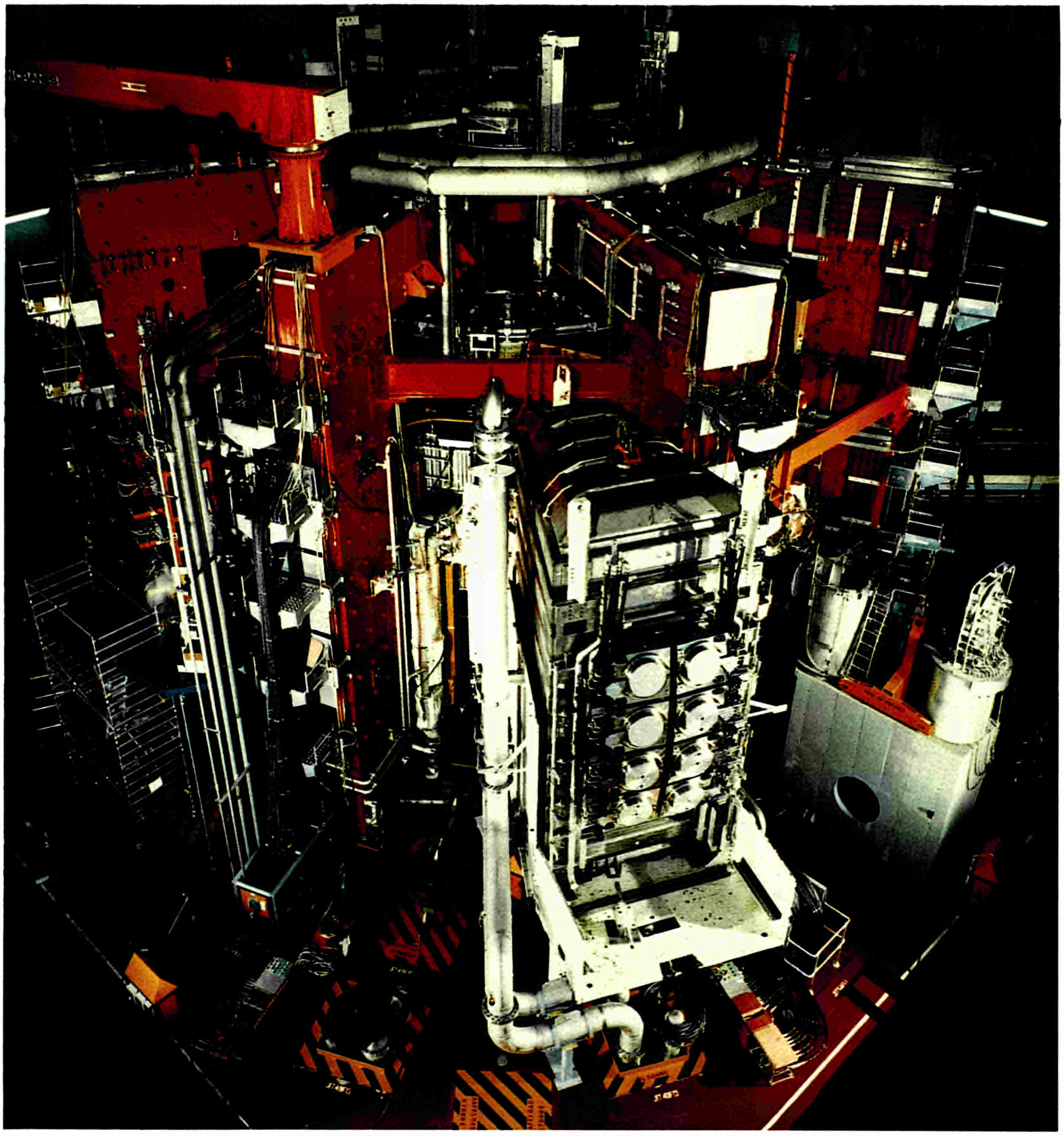

The Joint European Torus (JET)

Preface

In 1986, the JET Joint Undertaking completed its longest and most successful annual experimental programme.

During the thirty one weeks of tokamak operation, the machine operated reliably and routinely at its maximum design level with toroidal fields up to 3.45T and plasma currents exceeding 5MA.

An important step in the year's experimental programme was the commissioning and operation of the first neutral beam heating system. The expected level of operation was reached and up to 10MW of power has been injected into the torus with an 80keV deuterium beam. The first stage of the radio-frequency heating system, which started in 1985, also reached its full design capability with 12 MW of output power from the generators. Eight megawatts of net power have been launched into the torus which considerably exceeds the levels that have previously been used on a tokamak.

These excellent technical achievements have made it possible to carry out a diversified experimental programme with various heating scenarios, ranging from ohmic heating alone to combinations of ohmic, radio-frequency and neutral beam heating.

High peak ion temperatures have been achieved. However, the fusion product ($n_i.\tau_E.T_i$) obtained in material limiter configuration was similar for all methods of heating as any gains made in the values of temperature and density were offset by a degradation in the confinement time. Under these conditions, the value for the fusion product did not exceed $1\times10^{20}\mathrm{m}^{-3}\mathrm{s\,keV}$. A value for the fusion product of about $5\times10^{21}\mathrm{m}^{-3}\mathrm{s\,keV}$ would be needed in a fusion reactor. However, a lower value would be sufficient for studying the behaviour of the alpha particles produced during operations with tritium in JET, which is one of its major objectives.

A more encouraging result was obtained towards the end of the experimental period. Operation with an X-point magnetic limiter configuration has, using a single-null in the H-mode, yielded a record value for the fusion product of $2\times10^{20}\mathrm{m}^{-3}\mathrm{s\,keV}$ within a region relevant for achieving reactor conditions.

In 1985, it became obvious that if JET were to reach its objectives and, more specifically, if it were to provide a strong physical basis for NET, the experimental programme adopted at the beginning of the Joint Undertaking would have to be modified. These changes require the development and construction of some additional equipment. The JET Council has approved the orientation of the programme put forward by the JET Directorate on this matter. The new programme could not be completed by 1 June, 1990, and the JET Council has therefore proposed to the Commission that the Council of Ministers of the Community should be asked to extend the programme of the JET Joint Undertaking up until the end of 1992. I am convinced that all parties concerned are in agreement with this proposal and that the official decision regarding the extension depends only upon the date on which the framework programme is adopted.

There is no doubt whatsoever that JET is currently the project best suited for obtaining and studying a plasma under conditions close to those existing in a fusion reactor. It is therefore important that JET's potentialities are fully developed as soon as possible. This will of course require considerable technical effort.

At the end of November, a long shutdown began which will last until June 1987. The shutdown will allow the project to bring into operation several modifications which were prepared during 1986. More complex changes will have to be made at a later stage in order to allow for tritium operations in JET and the installation of new experimental devices. I am fully convinced that this difficult technical programme will be successfully implemented thanks to the sustained and dedicated efforts of all the staff of the JET Project.

I am aware of the problems which, for some members of the team, may be caused by the limited duration of the Undertaking, and also of the dissatisfaction caused by clauses in the Statutes. There is no doubt in my mind that solutions will be found, so that JET's activities can proceed harmoniously.

At its meeting in October 1986, the Council appointed Prof. Klaus Pinkau to succeed me as its Chairman when my appointment comes to an end in June 1987. As 1986 is my last full year as Chairman of the JET Council, I take this opportunity to extend all my very best wishes for the success of the JET Joint Undertaking.

June 1987

J. Horowitz
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 that an Annual Report should 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 description 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 1986 JET Progress Report.

Report Summary

The Report is essentially divided into two parts: a part on the scientific and technical programme of the Project; and a part setting out the administration and organization of the Project in relation to staff management, contracts and other service arrangements.

The first part of the Report starts with this section which includes a brief general introduction, provides a brief 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 Programme 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 that JET 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 1986, details of the operational organisation of experiments and pulse statistics, and advances and enhancements in machine systems for future operation. This is followed by a section on the results of JET operations in 1986 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 local behaviour observed; and the progress towards

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, see Fig.1.

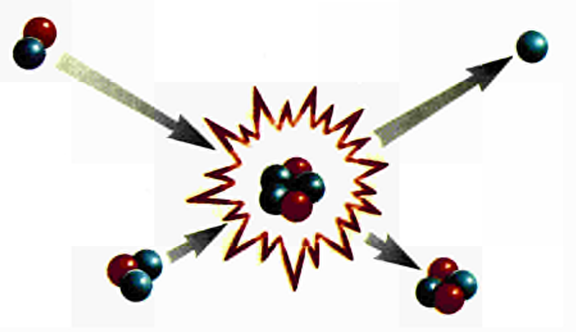

Fig. 1 The deuterium-tritium reaction which yields an energetic neutron and a helium nucleus

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.

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 in its relatively short period of operation. 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. Latest experimental results from JET and other tokamaks show that the sought after increase of the fusion product could not be achieved without making additions and some enhancements to JET systems. This new programme, which proposes an extension of the Project to the end of 1992, is explained.

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 and the contract arrangements during 1986. The staff complement and the continuing difficulties with maintaining strength are also detailed. This part concludes with a description of services provided by the Joint Safety Services and Public Relations Groups.

Fuels

As deuterium is a readily separated component of water, there is a virtually inexhaustable 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, see Table 1.

Table 1

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

The lithium will be incorporated within the surrounding jacket so that the neutrons released from the fusion reactions can be utilised for manufacturing tritium. The tritium produced would then be extracted for use in the reactor. There are sufficient reserves of lithium available to enable fusion reactors to be run for several hundreds of years.

Ultimately, it is hoped that the conditions might be reached to enable a reactor to be built utilising the deuterium-deuterium reactions below:

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

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. By the latter half of 1975, the team had completed its design for a very large device with a plasma current of 4.8MA.

The Council of Ministers of the European Communities on 30 May 1978 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.

The decision 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'.

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 100million degrees Celsius 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	10-20keV
Central ion density n_i	$2.5\times10^{20}m^{-3}$
Global energy confinement time τ_E	$\sim 2s$

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

Objectives of JET

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 the 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.

It was also 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.

The Members of the JET Joint Undertaking are Euratom, all its Associated Laboratories and Partners in the frame of the fusion programme including Sweden and Switzerland, together with Greece, Ireland and Luxembourg, which 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 drawn from the Associated Institutions, although some staff are assigned on a secondment basis from the Institutions and the Directorate General of the Commission responsible for Science Research and Development (DGxii).

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.

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

Assembly of the JET tokamak started in January 1982. The plasma is enclosed within the toroidal vacuum vessel which has a major radius 2.96m and D-shaped cross-section of 4.2m by 2.5m. The toroidal field on JET is generated by 32 large D-shaped coils with copper windings which are equally spaced around the machine. The primary winding of the transformer, used for generating the plasma current to produce the poloidal field and for initial heating, is situated at the centre of the machine and is coupled to the plasma by the massive eight limbed iron transformer core. Around the outside of the machine, but within the confines of the transformer limbs, is the set of six field coils used for stabilizing and shaping the plasma. The use of transformer action to produce the large plasma currents means that the JET machine operates in a pulse mode. Pulses can be produced at a maximum rate of one every ten minutes, with each pulse lasting about 25 seconds. Over 30 different measuring systems, called diagnostics, are used to determine what is happening to the plasma during each experimental pulse. A diagram of the JET apparatus is shown in Fig.2 and the principal design parameters are given in Table 2.

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 184.6MECU at January 1977 values.

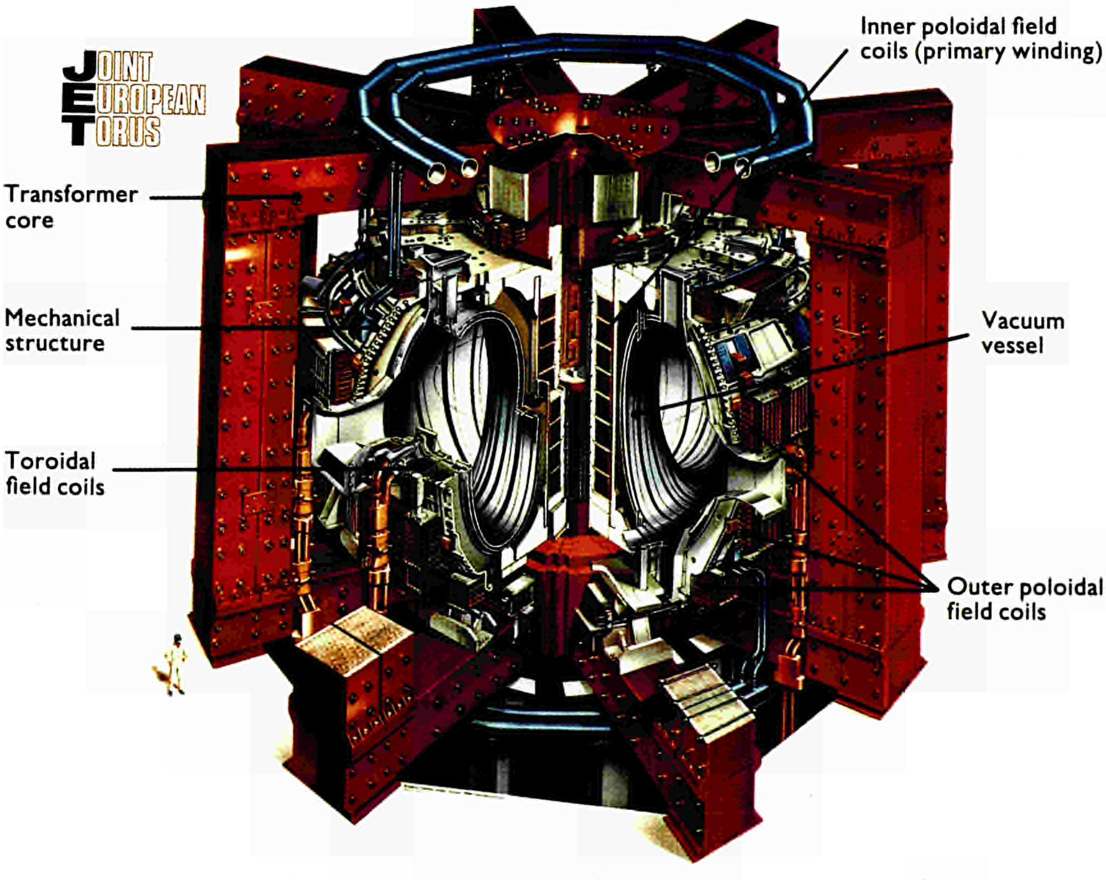

Fig. 2 Diagram of the JET Tokamak.

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The Tokamak

The main features of the tokamak magnetic field configuration are shown schematically in Fig.3. The plasma is contained within an annular vacuum vessel with a set of coils around the minor circumference. These coils produce one component of the magnetic field (toroidal field) around the major axis of the machine. A 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. A third set of loop coils are used to shape and stabilise the position of the plasma.

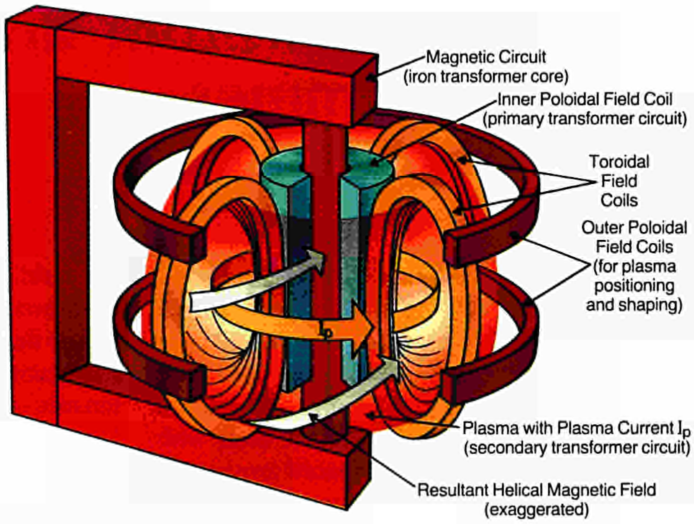

Fig.3 Tokamak magnetic field configuration.

Table 2
Main Design Parameters of JET

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

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.4 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 by the end of that year 6 MW of power was being coupled to the plasma from two antennae.

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.

Fig. 4 The JET Tokamak prior to the start of operations in 1983.

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

(Euratom Fusion Programme)

The position of JET within the Euratom Fusion Programme is described below.

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 fusion power-producing prototype reactors, with a view to their industrial production and marketing. Periodically, a new five-year programme is adopted which overlaps with the last two years of the previous one. The current programme, for the period 1985-89, was adopted by the Council on 12 March 1985.

The programme is implemented by means of Contracts of Association between Euratom and 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 became a member of the Community fusion programme on joining the European Communities in 1981 and formally joined the JET Joint Undertaking in 1983. In 1986 Portugal and Spain joined the European Communities and organisations in both countries forwarded applications to join the JET Joint Undertaking. A decision on these applications is expected during 1987. The locations of fusion research laboratories involved in the Euratom fusion programme are shown in Fig.5.

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 carrying out programmes in support of the tokamak confinement systems;
- 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 increased activity towards the development of the technology required in this context, guided by conceptual studies.

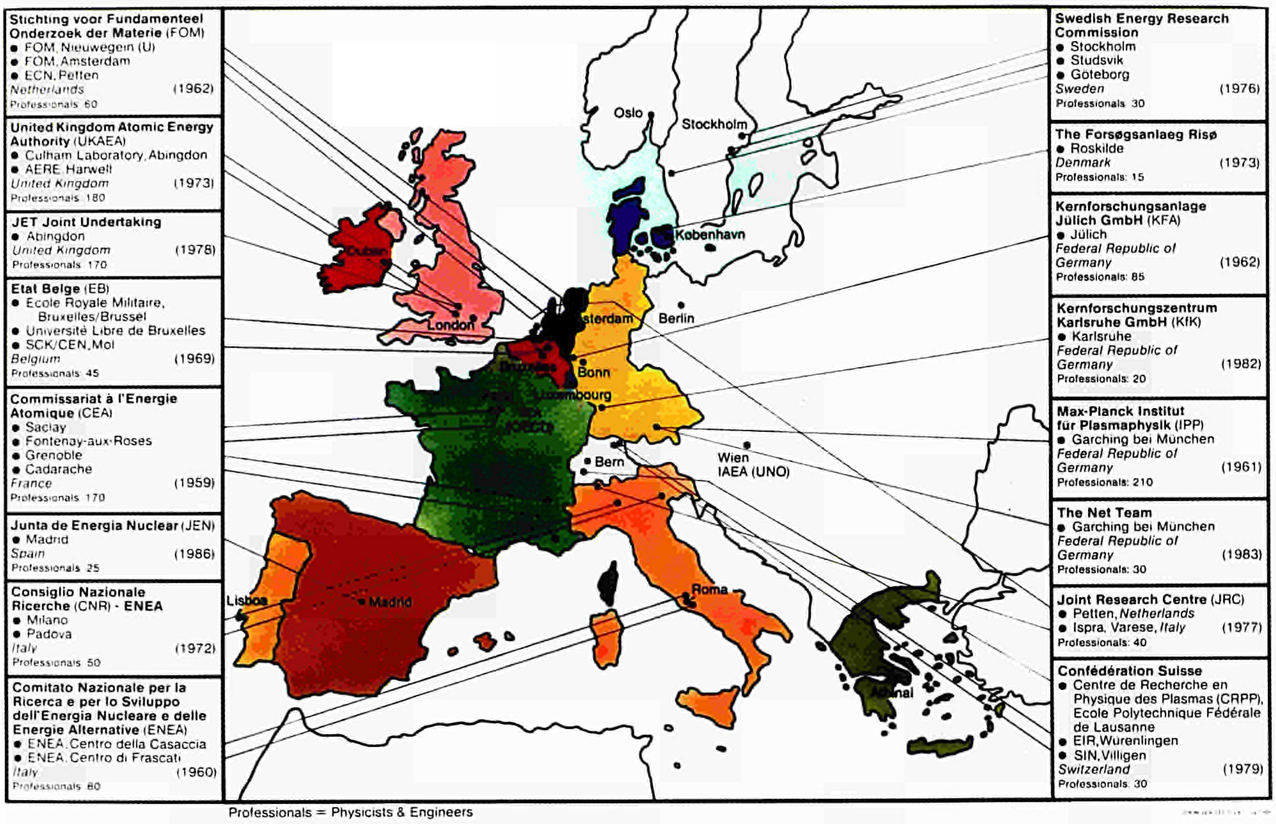

Fig. 5 Location of the organisations associated with the Euratom fusion programme.

