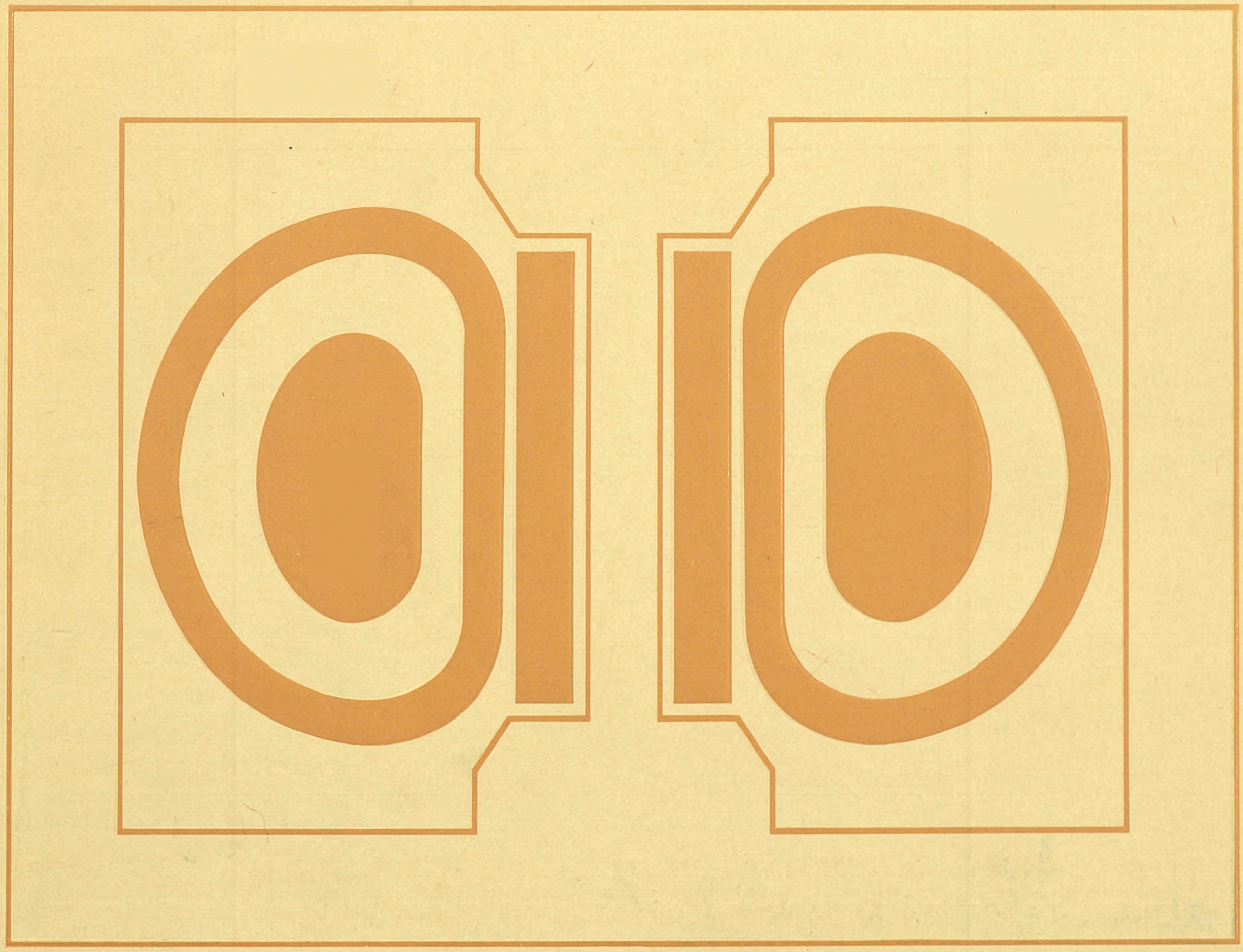
JOINT EUROPEAN TORUS JET

JET JOINT UNDERTAKING

ANNUAL REPORT 1989



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Editorial work on this report was carried out by
B.E.Keen and G.W.O'Hara.
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Preface

The scientific results achieved by JET during 1989 were outstanding. By the start of the year the Project has already met, and in many cases exceeded, its original technical design specifications. Furthermore, the study of heating and of the confinement of plasma, two of the main objectives of the JET Programme, had been successfully undertaken. JET had therefore arrived at a stage where it could, with confidence, define the main parameters of a Next Step device. In 1989, therefore, the Project was in a position to embark on the second half of its original programme, namely Phase III - Full Power Studies. This phase has a triple aim, namely, control of the plasma density and improving the plasma purity by the use of beryllium as a first-wall material; consolidating operation of the machine at full additional heating power; and exploring further the use of X-point operation for improving confinement.

The introduction of beryllium tiles and evaporated beryllium to cover the inner walls of the vacuum vessel was not in itself a difficult operation, but it involved for the first time personnel access to a beryllium contaminated vessel. All operations were carried out in safe conditions, beryllium contamination was well contained and considerable experience was gained in working with beryllium. The control procedures which the Project has introduced for beryllium operation and technical support for intervention in beryllium operated areas have been entirely satisfactory as is evidenced by the smooth running of shutdown periods since the introduction of beryllium into the machine.

The experimental programme in 1989 was directed towards work on plasma-wall interactions, and particularly the control of impurities in high performance plasmas. With the introduction of beryllium, the Project was able to demonstrate clearly the benefits to be derived from passive impurity control by the use of beryllium as a first-wall material for plasma facing components. Significant improvements in plasma performance resulted mainly from the reduction of impurities in the plasma. Plasma temperatures (T), plasma densities (n), and confinement times (τ_E) reached individually those values needed in a reactor but not simultaneously. In some experiments, ion temperatures of nearly 300M°C (~ 30 keV) were reached and energy confinement times considerable greater than 1s were obtained in JET - the only machine to achieve this. Plasma densities also reached values suitable for a reactor. The triple fusion product of plasma density, plasma temperature and confinement time obtained simultaneously, was significantly increased and reached a record value of $(n_i \tau_E T_i) = 9 \times 10^{20} m^{-3}$s keV which is close to 'breakeven' conditions. This provides a measure of the significant progress towards the parameters needed for a fusion reactor, and is within a factor 5-10 of reactor conditions, which would require a product of $5 - 10 \times 10^{21} m^{-3}$s keV. JET has therefore successfully achieved and contained plasmas of thermonuclear grade. It is the only machine in the world to reach that stage.

Although results achieved by JET are most impressive, they were obtained in a transient state. Plasma impurities still present a problem for steady-state operation which is required for a fusion reactor. In view of the central importance of impurity control for the success of a Next Step device, and of the unique position of JET to carry out the experiments, the Project has proposed the addition of a New Phase to the JET programme. The objective is to establish effective control of impurities in operating conditions close to those of a Next Step device and in a stationary state. This involves providing JET with a new configuration, including principally the installation of a pumped divertor. A prolongation of the JET programme for a further four years, until December 1996, is proposed to carry out the changes and to allow sufficient experimental time to demonstrate the effectiveness of the new configuration. This would provide for deuterium operation up to the end of 1994 followed by tritium operations in 1995-1996. The JET Council agreed the proposed prolongation and the Commission will make a proposal to the Council of the European Communities to amend the JET Statutes.

JET will ultimately operate with deuterium-tritium plasmas, rather than pure deuterium plasmas, so that the production of alpha-particles in a true thermonuclear plasma can be studied. This requires a tritium fuelling system and, since JET will become active, remote handling equipment will be used. Preparations for D-T operations continued during 1989. The Active Gas Handling Building is nearing completion and installation of the major subsystems has started. The planned commissioning programme in this area is consistent with a period of D-T operation during 1992.

The pre-eminent position which JET has earned in world fusion research owes much to the continuing and excellent support which it receives from all parties involved in the European Fusion Programme, particularly from the Commission and the Associations. I again record my gratitude to my colleagues on the JET Council and to the members of the JET Executive Committee and the JET Scientific Council for their assistance and guidance to the Project during the year and especially to those who retired from these Committees during the year.

Finally, I pay tribute to the Director of the Project, Paul-Henri Rebut, and to all JET staff who, with their dedication and hard work have brought JET to the forefront of fusion research. I am confident that by their perseverance, they will maintain this position for the future.

Klaus Pinkau

K. Pinkau
June 1990
Chairman of the JET Council

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. It provides an overview of the scientific, technical and administrative status of the JET programme which is comprehensible to the average member of the public. Where appropriate, descriptive sections (in italics and boxed) are included to aid the reader's understanding of 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:

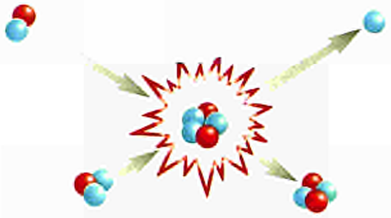
- The scientific and technical programme of the Project;
- The administration and organization of the Project.

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 1989; 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 1989 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. The first part of this Report concludes with a description of the proposed future programme of JET until its planned conclusion.

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 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 1989; and details of the staff complement.

Background

In the early 1970's, discussions were taking place within the European fusion research programme 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 tokamak 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 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.

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

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. As the host organisation, the UKAEA pays 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 Institutions, although some staff are assigned on a secondment basis from the

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* $5 \times 10^{21}\,m^{-3}$ *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	$2.5 \times 10^{20}\,\mathrm{m}^{-3}$
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 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.

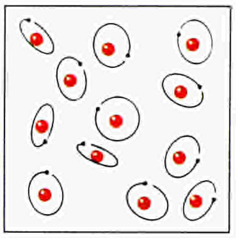
In addition, JET is pioneering two of the key technologies that will be required in subsequent fusion reactors. These are the use of tritium and the application of remote maintenance and repair techniques.

Plasma

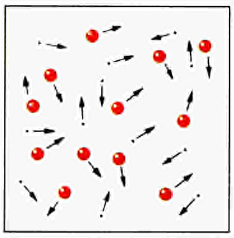
As the temperature of the fuel is increased, the atoms in the gas become ionised, losing their electrons, which normally orbit around the nuclei. The mixture of positively charged ions and negatively charged electrons is very different from a normal gas and is given a special name—PLASMA.

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.

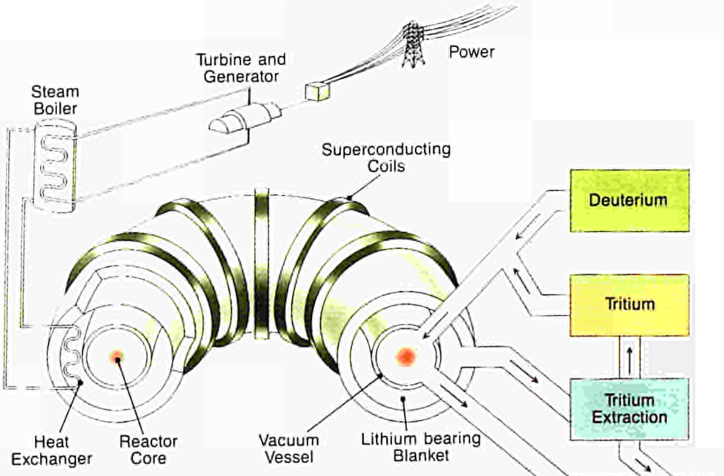


Gas



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:

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

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 toroidal 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

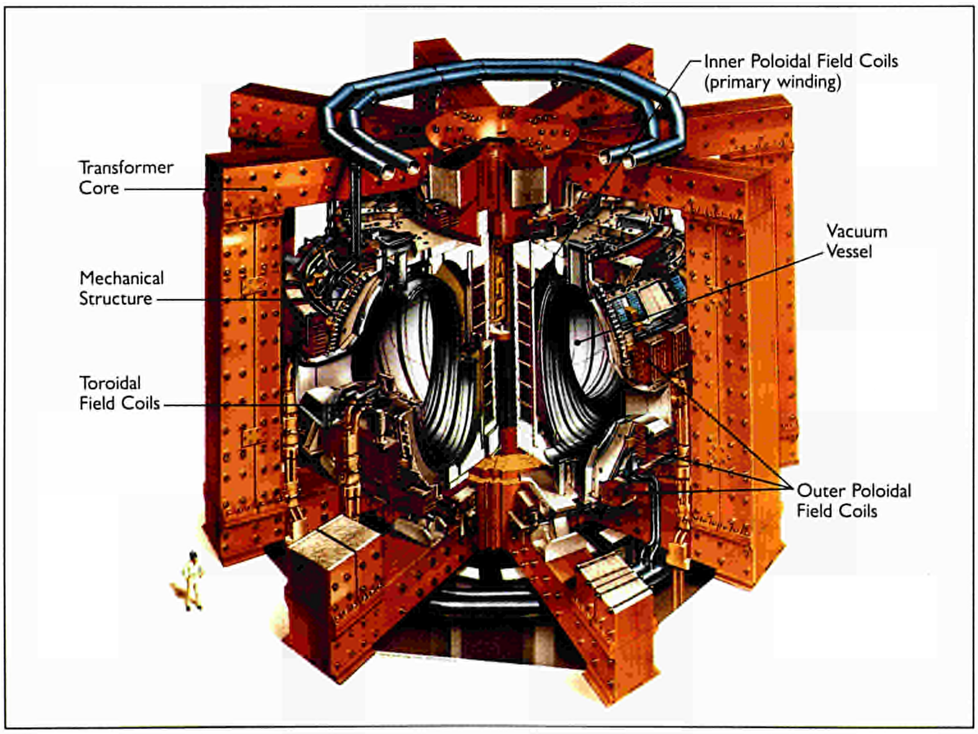


Fig. 2:
Diagram of the JET apparatus

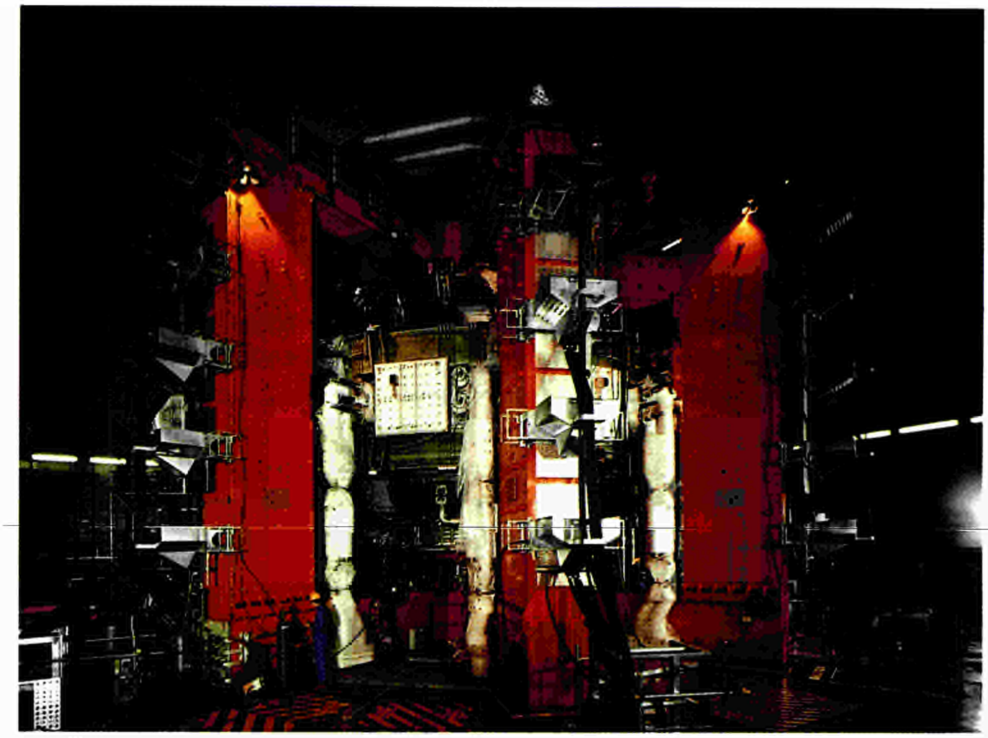


Fig. 3:
The JET experimental apparatus photographed in May 1983

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 60 s. The plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96 m and a D-shaped cross-section of 4.2 m by 2.5 m. 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 scheduled five year period and within 8% of the projected cost of 184.6 Mio ECU at January 1977 values.

TABLE 1: ORIGINAL DESIGN PARAMETERS OF JET

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

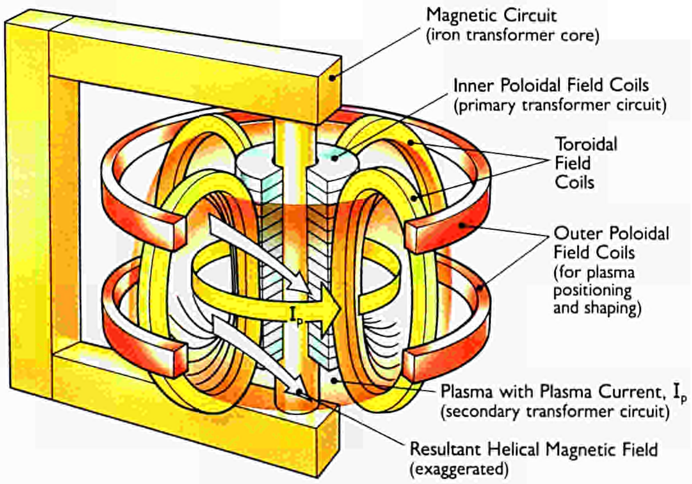
The first plasma pulse was achieved on 25 June 1983 with a plasma current of 17 000 A lasting for about one tenth of a second. The JET Tokamak is shown in Fig. 3 just prior to the start of operation in June 1983. This first phase of operation was carried out using only the large plasma current to heat the gas. In 1985, the first additional heating system, employing radio-frequency heating, came into operation and during 1986 reached 12 MW 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 21.6 MW of power injected into the torus.

So far, experiments have been carried out using hydrogen or deuterium plasmas. In the final stage of the programme it is planned to operate with deuterium-tritium plasmas so that abundant fusion reactions occur. The alpha particles liberated from the reactions should then produce significant heating of the plasma. During this phase of operation the machine structure will become radioactive to the 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 one 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 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 Agreement (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 the 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 Community 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. About 1750 professional scientists and engineers are 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

Plasma current is a determining factor in the confinement of the plasma and, in particular, of the energetic fusion products the alpha-particles. On a worldwide basis JET is the machine with the largest plasma current by far; followed by DIII-D General Atomics, San Diego, USA; JT-60 at JAERI in Japan; and TFTR at Princeton Plasma Physics Laboratory (PPPL), USA. Table 2 sets out an overview of these tokamaks with their main parameters and starting dates. Other operating devices with plasma currents in excess of 1 MA are also included.

Other smaller tokamaks exist throughout the world or are under construction, each dedicated to specific tasks of studying different aspects of physics, engineering and heating of plasmas. In addition, these large tokamaks

TABLE 2: LARGE TOKAMAKS AROUND THE WORLD

Machine	Country	Minor radius a(m)	Elongation k	Major radius R(m)	Plasma current I(MA)	Toroidal Field B(T)	Input Power P(MW)	Start Date
JET	EEC	1.20	1.8	2.96	7.0	3.5	36	June 1983
JT-60	Japan	0.90	1.0	3.0	3.2	4.8	0	April 1985
TFTR	USA	0.85	1.0	2.50	2.5	5.2	30	Dec 1982
TORE-SUPRA	France	0.70	1.0	2.4	1.7	4.5	23	April 1988
T-15	USSR	0.70	1.0	2.4	2.0	4.0	-	Jan 1989
DIII-D	USA	0.67	2.0	1.67	3.5	2.2	20	Feb 1986
FT-U	Italy	0.31	1.0	0.92	1.6	8.0	-	Dec 1988

have also been designed with specific tasks. For instance, in Tore Supra, France, the main magnetic field is created by superconducting coils. The various machines are also designed to test various heating systems. Ion Cyclotron Resonant Frequency (ICRF) and Neutral Beam (NB) heating are now commonly applied in excess of 10 MW each. Electron Cyclotron Resonant Heating (ECRH) of several MW has been applied in some devices. Non-inductive current drive by means of various heating methods include Lower-Hybrid Current Drive (LHCD). LHCD will also be carried out in JET in the near future to complement the ICRF and NB heating systems.

JET, JT-60 and DIII-D are 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 mechanical limiter in contact with the confined plasma. The magnetic limiter configuration, with its high shear, not only leads to higher plasma edge temperatures and a better global confinement, but also permits better particle and impurity control.

Two tokamaks differ from the rest of family of large tokamaks in that they have been designed for deuterium-tritium (D-T) operation to study alpha-particle heating on a sufficiently large scale. Indeed, these two 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 fusion quality factor Q_{DT} of 0.3 in TFTR and 0.8-0.9 in JET would be obtained (Q is the ratio of fusion power produced to the total power losses in the plasma). An equivalent calculated value Q_{DT} of 0.8 with an averaged fusion power of 10 MW has been reached in a transient phase in JET over a period of one energy confinement time of 1.1s. Table 3 shows the highest plasma parameters obtained simultaneously in one discharge in JET, TFTR, and DIII-D.

In burning reactor plasmas, the electron temperature should not be too different from the ion temperature due to the high equipartition rate between these species and the good confinement that must necessarily exist in such a device. Nevertheless, due to the decoupling of electron and ion temperatures at lower plasma densities, the highest ion temperatures and fusion yields have been achieved in the present devices with these type of

TABLE 3: PLASMA PARAMETERS FOR REACTOR LIKE PLASMAS

	Parameter	JET (H-mode)	TFTR (Hot-ion mode)	DIII-D (H-mode)
Electron Temperature	T_e (keV)	9	8	3.8
Ion Temperature	T_i (keV)	22	25	17
Central ion density	n_e ($\times 10^{19} m^{-3}$)	4	4	3.8
Effective charge	Z_{eff}	1.4	2.6	3.5
Confinement time	τ_E (s)	1.1	0.15	0.1
Neutral beam power	P_{NB} (MW)	16	30	15
Fusion product	$n_i T_i \tau_E$ ($\times 10^{20} m^{-3}$keVs)	8-9	2.6	0.05

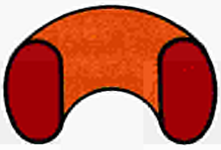
		TFTR	JET	NET
				
Minor radius	a	0.85m	1.25m	2.0m
Major radius	R	2.48m	2.96m	6.3m
Elongation	k	1.0	1.8	2.2
Toroidal Field	B	5.0T	3.45T	6T
Input Power	P	30MW	36MW	85MW
Fusion factor	Q	0.25	0.8	>100

Fig. 4: Operating parameters of three large tokamak designs

plasmas. Higher plasma currents are required for a fusion reactor in order to confine the plasma and the energetic alpha-particles. Typical values lie between 20 and 30 MA for moderate toroidal magnets fields (B_T = 5MA). Fig.4 shows the main parameters and schematic diagrams of the cross-section of TFTR and JET, the two machines closest to break-even (Q=1), together with a next step device (NET).

Both JET and TFTR have reached high fusion factors. However, JET has approached breakeven conditions transiently, with a calculated Q_{DT} value close to unity during one energy confinement time. The transient nature of the good fusion conditions is at present limited in JET by local overheating of sections of the wall surfaces. This leads to a high influx of carbon, which terminates the good plasma conditions. A new phase is planned for JET to demonstrate a reactor relevant solution to this problem, that should lead to a sustained production of a few MW of alpha-particle heating by 1996.

An extensive exchange of information, equipment and scientists exists within the worldwide fusion community. In particular, a collaboration agreement between the large tokamak groups in EEC, USA and Japan was signed in 1986. Subsequently, this culminated in the setting up of a collaboration between the EEC, USA, USSR and Japan, under the auspices of the International Atomic Energy Agency (IAEA), to perform a conceptual design of an International Thermonuclear Experimental Reactor (ITER). The main objective of the ITER project is to define a single concept that should suffice to demonstrate the scientific and technological feasibility of fusion and will be providing input to the ITER 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

The present technical status of JET is described in the following three sections:

- The first section outlines details of technical achievements made during the main operating periods of 1989 and the developments and improvements implemented during the shutdowns at the beginning and end of 1989;
- Machine operations during the operating periods 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

During early 1989, the machine was already well into a scheduled shutdown. The two main tasks during the shutdown were to reinforce the vacuum vessel and to inspect and, if required, repair the ohmic heating coil.

The vessel reinforcement had been planned in early 1988 and work started in October 1988. It consisted of welding inconel rings inside the vessel at the inboard wall to strengthen the vessel against disruption forces. This work which involved a large amount of accurate fitting and heavy welding inside the vessel was successfully completed by early-1989. This work was followed by a careful realignment of the wall protection tiles at both the inboard walls and upper X-point region, to distribute better the heat flux on these tiles contacted by plasma. After closure, operation restarted but an unusually high impurity level soon revealed that a foreign object had been trapped inside the vessel. After inspection, an overlooked cable was located behind the belt limiter tiles. It was then necessary to thoroughly clean the vessel with mild detergent before operation restarted. This unfortunate incident demonstrated the need for a tighter control of in-vessel work and of equipment brought into the vacuum vessel and necessary measures have now been implemented.

Inspection of the ohmic heating coils showed that the problem of coil rotation which had been discovered in 1987 had not recurred. The modifications carried out at the end of 1988 appeared to have been effective.

