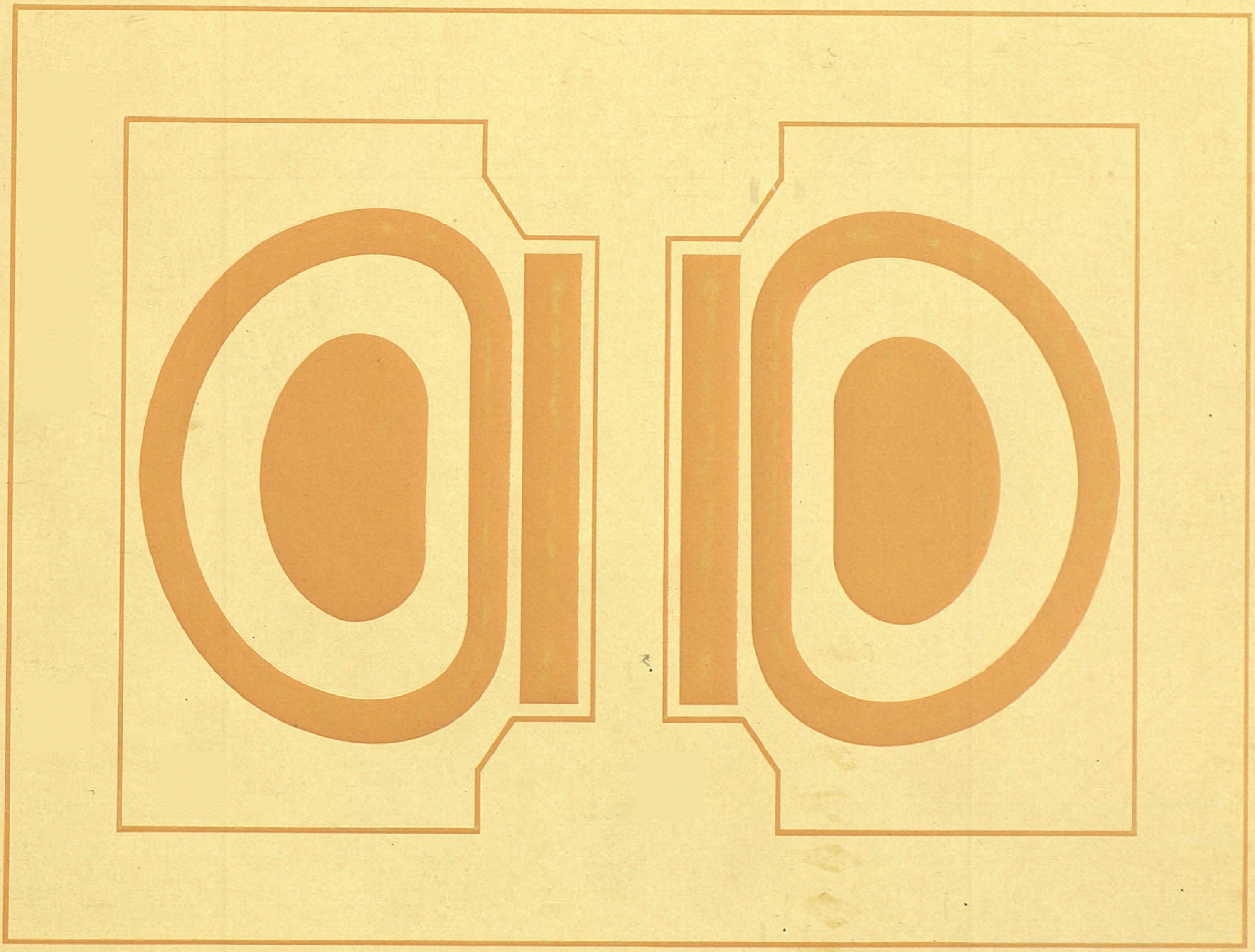
JOINT EUROPEAN TORUS JET

JET JOINT UNDERTAKING

ANNUAL REPORT 1988



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Preface

1988, in which JET completed the first half of its experimental programme (mid 1983 – 1988), was a particularly successful year for the Project in terms of scientific results and technical performance. This is an impressive achievement in view of the complexity and wide range of advanced technologies involved in JET. It is also a tribute to the skills and dedication of everyone involved in the Project.

During the year all the machine design parameters were met and in several cases exceeded. Most notable of these is the plasma current – a major factor influencing the performance of a tokamak – which reached a record value of 7 MA. This is more than twice the current in any other fusion experiment and is 45% higher than its design value. The additional heating systems have also performed particularly well. The neutral beam injection system is now operating at the full power level of 21 MW; in combination with the radio-frequency heating system 35 MW of power has been delivered into JET plasmas.

On the scientific side, plasma temperatures (T), plasma densities (n) and energy confinement times (τ) have now individually reached the values required in a reactor, although not simultaneously. Record ion temperatures over 200 million degrees Celsius have been obtained with full-power neutral injection heating, but more important from a reactor point of view was that both ion and electron temperatures of over 100 million degrees have been obtained simultaneously. Thus JET produces thermonuclear grade plasmas. The energy confinement times well over the required one second, are considerably longer than obtained in any other fusion experiment. High densities in the centre of the plasma have been obtained using the pellet injector operated as a joint US DoE / JET collaborative project.

A record value of the triple fusion product $(n_i.\tau_E.T_i)$ of $2.5\times10^{20}\,m^{-3}\,s\,keV$ was achieved during 1988. This provides a measure of the significant progress towards the parameters needed for a fusion reactor, which would require a product of $5\times10^{21}\,m^{-3}\,s\,keV$. If this product could be further increased in JET by a factor of four, then 'breakeven' conditions would be achieved. Nevertheless, the results obtained so far in JET enable the principal parameters of a Next Step device to be defined with confidence.

Sufficient knowledge exists from JET and other devices of the European Programme to design such a Next Step device, but experiments have shown that there are still a number of plasma engineering problems that remain to be solved. These relate mainly to density control and interaction of the plasma with the vessel walls – e.g. control of impurities, fuelling and exhaust – some elements of which will be studied by JET in the second half of its current programme (1989 – end 1992) and by other tokamaks. However, these problems have thrown into focus the importance of establishing reliable methods of impurity control before proceeding to the Next Step.

JET is particularly well placed to address these issues and the JET Council is currently discussing a proposal to add a new phase to the JET Programme. There is a strong case, in terms of the most effective operation of JET and of improved confidence in the design of the Next Step, for thoroughly tackling on JET the impurity problem before introducing tritium and thus effectively concluding the experimental life of the Project.

I am also pleased to record that as part of the current programme plans for operating JET with beryllium plasma facing components in the torus (which should assist in reducing impurities) are well advanced and preparations for tritium operation are also underway. The building to process tritium is nearing completion and impressive remote handling equipment for the active phase has been developed.

During the year, Dr Roy Bickerton, Deputy Director of JET retired. He has been deeply involved with JET from its beginning. His wisdom and wide experience will be greatly missed. This has resulted in some restructuring in the Project with the appointments of Dr Martin Keilhacker as the new Deputy Director and two new Associate Directors, Dr Alan Gibson, Head of the Plasma Heating and Operations Department, and Dr Michel Huguet, Head of Machine and Development Department.

The continued success of JET results from good teamwork at all levels and its complete integration in the European Fusion Programme. This includes the continuing support and cooperation that JET receives from the Commission and the Associated Laboratories. In addition, I wish to express my appreciation to my colleagues on the JET Council and to the members of the JET Executive Committee and the JET Scientific Committee for their continuing contribution.

The Appendices in this Report give the full membership of these committees and show that several members have retired during the year. I would like to record my sincere thanks to them all. A crucial element in the success of JET is the commitment and dedication of the JET staff under the inspired leadership of their Director, Paul-Henri Rebut. Their efforts have earned JET the international reputation it enjoys and this gives confidence that JET will continue to be the leader in world fusion research for the foreseeable future.

Klaus Pinkau

K. Pinkau
Chairman of the JET Council

July 1989

Introduction, Summary and Background

Introduction

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

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

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

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

A more detailed and comprehensive description of the technical and scientific aspects of the JET Project over the period covered by this report can be found in the 1988 JET Progress Report.

Report Summary

The Report is essentially divided into two parts:

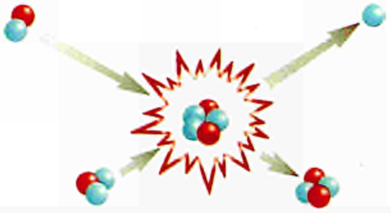
- The scientific and technical programme of the Project;
- The administration and organization of the Project.

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

The next section reports on the technical status of the machine including: technical changes and achievements during 1988; details of the operational organisation of experiments and pulse statistics; and progress on enhancements in machine systems for future operation. This is followed by the results of JET operations in 1988 under various operating conditions including 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 reactor conditions. In particular, the comparative performance between JET and other tokamaks, in terms of fusion product obtained, shows the substantial achievements made by JET since the start of operations in 1983. This section concludes with a discussion of future scientific prospects.

Nuclear Fusion

Energy is released when the nuclei of light elements fuse or join together to form heavier ones. The easiest reaction to achieve is that between the two heavy isotopes of hydrogen-deuterium and tritium.



Most of the energy released in this reaction is carried away by a high speed neutron. The remaining energy goes to the alpha particle (helium nucleus, ^{4}He) which is also produced in the reaction. In a fusion reactor, a jacket or blanket around the reactor region would stop the neutrons, converting their energy into heat. This could be extracted to raise steam for conventional electricity generation.

The first part of this Report concludes with a description of the proposed future programme of JET until the end of 1992. The second part of the Report explains the organisation and management of the Project and describes the administration of JET. In particular, this part sets out the budget situation; contractual arrangements during 1988; and details of the staff complement.

Background

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

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

The Council of Ministers in July 1988 adopted a new multi-annual European fusion programme for the period January 1988 to March 1992 and agreed the prolongation of the JET Joint Undertaking to 31st December 1992.

It was decided that the device would be built on a site adjacent to the Culham Laboratory, the nuclear fusion research laboratory of the United Kingdom Atomic

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

Energy Authority (UKAEA), and that the UKAEA would act as Host Organisation to the Project. Fig. 1 shows the site of the JET Joint Undertaking at Culham near Oxford in the U.K.

The Members of the JET Joint Undertaking are Euratom, its Associated Partners in the framework of the Fusion Programme including Sweden (NFR) and Switzerland, together with Greece, Ireland, Luxembourg and Portugal (JNICT), who have no Contracts 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 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

Fuels

As deuterium is a common and readily separated component of water, there is a virtually inexhaustible supply in the oceans of the world. In contrast, tritium does not occur naturally in any significant quantities 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.

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

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

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

$^7Li + n \rightarrow T + {}^4He + n$

There are sufficient reserves of lithium available to enable world electricity generation to be maintained at present levels, using fusion reactors, for several hundreds of years.

Conditions for Fusion

Fusion reactions can only take place if the nuclei are brought close to one another. But all nuclei carry a positive charge and therefore repel each other. By heating the gaseous fuels to very high temperatures, enough energy can be given to the nuclei for the repulsive force to be overcome sufficiently for them to fuse together. In the case of the deuterium-tritium reaction, temperatures in excess of 100 million degrees kelvin are required—several times hotter than the centre of the sun. Below 100 million degrees the deuterium-tritium reaction rate falls off very rapidly: to one-tenth at 50 million degrees, and 20,000 times lower at 10 million degrees.

A reactor must obtain more energy from the fusion reactions than it puts in to heat the fuels and run the system. Reactor power output depends on the square of the number (n_i) *of nuclei per unit volume (density) 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 their surroundings. The effectiveness of this isolation can be measured by the energy confinement time (τ_E)*—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* 5×10^{21} m^{-3} s keV. *Typical values for the parameters that must be attained simultaneously for a reactor are:*

Central ion temperature, T_i	10-20 keV
Central ion density, n_i	2.5×10^{20} m^{-3}
Energy confinement time, τ_E	1-2 s

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

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 (DG XII).

Objectives of JET

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

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

The principal objective of JET is to enable the essential requirements of a tokamak reactor to be defined. To do this, a plasma approaching reactor conditions must be created and studied.

There are 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.

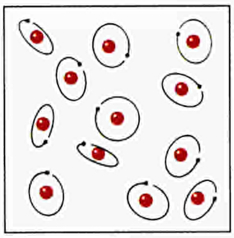
In addition, JET is pioneering two of the key technologies that will be required in subsequent fusion reactors. These are the use of tritium and the application of remote maintenance and repair techniques.

Plasma

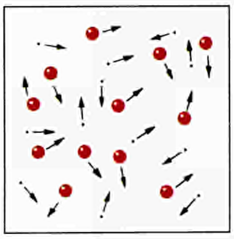
As the temperature of the fuel is increased, the atoms in the gas become ionised, losing their electrons, which normally orbit around the nuclei. The mixture of positively charged ions and negatively charged electrons is very different from a normal gas and is given a special name—PLASMA.

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 obtain net energy gain.

The configuration that has so far advanced furthest towards achieving reactor conditions and on which most data is available is the TOKAMAK, originally developed in the USSR.

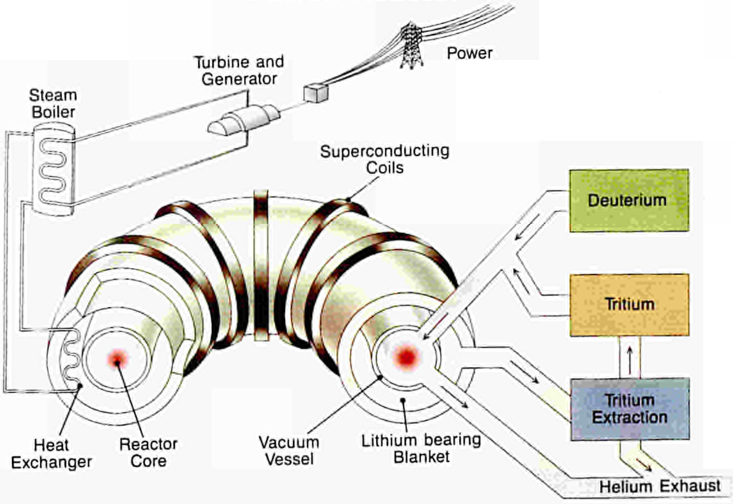


Gas



Plasma

Fusion Reactor



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

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

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

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

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

JET, Euratom and other Fusion Programmes

The Joint European Torus

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

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

The use of transformer action for producing the large plasma current means

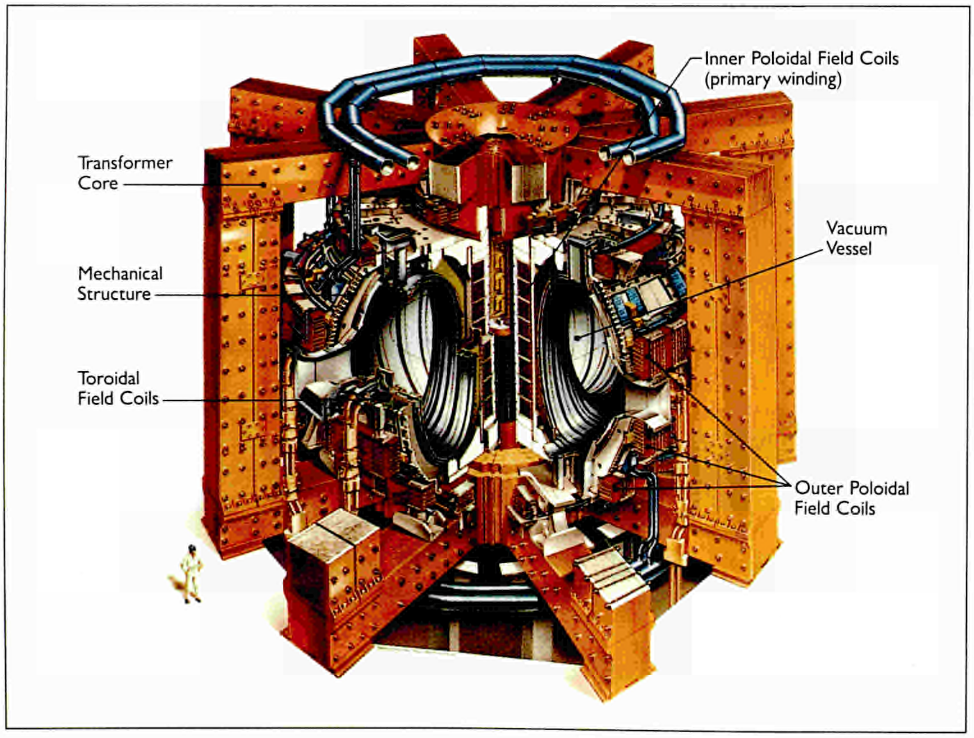


Fig. 2 Diagram of the JET apparatus

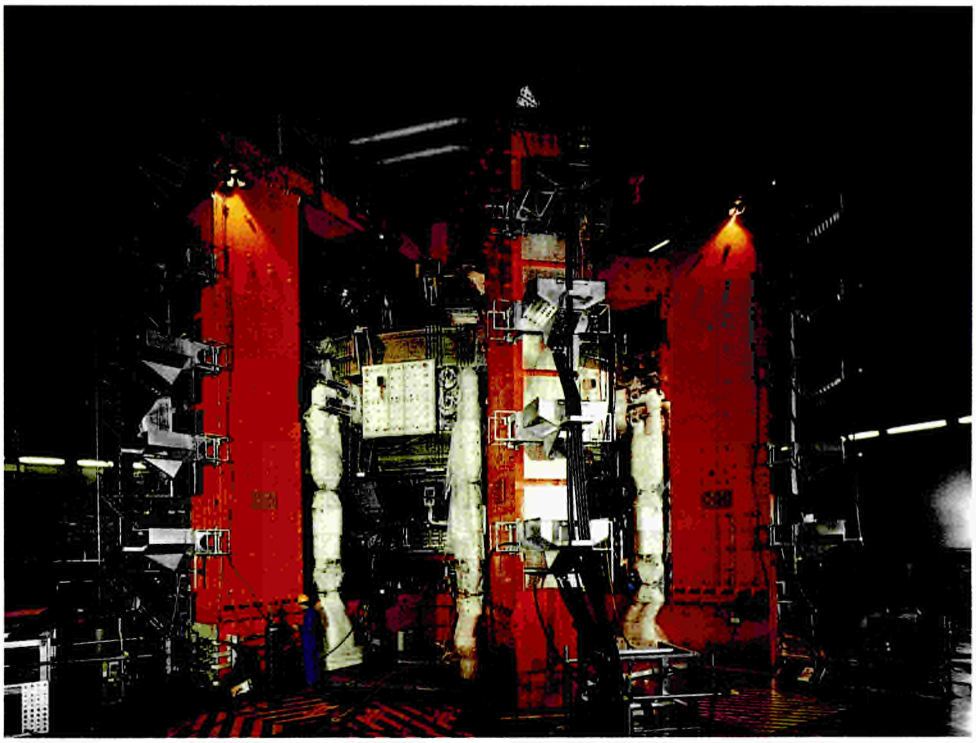


Fig.3 The JET experimental apparatus photographed in May 1983

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

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

TABLE 1: ORIGINAL DESIGN PARAMETERS OF JET

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

The first plasma pulse was achieved on 25 June 1983 with a plasma current of 17000A lasting for about one tenth of a second. The JET Tokamak is shown in Fig. 3 just prior to the start of operation in June 1983. This first phase of operation was carried out using only the large plasma current to heat the gas. In 1985, the first additional heating system, employing radio-frequency heating, came into operation and during 1986 reached 12MW of output power from the generators. The neutral beam heating system was brought into operation in 1986, and exceeded its design capability in 1988, with 21.6MW of power injected into the torus.

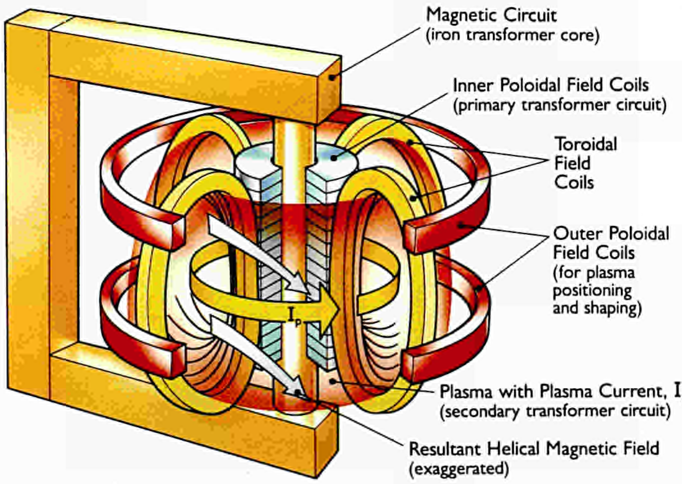
So far, experiments have been carried out using hydrogen or deuterium plasmas. In the final stage of the programme it is planned to operate with deuterium-tritium plasmas so that abundant fusion reactions occur. The alpha particles liberated from the reactions should then produce significant heating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

The Community Fusion Research Programme

All fusion research in Europe is integrated into a single Community Programme. Successive programme decisions by the Council of Ministers have described the Community Fusion Programme as "a long-term co-operative project embracing all the work carried out in the Member States in the field of controlled thermonuclear fusion". It is designed to lead in due course to the joint construction of prototype reactors with a view to their industrial production and marketing.

The Commission of the European Communities is responsible for the implementation of the Community programme. It is assisted in this task by the Consultative Committee for the Fusion Programme (CCFP), composed of national representatives. The programme is executed through Contracts of

The Tokamak



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

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.

Association between the Community and organisations within the Member States that are active in the field, through the JET Joint Undertaking, the NET Team (Next European Torus), and through the Community's Joint Research Centre (JRC).

This Community approach has led to an extensive collaboration between the fusion laboratories. For example, most of the Associations undertake work for other Associations. The Associations are partners in JET and NET and work for them through various types of contracts and agreements. The Community Fusion Programme has built across Europe a genuine scientific and technical community of large and small laboratories, readily able to welcome newcomers, and directed towards a common goal. Indeed, two non-Member States, Sweden and Switzerland, are now fully associated with Programme and enjoy the same rights and responsibilities as Member States.

The path towards a commercial fusion reactor can be divided, albeit somewhat arbitrarily, into three stages: first, the demonstration of scientific feasibility; then, of technological feasibility; and finally, of commercial feasibility. These stages are, however, far from being independent of each other and certainly overlap in time.

At present, with JET and the medium-sized devices in the Associated Laboratories, the Community Fusion Programme is primarily in the scientific stage. The Next Step, NET at the European level and ITER at the world level, is conceived as a Tokamak device that should fully confirm the scientific feasibility of fusion in a first phase and confront its technological feasibility in a second.

Within this three-stage strategy, the main objectives of the current Fusion Programme, which has been decided by the Council of Ministers for the period up to March 1992, are the following:

1. To establish the physics and technology basis necessary for the detailed engineering design of the Next Step. In the field of physics and plasma engineering, this implies the full exploitation of JET and of the medium-sized Tokamaks in the Associated Laboratories, and, in the field of technology, the strengthening of the current fusion technology programme;

2. To embark on the detailed engineering design of the Next Step before the end of the programme period, if the necessary data base exists at the time (though not before the next programme revision foreseen for January 1991);
3. To explore the reactor potential of some alternative lines (principally the Stellarator and the Reversed Field Pinch).

The scientific and technical achievements of the Community Fusion Programme place Europe in the forefront of world fusion research. JET, which is the leading fusion experiment in the world, has made substantial progress towards the demonstration of the scientific feasibility of fusion. A substantial contribution towards this sucess has been due to research carried out in the Associated Laboratories such as the discovery of the H-mode on ASDEX (IPP Garching, FRG) and developments in plasma heating systems (UKAEA Culham Laboratory and CEA France).

Currently, expenditure on fusion research through the Community budget is running at the rate of about 200 Mio ECU a year. When funding by national administrations and other national bodies is taken into account, the expenditure on fusion from all sources in Europe is estimated to total about 450 Mio ECU a year. There are over 1500 professional scientists and engineers currently engaged in fusion research in Europe.

This leading position of the Community Fusion Programme has made Europe an attractive partner for international collaboration. For example, bilateral framework agreements have now been concluded with Japan, USA and Canada. There are also eight specific agreements in the frame of the International Energy Agency, including the co-operation among the three large Tokamak facilities (JET in Europe, JT-60 in Japan and TFTR in the USA). However, the most far-reaching development in international collaboration has been in connection with ITER (International Thermonuclear Experimental Reactor). Following initiatives taken at the highest political level, the four parties (the European Community, Japan, USSR and USA) agreed in early 1988 to participate on an equal quadripartite basis in the joint development of a conceptual design for an engineering test reactor of the Tokamak type. The ITER conceptual design activities are to be concluded by the end of 1990. The single conceptual design thus developed would then be available to each of the Parties to use either in their own national programmes or as part of a larger international collaborative venture.

Large International Tokamaks

Various large tokamaks are now operating worldwide. Those machines with plasma currents in excess of 1 MA are: TFTR, at Princeton University, USA, which started in December 1982; JET followed in June 1983; JT-60 in Japan produced its first plasma in April 1985; and DIII-D at San Diego, USA, which first operated in February 1986.

The parameters of large tokamaks currently operating are summarised in Table 2. These machines do not only vary in their dimensions, currents and magnetic fields, but also in the way they are heated and in their magnetic field configuration. Ion Cyclotron Resonance Frequency (ICRF) and Neutral Beam (NB) heating are now commonly applied at powers exceeding 10 MW. Electron Cyclotron Resonance Heating (ECRH) of several MW has been applied in some devices. Non-inductive current drive by means of various heating

TABLE 2: LARGE TOKAMAKS AROUND THE WORLD

Machine	Country	Minor radius a (m)	Elongation K	Major radius R (m)	Plasma current I (MA)	Toroidal magnetic field B (T)	Input power P (MW)	Start Date
JET	EEC	1.20	1.7	2.96	7.0	3.45	35	June 1983
TFTR	USA	0.85	1.0	2.50	2.5	5.2	30	Dec 1982
JT-60	Japan	0.90	1.0	3.0	3.2	4.8	30	April 1985
T-15	USSR	0.70	1.0	2.4	2.0	4.0	–	Dec 1988
TORE-SUPRA	France	0.70	1.0	2.4	1.7	4.5	23	April 1988
DIII-D	USA	0.67	2.0	1.67	3.5	2.2	16	Feb 1986

TABLE 3: PLASMA PARAMETERS IN VARIOUS MACHINES

	Parameter	JET (H-mode)	TFTR (Hot-ion mode)	DIII-D (H-mode)
Electron temperature	T_e (keV)*	6.0	8.0	2.0
Ion temperature	T_i (keV)*	6.0	28.0	3.7
Central ion density	$n_i(0)$ ($\times 10^{19} m^{-3}$)	6.0	6.3	4.0
Energy confinement time	τ_E (s)	0.7	0.14	0.18
Neutral beam power	P_{NB} (MW)	15	30	8
Fusion product	$n_i.\tau_E.T_i$ ($\times 10^{20} m^{-3}$skeV)	2.5	2.5	0.25

* 1 keV is approximately equal to 12 million degrees K.

methods including Lower-Hybrid Current Drive (LHCD) has been achieved. LHCD is under construction for JET to complement the ICRF and NB systems already installed.

JET, JT-60 and DIII-D are all capable of producing magnetic field configurations that have open magnetic surfaces within the vacuum vessel near the edge of the plasma. The plasma is then defined by a magnetic limiter and not by a material surface in contact with the confined plasma. The magnetic limiter configuration not only leads to higher plasma edge temperatures and improved confinement, but also permits better particle and impurity control.

Two tokamaks, JET and TFTR, differ from the main family of large tokamaks, in that these are designed for deuterium-tritium operation to study alpha-particle heating on a sufficiently large scale. Indeed, these two machines have reached the highest fusion product ($n_i.\tau_E.T_i$), so far achieved in fusion devices. In particular, if tritium were introduced into these machines under these conditions, an equivalent calculated fusion factor Q close to 0.3 would be attained. (Q is the ratio of fusion power produced to the total input power to the plasma).

Table 3 shows the highest parameters obtained in JET during an H-mode, in TFTR during a hot-ion mode, and in DIII-D during an H-mode. These show fusion product ($n_i.\tau_E.T_i$) values up to $2.5 \times 10^{20} m^{-3}$ s keV.

High plasma currents are required for a fusion reactor to confine the plasma

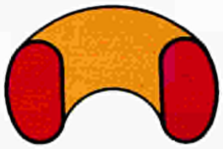
		TFTR	JET	NET
				
Minor Radius	a	0.85 m	1.25 m	2.0 m
Major Radius	R	2.48 m	2.96 m	6.3 m
Elongation	K	1.0	1.7	2.2
Toroidal Field	B	5.0 T	3.45 T	6 T
Input Power	P	30 MW	40 MW	85 MW
Fusion Factor	Q	0.3	0.3	>100

Fig. 4 Operating parameters of three large tokamak designs.

and its energetic alpha-particles. Typical values lie between 20 and 30 MA. From this point of view JET is the machine closest to reactor conditions. Fig. 4 shows TFTR and JET, the two machines closest to break-even ($Q = 1$), together with a possible next-step device and their main parameters.

Both JET and TFTR have reached high fusion factors with prospects of reaching even higher values with Q close to unity (breakeven conditions). High confinement modes (H-mode) of operation have been found at higher plasma currents (up to 5 MA) with confinement times well in excess of 1 second in the magnetic separatrix or X-point configuration in JET. In other high power discharges, as in TFTR, extremely high deuterium temperatures exceeding 20 keV have been reached. In both types of discharges in JET, fusion products ($n_i.\tau_E.T_i$) in the range 2.0-2.5$\times 10^{20}$ m^{-3} s keV have been reached (compared with the value of 5$\times 10^{21}$ m^{-3} s keV needed in a reactor).

JET's programme is tuned to providing a proof of scientific feasibility of fusion and will be providing input to the Next Step studies. JET's immediate directions are to improve impurity and density control and to investigate improvements in confinement and fusion products in various material and magnetic limiter configurations at high additional powers and increased plasma currents.

Technical Status of JET

Introduction

IN this chapter, the present technical status of JET is described under three headings, as follows:

- **The first section outlines details of technical achievements made during the main operating period in the first nine months of 1988 and the developments and improvements started during the shutdown at the end of 1988;**
- **Machine operations during this operating period are summarized in the second section;**
- **The final section sets out the main details of continuing technical developments on equipment for future installation.**

Technical Achievements

There was no major shutdown during the early part of 1988 and therefore the machine and associated systems were operated with basically the same configuration as that already achieved in 1987. The key objective during this period (January-September) was to extend the JET operating regime to plasma currents approaching 7MA in material limiter configurations and to 5MA in magnetic limiter (X-point) configurations both at the highest plasma heating powers available. The success of the major modifications and enhancements introduced during 1987 was amply demonstrated during 1988 operation. The most significant technical achievements of 1988 are summarized in Table 5.

These successes have been most encouraging but operations of the machine above the original design rated values are carried out with great care and a number of technical restrictions have been imposed so that it is operated within conservative limits. These limitations are being studied and tests or design modifications planned so that progress can be maintained during 1989.