The scientific and technical achievements of the European Fusion Programme places Europe in the forefront of worldwide 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. In addition, the Associations carry out a wide range of research on topics, both scientific and technological, relevant to the development of fusion as a source of energy.

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 followed in June 1983 and the Japanese machine, JT-60, 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. JT-60 has a form of divertor and will use a wide range of heating techniques. Fig.6 illustrates the relative sizes of these three tokamaks and their major operating parameters.

It is seen that JET has the largest plasma diameter, volume and current, but lowest toroidal magnetic field of the three large machines. In addition, JT-60 has the potential for the highest additional heating into the plasma. In terms of fusion product achieved, both JET and TFTR have obtained a fusion product ($n_i.\tau_E.T_i$) of 2×10^{20}m^{-3}s keV. However JET achieved this value of fusion product under directly relevant conditions for a reactor and this is discussed in further detail in the section on Results of JET Operations in this report.

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. These results were reported at the 11th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion (held in Japan in November) and were acclaimed as the highlight of the meeting. They keep JET clearly in the forefront of world fusion research.

An agreement was signed at IPP Garching, F.R.G. on 15 January 1986, for the exchange of information between the three large tokamak groups.

Present research is concentrated towards proving scientific feasibility and reaching the conditions that

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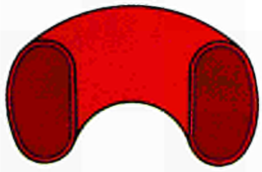
EUROPE



Minor Radius: horizontal	1.25 m
vertical	2.10 m
Major Radius	2.96 m
Toroidal Magnetic Field	3.45 T
Plasma Current	5.0 MA
Pulse Length	20 s
Additional Heating Power	44 MW (total)
	25 MW (high grade)

Designed for D-T Operation

TFTR
USA

Minor Radius	0.85 m
Major Radius	2.48 m
Toroidal Magnetic Field	5.0 T
Plasma Current	3.0 MA
Pulse Length	2 s
Additional Heating Power	27 MW (total)

Designed for D-T Operation

JT-60
JAPAN

Minor Radius	0.95 m
Major Radius	3.0 m
Toroidal Magnetic Field	4.5 T
Plasma Current	2.7 MA
Pulse Length	5-10 s
Additional Heating Power	54 MW (total)
	30 MW (high grade)

Magnetic Limiter Configuration
Hydrogen Operation Only.

Fig. 6 The operating parameters of the three large Tokamaks.

will be needed in a reactor. After the successful completion of this stage there will still remain the need for large programmes to develop suitable technology and prove the economic viability of a reactor system. Because of the long-term nature of these research programmes, it is unlikely that a fully developed commercial system will 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 developments and improvements made to the systems installed on JET for operations in 1986. The second section summarises machine operations in 1986 and the final section presents the technical developments, which continued through the year, on equipment for installation during 1987 and in future years.

Technical Achievements

Most of 1986 was devoted to machine operations with a planned major shutdown starting at the end of November. During this operational period the tokamak operated reliably and routinely at its maximum design level with toroidal fields up to 3.45 T and plasma currents up to 5 MA. The current-pulse distribution, see Fig.7, shows clearly the shift to higher plasma currents compared with operations in previous years. The excellent behaviour of the basic machine and the satisfactory availability of other systems resulted in an impressively successful experimental programme.

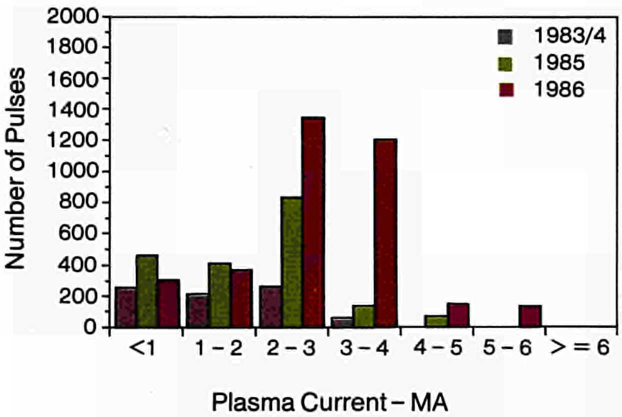


Fig. 7 Distribution of plasma current for the years 1983 to 1986.

Neutral Beam Heating

One of the highlights of the year's experimental programme was the commissioning and operation of the first neutral beam heating system, which is shown in Fig. 8.

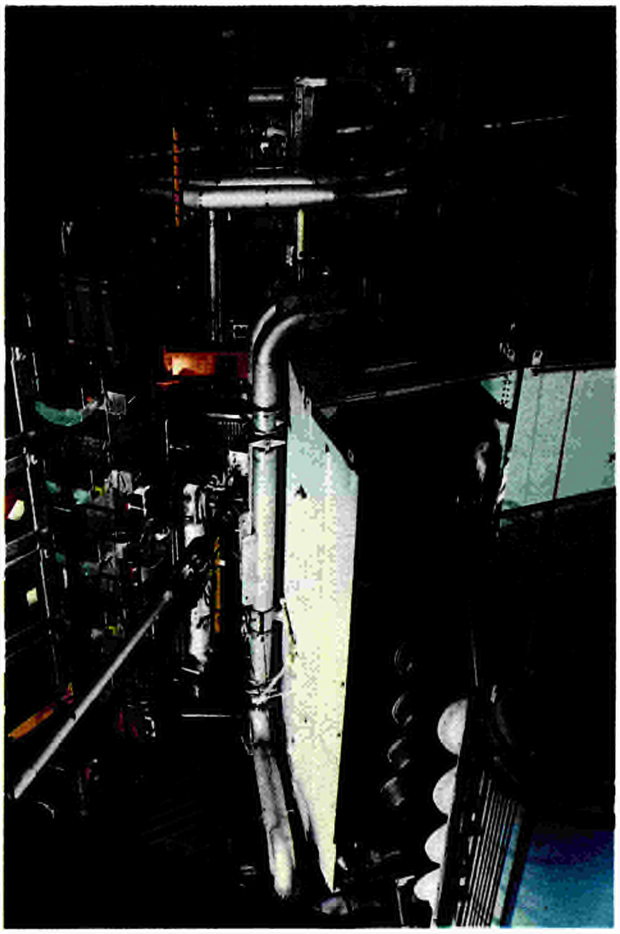


Fig. 8 The first neutral beam system installed at the torus.

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. Fig. 9.

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

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 160kV.

The first part of the experimental programme with this system was devoted to studies of hydrogen beam injection into a wide variety of deuterium plasmas, with beam energies up to 65keV and power levels up to 5.5MW. The major part of subsequent operation was devoted to deuterium beam injection into deuterium plasmas, with beam energies up to 80keV and power values up to 10MW.

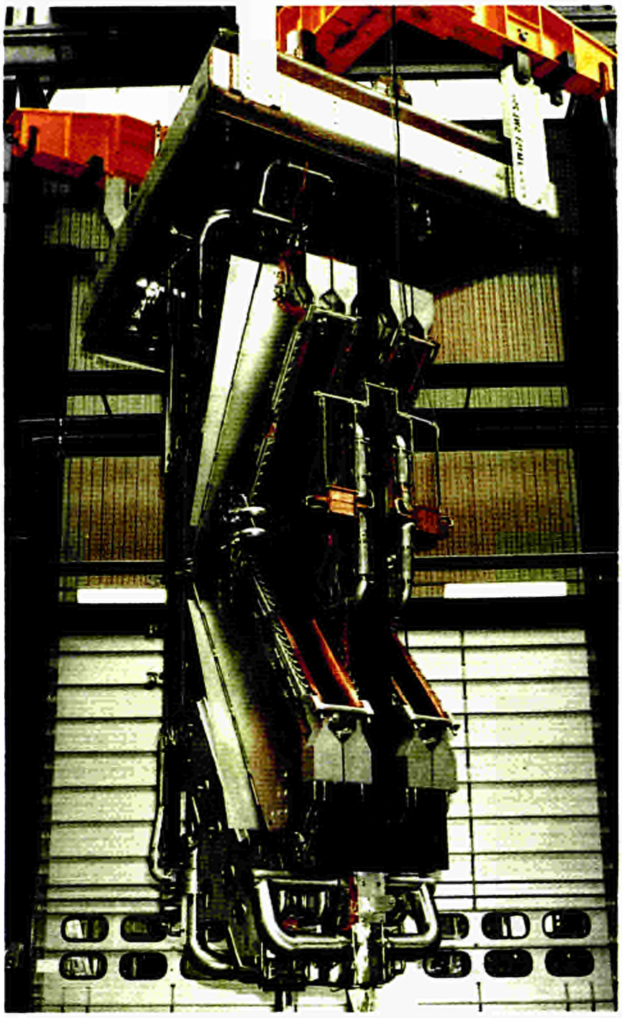


Fig. 9 Central column of the beamline system attached to the lid of the injector vacuum box. The 7m high structure is shown from the side of beam entrance into the deflection magnet.

Radio Frequency Heating

Ion Cyclotron Resonance Heating (ICRH) has been chosen for JET and the wide operating frequency band (25-55MHz) 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.

Radio Frequency Heating

The first stage of RF heating has been operating on JET since 1985 and the full design capability for this stage was reached in 1986 with 12MW output power from the generators. A record value of 8MW of net power has been launched in the torus. The power levels and pulse lengths achieved considerably exceeded values previously obtained on tokamak experiments with this type of heating. During this first stage, up to three complete units have been in operation and several types of antenna configuration have been tested.

In general, there have been few problems with the reliability and availability of the equipment and 19,600 filament hours have been recorded. The wide frequency band of the system and the automatic electronics for matching, which are original features of the design, have been used to full advantage and have allowed novel physics experiments to be carried out. During the last month of operation, an additional generator was combined onto one antenna which demonstrated that up to 4MW of power can be launched with a single antenna. One of the power combiners used in this experiment is shown in Fig. 10.

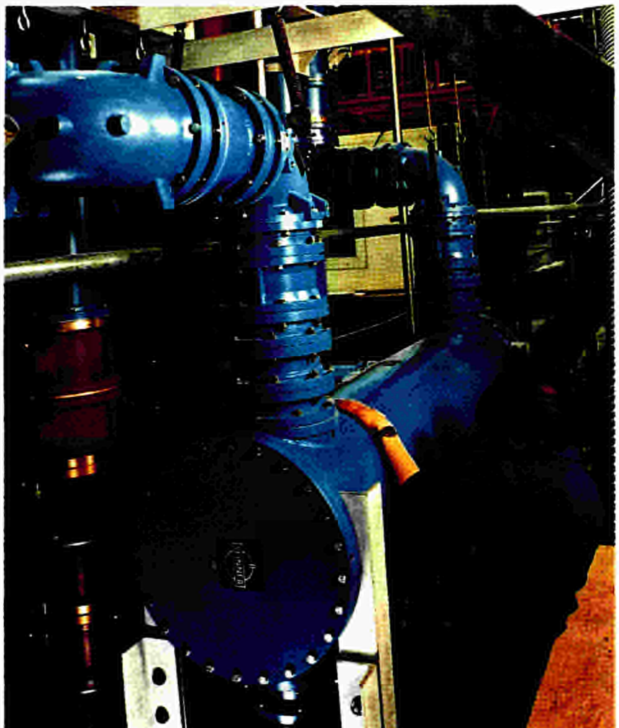


Fig. 10 One of the RF power combiners used in the experiment to demonstrate the 4MW capability of a single antenna.

X-point Operation

Another major breakthrough in 1986 was the establishment in JET of a magnetic limiter, or X-point, mode of operation with long pulse lengths (up to 4s flat-top). This configuration, which was obtained with a plasma current of up to 3MA with a single null and up to 2.5 MA with a double null, necessitated some changes to the poloidal field coil system. For the single X-point mode, the turns in the outer poloidal field coils had to be used in an asymmetric configuration. The additional heating power also had to be kept low enough to avoid damage to the wall protection tiles. Nevertheless, this new mode of operation has been successful and yielded good plasma performances.

In Vessel Components

The graphite inner wall protection withstood discharges where the power injected into the plasma, using combined neutral beam and radio-frequency heating, reached 18 MW for typically two seconds. The thermal load on the inner wall was all the more severe as the machine was frequently operated with the plasma touching the inboard wall. This was done with three objectives: to decrease the density to the ohmic limit after neutral injection, using the inner tiles as a very powerful pump; to study low density, high ion temperature discharges; and to investigate slide-away regimes. All of these operational modes, together with disruptions, led to local damage and local erosion of the inner wall.

When operation stopped in November, it was most encouraging that only minor damage had occurred to the graphite tiles. However, it was clear that the tiles in their present design could not be used as an inboard limiter when higher power levels and longer pulses are contemplated. For operation in the X-point mode, new graphite tiles were fitted at the top and bottom of the vessel in the vicinity of the nulls. These tiles after operation are shown in Fig. 11.

During 1985, local overheating of one of the graphite limiters was observed which was attributed to its radial misalignment as it protruded by 4 mm into the plasma. The absence of surface damage at the end of 1986 indicates that the vessel survey was successful in providing a means for limiter adjustment. This survey had been carried out to relate the position of the limiters to a datum ring at the inner wall. This gives confidence for the positioning of the belt limiter for which an identical survey was carried out.

Pellet Injector

A staged approach has been adopted for injecting deuterium pellets quasi-continuously and as centrally as possible (deep refuelling) within the plasma. Present moderate speed pneumatic gun technology is being used initially and will be complemented once higher speed technology becomes available.

During 1986 a single shot pellet injector, Fig. 12, was installed and made ready for operation by the end of June. It was operational for three months with six days of machine operation dedicated to pellet injection. A total of 170 pellets of two different sizes were fired into the plasma with high reliability. The cylindrical pellets, with velocities between 0.8 and 1.2 km s^{-1}, were injected into various different target plasmas (limiter, inner-wall and X-point) using different combinations of heating methods.

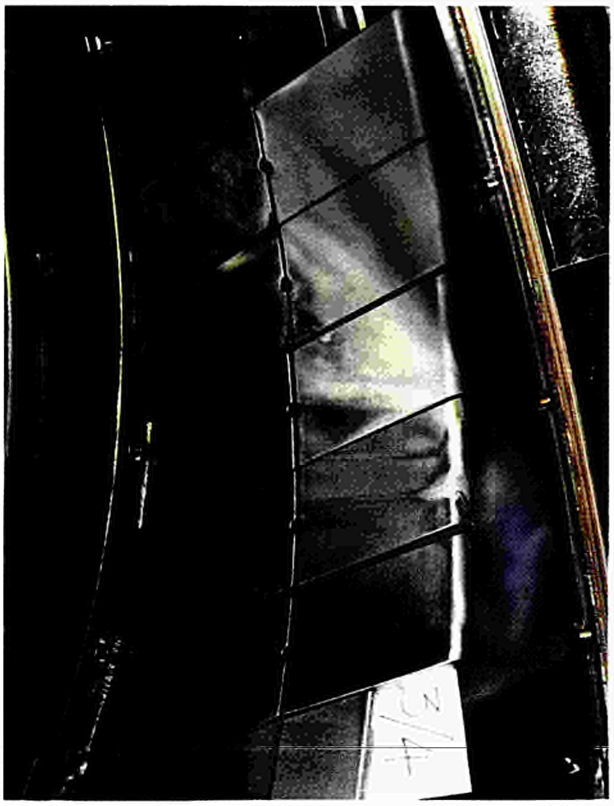


Fig. 11 Graphite tiles fitted in the vacuum vessel for X-point operation.

Fig. 12 Single shot pellet launcher installed on the torus.

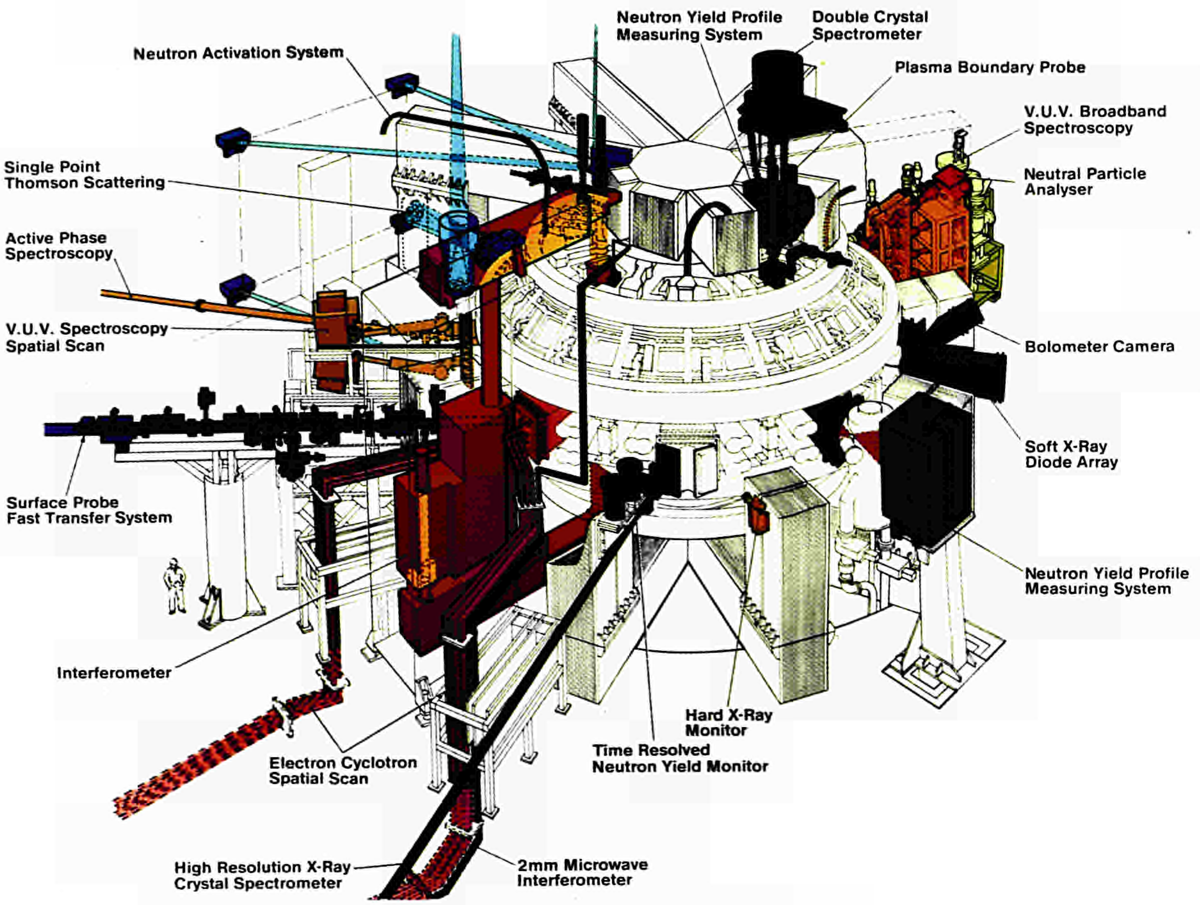


Fig. 13 Location of JET diagnostic systems.