The salient feature of 1989 operation was the use of beryllium as a first-wall material. For initial beryllium operation up to July 1989, the first-wall design was unchanged. In particular, graphite tiles were still used for the belt limiter, ICRF antennae and wall protections, but all surfaces were coated with a thick layer of evaporated beryllium. Beryllium coating was achieved by means of four beryllium evaporators located at the outboard wall near the equatorial plane. Operation of the evaporators was highly successful and led the way to important results. Some minor technical problems with the evaporators were rectified in July 1989 and this allowed fault-free operation until October 1989.

In July-August 1989, the graphite tiles on the belt limiters and certain ICRF antennae were replaced with beryllium tiles. This operation was not a difficult task in itself, but for the first time, personnel access to a beryllium contaminated vessel was required. The first intervention inside a beryllium contaminated vessel proved more time consuming than first expected. A major effort was required to provide manpower support in the use of air ventilated suits. Operations such as dressing and undressing of personnel and the cleaning of the suits required more personnel than anticipated. As a result, this shutdown for the installation of the beryllium belt limiter and antennae tiles took longer than planned. However, all operations were carried out in safe conditions, beryllium contamination was well contained and considerable experience was gained in the use of the Torus Access Cabin, the use of suits, and the safety requirements for beryllium monitoring. The smooth running of the subsequent late-1989 shutdown demonstrated that beryllium operation and technical support for intervention in beryllium contaminated areas was well under control.

Operation with beryllium tiles was successful but, as expected, local melting of tiles could not be avoided. Damage on the belt limiter tiles was minor but on some of the ICRF antennae protection tiles, bulk melting occurred at tiles adjacent to the neutral beam injection port. The cause of the melting seemed to be due to a local plasma-beam interaction leading to a significant fraction of the beam energy falling on the protection tiles. Although 1989 operation time was short, operation was a great success due to the use of beryllium and to the excellent reliability of other systems. Neutral beam operation was highly reliable and for the first time, included some injectors at 140kV (30A deuterium). A major improvement to the ICRF heating system was the successful operation of the real time automatic tuning system which allowed fast changes of the plasma parameters to be followed, in particular, those relating to transitions from L- to H-mode.

In late May 1989, an electrical fault was detected in a toroidal field coil. Investigation showed that this coil exhibited low turn-to-turn insulation resistance between a number of turns. The fault did not prevent operation but was potentially a threat to the machine since it was not possible to predict its evolution. It was decided to replace this faulty coil with one of the spare coils. The shutdown foreseen for November 1989 was brought forward to start in October 1989 and extended to allow for the coil replacement.

Other important activities during the shutdown were the installation of beryllium screens in the ICRF antennae, the assembly of the prototype lower hybrid current drive launcher and the installation of the prototype high-speed single-shot pellet injector. The removal of a toroidal field coil is a major operation requiring a large effort in terms of organisation, preparation of work procedures and planning. By the end of December 1989, the in-vessel work required to separate one machine octant was complete and Octant No.3 containing the faulty coil was ready to be lifted out of the machine.

Containment of Forces Acting on the Vacuum Vessel

To reduce the deformation of the vessel during disruptions at high current, internal restraint rings were installed during 1988/89 shutdown. An assessment of forces showed that during a typical disruption at 7MA, additional radial loads of 20,000kN and deflections of 15 to 20mm 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 in Fig 5. 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 the hoop strength. The new rings on the inboard wall will carry approximately 30% of the radial load in a radial disruption.

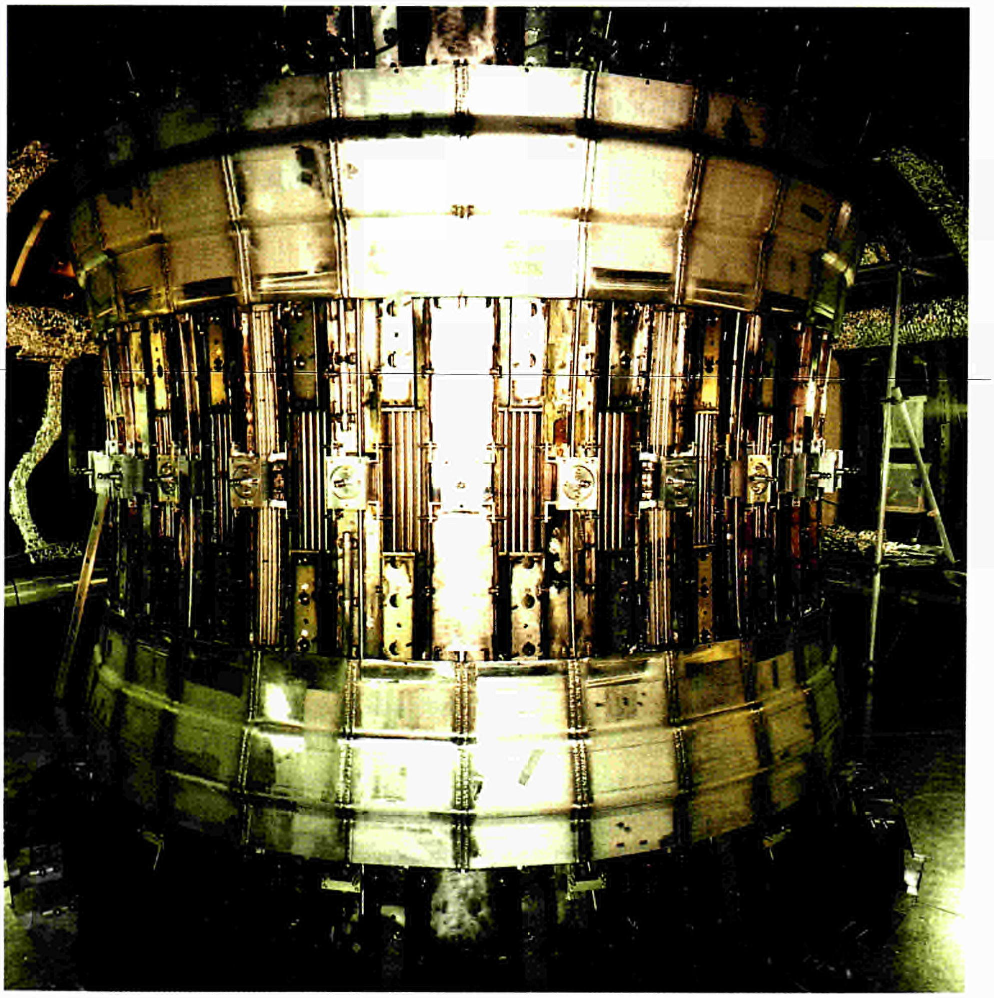


Fig 5:
Reinforcement rings installed inside the vacuum vessel.

Checks on the Poloidal Field Coil System

Previous 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

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.

stray magnetic fields were reduced and the breakdown of the gas and plasma start-up were improved. This modified coil connection system 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 permitted higher current values in the X-point configuration while reducing shear stress on the toroidal magnetic field coils. This arrangement has allowed X-point operations above 5MA plasma current. In addition, an improved poloidal vertical field booster amplifier has greatly assisted plasma break-down and initial rise of plasma currents. This has enhanced the flat-top period at the highest currents operation.

During the 1988/89 shutdown, 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.

In-Vessel Components

Following completion of the 1988/89 shutdown, operation resumed initially with graphite as the main first-wall material. The new internal configuration of the vacuum vessel is shown in Fig 6, where the main change is that the vessel reinforcement rings are protected against the plasma by carbon fibre reinforced graphite. Subsequently, beryllium was introduced into the JET vessel as a plasma facing material. Beryllium was first introduced in the form of a thin evaporated layer at the inner surface of the vessel, and at a later stage the carbon tiles on the belt limiter and on the RF antennae were exchanged for beryllium tiles. Essential elements in the exploration of beryllium as limiter and wall material were the evaporators for covering the inside of the vacuum vessel with beryllium layers of up to a few microns thickness. Twenty six evaporations were made with four evaporators and about 260 gm of beryllium were deposited inside the vessel. Fig. 7 shows one evaporator

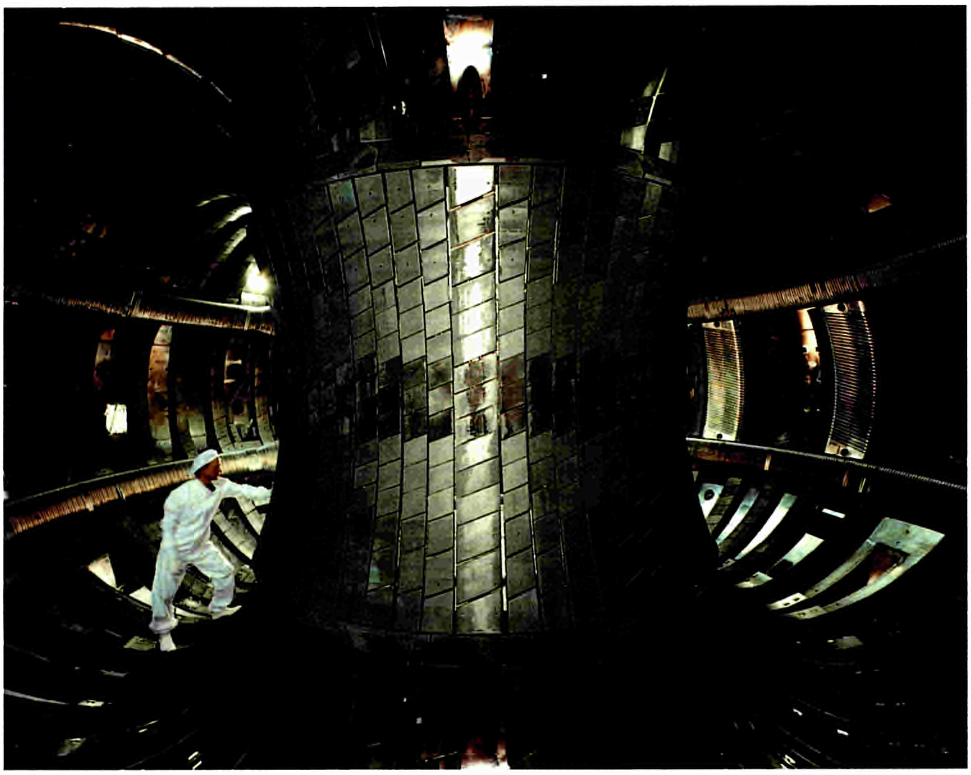


Fig 6:
Internal view of JET vacuum vessel

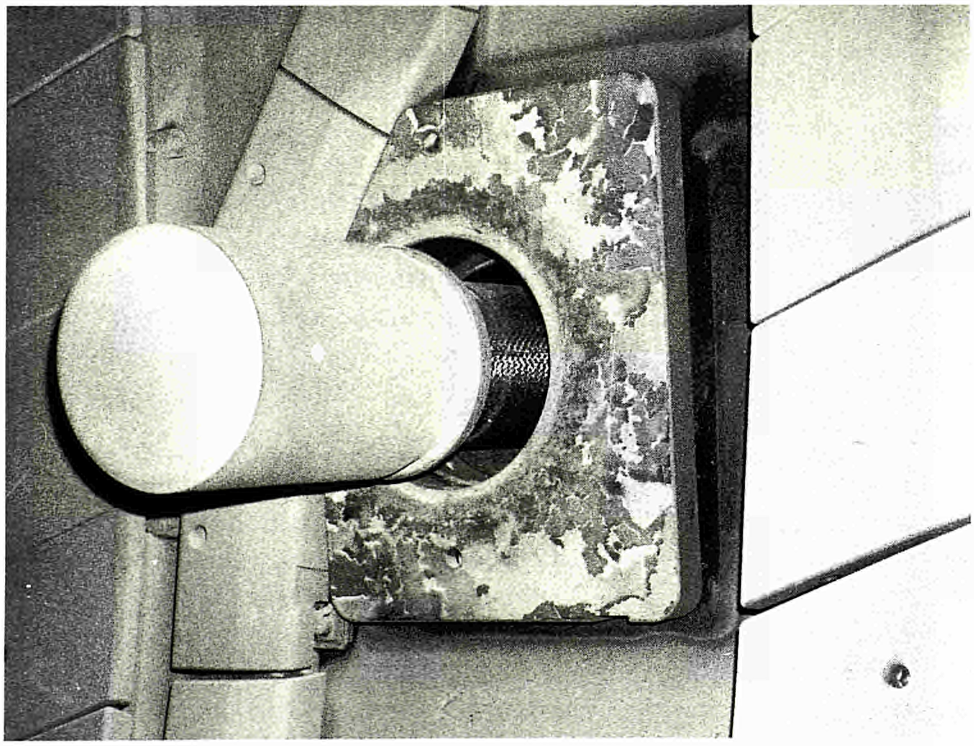


Fig 7:
A view of one beryllium evaporator inside the vacuum vessel

inside the vessel at the time of the installation of the beryllium limiter. During their use, the heads of the beryllium evaporators showed changes in the surface topology, and due to the related increase in emissivity the head temperature dropped and the evaporating rate decreased. This problem was reduced considerably by using cast heads instead of employing standard sintering techniques for their manufacture.

The second stage in the assessment of beryllium was the exchange of the limiter tiles, with the original graphite. The limiter design incorporated the facility of easy exchange of materials. As beryllium evaporation was already carried out before the installation of the beryllium tiles on the belt limiter, this work had to be carried out with full protection, since respiratory protection is required above a certain permitted concentration of beryllium in air. Fig 8 shows installed beryllium tiles at the lower and upper belt and a suited worker during cleaning of the vacuum vessel before operation resumed.

Fig 8:
Installed Beryllium tiles on the belt limiter. A suited worker is cleaning the vessel before operation

Toroidal Field Coil Replacement

During mid-1989, a fault was detected by the toroidal field coil fault detection system, which compares voltages across coils. It showed that an inter-turn fault existed in a coil at Octant No.3. Subsequent examination of previous magnetic data showed that the fault had been developing steadily since 1987, but much more rapidly in 1989.

Measurements pointed to a water leak causing a conductive path between turns. It was originally decided to detect and seal the leak and at the same time dry out the insulation and increase the interturn resistance. However, after drying out, the interturn fault resistance remained low, which pointed to more permanent damage. Consequently, it was decided to replace the faulty coil with one of the spare coils. The shutdown originally planned for November 1989 was brought forward to start in October 1989, and extended to allow for the extra work involved.

The replacement of the faulty coil required the removal of Octant No 3 from the machine. However, replacement of an Octant had been foreseen and the machine was designed to facilitate this. Even so, it is still a major operation. Preparatory work for removing the Octant was completed by the end of the year ready for moving it to the Assembly Hall at the beginning of 1990 (Fig 9) . A detailed analysis of the faulty coil will be undertaken after replacement, since only limited measurements were possible with the coil in the machine. New instrumentation will be incorporated to provide more information about the coils so that the development of any future faults can be monitored.

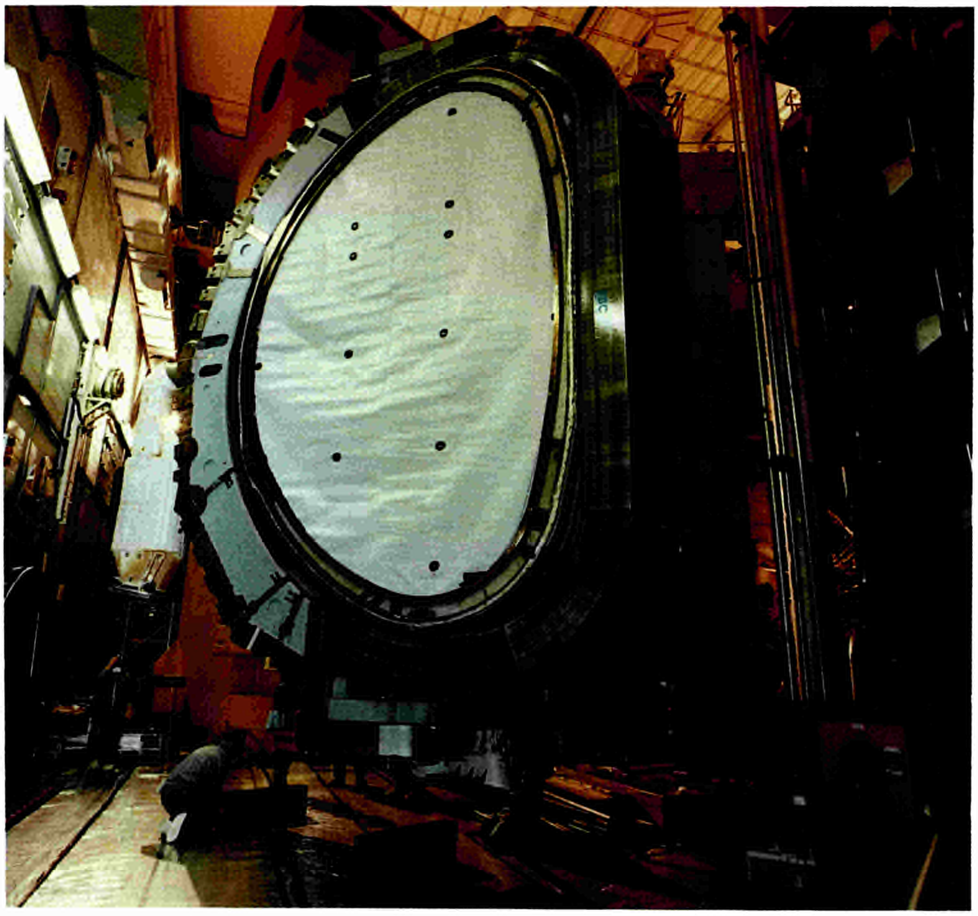


Fig 9
An octant being removed from the torus

Neutral Beam Heating

During the year, the successful operation of both the Octant No. 4 and Octant No. 8 neutral beam injection systems was further improved. No major difficulties or failures were encountered with either the mechanical or the power systems, and a high degree of availability and reliability were maintained throughout all periods of tokamak operation. Six of the sixteen beam sources and their associated power supplies have been successfully converted from 80kV to 140kV operation in deuterium during planned shutdown periods. This has enabled deeper penetration of the neutral beams into denser JET plasmas. These modifications in conjunction with the use of beryllium as a first-wall material have resulted in significant extensions to the plasma parameters achieved in JET, both by NB heating alone and also in combination with RF heating. This has included improvement of the peak ion temperature to near 30keV and production of the peak D-D neutron rate of 3.7×10^{16} s^{-1}.

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. Preliminary measurements on the performance of the deflection magnet and power profiles of the residual full energy ions in the ion dump have been obtained using 120kV He^4 neutrals to simulate 160kV T^+ beams. This indicates that satisfactory performance can be achieved. Considerable effort has been devoted to testing the feasibility of dispensing with the need to supply gas to the plasma sources at high potential during tritium operation. This would avoid tritium gas lines at high voltage, and would provide advantages with safety and inventory. It also offers the advantage of being able to exchange sources without disconnection of the gas feed. Tests have shown that it is feasible to supply all the gas at ground potential and only relatively minor modifications are necessary to minimise total usage of

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.

tritium. However, certain source problems remain to be overcome with gas breakdown at the high voltage.

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 57MHz) 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 original design power was for 15MW for 20s. The output stage of each sub-unit is being upgraded to 2MW instead of the original 1.5MW by replacing the high power tetrode and modifying the output circuit, providing an amended design power of 24MW in the plasma. This upgrade is not yet complete (two generators were still being upgraded at the end of 1989) but a maximum power of about 18MW for 2s has been coupled to the plasma. The maximum power was limited by arcs in the transmission and antennae components, while longer pulse lengths were not possible due to energy limitations on the vessel.

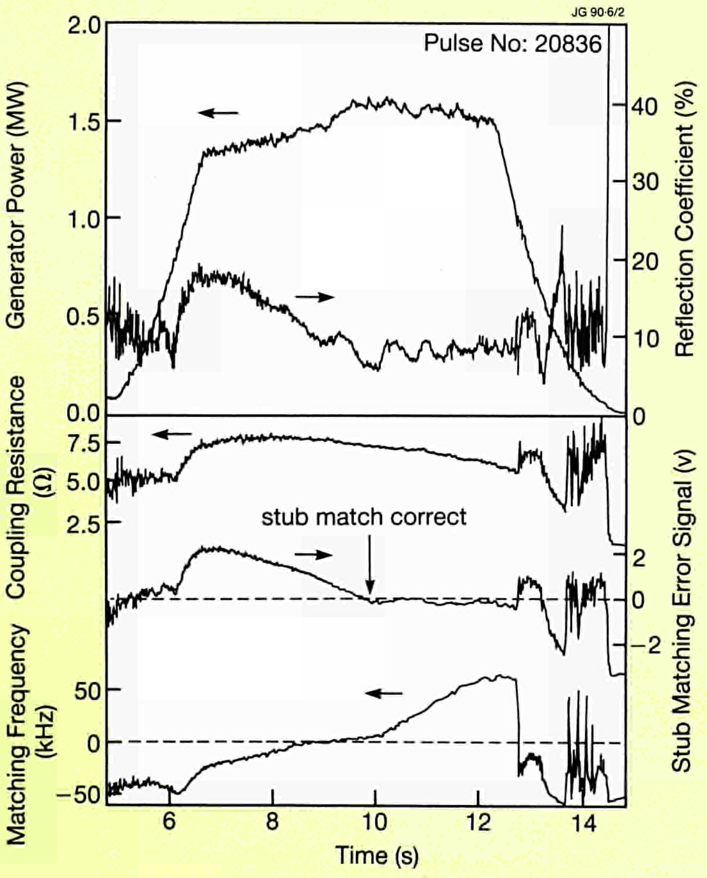


Fig 10:
Reaction of the automatic matching system to a variation of the loading resistance during a long ICRF pulse. The figure represents the change of wave frequency and the error signal driving the stub length to perform proper impedance transformation of the coupling resistance. Generator power fed to one antenna and reflection coefficient during the long ICRF heating is also shown. The automatic matching system maintains a low reflection coefficient despite the variation of the coupling resistance.

A particularly severe test of ICRF plant performance was the rapid change of plasma edge conditions imposed by the various facets of the JET experimental programme. The antenna loading can undergo rapid variations with plasma conditions. An example is shown in Fig 10 of the change of the loading resistance during a long monster sawtooth. Considerable progress was made in adjusting rapidly the plant settings to varying plasma conditions. During the plasma pulse, a triple feedback loop adjusts the wave frequency, the length of tuning stubs and the electrical length of the antennae circuits to minimise the power reflected back to the generators. The system was also used effectively to compensate partly for the resistance change by a factor of 2 - 3 during L- to H-mode transitions.

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. 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. By end 1989, all screen components had been delivered and high voltage tests had been successfully performed. It is planned to resume plasma operation in 1990 with all eight antennae equipped with the new screens. Fig 11 shows a photograph of the new design of screen (here equipped with aluminium bars for safety reasons).

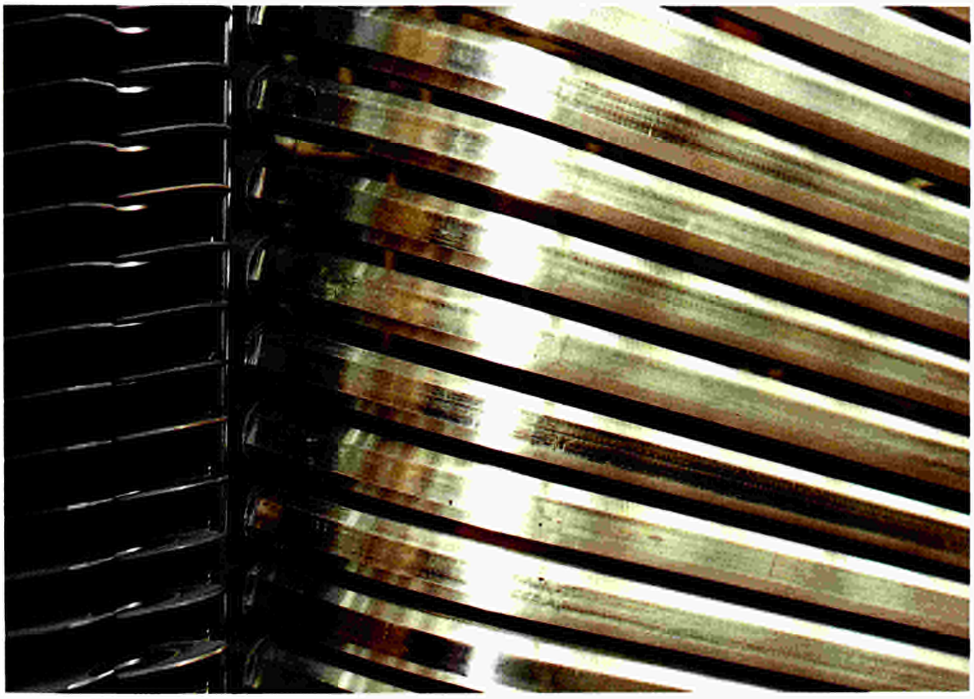


Fig 11:
Detail of the construction of a beryllium screen (here equipped with aluminium bars, for convenience) showing the open structure, the attachment of the bars and the cooling fins supporting the side protection tiles.