From October 1988, the machine entered a further planned shutdown. The two main tasks during the shutdown were to reinforce the vacuum vessel and to inspect and, if required, to repair the inner poloidal field coil. A decision was taken on the vessel reinforcement early in 1988 as an outcome of the so-called '7MA Study'. This study investigated the feasibility of longer pulse operation at 7MA and of setting up X-point configurations approaching 7MA. The reinforcements consisted of welding inside the vessel, at the inboard wall, inconel rings to stiffen and strengthen the vessel against disruption forces. By the end of 1988, the welding work was close to completion.

The ohmic heating coil inspection was made necessary because of the excessive rotational displacements observed on the individual subcoils making up the coil stack. The inspection revealed only minor damage. This damage was repaired and other modifications implemented to avoid the reoccurrence of the phenomenon.

Modifications to the Poloidal Field Coil System

During 1987, major modifications were made to the central poloidal field coil system to permit higher plasma currents with material limiters and in the X-point mode of operation. Two subcoils had been added, to bring the total to 10, so that stray magnetic fields were reduced and the breakdown of the gas and plasma start-up were improved. Additional bus-bars were also connected to the six centre subcoils so that these could be controlled separately from those at the ends. The modifications permitted a greater flux swing capability and allowed improved flexibility in controlling the plasma shape. As a consequence, plasma currents of 7 MA for 2 s flat-top were reached in the material limiter situation and exceeded 5 MA in the single-null magnetic limiter configuration.

This modified coil connection system also allowed the scheme whereby the poloidal vertical field power supply could be connected to produce a current imbalance between the top and bottom vertical field coils. This should permit even higher current values in the X-point configuration while reducing shear stress on the toroidal magnetic field coils. This arrangement has been set up and will be tested in the 1989 operations period.

In addition, an improved poloidal vertical field booster amplifier has been developed and introduced (see Fig.5), which should greatly assist plasma breakdown and initial rise of plasma currents. This should enhance the flat-top period at the highest currents for 1989 operation.

At the end of 1988, the inner poloidal field coils were removed from the centre of the machine for inspection, as external measurement indicated unexpected rotations. On inspection, the main part of the coil was found to be undamaged, but the keys connecting the coil stack to the upper and lower structure were tangentially displaced and, the steel support rings had rotated relative to the coils. Improvements were made, so that stronger keys were fitted at top and bottom of the stack; the support rings were keyed to the coils to prevent rotation; stiffer inter-coil springs were inserted; and low friction material was fitted between the coils to allow easier relative motion under the action of the springs.

Fig.5 The vertical field booster amplifier system.

Plasma Position and Control

The plasma position and current control system has been further developed and adapted for new operating scenarios. The radial position and shape control was modified to include control of the current difference in the upper and lower sections of the poloidal coil. The difference current is controlled to be proportional to the shaping current reference value. Therefore, this facility can be

Power Supplies

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

An agreement with the Cental 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 reach deliver 2.6GJ of energy with a peak power output of 400MW.

regarded as an enhancement of the plasma shape control. It has allowed production of single X-point plasmas up to 5MA. A digital version of the radial position and shape control system has been specified and implemented by CODAS. It includes additional features such as decoupling between radial position and elongation control and will be more flexible than the presently used analogue system. Preliminary tests have been carried out, but commissioning is planned for 1989.

Operation with single X-point plasmas has shown that the stabilisation system can fail when large perturbations occur, such as those seen during disruptions and H-mode transitions. Part of the problem was due to signal saturation arising from large amplitude helical plasma modes. As a first measure of improvement, the stabilisation system was extended to use simultaneous magnetic signals from two opposite octants of the torus so that saturation due to helical plasma modes was avoided. Subsequently, single X-point operation became more reliable. However, large asymmetric perturbations can still provoke vertical instability. Several options for improvement are being considered. It is concluded that a significant enhancement of stability is possible by increasing the power and the response speed of the radial field amplifier and by using additional stabilising elements (saddle coils) inside the vessel.

The present stabilising system is also subject to failure in magnetic signal transmission and conditioning. A ‘dual system’ has been implemented which maintains feedback stabilisation in the event of a fault being detected in any one of the two signal conditioning branches of two opposite octants of the torus. The dual system is being implemented as a pilot scheme. Initial tests led to some modifications and further tests are required before the system can be used for active stabilisation.

Vacuum Systems

Since 1988 was a major year of operation for JET, this provided the opportunity to gain experience of the reliability of installed equipment. Experience gained with the vacuum equipment showed that the vacuum components (pumps, gauges, valves, flanges, etc.) performed satisfactorily, but interruptions in operation of the machine due to vacuum leaks at various locations were quite frequent. One reason was due to operation of the tokamak in excess of the design values (high plasma current, X-point operation, etc.), which in cases of plasma disruption put larger loads on the vessel and also on attached components. Some cracks were encountered in welds due to inertial forces on components. The problems were analysed and remedial action was taken during maintenance periods and during the shutdown to strengthen the weaker points.

Furthermore, the reliability of some components was improved by changing operation mode (e.g. the dosing valves, where fatigue failure on the bellows was observed, due to unnecessary application of power to the valves which initiated vibration in the bellows). It was found that the vessel supports needed improved locking devices which could be operated and released remotely without entering the Torus Hall. Therefore, a new thermal locking device for the supports was developed and will be installed during the 1988/89 shutdown.

In-vessel Components

With JET approaching full power operation, the in-vessel components were exposed to their most extreme loads yet. This included not only high power heat loadings but also high mechanical loadings during disruptions. Some weak points came to light and were remedied, but overall the in-vessel components achieved their expected performance and proved the chosen concept. The components requiring some remedial work were the bellows protection tiles, of which several were shaken loose, and of which three, each carrying three tiles, were dislodged. The attachment of these plates has been successfully modified with no further problems. Alterations were made to the X-point tiles on the top of the machine which were highly loaded during X-point operation. It was found necessary, in two minor shutdowns, to improve the alignment of the tiles in order to distribute the power more evenly.

The belt limiter, installed during the 1987 major shutdown, operated throughout the year with no significant damage to either the tiles or the structure. This was in spite of the fact that the belt limiter was run without water cooling for a major period of the time due to restrictions imposed by interconnected antennae. New tiles were designed and manufactured for the areas adjacent to gaps in the belt limiter located at both the top and bottom at Octants Nos.3 and 6. These gaps were included to a allow certain diagnostic systems unobstructed view of the plasma. The alterations were necessary because the gaps allowed a localized but unacceptable power deposition on adjacent antennae. The alterations involved a change in the shape and size of twenty tiles on each side of the gaps. The new geometry, resulting from careful analysis, was aimed at intercepting more field lines which otherwise pass through the gap, whilst ensuring that the power deposition per unit area onto the new tiles remained within the original limits and that the ability of the belt limiter system to accept plasmas of varying shapes remained unimpeded. Subsequent operation with the new tiles showed that these objectives had been achieved.

Containment of Forces Acting on the Vacuum Vessel

To reduce the deformation of the vessel during disruptions at high current, internal restraint rings were designed, procured and installed during 1988. An assessment of forces showed that during a typical disruption at 7 MA, additional radial loads of 20,000 kN and deflections of 15 to 20 mm at the inboard wall of the vessel should be expected. To remedy this, two inconel strengthening rings, above and below the mid-plane of the torus, were welded onto the inboard wall as shown

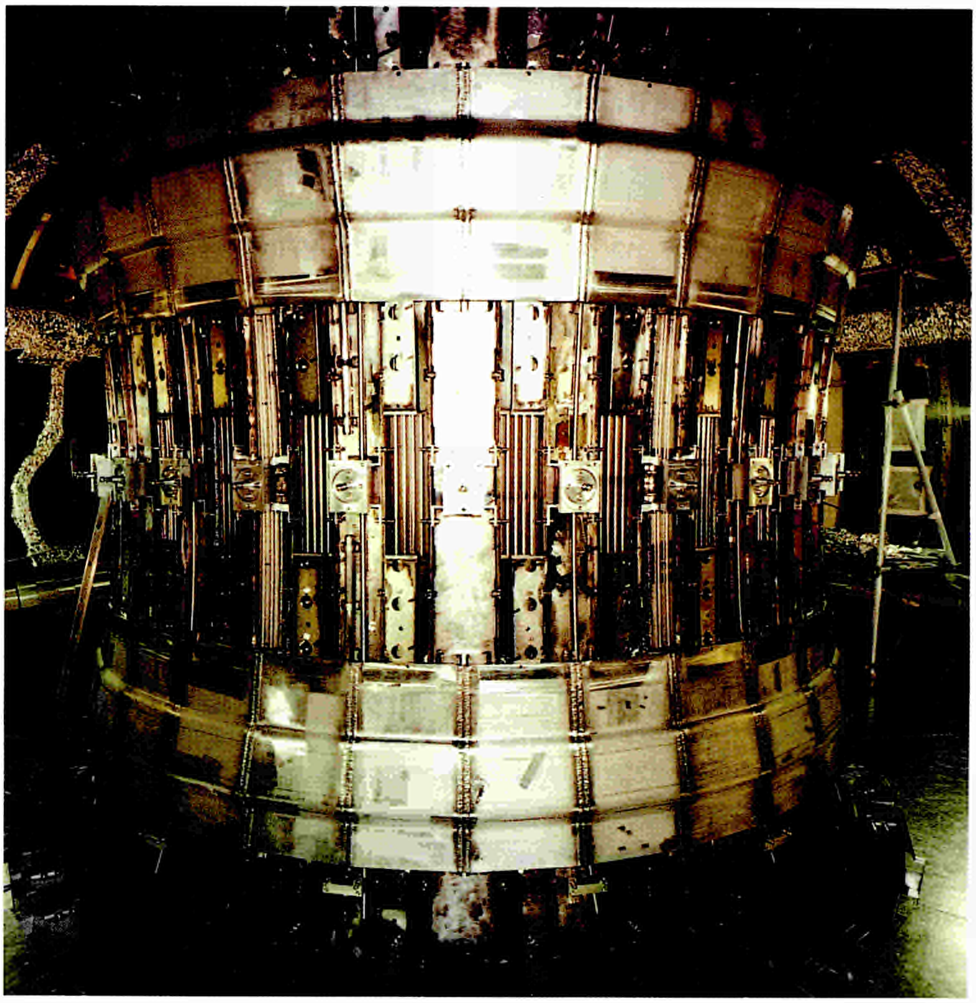


Fig.6 Reinforcement rings installed inside the vacuum vessel.

in Fig. 6. These should resist the local radial forces by their hoop strength and stiffness, and reduce the displacements of the vessel wall and ports down to less than 2mm. These should also eliminate the risk of overloading the existing ring reinforcements along the outside of the vessel, which at present carry all the radial loads by their hoop strength. The new rings on the inboard wall will carry approximately 30% of the radial load in a radial disruption.

Neutral Beam Heating

1988 proved to be a most successful year for neutral beam injection into JET. The two beamlines installed on JET were brought into full simultaneous operation at their maximum rated voltage of 80kV. This culminated in a maximum injected power of 21.6MW of deuterium atoms, which exceeded the design rating of 20MW (see Fig.7). Neutral beam heating made significant contributions to major scientific achievements in JET: hot-ion mode plasmas were obtained with ion temperatures up to 23keV; H-mode confinement in both single and double-null magnetic limiter configurations, with a maximum stored energy of 11MJ; combined heating (with RF power) in material limiter plasmas with 5MA and 6MA currents, achieved stored energies exceeding 9MJ. By the end of 1988, a high degree of availability and reliability was achieved.

To enable deeper penetration of the neutral beams into denser JET plasmas, the two beamlines will be converted from 80kV operation to work at 140kV

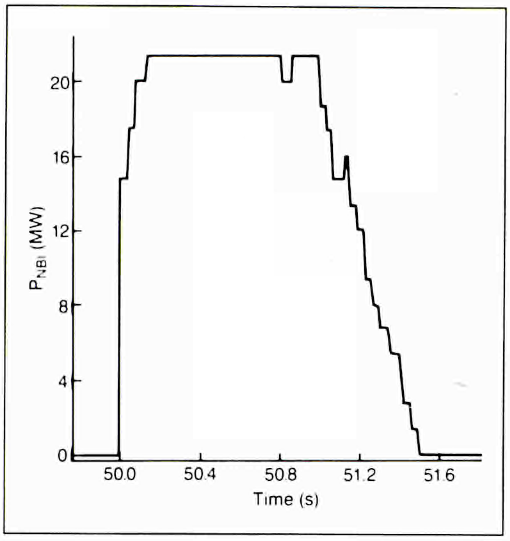


Fig.7 Injected power waveform showing 16 neutral beam sources operating at 80kV in deuterium to produce a record value of 21.6MW.

in deuterium; one will be reconfigured in 1989 and the second in 1990. During 1988, priority efforts were devoted to work on the Neutral Beam testbed to convert the beam sources to the higher voltage operation using two existing 80kV, 60A power supplies connected in series.

In addition, in the D-T phase of JET operation, one of the neutral beam lines will be converted to produce high energy tritium atoms at 160kV. This will provide tritium fuelling in the centre of the hot plasma, and control the isotopic fuel ratio. The existing beam sources, which deliver 30A at 140kV with deuterium, will deliver the same current in tritium at 160kV. Successful operation at 160kV has been demonstrated with beams of deuterium and helium. Due to its higher neutralization efficiency, the tritium injection produces 50% more neutral beam power than in deuterium. Consequently, a reassessment of the handling capabilities of various injector components has been undertaken, with the result that only the box scraper needed upgrading and this has been successfully achieved. An extensive and important area of work has been to establish the simulation of existing beam deflection magnets for tritium beams which require higher values of field than previously anticipated for deuterium beams at 140kV. Mapping of the magnetic field shows that suitable focusing can be achieved but extra cooling will be needed for the higher power dissipation in the magnetic coils.

Neutral Beam Heating

The two JET neutral beam systems have been designed for long (~ 10s) beam pulses. They have the unique feature that each injector consists of eight beam sources in a single integrated beamline system connected to the torus. The first beam sources have been designed to operate at accelerating voltages up to 80kV and for 1989/90 these will be substituted with units capable of operating up to 140kV. In the D-T phase, one unit will be converted for operation with tritium at 160kV.

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

Radio Frequency Heating

Ion Cyclotron Resonance Heating (ICRH) has been chosen for JET and the wide operating frequency band (23-57MHz) 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 ion cyclotron resonance frequency (ICRF) heating system is used for highly localized heating of the JET plasma. The wide frequency band (23 to 57 MHz) allows variation in the position of heating as well as the minority ion species which is resonant with the wave (H or ^{3}He at present, D in the future D-T phase). The heating system is composed of eight units, each driving an antenna installed between the belt limiters in the toroidal vessel. Each unit is made of two identical sub-units, sharing a common high voltage power supply and a common low power RF drive. The output stage of each sub-unit is being upgraded to 2 MW instead of the original 1.5 MW by replacing the high power tetrode and modifying the output circuit. During 1988, twelve sub-units (out of 16) were upgraded and successfully commissioned, and the rest will be completed in 1989. This progressive transformation has allowed good use to be made of the guaranteed life of the original power tetrodes and significant economies have been made in the operation budget. The original maximum design power of the system was 20 MW. Although, the system is not yet complete, in 1988 a maximum power of 18 MW was coupled to the plasma, and this should be raised to ~ 24 MW in 1989.

The ICRF power plant has operated regularly above 10 MW power level in a wide range of plasma conditions and frequencies. A particularly severe test of the plant performance was the rapid change of plasma edge conditions imposed by the various facets of the JET experimental programme. The antenna loading resistance could change from above 6Ω, in limiter configuration to less than 1Ω, in some X-point operations. In most cases, large variations of loading resistance during the pulse were produced by the crash of large sawteeth or by eigenmodes of the wave in the torus. New electronic devices and software packages were implemented to cope with these variations. An algorithm for software matching was developed. The parameters of the entire plan corresponding to a particular plasma condition can be stored in the computer and reset automatically for later use. A new electronic network automatically determines the frequency corresponding to the lower power reflected back to the generator. This system has been employed successfully during the year. In particular, the large load variation due to sawteeth could be compensated by a frequency variation automatically set by this system.

During 1988, the ICRF system reached a record power of 18 MW for 2 seconds and 6 MW for 20 seconds. Nevertheless, this value is slightly lower than the 20 MW which was expected. Certain difficulties prevented use of the plant to its full capability. The power upgrade pushed the auxiliary power supplies to their limits and their control circuits became more vulnerable. In particular, parasitic resonances due to sidebands generated by the new phase control system induced false alarms in several power supplies. These resonances were eliminated towards the end of the year and the amplifiers became technically capable of full power. The power was then limited by severe arcing near the end of the vacuum transmission line, where the RF voltage was highest. Some ceramic insulators were coated by a thick layer of sputtered metal and the two antennae halves could no longer be used during the last two weeks of 1988 operation. All antennae have been modified subsequently to reduce the electric field strength in the critical area. In addition, the generator tripping system was hardened to increase the reliability of arc detection, as the observed damage came from long arcs which had escaped detection.

The existing water-cooled nickel antennae screens can release nickel ions into the plasma during certain situations. Nickel radiation is normally negligible during material limiter operation but it is believed to be the main source of difficulty in obtaining good H-modes with ICRF heating in the magnetic limiter configuration. In addition, the existing screens have potential for creating the hazard of water leaks into the vessel. Consequently, a new set of screens made of beryllium elements has been designed, which should considerably reduce the impurity problems in the plasma. The new design avoids circulating water in the screen elements and eliminates the highly stressed welds between the elements and the water manifold (see Fig.8). The screen losses are much reduced due to the good electrical properties of beryllium and the heat can now be removed from the ends of the elements by the water flowing in a manifold forming a picture-frame for the screen. The beryllium elements have been fabricated and a proof assembly is under test. The eight beryllium screens will be installed in the machine in mid-1989.

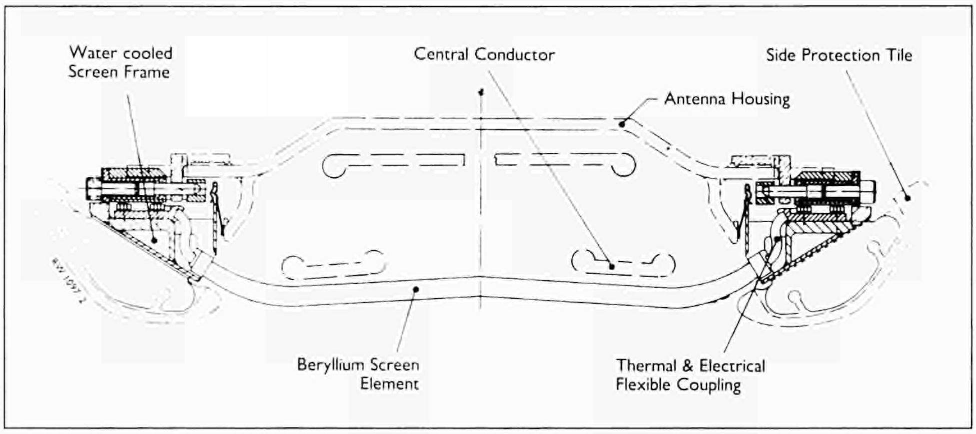


Fig.8 Cross section of the ICRF antenna equipped with the new beryllium screen.

Pellet Injection

Achievement and maintenance of a central plasma with sufficiently high density is an essential provision for a reactor. One method of raising the density, and replenishing it during operation, is to inject pellets of solid deuterium into the plasma at high speed so that these penetrate the outer layers and into the centre before completely evaporating. The clean plasmas resulting are comparatively resistant to disruption.

A multi-pellet injector has been built and is operated on JET under a collaborative bilateral agreement between JET and the US Department of Energy (USDoE) (see Fig.9). It has operated throughout 1988 and has performed satisfactorily in 88 experimental campaigns. Singly or bunched in sequences with repetition rates up to $5s^{-1}$, $\sim 1000 \times 2.7$mm and 250×4mm pellets were delivered into 337 plasma discharges. The major fraction of these experiments were performed within periods allocated to the 'Pellet Fuelling and Density Profile Effects' Task Force.

An enhanced confinement regime was found for central pellet deposition in conjunction with central ICRF heating of limiter discharges. There were also

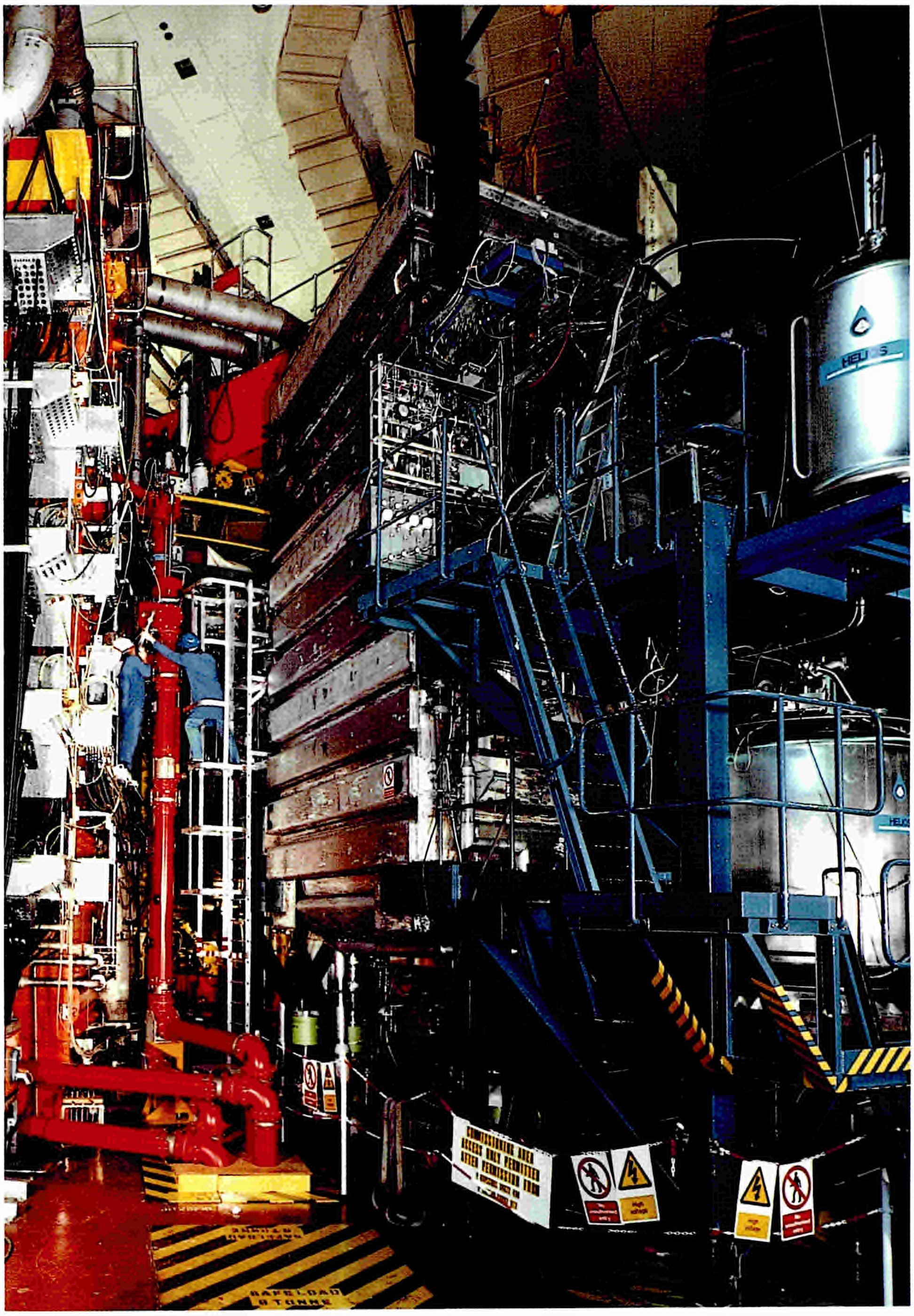


Fig.9 JET multi-pellet injector.

significant contributions to subjects of the other Task Forces, mainly preliminary experiments to probe other scenarios such as: injection into X-point and H-mode discharges; fuelling experiments, in which in one case 32×2.7mm pellets were injected at $4s^{-1}$; injection into neutral beam heating high-T_i shots starting at low density in which pellets were used in the density build-up and fuelled the shot with the highest neutron rate achieved so far. Further details are given in the section on the Results of JET Operations in 1988.

The flawless functioning of the injector and the participation of the US team in the complementary strength required by the Agreement contributed a great deal to this success. From March through to the end of the experimental period, the pellet injector worked particularly reliably with little maintenance, having

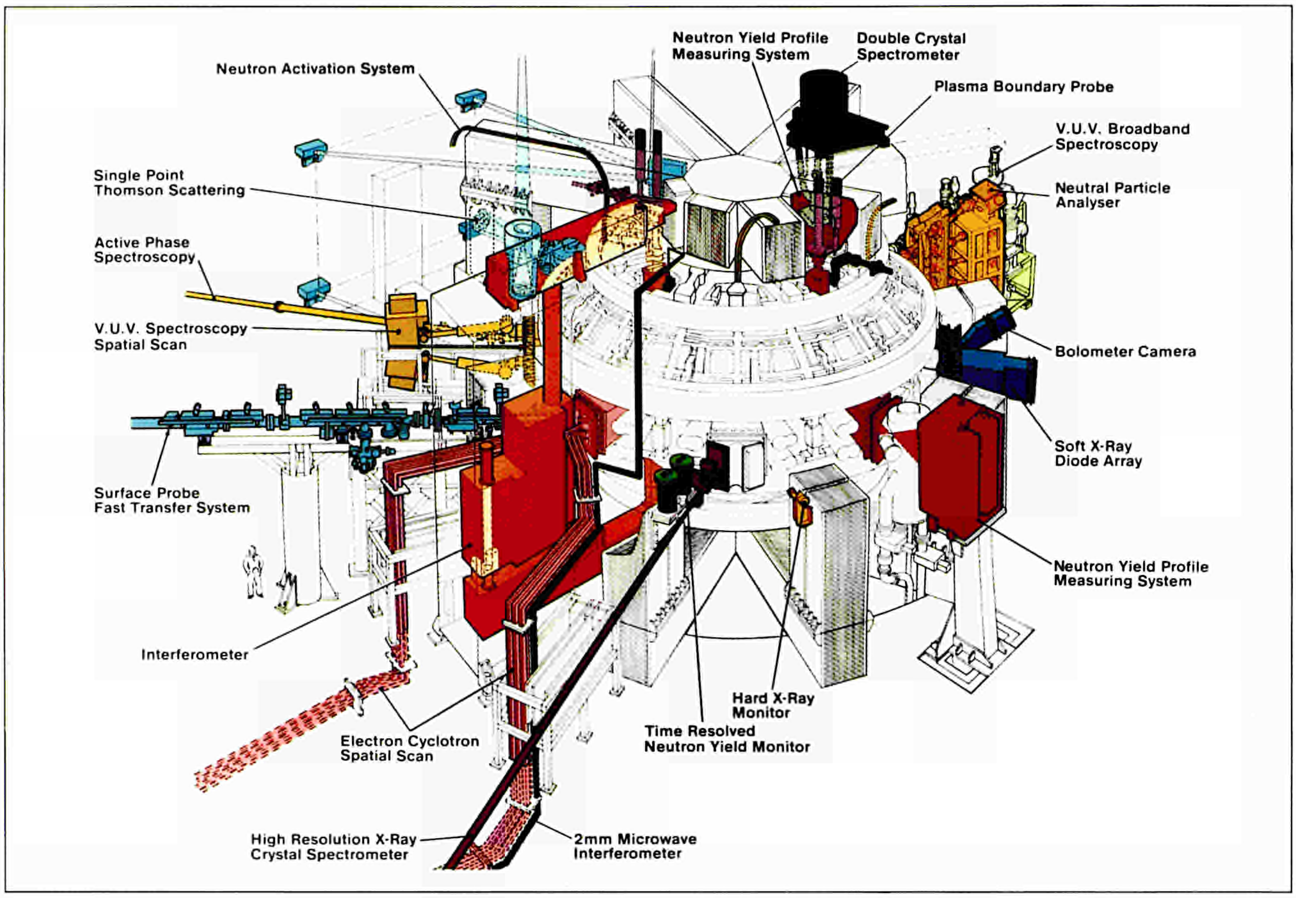


Fig.10 Location of JET diagnostic systems.

undergone a thorough overhaul and recommissioning prior to start-up. A few minor modifications and enhancements were identified in this period and most will be implemented in the 1988/89 shutdown.

Diagnostics

The location of the JET measuring systems (or diagnostics), whose installation is now nearing completion, is shown in Fig.10 and their status at the end of 1988 is shown in Table 4. Operational experience has been good and many of these systems operate automatically with minimal supervision from scientific staff. The measurements obtained are accurate and reliable and provide important information on the behaviour of the plasma.