Diagnostics

The staged introduction of the diagnostic systems is now nearing completion. The location of these systems on the machine is shown in Fig. 13. Their status is summarised in Table 3 which shows that out of the total of 39 systems, 24 are in routine operation, 10 are being installed or commissioned and five are still to be constructed. Operational experience with these diagnostics has been good and many of the systems are now operating automatically with minimal supervision from scientific staff. The resulting measurements are of high quality in terms of accuracy and reliability, and are providing important information on the plasma behaviour.

Boundary Measurements

The two systems for exposing samples to measure the hydrogen, deuterium and impurity fluxes in the boundary are now operational. One system introduces a time resolving collection probe from the top of the machine and has successfully monitored a standard ohmically heated discharge. The other system, based on a train powered by linear motors and running in a vacuum tube, transfers probes on a shot by shot basis from the torus to a surface analysis station, shown in Fig. 14, situated in the diagnostic hall. This system has been installed and is in the final stage of commissioning.

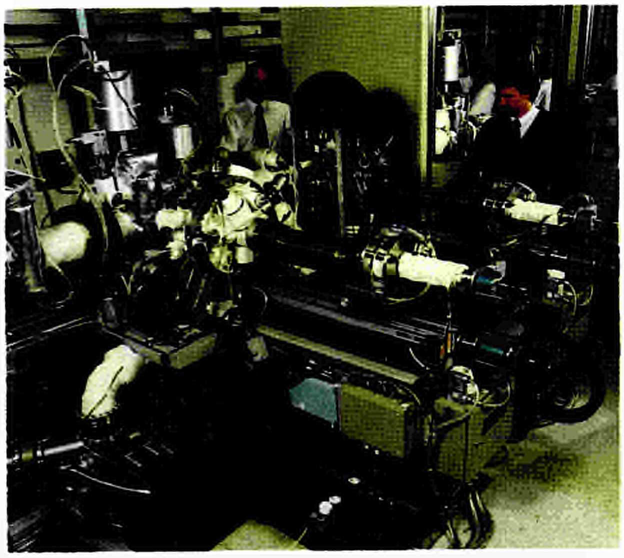


Fig. 14 The system used for the surface analysis of probes exposed to the plasma.

A new system for monitoring the interaction of the plasma with the limiters and wall, and working at a wavelength of 3-5 μm, has become operational. This is based on a cooled infra-red diode array of 32×32 pixels and has successfully produced the spatial temperature distribution of one of the standard limiters.

Table 3
Status of the JET Diagnostics Systems, December 1986

System	Diagnostic	Purpose	Association	Status (DEC. '86)	Compatibility with tritium	Level of automation
KB1	Bolometer Scan	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	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	Being installed Operational mid '87	Yes	Will be fully automatic
KG1	Multichannel Far Infrared Interferometer	$\int n_e ds$ on 7 vertical chords and 3 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 being constructed. Operational mid '87	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 early '87	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, after modification	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
KL1	Limiter surface temperature	Monitor of hot spots on limiter, walls and RF antennae	JET and KFA Jülich	Operational	No	Fully automatic
KL2	Limiter surface temperature	Temperature of belt limiters	JET	Under construction	No	Will be fully automatic
KM1	2.4MeV Neutron Spectrometer		UKAEA Harwell	Not yet fully operational	Yes	Will be fully automatic
KM3	2.4MeV Time-of-Flight Neutron Spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	NEBESD, Studsvik	Not yet fully operational	Yes	Will be fully automatic
KM4	2.4MeV Spherical Ionisation Chamber		KFA Jülich	Not yet installed	Yes	Will be fully automatic
KM2	14MeV Neutron Spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	Design completed	Yes	Not yet installed
KM5	14MeV Time-of-Flight Neutron Spectrometer		SERC, Gothenberg	Decision on construction under review	Yes	Not yet installed
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	Commissioning	Yes	Not yet implemented
KN3	Neutron Yield Profile Measuring System	Space and time resolved profile of neutron flux	UKAEA Harwell	Commissioning	Yes	Not yet implemented
KN4	Delayed Neutron Activation	Absolute fluxes of neutrons	Mol	Awaiting delivery	Yes	Not yet installed
KP1	Fusion Product Detectors	Charged particles produced by fusion reactions	JET	Prototype operational	Prototype - No	Prototype not automatic
KR1	Neutral Particle Analyser Array	Profiles of ion temperature	ENEA Frascati	Operational	Yes, after modification	Semi-automatic
KS1	Active Phase Spectroscopy	Impurity behaviour in active conditions	IPP Garching	Operational early '87	Yes	Not yet implemented
KS2	Spatial Scan X-ray Crystal Spectroscopy	Space and time resolved impurity density profiles	IPP Garching	Operational end '86	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
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
KT3	Visible Spectroscopy	Impurity fluxes from wall and limiters	JET	Operational	No	Semi-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	
KZ1	Pellet Injector Diagnostic	Particle transport, fuelling	IPP Garching	Operational	Yes	Not automatic

Temperature Measurements

All the major components of the Light Detection and Ranging (LIDAR) Thomson scattering system, which will measure the spatial profile of the electron temperature by a time of flight technique, have been constructed. A provisional system, which was installed late in the year, gave some promising first plasma measurements and will be completed and brought into full operation in 1987.

The system for electron cyclotron emission measurements has been extended with a high resolution Michelson interferometer which has been commissioned and preliminary measurements carried out. This device will provide measurements of the temperature over the entire plasma cross-section instead of just over half as is the case with the present Michelson interferometers. In addition, a heterodyne system, which will provide the time dependence of temperature at eight different locations, has been constructed and commissioned.

Neutron and Proton Measurements

A pneumatic transfer system has been installed to facilitate the removal of activated samples for neutron flux measurements to a remote counting station for analysis. A preliminary examination of the first measurements from indium foils, provides neutron yields somewhat lower than those estimated from the fission chambers.

A prototype detector mounted inside the vacuum vessel has been used to study the emission of 14.6MeV protons from the $^3He + d \rightarrow p + \alpha$ reaction. An upgraded version, based on the experience gained, has been constructed and should be operational by mid-1987.

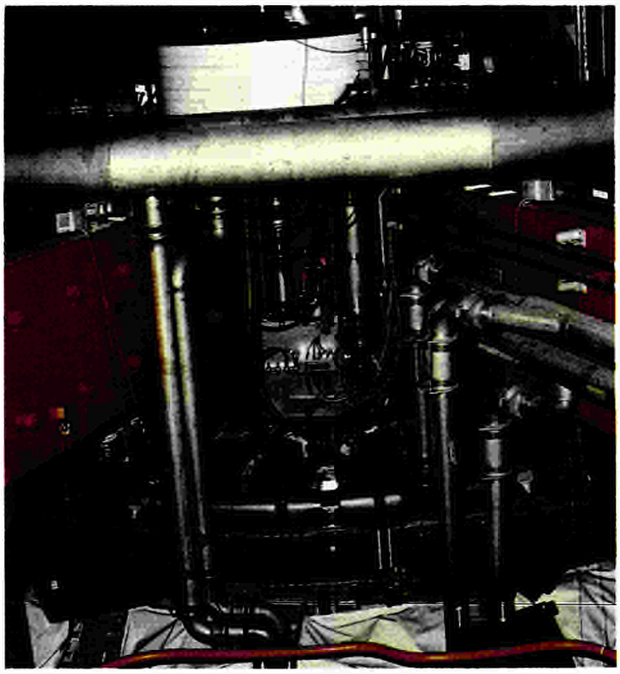


Fig. 15 The X-ray spatial scan monochromator installed on the machine.

Spectroscopic Measurements

A spectrometer working in the extreme ultra-violet from 1 to 33nm with two multichannel detectors became operational in the middle of the year.

The capability of the diagnostic for measuring the intensity of H_α/D_α emission has been enhanced by the addition of a 13-channel array aligned across a poloidal cross-section of the plasma.

An X-ray spatial scan monochromator, Fig. 15, which was built under contract with IPP Garching, F.R.G., has been delivered and tests were carried out at the end of the 1986 operation phase. A double crystal monochromator, also built at IPP Garching, was delivered at the end of 1986 and installed within concrete shielding on the outside of the torus hall wall. A high resolution curved crystal spectrometer (radius of curvature 24m), which measures X-ray spectra in the 0.2nm wavelength region has been installed and brought into operation.

Control and Data Acquisition

The main improvements in control and data acquisition have been the development of digital feedback control for the plasma current and the real time generation of a validated plasma density signal derived from various diagnostic channels. A sequencer unit has also been developed and delivered to Oak Ridge National Laboratory, USA, for inclusion in their pellet launcher, which is due for installation on JET early in 1987.

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 complete collection of all the information from the JET pulses is held in the JET Survey Data Bank.

Improvements in the data collection and archiving throughput have enabled the increased amount of data (~9Mbyte) now generated at each pulse to be accommodated. This is planned to rise to 15MByte per pulse by the end of 1987.

Since the start of operations JET has used the large IBM computer at Harwell for analysis and storage of data. JET has purchased its own IBM 3090-200 computer which will be installed at Harwell and should come into operation in mid-1987.

JET Computations

A complete systematic collection of all JET plasma pulses is provided in the JET Survey Data Bank. This now contains 300MByte of data from 5900 pulses. For comparison with theoretical predictions, data banks with well checked and validated plasma data (including spatial and temporal dependences) for a few selected discharges are being prepared. Among other data banks is Journal which contains machine settings and session aims, together with pre- and post-pulse comments.

Other activities, in which important advances have been made during 1986, are detailed in the JET Progress Report and are in the following areas:

- Improvements continue to be made on transport codes used both to predict the performance in new operating ranges, and to compare predictions with measurements from past discharges;
- A transport analysis code has been used to evaluate the local energy balance, and derive the electron energy flux;
- Predictive computations have been carried out which are related to important additions and modifications for future JET operation. These include relevant input into the design of using limiters; reductions in alpha-particle power during sawtooth oscillations (emphasising the need to stabilize or reduce oscillation amplitude); and the efficiencies of various non-inductive current drive methods to flatten the current profile and stabilize sawteeth oscillations;
- Particular attention has been devoted in analytic plasma theory to describing sawtooth oscillations, and their possible stabilization. An analytic derivation of energy flux in the plasma due to various instabilities has been re-examined and heat and particle flows due to drift instabilities have been found to have the correct form.

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.

Power Supplies

The peak pulse power drawn from the 400kV grid by the JET experiment in 1986 was over 300MW. During the Autumn, the experiment was supplied through two transformers instead of three and this resulted in the largest voltage drop so far on the CEGB system of 1.8%. The CEGB have made important concessions by raising the limit of the JET load reactive power to 475MVAR and allowing a voltage drop of up to 2.5%. These concessions were based on experience of operations from 1983 to 1986. Starting with the CEGB fiscal year 1985-6, the tariff has been revised to agree with the bulk supply tariff, which is the normal one for area board supplies. This revision has proved advantageous to JET and the overall cost of electricity has been reduced.

Metering equipment on the 11kV and 3.3kV feeders of the auxiliary power supplies is being installed to assess if savings in electricity costs from these supplies are possible.

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 575MW of pulse power to be taken directly from the 400kV grid which after transformation down to 33kV 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 9m in diameter weighing 775 tonnes. Between pulses, 8.8MW 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 225rpm to half speed, the generators can each delivery 2.6GJ of energy with a peak power output of 400MW.

Experiments performed with two X-points inside the vessel required the application of a strong shaping field to give a large elongation. In some cases, the vertical position of the plasma became unstable and additions were made to the system in an attempt to improve the performance of this stabilisation.

The majority of magnetic limiter experiments were performed with an asymmetric single X-point configuration. This has a smaller elongation ratio than the double X-point configuration and the stabilisation is less demanding. Inclusion of a slow current feed-back loop, with a waveform serving as a current reference, provided a convenient way of adjusting the position of the plasma and, within constraints, the distance of the X-point from the wall.

Summary of Machine Operation

A JET operational period consisted typically of a week of maintenance, a week of commissioning and six to seven weeks of tokamak operation. There were five such periods of operation in 1986 totalling 229 days of operation. In the latter half of the year, problems with the duct cooling for the neutral beam injection caused some loss of tokamak operation time. This period was used for repairs, and some maintenance and commissioning. A further week of operation was devoted to the installation of in-vessel protection tiles required for X-point operation. The remaining period, classified as shutdown, was used for modifications, maintenance and repair of existing systems and for the installation of new equipment.

Operation became more complex this year with the introduction of neutral beam heating and several new control systems. The organisation of operations time remained almost the same as that for 1985 apart from the introduction of double-shift working on the Mondays of operation weeks. This enabled the commissioning of both the machine and plasma diagnostics systems to take place on Mondays.

More time was devoted to tokamak operation in 1986 than in any year since the experimental programme started in mid-1983 with the relative number of commissioning pulses declining. The total number of pulses was 4900 in 1986 compared with 3132 for 1985, bringing the total number of pulses to 11222, see Fig. 16.

The allocation of time to the different activities and the number of days involved in the various tokamak operation programmes [ohmic heating (OH), radio frequency heating (RF), neutral beam heating (NB), combined heating (NB and RF) and Monday commissioning (C)] are shown in Fig.17.

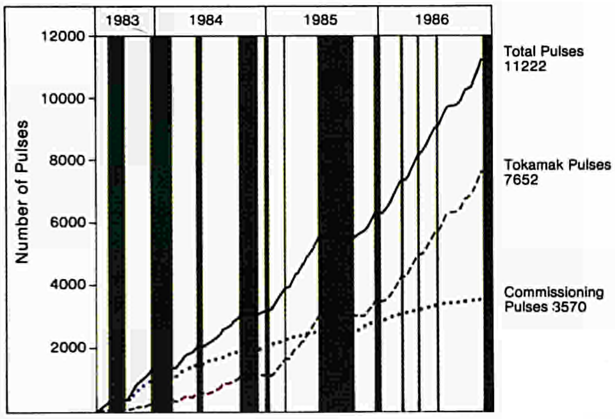


Fig. 16 Cumulative total of JET pulses.

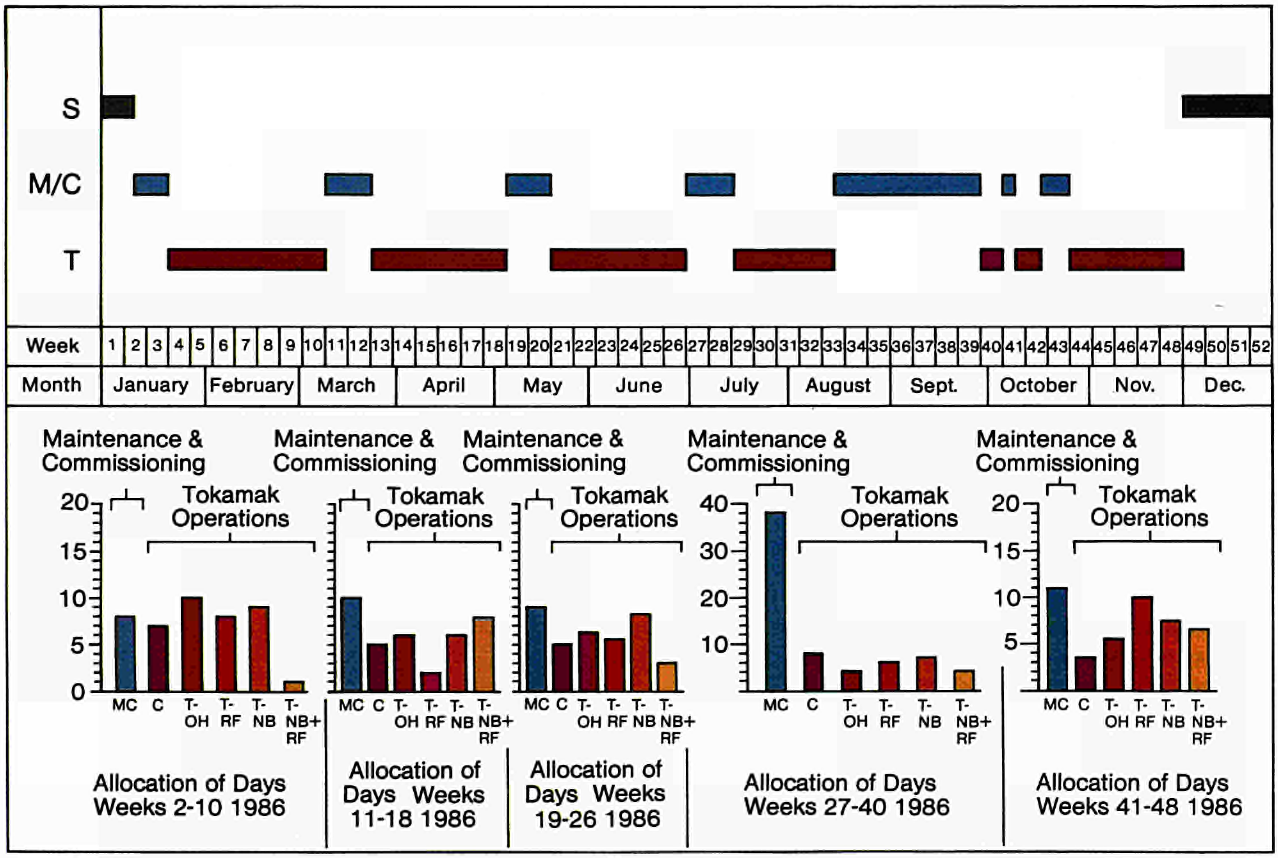


Fig. 17 Allocation of time to different activities of the operating programme for 1986.

Technical Developments for Future Operations

During 1986, considerable effort was devoted to the design and procurement of equipment for installation on the machine both during the planned major shutdown, which started at the end of November, and for later ones when further modifications and enhancements will be made to the machine. These additions are described in further detail in the chapter on the Future Programme of JET. Reference should be made to this section to put these technical developments in perspective.

Radio Frequency Heating

Eight antennae will be installed for the second stage of RF heating, which will start in 1987, with the complete system becoming operational at the beginning of 1988. These antennae are being installed between the two belt limiters and are actively cooled by water flowing inside each of the screen elements. These will allow 20s long pulses, a 1 to 30 repetition rate and will be compatible with D-T operation. An antenna housing and screen assembly are shown in Fig. 18 and a complete unit installed on the testbed in Fig.19. The RF power plant will be progressively upgraded from 3 to 4MW per unit using a specially developed higher power tetrode and a new output circuit.

A new system, using 12MW of power in the microwave frequency range (3.7GHz), has been proposed to provide Lower Hybrid Current Drive (LHCD) for controlling the radial profile of the plasma current. The much higher frequency is required to couple the electromagnetic waves to the fast electrons in the plasma. A waveguide system is used to launch a wave which travels in only one direction around the torus. The resulting asymmetric acceleration of electrons creates a current in the plasma which replaces the ohmic current drive and thus offers a way of controlling the current distribution profiles across the plasma. The conceptual design for this system, which was prepared in 1986, has been approved and the contract has been placed for the construction of the klystrons necessary for the first stage of the system.