Pellet Injection

An important requirement for the successful operation of future fusion plasmas is a fuelling and density control system. One method of raising the density, and replenishing it during operation, is to inject pellets of solid hydrogen into the plasma at high speed so that these penetrate the outer layers and reach the centre before completely evaporating. The clean plasmas resulting are comparatively resistant to disruption.

The multi-pellet injector in JET was built and operated under a collaborative bilateral agreement between JET and the US Department of Energy (USDoE) (see Fig 12). It has operated reliably throughout 1989 and has

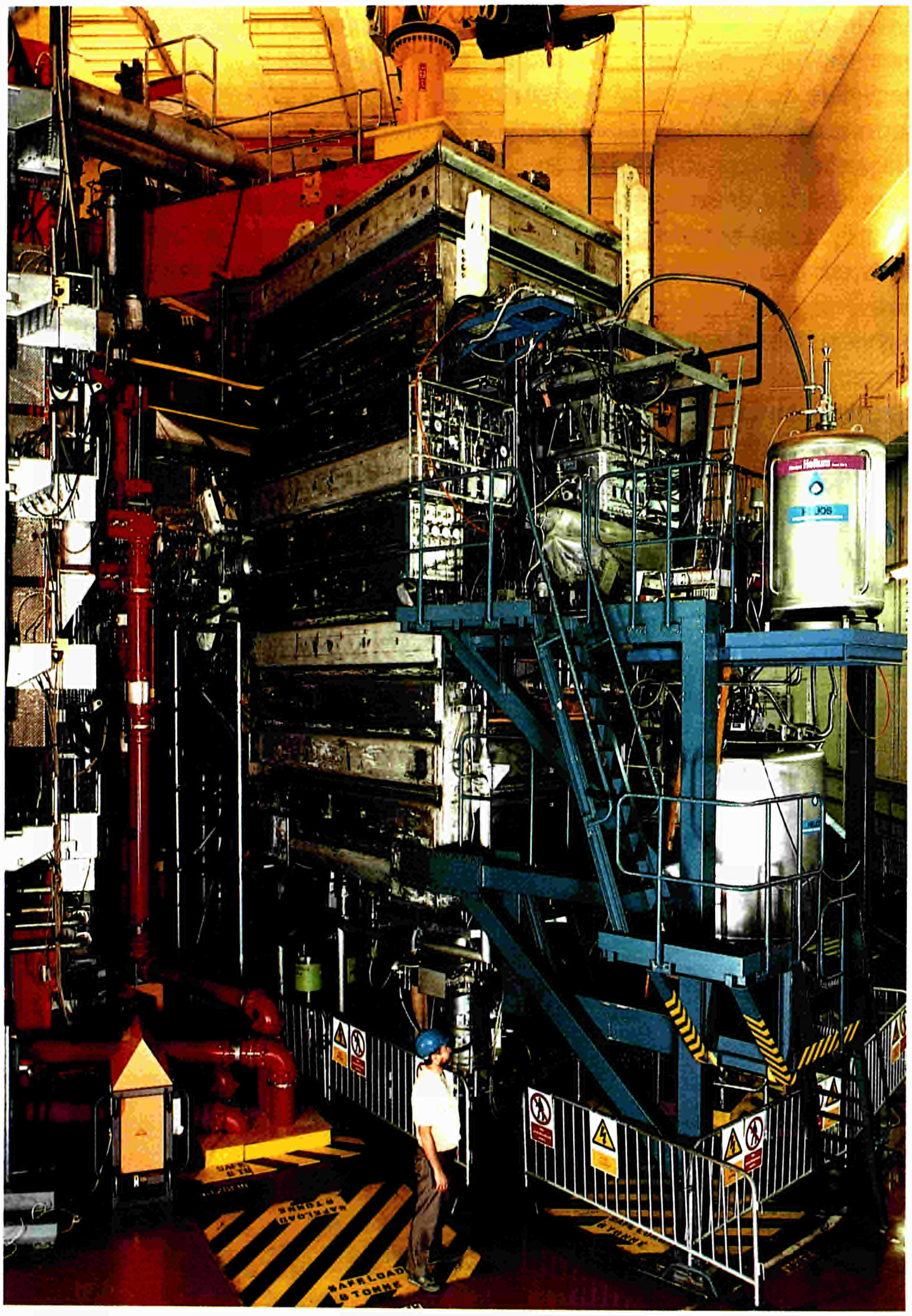


Fig 12:
The multi-pellet injector on JET

delivered pellets singly or bunched in sequences with repetition rates up to $5s^{-1}$, in sizes of 2.7mm, 4mm or 6mm diameter. It was possible to extend the pellet injection scenarios up to 5MA plasma current and to inject 6mm pellets successfully for the first time. The maximum central peak density immediately after injection achieved was raised to $4 \times 10^{20} m^{-3}$ for X-point and $2.8 \times 10^{20} m^{-3}$ for limiter plasmas. Participation by the US Team, required by the Agreement, has contributed greatly to this success.

Diagnostics

The location of the JET measuring systems (or diagnostics), whose installation is now nearing completion, is shown in Fig.13 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.

Temperature and Density Measurements

The electron cyclotron emission measurement system comprises four different types of spectrometer: rapid scan Michelson interferometers, Fabry-Perot interferometers, a twelve-channel grating polychromator and an eight-channel heterodyne radiometer. The Michelson interferometers provide measurements of the whole ECE spectrum from which the spatial dependence of the electron temperature is derived. The Fabry-Perot interferometers and grating spectrometer provide the time dependence of

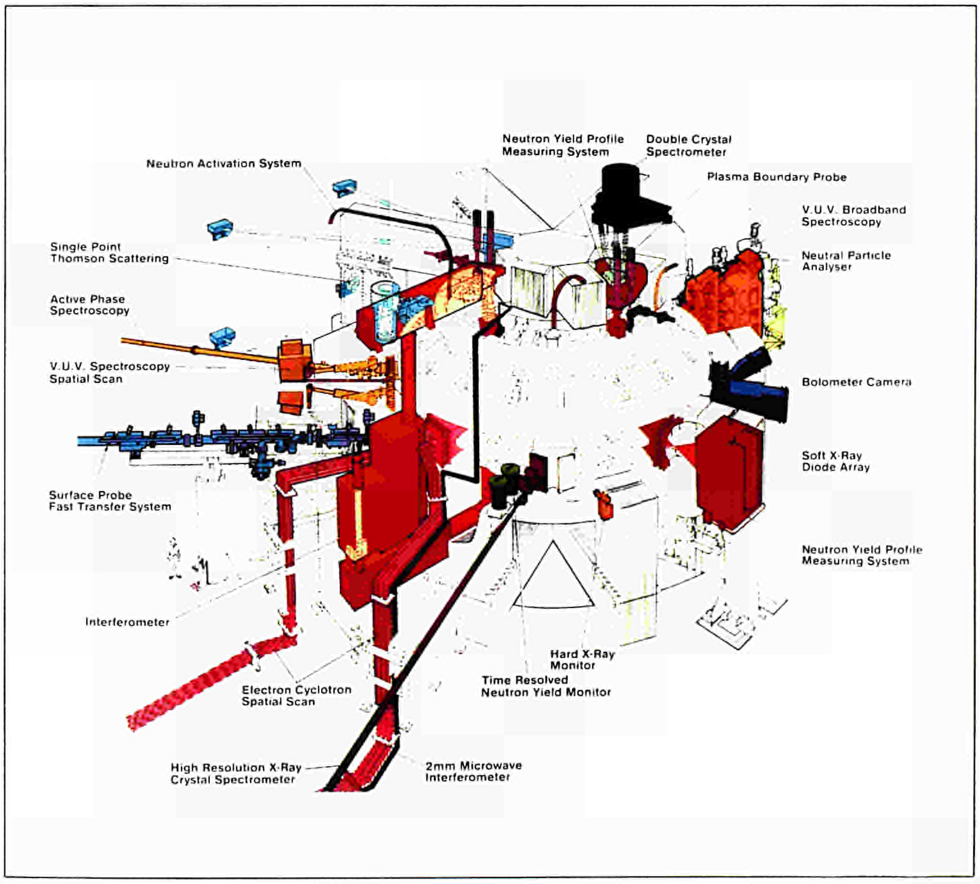


Fig 13:
Location of JET diagnostic systems.

TABLE 4: STATUS OF THE JET DIAGNOSTICS SYSTEMS, DECEMBER 1989

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
KE5	Fast ion and alpha-particle diagnostic	Space and time resolved velocity distributions	JET	Under Development	Yes	Not yet installed
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 and FOM Rijnhuizen	Operational	Yes	Fully automatic
KG4	Polarimeter	$\int n_e B_p ds$ on six vertical chords	JET and 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	Semi-automatic
KL1	Limiter viewing	Monitor of hot spots on limiter, walls and RF antennae, divertor target tiles	JET	Operational	No	Fully automatic
KL3	Surface temperature	Surface temperature of limiter and target tiles	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	Operational	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	Semi-automatic
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 from wall and limiter	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} (r)	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'90	Yes	Not yet implemented
KT4	Grazing incidence + visible spectoscopy	Impurity survey	UKAEA Culham	Operational	No	Fully automatic
KX1	High resolution X-ray crystal spectroscopy	Central ion temperature, rotation and Ni concentration	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 reciprocating Langmuir 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	JET and 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

the electron temperature at fixed points in the plasma, and the heterodyne radiometer provides temperature measurements in a limited region of the plasma with high spatial resolution and sensitivity. One of the Michelson interferometers is linked to a real-time processing system which provides the electron temperature profile, or derivatives from it, for plasma monitoring or control of JET systems.

During 1989, the Michelson interferometer, Fabry-Perot interferometers and the grating spectrometer were unchanged except that the detector on the Michelson system was replaced due to failure of the detector cryostat. This meant that the continuity of ECE calibration, which had existed since 1984, was temporarily lost. Retrospective calibration at the end of the operation period restored the calibration to its normal accuracy (± 10% in absolute level).

Progress with the upgrade of the heterodyne radiometer from eight to 44 channels has continued. The detailed design was completed and all major system components ordered. Some key components not available commercially were developed in-house. The existing eight-channel radiometer was used in a wide range of studies: a new area of application was the study of high-beta plasmas produced at toroidal fields (B_T<1.3 T) below the operating range of the other ECE instruments.

Work has proceeded with the phased installation of an upgrade to the LIDAR scattering system for measuring the spatial profiles of electron temperature and density to provide a 10 Hz repetition rate capability. The first stage upgrade was successfully completed early in the year with the installation of high reflectivity broadband dielectric collection mirrors. These will allow reduced laser energy (1-2 J instead of 2-3 J) to be used for the future 10 Hz laser without a reduction in signal-to-noise for the measurement. In addition, a bandwidth enhancement of the digitizers was commissioned to give a modest increase in spatial resolution. In late 1989, the second phase of the 10 Hz upgrade was successfully implemented.

The LIDAR system functioned routinely during the tokamak operation periods. Usually, it was operated with the 2-3J ruby laser in 0.5Hz/9-pulse mode but occasionally in 1Hz/6-pulse mode for improved time resolution, particularly for measurements with pellet fuelled discharges. The improved signal-to-noise afforded by the combination of the ruby laser and new mirror configuration revealed most notably the changes in the density profile when beryllium was introduced into JET as a wall material (see Fig 14).

The multichannel reflectometer operates at twelve frequencies in the range 18-80 GHz and so probes electron densities in the range 0.4-8.0 x $10^{19}m^{-3}$. It has been designed to have two modes of operation: narrow band swept, for measuring the electron density profile; and fixed frequency, for measuring movements of the different density layers on a relatively fast timescale. During 1989, significant progress was made and, except for the two highest frequency channels, the system is now fully operational. The principal system modification was the installation in the vacuum vessel of a new antenna assembly. The new antennae have their apertures close to the plasma and give a much improved coupling between launch and receive systems. Signals due to spurious reflections in the port are also significantly

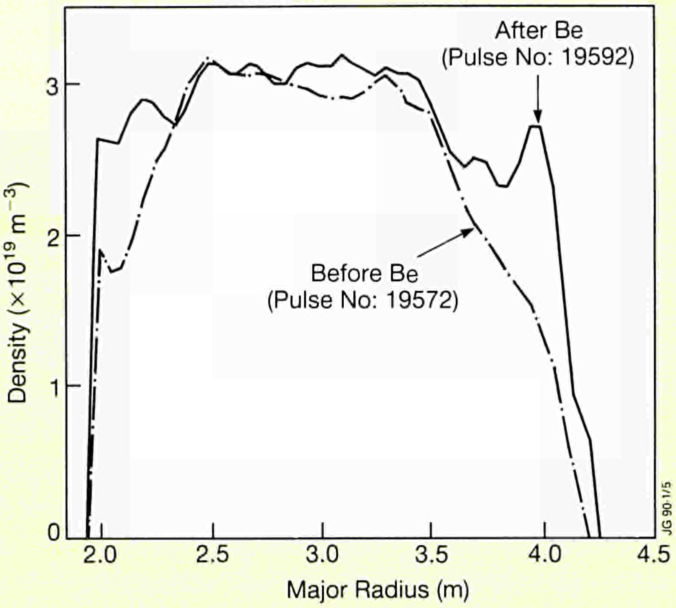


Fig 14:
Density profiles using LIDAR, before and after Beryllium evaporation.

reduced. In addition, techniques were developed for reducing the effects of high frequency density fluctuations and it is now possible to measure the profile of the electron density with a spatial resolution ±5 cm and a time resolution 5 ms under many conditions of interest.

Spectroscopic ion temperature measurements at JET are based on the Doppler broadening of spectral lines emitted by either highly ionized impurity atoms (e.g. Ni^{26+}) in the case of high resolution X-ray spectroscopy, or by fully stripped light impurity ions (e.g. Be^{4+} or C^{6+}) in the case of Charged Exchange Recombination Spectroscopy (CXRS). The passive emission of the resonance line of Ni^{26+} emanates from the hot plasma core, whereas the locations of the active charge exchange emission lines are defined by the intersection of neutral beam and a fan of viewing lines.

CXRS is used routinely at JET to measure radial profiles of impurity ion temperatures using a fan of viewing lines intersecting the neutral heating beams at several radii in the torus mid-plane. In 1989, radial ion temperature profiles were based on the spectral analysis of whichever was dominant of carbon or beryllium. Systematic errors due to energy dependent cross-sections for charge capture were analysed, but proved to be negligible even in hot-ion-mode plasmas with temperatures approaching 30 keV.

Boundary Measurements

A large number of fixed Langmuir probes were installed in target plates, limiters and RF antennae to provide routine measurements of the plasma density and temperatures close to the plasma edge. The fast moving reciprocating Laingmuir probe (which can scan 10cm of the edge profile in 200ms) has been used regularly and with high reliability to provide extensive profile information, identification of the plasma boundary and of the carbon sputtering yield (deuterium on carbon plus self sputtering) measured on its tip as a function of surface temperature. The system for exposing time resolved collector probes at the top of the machine has been used for the first time under remote control.

The integral exposure/analysis facility of the Fast Transfer System and the Surface Analysis System in which exposure, transfer and analysis are carried out under vacuum has been successfully operated throughout the campaign. It has provided direct measurements of the thickness of evaporated layers; a measurement of the evolution of an evaporated layer on a shot-by-shot basis (formation of beryllium oxide and carbide); and the time resolved deposition of carbon, beryllium, deuterium, etc, under various discharge conditions.

Observations of limiter surfaces have been made using cameras at up to eight different viewing ports from which five channels have routinely been recorded. Information from the cameras has been used mainly to optimise plasma performance by avoiding arcing and hot spots, optimising the plasma contact with limiters, etc. Cameras have been equipped with carousels containing filters for the observation of H_α, BeI, BeII and CI, II, III light and these have been used both for the beryllium limiters as well as for the divertor target plates to obtain spatially resolved influxes of various elements.

Evaluation of video recorded data has been greatly facilitated by the introduction of a PC based video analysis system. This has enabled more detailed analysis, particularly of temperature data, where problems due to the small dynamic range of the CCD cameras have been greatly reduced. Target temperatures at the X-point tiles of up to 2500°C have been measured using this facility. Viewing ports have been shared with other spectroscopic measurements to make correlations between the observations of impurity influxes. A CCD camera has also been used successfully to observe the top of the reciprocating probe to give both the surface temperature as well as the carbon/beryllium influx.

High resolution visible spectroscopy of neutrals and low charge state ions has been used to measure Doppler ion temperatures from ions near the plasma boundary. In particular, temperatures have been deduced from D_α and BeIV lines. The BeIV temperature is higher than the D_α temperature. This was expected because BeIV radiates from further into the plasma than D_α. However, both temperatures indicated that the boundary ion temperature is much larger than the electron temperature measured by Langmuir probes. The possibility that the ion temperature might be higher than the electron temperature had already been deduced by the inability of the Langmuir probe data to account for the power flow to the limiter.

Impurity Analysis

In 1989, JET operation offered a challenging variety of mixtures of light impurities in the hot plasma core, for analysis by spectroscopic means. Coverage of the vessel walls by a thin layer of evaporated beryllium and, in the second operation phase, the introduction of a beryllium tiled belt limiter, both caused a complete change in the visible spectrum emitted. The gettered layer on the graphite tiled walls reduced the level of carbon emission and effectively eliminated oxygen. Beryllium became the dominant impurity.

Radial profiles of the effective ion charge, Z_{eff}, were determined from Abel inverted profiles of the multi-chord visible Bremsstrahlung signals and simultaneous measurement of main light impurities by charge exchange spectroscopy. The dilution factor (the ratio of deuterium density to electron density, n_d/n_e) was derived from the density of electrons and light impurities. A statistical summary of the impurity concentrations is shown in Table 5, together with number of samples used in each phase. It appears that the reduction in the carbon levels during beryllium operation is associated with the elimination of the sputtering of carbon by oxygen.

TABLE 5: STATISTICAL SUMMARY OF LIGHT IMPURITY AND DEUTERIUM CONCENTRATIONS OBTAINED IN EACH OPERATIONAL PHASE

Concentrations	Carbon Phase	Beryllium Gettering	Beryllium Limiter	X-Point with Beryllium
(Carbon) [%]	5.5	3.0	0.5	1.6
(Oxygen) [%]	0.9	0.05	0.05	0.05
(Beryllium) [%]	---	0.8	3.0	1.1
$n_D(0)/n_e(0)$	0.6	0.85	0.85	0.87
No. samples	2421	8524	1394	5979

Neutron Measurements

Several types of neutron spectrometers are operated at JET so that a wide range of operating conditions can be covered. For normal well-behaved discharges, it is possible to unfold the neutron energy spectra to obtain good estimates of the plasma central ion temperature and the beam-plasma to thermal neutron emission strengths. In addition, by combining the analysis with data from the other neutron diagnostics, the beam-beam component can also be identified.

The instantaneous neutron yield from JET discharges is recorded with a set of fission chamber assemblies. During the year, an interpretation problem was encountered, related to the use of high power RF heating and was exacerbated by the introduction of beryllium belt limiters. Whenever ICRF heating is employed, a high energy tail of the minority ion species (H or ^{3}He) is formed. These accelerated particles can attain energies of up to 10MeV and readily interact with thermal deuterons and also with beryllium impurity ions. Under certain conditions, giant sawteeth and low electron densities, the neutron emission from RF-only heated discharges comes predominantly from fast ion-impurity reactions. However, with combined heating, the beam-plasma fusion reactions dominate, with less than 20% of the neutron emission being attributable to the RF-accelerated particles. Under these conditions, neutron and gamma spectroscopy play an important part in interpreting the nature of the neutron emission.

To explain the neutron emission from a JET discharge, it is necessary to supplement data from the fission chambers with information on neutron emission profiles from the profile monitor and with neutron energy spectra derived from the most appropriate of the neutron spectrometers. For example, this combination permits the deuterium density in the plasma to be determined, independently from all other diagnostic information, for most normal discharges.

Fast Ion and Alpha Particle Studies

A diagnostic system to measure the velocity and spatial distributions of fast ions, including α-particles in the D-T phase, is in preparation. The system is based on collective scattering of radiation with a frequency of 140 GHz generated by a powerful gyrotron source. During 1989, substantial progress has been made with the scientific and technical design although the procurement of the major system components has not been initiated due to delays in gyrotron development. Nevertheless, the development of some key system components has been started.

The scientific designs has concentrated on assessing the effects of the dielectric properties of the plasma. The principal effects are refraction of the launch and scattered beams, spreading of the beams due to density fluctuations, and modification of the scattering cross-section. The technical design has concentrated on the interfaces with the JET device and particularly on the in-vessel components, the high power transmission system and gyrotron installation. In addition, the detection system and control and data acquisition system have been designed. In each case, solutions to all the main technical problems have been obtained and potential suppliers identified. The in-vessel components are particularly important and so a mock-up of the proposed arrangement including steerable mirrors, is under construction. This will be tested before the detailed design is completed.

Predictions have been made of the performance of the diagnostic with plasmas similar to the best obtained in JET in 1989 assuming D-T fuelling, which show that is should be possible to measure the spatial and velocity distributions of the confined α-particles with energies in the range 0.5-3.5 MeV. For scattering with ordinary mode radiation, the signal-to-noise ratio would be >10:1 assuming standard settings of the diagnostic.

Remote Handling and Beryllium 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 14MeV 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.

A multimedia man-machine interface for the in-vessel inspection system (IVIS) has been developed and used successfully in routine and emergency inspection campaigns (see Fig 15). The interface console contains four black

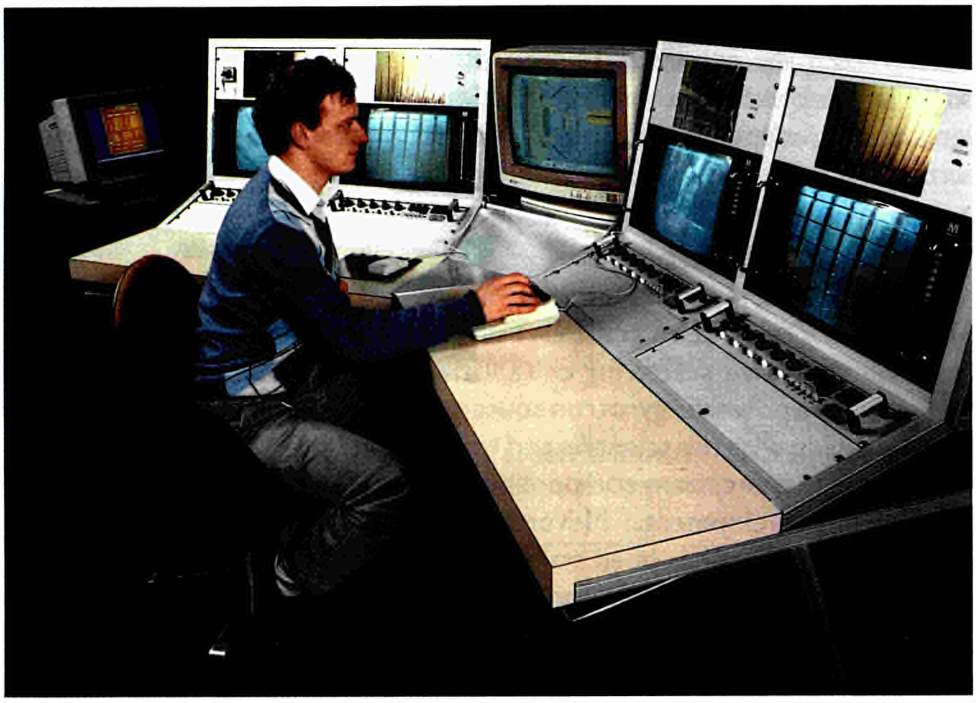


Fig 15:
The man-machine interface console of the in-vessel inspection system.

and white monitors and a workstation. It is connected to the four IVIS TV probes and provides manual and automatic tracking of areas of the vessel wall selected by the operator on a CAD graphical display. "Reference" photographs of the same areas shown on the monitors are also automatically displayed at the same time to facilitate interpretation of any possible defects. Fig 16 is a typical photograph taken with IVIS during an inspection campaign during operation with a beryllium first-wall showing melt marks on beryllium tiles of the belt limiter.