Boundary Measurements

Langmuir probes of all-carbon construction in the plasma contact area have been in operation in all important regions in JET. In particular, the Langmuir probes mounted in a band of X-point target tiles have given important information on plasmas obtained in this mode of operation. The fast moving (reciprocating) Langmuir probe drive which can scan 10 cm of the edge profile in 200 milliseconds, has been used extensively. It has given important details of the edge profile and, because this probe is designed to cross the last closed flux surface, it gives unambiguously the position of this surface. So far, the applicability of this probe has been limited by uncontrolled movements of the plasma boundary which cause an excessive power loading to the probe in its rest position. Therefore, a probe with a larger stroke of 25 cm is under design. The drive system for the plasma

TABLE 4: STATUS OF THE JET DIAGNOSTICS SYSTEMS, DECEMBER 1988

System	Diagnostic	Purpose	Association	Status	Compatibility with tritium	Level of automation
KB1	Bolometer array	Time and space resolved total radiated power	IPP Garching	Operational	Yes	Fully automatic
KC1	Magnetic diagnostics	Plasma current, loop volts, plasma position, shape of flux surfaces, diamagnetic loop, fast MHD	JET	Operational	Yes	Fully automatic
KE1	Single point Thomson scattering	T_e and n_e at one point several times	Risø	Operational	Yes	Fully automatic
KE3	Lidar Thomson scattering	T_e and n_e profiles	JET and Stuttgart University	Operational	Yes	Fully automatic
KG1	Multichannel far infrared interferometer	$\int n_e ds$ on six vertical chords and two horizontal chords	CEA Fontenay-aux-Roses	Operational	Yes	Semi-automatic
KG2	Single channel microwave interferometer	$\int n_e ds$ on one vertical chord	JET and FOM Rijnhuizen	Operational	Yes	Fully automatic
KG3	Microwave reflectometer	n_e profiles and fluctuations	JET	(1) Fixed frequency operational (2) Swept frequency in commissioning	Yes	Fully automatic
KG4	Polarimeter	$\int n_e B_p ds$ on six vertical chords	CEA Fontenay-aux-Roses	Operational	Yes	Semi-automatic
KH1	Hard X-ray monitors	Runaway electrons and disruptions	JET	Operational	Yes	Fully automatic
KH2	X-ray pulse height spectrometer	Plasma purity monitor and T_e on axis	JET	Operational	Yes	Semi-automatic
KJ1	Soft X-ray diode arrays	MHD instabilities and location of rational surfaces	IPP Garching	Operational	No	Semi-automatic
KJ2	Toroidal soft X-ray arrays	Toroidal mode numbers	JET	Operational	Yes	Semi-automatic
KK1	Electron cyclotron emission spatial scan	$T_e(r,t)$ with scan time of a few milliseconds	NPL, UKAEA Culham and JET	Operational	Yes	Fully automatic
KK2	Electron cyclotron emission fast system	$T_e(r,t)$ on microsecond time scale	FOM Rijnhuizen	Operational	Yes	Fully automatic
KK3	Electron cyclotron emission heterodyne	$T_e(r,t)$ with high spatial resolution	JET	Operational	Yes	Not yet implemented
KL1	Limiter surface temperature	Monitor of hot spots on limiter, walls and RF antennae	JET and KFA Jülich	Operational	No	Fully automatic
KL3	Infrared belt limiter viewing	Temperature of belt limiters	JET	Commissioning	No	Will be fully automatic
KM1	2.4MeV neutron spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	UKAEA Harwell	Commissioning	Not applicable	Semi-automatic
KM3	2.4MeV time-of-flight neutron spectrometer		NEBESD Studsvik	Operational	Not applicable	Fully automatic
KM4	2.4MeV spherical ionisation chamber		KFA Jülich	Commissioning	Yes	Semi-automatic
KM2	14MeV neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	Under Construction	Yes	Not yet installed
KM5	14MeV time-of-flight neutron spectrometer		SERC, Gothenberg		Yes	Not yet installed
KM7	Time-resolved neutron yield monitor	Triton burning studies	JET and UKAEA Harwell	Operational	Not applicable	Fully automatic
KN1	Time-resolved neutron yield monitor	Time-resolved neutron flux	UKAEA Harwell	Operational	Yes	Fully automatic
KN2	Neutron activation	Absolute fluxes of neutrons	UKAEA Harwell	Operational	Yes	Semi-automatic
KN3	Neutron yield profile measuring system	Space and time resolved profile of neutron flux	UKAEA Harwell	Operational	Yes	Fully automatic
KN4	Delayed neutron activation	Absolute fluxes of neutrons	Mol	Operational	Yes	Fully automatic
KP3	Fusion product detectors	Alpha-particles produced by D-T fusion reactions	JET	Under study	Yes	Automatic
KR1	Neutral particle analyser array	Ion distribution function, $T_i(r)$	ENEA Frascati	Operational	No	Automatic
KR2	Active phase NPA	Ion distribution function, $T_i(r)$	ENEA Frascati	Under construction	Yes	Automatic
KS1	Active phase spectroscopy	Impurity behaviour in active conditions	IPP Garching	Operational	Yes	Not yet implemented
KS2	Spatial scan X-ray crystal spectroscopy	Space and time-resolved impurity density profiles	IPP Garching	Operational	No	Not yet implemented
KS3	H-alpha and visible light monitors	Ionisation rate, Z_{eff}, impurity fluxes	JET	Operational	Yes	Semi-automatic
KS4	Charge exchange recombination spectroscopy (using heating beam)	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Operational	Yes	Semi-automatic
KS5	Active Balmer α spectroscopy	T_D, n_D and Z_{eff} (B_p)	JET	Under Construction	Yes	Not yet implemented
KT1	VUV spectroscopy spatial scan	Time and space resolved impurity densities	CEA Fontenay-aux-Roses	Operational	No	Semi-automatic
KT2	VUV broadband spectroscopy	Impurity survey	UKAEA Culham	Operational	No	Fully automatic
KT3	Active phase CX spectroscopy	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Operational in'89	Yes	Not yet implemented
KT4	Grazing incidence spectoscopy	Impurity survey	UKAEA Culham	Operational	No	Fully 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	Automated, but not usually operated unattended
KY2	Surface probe fast transfer system		UKAEA Culham	Operational	Yes	
KY3	Plasma boundary probes	Vertical probe drives for electrical and surface collecting probes	JET, UKAEA Culham and IPP Garching	Operational	Yes	
KY4	Fixed Langmuir probes (X-point and belt limiter)	Edge parameters	JET	Operational	Yes	Semi-automatic
KZ1	Pellet injector diagnostic	Particle transport, fuelling	IPP Garching	Operational	No	Not automatic
KZ3	Laser injected trace elements	Particle transport, T_i, impurity behaviour	JET	Operational	Yes, after modification	Not automatic
Kγ1	Gamma-rays	Fast ion distributions	JET	Operational	Yes	Manual

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boundary probes which carries either the fast reciprocating probe or a rotating collector probe has been redesigned to improve reliability, and these probes now operate reliably in a remote control mode.

Samples from limiters, inner wall, X-point tiles and special samples attached to the wall (all retrieved from the vessel after opening) have continued to confirm basic understanding of the plasma-wall interaction. In particular, detailed erosion/deposition measurements have been performed on the belt limiter tiles. Analysis of tritium originating from the $D+D \rightarrow T+p$ reaction and embedded in tiles has given preliminary information on the amount that would be found in the carbon protections of the JET vessel under active conditions.

The Fast Transfer System designed to transport probes to the plasma, expose them with time resolution, retract them to the exchange station and then exchange them to the analysis system, has shown increased reliability and flexibility. For the first time, observations on oxygen deposition have been reliably obtained. This required cleaning the surface before exposure with an argon sputtering gun, followed by transport and exposure, with final analysis by Auger electron spectroscopy and ion beam analysis using the reaction $^{16}O(d,p)\,^{17}O$.

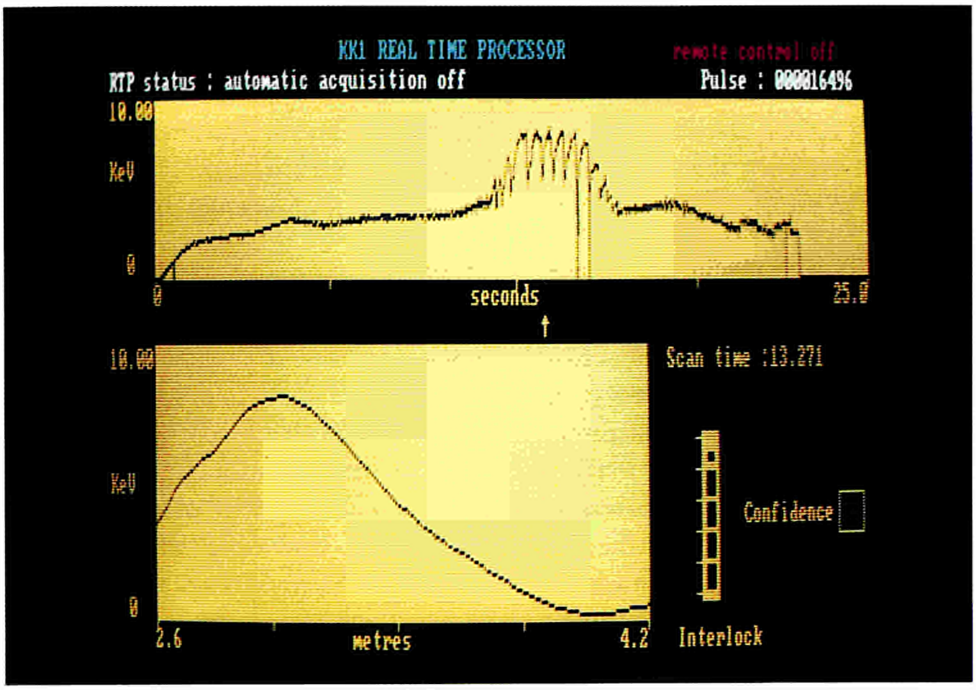
When beryllium is used inside the torus, the surface analysis station will be required to handle Be-covered components. Therefore, modifications are in progress to provide safe handling facilities for Be-covered probes. The surface analysis station can readily detect thin Be layers by Auger electron spectroscopy or ion beam techniques. Increased shielding for the beam line is being provided so that the latter technique can be operated in a more sensitive mode using a D^+ ion beam.

Observations of limiter surfaces and the X-point target plates have been extremely important in 1988 since JET has operated at much higher power loadings. Information from the camera systems has been used extensively to optimise the various modes of operation. This work was seriously hampered by the very limited view available of the X-point. However, by using D_α filters to confirm the measurements of the Langmuir probes, it has been possible to identify the position of the outer separatrix, and to estimate the heat deposition during L and H-modes. One camera equipped with a filter carousel was aimed at the lower belt limiter and has observed the increased fluxes of carbon due to local heating of the edges.

Temperature and Density Measurements

The electron cyclotron emission system consists of an array of rapid scan Michelson interferometers and rapid scan Fabry Perot interferometers, a twelve-channel grating polychromator, and an eight-channel heterodyne radiometer. During 1988, the performance of these measuring systems has been significantly enhanced and the quality of the measurements improved.

A real time processor for the Michelson interferometer was installed and commissioned early in the year. It uses state-of-the-art signal processing hardware and software to analyse data from the Michelson interferometer during the plasma pulse. It now routinely provides electron temperature profiles in real time, an example of which is shown in Fig.11. The line integral of the profile is transmitted to the control system of the JET high-speed pellet launcher, where it is used as one of the safety interlocks.



KK1 REAL TIME PROCESSOR

remote control off

RTP status : automatic acquisition off

Pulse : 000016496

Scan time :13.271

Fig.11 Display provided by the Real Time Processor in the JET control room. The upper curve is the time history of the central electron temperature and the profiles are displayed on the lower left. The small bar on the lower right is an analogue indicator of the signal transmitted to the pellet interlock system.

Considerable progress has been made with an upgrade of the heterodyne radiometer. The upgraded system will have four frequency channels, covering the frequency range from 73-120 GHz, and will give a much wider coverage of the temperature profile with the same level of detail as the original system. Part of the upgraded system, which measures at higher radiation frequencies, has already been used. It has proved valuable for edge temperature measurements in X-point plasmas, in particular, for the investigation of the L-mode to H-mode transition.

Installation of the multichannel reflectometer was completed and substantial progress made with its commissioning. The instrument probes the plasma along a major radius to detect electron density layers in the range $0.4\text{-}8.0\times10^{19}\,m^{-3}$. During the year, the LIDAR system was brought into full operation and now routinely measures the spatial profile of the electron temperature and density every 2 seconds throughout a JET discharge. The availability of the system has been ~90%, limited by some minor breakdowns of the ruby laser. In addition to the 0.5 Hz repetition rate, the system was operated occasionally close to 1 Hz in bursts of 4-5 pulses. With this mode of operation, the time evolution of the electron temperature and density profiles were investigated in more detail for some discharges with pellet injection, neutral beam and ICRF heating.

The existing LIDAR system is presently being upgraded for 10 Hz repetition rate. The new system will be based on an Alexandrite laser emitting at 760 nm which is due for delivery in mid-1989. During the shutdown at the end of 1988, necessary modifications of the existing LIDAR system were started. The transient digitisers have been modified for 10 Hz operation and increased bandwidth. A new data acquisition system is being set up to handle the larger data rate.

During the year, the charge exchange spectroscopy system was used to measure the central ion temperature on a routine basis. This was available for the majority of neutral beam heated plasmas and, in addition, for dedicated experiments where a minimum of neutral beam power was provided for diagnostic purposes. In addition, a multichord viewing line system was commissioned which enabled the temporally and radially resolved measurement of ion temperature and toroidal angular frequency profiles. Highly peaked ion temperature profiles were observed in the neutral beam heated low-density plasmas, with temperatures on-axis exceeding 20 keV. Densities of the dominant light impurities carbon and oxygen were derived from absolute measurements of charge exchange photon fluxes and used to reconstruct radial deuteron concentration profiles and from this the ion pressure.

Polarimetric measurements of Faraday rotation, and determinations of current density profiles in different regimes of JET operation, have been pursued vigorously during the year. These indicate that the value of the safety factor on the magnetic axis, $q(0)$, is always considerably less than unity in a sawtoothing discharge: not even the collapse of a monster sawtooth elevates $q(0)$ to unity. These radical observations merit further careful confirmation. Enhancements of the polarimeter are in preparation, increasing the number of chords from six to eight measurements along orthogonal chords, and more accurate measurements of the Faraday rotation angle. These improvements will permit more accurate deduction of the magnetic geometry giving a firmer assessment of the behaviour of $q(0)$.

Neutron Measurements

The Neutron Profile Monitor has been in routine operation throughout 1988. This is a 19 channel instrument, each channel being equipped with a neutron spectrometer (energy resolution, $\Delta E/E = 8\%$) which selects neutrons in the energy range 2 to 3 MeV and discriminates against background gamma-radiation. Each spectrometer can be operated at selected event-rates up to at least 100 kHz. Much effort has been devoted to checking the operation of this diagnostic and to obtaining absolute efficiency calibrations for each channel. For ohmic discharges, the neutron yields obtained from the profile monitor agree well with those from Neutron Fission Chambers. For additionally heated discharges, the Profile Monitor efficiency increases: this is not fully explained but the increase is partly due to the sensitivity of the spectrometer efficiency to neutron energy and to the non-isotropy of the neutron emission from D-D reactions. For ohmic discharges, the neutron profiles give ion temperature profiles which are very similar to the electron temperature profiles from the LIDAR diagnostic.

A time-of-flight neutron spectrometer and several ^{3}He ionization chamber spectrometers are used for high resolution ($\Delta E/E \sim 4\%$) neutron energy spectrum measurements and a liquid scintillator spectrometer is used for broadband studies. Now equipped with adjustable aperture collimators for intensity control, these spectrometers constitute a system which can cater for most circumstances. In particular, the time-of-flight spectrometer offers a time resolution of one second for high intensity discharges, compared with 4 seconds for the ^{3}He spectrometers.

Charged Particle and Gamma Ray Studies

The study of the confinement and slowing down of the 1.0 MeV tritons emitted from D-D reactions is of considerable importance because these tritons are expected to behave in the same way as the alpha-particles emitted from D-T reactions in respect of their single particle (as opposed to collective) properties. The major difference is that the tritons undergo T-D fusion reactions and emit 14 MeV neutrons as they slow down and so can be investigated through their related neutron emission. Triton burn-up measurements are being continued as the additional heating powers applied to JET plasmas are increased. Both the absolute yield of 14 MeV neutrons and the time-dependence of the emission can be simulated within experimental errors by numerical modelling, provided the electron temperatures provided by the LIDAR diagnostic are employed.

16.5 MeV gamma-ray emission from ^{3}He-D fusion reactions provides a means of measuring the fusion reaction rates between ICRF-heated ^{3}He ions and the bulk deuterium in high plasma current discharges. An initial investigation has been completed, with fusion powers of about 60 kW being generated. Gamma-ray emission has also been detected from interactions between the heated ions and the major plasma impurities, notably carbon. Acceleration of ions into the MeV energy region has been observed (protons to 10 MeV). When two or more gamma-ray lines originating from different energy threshold reactions are seen, then an effective temperature can be assigned to the high-energy ion tail. Provided the impurity species ion density is known, the ion density for the tail can be estimated.

Fast Ion and Alpha Particle Studies

A thorough study has been undertaken of possible techniques to diagnose the energetic alpha-particle population that will be produced and confined in JET plasmas during the D-T phase of operation. A system based on collective Thomson scattering of high power millimetre wave beam offered the best possibilities for JET. Before the D-T phase, the diagnostic would be used to diagnose the fast ion populations produced by ICRF heating which are important in experiments to simulate the effects of alpha-particles. During 1988, a detailed investigation of the proposed system and its possible application to JET was carried out. All relevant physical effects were examined.

In JET, it should be possible to measure the spatial and velocity distributions of the confined alpha-particle populations with a spatial resolution ~ 10 cm, a time resolution ~ 200 ms with a signal:noise ratio of typically 20:1, assuming the total alpha-particle heating power is ~ 5 MW. In the fast ion measurements and in the alpha particle simulation experiments, much higher scattered signal levels are expected and the signal:noise ratio could be as high as 100:1. The scientific and technical design work is now nearing completion and it is expected that construction of the system will commence in 1989.

Remote Handling

The main objective of the remote handling programme is to prepare for the introduction of tritium into JET, which will generate a large number of D-T fusion reactions, with a high flux of 14 MeV neutrons. Some of these neutrons will be captured by the structure of the machine, making it too radioactive to approach. Therefore all maintenance will need to be carried out by remote control from outside the Torus Hall. Special equipment and methods are also being developed for safe working with increased background radiation levels, slightly active dust and the use of beryllium in the torus.

Further progress has been made in specifying, acquiring and commissioning major items of remote handling equipment. This comprises special tools to suit the features and to provide access to JET components; end-effectors to lift and attach large components; large, high-precision transporters to carry the equipment to all parts of the JET machine; and control systems. During 1988, further efforts were devoted to analysis of tasks inside and outside the vessel to provide the basis for specifications of equipment and to supply material for data-bases which will be used to direct operations.

The articulated boom operated with joystick control was used successfully to replace eight antennae in the torus vessel during the late 1988 shutdown. Trials of installation of a limiter segment and an antenna housing and screen were carried out in simulated remote conditions using the spare vacuum vessel octant as a mock-up. For this type of operation, visual control is not possible, and the 'teach-and-repeat' facility was used with dynamic repositioning within 5 mm. Improvements to the control system have overcome difficulties with boom insertion through the port, and have also reduced insertion time significantly. Horizontal stiffness and load capacity of boom joints has been more than doubled.

New designs of welders and cutters have been used during the 1988/89 shutdown for maintenance of the RF vacuum transmission lines and will be used to install the Lower Hybrid Current Drive system. Tool designs used for belt limiter and antennae installation have been modified for work on neutral beam and radiofrequency lines. Commercial welding power packs have been modified for compatibility with existing equipment.

Further attention has been devoted to the special requirements of beryllium related maintenance. The Torus Access Cabin (Fig. 12), already used successfully

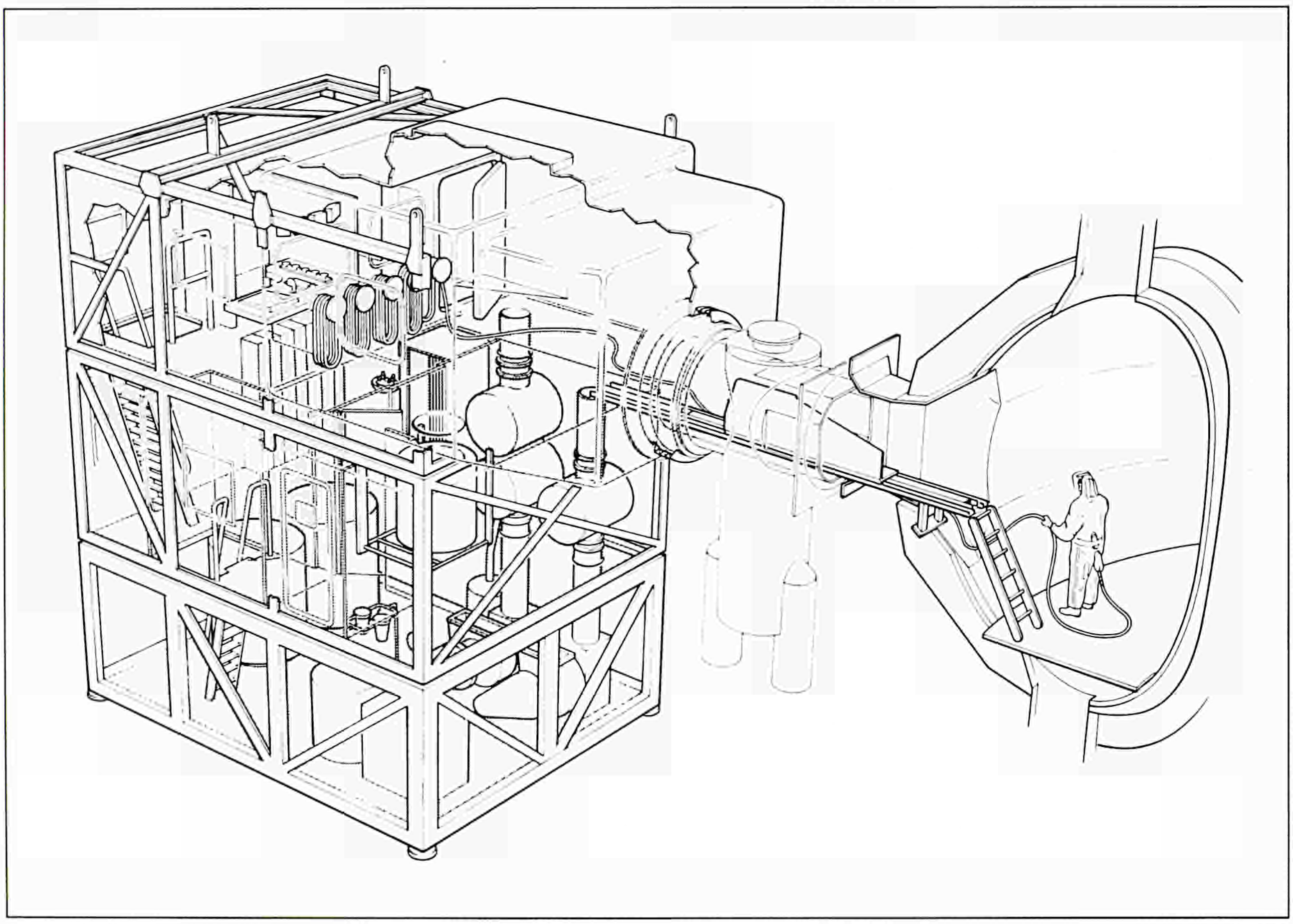


Fig.12 The torus access cabin.

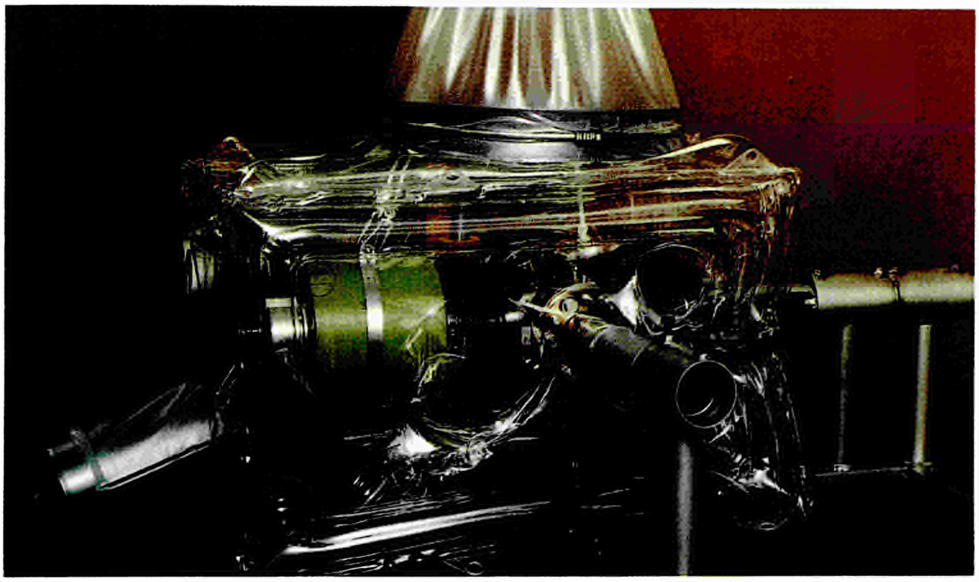


Fig.13 Beryllium isolator.

in several interventions, will provide controlled access to the torus following plasma operations with beryllium. Ex-vessel maintenance will involve the use of flexible isolators and continuing development for the JET specific requirements has been carried out (see Fig. 13). A workshop is being established for their fabrication. Other control area facilities include an experimental laboratory for evaporation trials and a central beryllium handling facility for support operations and tile handling which has been designed and constructed in the Assembly Hall. A difficult feature of working with beryllium is the time required for the analysis of samples. Using the standard technique of atomic absorbtion spectroscopy, this can take one hour per sample. To minimise machine downtime , JET has procured a new instrument developed at USDoE, Los Alamos, USA, utilising laser induced breakdown spectroscopy (Fig.14).

The conceptual design of the active handling facility has been completed, based on the studies of active handling and remote maintenance requirements during the D-T phase. The new control area, to be built in the Assembly Hall adjacent to the Hot Cell, will provide facilities for decontamination, active maintenance of the remote handling tools, active waste handling and storage, maintenance on the articulated boom and the telescopic transporter and controlled access to the Hot Cell and Access Cell areas. This will include a change room and barrier facility. Following detailed design, construction of the facility will commence in 1989 to allow commissioning prior to the start of the D-T phase. Whilst the main task will be in support of the remote handling intervention work, which will include specific tritium related problems, the area will also be used for beryllium related work.

Control and Data Management

The JET Computing Service is based on an IBM 3090/200E computer with one vector facility and some 70 Gigabytes of disc storage and a further 240 Gigabytes of IBM Mass Storage. The complex is housed at UKAEA Harwell and operated for JET by a team under contract from that Laboratory (see Fig.15). The JET Mainframe machine is also connected to the Harwell CRAY 2 computer.

The JET Computing Centre has operated since mid-1987 and the computing load has grown significantly since that date, such that at peak times the system

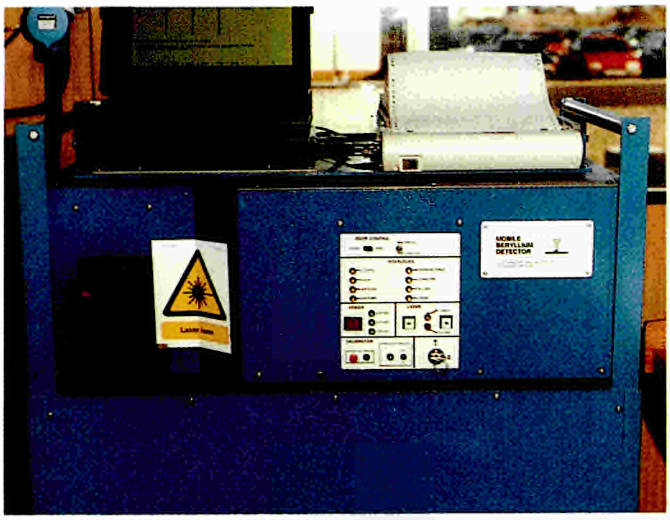


Fig.14 Beryllium analysis equipment using laser induced breakdown spectroscopy.

is reaching its capacity. However, by careful tuning of the system, good response time is maintained for interactive users and for the CAD systems in the JET Drawing Office. Also prompt execution of the intershot analysis is ensured. A background load of batch work is also serviced but the increasing long batch job work load, such as transport analysis and extensive structural analysis codes, now tends to be displaced outside daytime periods. The Data Management Group provides the contact between the users, operators and system programmers, through the Help Desk Service, backed up by specialists in the Group. This ensures the smooth running of the system. The data communications between the JET site and the Computer Centre are mainly the responsibility of CODAS Division and significant improvements have taken place in these areas.

The hardware and software configurations of the link between the JET mainframe computer located at Harwell and JET site facilities have been completed. Collection speeds (from subsystems to storage and analysis computer) of 65 kByte

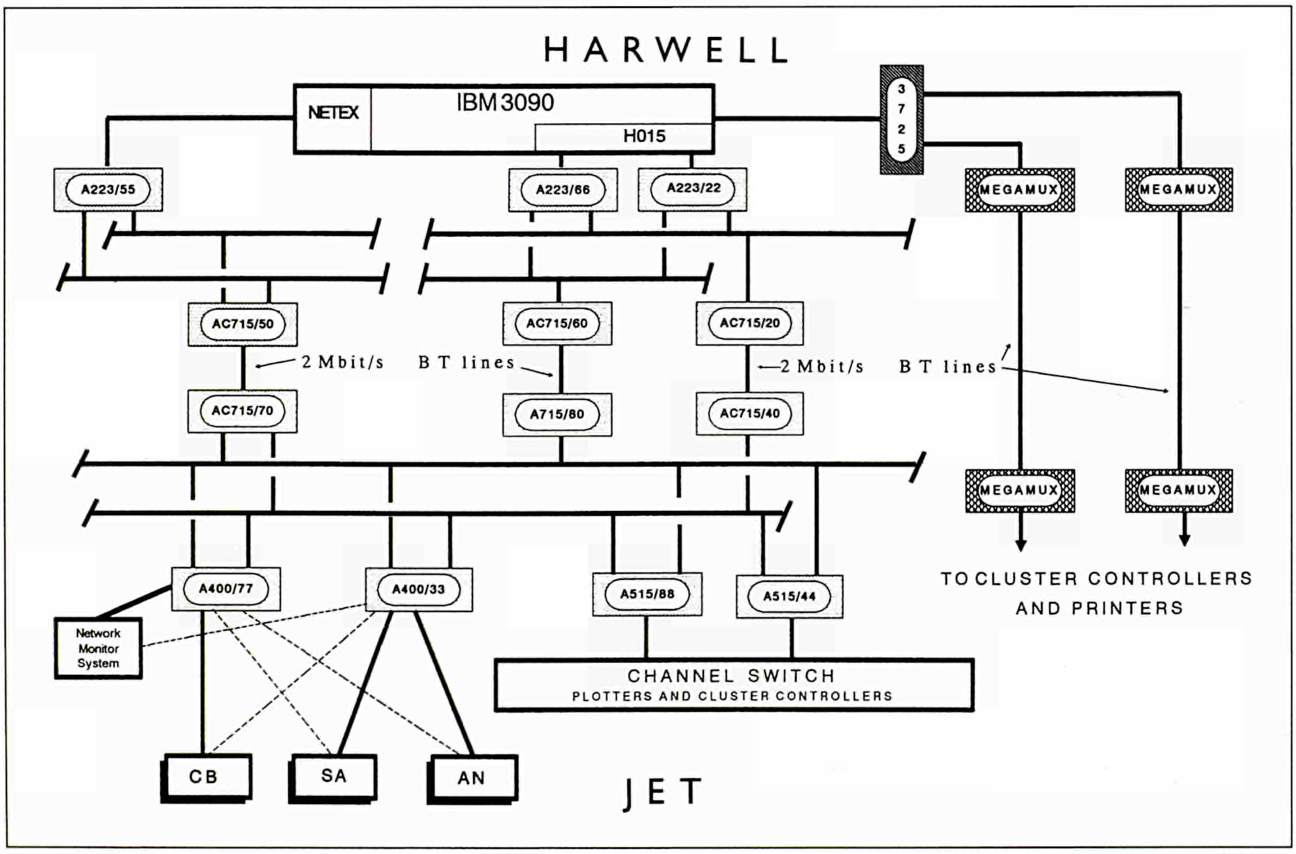


Fig.15 The JET-UKAEA Harwell link to the IBM 3090 computer.

Control and Data Acquisition

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

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.

per second and transfer speeds (from storage and analysis computer to JET main-frame) of 170 kByte per second were achieved routinely. The continuous growth of the JET Pulse File (JPF) size has required additional performance improvement. New software has been developed and tested and this should allow a JET Pulse File of 15MB to be delivered to the main-frame faster. As JET operates nearer its performance limits, the results of the detailed analysis made in the mainframe computer are becoming more necessary for its operation. Therefore, the data link performance improvements have a direct impact on the JET pulse repetition rate. Studies of the possible benefits of applying data compression techniques to JET Pulse File data have started, which show that a compression factor of about three could be achieved. Such compression will be used in the mainframe mass storage system early in 1989.