Fig. 18 The screen assembly on the right without its graphite tiles, fits on top of the antenna housing on the left.

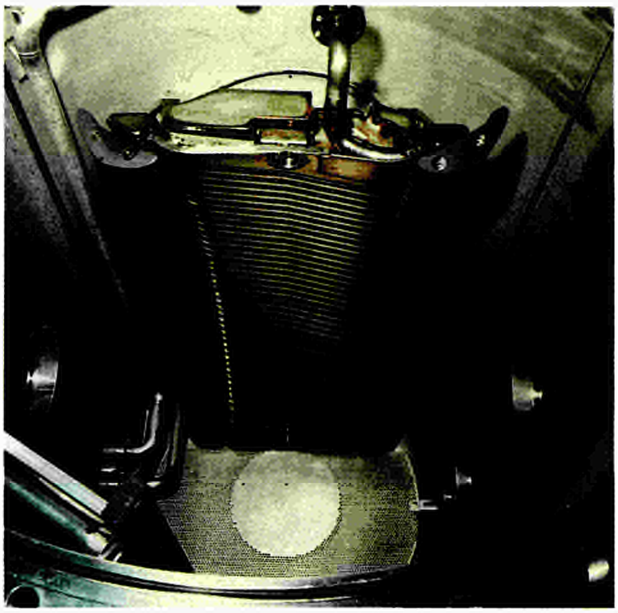


Fig. 19 A complete water cooled antenna installed in the testbed.

Neutral Injection Heating

During 1986, preparations and installation took place of equipment for the second neutral beam injection system which will come into operation in the latter half of 1987.

Testing of the beamline system for the second injector has been carried out in the JET neutral injection test bed using an 80kV four electrode and 160kV three electrode beam source. The data for hydrogen beams show that the beam is well contained within the dump and the power densities are within safe operational limits for beams of 70kV and 52A. With deuterium beams the system was found to be within safe limits of operation at 140kV and 30A.

A system of active field compensation has been designed to cancel the higher stray fields, up to 1.5×10^{-3}T at the beam source and neutraliser, that would be associated with operating with plasma currents up to 7MA.

An upgrade of the cryosystem has been started to enable sufficient helium to be supplied for the three cryopumps which will be in use when the second neutral beam injector and pellet launcher become operational.

In Vessel Components

From 1987 onwards, belt limiters will replace the existing localised limiters. By the end of 1986, the manufacture of the belt limiters had been completed and many sectors

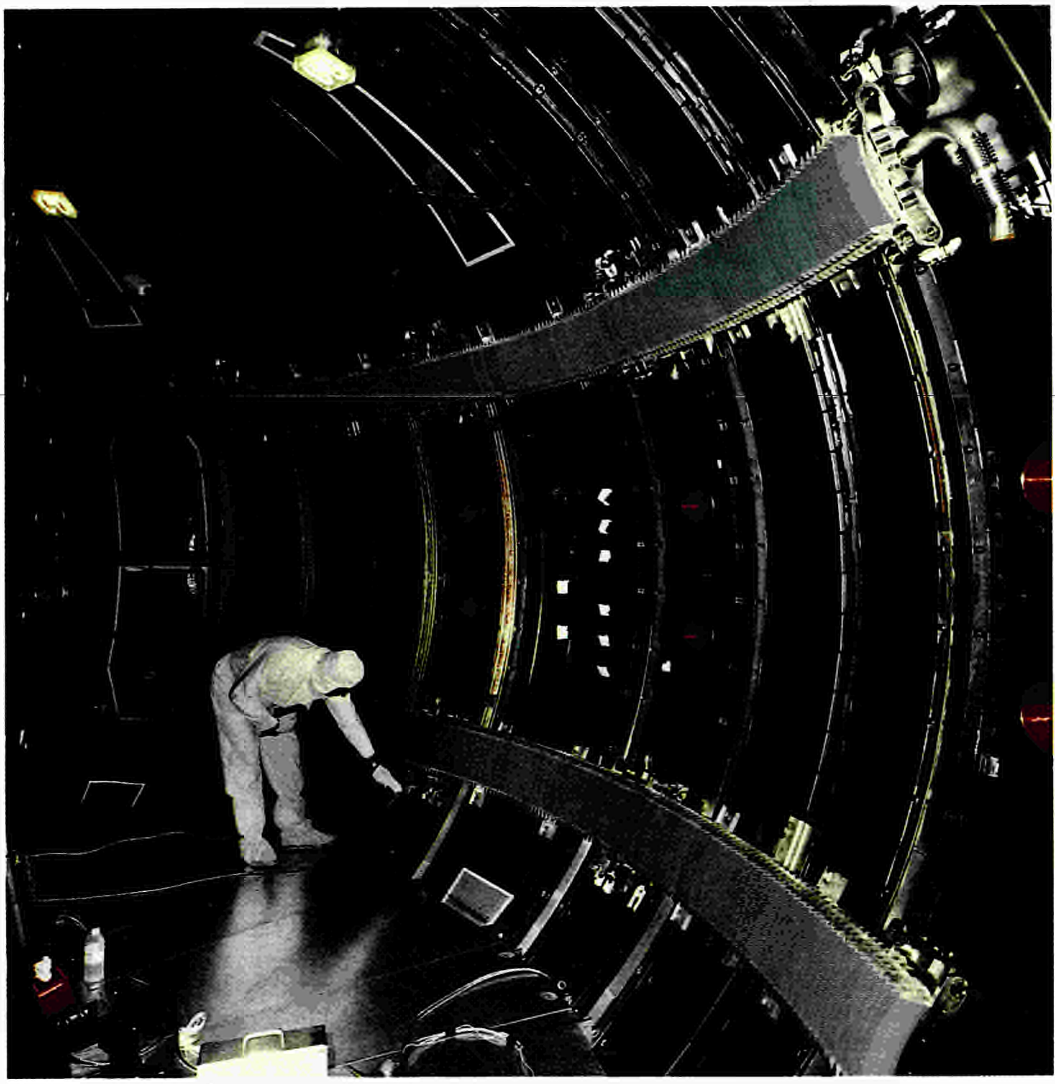


Fig. 20 Sections of the belt limiters installed on the interior of the vacuum vessel.

had been successfully leak tested ready for assembly in January 1987. Figure 20 shows sections of the belt limiters installed in the vacuum vessel. Both graphite and beryllium tiles were procured during the year for the belt limiters, but a decision has been taken to use graphite first. Beryllium will be used later, probably early in 1988, and the decision will be confirmed by the end of 1987 following experience gained with the carbon tiles. In this case, the rest of the walls would be covered with a 10 μm layer of beryllium and the evaporators to deposit such a layer were procured during 1986 for installation after external tests have been carried out.

A prototype pumped limiter has been under study for density control. This would use carbon fibre reinforced graphite or pyrolitic graphite for the high heat flux components. Installation of these new in-vessel components is planned to take place during the 1988 shut-down.

The procurement of additional graphite tiles to cover the bellows protection plates continued satisfactorily and most tiles, together with their support plates, were ready for assembly in the vessel by the end of the year.

New tiles for protection against neutral beam shine-through, using graphite-graphite composite, have been procured for installation in 1987. This material will allow 4 MW of power for a few seconds to be deposited on the tiles without destroying them.

Internal saddle coils aimed at stabilizing disruptions have also been designed. This set of eight coils, which comprises four coils at the top and four at the bottom of the vessel, will provide a magnetic perturbation to counter magnetic fluctuations which are the precursor to a disruption.

Containment of Forces during Vertical Instabilities

The fast movement of the plasma during a vertical instability gives rise to large vertical forces acting on the vacuum vessel. From the beginning of 1985 until November 1986, the vessel was reinforced by temporary supports capable of resisting a vertical force of 350 tonnes. As a consequence operational limitations were imposed. New supports capable of coping with vertical forces up to 1600 tonnes have been designed and during the year the testing of prototype components, in particular the inertial brake which allows for the thermal expansion of the vessel while restraining fast movements, was performed successfully. Completion of component delivery is expected ready for installation during the shutdown. Two of the new supports installed on the machine are shown in Fig. 21.

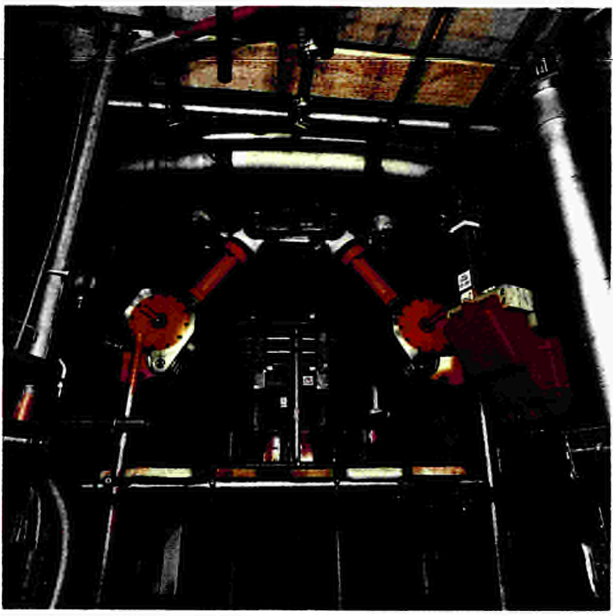


Fig. 21 Two of the new vacuum vessel supports installed on the machine.

The outer poloidal field coils are also subjected to large vertical forces during these instabilities. It was found that the mechanical pieces linking the outer poloidal fields coils P4 to the mechanical structure were of marginal strength. Stronger replacement pieces were procured in 1986 and installation is planned during the 1987 shutdown.

Modification to the Poloidal Field Coil System

In 1986, the decision was taken for major modifications to be made to the central poloidal field coils system during the 1987 shutdown. These modifications are:

- The central poloidal field coil stack will be increased from 8 to 10 sub-coils to reduce stray magnetic fields and improve discharge break-down and plasma start-up conditions;
- Additional busbars, connecting the six centre sub-coils, are being manufactured and installed to allow separate control of the current flowing in the coils.

This new poloidal field coil configuration will allow an increase in the total flux which should permit flat-top plasma currents of 7MA for seven seconds and an increase in the plasma current up to 4MA in the X-point mode of operation.

The preparation and procurement for these far-ranging modifications were carried out during the second half of 1986, with actual work on the machine starting in December. On dismantling the central poloidal field coil, some damage was observed on the sub-coils. Keys which locate and interlock the sub-coils together were fractured by their tendency to rotate relative to one another. Design modifications have been prepared to prevent the re-occurrence of this effect and these will be incorporated during the shutdown. Removal of the central poloidal field coil is shown in Fig. 22.

Study of the New Extended Operating Conditions

The new JET development plan includes modes of operation involving considerable extensions to the original design parameters.

Modifications to the poloidal field coil system are in line with the enhancement of JET performance up to a current of 7MA in the limiter mode of operation, and up to 4MA for X-point operation. Since this enhancement calls for a considerable extension to the original design parameters, a major design review was started in 1986. The aim of this is to reassess the machine and its power supplies from the mechanical, thermal and electrical points of view and to identify safe operating boundaries.

At the end of 1986, several study contracts were placed and analytical work had begun on the magnet system. Major results from this study are expected by July 1987.

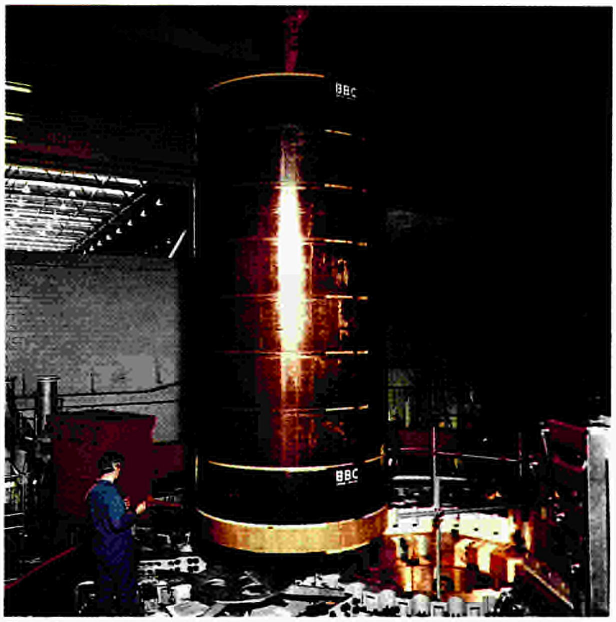


Fig. 22 The central poloidal field coil being removed for modifications and up-grading.

Pellet Injection

Multi-Pellet Injector (moderate speed)

JET and the US Department of Energy are collaborating on a specially-built ORNL launcher fitted to a JET interface for two operational periods (1987-1989). The main launcher features a three-barrel repetitive pneumatic gun capable of delivering, in independent firings, up to about ten pellets of three different sizes at velocities around 1.5 $km\,s^{-1}$ and repetition frequencies of several per second.

The interface consists of a pellet injector box with launcher platform, cryopump and vacuum services, injector cryo-equipment, gas introduction services, pellet diagnostics, controls and data acquisition. Most of these items had been delivered and were prepared for component testing by the end of 1986, with the remainder expected early in 1987. The multi-pellet injector will be installed and commissioned during the first half of 1987.

High speed Pellet Injector Development

The Ernst-Mach-Institute in Freiburg F.R.G. is developing a two stage pneumatic gun with the propellant gas heated adiabatically and its pressure increased as the pellet is accelerated. The maximum velocity achieved with plastic pellets is 4.3 $km\,s^{-1}$ and methods of increasing this are being investigated.

Investigations with an arc heated gun to accelerate pellets are being carried out by the National Laboratory in Risø, Denmark. So far promising results have been obtained at the start of the discharge.

A method of preparing solid deuterium pellets by direct cryo-condensation into the barrel is being developed by the CENG at Grenoble, France. A conceptual design is being undertaken to charge a repetitive gun with deuterium pellets at a frequency of several per second.

A testbed for the development of the high speed injector and its maintenance and re-commissioning is being built. It will come into operation in May 1987 for investigating two-stage guns using deuterium pellets.

Power Supply Development

Progress in power supply development has been especially important in view of the upgrade of the poloidal field system.

A new two quadrant AC/DC convertor, similar to the equilibrium and shaping field amplifiers, is being installed. This will be connected to the middle six sub-coils of the central poloidal field coil to facilitate X-point operation and also to provide an extended flux swing capability.

The voltage needed for plasma formation is created by diverting the magnetization current to resistors which absorb most of the energy initially stored in the central poloidal field coil. The thermal capacity of these resistors has been an experimental limitation and a second set of resistors is being installed.

The loop voltage for gas breakdown, which is determined by the premagnetization current and the setting of these resistors, does not necessarily satisfy the optimum voltage profile for the increase of plasma current during the fast rise phase. To alleviate this problem, six resistors are being installed in parallel with the central poloidal field coil, so that the loop voltage decay and hence the increase in plasma current during the fast rise can be controlled.

Tenders have been received for a booster amplifier to be connected in the circuit of the outer poloidal field coil P4 and an order has been placed for its installation in 1987.

The various magnetic (toroidal, vertical, radial, shaping, transformer, X-point) coil systems of the tokamak will be supplied in future from power supplies with no common connection. Additional busbars and earth switches are being installed to expedite this separation.

Remote Handling

Remote handling equipment is now being used extensively in conjunction with hands-on work to test the equipment and procedures of usage. Many special tools have been procured to fit the belt limiters and RF antennae and to replace blanks and windows in

Fig. 23. The articulated boom being used to install sections of the belt limiter.

the vertical ports. The control system for the articulated boom has been fully commissioned and it can now be operated in conjunction with a graphics display system. Figure 23 shows the articulated boom being used for mounting components on the interior of the vacuum vessel. A similar remote handling system has been designed which utilises a telescopic arm suspended from the crane and which is capable of reaching all parts of the tokamak outside of the torus.

The in-vessel inspection system has been valuable in identifying the need for unexpected maintenance and a version which can operate at 300°C is about to be fitted. The torus access cabin is now used by personnel requiring entry to the interior of the vacuum vessel.

Tritium Handling

Design and testing of components for the tritium plant continued throughout 1986. Prototypes of the cryogenic components and an experimental section of a gas chromatography column were tested in a specially built rig to prove the designs. Evolution of the requirements for isotope separation led to the adoption of cryodistillation as the separation means with a small gas chromatography unit as an auxiliary.

The Results of JET Operations in 1986

Resumé

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 5×10^{21} m^{-3}s keV for the deuterium-tritium reaction. The overall objective of the JET Project is to study plasma in conditions and with dimensions close to those needed in a reactor. Typical reactor values for these parameters, which must be attained simultaneously are given in Table 4.

Table 4

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

Using purely ohmic heating, peak ion and electron temperatures of 3 keV and 4 keV respectively have been achieved with a plasma density of about $4.2\times10^{19}m^{-3}$ and with energy confinement times exceeding 0.8s.

With radio frequency heating, peak electron and ion temperatures have reached 5 keV with peak ion densities of $3.5\times10^{19}m^{-3}$. However, although there was a substantial increase in temperature there was a drop in the energy confinement time to 0.3s.

There was a similar degradation in the energy confinement time when neutral beam heating was used. In this case ion temperatures of up to 6.5 keV at densities of

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

			June 1985	Nov. 1986
Toroidal field	B_T (T)	≤	3.4	3.4
Plasma current	I_p (MA)	≤	5.0	5.0
Duration of max. I_p	t_p (s)	≤	0.5	4.5
Plasma major radius	R_0 (m)	≤	3.0	3.0
Horizontal minor radius	a (m)	≤	1.2	1.2
Vert. minor radius	b (m)	≤	2.0	2.0
Elongation	b/a	≤	1.65	1.8
Safety factor at	q_{cyl}	≥	1.8	1.5
plasma boundary	q_w	≥	2.6	2.6
Input ICRF power	P_{RF} (MW)	≤	5.0	7.0
Input NBI power	P_{NB} (MW)	≤	–	9.0
Total input power	P_{TOT} (MW)	≤	8.0	18.0
Stored plasma energy	W_p (MJ)	≤	3.0	6.1
Volume average electron density	$\bar{n}$ ($10^{20}m^{-3}$)	≤	0.4	0.5
Central electron temperature	T_e (keV)	≤	5.0	8.0
Central ion temperature	T_i (keV)	≤	4.0	12.5
Global energy conf. time	τ_E (s)	≤	0.8	0.9
Fusion performance parameter (simultaneous $n_i.\tau_E.T_i$)	$n_e(0)T_i(0)\tau_E$ ($10^{20}m^{-3}$ s keV)	≤	0.5	2.0

$3 \times 10^{19} m^{-3}$ have been attained but with the energy confinement time falling again to between 0.3 and 0.4 s.

The maximum ion temperature achieved on JET was with neutral beam heating at lower peak densities of around $1.5 \times 10^{19} m^{-3}$ when values greater than 12.5 keV were observed. Peak electron temperatures up to 8 keV have been reached in helium discharges with RF heating. A summary of the main JET parameters and the values that have been achieved are given in Table 5.

The fusion products obtained from the above results are similar for ohmic, radio-frequency (RF), neutral beam (NB) and combined methods of heating. This is a result of any gains being made in the values of plasma density and temperature being offset by the degradation in energy confinement time. Under these conditions the value for the fusion products is $1 \times 10^{20} m^{-3}$ s keV.