Considerable effort has been devoted to the provision of equipment, services and expertise for the two shutdowns following the introduction of beryllium into JET. To co-ordinate preparations for post-beryllium maintenance, a Beryllium Task Force was created. The preparatory work comprised major efforts for: the design, construction and commissioning of a new Beryllium Controlled Area Facility within the Assembly Hall; the setting up, resourcing and running of a PVC isolator and tent workshop/manufacturing facility; the design, construction and commissioning of a controlled area for access to Octant No.3 whilst it is being repaired in the Assembly Hall; and modifications to the Torus Access Cabin (TAC) ventilation and water systems. In addition, a system was created for the handling, storage and

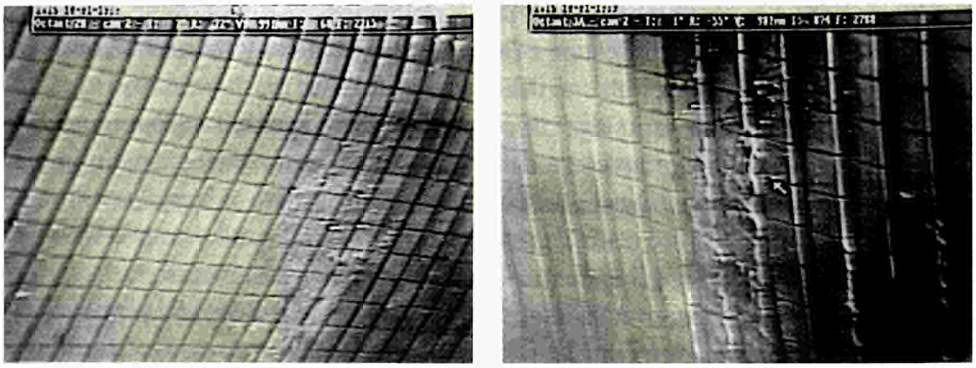


Fig 16:
Photographs taken with in-vessel inspection system showing melt marks on beryllium tiles of belt limiter.

disposal of both toxic and active waste and this is now in operation. Considerable time was invested in the definition of requirements for and the provision and recycling of protective clothing for work in controlled areas. This ranged from the fully pressurised suits used in the torus to simple disposable masks used in uncontaminated areas around the site.

Other beryllium related work consisted of preparing beryllium compatible remote handling equipment for the shutdown. Most notably, the Articulated Boom joints had to be fully gaitered, a tent to cover the boom when operating on the torus had to be installed and commissioned and a controlled transit storage cabin adjacent to the boom at Octant No.5 was designed and installed. With the use of beryllium in the torus, in-vessel intervention work supported from the Torus Access Cabin, required for the first time the use of all the service sub-systems. These included: HEPA filtered ventilation system; water wash system; breathing air system; intercom system; waste transfer system; and controlled area barriers.

To carry out beryllium related work in the Assembly Hall, an enclosed Beryllium Handling Facility was constructed and commissioned early in 1989 (see Fig 17). The facility has a working area of 72m^2 and includes an access and change area, a component transfer airlock, a HEPA filtered ventilation plant, electrical services and a water supply with filtered drainage system. Fume cabinets, ultrasonic cleaning baths and work benches have been installed. To meet necessary deadlines, the complete facility was designed, constructed and commissioned in-house in less than three months. Tasks performed in the facility include: preparation of beryllium tiles for RF

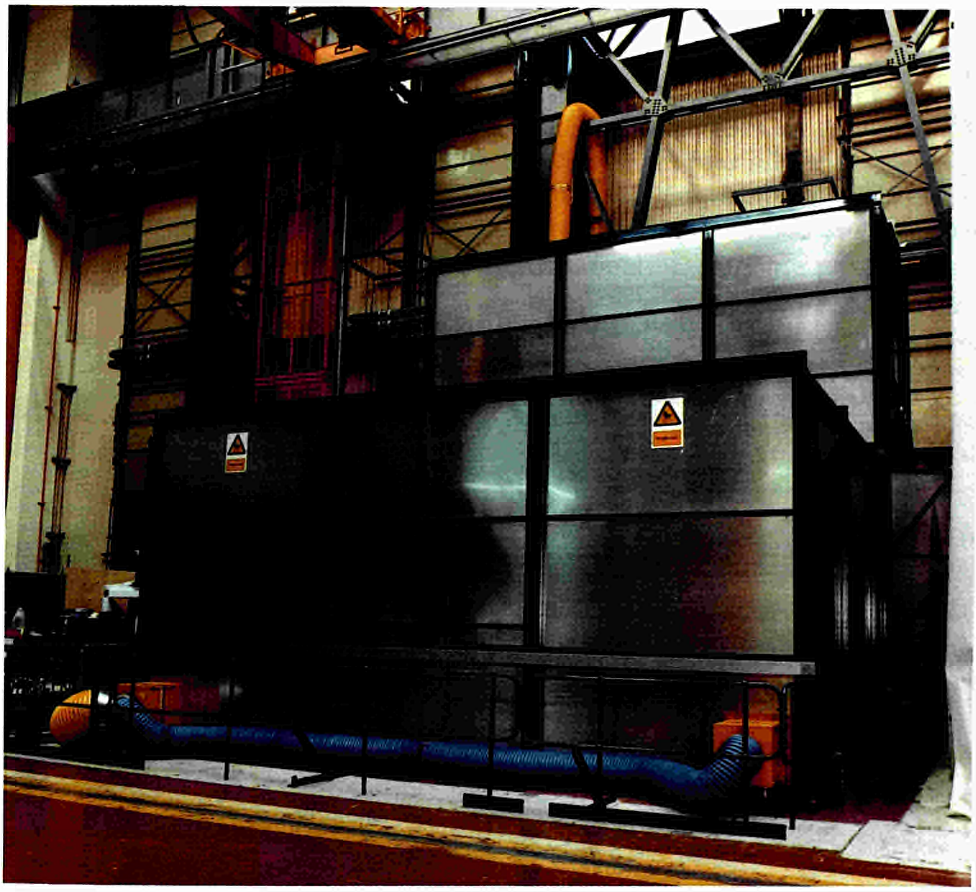


Fig 17:
Beryllium handling facility.

antennae and the belt limiters; maintenance on potentially beryllium contaminated equipment; decontamination of equipment from other beryllium controlled areas; and cleaning pressurised suits and other respiratory protection equipment. The major activity during the in-vessel intervention period was cleaning of pressurised suits.

Control and Data Management

The Computing Service is based on an IBM 3090/200E dual processor mainframe with a vector facility. There are 70 GBytes of disc storage and a further 240 GBytes of IBM mass storage. The JET Mainframe Data Processing Centre is housed in a specially designed building at UKAEA Harwell Laboratory and operated for JET under contract by a team from that Laboratory. The JET mainframe is also connected to the Harwell Laboratory CRAY2 computer.

The JET Computing Centre has been operating since June 1987 and the computing load has grown significantly since that date, such that at peak times the system 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, although some deterioration is noted at

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.

peak times. Also the 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. Studies have indicated the need to upgrade the central processor in order to maintain the good service with the growing workload over the next few years. Plans are in place to upgrade the present IBM 3090/200E to the latest technology IBM 3090/300J early in 1990.

The JET Data Management Group provides the contact between 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 system and the Computer Centre are mainly the responsibility of CODAS Division and significant improvements have taken place in these areas.

JET Computations

Currently, 135 GBytes of raw JET data (JPFs) are stored on the cached Mass Store in a compressed form, and a further 35 GBytes of analysed data are stored on the Processed Pulse File (PPF) online data base system. The Central Physics File (CPF), established during 1988, forms a complete higher level data selection and storage system. A subset of all data is extracted at time points of interest, determined by the Timeslice program and the interactive timeslice editor, TED, and stored in SAS databases. 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, and is used by many physicists in the Project.

Important advances have been made in the areas of:

- A new version of equilibrium magnetic surface identification code (IDENTD) has been implemented. In addition to the magnetic signals and pressure profiles from laser scattering, this code also uses Faraday rotation measurements from a multichannel interferometer as input to determine magnetic flux surface configuration and current density profiles. The configuration bank now contains 10 to 20 configurations for each of about 600 JET discharges.
- Out of the full wave propagation codes for ICRF heating, a simplified version for routine usage has been produced. This code PION calculates power deposition and velocity distribution of resonating ions in steady state in a self-consistent way. A data bank with, initially, about 40 spatial profiles for 19 RF discharges should grow rapidly.
- One of the main difficulties in deriving experimental energy and particle fluxes lies in the consistency and accuracy of the measured input data such as temperature, density and radiation profiles. A set of check programmes has been developed and run as initial step of the FALCON (**F**ast **A**nalysis of **L**ocal **C**onfinement) code. For about 1000 time points in 150 JET discharges, individually checked heat flux profiles are now available with estimated errors resulting from systematic error propagation studies.

Summary of Machine Operation

During 1989, JET operations were essentially made up of three main periods:

a) The first period (Weeks 4 to 21)

This period included the following activities:

- Extensive CODAS and Power Supplies commissioning were carried out as normal or extended day operation (during Weeks 4-14);
- Difficulties in re-establishing clean ultra-high vacuum conditions in the torus required further vessel washing, cleaning and baking extending to the end of Week 17;
- Restoration of plasma operation (Weeks 18-19). Long-pulse operation tests were carried out (B_T = 1.7 T for 60 s and 3 MA for 33 s. In addition, 10s duration X-point plasmas were produced;
- Operation (Weeks 20 and 21) with carbon tiles was carried out in this period to obtain results for comparison with those using Be first-walls. A new mode of operation was successfully introduced, that of sweeping the X-point position back and forth in front of the X-point tiles to reduce the heat load. This was undertaken for the double-null X-point configuration. First signs of a possible toroidal field (TF) coil irregularity were noted.

b) The second period (Weeks22 to 29)

- In this period, the in-vessel surfaces were coated with a layer of beryllium. This period included one week of scheduled maintenance (Week 24). Throughout this period there was a significant amount of time devoted to studying the suspected TF coil faults;
- The evaporation of beryllium produced outstanding performance and improvements. Extensive high power operation resulted in in-vessel overloading of protection tiles and their supports. Operation in Week 29 was terminated to prepare for the next phase in the assessment of beryllium as a first wall material.

c) The third period (Weeks 37 to 40)

- This period was preceded by seven weeks of in-vessel work in which wall damage was repaired and the graphite tiles on the belt limiter and on one RF antenna were replaced by beryllium tiles. This work was made more difficult as the vessel interior was coated with beryllium and therefore in-vessel staff had to wear pressurised air-suits. After a certain learning period, an effective routine for such work was established, including the precautions necessary and the safe handling of beryllium waste;
- Week 37 was devoted to recommissioning the power supplies and restoring plasma operation. Following intensive study of the suspected TF coil in operation and during local tests, the performance of the toroidal field was limited both in voltage applied and in the maximum current drawn;
- Weeks 38 to 40 were devoted to an assessment of the new in-vessel situation. This proved to be even more successful than the previous

period, resulting in new record plasma performance. Machine systems functioned well for a three week (6 days per week) period of high power operation without remedial or maintenance work.

The machine was operated for 90 days during the February - October period. A significant number of these days were required for commissioning of power supplies and for recommissioning of plasma operation. This latter activity was significantly time-consuming in 1989, following:

- In-vessel modifications (to strengthen the vessel to withstand disruptions at 7 MA); and changes in the radial position control power supplies (to improve the vertical field performance) which were carried out in the 1989/90 Shutdown. Other work carried out in this shutdown which required commissioning time included: the installation of Be evaporators; fibre reinforced upper X-point tiles; two 140kV NB lines at Octant No 4; and continued upgrading of the ICRF generators from 1.5 to 2 MW each;
- The first beryllium evaporations;
- The vessel entry in which the graphite limiter tiles and the graphite tiles for one antenna were replaced by beryllium ones.

This resulted in only 56.5 double-shift days during which the experimental programme could be carried out. The distribution of these operation days among the different heating programmes was as follows:

11.5%	Ohmic (OH) heating
20.4%	Radio-Frequency (RF) heating only
23.9%	Neutral-Beam (NB) heating only
44.2%	Combined (NB and RF) heating

The allocation of time to the different activities and the number of days in the various heating programmes is shown in Fig. 18. The experimental programme was carried out within four Task Forces and the 56.5 double-shift operation days in which they were involved were distributed as follows:

Task Force A (Performance Optimisation in Limiter Plasmas) 25.2%
Task Force B (Performance Optimisation in X-point Plasmas) 26.1%

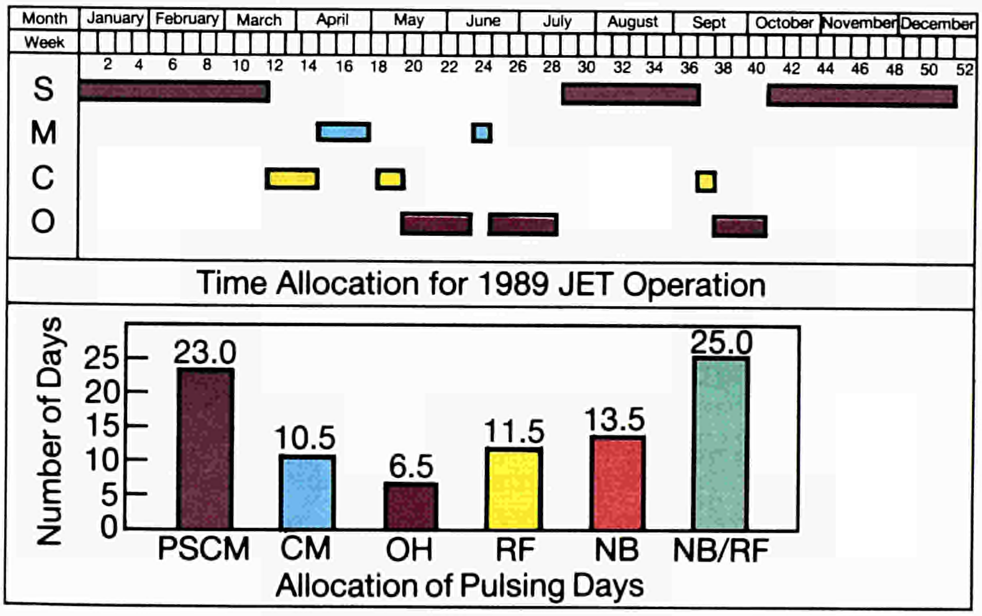


Fig 18: Allocation of days in which machine pulses were performed during 1989.
S = shutdown,
M = maintenance and repair,
C = commissioning,
O = operation:
PSCM = power supplies commissioning,
CM = integrated commissioning (not specifically power supplies),
OH = ohmic heating,
RF = radio-frequency heating,
NB = neutral beam heating,
NB/RF = combined (NB and RF) heating.

Task Force C (Reduction of Impurities and Fuel Enrichment)	30.4%
Task Force D (Physics Issues)	8.3%

The organisation of operation time was altered from 1988 in that a significant amount of commissioning was undertaken in double-shift days, and Saturday double-shift operation was extensively used (13 times). Further, considerable CODAS and Power Supply Commissioning was carried out in early 1989 in parallel with shutdown work.

The number of pulses in 1989 was 2244, bringing the total number of cumulative JET pulses to 21030. The relative number of commissioning pulses continued to decrease (Fig. 19). Even more significant was the increasing number of discharges with plasma current exceeding 3 MA, which for 1989 brought the cumulative total to about 5800. A comparison between the current pulse distributions for 1988 and 1989 is shown in Fig. 20 and reflects a continued movement to operation at higher current values in 1989 and a reduction in the number of low current (<1 MA) values.

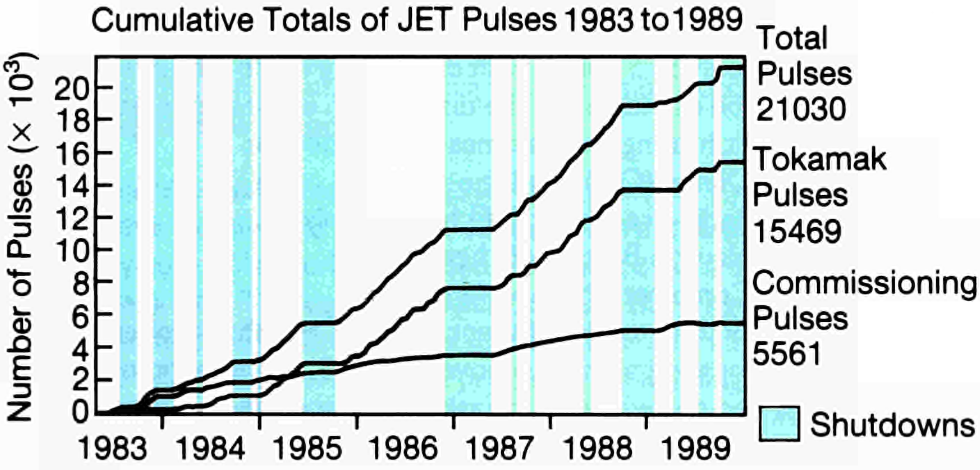


Fig 19: Cumulative total of JET pulses.

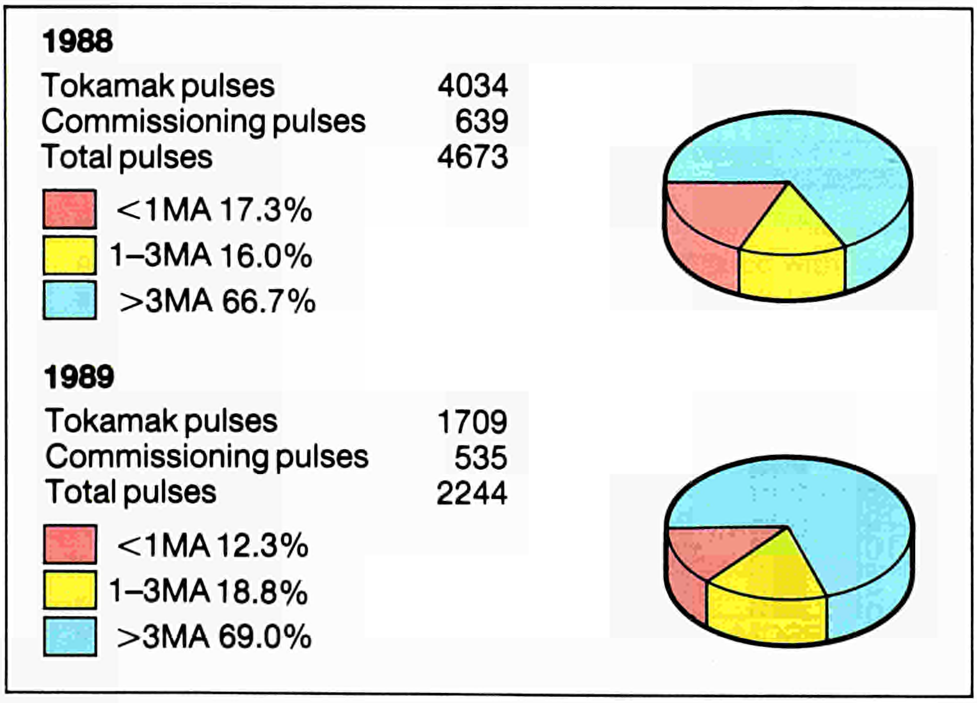


Fig 20: Relative plasma current distribution for 1988 and 1989.

In spite of the limited time available for operation and hence the smaller number of pulses, 1989 was a year in which considerable technical advances were made and progress achieved in plasma performance was outstanding.

Technical Developments for Future Operations

Considerable effort was devoted during the 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.

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.

The JET system is powered by 24 klystrons operating at 3.7 GHz. The original power rating of 500 kW per klystron has been uprated to 650 kW by using newly developed high power circulators. The launcher will produce a narrow wave spectrum with a parallel wave index which can be varied from 1.4 to 2.4. The horizontal row producing this spectrum is composed of 32 waveguides; with 12 rows, the total number of waveguides is 384. The system is summarized in Table 6.

The system will be installed in JET in two stages. The first prototype stage will launch 4 MW and the second stage, the final version, is intended to launch 12 MW power in the plasma. The first stage is composed of two prototypes, one built using the same technique as foreseen for the final system and one built by CEA Cadarache, France, using the technique developed for Tore Supra. They differ essentially in materials: carbonised copper-coated stainless steel is used for the JET design and zirconium copper for the Tore Supra design. The choice of stainless steel for JET has been based upon analysis of disruption forces and on the mechanical properties of the launcher material at high temperature. (500°C) which is necessary for HF conditioning.

The prototype launcher will be powered by eight klystrons. All klystrons have been tested simultaneously at power level of 500 kW for 20 seconds. The necessary adjustments of the klystron parameters to reach the maximum HF rated power value of 650 kW are underway. The waveguide transmission lines linking the source generators to the Torus Hall are installed. Some of these have been tested at high power and the measured

TABLE 6: LHCD SYSTEMS

Generator	
Frequency	3.7 GHz
No of klystrons	24
Power (generator) 10 s pulse	25 MW
20 s pulse	12 MW
Duty cycle	1/30
Efficiency	42%
Phase control	10 degrees
Maximum VSWR	1.8
Length of the transmission line	40 m
Estimated insertion losses	1dB
Launcher	
Number of waveguides (48 multijunctions)	384
Waveguide material	stainless steel
Coating	copper + carbon
Maximum temperature	500 C
Total weight	12 tonnes
Stroke	280 mm
Response	15mm/15ms
Pumping	100 000 l/s

HF losses are within specifications. Parts of the transmission line in the Torus Hall, including hybrid junctions and loads, have been installed but were subsequently dismantled to allow Octant No: 3 to be removed from the Torus Hall.

The design of the prototype launcher has all the features of the complete LHCD system. In particular, all features related to the tritium phase of JET are taken into account, such as double containment and remote handling. Already tens of remote control flanges are installed in the waveguide transmission line. The prototype launcher is ready for installation. A photograph of the grill mouth can be seen in Fig 21. The JET prototype is located at the bottom, and the Cadarache one at the top. The box shielding the launcher from disruption induced forces is also shown in the photograph together with the picture frame supporting the protecting carbon tiles. A photograph of the complete prototype launcher (with the exception of the picture frame) during its removal from the assembly area can be seen in Fig 22.

Stabilization of Disruptions

Disruptions limit the operating ranges of current and density in all tokamaks and similar limits have been reached in JET. Disruptions at high plasma currents impose large electromagnetic forces on the machines structure and considerable care must be exercised in programming the operation of JET to keep the number of disruptions at 7MA to an absolute minimum. These forces increase as the square of the current and consequently serious problems are foreseen for larger tokamaks such as NET and ITER.

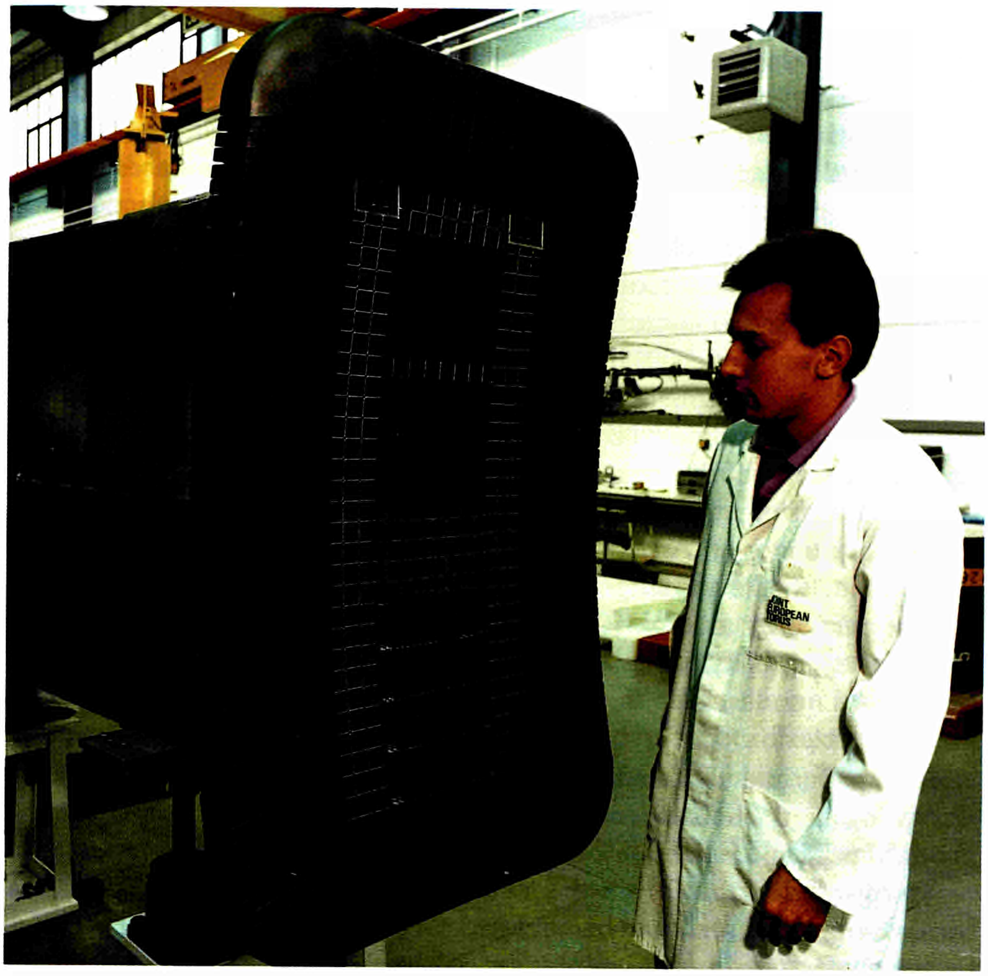


Fig 21:
The prototype launcher, with the JET launcher at the top and the Cadarache launcher at the bottom.