JET Computations

At present, 110 GBytes of raw JET data (JET Pulse Files) are stored on the much enhanced Processed Pulse File (PPF) online data-base system. During 1988, a complete higher level data selection and storage system, the Central Physics File (CPF), was established. A subset of all data is extracted at time points of interest, determined by a newly developed Timeslice program. These data are the basis for extended statistical analysis, and the source for other extracts such as the TRANSPORT bank. This complete system is a fully automated process. The JET

Survey Data Bank now contains basic plasma data for all JET discharges with plasma up to the end of 1988 (over 12,000 pulses; about 320,000 time traces; a total of one GByte of available data). For comparison with theoretical predictions, data banks with well checked and validated plasma data (included spatial and temporal dependencies) for a few selected discharges are being prepared.

Activities in which important advances have been made during 1988 are detailed in the JET Progress Report. Among these are:

- a number of codes in the code library have been upgraded to make them applicable to a wider class of problems, and to be more user-friendly and automatic. This relates particularly to the inversion code NEPROF which derives electron density profiles, and to the plasma equilibrium code IDENTC to include measured information on pressure profiles and diamagnetism in addition to the usual magnetic probe signals. A major effort was invested in a complete revision of the interpretive transport code JICS to provide reliable data for local transport;
- a new equilibrium code has been developed which self-consistently includes Faraday rotation data in the evaluation of the poloidal magnetic field profile. Another new package (STABM1) evaluates stability criteria for plasma sawtooth activity, and the new PIN code assists the interpretation of boundary plasma measurements. These and other codes have been used extensively for JET data interpretation. By combining these tomographic and inversion methods, ion temperature profiles have been derived from neutron emission measurements;
- major progress has been achieved in modelling the boundary plasma. A set of two dimensional two-fluid plasma equations have been solved in time, self-consistently with a three dimensional Monte-Carlo calculation for the recycled neutrals. Both limiter and single X-point configurations can be studied;
- various plasma models have been used extensively for predictive computations of the performance of JET and other tokamaks. The main plasma model code, JETTO, has been applied in a predictive (and interpretative) mode to the long standing plasma confinement problem.

Summary of Machine Operation

The machine was operated for 154.5 days during the January-September period. About 77% of these days were devoted to experimental operation with a distribution among different heating programmes as follows:

17.6% Ohmic (OH) heating;
11.7% Radio-frequency (RF) heating only;
33.5% Neutral Beam (NB) heating only;
37.2% Combined (NB and RF) heating.

The allocation of time to the different activities and the number of days in the various tokamak operational programmes is shown in Fig.16.

The organisation of operation time remained essentially the same as for 1987 but the frequent overnight use of a special HV (standby) isolation reduced the time spent in the power supplies isolation and re-energisation activities, thus liberating more time for tokamak operation.

The total number of pulses was 4673 in 1988 bringing the total number of

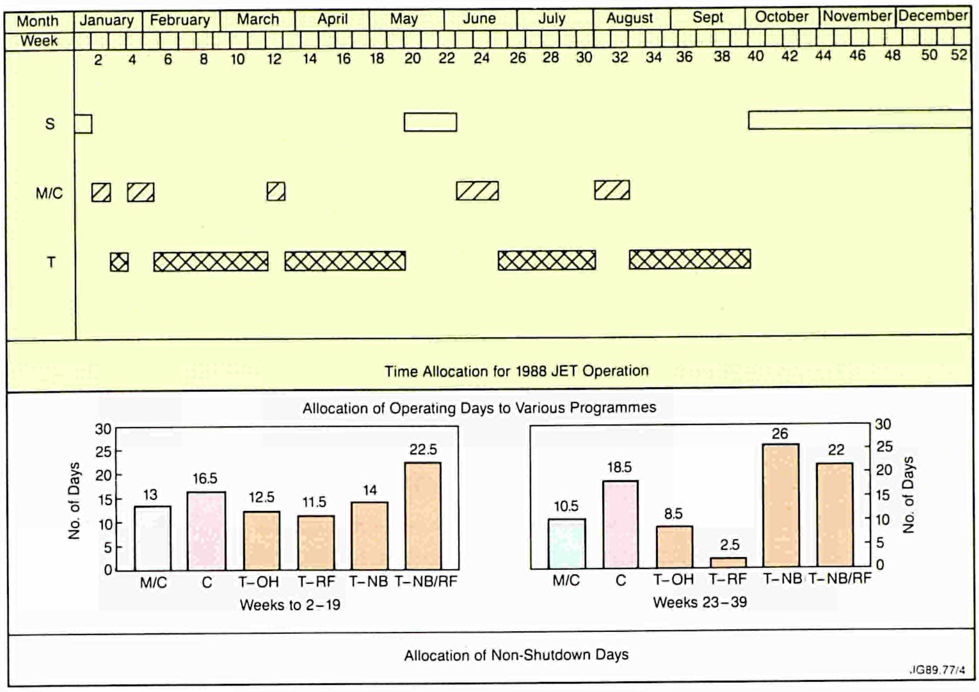


Fig.16 Allocation of time to different activities in 1988:
S = shutdown
M/C = machine commissioning
T = tokamak operation.

pulses to 18786. The relative number of commissioning pulses continues to decrease. Even more significant is the cumulative number of discharges with plasma current exceeding 3MA, which for 1988 was 2398 bringing the cumulative total to nearly 4800 (see Fig.17). A comparison between the current pulse distributions for 1987 and 1988 is shown in Fig.18, and this shows a clear movement to higher current values in 1988.

During 1988, JET operations (Weeks 1 to 40) were essentially made up of four main periods:

(a) The first period (Weeks 1 to 11) was intended to follow on from 1987 operation, but a leak in the Octant No.4 neutral beam duct scraper shortly before the close of the 1987 operation required a vessel entry in Week 1, to effect repairs. Throughout

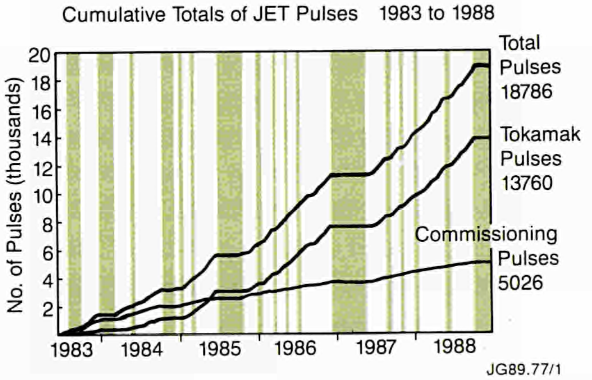


Fig.17 Cumulative total of JET pulses.

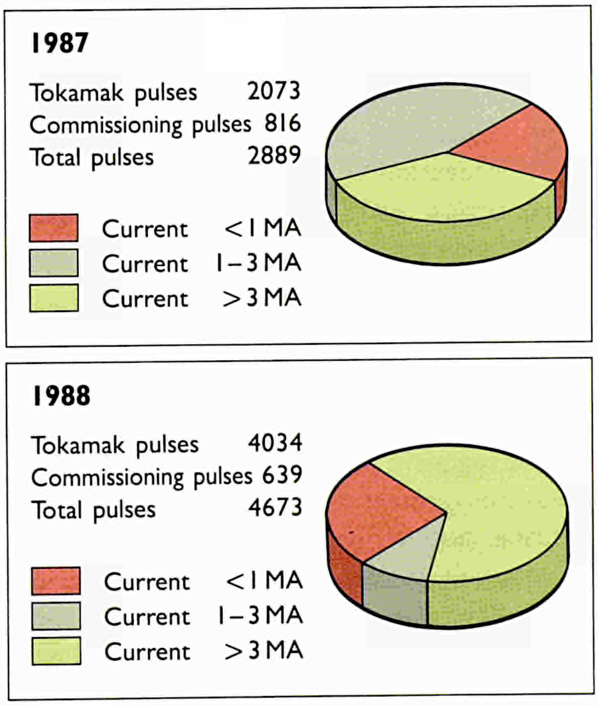


Fig.18 Comparison of current pulse distributions for 1987 and 1988.

this first period, the neutral beam (NB) heating system suffered a number of problems so that only limited use of the Octant No.8 injector was made, and the Octant No.4 injector did not achieve synchronous operation. Unfortunately, torus vacuum leaks and in-vessel water leaks required two further vessel entries in this period. In spite of these problems, improved operation was achieved, leading to a high pulsing frequency and a high average daily time available for pulsing.

(b) The second period (Weeks 12 to 19) began with one week of maintenance and recommissioning. The major innovation in this period was the synchronous operation of the Octant No.4 Neutral Beam injector. This allowed extended performance of the additional heating system (15 MW ICRF and 10 MW NB) and permitted previous high values to be exceeded.

Other notable achievements were:

(i) routine and successful use of pellet injection in the current rise phase to produce peaked density profiles;
(ii) the Poloidal Field central coil operation commissioned to 55 kA (design 60kA);
(iii) by means of chillers, the Toroidal Field magnet long pulse performance was extended to 16s at 67kA coil current;
(iv) relatively straightforward reconditioning of the vessel following disruptions by glow discharge cleaning, and/or pulsing in helium.

(c) The third period (Weeks 20 to 30) began with extended maintenance/commissioning activity to include the remedial work necessary in the vessel, as well as the installation of new protection tiles. Other activities were: modification of the Poloidal Field cooling system; modification of the vertical field control to allow different currents in the upper and lower central Poloidal Field coils, and the continued upgrading of the ICRF generators (from 3 to 4 MW).

There were several notable achievements:

(i) regular operation of both NB injectors to a peak power of 18 MW;
(ii) successful operation of the poloidal coils with the new outer coil cooling and the central coil current imbalance;
(iii) a 5 MA single X-point plasma was achieved;
(iv) record RF energy was transmitted (6 MW for 20 s);
(v) regular use of in-vessel inspection system (IVIS) at 250°C for in-vessel inspection;
(vi) regular use of pellets to create peaked density profiles, and the successful heating of such plasmas.

(d) The fourth period (Weeks 31 to 40) followed directly from the third, with one week of in-vessel and neutral beam injector remedial work. The main success of this period was the achievement of the simultaneous operation of all 16 neutral beam sources. Large additional heating power (greater than 30 MW) were applied regularly, producing plasmas with high energy content, and high ion temperatures (greater than 20 keV) in inner wall plasma operation.

Other achievements were:

(i) vertical stabilisation of high elongation ($\epsilon \sim 2$) plasmas;
(ii) 7 MA plasma current for 2 s flat-top, and routine high current (5 and 6 MA) discharges including 5 MA single-null X-points, and 3.5 MA double-null X-point configurations;

(iii) long duration H-modes (up to 4s);
(iv) commissioning of the digital radial position control system was started;
(v) increased purity of plasmas with neutral beam injection and, in particular, with pellet injection.

TABLE 5: SIGNIFICANT TECHNICAL ACHIEVEMENT DURING 1988

Operation with a material limiter:
- Plasma currents up to 7MA with 2s flat-top;
- Plasma currents up to 6MA with 6s flat-top;
- Plasma currents of 3MA for 24s flat-top duration;

Operation with a magnetic limiter (X-point configuration):
- Record plasma currents up to 5MA

Plasma heating systems:
- Record total power delivered to the plasma, exceeding 34MW;
- Quasi-steady state conditions achieved at 3MA with 6MW of RF heating power for 20s duration.

Technical Developments for Future Operations

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

Study of New Extended Operating Conditions: The 7MA Study

Operation at currents up to 7MA in the material limiter configuration and in excess of 5MA in the magnetic limiter configuration required a complete engineering reappraisal to determine the safe operating limits for major machine components and identify any changes that might be needed. The objectives of the study were ambitious since they called for a considerable extension of the machine design parameters both in terms of current level and energy dissipation. These objectives are highlighted in Table 6.

TABLE 6: OBJECTIVES OF THE 7MA STUDY

Parameter	Original Design Values	Objectives of the 7MA Study
Plasma current (limiter configuration), (MA)	4.8	7
Plasma current (X-point configuration), (MA)	Not foreseen	6
Plasma current flat top at 4.8MA (s)	10	–
at 7MA (s)	Not foreseen	10
Plasma elongation *b/a*	1.67	≃2
Toroidal field, (Tesla)	3.45	3.45
Toroidal field flat top duration, (s)	12	17
Primary winding current, (kA)	40	60*
Primary winding flux swing, (Wb)	34	42

**60kA in the six central coils only.*

Three problem areas were identified:

- Containment of forces acting on the vacuum vessel during disruptions and vertical instabilities.
- Safe limits for the lateral forces acting on the toroidal field coils and due to the poloidal magnetic field crossing these coils.
- Thermomechanical effects in the ohmic heating coil due to much increased energy dissipation.

Containment of Forces Acting on the Vacuum Vessel

The forces acting on the vacuum vessel during a radial disruption are due to eddy currents flowing in the toroidal and poloidal direction. The eddy currents flowing in the poloidal direction were found to be the most critical since these induce large displacements (~ 10 mm at 6 MA) of the inboard vessel wall and large amplitude radial oscillations (~6 mm at 6 MA) of the vertical ports. Extensive finite element calculations revealed that under such conditions the yield limit of the material is exceeded over a significant area at the base of the ports and structural failure could occur after only a few thousand disruptions. Although the pattern of eddy currents during vertical instabilities is still not well understood, a number of theoretical and experimental studies indicate that the vertical force acting on the vacuum vessel would reach an amplitude of 6,000 - 10,000 kN at plasma currents of 6-7 MA.

The containment of these forces required certain modifications to the vacuum vessel and its supports:

(a) The inboard wall of the vessel should be reinforced by toroidal inconel rings welded inside the vessel. These rings should virtually eliminate the radial deflection of the vessel wall and the radial oscillations of the ports during radial instabilities. This work was undertaken during the shutdown in October 1988 and completed in early 1989.

(b) The vacuum vessel supports, installed in 1987, should be complemented by inertial brakes linking the vertical ports to the mechanical structure, which should slow down radial displacements due to the rocking motion of the vessel. Installation has been planned for a short shutdown in September 1989.

These modifications should allow safe operation up to 7 MA in the limiter configuration and 6 MA in the X-point configuration.

Forces acting on the Toroidal Field Coils

The prototype toroidal field coil was subjected to test loads of mechanically applied cycled loads simulating the lateral loads due to the poloidal field. The coil survived 10,000 cycles without detectable damage, many at a stress level 1.75 times higher than the most severe stress expected during operation at 7 MA. It was concluded that lateral forces acting on toroidal field coils should not limit machine performance.

Thermomechanical behaviour of the Ohmic Heating Coil

Refined finite element calculations were completed in 1988 and confirmed a thermal stress problem due to the temperature gradient produced by the cold incoming cooling water. To circumvent this problem, a new cooling loop was designed and commissioned in 1988. Water is now circulated in a closed loop and the temperature brought down in a controlled manner so that temperature gradients are minimised. With this modification, the ohmic heating coil now has the current and flux capability shown in Table 6.

The main conclusion of this study is that the electromagnetic system (i.e. coils and power supplies) should allow operation at plasma currents in excess of 7 MA in both limiter and X-point configurations. The main limitation seems to come from the mechanical problems associated with the forces acting on the vacuum vessel during vertical instabilities. This should set a limit to the plasma current in the X-point configuration of ~6 MA.

Stabilisation of Disruptions

Disruptions have limited the operating range of current and density in all tokamaks and, despite continued efforts, they still limit operation in JET. Due to its large size and D-shaped cross-section, considerable care is needed to programme the rise and decay of the current and density to avoid disruptions at high current values up to 7 MA. Since the electromagnetic forces exerted on the vacuum vessel increase in proportion to the square of the plasma current, high current disruptions could present a serious risk to the machine. Furthermore, the design of the next step devices depends very much on the expected severity and frequency of disruptions. Due to their importance, considerable effort has been devoted to understanding the causes of disruptions and attempting to stabilise them.

On JET, it is proposed to stabilise disruptions by utilising a system with magnetic feedback. Perturbations, which usually precede a disruption, will be detected by pick-up coils (see Fig.19). The signal from these will be used to drive large saddle coils via a feedback circuit. The saddle coils, mounted on the interior of the vacuum vessel, will produce magnetic field perturbations to cancel out those due to the growing instability. The design of the large saddle coils and their support structures inside the vessel has been completed and the components are being manufactured. Due to the large size of the saddle coils and their optimal placement inside the vessel, there have been many constraints on design. In particular, these coils have been designed around existing structures and to avoid

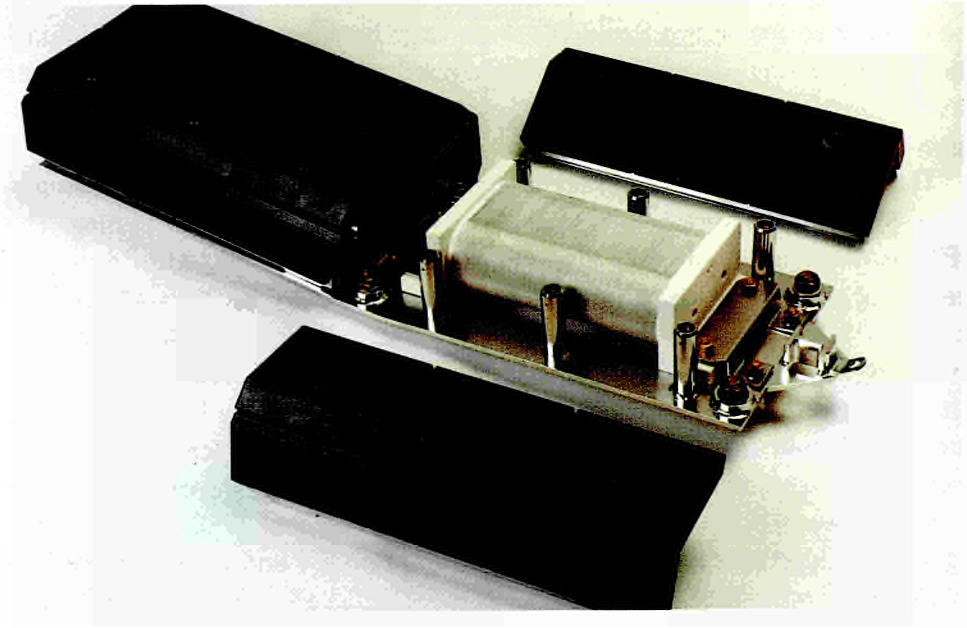


Fig.19 One of the disruption feedback stabilisation poloidal field pick-up coil assemblies. Each assembly contains two 20 cm long coils to be mounted vertically in the outer midplane between every two adjacent ICRF antennae.

interference with diagnostic lines-of-sight. Due to the electromagnetic forces exerted by the strong magnetic fields in the tokamak on the current carrying busbars, the maximum current has been set at 5 kA per turn in order to adequately support the busbars within the vessel. It is expected that the saddle coils may be installed during the next major shutdown.

A set of eight dedicated high sensitivity diagnostic poloidal field pick-up coils has been designed and constructed to measure the perturbations in the magnetic field from the plasma preceding disruptions. The coils will be mounted in pairs inside the vessel between every two adjacent RF antennae with one coil just above and the other coil just below the outboard midplane of the tokamak. These each have large poloidal surface area to give high sensitivity to small magnetic field perturbations. Appropriate combinations of these coils should be highly sensitive to the magnetic field perturbations from the plasma and comparatively insensitive to the driving field of the saddle coils. These combinations of pick-up coils can be used as input to the feedback circuit to drive the saddle coils to stabilise the modes that arise in the plasma. Two pairs of the pick-up coils will be installed in opposite octants during the 1988/89 shutdown to assess the noise levels of the system and determine the measurement capabilities of the diagnostic. The remaining two pairs will be installed during the following shutdown.

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) technique will be the main method of decoupling the plasma current and temperature profiles in JET. The main objectives of current drive and profile control are:

- to suppress sawteeth activity and to benefit from higher core reactivity by sustaining peaked profiles of both density and temperature;
- to modify local values of the current gradient and improve energy confinement in the plasma centre;
- to assess the current required for non-inductive operation of large tokamaks.

This programme is aimed at installing a prototype launcher with a nominal power of 2 MW during the 1988 shutdown and installation of the full size launcher for the 12 MW system in the 1990 shutdown. The microwave frequency power will be coupled to the plasma through a single large horizontal port by a multijunction phased waveguide array. This allows a good match to the power source over a wide range of plasma conditions and provides for flexibility in the relative position of the grill to the plasma surface.

The system design has been completed and manufacture is close to completion. Most of the components have already undergone extensive testing. The JET system is powered by 24 klystrons operating at 3.7 GHz. After extensive testing of seven tubes, the original power rating of 500 kW for 20 s was increased to 650 kW for 10 s. The higher power rating leads to lower reflected power, requiring a circulator to protect the klystron, which has been successfully developed and tested. Two klystrons have already operated from July 1988, alternately, on a high power testbed (see Fig. 20), enabling high power microwave components to be tested prior to installation on JET. Commissioning of the final high voltage power supply for four klystrons began in December 1988. The first module of four klystrons is presently being installed on JET and will be operational during the first half of 1989.

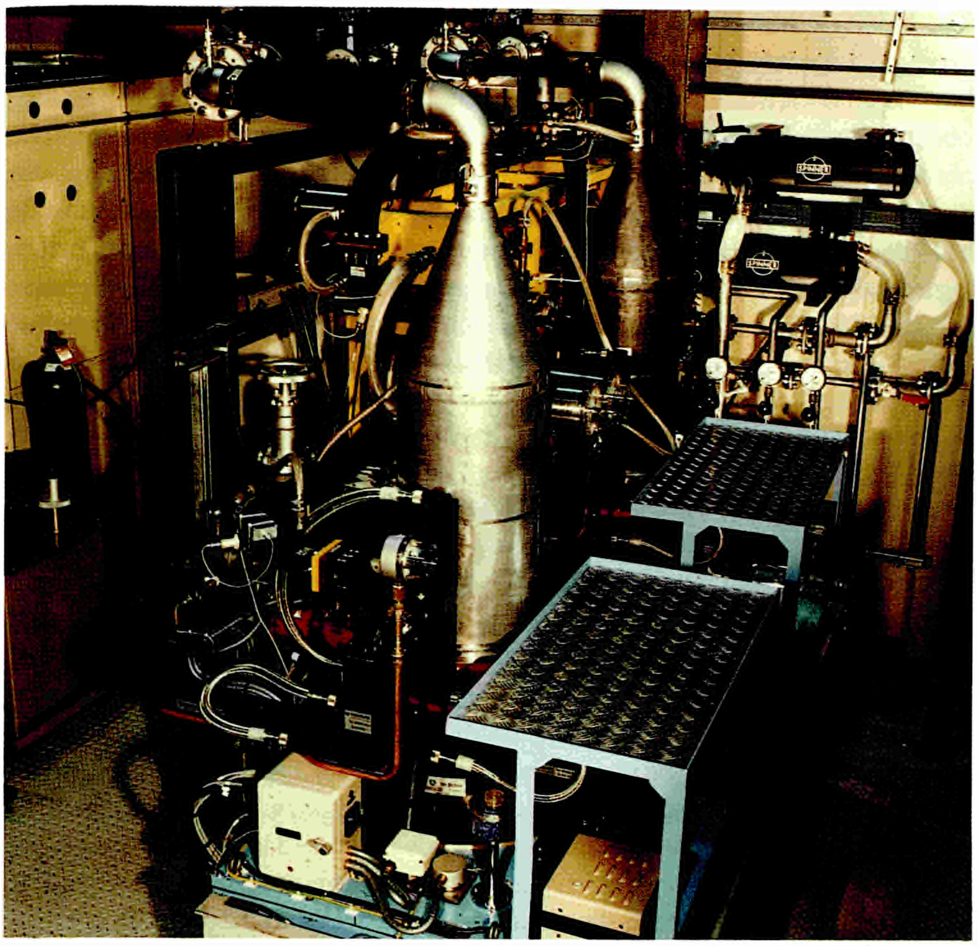
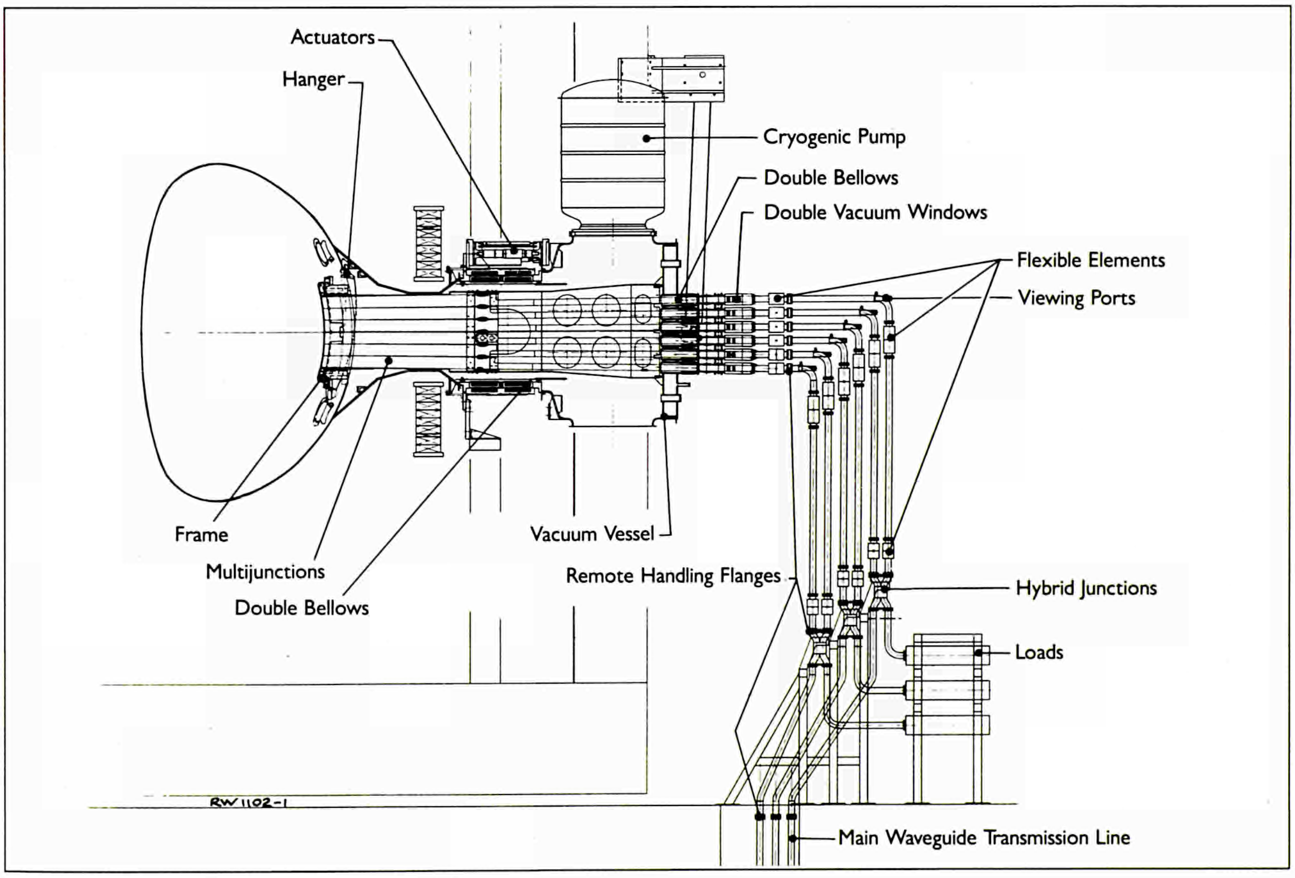


Fig.20 Two klystrons on the LHCD testbed.

Fig.21 Schematic diagram of LHCD launcher.



The LHCD launcher will be installed in the equatorial port at Octant No.3 to produce a narrow wave spectrum through an array of 32 waveguides in the horizontal direction. The total number of waveguides in the launcher is 384, obtained from 48 microwave modules using the multi-junction technique. Integral phase shifters provide the desired phase distribution at the grill mouth. A schematic diagram of the LHCD launcher is shown in Fig.21. All the components shown have been tested at high power for their nominal operating conditions, including a prototype multi-junction which has been successfully tested under vacuum up to 200kW for 20 seconds with short circuit termination. A test launcher will be installed on JET in 1989, comprising one third of the final number of waveguides.

High-speed Pellet Injector

The presently installed multiple-pellet injector is only capable of delivering solid hydrogen pellets with speeds up to 1.5 km s^{-1}. To investigate the velocity dependence of pellet penetration, with the aim of more central pellet fuelling in heated high-temperature discharges, velocities up to or exceeding 10 km s^{-1} are required. JET is presently developing a high-speed prototype pellet launcher (i.e. a gun in combination with a pellet-forming and breech-loading cryostat) capable of accelerating pellets of ~5mm diameter with velocities of 3-5 km s^{-1} on the basis of a two-stage light gas gun. To reach higher speeds, hydrogen isotope pellets must be contained in sabots (capsules) due to a progressive erosion effect of the bare pellet at the barrel wall when speeds reach ~3 km s^{-1}. Although the majority of essential problems on the way to the high-speed gun are solved 'in principle', some exploratory development must still be carried out. In particular, this relates to the areas of optimum mechanical strength of the pellet/sabot compound and of optimised gun performance. A number of technical details also have to be improved to increase the pellet velocity to ~4 km s^{-1}. Processes and components will be further optimised to permit installation of a high-speed prototype launcher by late 1989.

CEA, France, in collaboration with JET under an Article 14 Contract, are involved in a prototype development in design and testing and to produce the conceptual design of a repeating (~1 Hz) launcher suitable for an advanced system. This more comprehensive activity started in mid-1988 to solve the problems of launcher repetitivity and reliability of components, to permit the availability of a conceptual design of such a launcher in 1989, ready for a systems procurement decision. So far, the gun parts and a test-stand are under manufacture for test trials in early-1989 and a repetitive cryostat is also under design. The aim is to install a multiple high speed pellet injector in the 1990/91 shutdown.

In-vessel Components

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

The study and design of the pumped limiter was completed successfully on a collaborative basis with the U.S. Department of Energy (USDoE). Material tests showed that loads of up to 4W/m^2 could be sustained for one to two seconds at the leading edge, with surface temperatures rising up to 2200°C. However, in the light of recent results on temperature limitations in graphite to a maximum of 1100°C to avoid avalanche impurity generation, it was accepted that the scheme of a pumped limiter for JET could not be validated. It is therefore not being followed in the future. Alternative pumping methods are now being considered.

For the last few years, preparations have been made to use beryllium as an alternative to graphite. Because of dilution effects (in extreme cases, up to 80% of the particles in the plasma may result from impurities, mainly graphite) and temperature limitations due to self sputtering of graphite, it has now been agreed to introduce beryllium into JET for the next operational period in mid 1989, to enhance performance. Preparations for the required installation of beryllium components into the machine as well as the components themselves were in their final stages by the end of 1988. The components to be installed include: four beryllium evaporators, a complete set of beryllium tiles for the belt limiter as well as for RF-antennae protection and, in addition, eight new beryllium antennae screens. Successful evaporation tests have been carried out using beryllium in a testbed.

Tritium Handling

The JET schedule requires that the Active Gas Handling System should be ready for final commissioning by mid-1990 and able to commence D-T operation in mid-1991. To achieve this schedule, components must be installed by early 1990. The multi-column cryogenic distillation system for isotope separation was identified as the time critical item and a design and procurement contract was placed by the end of 1987. During 1988, the design of the major Active Gas Handling subsystems was completed and procurement contracts were placed. Detailed design work on an analytical laboratory, the gas introduction systems and piping systems were continuing into 1989. An experimental programme running in parallel gave results on crucial components in full agreement with design objectives.