However, operating with the X-point configuration in JET with 10MW of NB heating has yielded a record value for the fusion product of $2 \times 10^{20} m^{-3}$ s keV within the region relevant for obtaining reactor conditions. This value would need to be increased about 25 times to reach the conditions that would be needed for a reactor and by about a factor of five to reach breakeven. Fig. 24 shows the performance of JET and other tokamaks since 1965.

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 global energy confinement time shows a favourable scaling with plasma current and this has led to a detailed study being undertaken to determine the possibility of increasing the plasma current on JET to 7MA in the limiter mode and 4MA with X-point operation.

According to present results breakeven conditions should be approached when tritium is used in JET after 1990.

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.

Operating Conditions

Experiments started on the JET tokamak in June 1983 after completion of the five-year construction programme. Since the first pulse, when a current of 17,000 amperes flowed for less than one tenth of a second, the performance of the machine has gradually been enhanced to a state where almost all of the design criteria have been met or exceeded. Discharges have been produced with plasma currents of over 5MA with flat top duration lasting 4.5s. The toroidal magnetic field (B_T) has been operated routinely up to its maximum design value of 3.45T. Following considerable work on the feedback systems to the poloidal field coils for control of plasma

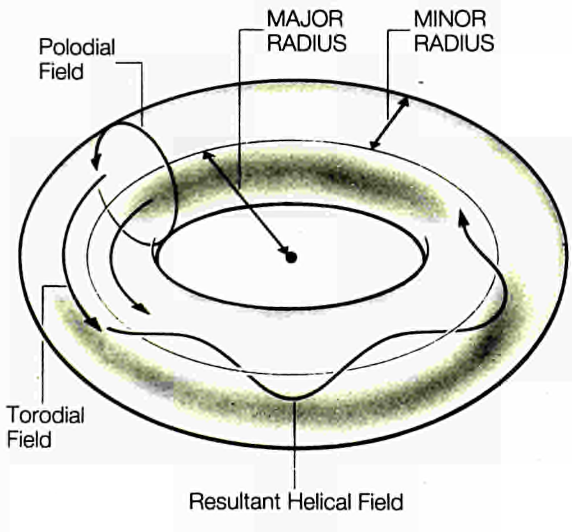
Magnetic Field Configuration

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 decrease 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.



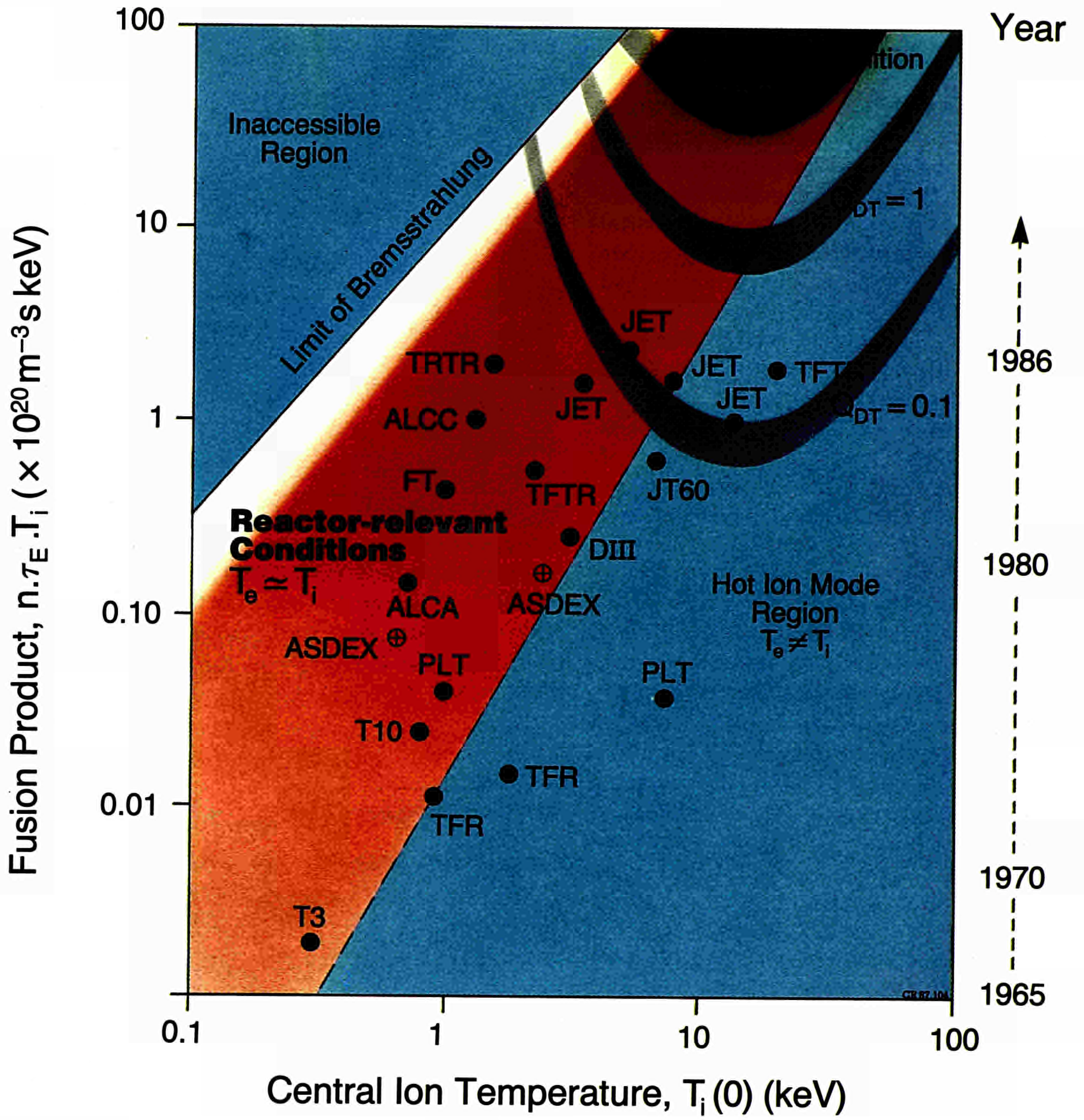


Fig. 24 The comparative peformance between JET and other tokamaks is given in terms of the fusion product and temperature of the ions. Although a large range of values is covered, not all of the region indicated on the figure can be considered as relevant to those needed for a reactor.

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 ins 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.

current, horizontal plasma position, plasma elongation (ϵ) and shape, stable control of the plasma has been obtained with elongations in the range from 1.2 to 1.7. However, the plasma vertical position is naturally unstable due to the poloidal field necessary for producing elongated plasmas and the de-stabilising effect of the iron magnetic circuit. Loss of vertical position feed-back control at higher elongations can lead to large vertical forces on the vessel. Some additional vessel support has been introduced but even so the plasma current has had to be restricted with highly elongated plasmas. The full inductive flux (34 Vs) has not yet been used as the maximum premagnetisation current creates stray fields which inhibit reliable plasma breakdown.

The vacuum vessel is usually operated with wall temperatures of 250-300 °C and with a base pressure of 10^{-7} mbar of hydrogen and 10^{-9} mbar of residual impurities. Eight carbon limiters are located symmetrically on the outer equatorial plane of the vessel. The inner walls have been covered with carbon tiles to a height of ± 1 m around the mid-plane. Similar tiles have been used to protect the frames of the RF antennae, the eight octant joints and the outer wall from any of the neutral beam shining through the plasma. Additional tiles have also been installed to protect the top and bottom of the vessel during X-point operation. The total surface area now covered with tiles is 45 m^2, which corresponds to about 20% of the vacuum vessel area.

Radio Frequency Heating Systems

Three RF antennae have been installed on the inside of the vacuum vessel on the outer wall. Fig. 25 shows an antenna and limiters on the interior of the vacuum vessel. Power is transferred to the plasma at frequencies in the range from 25 to 55 MHz. The three units have been used regularly with pulses up to 7.2 MW for 2 s. Experiments have also been performed with pulses of 8 s duration which have delivered 40 MJ of energy to the plasma.

Neutral Beam Heating Systems

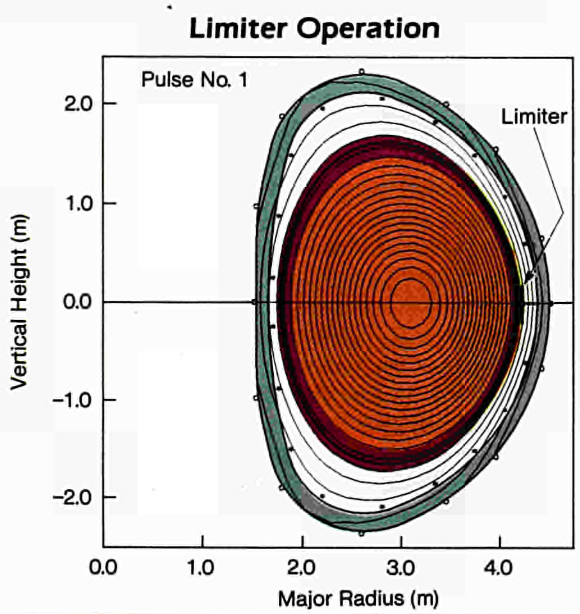
A neutral beam heating system with eight beams and capable of operating with long pulses of about 10 s has been in operation on JET since the beginning of 1986. Hydrogen beams have been injected into deuterium plasmas with particle energies of up to 65 keV and a total beam power of about 5.5 MW. Beams of neutral

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.



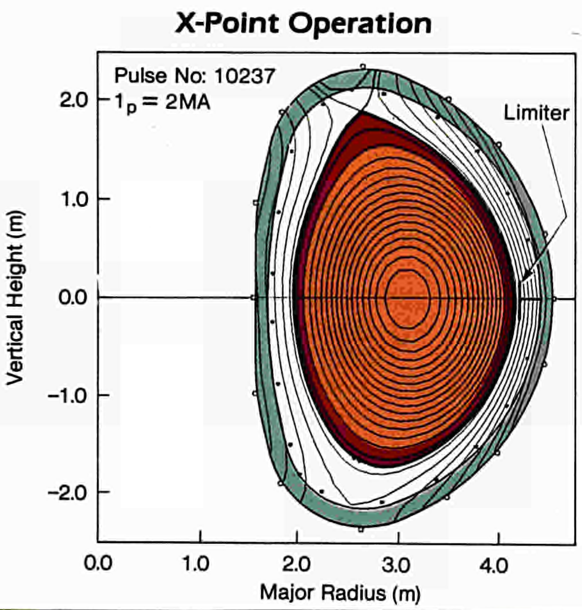


Fig. 25 An RF antenna and limiters mounted on the interior of the vacuum vessel.

deuterium atoms have been injected with energies up to 80 keV and total power values up to 10 MW. Up to 40 MJ of energy have been delivered to the plasma during a pulse. The first neutral beam heating system to come into operation on JET is shown in Fig. 26.

Dedicated Experiements

During 1986, experiments were performed on JET with different magnetic field configurations and with various heating scenarios, ranging from ohmic heating alone to combinations of ohmic, radio-frequency and neutral beam heating. An overview of the 1986 experimental

Table 6
Percentage Operating Time Devoted to Major Research Areas

Topic	Percentage of Operating Time
Ohmic Heating	12
RF Heating	22
NB Heating	22
Combined Heating	13
X-point Studies	9
Pellet Injection	4
Diagnostic Commissioning and Calibration	5
Machine Commissioning	13

programme giving the percentage of operating time devoted to each major research area is given in Table 6.

ICRF Heating Experiments

Operations on JET have been devoted to checking the validity of the existing theory of ion cyclotron wave absorption. By comparison with previous experiments performed on smaller tokamaks, the large size of the JET plasma relative to the wavelength, allows a better identification of the mechanisms involved in the wave plasma interaction. By modulating the amplitude of the wave, it has been verified for the first time that the wave power is mostly deposited in a narrow region of the JET plasma extending radially about 0.6m, where the frequency of the applied wave matches the cyclotron frequency of the resonant ion species.

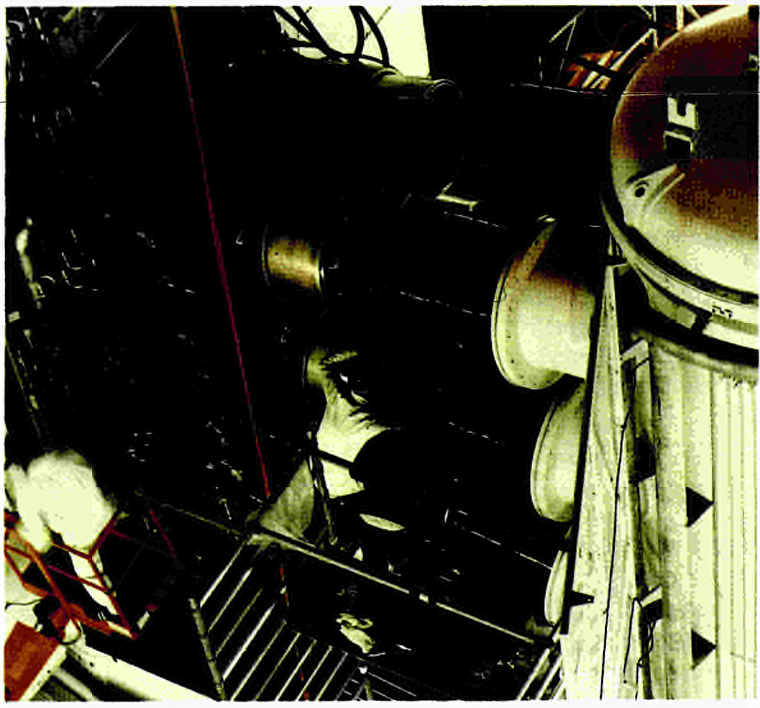


Fig. 26 The eight beam sources and the high voltage transmission tower of one of the neutral beam injection systems.

Neutral Beam Heating

The first year of neutral beam heating on JET has been successful and essentially all the phenomena that were expected have been observed. These include electron and ion heating, fuelling of the plasma and a significant increase in the disruptive density limit, a modest reduction in the average charge carried by the nuclei, Z_{eff}, rotation of the plasma and the generation of a beam driven current. The latter two phenomena arise because the injected beam has a component of velocity and hence momentum parallel to the plasma current. The preferential component of momentum gives rise to rotation of the bulk plasma and velocities of up to $2\times10^5\,ms^{-1}$ have been measured. Differences in the interaction of the plasma electrons with the bulk plasma ions and the fast beam ions results in a net current flowing in the plasma, which can either enhance or reduce the inductively driven current depending upon whether the beams are injected with or against it.

Beam driven currents of up to 0.5MA have been observed and are in reasonable agreement with theoretical predictions.

Disruption Studies

Density limit disruptions are always preceded by an increase in the impurity radiation at the plasma edge. This is thought to be caused by a contraction of the electron temperature profile, which is followed by the growth of a magnetic island where the safety factor $q=2$. Alternative theoretical models predict that either the contraction of the temperature profile leads to an unstable current profile, or that the increased radiation losses at the $q=2$ surface lead to a thermal instability. It is also possible that both of these effects may be involved. Observations and theoretical considerations both show that the central plasma density can be increased by deep fuelling.

Disruptions

There is a maximum value of electron density that can be contained with a given plasma current. If this limit is exceeded, violent instabilities can occur. These cause a disruption when the plasma current falls to zero within 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 $q=2$.

Pellet Injection

The use of small high speed pellets of solid deuterium is one of the possible methods of supplying fuel to a fusion reactor. Preliminary deuterium pellet experiments have been performed on JET with an injector delivering single 3.6 or 4.6mm diameter pellets at a speed of between 1 and $1.2\,km\,s^{-1}$. This technique allows the density limit to be increased beyond the value obtained in normal ohmic discharges and results in a reduction of the effective charge Z_{eff} to values close to 1. The sudden increase in density following the introduction of the pellet is accompanied by a transient decrease in plasma temperature.

First indications show that pellet injection is compatible with both forms of additional heating used on JET and that these do not appear to introduce any abnormalities into the ablation mechanism governing the penetration of the pellet into the plasma.

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.

Slideaway Discharges

When the collision rate between particles in the plasma is low enough; ie, at low density, some electrons can be continuously accelerated in the tokamak to an energy considerably exceeding the average particle energy. Most of the plasma current is then carried by these 'slideaway' electrons. A preliminary study of slideaway discharges has started with a view to decoupling the current and electron temperature profiles. With this type of discharge, a plasma with a current of 3MA and a mean density of just below $1\times10^{19}\,m^{-3}$ has been obtained with a good confinement time for these conditions of between 0.6 and 0.7s. The voltage per turn was 0.2V considerably lower than that achieved in normal discharges. When trying to increase the density by gas puffing, the discharge reverted to normal conditions.

Ultra-long Sawteeth

Sawtooth oscillations of the central values of temperature and density occur in almost all JET discharges. With the central deposition of additional power, especially RF heating, sawteeth may develop large amplitudes (with up to a doubling of the central electron temperature) and longer periods (up to 0.6s). Ultra-long sawteeth (nicknamed *monster*) with a duration of up to 1.6s have also been observed. During this time period, the central electron temperature can reach values above 7keV, with usually a rise in the ion temperature and an improvement in the thermonuclear reactivity. Fig. 27 shows the sawteeth oscillation of the central electron temperature and the effect of NB and RF heating. These ultra long sawteeth were initially observed in a plasma with a 2MA current using combined heating with hydrogen as the minority species. Since then, this phenomenon has been observed in various conditions: NB heating only, ICRF only (in helium plasma) even after the injection of a deuterium pellet, limiter or X-point discharges and at values of plasma current up to 5MA.

The only necessary condition seems to be a threshold in the input power per particle of about 5×10^{-19}MWm^3 in deuterium plasma but down to 3×10^{-19}MWm^3 in helium plasma, where charge exchange losses and outgassing are strongly reduced. The mechanism holding the central electron temperature at high values and preventing the usual crash characteristic of sawtooth oscillations is still conjectured. The most plausible one would be a slight change in the current profile, which causes the central value of the safety factor q(0) to rise above unity.

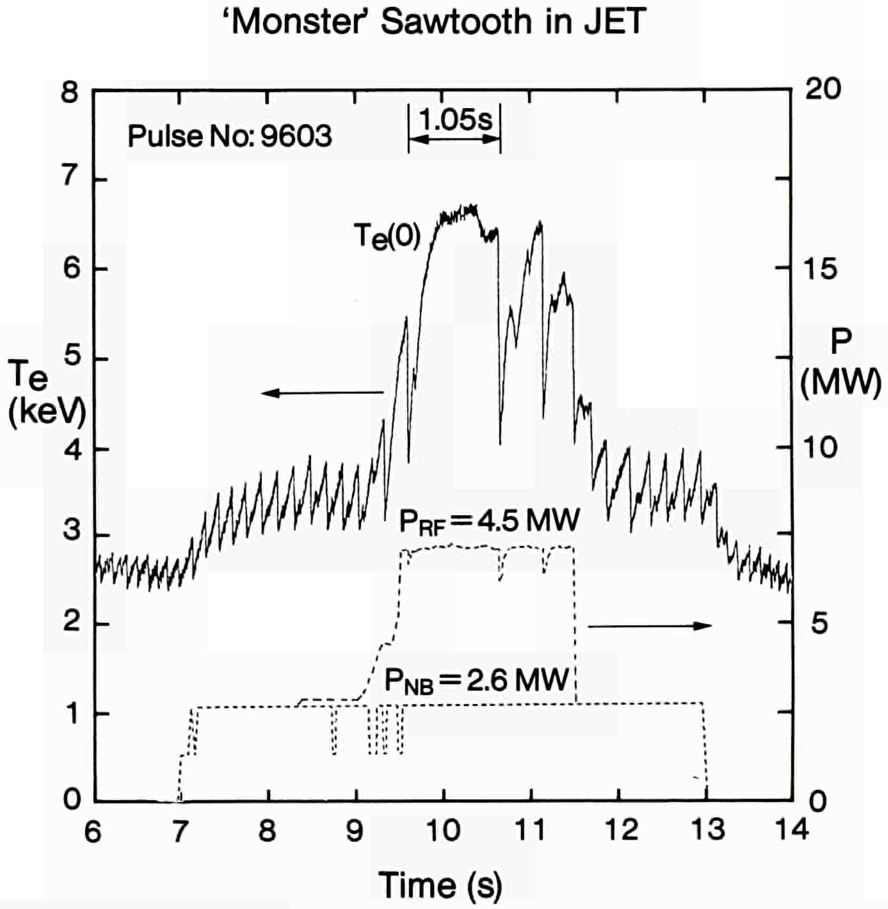


Fig. 27 Sawtooth oscillations of the central electron temperature, showing the effects of neutral beam and radio frequency heating.