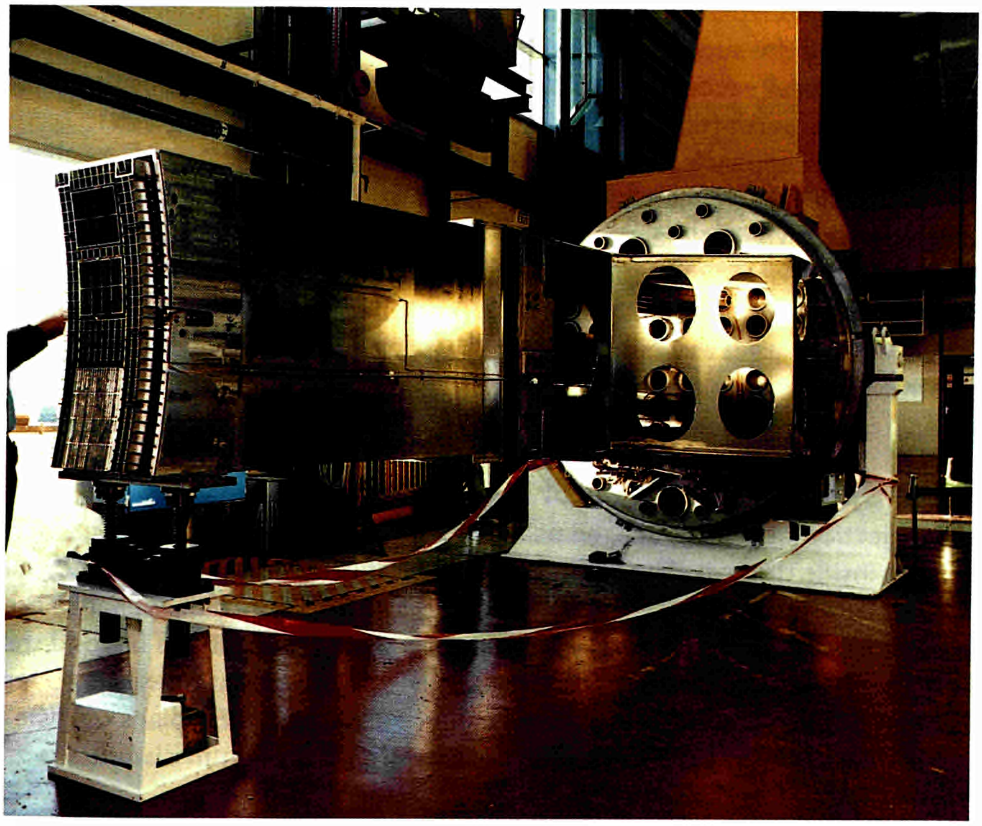


Fig 22:
Photograph of complete prototype launcher (except picture frame protections) leaving the Assembly Area.

Detailed studies of disruptions in JET have stimulated considerable progress in understanding the physical processes involved. The disruption at the density limit is a complex sequence of events that is initiated by a cooling of the plasma edge due to increasing radiation. This destabilises a magnetohydramic (MHD) oscillation, usually with the mode numbers $m = 2$, $n = 1$. This growing mode can be detected using diagnostic coils placed inside the torus vacuum vessel when it is still only about 0.001% of the equilibrium field of the tokamak. Combinations of signals from these coils will be amplified and used as input to a feedback control circuit that will drive a set of large saddle coils also inside the vessel. Through a sophisticated feedback control system the amplitude and phase of the corrective magnetic fields produced by the saddle coils will be used to cancel the growing instability.

The feasibility of this control method has now been demonstrated by a series of experiments on the DITE tokamak at UKAEA Culham Laboratory carried out under an Article 14 Contract, successfully concluded in April 1989. Using saddle and diagnostic coils similar to those that will be used in JET connected by a linear feedback loop, the DITE experiments demonstrated the feasibility of substantially reducing the amplitude of saturated $m = 2$, $n = 1$ modes, delaying the onset of disruptions and increasing the maximum plasma density by a modest amount. These results, provide valuable experimental data to stimulate and guide the theoretical studies of disruptions and feedback control that are continuing and also provide the proof of principle for the JET feedback system.

The diagnostic coils for the JET feedback experiment were installed in the torus during 1989 and have been tested successfully. The saddle coils have been manufactured and are awaiting installation, scheduled for late 1990. A contract has been placed for two of the eight modules of the power amplifiers and following the success of the DITE experiment, this has been extended to include the full set of eight modules. Delivery will be made during the latter part of 1990, permitting feedback experiments starting during 1991.

As well as appearing as precursors to disruptions, locked modes have been observed in JET to cause degradation of confinement and to degrade discharges with pellet injection. Therefore, the ability to stabilize and control the amplitude of locked modes, as demonstrated by the DITE experiment, may have beneficial effects in JET in improving confinement and pellet refuelled discharges as well as delaying the onset of disruptions and extending the working density range.

High Speed Pellet Injector

The injection of solid hydrogen pellets is one method of providing a particle source inside the recycling boundary layer of a future fusion reactor without simultaneously depositing excessive power. The ablation of the pellet by hot plasma electrons requires very high speed pellets to penetrate beyond the $q = 1$ surface to the plasma centre. So far JET measurements have only been carried out in a limited velocity range, up to 1400 ms^{-1}. JET plans to install a pellet launcher in 1990 capable of delivering pellets of 6mm diameter with speeds exceeding 4000 ms^{-1}.

During 1989, an essential milestone in developing a high speed injector was reached. Using a two-stage gun, it was possible to accelerate reliably and reproducibly pellets to speeds of 4000 ms^{-1}. To achieve such velocities, the solid deuterium pellet had to be supported by sabots. It is now possible to separate these from the deuterium pellet in such a way that the holders and their fragments are not injected into the restraint tube situated between the launcher and the torus. This was achieved by establishing methods to produce deuterium ice pellets with good and reproducible mechanical properties, and by developing a sabot which acted as an efficient seal between the pellet and the hot (5000°C) high pressure (~400 bars) driving gas. For separation from the pellet, the sabot splits into two halves as soon as it is no longer supported by the barrel. The reliability of the two stage gun and its driving piston have also been improved. The cryostat forming an integral part of the prototype gun has been ordered and assembly will start at the beginning of 1990.

In parallel to tests of pellet acceleration and sabot separation, provisions were made for the installation, commissioning and operation of the prototype gun which will be assembled on the back of the existing pellet injector box. The geometry of the launcher configuration is shown in Fig 23. Required structural enhancements are being carried out. The prototype two-stage gun is delivered and is installed on the pellet testbed. The related control electronics are being connected. Implementation of the high-speed pellet launcher prototype is underway and operation should be possible at the end of the 1989/90 shutdown.

The development of this JET prototype does not allow multiple injection (10-20 pellets) of high speed pellets in one discharge. The development aimed at multiple injection as well as at the related requirements of low maintenance, remote handling, and tritium compatibility is currently being undertaken by an Association and a design should emerge in the near future.

Tritium Handling

The planning for tritium handling requirements is still based on the introduction of tritium into JET in May 1992. During 1989, the design of the Active Gas Handling System (AGHS) was almost completed and procurement proceeded for most subsystems. The construction of the Gas Handling Building was nearing completion at the end of 1989.

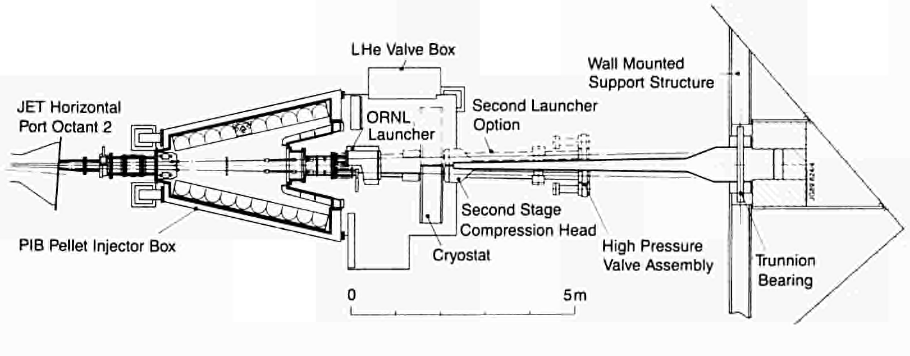


Fig 23:
The Pellet Injection Box (PIB) launcher configuration.

Parts of the multi-column cryogenic distillation system for isotopic separation - Helium compressors, Helium refrigerator instrumentation rack and electronics cubicles - have been placed in the building. Delivery and installation of the main plant components - process cold box, valve box, instrumentation box - is imminent. Operation and control of this complex plant will be performed by a Distributed Control System, which was selected and ordered in 1989 and will be installed in early 1990. Procurement and assembly of hardware is well advanced. The contract includes provision of the basic operating software: mimics for all subsystems are defined and specifications for most of the operation sequences are written.

JET is required under the Host Support Agreement to satisfy the United Kingdom Atomic Energy Authority (UKAEA) in advance of arrangements for tritium operation. Formal permission is also needed from Her Majesty's Inspectorate of Pollution (HMIP) and JET must comply with various statutory requirements monitored by the UK Health and Safety Executive (HSE). The preliminary Safety Analysis Report (PSAR) for the torus and subsystems was submitted to the UKAEA Safety and Reliability Directorate (SRD) to enable an assessment at an early stage, before designs are finalized, of whether there are any major radiological concerns. In parallel, detailed design safety analysis reports of components have been prepared and submitted to SRD for review. The first draft of this document has been discussed with SRD and in view of the novel nature of some of the processes they have recommended that Hazard and Operability (HAZOP) studies should be carried out on critical areas. A HAZOP study has been undertaken on the High Speed Pellet Injector and has shown that no major design changes were necessary.

The main objective for 1990 is to install and test components and subsystems in the Gas Handling Building and to prepare commissioning documents as well as to prepare the remaining detailed safety analysis reports and Final Safety Analysis Reports (FSAR) for the Active Gas Handling System and torus systems. This schedule leaves ~16 months for final commissioning of the AGHS including connection to the torus and auxiliary systems.

Results of JET Operations in 1989

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.

TABLE 7: REACTOR PARAMETERS

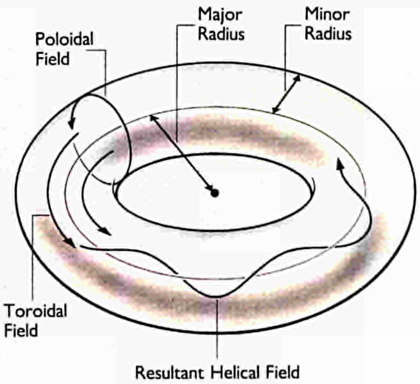
Central Ion Density, n_i	2.5×10^{20} m^{-3}
Global Energy Confinement Time, τ_E	1-2 s
Central Ion Temperature, T_i	10-20keV
Fusion Product, (n_i τ_E T_i)	5×10^{21} m^{-3} s keV

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.

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

However, a substantial increase in the value of the fusion product has been achieved, by operating with the magnetic limiter (X-point) configuration in

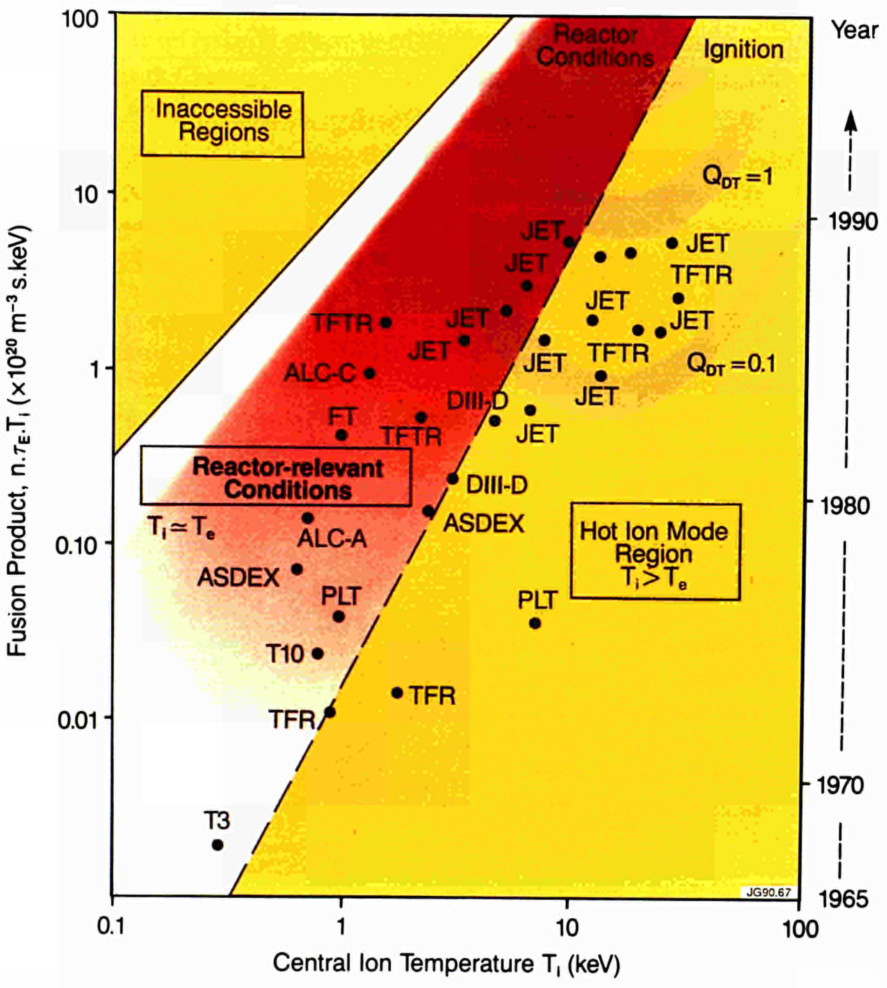


Fig. 24:
Fusion Parameter ($n_D\tau_E T_i$) versus central ion temperature, $T_i(0)$, for a number of machines worldwide in the period 1965-1989.

JET. During 1989, a value of 8-9x$10^{20}m^{-3}$skeV was obtained using 16 MW of neutral beam injection heating.

Considerably higher 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 up to 30 keV, energy confinement times of up to 1.8s and central densities of up to 4 x $10^{20}m^{-3}$.

The highest value of the fusion product attained so far in JET is near to breakeven conditions. A factor of 5-7 increase would bring the conditions in JET to those required in a reactor. The increases in performance that have been achieved on JET and other tokamaks since 1965 are shown in Fig. 24.

As the global energy confinement time scales favourably with plasma current in discharges with both magnetic and material limiters, the modifications carried out in JET, 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.

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 original scientific programme of JET was divided into four phases as shown in Fig. 25. 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

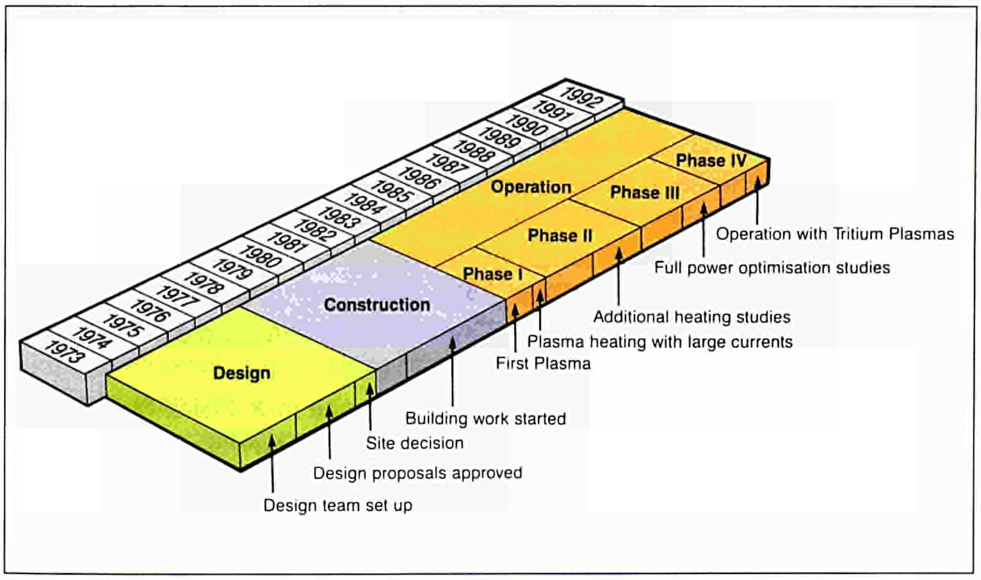


Fig. 25:
The Overall JET Programme

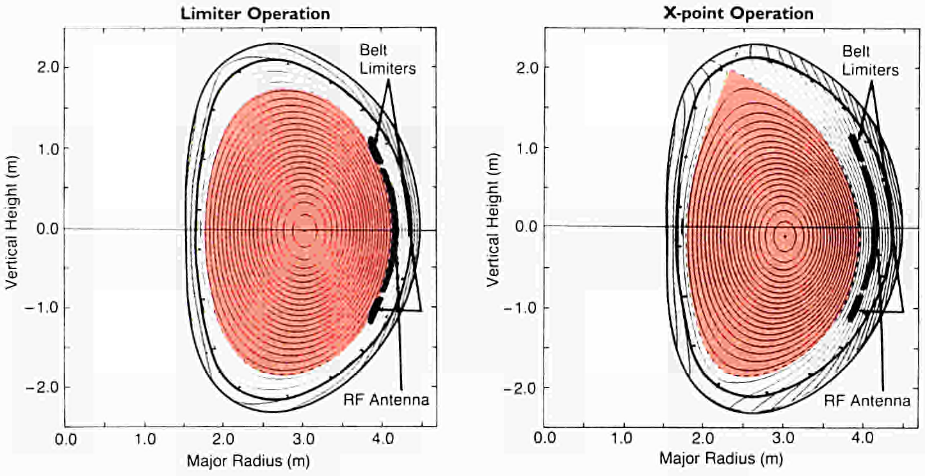
Operating Modes

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.



for energy confinement and high fusion 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 20 MW at 80 kV. The ultimate objective was to achieve full performance with all systems operating simultaneously. Phase III of the Programme on Full Power Optimisation Studies started in 1989.

The 1989 experimental programme was executed by four Task Forces, with the programme objectives divided into the following four main areas:

- **Task Force A:** Optimisation of Performance in Limiter Plasmas (including progression to the highest fusion product, long pulse operation, investigating high confinement regimes, α-particle simulations, etc);
- **Task Force B:** Optimisation of Performance in X-Point Plasmas (including progression to the highest NB and RF powers and attempts at quasi-steady-state operation);
- **Task Force C:** Reduction of Impurities and Fuel Enrichment (exploring methods of reducing impurity production by developing

wall conditioning and appropriate operational procedures, including beryllium operation, density control experiments, pellets, fuelling with beams, gas puffing, etc);

- **Task Force D:** Physics Issues
  (studying physics issues particularly relevant to next-step devices, including disruption control, sawtooth stabilisation, particle and energy transport studies, current drive (NB, RF, LHCD, etc), operational scenarios for next-step devices, etc).

Main Scientific Results

JET operation during 1989 was devoted mainly to the assessment of beryllium as a first-wall material. The reason for the introduction of a new first-wall material was that impurity control in JET, as for other long-pulse high power tokamaks, is of fundamental importance.

Plasma facing materials must be selected so that impurity influxes and their impact on the plasma are minimised. Therefore, these materials should have very low atomic number (low-Z), low chemical interaction with hydrogen, high melting point or sublimation temperature, good thermal conductivity and shock resistance, low erosion through sputtering and should preferably be a getter for oxygen.

During 1988, it had become apparent that impurities and density control were the main obstacles to the improvement of JET performance. Graphite components had been improved so that they were mechanically able to withstand the power loads encountered.. However, the interaction of the plasma with these components, even under quiescent conditions, was causing unacceptable dilution of the plasma fuel. In addition, imperfections in the positioning of the plasma facing components led to localised heating during high power which caused enhanced impurity influxes. The enhanced influxes produced a condition called the "carbon catastrophe" (or alternatively the "carbon bloom" because of the appearance of the observed hot spots), in which the plasma hydrogen concentration, plasma temperature and the neutron yield collapse.

As a consequence, it was proposed that beryllium should be used as a plasma facing material in JET instead of graphite. Apart from its low atomic number (low-Z), which makes the radiation cooling smaller than with carbon, it has a small sputtering rate, good thermal shock characteristics and a tolerably high melting temperature (1278°C). Although this is much lower than the sublimation temperature of carbon, it is considerably offset by beryllium's greater thermal conductivity and the onset of radiation enhanced sublimation in graphite.

Beryllium was introduced into JET in two different ways: initially as a thin evaporated layer on the graphite walls and limiters; and later, in addition as a limiter material. Operations under these conditions were compared with results in graphite.

Operations were carried in three stages:

Stage I: Start-up as a graphite machine after prolonged shut-down, to re-establish conditions and provide a reference set of parameters in this new configuration;

Stage II: Beryllium evaporated on all internal surfaces; with about 300Å average thickness for each evaporation;

Stage III: Operation with beryllium tiles on the belt limiter, and around certain RF antennae. (Carbon tiles continued to be used elsewhere).

The scientific results for 1989 in these phases are described in the following sections, within the areas of Impurity Studies; Density Effects; Temperature Enhancements; and Energy Confinement Studies.

Impurities

Impurities present a major problem in tokamak plasmas as they cause:

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

With a carbon first-wall, the main impurities observed in JET were carbon and oxygen. The carbon levels ranged from 2% to over 10%, with the level depending strongly on average density, plasma current and input power. In ohmic discharges, the concentration decreased as the density increased, and increased as the plasma current increased. Oxygen concentrations were at the few per cent level, and at high densities, this was the source of a major power loss by radiation.

With the introduction of beryllium evaporated inside the vessel, oxygen was reduced by a factor greater than 20, and carbon decreased by a factor greater than 2. Although the beryllium levels increased, carbon remained the dominant impurity for this phase. In the operating phase in which beryllium tile limiters were used, the concentration of carbon was reduced by a further factor of 10, but beryllium levels increased by about 10, and beryllium became the dominant impurity.

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 monitored routinely throughout each pulse by measuring Z_{eff}. Due to the virtual elimination of oxygen, and the replacement of carbon by beryllium, the effective plasma charge, Z_{eff}, was reduced significantly, first in the beryllium evaporation phase, and then more so in the beryllium limiter phase for both Ohmic and additionally heated discharges.

A comparison of Z_{eff} as a function of line density for ohmic discharges for the three phases of operation is shown in Fig. 26. It can be seen that the introduction of the beryllium gettering reduced Z_{eff} over the whole range of densities attainable in ohmic discharges, due to the elimination of oxygen and the reduction of carbon. When the beryllium limiter was introduced, Z_{eff} was reduced further, primarily because of the substitution of beryllium for carbon.

Due to the reduced impurity level in beryllium limiter discharges, and the resulting lower fraction of edge radiated power, it was found possible to further reduce the impurity concentration in additionally heated discharges

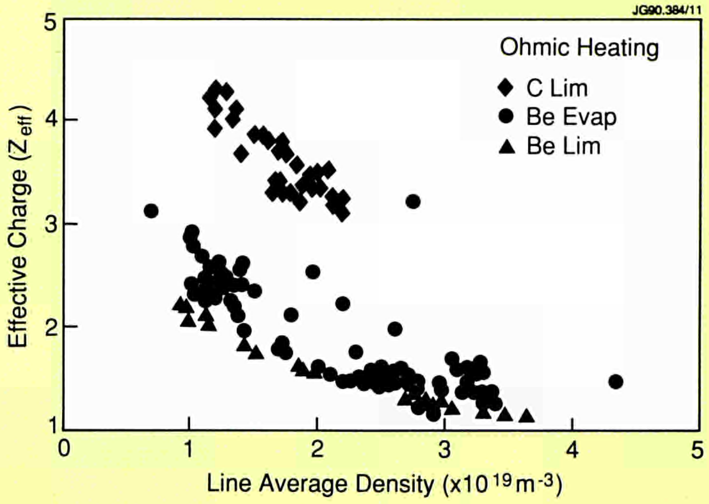


Fig. 26: The effective charge, Z_{eff} , versus average electron density, $<n_e>$ for the carbon-phase and the beryllium evaporation and the beryllium limiter phases, showing the improvement resulting from the use of a beryllium first-wall.

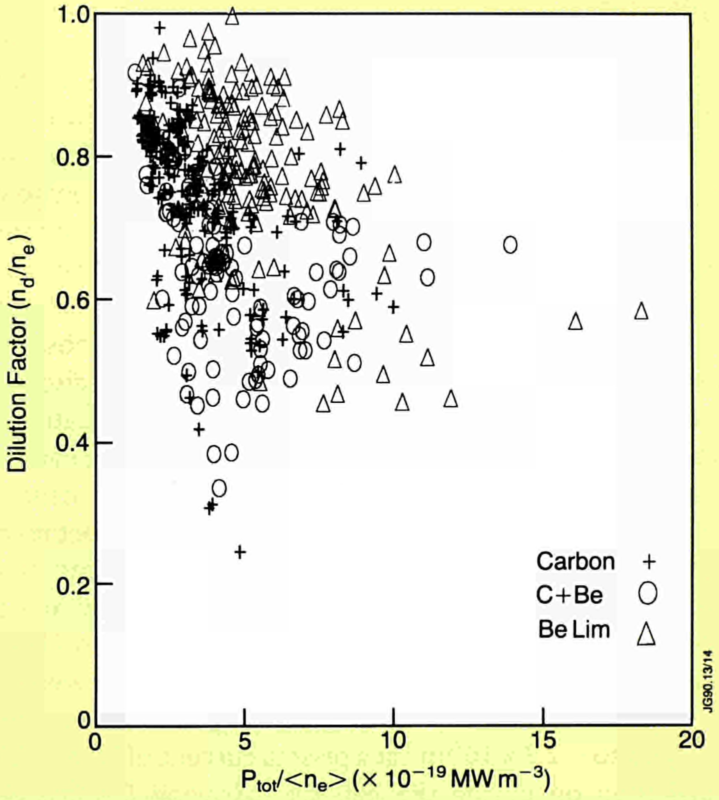


Fig. 27: The dilution factor, n_D/n_e, as a function of the total input power per particle ($P_t/<n_e>$) in the three experimental phases.

by using a strong neutral gas input (or puff) at the beginning of the heating pulse. Such strong gas puffing was not possible in the carbon phase, as it led to strong edge radiation and usually plasma disruption. This was due, in the beryllium limiter operating phase, to decoupling the edge density from the plasma core without adversely affecting the performance of the latter. This has important implications for control of plasma surface interactions in the future. Consequently, for additionally heated discharges with beryllium tile limiters, it was possible to operate at very high power per particle while maintaining a low Z_{eff}. Fig. 27 shows the dilution factor, n_D/n_e, as a function of input power per particle, $P_{tot}/<n_e>$. Whereas it had not been possible in the carbon configuration to maintain (n_d/n_e), much above 0.6 for moderate power pulses, values greater than 0.8 were routinely achieved in beryllium limiter discharges. This contributed significantly to improved fusion performance.