A contract has been placed to define requirements for additional radiological protection instrumentation for the D-T phase. This includes monitoring of discharge stacks, environmental sampling on site and working area monitoring. Prototype samplers for HT and HTO which use a wet-proofed catalyst are proposed for environmental and stack monitoring.

Good progress has been made on the submissions to the UKAEA's Safety and Reliability Directorate (SRD) and UK's Her Majesty's Inspectorate of Pollution (HMIP) which are required to justify the safety of the Active Gas Handling System. In particular, the Preliminary Safety Analysis Report (PSAR) which sets down the design safety criteria and qualitatively assesses the safety of the overall process concept and building design was endorsed by the Safety and Reliability Directorate.

Phase 2 of the SRD approval process is the detailed design safety review of individual Active Gas Handling sub-systems. This examines in detail containment systems and protection against overpressurisation.

Design safety reviews have been completed on Impurity Processing, Cryogenic Forevacuum, and Gas Chromatography Systems and have allowed procurement of these systems to proceed with the knowledge that the basic safety of the design is sound. These Design Safety Reviews and that of the Cryodistillation system have been endorsed by SRD. Analysis of the remaining sub-systems is now in progress and the Final Safety Analysis Report, which considers system interfaces and the environmental impact is in course of preparation.

Regular meetings with HMIP and SRD are held to discuss progress on the actions required for JET to receive approval for D-T operation.

Results of JET Operations in 1988

Introduction

THE overall objective of the JET Project is to study plasma in conditions and with dimensions close to those that would be needed in a fusion reactor. The central values of temperature, density and energy confinement time needed for a reactor operating with deuterium and tritium must be obtained in which their product, ($n_i . \tau_E . T_i$) exceeds the figure of $5 \times 10^{21} m^{-3}$ skeV. Typical values for these parameters, which must be attained simultaneously in a reactor, are given in Table 7.

Using ohmic heating only, ion and electron temperatures of 3keV and 4keV, respectively, have been achieved on JET with a plasma density of $4 \times 10^{19} m^{-3}$ and energy confinement time exceeding 1.0s. These values were obtained simultaneously during one discharge and result in a fusion product of $1.2 \times 10^{20} m^{-3}$ skeV.

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

TABLE 7: MAXIMUM VALUES OF FUSION PRODUCT $\langle n_i . \tau_E . T_i \rangle$ (DECEMBER 1988)

Experimental Programme	Peak Density	Energy Confinement	Ion Temperature	Fusion Product	Plasma Current
	n_i ($\times 10^{19} m^{-3}$)	τ_E (s)	T_i (keV)	$\langle n_i . \tau_E . T_i \rangle$ ($\times 10^{19} m^{-3}$ skeV)	I_p (MA)
Ohmic (4.6MW)	4.0	1.0	3.1	12	5
ICRF (16MW)	3.8	0.4	8.0	12	3
Pellets ICRF (12MW)	5.4	0.5	7.2	20	3
NBI (20MW) low n:	1.5	0.4	20.0	12	3
Combined NBI+RF (22MW)	4.5	0.5	8.1	20	3.5
X-point (H-mode) (NBI – 15MW)	6.0	0.7	6.0	25	4

A substantial increase in the value of the fusion product has been achieved, however, by operating with the magnetic limiter (X-point) configuration in JET. During 1988, a value of $2.5 \times 10^{20} m^{-3}$ skeV was obtained using 15MW of neutral beam injection heating.

Considerably higher individual values of temperature, density and energy confinement have been obtained individually in separate experiments, but not simultaneously during one discharge. These include peak ion temperatures in excess of 23 keV, energy confinement times of up to 1.5 s and densities of about $2\times10^{20}\mathrm{m}^{-3}$.

The highest value of the fusion product that has been attained so far would need to be increased by about a factor of 20 to reach the conditions needed in a reactor. A factor of four increase would bring the conditions in JET to breakeven. The increases in performance that have been achieved on JET and other tokamaks since 1965 are shown in Fig.22.

TABLE 8: REACTOR PARAMETERS

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

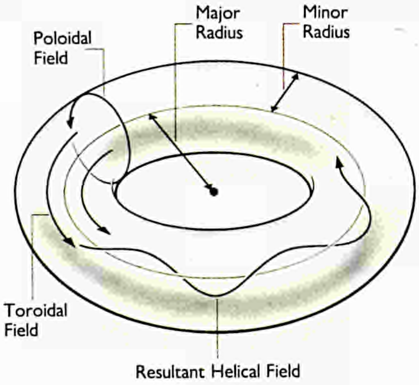
As the global energy confinement time scales favourably with plasma current in discharges with both magnetic and material limiters, the modifications carried out in 1988, to increase the plasma current in both of these modes of operation, give confidence that significant alpha-particle heating will be observed when JET is operated with deuterium and tritium together.

Magnetic Field Configuration

The toroidal and poloidal magnetic fields combine to form helical magnetic field lines which define a set of magnetic surfaces. As the strengths of the magnetic fields vary across the minor cross-section of the machine, the pitch of the field lines varies and usually decreases with increasing minor radius. The number of turns a field line must traverse around the major direction of the torus, before closing on itself, is denoted by the safety factor q. Of special importance are the positions where q is the ratio of small integers as these regions are specially sensitive to perturbations. Instabilities arising from these perturbations can result in enhanced energy losses.

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

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



Breakeven

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

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 to maintain the temperature of the plasma.

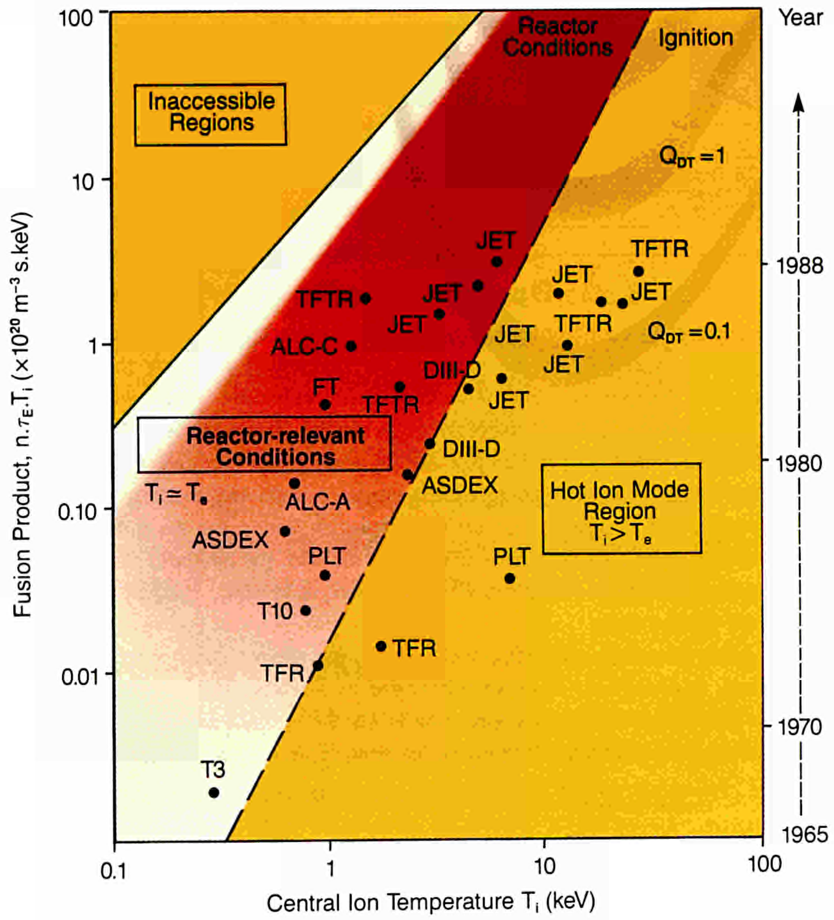


Fig.22 Fusion Parameter ($n_i.\tau_E.T_i$) versus central ion temperature, $T_i(0)$, for a number of machines worldwide in the time period 1965-1988.

Experimental Programme

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

The overall scientific programme of JET is divided into four phases as shown in Fig.23. The Ohmic Heating, Phase I, was completed in September 1984 and Phase II—Additional Heating Studies—started early in 1985. By December 1986, the first part of this phase, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the start of the second part of the additional heating studies, Phase IIB, in June 1987. The general objective of this phase, from mid-1987 until late-1988, was to explore the most promising regimes for energy confinement and high fusion

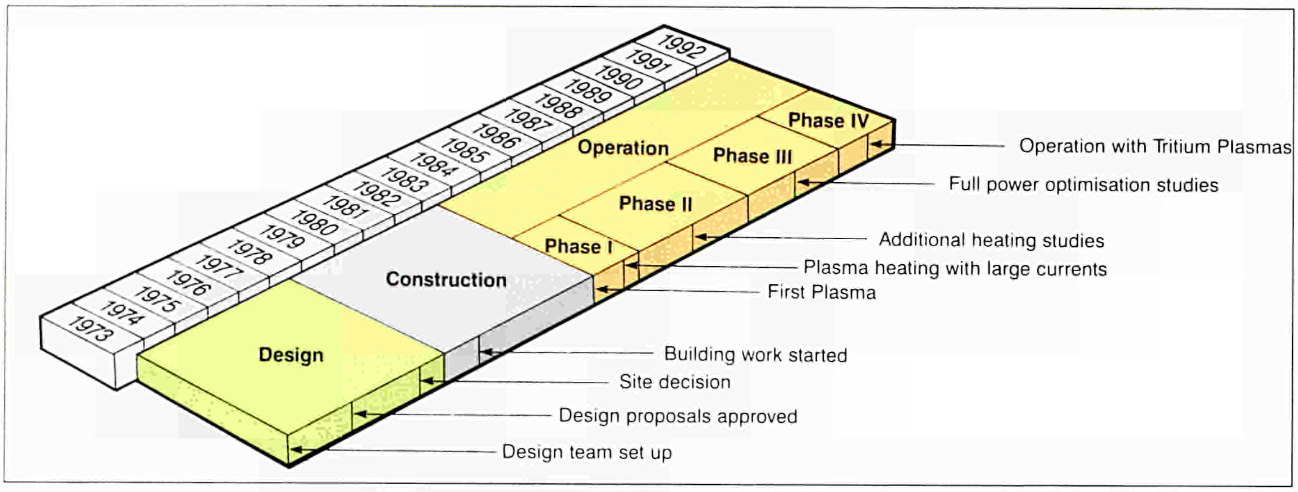


Fig.23 The overall JET Programme.

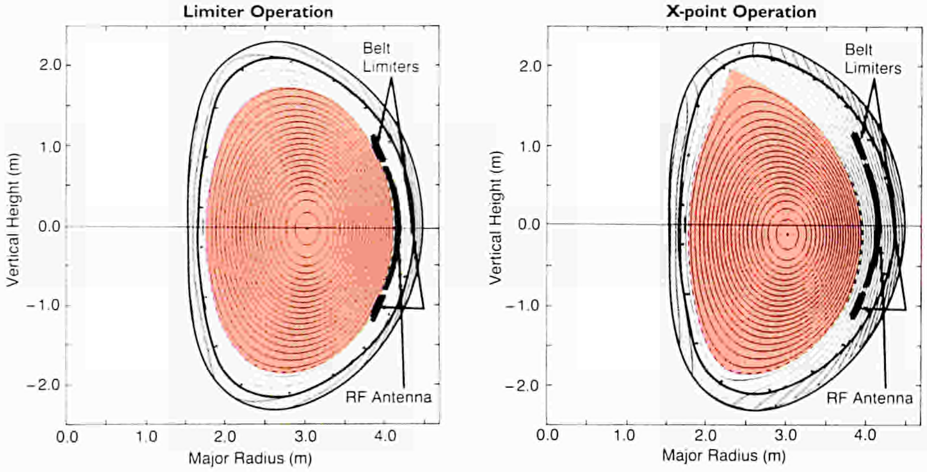
Operating Modes

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

The magnetic field configuration on JET can be modified so that one of the closed surfaces near the limiter is opened up so that it intersects with the vacuum vessel wall. In this configuration, the magnetic separatrix is moved to within the vacuum chamber.

This so called X-point configuration can be operated with the two nulls of the separatrix within the vacuum chamber (double null) or with only one inside (single null) as shown in the diagram on the right.

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


Limiter Operation

X-point Operation

yield and to optimise conditions with full additional heating power in the plasma. Experiments were carried out with plasma currents up to 7MA in the material limiter mode and up to 5MA in the magnetic limiter (X-point) mode and with increased radio frequency heating power up to 18MW and neutral beam injection power operating to over 20MW at 80keV. The ultimate objective was to achieve full performance with all systems operating simultaneously.

The 1988 experimental programme was executed by four Task Forces, with the programme objectives divided into the following four main areas:

- **Task Force A:** Full Performance and Operational Limits

  Experiments to move towards full performance conditions in the material limiter configuration by gradually increasing plasma current, from above 5 MA towards 7 MA, and with the use of full additional neutral beam injection and radio frequency heating. This would enable the performance of the belt limiters to be assessed and improve plasma confinement at high temperatures with high elongation, full-bore plasmas;
- **Task Force B:** X-Point and H-Mode Phenomena;

  Experiments in the magnetic limiter (X-point) configuration at plasma currents up to 5 MA and with high additional heating, to explore the high confinement (H-mode) regime of operation;
- **Task Force C:** Pellet Fuelling and Density Profile Effects;

  Experiments to produce dense core plasmas by injecting solid hydrogen and deuterium pellets as well as investigating the possibility of sustaining these with centralised heating, using radio frequency and neutral beam injection heating, and of tailoring the profiles for optimum fusion product;
- **Task Force D:** High Temperature Performance and High Neutron Yield;

  Experiments to obtain high fusion yields including high ion and electron temperature regimes involving a dominant non-thermal yield.

Main Scientific Results

Plasma currents exceeding 5 MA were quickly established in early 1988. There was steady progress towards higher current operation with longer duration flattops, as well as progressively increased additional heating power. Experiments were performed by the Task Forces in the four main programme areas mentioned above, involving operation in both material limiter and magnetic limiter configurations in various additional heating and pellet injection scenarios. An overview of the 1988 operation giving the percentage of time devoted to each major research area is shown in Table 9 and a summary of parameters achieved by the end of 1988 is shown in Table 10.

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

TABLE 9: PERCENTAGE OPERATING TIME DEVOTED TO MAJOR RESEARCH AREAS

Topic	Percentage of Operating Time
Task Force A	20
Task Force B	24
Task Force C	14
Task Force D	18
Diagnostic and Systems Commissioning	17
Machine Commissioning	7

TABLE 10: SUMMARY OF MAIN JET PARAMETERS
(Not necessarily in the same plasma pulse)

Toroidal field	B_t (T)	$\leq$	3.4	
Plasma current	I_p (MA)	$\leq$	6.0	7.0
Duration of maximum I_p	t_p (s)	$\leq$	8.0	2.0
Plasma major radius	R_0 (m)	$\leq$	3.0	
Horizontal minor radius	a (m)	$\leq$	1.2	
Vertical minor radius	b (m)	$\leq$	2.0	
Elongation	b/a	$\leq$	1.7	
Safety factor at plasma boundary	q_{cyl}	$\geq$	1.5	
	q_{ψ}	$\geq$	2.1	
Input ICRF power	P_{RF} (MW)	$\leq$	18.0	
Input NBI power	P_{NB} (MW)	$\leq$	21.0	
Total input power	P_{TOT} (MW)	$\leq$	35.0	
Stored plasma energy	W_p (MJ)	$\leq$	11.0	
Volume average electron density	n_e (10^{20}m^{-3})	$\leq$	0.6	
Central electron temperature	T_e (keV)	$\leq$	12.0	
Central ion temperature	T_i (keV)	$\leq$	23.0	
Global energy confinement time	τ_E (s)	$\leq$	1.5	
Fusion product (simultaneous $n_i.\tau_E.T_i$)	$(n_i.\tau_E.T_i)$ $\times(10^{20}$m^{-3}.s.keV)	$\leq$	2.5	

Density Effects

Pellet Injection

For a reactor, it is important to maximise the central density, $n(0)$, while minimizing the edge density in contact with cool material surfaces. This optimizes the number of useful nuclear fusion reactions whilst providing good insulation of the hot plasma from its surroundings. This means that a large peaking factor ($n(0)/\bar{n}$, where $\bar{n}$ is the average density) is desirable for optimum performance. An attractive method of achieving this aim is to deposit solid pellets of hydrogen or deuterium in the plasma centre.

The multiple injection of 2.7 and 4mm diameter solid deuterium pellets has been undertaken into JET plasmas under various conditions including material limiter and magnetic limiter (X-point) discharges, with plasma currents up to 5MA in ohmic, neutral beam and RF heating situations. This has been carried out as a collaborative effort between JET and a US team, under the umbrella of the EURATOM-USDoE (US Department of Energy) Fusion Agreement on Pellet Injection. The Pellet Agreement involves joint experiments during two major operational periods of JET, the first of which was completed in September 1988.

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.

A jointly built three-barrel, repetitive multi-pellet injector was used from which pellets can be injected at a maximum frequency of several per second with nominal speeds up to 1500 $\mathrm{m\,s^{-1}}$.

Experiments have shown that density peaking factors up to 3 can be achieved in JET if the pellet is deposited near the plasma centre, as shown in Fig.24. Central deposition can only be achieved if the injection velocity is sufficiently high or if the target plasma temperature is not too high. At present, the injection velocity is limited to a value of 1500 $\mathrm{m\,s^{-1}}$. In order to achieve central deposition at this velocity, one or two 2.7 mm diameter pellets were injected early into a discharge to keep the temperature low. These were followed by a high-speed 4 mm pellet which penetrated to the plasma centre. Central densities up to $2\times10^{20}\,\mathrm{m^{-3}}$ were obtained, although values of up to $1.4\times10^{20}\,\mathrm{m^{-3}}$ were more common. A typical example is shown in Fig.25, where the decay time of the density is several seconds. At these high densities, central heating with ICRF power up to 10 MW was applied and this yielded electron temperatures, $T_e(0)$, up to 12 keV and ion temperatures, $T_i(0)$, up to more than 10 keV. A typical example is shown in Fig.26, where $T_e(0)$ reaches 11 keV and the density decreases from its peak value of $1.2\times10^{20}\,\mathrm{m^{-3}}$ to $0.6\times10^{20}\,\mathrm{m^{-3}}$ during the heating period of two seconds. These successful results were achieved with a plasma current of 3 MA.

Attempts to extend experiments to 4-5 MA have resulted in the frequent occurrence of instabilities, which destroy the density peakedness quite rapidly. In some cases, with broadening of the density profile, disruptive plasma loss can occur. Experiments will continue to extend the successful experiments of clean plasmas with peaked profiles to higher currents.

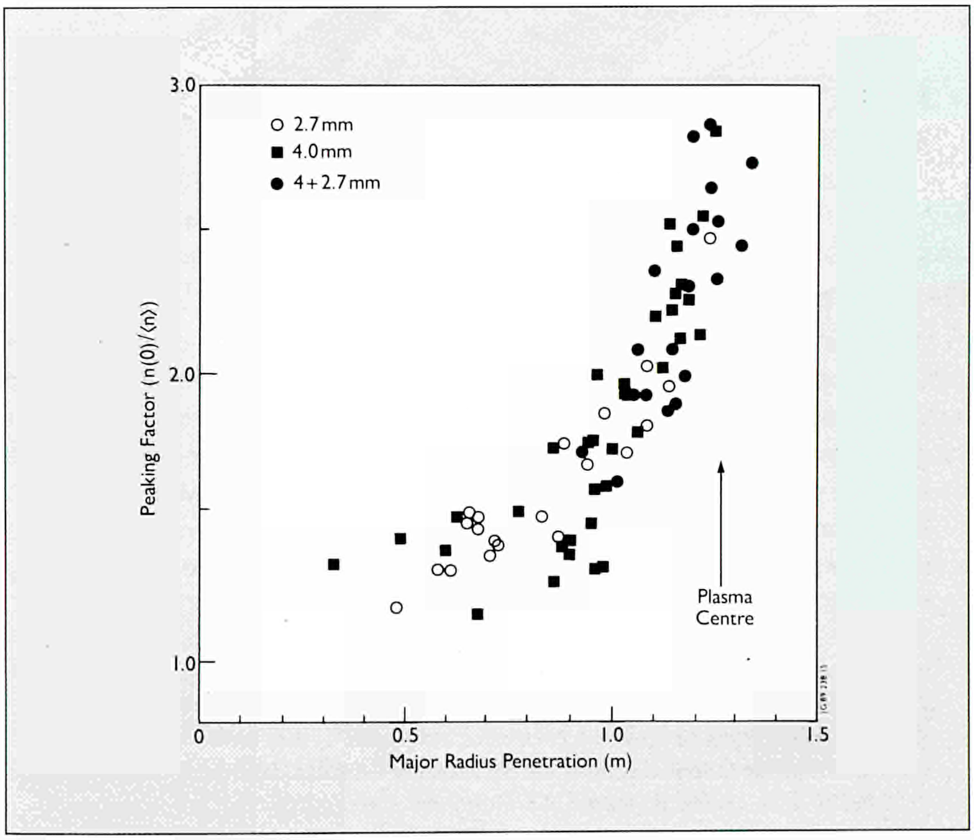


Fig.24 The density peaking factor $(n(0)/\langle n\rangle)$ as a function of major radius penetration into JET for different pellets.

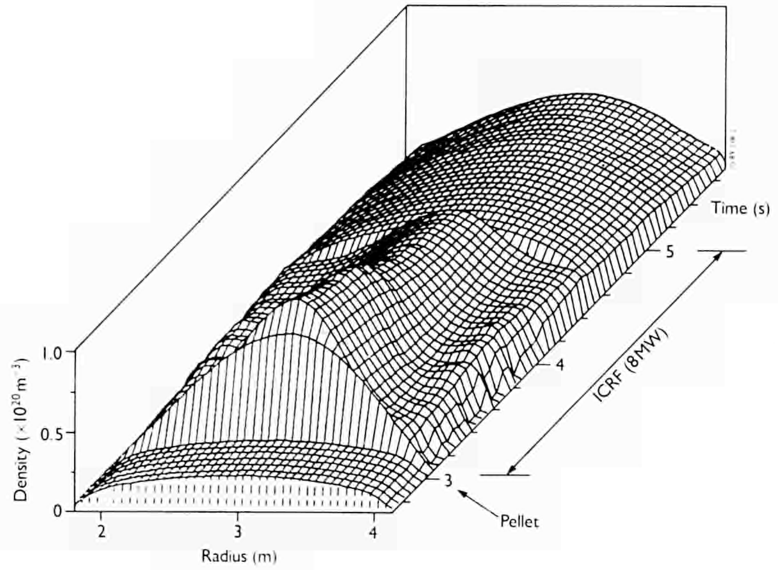


Fig.25 Plot of density profile as a function of time following injection of a pellet at $t=3$ s and then subsequent ICRF heating at 8MW.

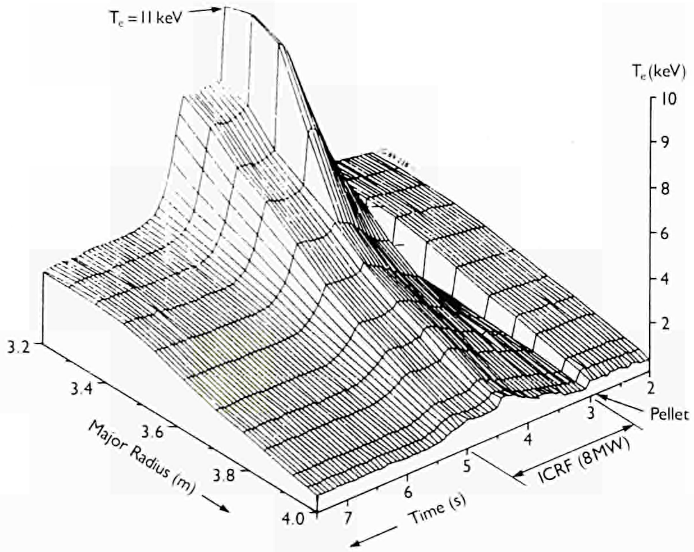


Fig.26 Electron temperature profiles as a function of time following injection of a pellet at $t=3$ s and then subsequent ICRF heating at 8MW.

Density and Current Limits due to Disruptions

In a tokamak, a disruption is a dramatic event in which plasma confinement is suddenly lost, followed by a complete loss of plasma current. Disruptions pose a major problem for tokamak operation as they limit the density and current range in which stable plasmas can be achieved and their occurrence leads to large mechanical stresses and to intense heat loads on the vacuum vessel.

A diagram of the stable operating regime (without disruptions) can be constructed by mapping the normalised current $1/q \propto I_p/B_t$ (where q is the safety

Disruptions

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

factor, I_p the plasma current and B_t the toroidal field) against the normalised density $\bar{n}R/B_t$ (where $\bar{n}$ is the average density and R the major radius). This is shown in Figs.27 and 28. The density limit is dependent on plasma purity and the power to the plasma. In ohmically heated plasmas, the operating diagram is shown in Fig.24 and the density limit is given by:

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

However, with pellet injection, the plasma impurity is improved and the limit can be increased as shown in Fig.27.

With substantial additional heating from RF, NB or combinations of both, the limit is increased substantially, as shown in Fig.28 to:

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

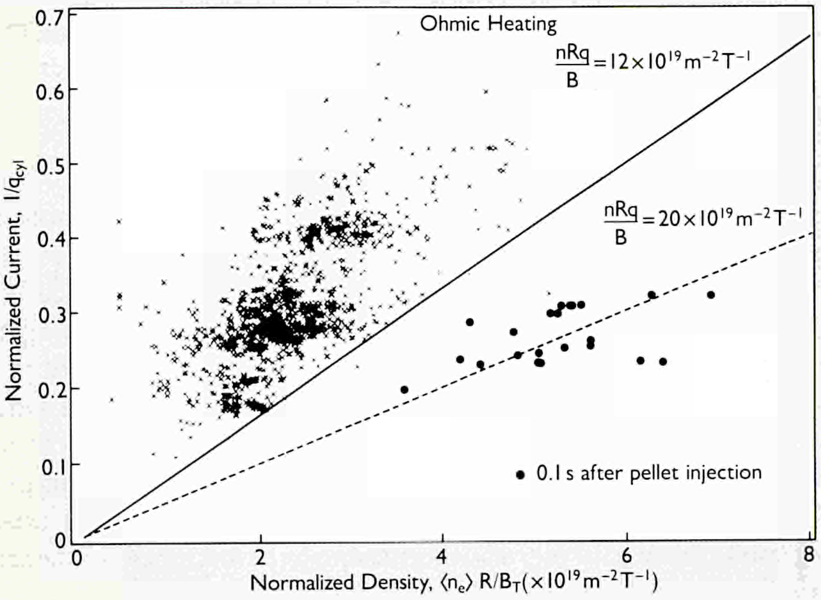


Fig.27 Normalized current ($1/q$) plotted versus normalized density ($\bar{n}R/B$) for ohmic discharges in JET.

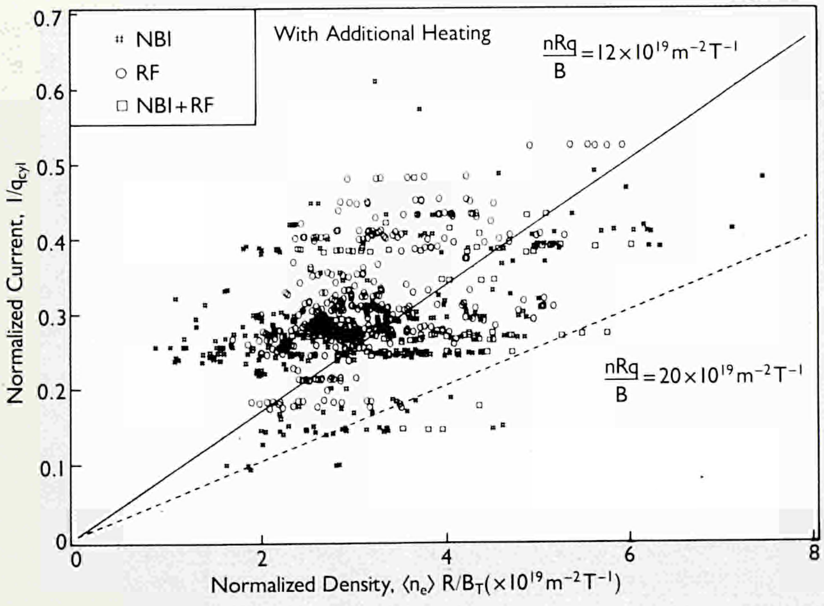


Fig.28 Normalized current ($1/q$) plotted versus normalized density ($\bar{n}R/B$) for plasma with additional heating.

If the neutral beam heating is switched off at high density the plasma disrupts, which indicates that power input plays an important role in the disruption mechanism.

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

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

Temperature Enhancements

Sawtooth Oscillations

In almost all JET discharges, the central temperature and density is modulated by sawtooth-like oscillations. This is due to the periodic occurrence of a magnetohydrodynamic (mhd) perturbation associated with a plasma surface whose safety factor, q, has a value of unity. Heating in the plasma centre leads to a gradual rise in the central temperature which is terminated suddenly by the rapid growth of the mhd instability. The principal effect is to flatten the temperature and density profiles across the region inside the so-called mixing radius, which can range from about one to two thirds of the plasma radius. In addition, high energy particles, produced by the auxiliary heating or by fusion reactions, can be expelled from the plasma centre to larger radii where they may be lost rapidly to the plasma periphery.

Therefore, the consequences of the sawtooth instability are serious in two respects. Firstly, the modulation of the central plasma parameters leads to a significant fluctuation in the fusion power produced. The magnitude of this effect may be appreciated from the observation that the temperature modulation may reach 50% and the fusion power scales as n^2T^2. In addition, the loss of energetic α-particles from a reactor plasma may constitute a significant degradation in the power balance, increasing the power threshold for breakeven.

Extensive studies are underway at JET to develop techniques for suppressing this instability. In particular, it is planned to control the current profile directly, and hence to eliminate the $q = 1$ surface. This will be achieved by the injection

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.

of radio-frequency waves or neutral beams in the plasma. Recently, however, a spontaneous stabilization process was discovered during additional heating experiments in JET, which has resulted in the production of sawtooth-free periods (called 'monsters') of up to 3.2s. It has also been possible to influence the current profile through the modification of the temperature profile which results from the injection of solid deuterium pellets, which are used in plasma refuelling experiments. Additionally heated sawtooth-free periods lasting up to 5.1s have been produced in this way.

The discovery of these regimes has led to experiments designed to optimise confinement, plasma temperature and fusion power in the absence of the deleterious effects of sawteeth. Fig.29 illustrates an example in which both central ion and central electron temperatures were maintained above 10keV for more than 1s. The very peaked ion and electron temperature profiles which can be achieved by the suppression of sawteeth are illustrated in Fig.30, and indicate the substantial improvement in peak ion and electron temperatures achieved in the plasma during the stable period.