> **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.*

Magnetic Separatrix Operations

Stable discharges with magnetic separatrix (or X-point) inside the vessel have been maintained in JET for several seconds, at plasma currents up to 3MA with a single null and up to 2.5MA with a double null. The single null discharges have an elongation of 1.65 compared with 1.80 for the double null and are therefore more stable against vertical displacements. While interaction of the discharges with the limiters was curtailed, the increased localised power deposition on the top and bottom target plates has up to now limited

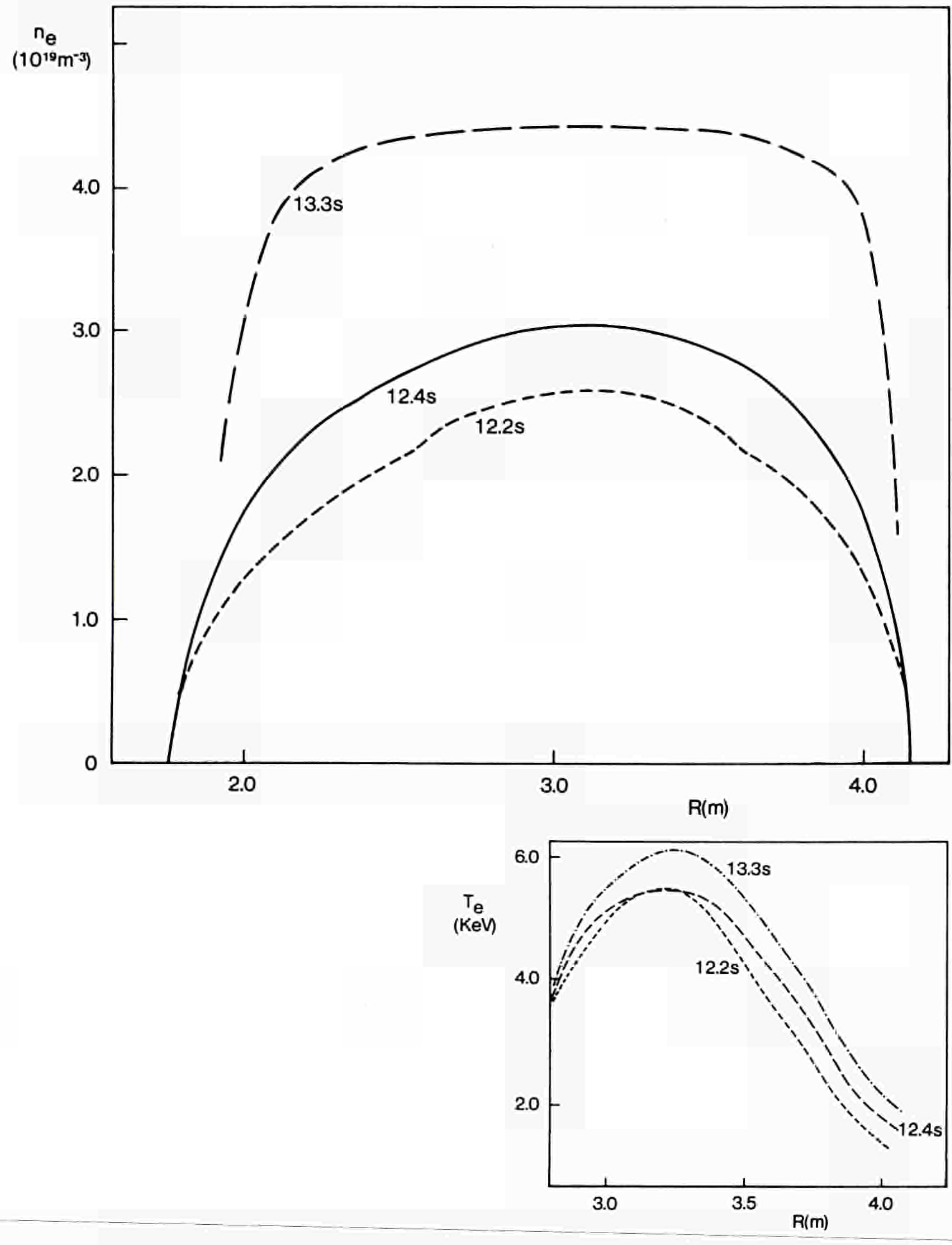


Fig. 28 Density and temperature profiles during the transition from low to high mode

the total input power to 8MW.

With a neutral beam heating power larger than 5.5MW, a transition to enhanced plasma confinement (H-mode) has been obtained in single null operation wth a toroidal magnetic field (B_T) of 2.2T. Usual features of the H-mode are observed; decreased $D\alpha$ light emission at the plasma boundary, reduced broad-band magnetic fluctuations near the X-point, a rise in the plasma density and in energy content, a sudden increase of the electron temperature near the separatrix producing a pedestal to the temperature profile and a flat density profile with a steep gradient near the separatrix. Fig. 28 shows the variation in electron density and temperature during the transition from L to H-mode. The H-mode phase can be sustained for durations approaching two seconds. The continuous density rise increases the radiated power from the bulk plasma and is likely to be the cause of the termination of this phase. There is no indication of a peaking of the impurity profile. While the energy content reaches a quasi-steady state for times approaching one second, the electron temperature may reach a maximum before the end of the H-mode phase. In these conditions, a plasma energy content of 6MJ has been obtained with 8MW of NB heating in addition to an ohmic power of 2MW with a plasma current of 3MA. The global confinement time in this mode exceeds by more than a factor of two the value obtained with limiter or inner wall discharges. It has been observed that increasing the magnetic field raises the power threshold required to switch to an H-mode, and has up to now prevented a transition occurring with toroidal fields above 2.8T. H-modes have not yet been achieved with a double null configuration.

Global Plasma Behaviour

Impurities and Effective Charge of the Plasma

In most cases, impurity radiation losses are caused mainly by carbon and oxygen and originate generally from near the plasma edge. In limiter discharges, the metal concentration was only significant (i.e. $>0.1\% \, n_e$) if the carbon limiters were metal-coated subsequent to accidental melting and evaporation of wall material. The release of metals from the limiters can be explained by a combination of sputtering by deuterium and light impurities. The metal fluxes decrease as the plasma density increases and the plasma current decreases. These fluxes are inversely correlated with the light impurity behaviour. At high plasma density, radiation losses have been mainly due to oxygen. In most of these discharges the power lost by radiation accounts for about half of the input power to the plasma.

The effective plasma charge Z_{eff} is usually in the range of between two and three for a line-averaged electron density $\bar{n}_e$ greater than $3 \times 10^{19} \mathrm{m}^{-3}$. After the injection of a deuterium pellet Z_{eff} fell and approached unity for a time duration exceeding 0.5s.

Impurities

Impurities released from interactions between the plasma and material surfaces can have a 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.

Density Limits

If the density is increased above a critical limit in JET, as with other tokamaks, a disruption occurs. In ohmically heated plasmas, when gas puffing is used to increase the density, the limit reached is given by:

$$n_c(\mathrm{OH})(\mathrm{m}^{-3}) = 1.2 \times 10^{20} \frac{B_T(\mathrm{T})}{qR(\mathrm{m})}$$

and is dependent upon plasma purity. With RF heated discharges this limit is only slightly increased, possibly because the effect of the extra power is cancelled by the increased relative importance of radiation losses.

In neutral beam heated plasmas and during preliminary experiments with the single shot pellet launcher, refuelling takes place towards the centre of the plasma. Under these circumstances, the density limit is substantially increased to:

$$n_c(\mathrm{NB})(\mathrm{m}^{-3}) = 2.0 \times 10^{20} \frac{B_T(\mathrm{T})}{qR(\mathrm{m})}$$

If the neutral beams are switched off at high densities, the plasma can disrupt indicating that the power input plays an important role in the disruption mechanism.

Plasma Temperature

Electron and ion temperatures react differently to the application of additional heating power. With a power input per particle of:

$$\frac{\mathrm{P}}{\bar{n}} > 4 \times 10^{-19} \mathrm{MW\ m}^{-3}$$

values of the ion temperature on axis of up to 12.5keV have been reached, which can be greatly in excess of the electron temperature. Fig. 29 shows how the central electron and ion temperature react differently to changes in the input power per particle for different heating scenarios.

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.

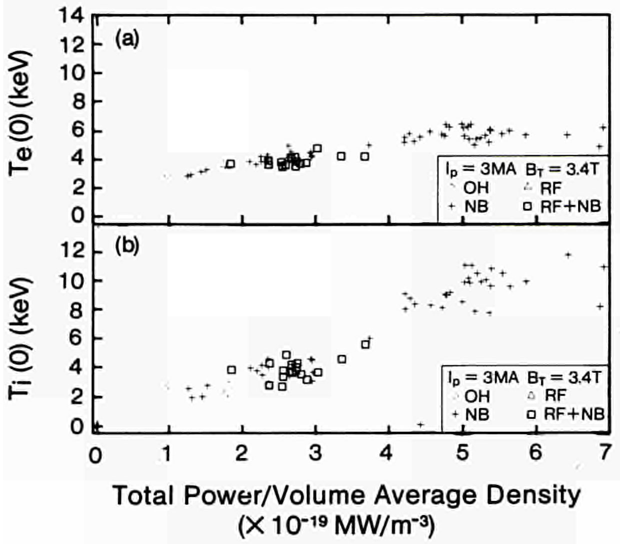


Fig. 29 (a) Central electron Temperature (T_e) and (b) ion temperature (T_i) as a function of input power per particle for various heating scenarios.

The peak electron temperature at the centre of the plasma can be raised significantly above the value reached with ohmic heating as exemplified by the ultra long sawteeth where the variation in electron temperature, $\Delta T_e(0)$, has exceeded 4keV. Fig. 30 shows how the central electron temperature varies with the input power per particle for ohmic, RF, NB and combined heating scenarios. The dotted lines indicate the variation in electron temperature between the top and bottom of the sawteeth. In contrast to the temperature at the top, the temperature at the bottom of the sawteeth shows only a weak dependence on the input power per particle for a given plasma current and toroidal field. The different behaviour of the electron and ion temperatures in response to additional heating is also illustrated in Fig. 31. The radial profile of the ion temperature, obtained from the analysis of neutral particles, can be strongly modified by off-axis deposition of RF power while the shape of the electron temperature profile is hardly affected.

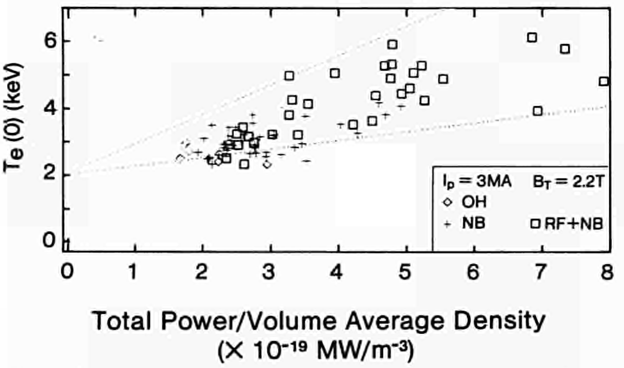


Fig. 30 Variation of the central electron temperature (T_e) with input power for different heating scenarios. The dotted lines indicate the variation arising during sawteeth oscillations.

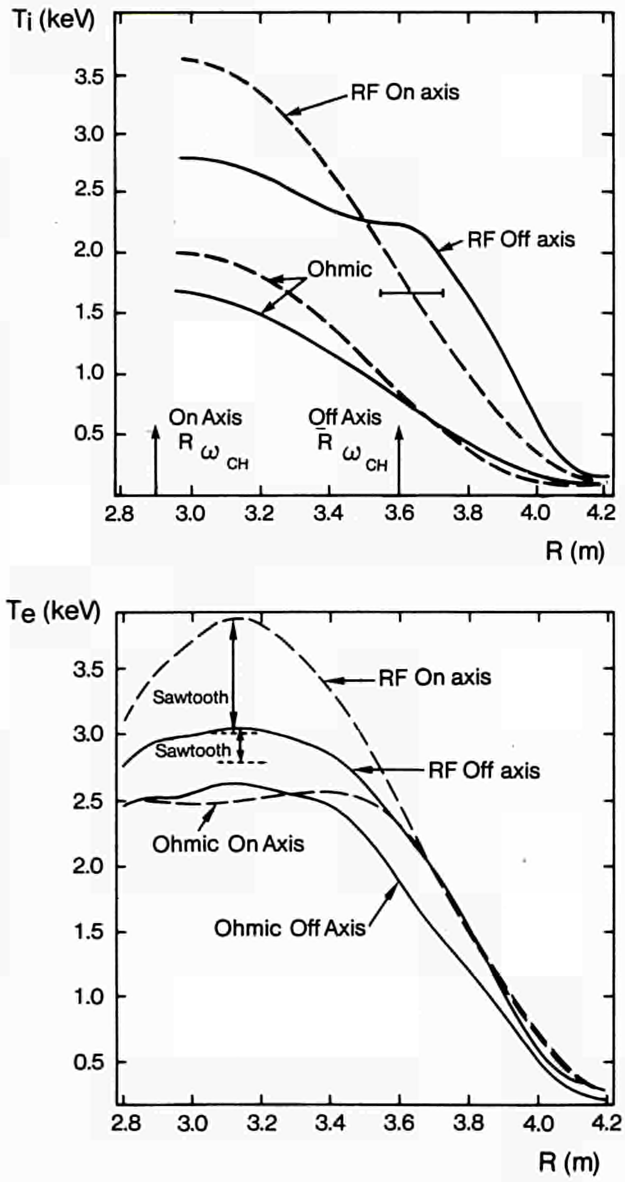


Fig. 31 Temperature profiles of electrons and ions during the ohmic heating phase and during on-axis or off-axis RF heating. The main effect of the off-axis heating is a broadening of the ion temperature profile.

Energy Confinement

The total energy confinement time on JET is defined as:

$$\tau_E = W_K \Big/ \left(P_t - \frac{dW_K}{dt}\right)$$

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

The energy confinement time on JET falls with increasing heating power as seen in a number of other experiments. This degradation in confinement time is independent of the type of additional heating, whether NB, RF or combined. 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 0.3 MJ/MW at high powers. This indicates that there is a lower limit to the global energy confinement time, τ_E, in JET of between 0.1 and

0.3s. Although a weak dependence on plasma density has been found for the energy confinement time there is a favourable scaling with plasma current. The way in which the energy confinement time falls with increasing heating power is shown in Fig.32.

The global energy confinement time results can be fitted by a relationship developed at the University of Princeton, USA. However, the measured radial propagation of heat pulses following sawtooth crashes, strongly supports a linear offset relationship between plasma kinetic energy and power input of the form:

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

The best fit in the case of limiter or inner wall discharges gives: $W(0) = 0.225\ n^{0.6}\ I^{0.5}\ B^{0.4}$ and the incremental confinement time, $\tau_{inc} = 0.047\,I$. The units are W(MJ), $n(\times 10^{-19}\mathrm{m}^{-3})$, I(MA), B(T), τ_{inc}(s).

In the H-mode, the energy confinement time is more than twice that obtained with limiter discharges. A degradation in confinement time is also observed with increasing input power and a similar offset linear scaling between kinetic energy and input power is likely. It is too early to determine how the corresponding incremental confinement time compares with that obtained in limiter discharges. In both cases, however, higher plasma currents look beneficial.

Progress Towards Breakeven

A record value of the fusion product ($n_i.\tau_E.T_i$) of $2\times 10^{20}\mathrm{m}^{-3}$s keV has been achieved with 10MW of neutral beam heating during X-point operation in the H-mode. For limiter discharges, the values of the fusion products are similar for ohmic heating, RF, NB and combinations of these methods. This is a result of the degradation in confinement time offsetting gains made in the values of the other parameters. The maximum values of the fusion product and the corresponding values of plasma temperature, density and energy confinement time are given in Table 7 for different operating scenarios.

Neutron yields up to $3\times 10^{15}\ \mathrm{s}^{-1}$ have been obtained with neutral beam heating, mainly from deuterium-deuterium reactions occurring between the deuterium particles in the heating beams and the plasma. The best ratio of fusion power to input power obtained was $Q_{DD} = 3.5\times 10^{-4}$ which is equivalent to $Q_{DT} \simeq 0.2$ if tritium were introduced into the machine under these conditions and would correspond to a fusion power production of above 1 MW. This value of fusion power is considerably above those shown in Fig.24 because of the enhanced reaction rate due to interactions between the plasma and neutral heating beams.

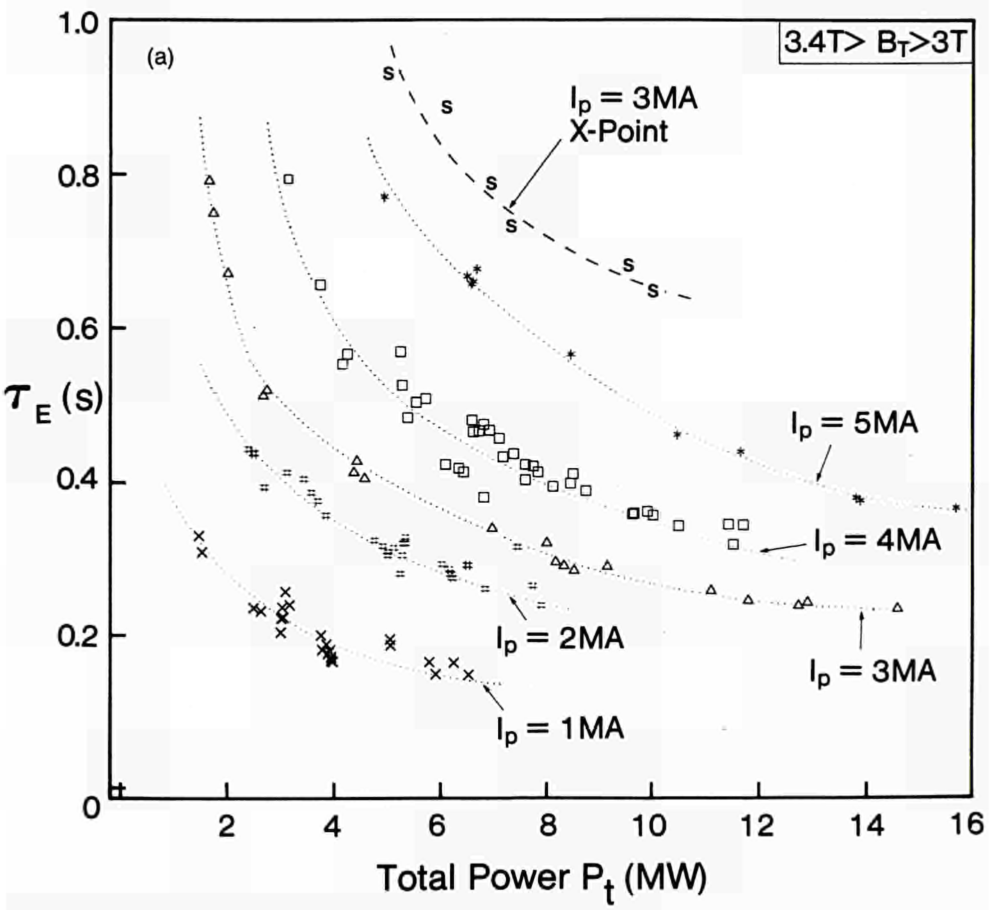


Fig.32 The energy confinement time (τ_E) as a function of additional heating power for various plasma currents during limiter dishcarges and at 3MA with X-point operation.