In addition, the introduction of beryllium produced a marked improvement in the ability to control the plasma density in JET. This arose partly from the reduction in the amount and charge of the dominant impurity, but also depended strongly upon the fact that beryllium pumped deuterium very effectively during the discharge. It was also found to retain very little deuterium, relative to graphite, on longer time scales (minutes to hours); over 90% of the neutral gas admitted to JET is recovered, compared to about 50% in the carbon phase. This has important advantages for the tritium phase in JET.

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 density peaking factor (n(0)/<n> where <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, 4mm and 6mm 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 which started in 1988. A jointly built three-barrel, repetitive multi-injector was used from which pellets can be injected at a maximum frequency of several per second with nominal speeds up to $1500ms^{-1}$.

In beryllium limiter experiments, a string of 4mm pellets were injected at intervals throughout the current rise to build up a peaked density profile with central density up to ~ $2.3 \times 10^{20}m^{-3}$ at a plasma current of 5MA. ICRF heating was then switched on during the flat-top following the last pellet. An

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.

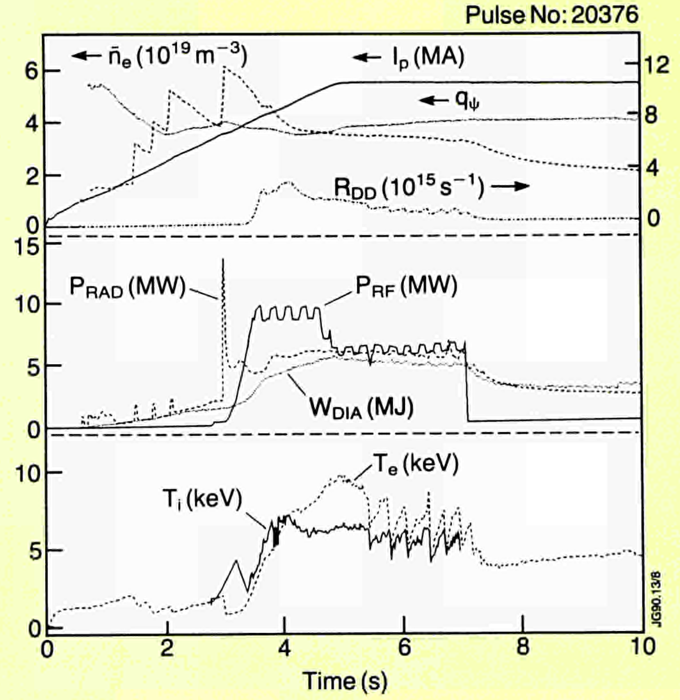


Fig. 28:
Pellet fuelling during the current rise to 5MA to produce a peaked density profile, which is then reheated by ICRF during the remainder of the current rise.

enhanced neutron production feature was produced, with neutron rates peaking at $4 \times 10^{15}s^{-1}$. Thereafter, this rate decayed but 1.5s after the start of the RF power, a vestigial remainder of the peaked profile with $n(0) \approx 6 \times 10^{19}m^{-3}$ was still observed. The time history of such a shot is shown in Fig. 28. In a variant of this type of experiment, the last pellet was a large one (6mm) producing a record central density of $2.8 \times 10^{20}m^{-3}$ for a limiter plasma, which was successfully reheated with ICRF power. A substantial improvement in thermal stored energy (8MJ for only 10MW RF) was obtained transiently. The temperatures were low (≈ 3keV) and the density profile evolved to become very flat after about 1.5s with $n(0) \approx 8x10^{19}m^{-3}$. In addition, in magnetic limiter plasmas, a record central plasma density of $4 \times 10^{20}m^{-3}$ has been achieved with a peaked profile as shown in Fig. 29.

Density 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 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 factor, I_p the plasma current and B_t the toroidal field) as a function of the normalised density $<n>R/B_t$ (where <n> is the average density and R the major radius). This is shown in Fig. 30. The density limit is dependent on

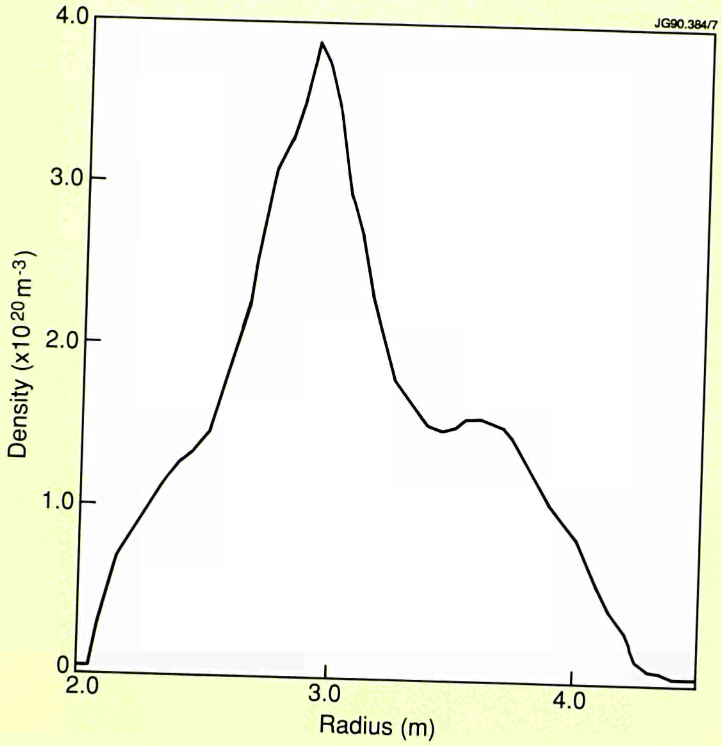


Fig. 29: Record peak density of 4 x $10^{20}m^{-3}$ achieved in a magnetic limiter plasma;

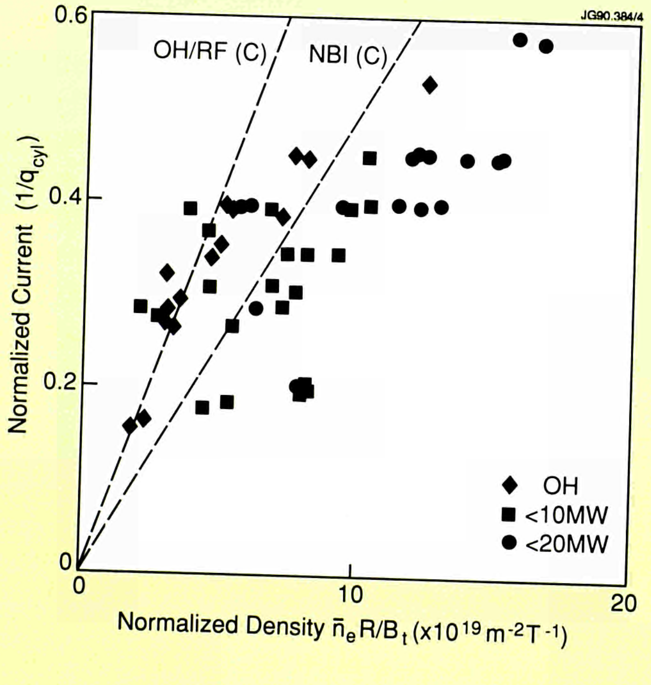


Fig. 30 Normalized current (1/q) versus normalized density (<n>R/B_t). The points show the results with a beryllium first-wall. The lines show the density limits achieved with carbon walls using ohmic heating (OH(C)) and with additional heating (NB(C)).

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 $q = 2$.

plasma purity and the power to the plasma. In ohmically heated plasmas with carbon limiters, the density limit was given by:

$$n_c(OH)\ (m^{-3}) = 1.2 \times 10^{20}\ B_t(T)/qR(m)$$

as shown by the line marked OH(C).

However, with pellet injection, the plasma impurity was improved and the limit was increased. With substantial additional heating the limit was also increased substantially, as shown by the line marked NB(C), to:

$$n_c(AH)\ (m^{-3}) = 2.0 \times 10^{20} B_t(T)/qR(m)$$

Previous experiments in JET have explored the range of densities accessible with carbon plasma-facing components and have elucidated the mechanism for the density limit. This generally occurred when the radiated power reached 100% of the input power, which led to the growth of MHD instabilities and ended in a major disruption.

With a beryllium first-wall, the maximum operating density was found to increase significantly by a factor of 1.6 - 2 relative to that obtained under equivalent operating conditions with a carbon limiter as shown in Fig. 30. Moreover, it was possible to increase the density achieved simply by increasing the total input power, the limiting density increasing approximately as the square root of the power as shown in Fig. 31. In addition, it was observed that the nature of the density limit had changed and that the frequency of disruptions at the density limit were much reduced. While the limit was still determined by radiation, it was associated with the formation of a poloidally asymmetric, but toroidally symmetric radiating structure (or MARFE) which clamped the plasma density, but usually did not lead to a disruption. These results constitute a substantial enhancement of the operating capability of JET.

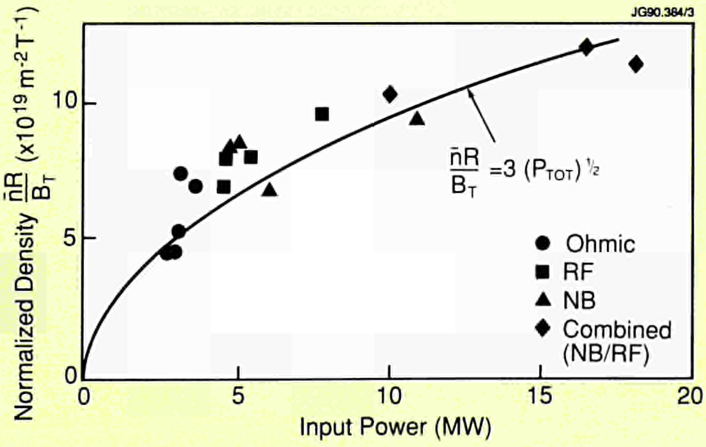


Fig. 31:
The normalized density limit parameter (n_cR/B_t) as a function of total input power, P_t, for beryllium limiter discharges showing scaling $P_t^{1/2}$ independent of the mode of heating

A significant result obtained during these experiments was the identification of the edge density as the limiting parameter. During the beryllium gettering phase, a series of experiments were performed in which heating and plasma fuelling were varied systematically: both gas and pellet refuelling were investigated additional heating were applied at similar power levels (≈ 10MW), and both gas and pellet refuelling were investigated. With pellet injection heating deeper penetration was possible, and a more peaked density profile was established. Pellet fuelled discharges reached the same edge density as gas fuelled discharges, but obtained a considerably higher central density.

These results are illustrated in Fig. 32, which shows density profiles, just before the density limit MARFE occurred in the cases shown. The density profiles are very similar near the edges, but the gas fuelling case is remarkably flat across the profile (case(a)). With deep pellet fuelling and NB heating, a peaked profile is obtained (case (b)). These studies suggest that the critical parameter in determining the limit is the edge density. These results emphasize the need to consider the question of the density limit as a fuelling problem as much as a problem of plasma stability.

Temperature Enhancements

Sawtooth Oscillations

In most 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

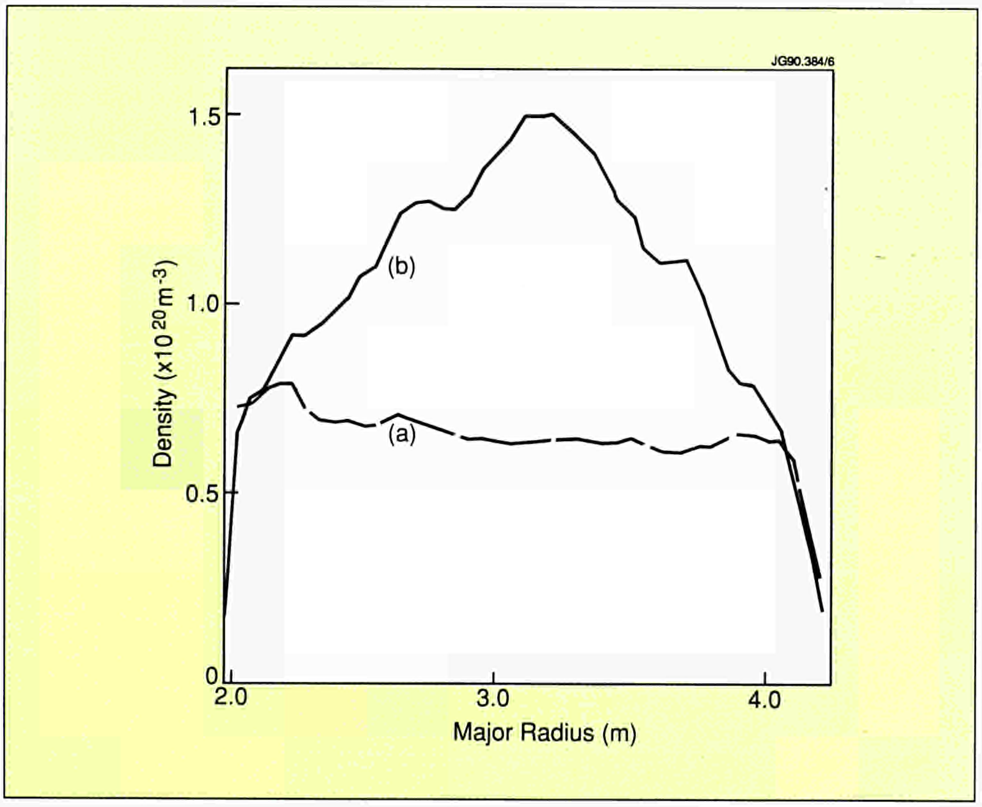


Fig. 32:
Density profiles obtained just before the occurrence of the MARFE marking the density limit in the beryllium limiter phase. The profiles show the effects of (a) NB heating plus gas fuelling and (b) NB heating plus pellet fuelling. This illustrates that the critical parameter in determining the limit is the edge density.

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. This instability flattens the central plasma temperatures and density, and it can expel energetic particles (injected by the neutral beam system, accelerated by the ICRF fields, or produced in fusion reactions) from the plasma core. Therefore, the repetitive occurrence of this instability can significantly limit the fusion power produced by the plasma. However, a number of techniques have been developed for the suppression of these instabilities and the resultant improvements in performance explored in some detail. 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 of lower hybrid (LH), radio-frequency (RF) 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 5 seconds.

Extensive studies have been performed in the so-called 'monster-sawtooth' regime. One of the longer cases, lasting for 4 seconds, is illustrated in Fig. 33. As shown, the central value of the safety factor, q(0), falls well below unity. Since sawteeth would normally be expected to occur in these circumstances, it has been proposed that, in this regime, sawteeth are stabilized by fast particles, principally those accelerated by the ion cyclotron radio-frequency (ICRF) heating system. It has been found that peaked

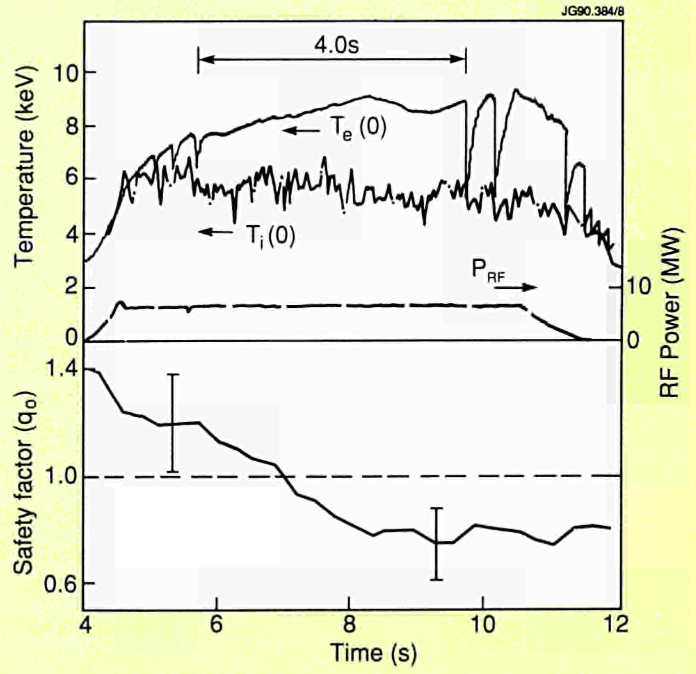


Fig. 33: Evolution of the central electron temperature, $T_e(0)$, the central ion temperature, $T_i(0)$, and the value of the safety factor on the plasma axis, q(0), during a long 'monster sawtooth'. P_{RF} is the ICRF heating power.

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.

Current Profile Control

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

temperature profiles (with both central ion and electron temperatures above 10keV) can be maintained for period of several seconds, which would, in a D-T mixture, result in a significant enhancement in the time-averaged fusion reactivity compared to a sawtoothing discharge. By heating during the current ramp phase of the discharge, it has been possible to extend this regime to flat-top currents in excess of 5MA. In addition, similar enhancements in plasma performance have been achieved by suppressing sawteeth via the injection of frozen pellets of deuterium. Ablation of these pellets by the plasma broadens the temperature, and hence current profile and raises q(0) above unity, which results in suppression of the sawteeth.

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 (23-57MHz) allows variation in the heating position at which the ion cyclotron resonance frequency matches the local magnetic field position, (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 main plasma electrons and ions, transferring energy to them and causing a rise in the local electron temperature (T_e) and ion temperature (T_i) of the main plasma.

The original design power of the ICRF heating system was 15MW for 20s. However, the system has been undergoing an upgrade of each of the eight generators from 3 MW to 4 MW each. This upgrade is not yet complete (two generators were still being upgraded at the end of 1989) but a maximum power of about 18MW for 2s has been coupled to the plasma. The maximum power was limited by arcs in the transmission and antennae components, while longer pulse lengths were not possible due to energy limitations on the vessel.

ICRF heating studies have been carried out using both hydrogen and ^{3}He minority ions with input powers to the plasma of up to 18MW. 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 ion temperature, $T_i(0)$, versus the ratio of RF power to density, P_{RF}/n_e, is shown in Fig. 34 for values of the minority concentration (n_{min}/n_e) in the range 1-11%. The highest values of $T_i(0)$, up to 8 keV for 12 MW 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.

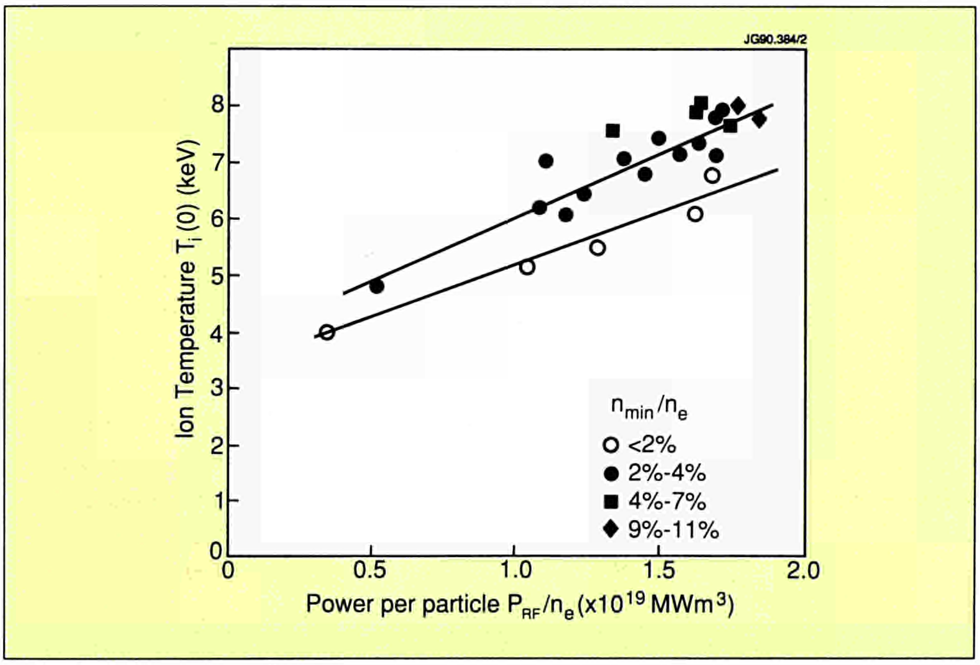


Fig. 34
Central ion temperature versus power input per particle (P_{RF}/n_e) for various ^{3}He minority ion concentrations.

Neutral Beam Injection Heating

The two neutral beam injectors are located diametrically opposite each other on the JET machine at Octant No:4 and Octant No:8 and inject high energy neutral beams tangential to the plasma torus. During 1988, both beams were brought into full operation with maximum injected power into the plasma of 21.6 MW of neutral deuterium atoms at 80kV. For 1989 operation, six of the eight sources on the Octant No:4 system were converted to 140kV operation in deuterium. This was to achieve greater penetration of the neutral beams into denser JET plasmas and deposit more energy nearer the centre of the plasma. In this configuration, about 18MW of total neutral beam power was available. Ultimately, both neutral boxes will be converted to 140kV operation, but with slightly reduced total power.

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. With the introduction of the beryllium first-wall, improved density control was possible. This coupled with the increased neutral beam penetration achieved at this higher energy (140 kV) allowed higher ion temperatures to be obtained. Record ion temperatures were achieved up to 18 keV in material limiter plasmas and up to 30 keV in magnetic limiter plasmas, with powers up to 17 MW. A typical example is shown in Fig. 35 in which the ion temperature reached 26 keV for about 15MW input in a magnetic limiter configuration. In this mode, the ion temperature profile is sharply peaked, and the electron temperature is significantly lower than the ion temperature, by a factor of 2-3.

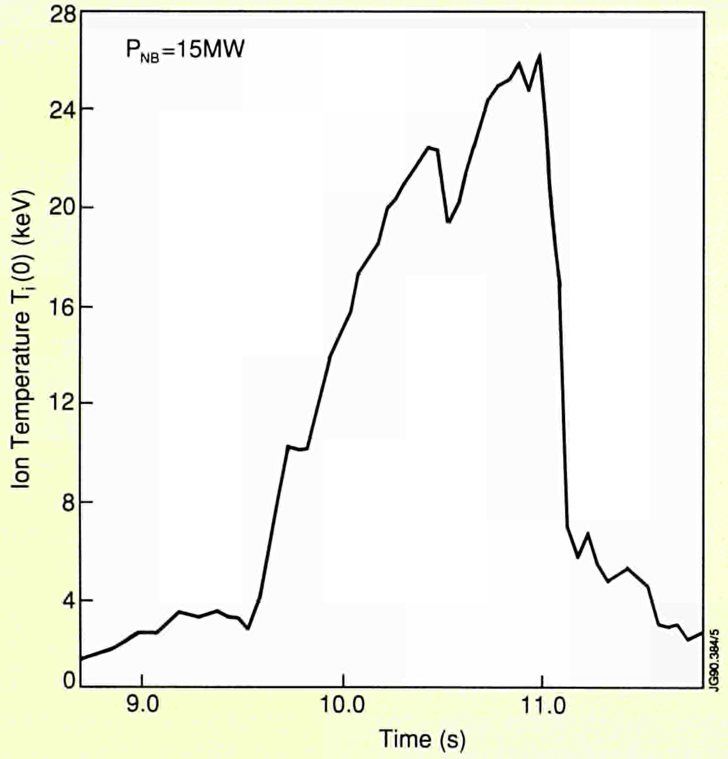


Fig. 35
Central ion temperature, $T_i(0)$, as a function of time for neutral beam input of 15MW.

Experiments have been carried out at higher densities ($n(0)>2\times10^{19}m^{-3}$) with combined neutral beam and ICRF heating in 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 3 MA plasma for a power input of 33MW (21 MW of NB and 12MW of ICRF heating). This example is shown in Fig. 36, where the central density, n(0), exceeded $2\times10^{19}m^{-3}$. In addition, with a 6MA plasma and a input power of 24MW, the central ion and electron temperatures have exceeded 6keV for a central density of $6\times10^{19}m^{-3}$.