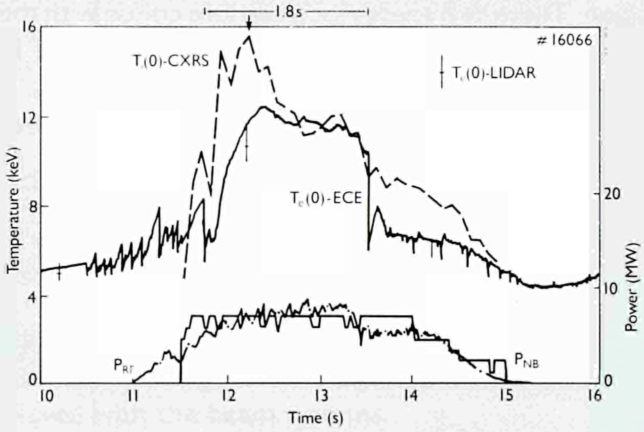


Fig.29 Electron and ion temperatures, T_e and T_i, as a function of time showing a 'monster' sawtooth of 1.8s duration. The duration of input neutral beam and RF power, P_{NB} and P_{RF} is indicated.

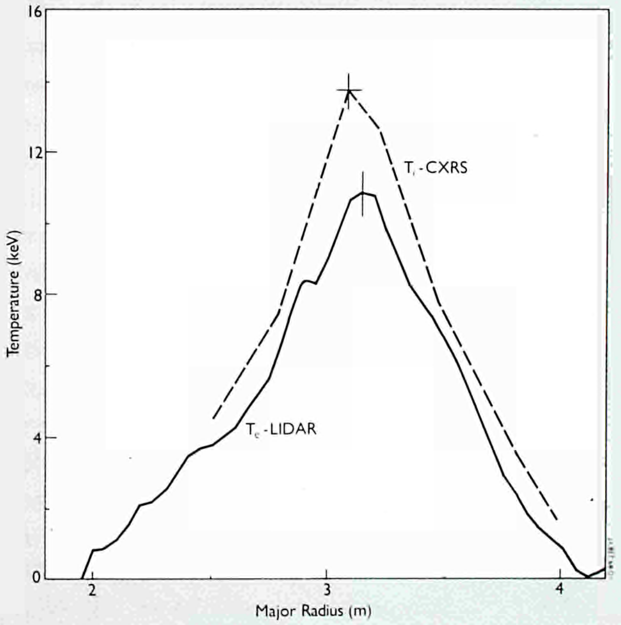


Fig.30 The electron and ion temperature profiles taken at their maximum values ($t = 12.2$s) during the 'monster' sawtooth.

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 3.7 GHz.

Radio Frequency Heating

The ion cyclotron resonance frequency (ICRF) heating system is used for highly localized heating of the JET plasma. The wide frequency band (23-57 MHz) allows the heating position to be selected where ion cyclotron resonance occurs with the local magnetic field, which varies across the radius of the machine. A minority ion species (H or ^{3}He (1 - 10%), at present, and D in the future D-T phase) is injected into the plasma for this purpose, and absorbs the RF power at the local resonance position. These high energy localized ions collide with the plasma electrons and ions, transferring energy and causing a rise in the local electron temperature (T_e) and ion temperature (T_i) of the main plasma.

ICRF heating studies have been carried out using both hydrogen and ^{3}He minority ions with input powers to the plasma of up to 18 MW. Optimum efficiency in heating has been found with the resonance position on-axis. The effect of minority ion concentration on electron and majority ion heating by ICRF power has been investigated in both ^{4}He and deuterium plasmas. The resulting central

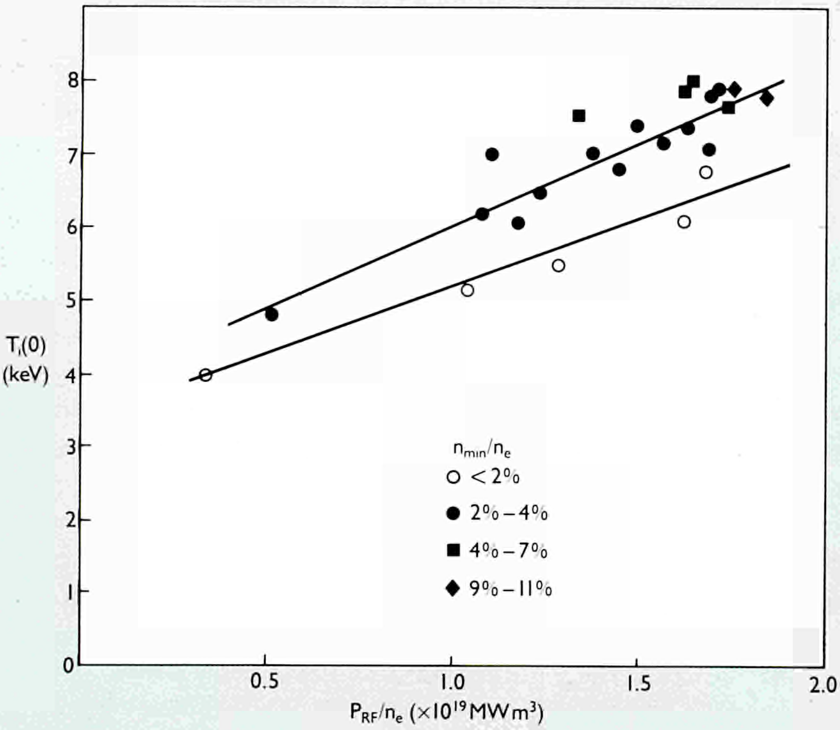


Fig.31 Central ion temperature versus power input per particle (P_{RF}/n_e) for various ^{3}He minority ion concentrations.

ion temperature, $T_i(0)$, versus the ratio of RF power to density, P_{RF}/n_e, is shown in Fig.31 for values of the minority concentration (n_{min}/n_e) in the range 1 - 11%. The highest values of $T_i(0)$, up to 8keV for 12MW of RF power, were achieved with the higher minority concentrations. Such a trend was expected since the minority ion temperatures were smallest under these conditions, thereby enhancing the collisional power transfer to the majority ions at the expense of electron heating. Electron heating was expected to be strongest at low minority concentration and this tendency was also observed.

ICRF heating applied to pellet produced high density peaked plasmas has achieved electron and ion temperatures up to 12keV and 10keV, respectively. This was obtained with 10MW of power input to a 3MA target plasma in which the peaked density profile was sustained for up to 1.5 seconds as shown in Fig.25. In addition, 13MW of RF power injected into a 5MA material limiter plasma achieved a plasma stored energy exceeding 7MJ.

Long pulse operation has been successfully achieved on JET, in which the 3MA plasma current was maintained for over 30 seconds. During this time, ICRF heating power at 5MW was applied for about 20 seconds, exceeding 100MJ energy into the plasma. Ion and electron temperatures both exceeded 5keV throughout this period. This was an important demonstration of long period stable operation in JET.

Neutral Beam Injection Heating

During the year, the second neutral beam injection box was commissioned and both beam lines were brought into full simultaneous operation. This culminated in a maximum injected power into the JET plasma of 21.6MW of neutral deuterium atoms at 80kV, which exceeded the design power of 20MW. Towards, the end of the 1988 operating period, a high degree of availability and reliability have been achieved with the beam systems.

If densities are not too high, the neutral beams penetrate to the centre of the plasma and deposit their energy centrally. In these conditions, the beam energy is transferred mainly to the plasma ions, causing large increases in ion temperature. This is the so called 'hot-ion mode' of operation. Fig.32 shows a plot of central ion temperature. $T_i(0)$, has a function of total input power per plasma particle, $P_t/n(0)$, in this mode. It is seen that temperatures of up to 23keV have been achieved in JET for neutral beam powers of 20MW. In this mode, the ion temperature profile is sharply peaked, as shown in Fig.33, and the electron temperature is significantly lower than the ion temperature.

Experiments have been carried out at higher densities ($n > 2\times10^{19}m^{-3}$) with combined neutral beam and ICRF heating into the plasma. In this situation, the ions and electrons are heated together and both central ion and electron temperatures have exceeded 11 keV in a 3MA plasma for a power input of 33MW (21 MW of NBI and 12MW of ICRF). This example is shown in Fig.34, where the central density, $n(0)$, exceeded $2\times10^{19}m^{-3}$. In addition, with a 6MA plasma and a total input power of 24MW, the central ion and electron temperatures have exceeded 6keV for a central density of $6\times10^{19}m^{-3}$.

Fig.32 Central ion temperature as a function of power input per particle $(P_t/n(0))$.

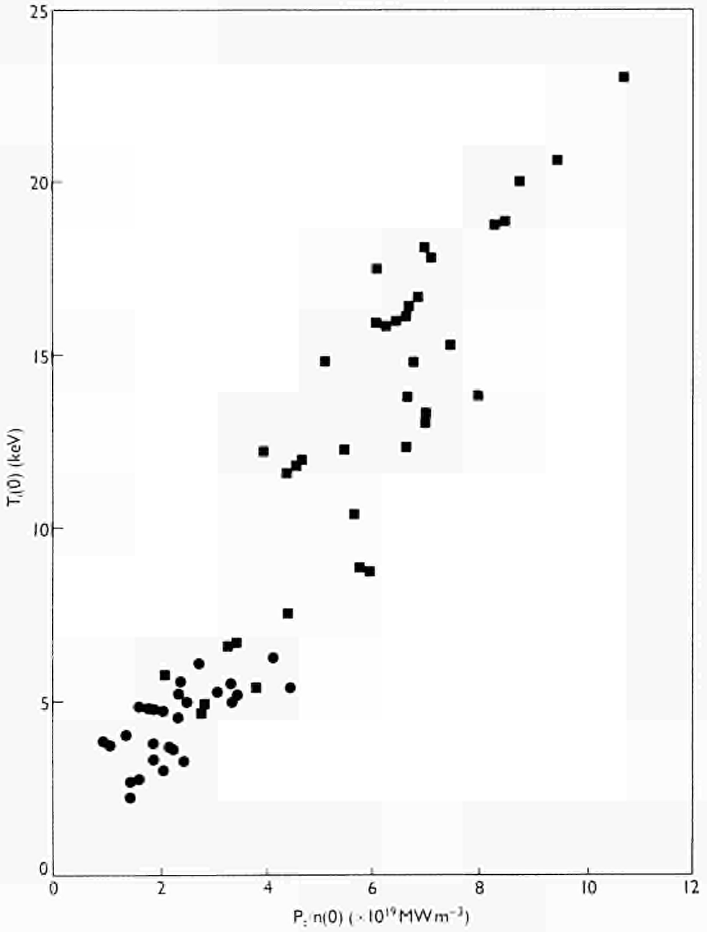
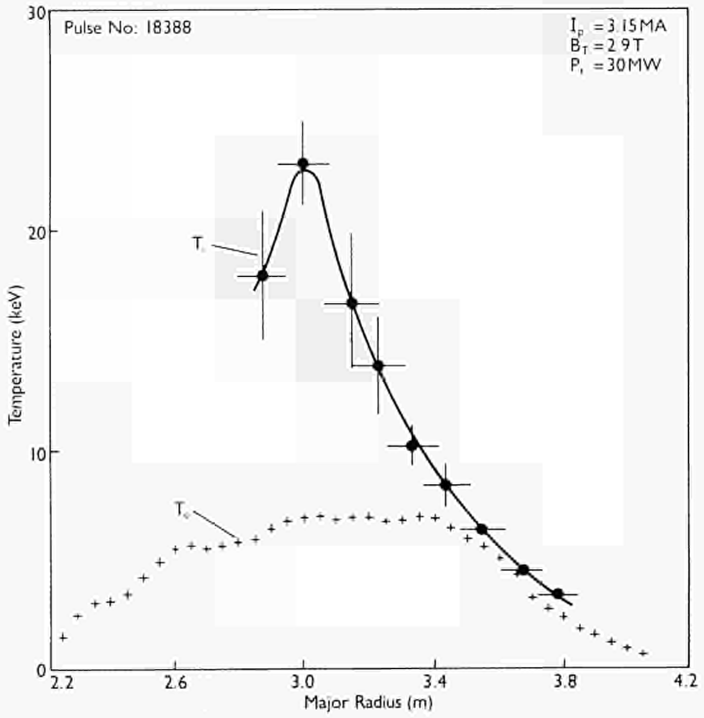


Fig.33 Ion and electron temperature profile for high power input of 30MW.



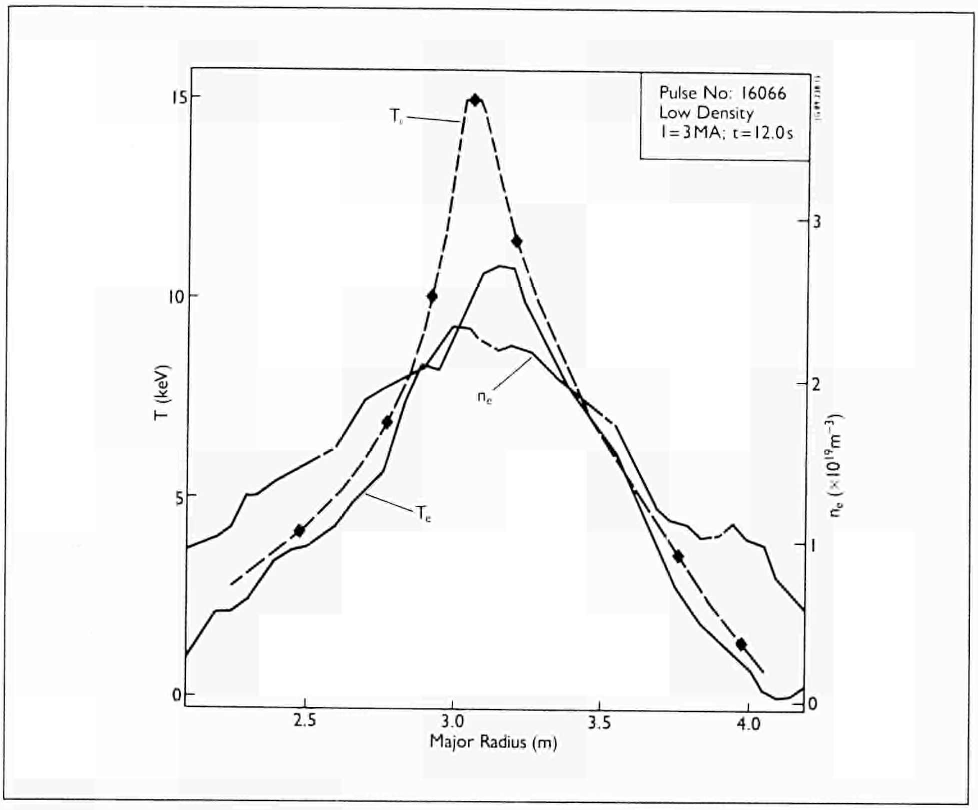


Fig.34 Ion and electron temperature profiles and density profile during a large (33 MW) combined heating scenario.

Energy Confinement

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

$$\tau_E = \frac{W_k}{P_t - dW_k/dt}$$

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

Material Limiter Configuration

The energy confinement time in JET ohmic discharges reaches values in excess of 1.2s. However, the temperatures reached in these plasmas are too low for fusion, so the important confinement time behaviour is that in additionally heated conditions.

The energy confinement time on JET falls with increasing heating power, as seen in a number of experiments and this effect is independent of the type of heating, whether neutral beam injection, radio frequency or a combination of the two methods. The decrease of energy confinement time with increasing heating power in material limiter cases is shown in Fig.35. The rate of increase in plasma energy with power input, $\Delta W_k/\Delta P_t$, appears to reach a limit of between 0.1 and 0.3s at high powers. This indicates that there is a lower limit to the energy confinement time in JET of between 0.1 and 0.3s. Only a weak dependence on plasma density has been found for the energy confinement time but there is a favourable scaling with plasma current.

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

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

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

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

with an incremental confinement time of $\tau_{inc} = 0.22 I_p^{0.5}$ in non-sawtooth cases. The units are W(MJ), $n(\times 10^{19} m^{-3})$, I(MA), B(T), and τ_{inc}(s).

Magnetic Limiter Configuration

In the magnetic separatrix (X-point) configuration, the plasma is detached from both the limiter and inner wall and recycling occurs in an open divertor region near the X-point. Stable discharges with a magnetic separatrix have been maintained in JET for several seconds at plasma currents up to 5MA with the single-null configuration and up to 3.5MA in the double-null situation. Operations in this configuration have been undertaken to compare the global confinement characteristics with those with limiter discharges, as well as to study the conditions for the creation of a high density, highly radiative, cool plasma region near the X-point which is capable of screening and isolating the bulk plasma.

With neutral beam injection heating above a certain threshold value, which is dependent upon the toroidal magnetic field, a transition occurs to an improved plasma confinement (H-mode) regime. Fundamental characteristics include a rise in the plasma density and energy content as well as an increase in electron temperature near the separatrix, which produces a pedestal in the temperature profile, and a flat density profile with a steep gradient near the separatrix. The global energy confinement time in the H-mode exceeds that obtained with limiter discharges by more than a factor of two, as shown in Fig.36.

During 1988, H-mode operation in JET single-null X-point configurations has been extended to plasma currents up to 5MA, toroidal magnetic fields of 3.4T and neutral beam powers of 20MW. The threshold power for achieving an H-mode was found to increase with toroidal field, from ~5MW at 2.0-2.4T to ~10MW at 3.0-3.4T. In addition, minimum separations of the separatrix from the inner wall (~0.05m) and from the belt limiter (~0.05-0.08m) and of the X-point from the target plates (~0) were required.

During some magnetic limiter discharges Edge Limiter Modes (ELM) of instability appear at the plasma edge, leading to loss of confinement. However, a characteristic of most JET H-modes was the absence or very low level of ELM activity throughout the whole H-mode phase. This resulted in a continuous rise in plasma density and a corresponding increase in bulk plasma radiation which finally terminated the H-mode when the bulk radiation reached about 60% of the input power. The longest H-phase observed was ~4s. The increase in the total energy content of the plasma during the H-phase resulted largely from the plasma density increase, while the central electron temperature was roughly constant or even decreased slightly with time. Density profiles during the H-phase were flat or even hollow. The electron temperature profile was broad and changed little with time. The most characteristic feature of the temperature and density profiles were the very steep gradient at the plasma edge giving rise to so-called pedestals.

The global energy confinement time of these ELM-free H-mode discharges is a factor of 2-3 larger than in comparable limiter discharges, as shown in Fig.37.

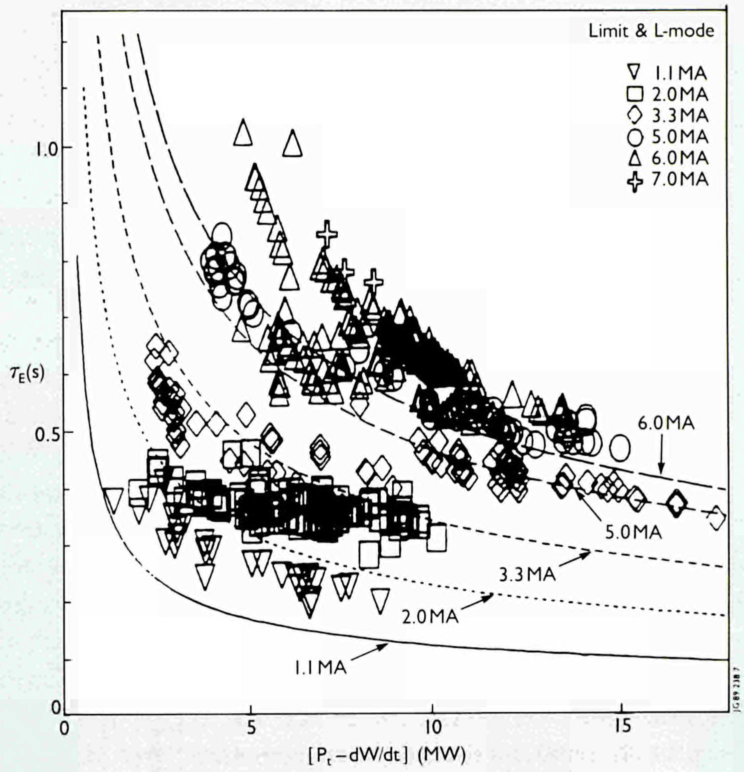


Fig.35 Confinement time as a function of input power for material limiter and L-mode conditions.

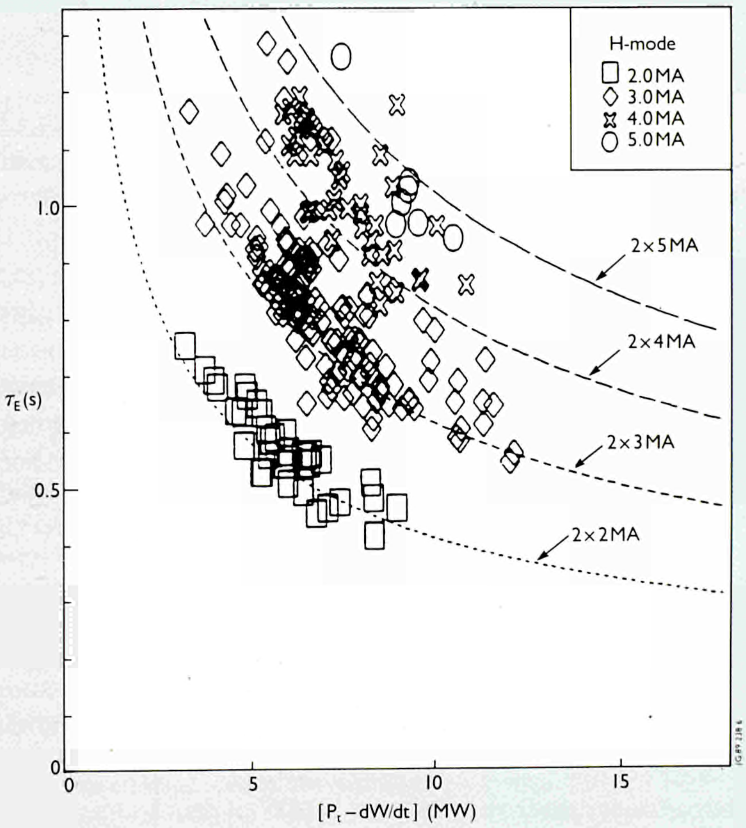
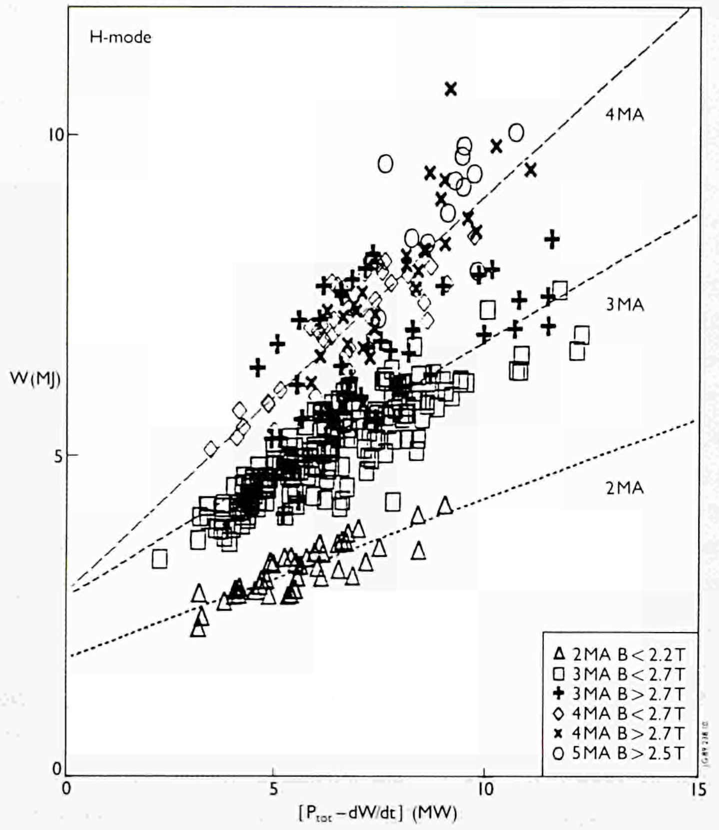


Fig.36 Confinement time as a function of input power for H-mode conditions.

Fig.37 Stored energy as a function of input power for H-mode plasmas.



In addition, the plasma energy has reached 11 MJ in the plasma with 12 MW of beam input power. The confinement times increased roughly linearly with plasma current and to a lesser extent with toroidal magnetic field but decreased with increasing neutral beam heating power, P_{NB}, (approximately proportional to $P_{NB}^{-0.7}$). Part of this degradation with power can be attributed to poor beam penetration at the higher densities corresponding to improved particle confinement at higher power levels.

So far, attempts to achieve the H-mode using radio frequency heating alone have not been successful during limited experiments but encouraging results have been obtained with RF and neutral beam heating in combination. Further experiments will be carried out during 1989.

In summary, in the H-mode:

- the H-mode was obtained at currents up to 5 MA, with energy confinement times of up to 1.2 s;
- the fusion product $(n_i.\tau_E.T_i)$ has reached $2.5\times10^{20}m^{-3}$ keV.s at temperatures exceeding 5 keV;
- Total plasma energy reached 11 MJ with 12 MW of deuterium neutral beams.

Other Material Studies

Impurities

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

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

There are three main impurities observed in JET; carbon, oxygen and nickel. The carbon levels currently on JET range from 2% to over 10%. The level depends strongly on average density, plasma current and input power. In ohmic discharges, a consistent pattern is observed with the concentration decreasing as the density increases. This behaviour is also characteristic of metal impurities though the dependence on density is much stronger with metals. The carbon concentration increases as the plasma current increases. This general behaviour is consistent with the global behaviour of the edge density and temperature and is in quite good quantitative agreement with physical sputtering by plasma ions at the limiter.

During some phases of JET operation, oxygen concentrations have been at the few per cent level, and at high densities, this has been the source of a major

Impurities

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

(a) increased radiation losses;

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

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

Major energy losses can result from two radiation processes:

(1) Bremsstrahlung Radiation—radiation is emitted when electrons are decelerated 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 upper and lower belt limiters. These are cooled structures circling the outboard torus wall with carbon tiles attached. Carbon has a relatively low electric charge on the nucleus. Prior to some experimental pulses, a glow-discharge is operated in methane so that the walls become carbonised. This reduces the level of heavy impurities released from the walls.

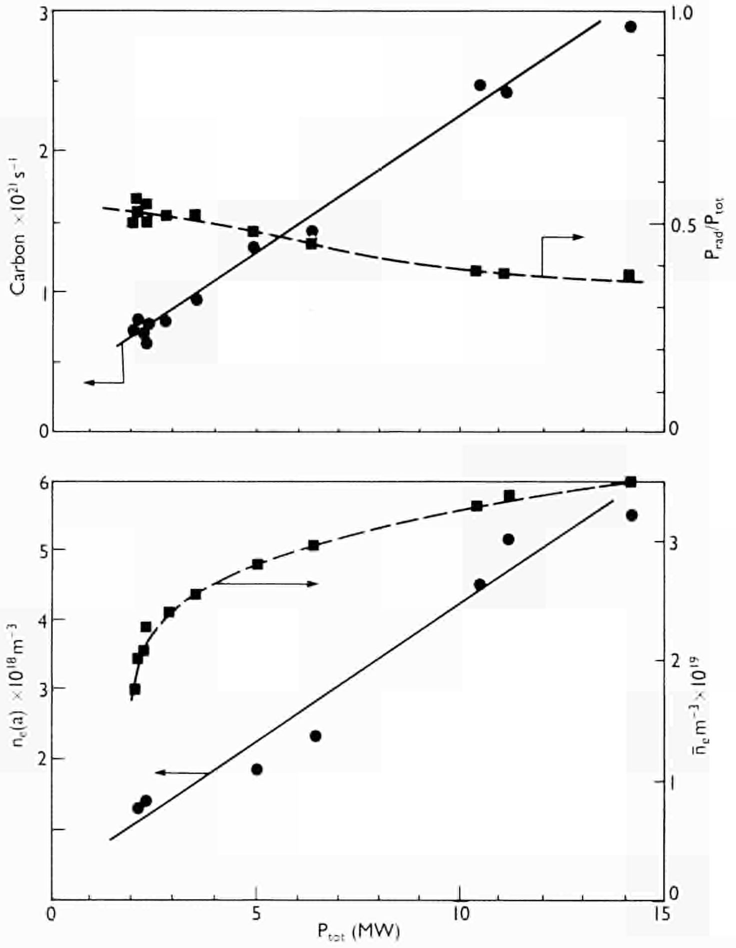


Fig.38 The ICRF heating power scaling of the carbon influx from the lower belt limiter, the radiated power fraction P_{rad}/P_{tot}, the edge density $n_e(a)$ and the volume-averaged density $\bar{n}_e$ in a 3.3MA discharge.

power loss by radiation. However, during 1988, the oxygen level has been consistently low, typically ≤0.5%. This may be attributable to the consistent use of helium glow discharge cleaning before each operational day. At its present levels, under most operating conditions, oxygen plays only a minor role in the radiation and in Z_{eff}, compared with carbon. The concentration of nickel over the last operational period has been generally in the range 10^{-6} to 10^{-4} of the electron density. At these levels the contribution to radiation and to Z_{eff} can be neglected. During RF heating, nickel levels have occasionally risen to ~0.1%, radiating up to 3MW. Earlier work established that the nickel comes directly from the RF antennae shields. It has also been shown that metal injected into the plasma can be deposited on the limiters and the carbon antennae protection tiles. When the source of nickel stops the nickel is progressively removed from the surface of the limiters by a process of erosion and redeposition. The mechanism of nickel injection into the plasma during RF heating is not clear. The metallic flux into the plasma is quite reproducible and depends roughly linearly on RF power (~5×10^{19} atoms/MW).

The fluxes of fuel and of impurities into the plasma from the limiter and the wall are routinely measured using neutral or low ionisation states and calculated values of the photon efficiency. The carbon flux, measured by CIII spectroscopy, is roughly constant with increasing average density, $\bar{n}_e$, at a given plasma current, while the oxygen flux depends strongly on the condition of the machine. The oxygen flux is always high after opening the vacuum vessel, but can drop rapidly to well-conditioned values after only one or two weeks of operation.

As the ICRF input power is increased, the central plasma density increases. The resulting edge density rise is somewhat greater, being roughly proportional to the total input power. The increase in density is such that the electron temperature in the boundary $T_e(a)$ remains constant at ~ 55eV. The carbon sputtered from the limiter increases roughly in proportion to the edge density (as shown in Fig.38), as expected, since a constant electron temperature implies a constant sputtering yield and a constant photon efficiency for the radiating atoms.

Since the sputtered carbon flux is proportional to the edge density, in turn, it is proportional to the total input power (see Fig.38). During high power operation, this scaling breaks down, as enhanced carbon erosion occurs at 'hot spots' that appear at the limiter tile edges, typically with an area of $\sim$ 10cm^2. The temperature of the hot spots reaches $\sim$ 1600°C. As a result of a massive carbon influx from this and other locations, the discharge detaches from the limiter, the total radiation abruptly jumps from $\sim$ 40% to $\sim$ 100%, and the edge density and temperature drop significantly. Once the heating power is reduced, the discharge re-attaches and the edge signals and radiated power revert to more typical values. In X-point discharges, there is also evidence for suddenly enhanced carbon influxes and plasma detachment. Tile temperatures frequently exceed 2100°C during H-modes.