Table 7
Maximum Values of the Fusion Product (Nov 1986)
$\langle n_i(0)\tau_E T_i(0)\rangle$

	Peak Density	Energy Confinement Time	Ion Temperature	Fusion Product
Experimental Programme	$n_i(0)$ $(\times 10^{19}m^{-3})$	τ_E (s)	$T_i(0)$ (keV)	$\langle n_i(0)\tau_E T_i(0)\rangle$ $\times 10^{20}m^{-3}$skeV)
Ohmic (4.6MW)	4.2	0.8	3.0	1.0
ICRF (7MW)	3.7	0.3	5.4	0.6
NBI (6MW) High n_i Low n_i	4.4 1.5	0.4 0.4	4.0 10	0.7 0.6
Combined NBI + RF (14MW)	5.0	0.4	3.5	0.7
X-point (NB – 10MW)	5	0.65	6	2.0

Prospects

During the major shutdown, which started at the end of 1986, new equipment and diagnostics are being installed. Among the major changes being made are, the strengthening of the vacuum vessel, modifications to the primary winding and improvements to the power supply, which will allow the plasma current to be increased to 7MA at the full elongation of $\epsilon = 1.7$ and to 4MA in magnetic separatrix operations. The coverage of the inner wall with protection tiles is being extended and two toroidal belt limiters are replacing the existing ones. The tiles already installed are made of carbon, while beryllium may be used later on. A second neutral beam heating system and the installation of eight water cooled RF antennae will allow up to 44MW of additional heating power to be delivered to the plasma. A multipellet injector, built by the Oak Ridge National Laboratory (USA), is being installed ready for the restart of plasma operations.

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

While present achievements show that the first three objectives of JET are being actively addressed and substantial progress is being made, the strategy for JET 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 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.

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.

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 interaction 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

New additions proposed for JET aim, through the following mechanisms, 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 through the use of lower hybrid current drive and neutral beam injection to ensure that, at high central temperatures, the current density in the centre does not reach the critical value that causes sawteeth oscillations;
- Increasing the density of deuterium and tritium ions in the central region to between 1 and $2\times10^{20}m^{-3}$ by high velocity pellet injection;
- Reducing the edge density by pumping, since it is observed that the temperature at the $q=1$ surface is higher when the edge density is lower. Other advantages of lowering the density in the outer region are the inhibition of disruptions and a higher efficiency for the lower hybrid current drive systems;
- Achieving high central temperatures (12-15 keV) by the combination of 'on-axis' ion cyclotron resonance frequency (ICRF) heating, neutral beam injection at 160 keV and current profile control, which is aimed at maintaining the conditions of giant sawteeth for longer periods.
- Since scaling laws have shown that improved energy confinement is obtained, in both ohmic and additional heating modes, with increasing current, such schemes will be attempted in two main configurations: (*a*) with a magnetic separatrix (X-point operation) up to 4 MA; (*b*) with low-*Z* material limiters at higher currents up to 7 MA.

These additions, described below, are all aimed at optimising the central values of the ion density, temperature and global confinement time.

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.

Flattening of the current profile in JET will be obtained by driving approximately 2MA current in the outer half radius of the plasma by using 10MW of lower hybrid current drive power at 3.7GHz and approximately 0.5MA with the two neutral beam injectors.

Control of the Density

A multi-pellet injector (supplied by the Oak Ridge National Laboratory, U.S.A.) will be used to improve the central density well above present values by injecting 2.6, 4 and 6mm diameter hydrogen pellets into the plasma at a repetition rate of respectively 5, 3 and 2Hz with speeds of about $1.5\,\mathrm{km\,s^{-1}}$. As the speed of these pellets is not high enough for them to reach the plasma centre, a research programme has been undertaken to increase the pellet speed above $5\,\mathrm{km\,s^{-1}}$ to achieve deeper density fuelling.

The increase in the central density needs to be obtained without increasing the density at the edge of the plasma. A particle exhaust system is therefore required to control the edge density and a research programme has been started to develop pumped limiter systems and pumping panels. The panels will make use of the large pumping effect of the carbon wall that has been observed on JET.

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 RF generators with eight antennae in the torus, which should produce at least 30MW power in the plasma;
- Two neutral beam injectors providing at least 10MW of 160keV 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 will be 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, will make 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 must be made to the magnets and their electrical power supplies, as well as providing additional protection or dump plates in the vacuum vessel to absorb the energy of the plasma reaching the wall in the vicinity of the X-points.

The Proposed JET Programme

The additions mentioned above, together with the ambitious JET programme on additional heating and the preparation for the radioactive 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 the necessary steps have been taken to seek the approval of the Council of Ministers.

Figure 33 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 future phases are as follows:

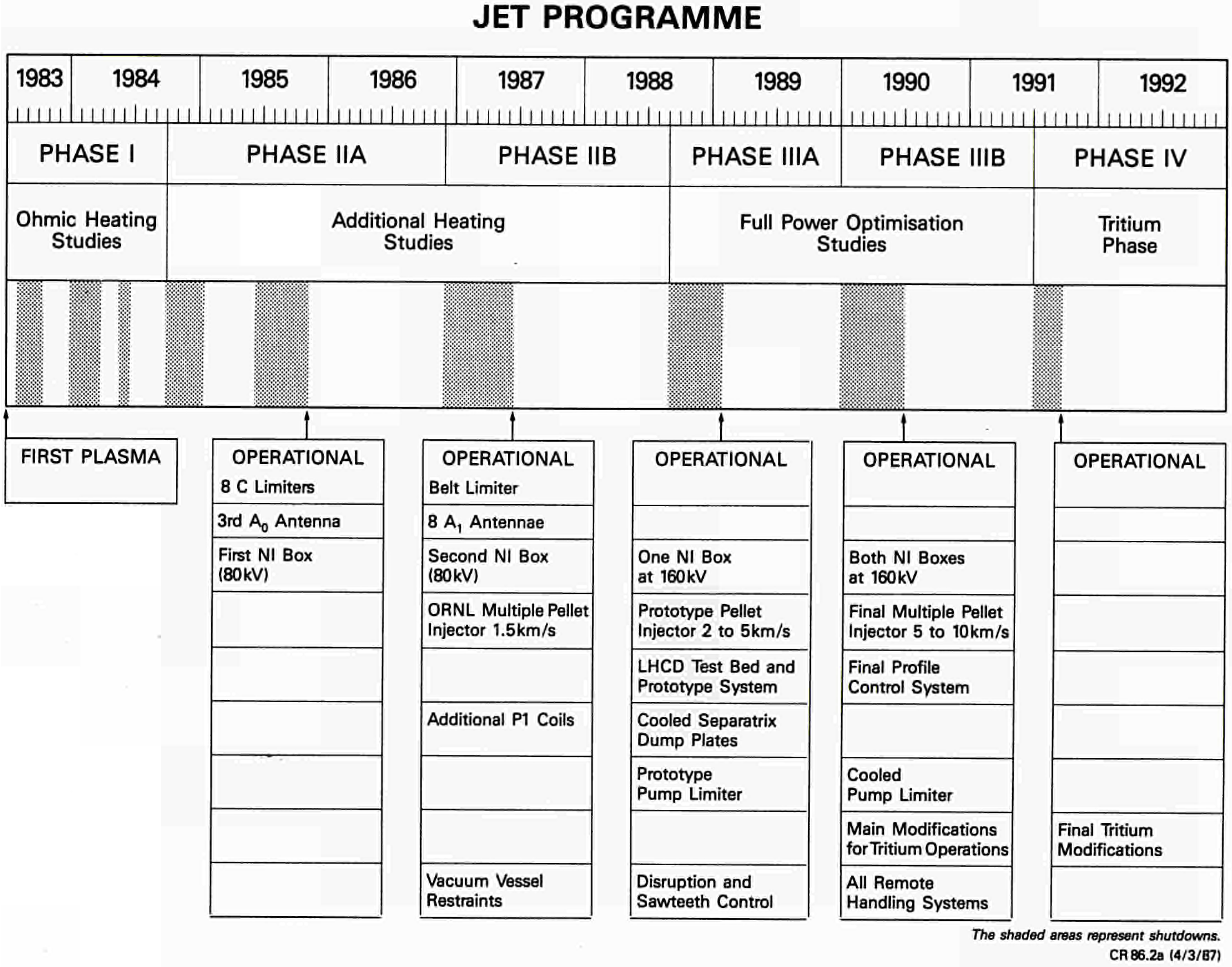


Fig. 33 The proposed future JET programme.

Phase IIB (mid-1987—mid-1988)

At the end of 1986, the machine was shut-down to enable a large number of modifications to be made. These include the installation of the second neutral beam system (doubling the available injection power), the installation of eight cooled antennae for ion cyclotron radio frequency heating (increasing the coupled RF power by about a factor three), installation of belt limiters (providing increased power handling capability in the torus), strengthened vessel supports (permitting higher plasma currents), installation of a multiple pellet launcher (permitting experiments with internal fuelling), modifications to the primary winding and power supplies, (permitting higher current separatrix-bounded plasmas).

With all these improvements, it should be possible to run JET in the second half of 1987 with additional heating power in excess of 30MW and to investigate further operation modes, such as X-point operation and pellet fuelling, which may reduce or eliminate confinement degradation.

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;
- Conversion of one neutral injector to 160keV;
- Prototype pump 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;
- Sawteeth control system;
- Disruption control system, perhaps using internal saddle coils.

The main aims of this phase should be to consolidate the operation of the machine at full additional heating power and to explore further the use of X-point operation as a means of improving confinement.

Phase IIIB (early 1990—mid 1991)

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

- Final pellet injector system capable of multiple injection at 5 to 10km s^{-1};
- Final lower hybrid current drive system for profile

control;

- Cooled pump limiters;
- Both neutral injectors at 160 keV;
- All remote handling systems required for the active phase.

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

The main aim of this phase should be to reach maximum performance with deuterium plasmas before proceeding to the next and final phase of introducing tritium.

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 questions to be studied should be:

- Are the α-particles confined?
- Do the α-particles behave as expected, slowing down classically and giving most of their energy to the electrons?
- 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 production rate and spatial distribution of the initial source should be given by the measured neutron yield and source distribution. Direct loss of energetic α-particles should be measured with detectors at the wall of the torus. The heating effect should be detectable through the changes in plasma temperature and density. For this purpose, the α-particle power needs to be at least 20% of the total power input from other sources (i.e. Q_{DT} of about one or higher). The preferential localisation of the α-particle heating in the plasma core should make such experiments easier.

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 Ecole Royale Militaire) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the ULB);
- The Commissariat à l'Energie Atomique (CEA), France;
- The 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.
- The Hellenic Republic, Greece;
- The Forskningscenter Risø (Risø), Denmark;
- The Grand Duchy of Luxembourg, Luxembourg;
- 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 Energy Research Commission (SERC), 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. 34.

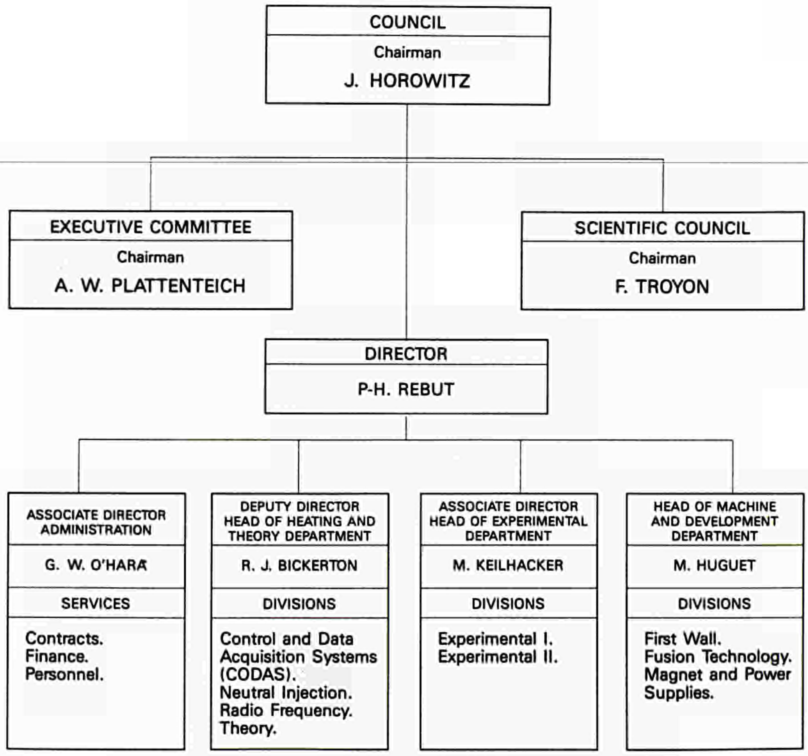


Fig. 34 Organisation of the JET Joint Undertaking.

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 held during 1986, on 20–21 March, 20 June and 23–24 October. The membership of the JET Council is shown in Appendix I.

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 4 February, 6–7 March, 6–7 May, 17 July, 25–26 September, 7 November, 11–12 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 five times during the year on 4–5 March, 23–24 April, 5–6 June, 15–16 July and 18—19 September.

The main work of the JET Scientific Council in 1986 was to assess and report to the JET Council on:

- New additions planned for JET (namely, X-point operation, pellet injection, plasma exhaust, current profile control);
- Taking account of the status of tokamak research and the relevant programmes in the associated laboratories;
- Prospects for alpha power in JET;
- Implications of the JET programme, includings its relationship to NET.

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 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.

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 rationalisation of the Project Structure, which was started towards the end of 1985 was completed in 1986. The internal structure of the organisation now consists of four Departments:

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

The overall Project Structure is shown in Fig.34.

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 computer-based control and data acquisition systems for JET;

(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;
physics of RF 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 the JET 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 JET 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 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 is responsible for machine services. The Department is composed of three Divisions:

(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. In addition, the Department is responsible for maintenance and operation of the coil systems, structural components and machine instrumentation;

(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.

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 Sections.

Finance

The budgets for 1986 were approved at 94.13 Mio ECU for Commitments and 99.25 Mio ECU for both Income and Payments Budgets. The Commitments and Payments budget each subdivide into three phases of the Project - Basic Performance, Extension to full Performance and the Operational Phase; further subdivisions distinguish between investment, operating and personnel costs. The Basic Performance Phase has now been completed.

Commitments (Tables 8 and 9)

Of the total appropriations in 1986 of 130.60 Mio ECU

Table 8
Commitment Appropriations for 1986

	Mio ECU
1986 Commitments Budget	94.13
Uncommitted amounts available from 1985	36.47
	130.60
Commitments made during the year	100.15
Balance uncommitted in 1986 available for use in 1987	30.45

Table 9
Commitments and Payments for 1986

Budget Heading	Commitments: Budget Appropriations Mio ECU	Commitments: Out-turn Mio ECU	Payments: Budget Appropriations Mio ECU	Payments: Out-turn Mio ECU
Phase 1 — Basic Performance Title 1 — Project Investments	−0.04	−0.04	0.62	0.6
Phase 2 — Extension to Full Performance Title 1 — Project Investments	52.07	24.12	34.15	30.76
Phase 3 — Operational				
Title 2 — Operating Costs	54.67	54.10*	51.12	42.96*
Title 3 — Personnel Costs	23.90	21.97	21.97	21.01
TOTAL Phase 3	78.57	76.07	73.09	63.97
Project Total—all phases	130.60	100.15	107.86	95.33

**Includes 6.76 Mio ECU commitments and 5.71 Mio ECU payments in respect of JET non-tea.. personnel.*

Table 10
Income and Payments for 1986

	Mio ECU		
Income			
Budget for 1986		99.25	
Income received during 1986			
(i) Members Contribution	85.31		
(ii) Bank Interest	1.81		
(iii) Miscellaneous	0.01		
	87.13		
(iv) Unused payment appropriations brought forward from 1984	12.44		
Total Income		99.57	
Excess income to be carried forward against Members' future contributions			0.32
Payments			
Budget for 1986		99.25	
Add amounts available in the Reserve Account to meet outstanding commitments at 31 December 1985		8.61	
		107.86	
Actual Payments in 1986		95.33	
Balance of unutilised appropriations:			
Reserve no longer required			0.27
Unused payment appropriation			12.26
Total unutilised appropriations carried forward at 31 December 1986			12.85
Allocated as follows:-			
(i) Reserve at 31 December 1986 to meet outstanding commitments at that date			12.26
(ii) Reduction of Members' future Contributions			0.59
			12.85

(including 36.47 Mio ECU brought forward from previous years) 100.15 Mio ECU was committed and the balance 30.45 Mio ECU was available for carry forward to 1987.

The details of the commitment appropriations available and of the amounts committed in each Phase during the year given at Table 9 are summarised as follows:-

- In the Basic Performance Phase Commitments no longer required of 0.04 Mio ECU have been transferred to the Extension to Full Performance Phase.
- In the Extension to Full Performance Phase of the Project 24.12 Mio ECU was committed leaving commitment appropriations not utilised at 31 December 1986 of 27.95 Mio ECU to be carried forward to 1987.
- In the Operational Phase 76.07 Mio ECU was committed leaving a balance of 2.50 Mio ECU to be carried forward to 1987.

Table 11
Final pecentage contributions to JET 1986 based on the Euratom participation in Associations' contracts for 1985.

Member	%
Euratom	80.0000
Belgium	0.2250
CEA, France	2.5473
ENEA, Italy	0.9593
CNR, Italy	0.1903
Risø, Denmark	0.0757
Luxembourg	0.0021
KFA, FRG	0.7295
IPP, FRG	2.4606
KFK, FRG	0.5076
SERC, Sweden	0.1654
Switzerland	0.4122
FOM, Netherlands	0.4117
UKAEA	11.3133
	100.0000

Income and Payments (Table 10)

The actual income for 1986 was 87.13 Mio ECU to which was added 12.44 Mio ECU available appropriations brought forward from 1984 giving a total of 99.57 Mio ECU; this total compares with the 1986 Income Budget of 99.25 Mio ECU; the excess of 0.32 Mio ECU is carried forward in reduction of Members' future contributions. Of the total payments appropriations for 1986 of 107.86 Mio ECU, payments made were 95.33 Mio ECU and transfers to the Special Reserve Account to meet commitments outstanding at 31 December 1986 were 12.26 Mio ECU leaving a balance of 0.27 Mio ECU to be carried forward against Members' future contributions. More detailed comments are given in the following paragraphs. (Payments by Phase are summarised in Table 9).