Energy Confinement

The global energy confinement time of JET in all plasma configurations, is defined by the relationship:

$$\tau_E = W_k/(P_t - dW_k/dt)$$

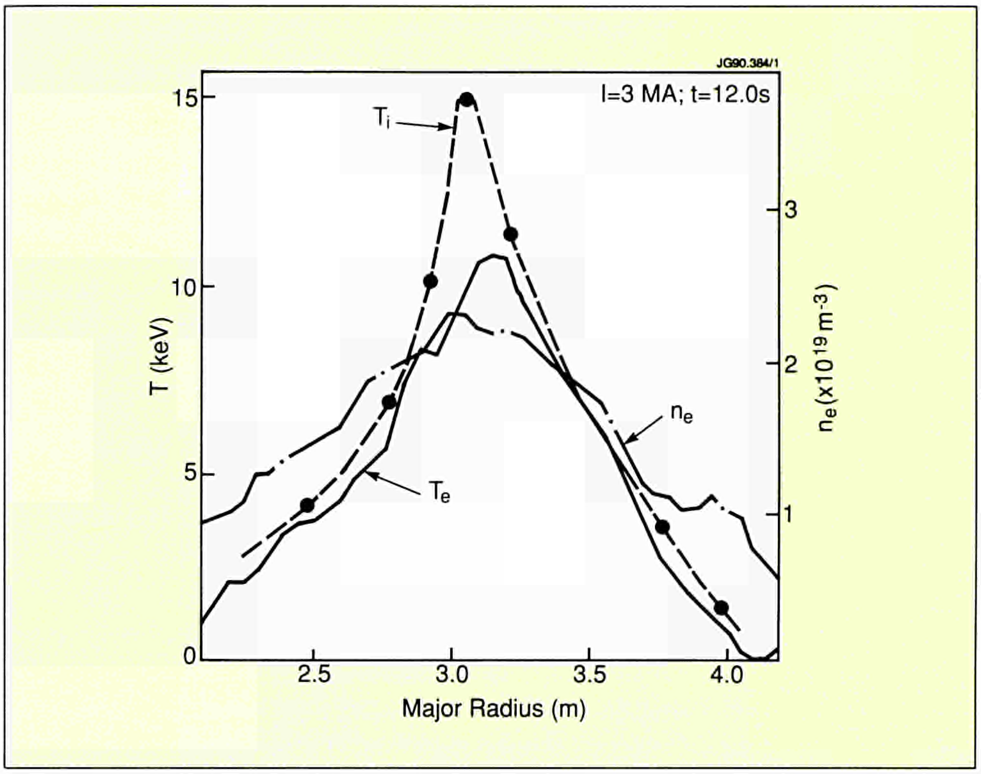


Fig. 36:
Ion and electron temperature profiles and density profile during combined heating (P_t= 33MW).

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 up to 1.8 seconds. However, the temperatures reached in these cases are too low for a fusion reactor, so the important confinement time behaviour is that in additionally heated plasmas.

With carbon limiters, 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 heating or a combination of the two methods. This situation is similar with a beryllium first-wall and global energy confinement times are effectively unchanged. However, the advantages with the use of a beryllium first-wall is that improved density control is achieved due to high wall pumping and impurity content (and radiation) is reduced. These factors permit higher inputs to the plasma and result in improved fuel concentrations (n_d/n_e). This provides improved fusion performance (which will be described in more detail in the following section).

The decrease of energy confinement time with increasing heating power in material limiter cases is shown in Fig. 37. 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.

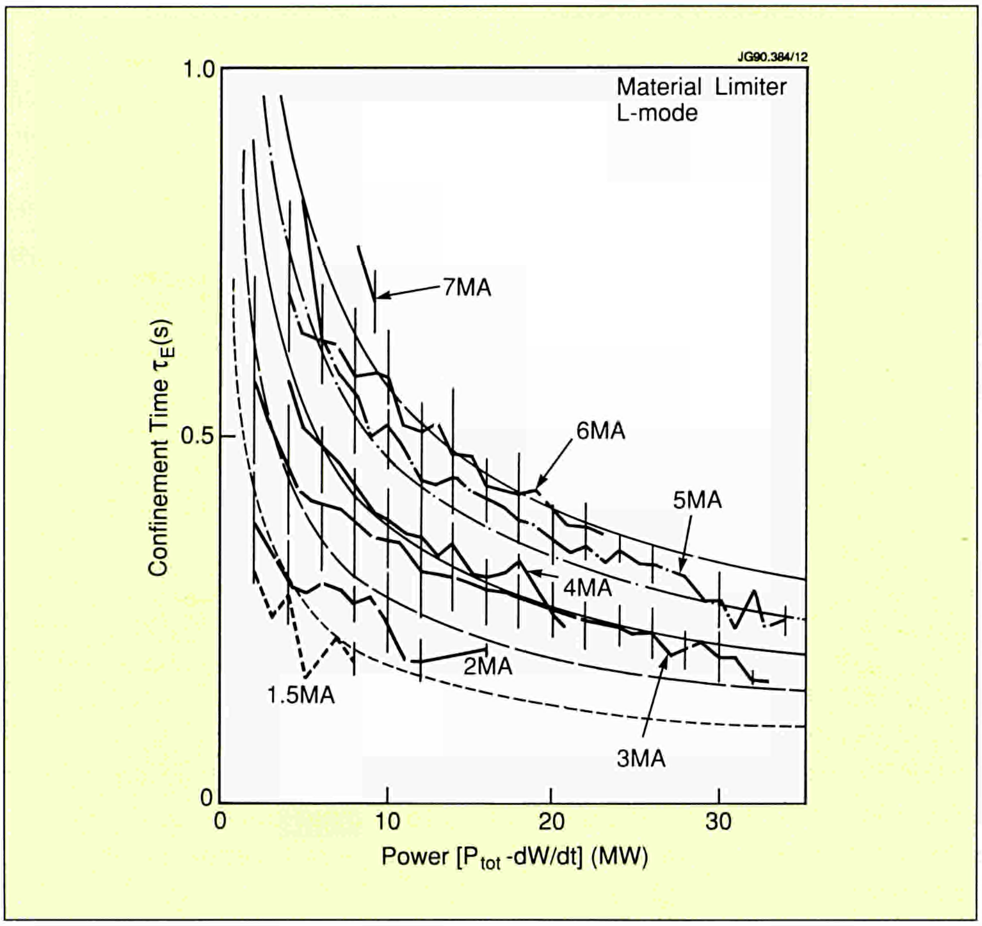


Fig. 37: Confinement time as a function of input power for material limiter conditions, for different plasma currents.

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 W_k and power input P_t 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 is unchanged from the carbon limiter saturation and 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 over 5MA, with the single-null configuration and up to 4MA in the double-null situation. Operations in these configurations 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 additional heating above a certain threshold value, 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 flatter 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. 38.

The 1989 experimental programme in the X-point configuration was mainly devoted to the study of H-modes with high power additional heating. Plasma purity was improved by the use of a beryllium first-wall, and central values of the fuel concentration (n_d/n_e) were in the range 0.7 to 0.9. Use of beryllium gettering also improved the control of plasma density, with high deuterium pumping rate. However, these experiments were still carried out with carbon X-point target plates. Even so, this enabled H-mode operation with additional heating powers up to 25MW. In this situation, the confinement times were unchanged from the carbon limiter cases, but the fusion performance improved substantially. The global confinement time scaled with power, P, as $P^{-0.5}$, with both ICRF and NB heating in the range 4 - 25 MW, confirming results found in 1988.

During some magnetic limiter discharges, Edge Limiter Modes (ELM's) 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. For powers below 10MW, this was the main termination mechanism, caused by excessive radiation losses at high plasma densities, corresponding practically to a density limit. By sweeping the position of the X-point radially and vertically, it was possible to spread the area of the contact of plasma with the target plate and to extend the duration of the H-mode by 50%. By introducing strong edge gas puffing during the H-mode the impurity content and the radiation losses were also reduced. This permitted extension of ELM-free H-phases for longer periods up to 5.3 seconds. In addition, very high density regimes were produced by using repetitive pellet injection in this H-mode ($n(0) \approx 4 \times 10^{20}m^{-3}$).

With the carbon limiter, coupling ICRF heating to H-modes generated with NB heating led to relatively strong impurity influxes, a high rise rate of the radiated power losses, and a short duration of the H-mode. The generation of H-modes with ICRF heating alone was not successful. With a beryllium first-wall, H-modes with ICRF heating alone were successfully obtained. This was due to two important enhancements of the JET system. The ICRF heating subsystem was equipped with automatic tuning, which automatically maintained the impedance matching to antennae despite rapidly changing coupling resistance and this allowed improved coupling of ICRF powers. In addition, beryllium evaporation on the nickel antennae screens produced fewer impurities. Fig. 39 shows an overview of the

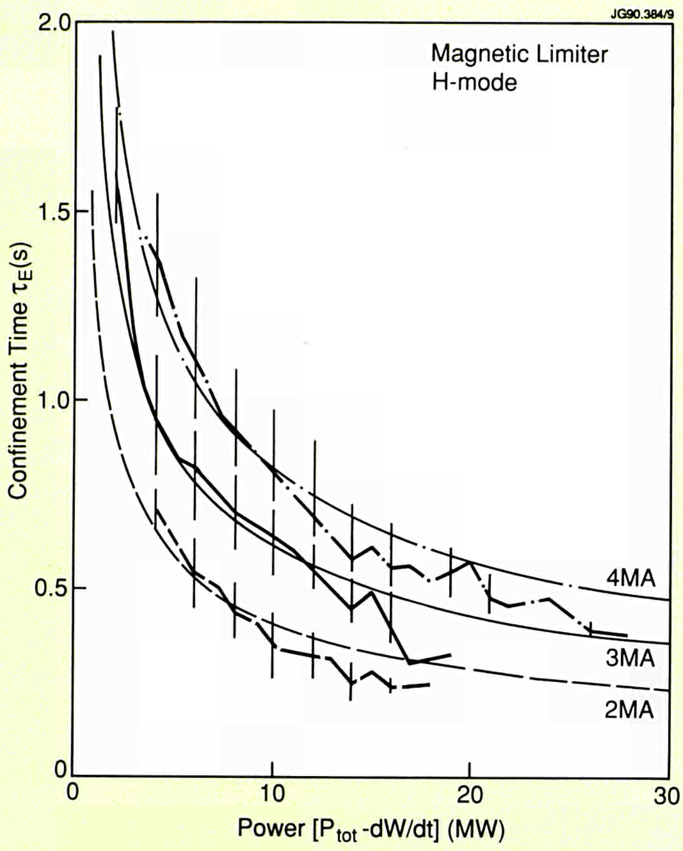


Fig. 38:
Confinement time as a function of input power for magnetic limiter conditions, for a different plasma current.

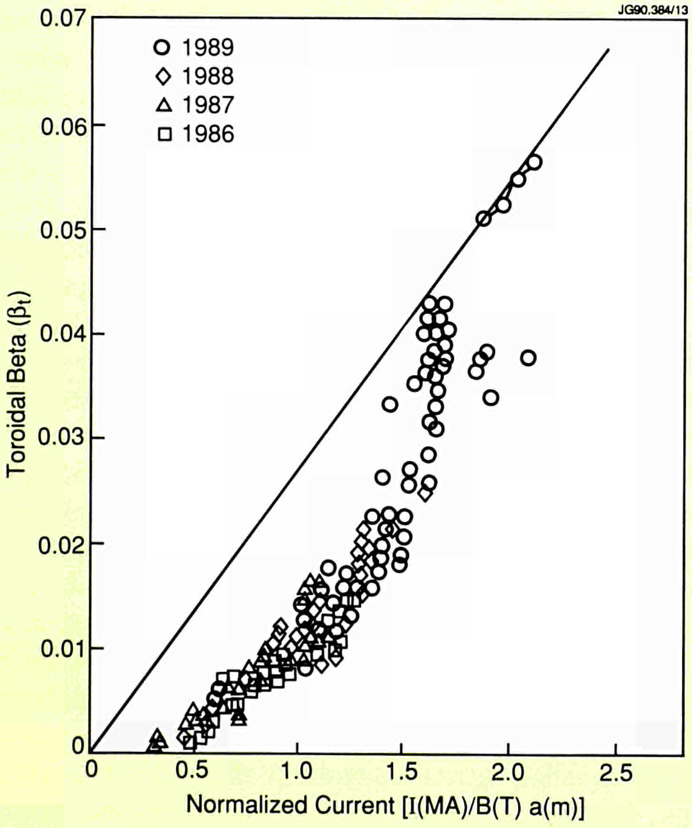


Fig. 39:
β_t for high-β discharges as a function of normalized current. The solid line represents the Troyon limit, $\beta_t(\%) = 2.8\ I_p(MA)/B_t(T)\ a(m)$.

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 or beryllium tiles attached. Carbon and beryllium have a relatively low electric charge on the nucleus.

confinement of the H-modes with ICRF heating alone, compared with NB heating alone, at the same plasma current (3MA). The confinement of ICRF heating H-modes was similar to those of the NB cases, typically corresponding to x2 L-mode scaling confinement times. For comparison, 3MA L-mode limiter discharges are shown. The power threshold for the H-modes with ICRF power is similar to NB-only H-modes.

Energy confinement predictions for H-mode operation in Next Step tokamaks require a scaling law based on tokamaks of differing sizes. Scaling comparisons have been undertaken between JET, ASDEX and DIII-D (General Atomics, USA). In particular, JET and DIII-D have similar aspect ratios. Thermal energy confinement scaling has been obtained, in which the fast ion contribution due to the injected NB ions was excluded. The resulting scaling was:

$$\tau_{th} = (0.11 \pm 0.01)\, I_p^{0.98\pm 0.06}\, P_L^{-0.43\pm 0.07}\, R^{1.44\pm 0.08},$$

where τ_{th} (s) is the thermal energy confinement time, I_p (MA) is the plasma current, P_L(MW) is the loss power and R(m) is the major radius.

Progress Towards a Reactor

Beta Limits

The economic efficiency of a tokamak reactor will be determined, in part, by the maximum plasma pressure which can be maintained in the device. More precisely, the important parameter is the plasma beta, β_t, defined as the ratio of the plasma pressure to the pressure of the confining magnetic field (which is proportional to nT/B_t^2, where n is the plasma density, T the plasma temperature and B_t the toroidal magnetic field). Experiments have been performed to explore the range of values of beta which can be sustained in JET and to investigate the plasma behaviour near to the expected limit. In particular, experiments have been carried out in a double-null H-mode configuration, at high density and temperature and low magnetic field (B_t = IT). To date, values of β_t up to ~ 5.5% have been obtained. The β_t limit is close to the value expected theoretically, which is the so-called Troyon limit $\beta_t(\%) = 2.8\ I_p(MA)/B_p(MA)/B_t(T)\ a\ (m)$, where I_p is the plasma current and a is the plasma minor radius. Fig. 39 shows the results of β_t obtained in JET. Significantly, it is found that the limit in JET does not appear to be disruptive. Rather, a range of magneto-hydrodynamic (MHD) instabilities occur and these limit the maximum value of beta without causing a disruption.

Alpha-Particle Simulations

The behaviour of alpha-particles has been simulated in JET by studying fast particles such as 1 MeV tritons, and ^{3}He and H minority ions accelerated to energies of a few MeV by ICRF heating. The fast population (in the MeV range) has up to 50% of the stored energy of the plasma and possesses all the characteristics of ignited plasmas (except for anisotropy). 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 $1\text{-}2 \times 10^{-2}$, 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 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 ICRF 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.

Fusion reactivity measurements were undertaken on the D-He^3 reaction, in which minority He^3 ions were accelerated to energies in the MeV range using ICRF heating. During a 5s monster sawtooth produced by 10 MW of ICRF heating, a reaction ratio of $4 \times 10^{16}s^{-1}$ was achieved, which corresponded to 100 kW of fusion power and $Q \approx 1\%$ was reached. This was carried out with a beryllium first-wall and benefitted from an improved fuel concentration of n_D/n_e up to 0.7. Typical results are shown in Fig. 40, which shows the fusion power as a function of the ICRF input power. The fusion power is greater by a factor x2 with the beryllium first-wall compared with the carbon case. Comparison of the measurements with theoretical predictions suggest that the trapping and slowing down of the fast particles are close to classical expectations.

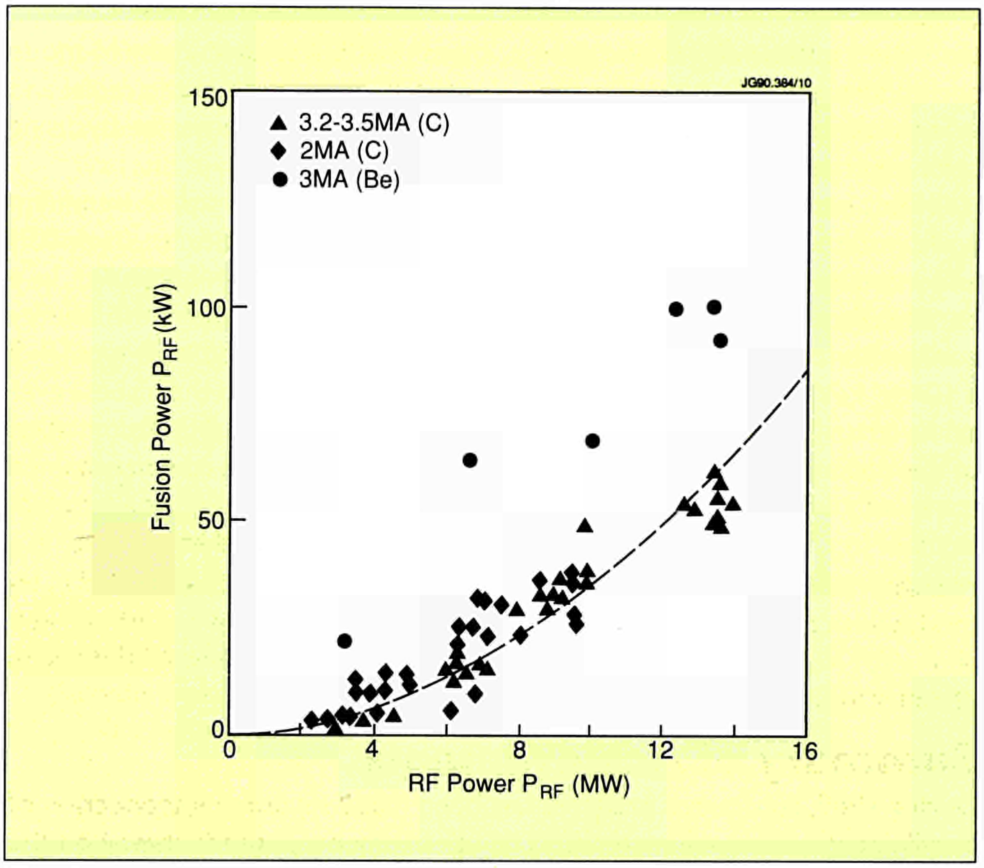


Fig. 40:
D-^{3}He fusion power as a function of RF input power, P_{rf}, for both the C-limiter and the Be-limiter experiments. The maximum fusion multiplication Q value (= P_{fus}/P_{rf}) is 1%, approximately twice that obtained in the carbon-limiter experiments. The dashed line is the scaling law: P_{fus} α $P_{rf}^{1.7}$.

Fusion Performance

Fusion yield optimisation experiments were performed in which the plasmas were in contact with the inner wall and separately with the belt limiter. Compared with a carbon first-wall, the most notable gain occurred for plasmas on the belt limiter, where improvements both in the fusion product ($n_DT_i\tau_E$) and Q_{DD} of about a factor x2 were observed. The improvement in plasma purity, density control and density profile shape were all important factors.

A further improvement in the yield with a beryllium limiter was obtained by using pellet injection to create a peaked density profile. Although the density decayed during heating, the profile remained peaked. In this scenario, the fusion gain was $Q_{DD} \approx 9 \times 10^{-4}$, and the neutron rate was $2.1 \times 10^{16} s^{-1}$. These were the highest values yet achieved in a materially limited plasmas. The fusion parameter ($n_DT_i\tau_E$) reached a record value of $4 \times 10^{20} m^{-3}$ keV s for a limiter plasma. Also in this discharge, RF accelerated neutrons contributed significantly to the yield. Unlike other discharges, the high yield regime was not terminated by a beryllium influx but rather the ion temperature and neutron yield decayed as the peaked density feature disappeared.

In magnetic limiter configurations with a carbon first-wall, at high heating power levels ($P \geq 12$ MW), discharges were always troubled, not only by a severe dilution of the plasma ($n_D/n_e \approx 0.5$), but also by a strong influx of carbon (the "carbon bloom") after 0.5 - 1.0s, which quenched the neutron production and terminated the H-mode. The use of beryllium gettering improved the plasma purity due to the elimination of oxygen and reduction of carbon flux, and n_D/n_e rose to 0.9. However, it did not affect the carbon bloom in a major way. Nevertheless, it was possible to extend the H-mode period by up to 50% by either sweeping the X-point, both in the radial and vertical directions to reduce the X-point tile temperatures, or by using strong gas puffing in the divertor region.

In this situation, improved H-mode plasma performance with beryllium walls resulted from a combination of reduced plasma dilution ($n_D/n_e \approx 0.9$) and increased ion temperatures (T_i (0) in the range 20 - 30 keV). In a particular case, the central ion temperature reached 22 keV, the energy confinement time, τ_E, was 1.1s, with a record fusion product ($n_D T_i \tau_E$) of 8–9 x $10^{20}m^{-3}$ keVs. The neutron yield for this discharge was also the highest ever achieved on JET at 3.7 x 10^{16} ns^{-1}, with a $Q_{DD} = 3.1 \times 10^{-3}$. A full D-T simulation of this pulse showed that 13MW of fusion power could have been obtained transiently with the 16MW of injected NB power, giving a fusion product value of ($n_i \tau_E T_i$) which would be within a factor of 5-10 of that required in a reactor. Similar high values of the fusion product have been obtained in H-modes with central pellet injection. In this case, $T_i(0)$ = 9keV, $T_e(0)$ = 7keV and $n_D(0)$ = 5.x $10^{19}m^{-3}$ were achieved. The achieved values of the fusion product in the various configurations are listed in Table 8.

Summary of Achievements

During 1989, substantial progress has been made since the introduction of beryllium as a first-wall material. The effect of a beryllium first-wall on the impurity influxes was:

- Oxygen impurity was essentially eliminated from the plasma;
- Carbon was the main impurity in the beryllium evaporation phase, but its influx was lower by a factor x2 than with carbon limiters;

TABLE 8: MAXIMUM VALUES OF FUSION PRODUCT

Experimental Programme	Peak Density $n_i(0)$ ($\times 10^{19}m^{-3}$)	Energy Confinement Time $\tau_E(s)$	Ion Temperature $T_i(0)$ (keV)	Fusion Product $<n_i(0)\tau_E T_i(0)>$ ($\times 10^{20}m^{-3}s$ keV)	Plasma Current I_p (MA)
Ohmic (4.6MW)	4.0	1.0	3.1	1.2	5
ICRF(16MW)	3.8	0.4	8.0	1.2	3
Pellet +ICRF (12MW)	5.4	0.5	7.2	2.0	3
NBI (20MW)	2.3	0.3	20	1.5	4
Combined NBI + RF (22MW)	4.5	0.5	8.1	2.0	3.5
X-point (NB-16MW)	3.7	1.1	22	8 - 9	4

- the effective plasma charge, $Z_{eff'}$ was significantly reduced in ohmic plasmas (down to 1.2) and with strong additional heating (down to <1.5);
- a severe carbon influx ('carbon bloom') was still a problem for inner wall and X-point plasmas, and is a serious limitation in H-mode studies.

Reduced impurity levels allowed prolonged operation at higher densities and improved the general JET performance, as follows:

- the pumping of deuterium with beryllium was more efficient than with carbon walls and provided improved density control. This permitted low density and high temperature (up to 30keV) operation for times >1s;
- the density limit increased to $(<n>Rq/B) \approx 30$ (with a record peak density of $4x10^{20}m^{-3}$ with pellet fuelling). This limit is principally a fuelling limit and not a disruption limit, as found with carbon limiters;
- the vessel was no longer deconditioned by disruptions;
- sawtooth free periods exceeding 5s were achieved, but the stabilisation mechanism is still not yet clear.
- H-modes were created with ICRH heating alone for periods >1s. The confinement characteristics were similar to those with neutral beam (NB) heating alone;
- β values up to the Troyon limit were obtained in low field double-null X-point plasmas;
- the neutron yield doubled to $3.7x10^{16}s^{-1}$ and the equivalent fusion factor Q_{DT} increased to 0.8-0.9;
- the fusion product $(n_D\tau_ET_i)$ increased to $8\text{-}9x10^{20}m^{-3}$ s keV for both high (>20keV) and medium temperatures (9keV), reaching near breakeven conditions and was within a factor 5-10 of that required in a reactor.

However, these results were obtained in a **transient** state and could not be sustained in a steady state. Ultimately, the influx of impurities caused a degradation in plasma parameters.