The parameter which provides a measure of the impurity content of a plasma is the effective ion charge, Z_{eff}, which is the average charge carried by an ion in the plasma. The global impurity content is measured routinely throughout each pulse by measuring the radial profile of Z_{eff}. In general, during the ohmic phase, $Z_{eff}(r)$ is peaked on axis with $Z_{eff}(0)/Z_{eff}(a) \lesssim 2$ and $Z_{eff}(0)/\bar{Z}_{eff} \lesssim 1.3$. On the application of high ICRF powers to the plasma ($\gtrsim$4MW), a steady rise in $\bar{Z}_{eff}$ occurs and $Z_{eff}(r)$ becomes broader. These effects are due to increased impurity production at the plasma edge, resulting from the power loading of the RF antennae. Careful attention to antennae operation and preconditioning of the vacuum vessel by running a number of discharges in helium reduces the plasma contamination by impurities. In magnetic limiter plasmas, with an H-mode following neutral beam injection, $Z_{eff}(r)$ is quite hollow on-axis and peaks at $r/a \sim 0.5$, which is approximately the location of the $q=1$ surface. $\bar{Z}_{eff}$ rises steadily throughout the H-mode by a factor of 3 - 5, due to an increase in impurity confinement by a factor of 3 - 5.

With neutral beam injection in limiter discharges, the increased fuelling from the beams causes a steady reduction in $\bar{Z}_{eff}$, although the relative phase $Z_{eff}(r)$ is little changed from the ohmic phase. Even though the beams can increase the source of deuterium on-axis by over two orders of magnitude, it is the recycling at the plasma edge that dominates the global particle balance. The injection of deuterium pellets into the JET plasma has the most dramatic effect on the temporal evolution of $Z_{eff}(r)$. Where deep penetration is achieved, values of $Z_{eff}(0)$ of < 1.3 are transiently produced due to an abrupt dilution of the core impurities by deuterium ions from the pellet. Subsequently, on a time-scale of 3 - 4s, recycling establishes a higher $\bar{Z}_{eff}$ which is consistent with edge fuelling.

Under normal operating conditions, the dominant impurities are carbon, with oxygen being the next most important—usually at a concentration of 2-3 times less. $\bar{Z}_{eff}$ values, and hence the fuel dilution n_D/n_e, vary considerably, depending on the mode of operation of the tokamak. In general, the deuterium concentration improves with increasing density. In the case of low-density discharges, with high T_e achieved using $\gtrsim 20$ MW of additional heating, n_D/n_e, can be as low as ~ 0.25. The value improves to ~ 0.4 in the case of medium-density discharges, with 30 MW of auxiliary heating, and for high-density H-mode discharges, achieved using 15 MW of neutral beam injection, n_D/n_e is ~ 0.5. Undoubtedly, the best results have been achieved by the simultaneous application of auxiliary heating and pellet injection—values of n_D/n_e of $\lesssim 0.8$, with 20 MW of heating, have been measured.

Plasma Boundary Phenomena

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

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

With the new belt limiters, extensive measurements have been made of radial flux profiles, edge density, electron temperature and floating potential for ohmic, ICRF heating and X-point discharges. Scaling of edge density and temperature with line average density (ohmic discharges) and total input power (ICRF discharges) show similar results to those for the previously-used discrete limiters, although absolute values are lower. As the additional heating power to the plasma increased, the edge density increased almost linearly with power and the edge temperature stayed approximately constant. At low to moderate input power, the impurity influx increased proportional to the edge density, so that Z_{eff} stayed nearly constant. This contrasted with the situation when the plasma density was increased at constant power, where Z_{eff} increased.

At the highest additional heating powers used (20 – 30 MW), enhanced impurity production was observed. The effective carbon atom yield per ion incident on the limiter increased significantly above that expected for physical sputtering. The enhanced yield was associated with high limiter surface temperatures. It occurred for inner wall discharges, belt limiter discharges and X-point discharges. The lowest power threshold was for inner wall bounded discharges. The increased carbon influx resulted in increased fuel dilution, increased radiation and reduced neutral beam penetration.

The thickness of the scrape-off layer has been studied as a function of input power, plasma current and density. The thickness of this layer decreases with increasing plasma current to a value of typically 5 – 10 mm at 5 MA. The decrease is at least partially due to the change in safety factor, q. The layer thickness does not change significantly with density over the range so far studied ($\bar{n}_e = 1 - 5 \times 10^{19} \mathrm{m}^{-3}$). Unfortunately, the decrease of the scrape-off layer thickness with current leads to increased local power loading on the limiter and hence higher surface temperatures, and so contributes to the higher impurity production rate.

The divertor plasma in the vicinity of the X-point target plates has been investigated. Profiles of density, temperature and ion saturation current in front of the target plates have been measured for a 4.6 MA discharge (ohmic and H-mode) with neutral beam power of 14 MW (see Fig. 39). The inner divertor plasma is colder and denser than the outer, and more power is carried to the outer divertor target. The scrape-off layer current flows from the outer to the inner divertor and returns through the target plates, thus flowing in the same direction as the plasma current. The plasma power carried to the target plates increases from 0.8 MW in the ohmic phase to 1.9 MW at the end of the H-mode. For most of the discharge (L and H-modes), this is about 15% of the total power, but is about 25% during the ohmic phase. The location of the separatrix in the divertor is dependent on plasma conditions. The point where the outer separatrix intersects the divertor target moves to smaller major radius as the discharge changes from ohmic to L- to H-modes. The movement shown is of the order of 1 cm. There is an outward movement when a sawtooth arrives in the plasma edge evident in the D_α profile. These results suggest a β-dependence of separatrix location in the divertor.

During 1988, the pumping effects of the walls and limiters were investigated in different modes of operation, as shown in Fig.39. The density decay behaviour in a discharge is shown for three conditions: (a) with belt limiters; (b) with inner bumper limiter; and (c) with an elongated plasma limited by the top and bottom wall tiles. The density decayed, indicating wall pumping, in all three cases. There are two different pumping mechanisms: first, the density decay when the plasma resides at a certain surface; and second, the density decay when the plasma is moved from one place (for example the limiter) to another (such as inner wall or top/bottom). The first mechanism produces a permanent particle loss at a slow rate of $\sim 5\times10^{19}$ electrons/s. The second mechanism pumps at an initial rate of about 10^{21} electrons/s and occurs only in a transient phase for one second after moving the plasma. This can be explained by the increase in edge density when the limiter is on the high field (inner wall) side of a tokamak. The radial expansion of magnetic flux tubes at the plasma edge on the inboard side enhances the screening of recycled neutrals so that the fuelling efficiency is much reduced and thus the plasma density decreases provided the particles can stay in the wall for a particle confinement time. This effect is strongest for plasmas limited by the top or bottom of the wall (expansion of field lines), which is consistent with the experimental observations (see Fig.40).

Summary of Achievements

During 1988, the operational domain has been extended, and, in particular, the following technical and scientific achievements have been made:

In quasi steady-state:

- a plasma current of 7MA has been obtained for 2s in the plasma;
- JET has operated routinely with the current above 5 MA, and a current of 6 MA has been maintained for 7 s;
- ion and electron temperatures, T_i and T_e, in excess of 5 keV have been sustained for over 20 s at a plasma current of 3 MA;

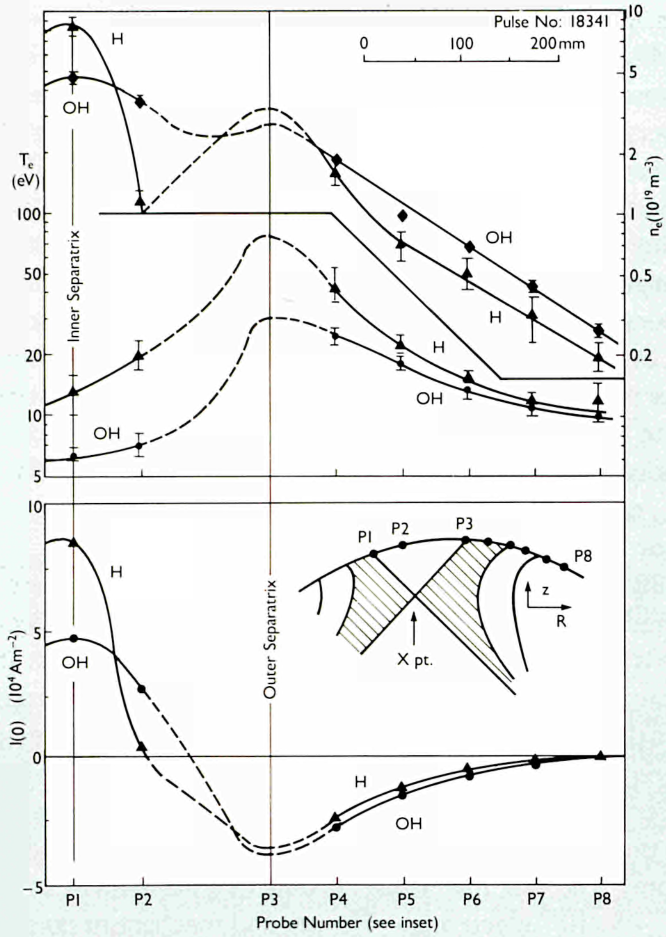


Fig.39 Profiles of density, temperature and ion saturation current in front of the target plates, measured with Langmuir probes mounted in these plates during the ohmic phase of a $I_p = 4.6$MA discharge and during an H-mode with 14MW of neutral beam heating.

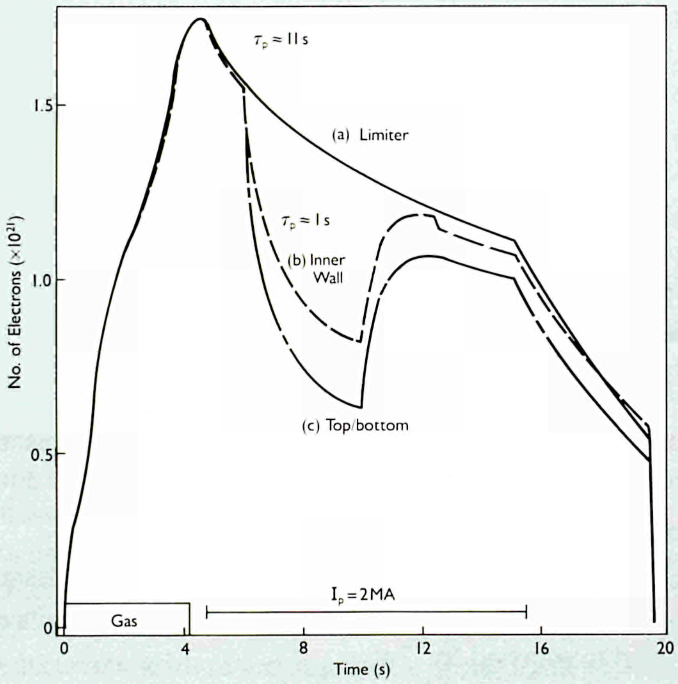


Fig.40 Total electrons in the plasma as a function of time for three discharges, defined by (a) the limiter, (b) the inner wall and (c) the top/bottom of the vacuum vessel.

- additional heating power up to 32 MW has been delivered to a 5 MA plasma producing a total stored energy exceeding 10 MJ;
- both electron and ion temperatures simultaneously in excess of 10 keV for 2 s were observed at a plasma density of $2\times10^{19}m^{-3}$;
- confinement times exceeding 1 s have been observed;
- neutron yields have reached $1.2\times10^{16}n.s^{-1}$ with 20 MW of deuterium neutral beams (at 80 kV).

In a more transient situation:

- JET has routinely operated with a magnetic separatrix at a plasma current of 4.5 MA. H-mode plasmas were regularly observed during neutral beam heating;
- A record H-mode plasma at 5 MA has been obtained. Transiently, during an H-mode, the fusion product $(n_i.\tau_E.T_i)$ reached $2.5\times10^{20}m^{-3}.s.keV$ at temperatures exceeding 5 keV;
- the maximum neutron yield reached $9\times10^{15}n.s^{-1}$ produced by D-D fusion reactions during an H-mode at 4.5 MA; the plasma was heated by 12 MW of deuterium neutral beams at an energy of 80 keV;
- the total plasma energy content has transiently exceeded 11 MJ in X-point operation with 27 MW of input power;
- peaked density plasmas ($n(0) > 10^{20}m^{-3}$) were obtained by using pellet injection. On-axis ICRF heating of such target plasmas produced transiently peaked electron pressures in excess of one bar;
- 'monster' sawteeth have been observed with ICRF heating during which q_0, the central safety factor, decreased below unity (0.8).

Progress towards a Reactor

Recent minority ^{3}He ion cyclotron resonance frequency (ICRF) heating experiments carried out in JET have provided an excellent simulation of alpha-particle confinement in a reactor. The mean energy of the minority species is about 1 MeV, and the ratio of the number of ^{3}He ions to the electron density is $1\text{-}2\times10^{-2}$, which is similar to the ratio of alpha-particles to plasma electrons in an ignited reactor (7×10^{-2}). No evidence of non-classical loss or deleterious behaviour of minority ions was seen in these experiments. Checks of both the fast ion energy and the gamma yield were made.

These experiments actually provided a much more stringent test of alpha-particle behaviour, in that the value of the fast ion diffusion coefficient that is required for good fast ion confinement in JET is less than that needed for good alpha-particle confinement in a reactor. The only difference between this ICRH simulation and the real situation is the anisotropy of the fast ion distribution; for alpha-particles this is approximately isotropic, whilst in the ICRF heating experiments the ratio of the perpendicular to parallel pressure is between 3 and 10.

During 1988, fusion reactivity studies were undertaken of both the D-^{3}He and D-D reactions. In the D-^{3}He experiments, minority ^{3}He ions were accelerated to energies in the MeV range using ICRF heating. The fusion reactivity at the highest power levels (>15 MW) was $2\times10^{16}s^{-1}$, which is equivalent to 60 kW of fusion power in the charged particle products. Although this is small compared with the input, it is the highest that has been achieved in a fusion device so far. The reactivity was close to theoretical predictions and several other features in this series of experiments were used to confirm the theoretical model of ICRF heating.

In the D-D fusion yield experiments, the full neutral beam heating (21 MW) and ion cyclotron resonance heating ($\sim$ 18MW) powers were injected into a low density plasma to maximise the neutron yield from both the fast and thermal ion components. The best yields were obtained using plasma limited on the inner wall or using magnetic limiters (X-points) and in these configurations more than 10^{16} neutrons per second were obtained. Very high ion temperatures of up to 23keV and electron temperatures ($\sim$ 10keV) were achieved in these plasmas.

A record value of the fusion product $\langle n_i.\tau_E.T_i \rangle$ of $2.5\times10^{20}m^{-3}$.s.keV was achieved in 1988, with 15MW of neutral beam heating during X-point operation in the H-mode. In addition, for limiter discharges, the values of the fusion products obtained for ohmic heating, RF, NB, combinations of these methods and with injection of solid pellets of deuterium have been in the range $1.2\text{-}2.0\times10^{20}m^{-3}$.s.keV. These similar values result from degradation in confinement time offsetting gains made in the values of the other parameters.

The record fusion parameter value of $2.5\times10^{20}m^{-3}$skeV was achieved in the H-mode of magnetic limiter operation (X-point) with $\sim$ 15MW of neutral beam input into a 4MA plasma, following optimization of the various plasma parameters. However, a significant improvement was made in the fusion product with RF heating of a pellet seeded plasma. A value of $2.0\times10^{20}m^{-3}$skeV ($n_i(0)=5.4\times10^{19}m^{-3}$, $T_i(0)=7.2$keV, and $\tau_E=0.5$s) was reached using 12MW RF heating in a 3MA deuterium plasma. The maximum values of the fusion product and the corresponding values of plasma temperature, density and energy confinement time are given in Table 7 for different operating scenarios.

In the RF heated plasma with pellet injection, 12MW of RF power produced a plasma stored energy in excess of 7MJ and a D-D fusion rate of $5\times10^{15}s^{-1}$. In this discharge, a significant fraction of the stored energy resulted from the minority ions which are expected to produce high fusion yield in (D)T heating schemes. In the steady state, with additional heating powers up to 32MW in a 5MA plasma, a total stored energy of 10MJ in the plasma has been achieved. In addition, in a more transient situation, 11 MJ stored energy has been obtained in H-mode plasma with 27MW of combined heating power.

The maximum neutron yield obtained so far was $1.2\times10^{16}s^{-1}$ produced with neutral beam heating. This resulted mainly from D-D reactions occurring between the deuterium particles in the heating beams and the plasma. The best ratio of fusion power to input power obtained was $Q_{DD}=5\times10^{-4}$ which is equivalent to $Q_{DT}\sim 0.3$, if tritium was introduced into the machine under these conditions. This would correspond to a fusion power production of above 1.5MW. This enhanced reaction rate is due to interactions between the plasma and neutral heating beams.

Future Prospects

During 1988, operation concentrated on bringing the two neutral beam boxes and the RF heating system into full operation. During the first half of 1989, one of the neutral beam boxes should be ready for operation at increased energy

(~ 140 keV) allowing greater penetration into the plasma at higher density. In addition, all eight generators of the radio frequency heating system should be upgraded to a total power of 32 MW which should provide about 24 MW into the plasma. This should make available a total additional heating power of 44 MW. Reinforcements will have been introduced to strengthen the vacuum vessel and this should allow high powers into the plasma for longer duration at the highest currents. This should make operations possible with 7 MA plasma currents in the material limiter configuration and over 5 MA in the magnetic limiter mode at the highest power levels.

In addition, the belt limiter and the RF antennae carbon protection tiles will be replaced by beryllium to improve the plasma purity and assist in controlling the plasma density. A prototype lower hybrid current drive (LHCD) system and a prototype high speed pellet injector will be installed later in 1989. These should allow checks on the confinement properties as the current and density profiles are tailored. However, emphasis will be given to controlling plasma density and improving plasma purity. These enhancements should enable improved plasma parameters to be obtained as well as higher fusion products.

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

Future Programme

Introduction

SO far, the initial JET objectives have remained unchanged and the same four areas of work continue to provide the focus of the Project's activities today. The study of energy confinement and its degradation with additional heating is covered by areas (1) and (3). The study of different low atomic number (low-Z) materials, edge effects, exhaust and fuelling is covered by area (2). The main study of alpha-particles produced in D-T plasmas, area (4) must clearly wait until areas (2) and (3) have been successfully addressed, as alpha-particles will need to be produced in sufficient quantities for their effect on the plasma to be observed.

At the end of 1988, the JET Project was half-way through its planned experimental programme. Two of the main areas of work—the study of scaling laws and of additional heating—have, to a large extent, been covered. The phenomenon of confinement degradation has been confirmed and requires that the physical dimensions of a reactor must be a little larger than was thought in the early 1970's. Some aspects of alpha-particle heating have been simulated; further studies in this area will take place with experiments in deuterium-tritium during the final phase of the programme. Recent experimental results at high input power (exceeding 30 MW) have shown clearly that area (ii), the study of plasma-wall interactions (including the reduction of impurities to an acceptable level), will remain a most important and pressing topic for investigation.

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. *Scaling of plasma behaviour as parameters approach the reactor range.*
2. *Plasma wall interactions in these conditions.*
3. *Plasma heating.*
4. *Alpha-particle production, confinement and consequent plasma heating.*

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

Plasma temperature, density and confinement values already achieved in JET, but not simultaneously, are individually close to the requirements of NET. JET results have allowed some of the parameters of a reactor to be specified. In particular, the plasma current capability of a next step tokamak is now foreseen to be ~25MA, compared with 6-10MA predicted when JET started operation in 1983. On the other hand, the control of impurity influx and exhaust which can be achieved without a divertor is still inadequate. This contributes to the limitations of present JET performance. The level of impurity control which could be achieved has a direct consequence on the design of the next step.

Based largely on JET results, the present studies to define a next step tokamak clearly emphasize the need for obtaining additional information not only on impurity control and plasma-wall interaction but also on modes of operation, such as those avoiding plasma disruptions and enhanced confinement regimes.

By virtue of its size, its already demonstrated plasma performance and its long pulse capability, JET is well placed to address these problems in the basic geometry considered for the next step. Furthermore, the expertise of the JET team in these areas is a major asset ensuring the best use of the machine. Such studies are the original *raison d'être* of JET and it is important that JET contributes this necessary information in furtherance of the EURATOM Fusion Programme.

New and Enhanced Systems

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

- Decoupling the temperature profile from the current density profile;
- Increasing the density of deuterium and tritium ions in the central region to between 1 and $2\times10^{20}m^{-3}$;
- Achieving high central temperatures 12-15keV;
- Increasing the plasma current in two main configurations
  - (a) with a magnetic separatrix (X-point operation) up to 6MA;
  - (b) with low-*Z* material limiters at higher currents up to 7MA.
- Introducing tritium into the machine to produce alpha-particles and study their confinement and heating effects on the plasma.

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

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

Control of Current Density Profile

In an ohmically produced (inductively driven) plasma, there is a strong link between the temperature profiles and the current density profile existing in the discharge. This strong correlation can be removed by using non-inductive current drive mechanisms such as neutral beams, ion cyclotron resonance frequency (ICRF) waves and lower hybrid current drive techniques. This would keep the safety factor *q* above unity everywhere in the plasma, and thus avoid (or considerably reduce) the sawtooth phenomena. JET would then benefit from higher core reactivity by sustaining peaked profiles of plasma density and temperature. These methods would help to flatten the current profiles. In addition, this would modify local values of the current gradient and improve energy confinement at the plasma centre.

In JET, all three methods of current drive will be carried out, but the main method for controlling the current profile will be by driving 1–5 MA current, depending upon density, in the outer half radius of the plasma using 12 MW of lower hybrid current drive (LHCD) power at 3.7 GHz. A prototype launcher will be installed in mid-1989 and the final system is planned for introduction in mid-1990.

Control of Density and Impurities

A high speed multi-pellet injector will be used to increase the central density well above present levels by injecting solid hydrogen pellets into the plasma. To achieve deep density refuelling, pellet speeds in excess of 5 $\mathrm{kms^{-1}}$ will be needed to reach the centre of the plasma. A prototype single pellet high speed ($>3\,\mathrm{km\ s^{-1}}$) gun has been developed and will be installed in mid 1989. The final multiple pellet high speed gun ($>5\,\mathrm{km\ s^{-1}}$) will be introduced in 1991. In addition, further plasma fuelling will be ensured by injection of neutral beams at 140 keV.

Any increase in central density must be obtained without increasing that at the plasma edge. A particle exhaust system is therefore required to control the edge density. It is not clear that wall pumping, which is the main mechanism presently used, can be utilised in the tritium phase as most of the pumped particles remain within the vessel walls. As an alternative, pumped limiters were studied and a feasible design was completed. However, avalanche impurity generation from carbon components at high temperatures ruled out this approach. Alternative methods of edge pumping are being considered.

The use of beryllium as the plasma facing component in JET will be tested early in 1989. The expected advantages are:

- Plasma impurity should be improved, leading to higher plasma performance in terms of the fusion product;
- Line radiation and bremsstrahlung will be reduced, leading to higher density limits and higher edge temperatures, which may facilitate access to the H-regime;
- Physical sputtering will be lower, especially self-sputtering;
- Beryllium is a strong getter for oxygen;
- Chemical activity with hydrogenic ions will be reduced, leading to lower hydrogenic inventories in surface materials, but also, perhaps, a lower pumping capability.

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, will be replaced with beryllium in early 1989, which has the additional advantage of gettering oxygen;
- Stabilising the magnetic oscillations present at the onset of a disruption using feedback control of magnetic perturbations produced from a set of internal saddle coils.

Increasing the Central Plasma Temperature

High central plasma temperatures ($\sim$ 12-15keV) should be achieved by a combination of additional heating from:

- On-axis ion cyclotron resonance frequency (ICRF) heating using upgraded radio frequency (RF) generators with eight antennae in the torus, which should produce at least 24MW power in the plasma;
- Two neutral beam (NB) injectors providing at least 16MW of 140keV neutral particles in the plasma.

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

Increasing the Plasma Current

To assist improvements in the confinement time, the plasma current is being increased in two main modes of operation: with a material limiter, the conditions at currents up to 7MA will be optimized; and in the magnetic limiter mode (X-point configuration) the current will be gradually increased up to 6MA.

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 JET Programme

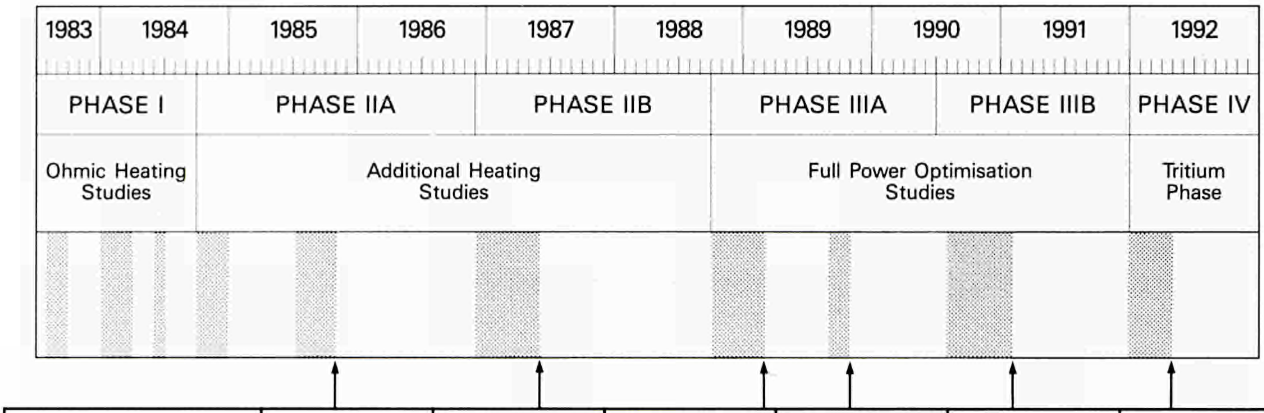
The future JET programme has been divided into phases governed by the availability of new equipment and fitting within the accepted lifetime of the Project (up to the end of 1992), see Fig. 41. Taking account of the adjustments to the shutdown schedule and the need to allow for sensible periods of operation to establish high reliability in preparation for the active phase of operation, the D-T phase is now expected to start six months later than previously planned and this will reduce the period for such operation to no more than eight months.

The Project is proceeding along the paths of:

- Optimisation of plasma parameters and device performance;
- Preparation for tritium operation.

These are due to converge in the final Tritium Operation Phase of the Project.

In terms of plasma performance the strategy is to raise the value of the fusion product ($n_i.\tau_E.T_i$) towards values of reactor relevance. In order to achieve this,



Ohmic Systems	5MA	Vessel restraints and improved volt-seconds for 7MA operation	Vessel reinforcements			
Separatrix		Additional P1 Coils	Separatrix dump plate supports		Cooled separatrix dump plates	
Limiters	Eight carbon mid-plane limiters	Carbon belt limiters	Beryllium belt limiters			
Pellets	Single pellet injector	ORNL multiple pellet injector (1.5 km s^{-1})		Prototype high speed pellet injector (>3 km s^{-1})	Multiple high speed pellet injector	
NBI	First NBI line (80kV)	Second NBI line (2×80kV)	One line modified to 140kV D		Second line modified to 140kV D	One line modified to 160kV T
ICRH	Three A_0 antennae	Eight A_1 antennae		Be antennae Screens		
LHCD			Install Vacuum Chamber	Prototype system	Full system	
Disruption control					Saddle coils	
Tritium and Remote handling					Tritium plant and main RH modifications	Final modifications

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Fig. 41
The JET Programme (shaded areas represent the planned shutdown periods)

and especially in view of the current understanding on plasma density and purity control, all elements of the existing JET Programme play specific and crucial roles during the coming operating periods.

In parallel, preparations for tritium operation are proceeding at full speed to ensure that the necessary systems for gas processing, remote handling, radiological protection, active handling and operational waste management are fully commissioned and operating satisfactorily in good time before the introduction of tritium into JET.

In the programme, there are two notable changes from that set out in the 1987 JET Annual Report:

- as requested by the JET Council, successful development work on a multiple high speed pellet injector has taken place outside the Project by CEA, France working in collaboration with JET under an Article 14 contract. Thus the programme now provides for the procurement and installation of such a system;

The programme now also allows for one of the neutral injectors to operate in tritium at 160kV during the D-T Phase.

On the JET programme, Phase I, the Ohmic Heating Phase, was completed in September 1984, and Phase II (Additional Heating Studies) was completed in October 1988. The present Phase IIIA (Full Power Optimization Studies) has just started and future phases are as follows.

Phase IIIA (end 1988–mid 1990)

The following work was planned in the shutdown at the start of this Phase:

- Reinforcements to strengthen the vacuum vessel;
- Welding of the separatrix dump plate supports;
- Installation of beryllium evaporators and belt limiter tiles;
- Conversion of the first neutral injector to 140 kV;

A short opening (2 months) of the vacuum vessel is foreseen in October 1989 to install:

- Beryllium antennae screens;
- Prototype Lower Hybrid Current Drive launcher system;
- Prototype high speed pellet injector.

The main aim of this phase will be to control the plasma density and improve the plasma purity, by use of beryllium. In addition, work will continue on consolidating 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. The effect on confinement of the current and density profiles using pellet injection and current drive by ICRH, NBI and LHCD in quasi-stationary states will be established. Emphasis will be given to controlling the plasma density and improving the plasma purity, including, the use of beryllium.

Phase IIIB (mid 1990–end 1991)

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

- Cooled separatrix dump plates;
- Second neutral injector at 140 kV;
- Final Lower Hybrid Current Drive system for profile control;
- Disruption control system using internal saddle coils;
- All remote handling systems required for the active phase;
- Diagnostic systems required for the active phase.

The following will also be implemented during Phase IIIB:

- Commissioning of the tritium plant;
- Installation of the multiple high-speed deuterium pellet injector.

The scientific aims of Phase IIIB will be to reach maximum performance with high reliability in deuterium plasmas and to control the development of disruptions (through feed-back to stabilize magnetic perturbations) and sawteeth (through current-drive effects).

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

Phase IV (D-T Phase, early 1992–end of 1992)

The following work will be undertaken during the shutdown at the beginning of this phase:

- Conversion of one neutral injector to operate with tritium at 160kV;
- final modifications for tritium operation including alpha-particle diagnostics.

D-T operation will begin when the overall reliability of all systems operating simultaneously is acceptable. D-T operation is scheduled to last eight months and should provide essential information on the confinement properties and behaviour of hot plasmas close to those needed in a thermonuclear reactor.

In the light of present knowledge, all of the currently planned new equipment will be needed to bring the performance to a level justifying the introduction of tritium in the torus. The phase will develop along two main directions:

(a) *Establishment of Tritium Operation*

The characteristics of D-T plasmas will be studied, including their confinement properties and impurity content. An important element will be control of the composition of the core plasma using tritium neutral beam injection. New scenarios will be explored leading to the optimisation of ICRH and NBI for D-T plasmas;

(b) *High Fusion Yields and the Detection of Alpha-particle Heating*

The study and optimisation of intensely heated D-T plasmas will be required both for the maximisation of the fusion yield and for the database for future devices. It is anticipated that current and density profile control should play important roles.