1. Contributions from Members

The budget for Members' contributions was 85.31 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 having Contracts of Association with Euratom in proportion to the previous year's contribution from Euratom towards the cost of their Association Contracts. (Unavoidable delay in the confirmation of the final proportions results in provisional figures being included in the Annual Accounts with a final adjustment in the following year. Table 11 gives the final percentage contributions from Members relating to 1985).

2. Bank Interest

Income is normally received on a quarterly basis in respect of Members' Contributions and intermittently in respect of other items. The Project usually has funds which are not immediately required for the discharge of its commitments; these funds are placed on deposition account at market interest rate; during 1986 interest earned amounted to 1.81 Mio ECU.

3. Unused Payment Appropriations and Excess Income from Earlier Years

12.44 Mio ECU of unused payment appropriations and excess income arising in 1984 and held for reduction of Members' future contributions was transferred to income in 1986.

Summary

Table 12 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1986, which have yet to be audited. The final audited accounts will be published in due course.

Table 12
Summary of Financial Transactions at 31 December 1986

	Mio ECU
Cumulative commitments	700.6
Cumulative payments	637.7
Unpaid commitments	62.9
Of which carried forward on reserve account	12.3
Amount available from 1985 and 1986 due to be set off against future contributions from Members	3.6

Contracts

1986 has seen a continued increase in the volume of work carried out by JET Contracts Service. The pattern of work has followed the trend evident in 1985, namely a shift from Construction Contracts to smaller but more numerous Service Contracts.

Major Contracts

Major contracts are those with a value greater than 50,000 ECU. The number of these contracts placed increased from 91 in 1985 to 166 in 1986. This 82% increase is mainly accounted for by the growing requirement for contract staff and services at JET, reflecting the progress of the Operational Phase and the completion of many of the major supply contracts. Substantial numbers of hardware contracts were also let to cover enhancements to the JET device. Many of the larger contracts involve advance and retention payments for which bank guarantees are required by JET. The total value of guarantees held as at 31 December 1986, was 5.6Mio ECU.

Minor Contracts

Minor contracts are those with a value less than 50,000 ECU. The volume of these handled by the Contracts Service increased from 6578 in 1985 to 8049 in 1986, an increase of 22%. Many of the minor contracts are below 500 ECU and are therefore processed through the small value order system. This system, introduced in January 1985, allows the swifter processing of requisitions (other than amendments to existing orders) below 500 ECU. These requisitions are normally processed within 24 hours of receipt. The number of orders processed in this way totalled 4083, representing 51% of all minor contracts placed, while their aggregate value of 793574 ECU amounted to 3% of the total value of all minor contracts placed, including amendments.

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 customs duties and VAT on its goods under privileges granted by the Host Country. Goods dealt with include new supplies arriving on Site for the first time and items exported for repair, analysis, etc. Such movements are continuous throughout the year, but their volume tends to be considerably higher during machine shutdown periods.

The total number of imports handled in 1986 was 1108, representing an increase of 29% over the 1985 figure. Similarly, the total of exports for 1986, at 479, is an increase of 44%. There were also 636 issues of goods to UK firms during 1986, an increase of 22% on the 1985 figure.

The total value of issues to all countries in 1986 was 9.8 Mio ECU. Details of all transport transactions are held on a new 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 also handled within the service.

Administration of Contracts

The computerised system for requisitions continues to operate successfully. In addition, to allocating contract numbers, the data input is absorbed into the data bases of both Contracts Service and Finance Service. Data is also retained on the distribution of contracts between countries which are shown in Table 13. Included in the figures are all contracts with a value of 10,000 ECU and above placed prior to 1984, together with all contracts placed during the period 1984-86, regardless of value.

Table 13
Allocation of JET Contracts
(position as at 31 December 1986)

Country	Total of ECU Values	% of Total
UK	223875380	47.20
Germany	106553883	22.46
France	45263527	9.54
Italy	31452755	6.63
Switzerland	26787015	5.65
Netherlands	8966034	1.89
Denmark	8727978	1.84
Belgium	6051000	1.28
Sweden	5257735	1.11
Ireland	346720	0.07
Others	11049153	2.33
Totals	474331180	100.00

Register of Suppliers

As an additional means of ensuring that suppliers from all members countries are considered before placing large contracts, Contracts Service has established a Register of Suppliers. This takes the form of a computer database covering 466 different categories of supply. The number of suppliers registered has expanded by 17% over 1986 to a new total of 2,219. Information from this Register is available to all JET technical officers and a new Catalogue of Suppliers was issued to divisions and departments in December, 1986.

Personnel

In the autumn of 1986, the overall complement for the programme was re-defined to take account of the needs of the Project and of the necessity for increased use of contract staff to meet the manpower requirement.

Whereas the approved composition of team posts remained at 165 Euratom posts, 260 and 19 posts seconded, respectively, from the UKAEA and DGxII Fusion Programme, the JET Council approved a new ceiling of 210 contract posts, ie. an overall increase of 44 posts from the previous year. Contract posts are filled by personnel employed by companies and other organisations and supplied under contracts placed with those companies by JET.

Furthermore, it was decided not to limit in number the assignment of attached staff from the Associations to JET.

The composition of the allocation of posts for 1986 is shown in Table 14.

Table 14
Distribution of Posts

Team Posts:	
EURATOM	165
UKAEA	260
DG XII Fusion	19
	444
Non-Team Posts:	
Contract Posts	210
Total	654

Recruitment

The Personnel Service maintained its efforts to achieve full complement of Euratom/JET team posts. Whilst the difficulties experienced in previous years continued, for a short period during 1986, for the first time, all the allocated Euratom/JET posts were committed. This restricted mainly to the UKAEA, the filling of the remaining vacancies.

The result of efforts by JET and the UKAEA to attract suitable staff from the open market remained disappointing. The DGxII Fusion Programme has so far not been able to attach more than 12 staff to the Project, ie. a shortfall of seven posts.

The number of contract personnel working on JET increased by 30 during the year.

Table 15 illustrates the filling of posts against the approved complement.

Euratom Staff

In 1986, 11 newly appointed Euratom staff joined the team. During the same period, four staff members left. The number of staff in post at the end of the year was 169 including 12 from DGxII. Fig. 35 shows the composition of team staff by nationality.

UKAEA Staff

During the year, 15 staff were seconded to JET by the UKAEA but this was more than offset by the departure of 20 UKAEA staff from the Project. The majority of these were secretarial and administrative staff. The number of UKAEA staff in post at the end of the year was 215.

Table 15
Post Filled Against Complement

	Complement	In Post
Team Posts:		
EURATOM	165	157
UKAEA	260	215
DGXII	19	12
	444	384
Non Team Posts:		
Contract Personnel	210	229*
Total	654	613

**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.*

The average age of professional JET staff is now 42 years.

Assigned Associate Staff

The Assigned Associate Staff (AAS) scheme, which came into operation towards the end of 1981 enabled staff of the Associated Laboratories to be seconded to JET for up to two years. Whilst at JET, the Associate Laboratory continues to pay the assignee his or her home salary and JET pays a monthly expatriation allowance directly to the assignee.

During 1986, 79 staff from the Associated Laboratories (other than the UKAEA) were assigned under the scheme. The total contribution (including an estimated contribution of 11 man-years by staff assigned from the UKAEA) was about 42 man-years, compared with 30 man-years in 1985, 23 in 1984 and eight in 1983.

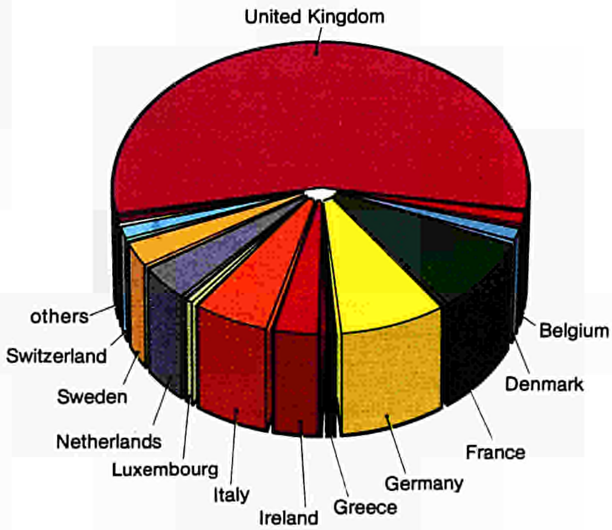


Fig. 35. Project team staff by nationality.

Table 16
Contribution made by Associated Laboratories during 1986

Associated Laboratory	Man-Years
UKAEA (Great Britain)	*11.00
IPP (The Federal Republic of Germany)	7.73
CEA (France)	5.48
ENEA (Italy)	4.15
FOM (The Netherlands)	3.48
SERC (Sweden)	2.50
ERM (Belgium)	2.00
CRPP (Switzerland)	1.75
Risø (Denmark)	1.25
KFA (Federal Republic of Germany)	1.10
JEN (Spain)	1.00
CNR (Italy)	0.33
Total	41.77

**The UKAEA contribution is estimated.*

Tables 16 and 17 show respectively the contribution by the partners during 1986 and the deployment of AAS within the Project.

Visiting Scientists

During 1986, there were only eight Visiting Scientists working at JET compared to nine in 1985. Two came from the United States and one each from Australia, China, Italy, Poland, The United Kingdom, and the Federal Republic of Germany.

The Project has experienced difficulties in attracting suitable candidates for this scheme, and intends to step up its efforts in the coming year.

Consultants and Attached Staff

Four consultants were appointed during the year compared with seven in 1985. The areas of work in which specialist advice was provided by consultants included additional heating, diagnostics and computing.

Four attached staff from the Netherlands, Japan and the USA worked on JET during the year. They were supported financially by their parent laboratories.

Table 17
Assigned Associated Staff within the Project

Division	Man-Years
Experimental Division I	17.88
Experimental Division II	14.67
Radio Frequency Heating Division	5.04
Theory Division	2.77
Fusion Technology Division	0.83
Neutral Beam Heating Division	0.33
Heating and Theory Department	0.17
Experimental Department	0.08
Total	41.77

Students

During the year, 73 students from 11 different countries (less than 50% from the UK) were employed for a total of 224.5 man-months, in experimental, computing, engineering and administrative work. Twelve of these students stayed six months or more.

Fellowships

The review of the scheme was completed by the Commission in the early part of 1986, and came into operation later in the year. The first selection Committee was convened in October and five applicants were selected. One was in post by the end of the year. It is planned to make the scheme more widely known during the coming year.

Shift Work

From the beginning of February 1986, the machine was operated from Monday to Friday between 0630 and 2230 hours on a two-shift system. The early shift on Mondays is for commissioning of machine systems and the late shift is for commissioning of plasma diagnostics. This is followed on Tuesdays to Fridays by eight shifts of operations. A pattern of six weeks of such operations followed by two weeks of maintenance and commissioning involving extended day working from 0815 to 1800 hours was continued throughout the year until the shutdown at the end of November.

The basic operation of the machine systems has required the manning of 23 posts per shift by staff drawn from both the Heating and Theory Department and Machine and Development Department.

The Experimental Department has been required to man approximately 10 posts on a shift basis. This has varied with the scientific programme, the requirement being considerably greater when the experiments are operated in the enhanced mode.

Over the year, all these posts have been covered by a total of approximately 240 staff.

Overtime

Recorded overtime has averaged 500 hours per week which represents the equivalent of an additional 12 man years. An increase was anticipated during the major shutdown starting at the end of the year with six day working weeks planned for the duration of this period.

The monthly pattern of overtime worked has remained relatively stable over the year; 65% was weekend work.

The breakdown of overtime per Department was as follows:

Heating & Theory Department	37%
Experimental Department	20%
Machine & Development Department	28%

Due to pressure of work a number of staff experienced difficulties in taking all their leave entitlement during the year.

On-Call

The re-organisation of the Project structure at the end of 1985 and the additional contribution of the shift technicians team following further training, led to a review of the on-call systems as a result of which the number of sub-systems of the torus requiring full on-call provision was further reduced by 30%. The remainder of the systems were covered by emergency call-out alone. The number of staff per roster nominated to undertake these duties was also reduced by 40%

Staff Training

During 1986, 31 staff were recalled by their parent Associations to undertake short periods of training and nine staff were allowed to pursue part-time courses in furtherance of their long-term career development with the Associations.

The one-day JET Induction programme continued throughout the year; a total of 66 staff attending the six sessions held.

Under the language training scheme, 28 staff from non-English speaking countries received English tuition and 119 staff took lessons in other European languages.

The Joint Safety Services held a number of courses throughout the year, attended by 66 staff. Courses were also organised to brief identified radiation workers of the implication of the new Ionising Radiation Regulations introduced in June 1986.

Specific industrial training was organised for 33 of the staff an an in-house three day training session, in conjunction with an external software house to assist data interpretation.

Conferences

As the successful development of the JET experiment continued the number of papers and results presented at conferences and workshops increased. During the year, about 130 JET attendances were recorded. The major events included the IAEA 11th International Conference in Japan, the EPS 13th Conference in Germany, the SOFT Conference in France and the APS 28th Annual Meeting in the 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

Three meetings were held during the year between JET management and the Staff Representatives 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. The Joint Safety Services provides support to both JET and Culham Laboratory in a range of areas, including health physics, safety training, and safety documentation. JET meets, as a minimum, all the requirements of the relevant UK legislation. Further to this, under the Host Support Agreement, JET has agreed to comply with the safety regulations of the host organisation with special reference to radiological safety standards. There is a continuing consultation between JET and Culham Laboratory on all safety matters, through the Joint Safety Service and the JET-UKAEA Liaison Committee set up under the support agreement.

Safety in 1986

The major potential hazards continued to be primarily electrical due to the high-voltage, high-current pulses used to produce strong magnetic fields. During the year, the personnel safety and access control system of interlocks controlled access to the torus hall and basement. The turnstile access became fully operational during 1986 and was extended to cover access to the vacuum vessel during the 1986/87 shutdown. The whole access control system was subjected to a safety and reliability assessment.

The low level activation of the vacuum vessel detected at the start of the 1986/87 winter shut-down resulted in it being classified as a radioactivity controlled area in pursuance of the Ionising Radiations Regulations 1985. Access to the torus was made via the torus access cabin and all persons entering the vessel were subject to radiation control and dosimetry procedures. All members of staff and contractors who work inside the vessel are classified radiation workers and are closely monitored. The neutron yield from the plasmas was in line with that forecast for this stage of the operation. Some short-lived radioactivity (half life approximately 2½ hours) was detected at the end of each day of deuterium plasma operations. These results all enhance confidence in the calculation of future radiation levels and in the adequacy of the protection measures envisaged. No radiological hazard due to JET machine operations existed outside the shielded torus hall and basement at any time during the year. In late December, an incident occurred involving two contractors who became unconscious whilst working in a confined space due to oxygen deficiency. The incident was reported to the Health and Safety Executive and a Board of Enquiry was held. Further assessments of the problems associated with beryllium limiters in JET were made during the year.

The Tritium Safety Assessment Panel, set up under the chairmanship of the head of the Joint Safety Services, continued its review of the safety of the design of the tritium plant, the proposed system of operations with tritium and the means of disposing of radioactive waste. It also ensures that all statutory requirements for holding and discharging radioactive materials are met as the need for them arises.

Public Relations

During 1986, public, scientific and media interest in the JET Project has remained high. Almost 4000 visitors were shown around the facilities, mainly in groups organised by local societies, professional institutions and both British and European schools and colleges. Delegates to various conferences also included a visit to JET in their programme. These included delegates from the International Physics Olympiad, the London International Youth Science Fortnight, the Inaugural Meeting of the UK Pulsed Power Club, the 23rd Culham Laboratory Plasma Physics Summer School and the IAEA Technical Committee Meeting on Fusion Reactor Safety, which was held at Culham in November.

The most prestigious visitor during the year was the President of the Italian Republic, His Excellency Signor Francesco Cossiga, who made a private visit to JET in November, see Fig. 36. Among the more notable visitors to the Project during the year were Mr C J Audland, CEC Director General for the Energy (DGX II), Members of the Committee on Science and Technology of the Parliamentary Assembly of the Council of Europe, Members of the European Democratic Group of the European Parliament, the Italian Ambassador to the UK, Signor Bruno Bottai, and a delegation of Japanese MPs and Embassy staff. September was an extremely busy month with visitors including Rapporteurs to the European Parliament's Committee on Energy, Research and Technology, a delegation of European Energy Ministers, Members of the Research Group of COREPER and the CEC Budget Committee. Representatives from the Diplomatic Science Club of the London Embassies visited JET in October.

In collaboration with the JET Information Network, two 'Journalists' Days' have been held during the year, when representatives from JET member countries were able to view the latest developments at first hand. There has been also a steady stream of British and European Journalists visiting the Project, as well as those from the USA and Japan. In addition, several interviews have been recorded for local and national radio programmes and a television crew from New Zealand spent three days filming at JET in July.

Nineteen eighty-six has also seen an increase in the demand for display material and JET has participated in a number of exhibitions, held by institutions ranging from the European School at Culham and the Royal Society to the CEC, whose London Office organised a mobile exhibit which toured Britain.

Fig. 36 His Excellency Signor Francesco Cossiga, President of the Italian Republic, meeting Italian members of the JET Project.

Appendix I
The JET Council

Member	Representative
The European Atomic Energy Community (EURATOM)	*P. Fasella* (Vice-chairman) *D. Palumbo* (to July)*
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*
The Commissariat à l'Énergie Atomique (CEA), France	*J. Horowitz* (Chairman) *F. Prevot*
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*
The Grand Duchy of Luxembourg (Luxembourg)	*J. Hoffmann* *P. Gramegna*
Ireland	*N. V. Nowlan* *D. Byrne*
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*
The Swedish Energy Research Commission (SERC)	*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*
The United Kingdom Atomic Energy Authority (UKAEA)	*F. Chadwick* *R. S. Pease*

Observers since May:

The Centro de Investigaciones Energeticas Medioambientales y Tecnalogicas (CIEMAT), Spain	*J. L. Alvarez-Rivas* *G. Madrid-Gonzalez*
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	*J. T. Mendonça*

**C. Maisonnier was the second representative for the Commission at the JET Council Meeting held on 23-24 October 1986.*

Appendix II

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 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 The Consiglio Nazionale delle Ricerche (CNR), Italy	*R. Andreani* *M. Samuelli*
The Hellenic Republic (Greece)	*A. Theofilou*
The Forskningscenter Risø (Risø), Denmark	*O. Gunneskov (to December)* *V. O. Jensen*
The Grand Duchy of Luxembourg (Luxembourg)	*R. Becker*
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)	*E. Hellstrand*
The Swiss Confederation	*A. Heym* *P. Zinsli*
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	*C. Westland (January – November)* *H. Roelofs (from December)* *L. T. M. Ornstein*
The United Kingdom Atomic Energy Authority (UKAEA)	*D. M. Levey* *W. M. Lomer*

Observers since May:

The Centro de Investigaciones Energeticas Medioambientales y Tecnalogicas (CIEMAT), Spain	*F. Manero*
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	*Mrs M. E. Manso*

Appendix III

JET Scientific Council

Members appointed by the JET Council:

F Troyon (Chairman)
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Centre de Recherches en Physique des Plasmas
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K Lackner (from March 1986)
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Federal Republic of Germany

A Messiaen
EURATOM-EB Association
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D Palumbo (from June 1986)
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D C Robinson (Secretary)
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Great Britain

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