Members and Organisation

Members

The JET Joint Undertaking has the following Members:

The European Atomic Energy Community (EURATOM);

The Belgian State, acting for its own part ('Laboratoire de Physique des Plasmas of the École Royale Militaire') and on behalf of the Université Libre de Bruxelles' ('Service de Chimie-Physique II de l'ULB'); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studiecentrum voor Kernenergie' (SCK);

The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain;

The Commissariat à l'Énergie Atomique (CEA), France;

The Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy;

The Hellenic Republic, Greece;

The Forskningscenter Risø (Risø), Denmark;

The Grand Duchy of Luxembourg, Luxembourg;

The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal;

Ireland;

The Kernforschungsanlage Jülich GmbH (KFA), Federal Republic of Germany;

The Max-Planck-Gesellschaft zur Förderung der Wissenschaften eV—Institut für Plasmaphysik (IPP), Federal Republic of Germany.

The Swedish Natural Science Research Council (NFR), Sweden;

The Swiss Confederation, Switzerland;

The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands;

The United Kingdom Atomic Energy Authority (UKAEA), Host Organisation.

Management

The JET Joint Undertaking is governed by Statutes which were adopted by the Council of the European Communities on 30 May 1978. The organs of the Joint Undertaking are the JET Council and the Director of the Project. The JET Council is assisted by the JET Executive Committee and is advised by the JET Scientific Council, see Fig. 42.

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

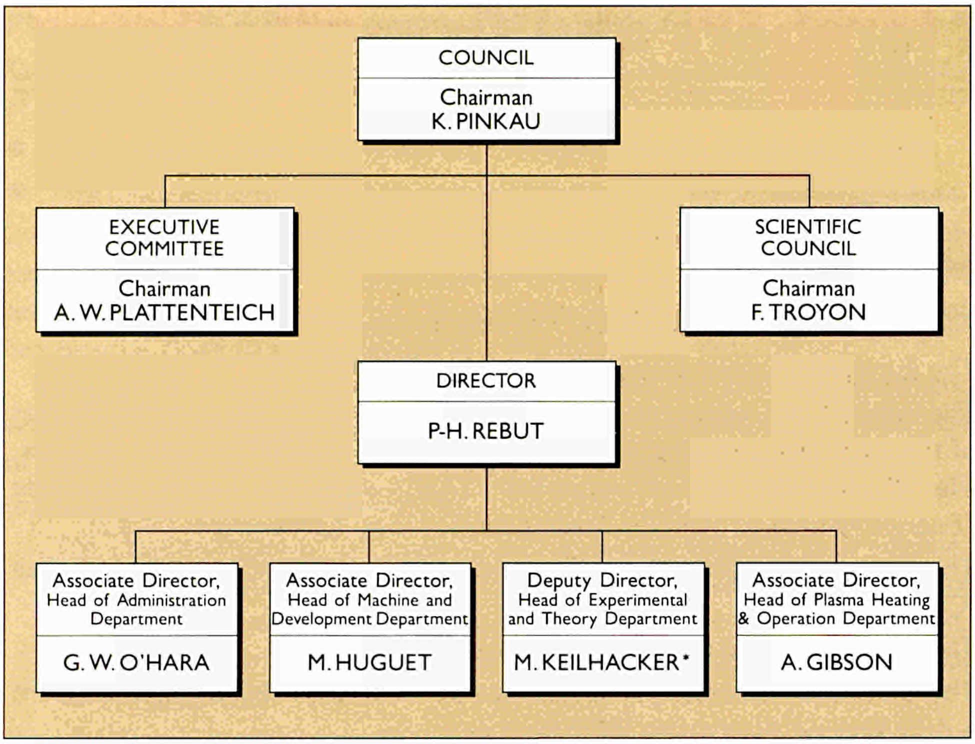

Fig. 42 Organisation of the JET Joint Undertaking

**From November 1988; (R.J. Bickerton, Deputy Director, Head of Heating & Theory Department to October 1988)*

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 the year on 17-18 March, 23-24 June and 27-28 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 the JET Executive Committee is shown in Appendix II. The

Committee met seven times during the year on 1-2 February, 8-9 March, 9-10 May, 7-8 July, 26-27 September, 10 November and 9 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 twice during the year on 3-4 March, and 6-7 October.

The main work of the JET Scientific Council in 1988 was to assess and advise the JET Council on:

- the beryllium screens for ICRF antennae; a Thomson scattering diagnostic to measure fast ion and alpha-particle distributions; the critical temperature gradient model for confinement; the distribution of JET data to the Associations and the exchange of data within the fusion community; the scientific and technical status of JET, including the re-scheduling of the 1988/1989 shutdowns; and the limits to JET operations posed by vacuum vessel activation due to D-D neutron production.

Host Organisation

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

Project Team Structure

The Director of the Project

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

Internal Organisation

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

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

The overall Project Structure is shown in Fig. 42.

Directorate

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

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

Plasma Heating and Operation Department

The Plasma Heating and Operation Department is responsible for heating the plasma, the organisation of experimental data and the day-to-day operation of the machine. The main functions of the Department are:

- 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 three groups (Machine Operations Group, Physics Operations Group and Data Management Group) and three Divisions:

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

(2) Neutral Beam Heating Division, which is responsible for the operation of the neutral injection system. The Division also participates in studies of the physics of neutral beam heating;

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

Experimental and Theory Department

The main functions of the Department relate to the measurement and validation of plasma parameters and the theory of tokamak physics. 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, the quality of measurements and the definition of the plasma parameters;
- to play a major role in the interpretation of data.
- to follow the theory of tokamak physics;

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

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

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

(3) 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.

Machine and Development Department

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

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

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

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

Administration Department

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

Coordinating Staff Unit

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

It comprises four groups:

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

Administration

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 initial budgets for 1988 were approved at 111.08 Mio ECU for Commitments and 105.59 Mio ECU for both Income and Payments. In addition to each of these budgets a Supplementary budget of 11.30 Mio ECU was adopted during 1988 following the judgement of the Court of Justice of the European Communities in respect of retrospective adjustments to the salaries of Euratom staff. The Commitments and Payments Budget each subdivide into two phases of the Project—Extension to Full Performance and the Operational Phase; further subdivisions distinguish between investment, operating and personnel costs.

Commitments

Of the total appropriations in 1988 of 143.48 Mio ECU (including 21.10 Mio ECU brought forward from previous years) 122.80 Mio ECU was committed and the balance of 20.68 Mio ECU was available for carrying forward to 1989.

The details of the commitment appropriations available (Table 11) and of the amounts committed in each Phase during the year shown in Table 12 are summarised as follows:

- In the extension to Full Performance Phase of the Project 15.12 Mio ECU was committed leaving commitment appropriations not utilised at 31 December 1988 of 8.24 Mio ECU to be carried forward to 1989.
- In the Operational Phase 107.68 Mio ECU was committed leaving a balance of 12.44 Mio ECU to be carried forward to 1989.

Income and Payments

The actual income for 1988 was 116.50 Mio ECU to which was added 0.59 Mio ECU available appropriations brought forward from previous years giving a total of 117.09 Mio ECU; this total compares with the 1988 Income Budget of 116.89 Mio ECU; the excess of 0.20 Mio ECU is carried forward to be offset against future contributions of Members. Of the total payment appropriations for 1988 of 118.72 Mio ECU payments made were 105.47 Mio ECU and the balance of 13.25 Mio ECU was transferred to the Special Reserve Account to meet commitments outstanding at 31 December 1988. (Payments by Phase are summarised in Table 12.)

TABLE 11: COMMITMENT APPROPRIATIONS FOR 1988

	Mio ECU
Initial Commitments Budget for 1988	111.08
Supplementary Budget	11.30
Uncommitted amounts available from previous years	21.10
	143.48
Commitments made during the year	122.80
Balance uncommitted in 1988 available for use in 1989	20.68

TABLE 12: COMMITMENTS AND PAYMENTS FOR 1988

Budget Heading		Commitments		Payments	
		Budget Appropriations Mio ECU	Outturn Mio ECU	Budget Appropriations Mio ECU	Outturn Mio ECU
Phase 2	Extension to Full Performance				
Title 1	Project Investments	23.36	15.12	13.97	11.44
Phase 3	Operational				
Title 1	Project Investments	28.72	16.80	11.76	10.71
Title 2	Operating Costs	42.74	42.52	44.40	41.19
Title 3	Personnel Costs	48.66	48.36	48.59	42.13
Total Phase 3		120.12	107.68	104.75	94.03
Project Total—all phases		143.48	122.80	118.72	105.47

Contributions from Members

The budget for Members' contributions was 115.30 Mio ECU funded as follows:

- 80% from the general budget of the European Atomic Energy Community (Euratom);
- 10% from the UK Atomic Energy Authority as Host Organisation;
- 10% from members who have Contracts of Association with Euratom in proportion to the previous year's contribution from Euratom towards the cost of their Association Contracts. Table 14 gives the percentage contribution from Members for 1988.

Bank Interest

Income is normally received on a quarterly basis in respect of Members' contribution and intermittently in respect of other items. The Project, therefore, has funds which are not immediately required for the discharge of its commitments; these funds are placed on deposit account at market interest rate; during 1988, earned interest amounted to 1.17 Mio ECU.

TABLE 13: INCOME AND PAYMENTS FOR 1988

	Mio ECU	
Income		
Budget for 1988		116.89
Income received during 1987		
(i) Members' Contributions	115.30	
(ii) Bank Interest	1.17	
(iii) Miscellaneous	0.03	
(iv) Unused Appropriations brought forward from 1986	0.59	
Total Income		117.09
Excess of budgeted income carried forward for off-set against Members' future contributions		0.20
Payments		
Budget for 1988		116.89
Amounts available in the Reserve Account to meet outstanding commitments at 31 December 1987		1.83
Total Available Appropriations		118.72
Actual payments during 1988		105.47
Unutilised appropriations at 31 December 1988 carried forward in the Reserve Account to meet outstanding commitments at that date.		13.25
Excess of Income over Payments		13.45

TABLE 14: PERCENTAGE CONTRIBUTIONS TO JET FOR 1988
Based on the Euratom Participation in Associations' Contracts for 1987

Member	%
Euratom	80.0000
Belgium	0.2448
CIEMAT, Spain	0.0833
CEA, France	2.7383
ENEA, Italy	1.4552
Risø, Denmark	0.0737
Luxembourg	0.0021
KFA, FRG	0.8020
IPP, FRG	2.2161
KfK, FRG	0.5735
NFR, Sweden	0.1174
Switzerland	0.4185
FOM, Netherlands	0.3842
UKAEA	10.8284
	100.0000

Unused Payment Appropriations and Excess Income from Earlier Years

0.59 Mio ECU of unused payment appropriations and excess income arising in previous years and held for reduction of Members' future contributions was transferred to income in 1988.

Summary

Table 15 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1988, which have yet to be audited. The final audited accounts will be published in due course.

TABLE 15: SUMMARY OF FINANCIAL TRANSACTIONS AT 31 DECEMBER 1988

	Mio ECU
Cumulative commitments	925.8
Cumulative payments	857.5
Current commitments	68.3
Of which carried forward on reserve account	13.3
Amount available from 1987 and 1988 due to be set off against future contributions from Members	0.3

Contracts

Annual Report

In 1988, the total number of contracts processed was broadly similar to the totals for 1986 and 1987. Major contracts (value greater than 50,000 ECU) rose from 144 in 1987 to 164 in 1988, an increase of 14% which reflects the increasing use of contract personnel at JET and the progress on Fusion Technology work.

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 1988, was 8.9 Mio ECU.

The volume of minor contracts (value less than 50,000 ECU) decreased by 5% relative to 1987. Many of these minor contracts fall within the small value order system which allows for the swifter processing of small requisitions (other than amendments to existing orders) below 750 ECU. The number of orders processed in this way totalled 5233 representing 61% of all minor contracts placed, while their aggregate value of 1.5 Mio ECU amounted to 2% of the total value of all minor contracts placed, including amendments.

Imports and Export Services

Contracts Service is also responsible for the import and export of JET goods. Every incoming consignment is closely monitored en route as JET is exempt from Customs duties and VAT under privileges granted by the Host Country.

The total number of imports handled in 1988 was 1088 while the total exports amounted to 417. There were also 769 issues of goods to UK firms during 1988. The total value of issues to all countries in 1988 was 5.3 Mio ECU.

Insurance

Insurance for all consignments is arranged by the Contracts Service except for imports against major contracts which are insured by the suppliers. Contracts are also maintained for Site, All Risks and Contract Works insurance. Insurance policy claims are also handled within the service.

Administration of Contracts

The distribution of contracts between countries is shown in Table 16. 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 1984-8, regardless of value.

TABLE 16: ALLOCATION OF JET CONTRACTS
(position as at 31 December 1988)

Country	Total of ECU Values	% of Total
UK	311 484 595	50.02
Germany	126 660 381	20.34
France	61 850 585	9.93
Italy	39 154 578	6.29
Switzerland	36 131 356	5.80
Netherlands	9 058 737	1.45
Denmark	10 143 737	1.63
Belgium	7 196 183	1.16
Sweden	5 770 830	0.93
Ireland	359 720	0.06
Others	14 886 241	2.39
Totals	622 696 943	100.00

To ensure that suppliers from all member countries are considered before placing large contracts, Contracts Service carries out many tender exercises. In 1988 there were 169 new tender actions covering supply, service and personnel requirements.

Contracts Service also maintains a Register of Suppliers, a computerised database covering 475 different categories of supply and 2405 suppliers. The register is continuously revised and is used extensively in the tendering process as suppliers from all member countries are represented. Information from the register is available to all JET Technical Officers and Associated Laboratories on request.

Personnel

Complement and Recruitment

In July the complement of temporary Euratom staff was increased by 21 to 191 as a result of the agreement of the Council of Ministers to the revised Fusion Programme. The composition of the complement of posts for 1988 is shown in Table 17.

TABLE 17: STAFF COMPLEMENT

Team Posts	
Temporary Euratom Staff	191
UKAEA Staff	260
DG XII Fusion Programme	19
	470
Contract Posts	210
Total	680

An important activity of the Personnel Service during the year was the recruitment of staff to fill the remaining posts in the JET team complement. Despite the effort made to do this, the number of Team staff in post fell from 372 at the start of the year to 366 at the year end. This reduction was a continuation of the trend which started in 1987 and reflected the general lack of suitable candidates from both the Associated Laboratories and the UKAEA. However in the latter part of the year there was an increase in the number of applications from Euratom candidates. Because of the shortfall in the filling of team posts the number of contract personnel working at JET increased by a further 15 during the year compared with the previous year. Table 18 illustrates the filling of posts against the approved complements. Fig.43 shows the composition of team staff by nationality.

TABLE 18: POSTS FILLED AGAINST COMPLEMENT
(position as at 31 December 1988)

	Complement	In Post
Team Posts		
Temporary Euratom Staff	191	148
UKAEA Staff	260	207
DG XII Fusion Programme Staff	19	11
	470	366
Contract Personnel	210	274*
Total	680	640

**This includes additional contract personnel temporarily set against vacant team posts as authorised by the JET Council pending the filling of these posts with team members.*

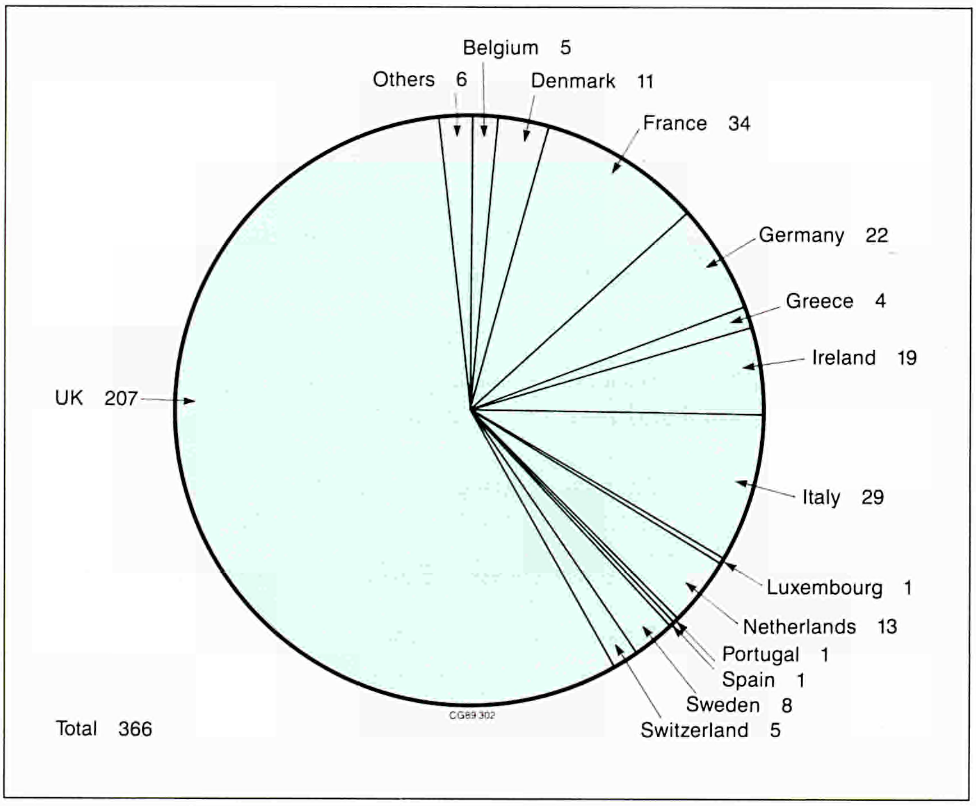

Fig.43 Composition of team staff by nationality

Euratom Staff

In 1988, 13 staff joined the team of which nine had previously worked for a JET partner. During the year 18 staff members left of which seven returned to employment with a JET partner. In the same period, one additional DG XII staff member joined the team.

The number of Euratom staff in post at the end of the year was 159 including eleven from DG XII.

UKAEA Staff

During the year 17 new staff were assigned to JET by the UKAEA of which ten were employees of the UKAEA when selected. This increase was offset however by the departure of 19 UKAEA staff, of which six returned to the Authority. The number of UKAEA staff in post at the end of the year was 207.

The payment of a Retention of Experience Allowance was introduced in 1987 to encourage experienced UKAEA staff to remain in the JET team until the end of the Project. In 1988 the allowance was paid to 173 UKAEA staff.

Assigned Associate Staff

During 1988, 66 staff from the JET partners (other than the UKAEA) were assigned to JET under the Assigned Associate staff scheme. The total contribution was about 38 man-years including an estimated 12 man-years from the UKAEA which was virtually the same as in 1987.

Table 19 shows the contribution by the partners in 1988 and Table 20 the deployment of Assigned Associate Staff within the Project.

Liaison with JET Partners

Contact between JET and the Associated Laboratories was maintained during the year on such matters as recruitment of staff; revision of the Agreement for the Assignment of Associate Staff and the re-employment of staff at the end of their assignment to JET.

Annual Staff Assessment Reports required by the partners on their staff in the JET team continued to be provided by the Project during the year.

Visiting Scientists

Sixteen Visiting Scientists worked at JET during 1988 for periods varying from three months to two years.

Six came from China, three from the United States, two from Brazil and one each from Japan, India, Australia, New Zealand and the United Kingdom, to work mainly on experimental and theoretical problems.

Consultants

During 1988, eight consultants gave advice on a range of topics from beryllium handling to theoretical modelling of plasma behaviour.

Exchange of Personnel

Exchange of personnel under the International Energy Agency Tripartite Agreement between JET, JT60 and TFTR for Co-operation on Large Tokamak Facilities continued during the year.

Two JET staff members were attached to the TFTR Project for one month

TABLE 19: CONTRIBUTIONS MADE BY ASSIGNED ASSOCIATE STAFF DURING 1988

		Man-Years
UKAEA	(United Kingdom)	*12.00
IPP	(The Federal Republic of Germany)	7.13
NFR	(Sweden)	3.81
FOM	(The Netherlands)	3.69
CEA	(France)	3.17
ENEA	(Italy)	2.52
CIEMAT	(Spain)	1.93
RISØ	(Denmark)	1.00
JNICT	(Portugal)	0.92
ERM	(Belgium)	0.75
LNETI	(Portugal)	0.66
CRPP	(Switzerland)	0.63
CNR	(Italy)	0.27
	Total	38.48

**The UKAEA contribution is estimated.*

TABLE 20: ASSIGNED ASSOCIATE STAFF WITHIN THE PROJECT

	Man-years
Experimental Division I	18.77
Experimental Division II	9.45
Radio Frequency Heating Division	3.79
Theory Division	3.25
Fusion Technology Division	1.58
First Wall Division	1.00
Experimental & Theory Department	0.39
CODAS	0.25
Total	38.48

each and one member of the TFTR Team came to JET for six months. Two members of the JT60 Team came to JET for six and three months respectively.

Under the bilateral agreement between the United States Department of Energy and the European Atomic Energy Community in the field of controlled thermonuclear fusion several sub-agreements have been established covering specific collaborative areas of work.

During the year a total of 43 months of manpower has been contributed to the Project from the following US laboratories:

Oak Ridge National Laboratory	*(Pellet Fuelling and Remote Maintenance Programme)*
Sandia National Laboratory	*(Particle Control Programme)*
Los Alamos National Laboratory	*(Fusion Fuel Processing Programme)*

In addition, personnel have been attached to JET for short periods under various agreements including an exchange agreement of the Royal Society with the GDR Academy of Sciences, the co-operation agreements between the CEC and the People's Republic of China, and attachment agreements between JET and the Academy of Sciences of the USSR. Three physicists came from the GDR, two from China and four from the USSR.

Students

Interest in the JET Studentship Scheme continued to increase resulting in 110 student placements during 1988 from 12 countries, the largest contribution being from the United Kingdom. The average length of appointment was four months.

JET Fellowships

Nine JET Fellows worked for the Project during 1988 and a further six will take up grants as places become available.

Shift Work

During 1988 there were four main periods of operation from the beginning of the year to the commencement of the major shutdown in October. Apart from a three-week shutdown period in May, there were 144 days of double-shift working and 54 days of extended day work.

A total of 245 staff have worked on a casual shift basis during the year. In addition, 12 technicians have worked a regular shift system seven days per week to monitor the safety of the JET machine on a continuous basis.

Overtime

Recorded overtime averaged 500 hours per week, representing the equivalent of 12 man-years of effort. This was a 30% reduction compared with 1987. Approximately 60% of the total overtime was undertaken at weekends.

On-Call

To provide emergency cover outside working hours during the operation period on-call rosters were maintained for 12 sub-systems of the JET machine. A total of 57 staff each working an average of 7 weeks undertook this on-call duty.

The start of the shutdown in October enabled the number of sub-systems covered by the on-call duty to be reduced to five.

Staff Training

During 1988, 31 staff were recalled by their parent Associations to undertake short periods of training and eleven staff pursued part-time courses for their long-term career development.

The one-day JET Induction Programme for new staff continued throughout the year and 17 staff from non-English speaking countries received English language tuition. 103 staff received tuition in other European languages.

157 staff attended safety training courses organised by the Joint Safety Services who this year, in consultation with JET, introduced courses in beryllium handling which were attended by 161 team staff and contractors' personnel. In addition, specific vocational training was organised by the Personnel Service for 72 staff, ranging from a course in Presentational Skills to a Tritium Safe Handling course.

Conferences and Workshops

JET was well represented at most international fusion conferences. The major events included the 15th Symposium on Fusion Technology (in the Netherlands) and the 12th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research (France).

Staff Representation

Three official meetings between the JET management and the Staff Representative Committee were held during the year 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 satisfy relevant safety requirements. JET continues to meet all the requirements of relevant UK legislation and, in accordance with the Host Support Agreement, JET complies with the safety regulations of the host organisation.

The JET Safety Committee, chaired by the Director of JET, is concerned with all aspects of safety related to the JET Project. It receives reports of safety audits and inquiries into accidents, and accounts of the activities of the Safety Working Group and the Tritium Safety Assessment Panel. The Culham Laboratory and JET Joint Health and Safety Committee consists of representatives of management and staff from both organisations. It keeps under review all matters affecting the health and safety of all persons working on site. The Joint Safety Service provides support to both JET and Culham Laboratory and there is a continuing consultation between the two organisations through this service and the JET-UKAEA Liaison Committee, as provided for under the Host Agreement.

Safety in 1988

Higher neutron yields during 1988 led to increased activation of the vacuum vessel. As a consequence the interior of the torus was classified as a Controlled Area (under the Ionising Radiations Regulations 1985) during interventions. There were three such interventions in the year, and the 1988/89 shutdown started in October. The dose rate in the torus was 30μSv/h at the start of this shutdown, but fell to 14μSv/h by the end of December. The collective dose accrued in the torus during the period October-December 1988 was approximately 86 man mSv, which was some 63% of the collective dose for the whole of the 1988/89 shutdown. Radiation doses accrued by individuals during 1988 remained low and within the JET dose limitation policy and UK statutory limits. There continues to be no radiological hazard due to JET operations outside the shielded torus hall and basement.

During June there was a fire in the Neutral Beam Test Bed within the Hot Cell. The source of the fire was an oil filled resistor in the PINI power supply. Access to the Hot Cell was restricted during the decontamination operations. Apart from some short term mild irritation of the eyes, noses and throats of those directly involved with the incident, there were no subsequent medical problems. The resistor is being redesigned as an air-cooled component.

The Tritium Safety Assessment Panel has as its chairman the Head of Joint Safety Services, with members from JET, Joint Safety Services, the Safety and Reliability Directorate of the UKAEA, and Harwell Laboratory, UKAEA. It continued to monitor the safety of the design for the active gas handling plant and of the proposed tritium operating system, and the safe disposal of radioactive waste. All statutory requirements for holding and discharging radioactive materials are being met. The formal arrangements for liaison between JET, the UKAEA Safety and Reliability Directorate and Culham Laboratory continue. The panel membership now includes a member of the operations team in JET, and further changes in membership and terms of reference will be appropriate as JET approaches operation with tritium.

The JET Safety Working Group, which is chaired by the Head of the Co-ordinating Staff Unit with members drawn from JET, Joint Safety Services and the Patrol Service, has continued to review all aspects of day-to-day safety. Comprehensive procedures controlling the use of beryllium on site have been endorsed, and a review of all safety documentation has been carried out. Special attention has been paid to improving safety training, particularly basic safety instructions to new staff and to contractors.

Public Relations

During 1988 the JET Project commanded a great deal of interest from the press, media, the general public and the international scientific community.

A major media event during the year was a Press Conference during October attended by over 25 journalists, at which the Director of JET presented the latest achievements of the Project. The Director and senior staff gave interviews for both radio and television; press and media coverage in both the UK and elsewhere in Europe was exceptionally high. Media interest in general continued throughout the year at a high level, with visits by 39 journalists and three television film crews.

Eminent visitors to the Project included Mr S. Rolf Jacobsen, Danish Minister for Research; Mr Y. Ihara, President of the Japanese Atomic Energy Research Institute; Mr J. Chinal, French Scientific Counsellor; The Rt. Hon. Cecil Parkinson, Secretary of State, UK Department of Energy; Lord Glenarthur, Minister of State, UK Foreign and Commonwealth Office; Lord Trefgarne, UK Minister of State for Defence Procurement; members of the House of Lords Sub-Committee on Science and Technology and a party of senior officials from COST (European Co-operation in Science and Technology).

Amongst the 4000 members of the public who visited JET during 1988 were students from local and European universities, colleges and schools, and professional and social groups, including many from the Oxfordshire Federation of Women's Institutes.

Lectures continued to be given on JET and nuclear fusion at outside events and to parties of visitors.

JET also participated in the following exhibitions during this period: Eurotech (Glasgow), Jeune Citoyen Européen (Poitiers), Hanover Fair Industrie 88 (Hanover), and the British Association for the Advancement of Science (Oxford).

APPENDIX I

The JET Council

Member	**Representative**
The European Atomic Energy Community (EURATOM)	*P. Fasella (Vice-chairman)* *C. Maisonnier*
The Belgian State, acting for its own part (Laboratoire de Physique des Plasmas of the École Royale Militaire) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the ULB); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studiecentrum voor Kernenergie' (SCK)	*P. E. M. Vandenplas* *T. van Rentergem*
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	*A. Grau Malonda*
Commissariat à l'Énergie Atomique (CEA), France	*D. Cribier* *F. Prevot (to Sept)* *R. Aymar (from Oct)*
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	*A. Bracci* *P. Longo*
The Hellenic Republic (Greece)	*A. Katsanos*
The Forskningscenter Risø (Risø), Denmark	*H. von Bülow* *H. Bjerrum Møller (to June)* *J. Kjems (from June)*
The Grand Duchy of Luxembourg (Luxembourg)	*J. Hoffmann* *J. P. Zens*
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	*J. A. da Costa Cabral (from Jan)* *Mrs M. E. Manso (from June)*
Ireland	*D. Byrne* *F. Turvey (from February)*
The Kernforschungsanlage Jülich GmbH, Federal Republic of Germany (KfA)	*A. W. Plattenteich*
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	*K. Pinkau (Chairman)*
The Swedish Natural Science Research Council (NFR), Sweden	*G. Leman* *S. Bergström (to June)* *H. Wilhelmsson (from June)*
The Swiss Confederation	*F. Troyon* *P. Zinsli*
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	*M. J. van der Wiel* *K. H. Chang*
The United Kingdom Atomic Energy Authority (UKAEA)	*M. A. W. Baker* *D. R. Sweetman*

Secretary: J. McMahon, JET Joint Undertaking.

APPENDIX II

The JET Executive Committee

Member	Representative	
The European Atomic Energy Community (EURATOM)	*C. Maisonnier* *(Vice-Chairman)*	*(to Sept)*
	J. P. Rager	*(from Oct)*
	K. Melchinger	*(to Sept)*
	P. J. Kind	*(from Oct)*
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); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studiecentrum voor Kernenergie' (SCK)	*R. Vanhaelewyn*	
The Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain	*F. Manero*	
The Commissariat à l'Énergie Atomique (CEA), France	*C. Gourdon*	
	J. C. Saey	
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	*R. Andreani*	
	M. Samuelli	
The Hellenic Republic (Greece)	*A. Theofilou*	
The Forskningscenter Risø (Risø), Denmark	*F. Øster*	
	V. O. Jensen	
The Grand Duchy of Luxembourg (Luxembourg)	*R. Becker*	
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal.	*Mrs M. E. Manso*	*(to June)*
	J. Bonfim *F. Serta*	*(from June)*
Ireland	*N. V. Nowlan*	*(to Feb)*
	F. Turvey	*(from Feb)*
	F. G. Burrows	*(to May)*
	D. Kearney	*(from May)*
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*	*(to June)*
	K. Tichmann	*(from July)*
The Swedish Natural Science Research Council (NFR) Sweden	*E. Hellstrand*	
	G. Leman	*(from June)*
The Swiss Confederation	*A. Heym*	
	P. Zinsli	
The Stichting voor Fundamenteel Onderzoek der Materie (FOM) The Netherlands	*H. Roelofs*	
	L. T. M. Ornstein	
The United Kingdom Atomic Energy Authority (UKAEA)	*D. M. Levey*	
	W. M. Lomer	

Secretary J. McMahon, JET Joint Undertaking.

APPENDIX III

The JET Scientific Council

Members appointed by the JET Council:

(a) until 31 March 1988

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APPENDIX III (continued)

(b) from 1 April 1988

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Staff Secretary: M. L. Watkins, JET Joint Undertaking