The 1990 operation programme will be aimed at further prolonging the inflow of impurities into the plasma and to improving plasma performance in limiter operation up to 7MA with high energy content, and in X-point operation up to 6MA to exploit the H-mode regime of operation. Profile effects and related physics issues will also be studied using the new equipment installed. In the longer term, a new phase is proposed for JET which aims to demonstrate effective methods of impurity control in operating conditions close to those of a Next Step tokamak in an axi-symmetric pumped divertor configuration. This is described in further detail in the following section.

Future Programme

Introduction

The initial JET objectives still remain valid and continue to provide the focus of the Project's plans. In addition, the JET Project, as a central part of the European Fusion Programme, is directed towards the objectives of that Programme, agreed by the Council of Ministers in the following terms:

> *'The main objectives of the programme are: to establish the physics and technology basis necessary for the detailed design of NET: in the field of physics and plasma engineering this implies the full exploitation of JET and of several medium-sized specialised tokamaks in existence or in construction...'*

At the start of 1989, the JET Project entered its planned Phase III - Full Power Studies. The original design specifications of JET had been achieved and in many cases exceeded. Two of the main programme objectives of the JET programme - the study of plasma heating and of the confinement of plasma - had to a large extent been met in that the results from JET have made it possible to define with confidence the main parameters of a Next Step device. Some aspects of alpha-particle heating had also been studied in simulation experiments.

During 1989, emphasis within the programme was directed towards the area of study on plasma-wall interactions, particularly, the control of impurities in high performance plasmas. The Project has now demonstrated clearly the benefits to be derived (albeit transiently) from passive impurity control by the use of beryllium as a first-wall material for plasma-facing components.

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.*

In parallel, preparations for D-T operations have continued; after some delays in the construction work and in plant manufacture, the Active Gas Handling Building is nearing completion and installation of the major subsystems has started. The planned commissioning programme in this area has been slightly revised, but it is still consistent with a period of tritium operation during 1992.

The most recent experiments on JET achieved plasma parameters approaching breakeven values for about a second, resulting in a large burst of neutrons. These neutrons indicate that fusion D-D reactions are taking place. However, in spite of the plasma pulse continuing for many seconds after reaching peak plasma values, the neutron count fell away rapidly as impurities entered the plasma and lowered its performance. This limitation on the time for which the near-breakeven conditions could be maintained is due to the poisoning of the plasma by impurities. This has further emphasised the need to devise a scheme of impurity control suitable for a next step device.

The JET aims clearly state that JET is an experimental device and that, to achieve its objectives, the latest developments in Tokamak physics must be allowed to influence its programme. However, within a JET programme to 1992, it would not be possible to tackle thoroughly problems associated with impurities. In view of the central importance of impurity control for the success of a Next Step device, the JET Council unanimously supported in October 1989 a proposal to add a new phase to the JET programme, the objective of which would be to establish effective control of impurities in operating conditions close to those of the Next Step. This involves providing JET with a new magnetic configuration, including principally the installation of a pumped divertor. A prolongation of four years from the current end date of 31 December 1992 is needed to carry out the changes and then to allow sufficient experimental time to demonstrate the effectiveness of the new configuration in controlling impurities. This would provide for deuterium operation up to the end of 1994, followed by tritium operations in 1995 and 1996.

In October 1989, the JET Council agreed to the proposed prolongation and invited the Commission to make a proposal to the Council of the European Communities for amending the JET Statutes to allow this prolongation. The JET Council also authorised preliminary expenditure on the New Phase Programme, within a limit on commitment, on items necessary to maintain the schedule of the proposed programme. The possible prolongation of JET was explicitly referred to in the European Commission's proposal for a revised Framework Programme for the period 1990-94.

The current status of the JET programme is that, subject to Decisions of the Council of Ministers on budgets, programmes and statutes, the Project is planning to pursue the New Phase Programme, on the presumption of a prolongation until the end of 1996 but is also, for the present, in a position to proceed towards completion of the programme with D-T operation by the end of 1992.

JET Strategy

While present achievements show that the main objectives of JET are being actively addressed and substantial progress is being made, the strategy for JET can be summarised as a strategy to optimise the fusion product ($n_i T_i \tau_E$), For the energy confinement time, τ_E, this involves maintaining, with full additional heating, the values that have already been reached with ohmic heating and in the H-mode with the X-point configuration. For the density and ion temperature, it means increasing their central values $n_i(0)$ and $T_i(0)$ to such an extent that D-T operation would produce alpha-particles in sufficient quantity to be able to analyse their effects on the plasma.

The enhancements to JET aim to build up a high density and high temperature plasma in the centre of the discharge (with minimum impurity levels) where alpha-particles could be observed, while maintaining an acceptably high global energy confinement time, τ_E. The mechanisms involved are to decouple the temperature profile from the current density profile through the use of lower hybrid current drive and neutral beam injection to ensure that, at higher central temperatures, the current density in the centre does not reach the critical value that causes sawteeth oscillations.

This will involve the following:

a) Increase the Central Deuterium Density $n_D(0)$ by:
- injecting high speed deuterium pellets and higher energy deuterium neutral beams to fuel the plasma centre and dilute impurities;
- injecting pellets to control the influx of edge material;
- stabilising the m=2, n=1 magnetic oscillations present at the onset of a disruption with magnetic perturbations produced from a set of internal saddle coils which will be feedback controlled;

b) Increase the Central Ion Temperature, $T_i(0)$ by:
- trying to lengthen the sawtooth period;
- controlling the current profile (by lower hybrid current drive in the outer region, and by counter neutral beam injection near the centre) to flatten the profile;
- on-axis heating using the full NB and ICRF additional heating power (24MW, ICRH, and 20MW, NB)

c) Increase the Energy Confinement Time τ_E by:
- increasing up to 7MA the plasma current in L-mode operation;
- increasing up to 6MA the plasma current in the full power, H-mode operation in the X-point configuration.

d) Reduce the impurity content, by:
- using beryllium evaporators, beryllium tiles on the belt limiters, beryllium antennae screens to decrease the impurity content;
- Controlling new edge material by using the pumped divertor configuration.

In parallel, preparations for D-T 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 the JET device. In addition, the tritium neutral injection system at 160kV and alpha-particle diagnostics are being developed for this phase.

The following section describes the developments which are underway on JET to implement the proposed pumped divertor configuration in the New Phase.

New Phase For JET

Motivation and Status

Since the beginning of its operational phase, JET has made major achievements but further advances must be accomplished to provide a secure basis for a Next Step Tokamak. Plasma temperature, density and confinement values already achieved, 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 in the range 25-30MA for a machine with a toroidal magnetic field of 3-5T, compared with 6-10MA predicted when JET started operation in 1983.

However, 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 might ultimately be achieved has a direct consequence on the size of the Next Step. It also precludes starting the construction of components of the Next Step device before the specifications for the divertor and its associated pumps can be defined.

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 in the best position to address these problems in the basic geometry considered for the next step. Such studies are the original *raison d'etre* of JET and represent a natural development of its presently agreed programme.

Consequently, a New Phase was proposed for JET, with the aim:

> *To demonstrate effective methods of impurity control in operating conditions close to those of the next step Tokamak; that is in a stationary plasma of "thermonuclear grade" in an axi-symmetric pumped divertor configuration.*

The expected results of this new phase are:

- demonstration of a concept of impurity control in JET;
- provide the size and the geometry needed to realize this concept in the next step;
- allow a choice of materials for the plasma facing components;
- provide information on the operational domain for the Next Step, including the impact of particle and impurity control on enhanced confinement regimes.

This objective could be achieved on JET by means of an axisymmetric pump divertor configuration. The proposal is based on experience at JET with X-point operation and on experience with divertor operation on other machines.

The basic concept and engineering features of the JET divertor were discussed at several meetings of the JET Scientific Council and JET Council in 1989. A workshop dedicated to the presentation and discussion of the JET divertor was also held at JET on 25th-26th September 1989. The JET Scientific Council and JET Council have both strongly supported the JET proposal and recommendations have been made to extend the duration of the JET Project to the end of 1996 in order to allow adequate time for the JET divertor experiment. Pending a future decision of the Council of

European Ministers on prolongation of the Project, the JET Council has allowed the project to proceed with the procurement of long-term delivery items for the divertor.

In order to allow the work to proceed swiftly, a Divertor Task Force was created. This Task Force includes members from all JET Technical Departments and Divisions and thus ensures a strong coordination of the work. Regular progress meetings together with design reviews are held. Responsibilities have been defined and interfaces between the various Divisions or Groups involved have been delineated.

Key Concepts

The key concept of the proposed JET pumped divertor is that since sputtering of impurities cannot be suppressed at the target plate of a divertor, those impurities should be confined in the vicinity of the target plate itself. This confinement can be achieved by maintaining a strong directed flow of plasma particles along the divertor channel towards the target plates, to prevent back diffusion of impurities by the action of a frictional force. A most important feature of the configuration is the connection length, along the magnetic field lines, between the X-point region and the target plates. This distance should be long (~10m) to achieve effective screening effect of the impurities. In other words, the X-point should be well separated from the target plates and in JET this can only be achieved by a **coil which is internal to the vessel.** The proposed configuration shown in Fig. 41 consists of a single additional poloidal field coil, inside the vessel and at the bottom.

The formation of a **target plasma** in the divertor channels is another essential feature of the pumped divertor. The cold (radiatively cooled) and dense plasma, which is expected to form in front of the target plates, plays a number of key roles:

- It should radiate a significant fraction of the plasma input power, thus reducing the heat load on the target plates;
- It should reduce the impurity production by screening the target ;
- It should reduce the probability of the impurities diffusing back to the plasma.

In the vicinity of the outer target plate, a pumping chamber with a cryogenic pumping system is planned to contr**ol the main plasma density.** It should be noted that only a small fraction (~5%) of the hydrogenic neutrals generated at the target plate are expected to be pumped. Some of these neutrals will be able to recycle towards the X-point region (there is a gap between the coil casing and the water cooled elements which defines the divertor channel), re-enter the scrape-off plasma there and enhance the plasma flow to the target plate. This local recirculation of hydrogenic particles should improve the impurity confinement. If required, gas can also be injected near the X-point to further increase the particle flow in the divertor channels.

Engineering Aspects

Fig.41 shows a typical single-null configuration obtained at a plasma current of 6 MA and a divertor coil current of 800 kA-turns. The configuration fills

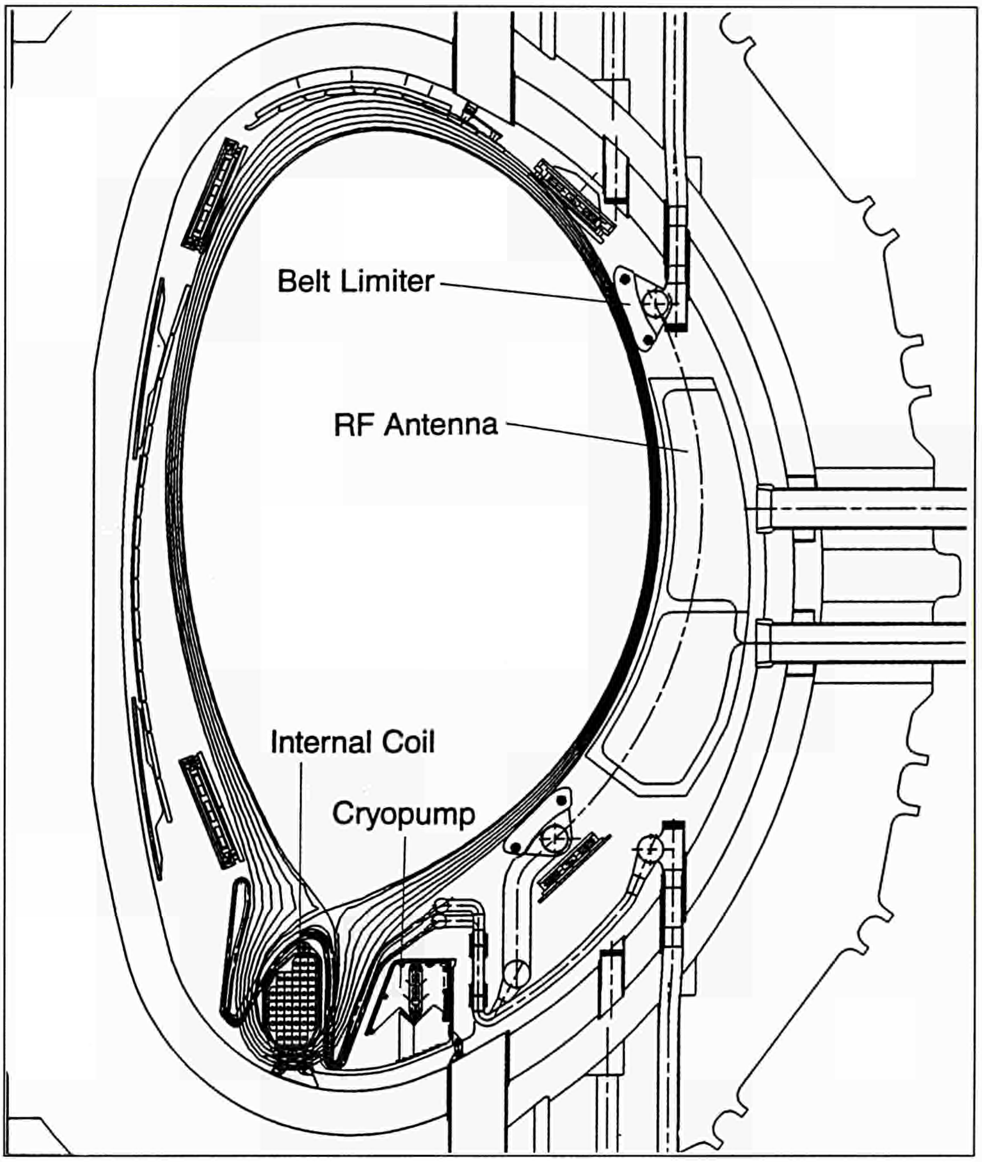


Fig. 41:
The Proposed Pumped Divertor Configuration;

the vessel volume well, while keeping clear of all internal vessel features by at least three e-folding scrape-off lengths. The connection length along magnetic field lines between the X-point and the target plate has been calculated to be ~10m and preliminary calculations indicate that this is sufficient to screen impurities.

The **divertor coil** is a conventional copper, water-cooled coil with 29 turns and able to carry 1 MA-turn for 20s. The coil will be wound inside the vacuum vessel. It is enclosed in a thin (0.8mm) stainless steel casing which will also be used during manufacture for vacuum impregnation with epoxy resin. Magnetic forces on the coil could reach 600-900 tonnes and are restrained by hinged supports which allow differential expansion between the coil and the vacuum vessel.

Although the **target plates** are expected to be shielded by the target plasma they are being designed with the capability to dissipate a large fraction of the plasma input power (40MW) in stationary conditions. The present design uses water-cooled hypervapotrons similar to those used at JET for the high heat flux elements of the JET Neutral Beam systems. Hypervapotrons can easily cope with power densities of 10MWm^{-2} and it is estimated that the divertor target plates should cope with 40MW power in steady-state conditions. This estimate includes the benefit expected from sweeping the impact line by about ±100 mm. Sweeping is achieved by a modulation of the divertor coil current between 750 kA and 1 MA. The surfaces facing the plasma will be clad with 2 mm thick beryllium plates brazed onto the hypervapotron. The choice of beryllium is not ideal since beryllium impurities will not radiate sufficient power. However, the choice of an alternative material could lead to migration of this material onto beryllium tiles elsewhere in the vacuum vessel and ultimately jeopardise the benefits from using beryllium.

For the pumping system, a **cryopump** has been selected because it avoids problems with hydrogen retention and its technology is well known to JET. The pump includes a water cooled entrance baffle, inner liquid nitrogen cooled baffles and liquid helium (LHe) cooled pumping pipes. During plasma pulses, the heat load on the LHe cooled pipes is due to particles and radiation from the target plasma in the divertor channels, whereby the latter predominates. If the total 40MW input power to the plasma is radiated by the target plasma, then the radiative heat load on the LHe cooled pipes could reach 1kW. However, the most severe load is due to the neutrons and gamma rays expected during deuterium-tritium operation. In case of operation at Q ~ 1 with a neutron production rate of 10^{19}ns^{-1} power in excess of 5 kW would be absorbed by the liquid helium and the stainless steel conduits. This has led to a design with thin walled conduits and a large liquid helium inventory. Of course, aluminium conduits rather than stainless steel would reduce the nuclear heating but eddy currents and associated mechanical forces become prohibitive. It is expected that sub-cooling of the LHe before a pulse together with partial boiling during the pulse, would allow several seconds (3-5s) of operation at Q = 1.

Most neutrals produced at the target plate will be re-ionised before reaching the entrance of the cryopump and, therefore, only a few percent (~5%) would be pumped. This should be sufficient to provide a pumping rate of a few x10^{21}s^{-1} which is adequate for density control of the main plasma.

In addition to components which are specific to the pumped divertor, other in-vessel components must be modified to match the new magnetic configuration.

- New ICRH antennae are being designed to match more closely the new plasma magnetic surfaces in the divertor configuration. The new antennae will be deeper and wider than the existing ones and it is expected that the coupling between antennae and plasma will be improved and less sensitive to the distance between the plasma and the RF conductor. New beryllium screens will be provided for these antennae;
- The front end of the lower hybrid launcher must be modified to match better the plasma shape;
- A new belt limiter must be provided. It will comprise two new belts on a smaller major radius than at present and also vertical sections to

protect the new ICRH antennae. It is expected that the existing beryllium tiles can be reused for the new belt limiter;

- The saddle coils at the bottom of the vessel must be raised towards the plasma to produce sufficient perturbation field at the plasma boundary. The saddle coils themselves require no modification since they are translated along the vertical axis of the machine but new supports and busbar sections must be provided.

Planning

The overall pumped divertor planning calls for a start of installation inside the JET vessel, early in 1992. This tight schedule requires that all major manufacturing contracts for long term delivery components should be placed in May-June 1990. By end - 1989, the beryllium screen elements of the new ICRF antennae had been ordered. The overall plan for the New Phase of JET is shown in Fig. 42.

In addition, Calls-for-Tender had been issued or were being finalised for the divertor coil and coil case, the target plate elements, the cryopump, the ICRH antenna housing and the belt limiter.

Future Plans

The JET programme was divided into phases governed by the availability of new equipment and fitting within the accepted lifetime of the Project. At the beginning of 1989, the planned programme was as set out in Table.9. 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 period remaining for D-T operation was no more than eight months. However, with the advent of the proposal for a New Phase for JET until the end of 1996, the proposed programme is now as set out in Fig. 42

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) is underway and future phases are as follows:

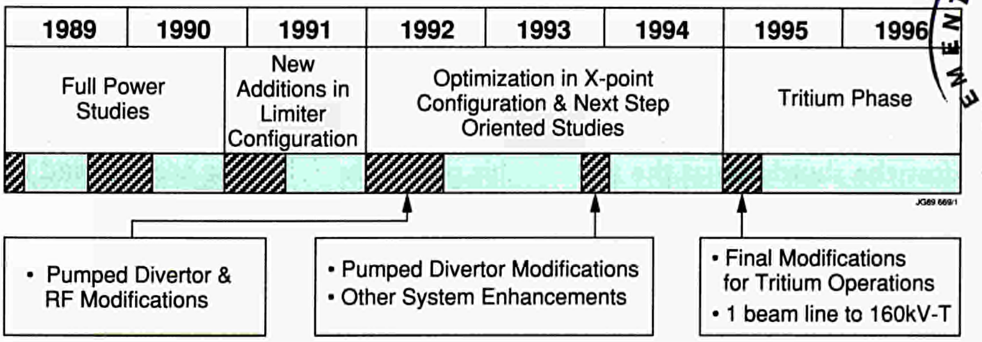
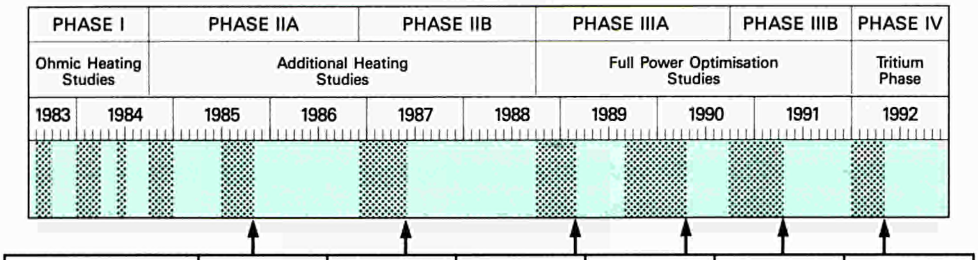


Fig. 42: Overall Plan for the JET New Phase

TABLE 9: JET PROGRAMME TO 1992



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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Full Power Studies - Phase IIIA (Oct 1989 - Sept 1990)

The current shutdown at the start of this phase includes the following:

- replacement of a toroidal coil;
- installation of beryllium RF antennae screens;
- installation of prototype LHCD system;
- installation of prototype High Speed Pellet Launcher;
- installation of beryllium tiles as lower X-point dump plates.

During the operational phase that follows, the second neutral beam box will be progressively brought up to 140kV (deuterium).

The main aims of the experimental programme in 1990 will be to improve plasma performance operating with high reliability, in limiter configuration with currents up to 7MA with high energy content and at up to 6MA in X-point plasmas, in order to exploit the H-mode regime of operations. Profile effects and related physics issues will also be studied using the prototype LHCD, RF, and Neutral Beam systems and High Speed Pellet injection (eg particle and energy transport in transient conditions, disruption and sawtooth stabilisation).

Installation and initial commissioning of Tritium Plant components will also be taking place throughout 1990.

New Additions in Limiter Configuration - Phase IIIB (Oct 1990-Dec 1991)

After the shutdown at the start of this phase, the following are planned to be operational:

- cooled separatrix dump plates (with beryllium protection);
- full LHCD system for profile control;
- disruption control system using internal saddle coils.

A multiple high speed pellet gun would also be installed at this time (or during a break in subsequent operations) as soon as it is available.

The scientific aims of the following operation period will be to exploit these new additions fully, in order to:

- obtain maximum performance in limiter configuration with high reliability;
- control disruptions by feedback system and control sawteeth full power LHCD;
- optimise transient performance in X-point operation.

Preparations for D-T operations will also continue during his period, including active commissioning of the tritium plant (subject to consent by the approving bodies).

The New Phase Programme - Phase IVA (Jan 1992-Sept 1993)

At the start of 1992, the Project will enter an extended (~9 months) shutdown in order to install equipment for the New Phase Programme. This will involve intensive in-vessel work to install:

- divertor structure;
- pumping chamber and cryopump;
- internal poloidal coil;
- modified belt limiter;
- A2 ICRF antennae and modified protection;
- modified LHCD grill and protection;
- divertor diagnostics.

The single-null X-point pumped divertor configuration should enable JET to progress towards quasi-steady state high power operation - at 6MA for up to 10s; at 3MA for up to 20s (B=3.4T); and at 3MA for up to one minute (B=2.1T).

The first operating period of the new phase should focus initially on establishing reliable operation in this configuration. Subsequently, attention should be devoted to the study of the performance and effects of the pumped divertor in controlling impurities, plasma density and exhaust and of power loading on the target plates.

New Phase Programme - Phase IVB (Oct 1993-Dec1994)

The proposed shutdown (~4 months) in late 1993 would be to provide an opportunity, in the light of information from the experimental programme and elsewhere, to install modifications to the pumped divertor (eg enhanced divertor geometry). In addition, it would be possible to install other enhancements aimed at improving performance in the new configuration or for the Tritium Phase (eg enhanced pellet injection or fuelling system, modifications to LHCD or additional heating systems).

The primary objective of the following operating period would be to provide information necessary to establish with confidence the key design features of the Next Step in relation to:

- impurity control;
- fuelling;
- helium transport and exhaust of ashes.

With regard to JET's own requirements, the objective will be to optimise reliability and plasma performance in the divertor configuration in anticipation of D-T operations. A two-fold increase in potential alpha-particle power has been estimated for the new configuration. In parallel, active commissioning of the Tritium Plant and Remote Handling preparation should have been completed.

D-T Operations - Phase V (Jan 1995 - Dec 1996)

Subject to the approval of the JET Council and to necessary official consents, and when it is clear that the results in deuterium and general levels of system reliability justify it, the D-T phase would start in 1995 after a short shutdown for final pre-tritium modifications.

During tritium operations, it would be possible to study in depth the physics of alpha–particle production, confinement and heating and thermal excursions. In addition, the real experience of tritium operation in a relevant scale tokamak (ie tritium handling and recovery, fuel mixture control, confinement properties of D-T plasmas, remote maintenance and plasma diagnostics with large neutron and gamma backgrounds) should provide essential information for the detailed design and operational planning for the Next Step.

Cessation of Operations

As noted, the Project is for the present proceeding in a manner compatible both with pursuing the New Phase programme towards 1996 and with completing its experimental life with D-T operations in 1992. In terms strictly of the experimental programme, the two paths diverge at the end of 1991. However, as the JET Council recognised, it is becoming increasingly difficult to maintain both options within the constraints on staff, money and time available. By the end of 1990, the Project will be forced, in the absence of a decision on extension for the New Phase, into making choices which will adversely affect at least one of the possible paths.

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.43.

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

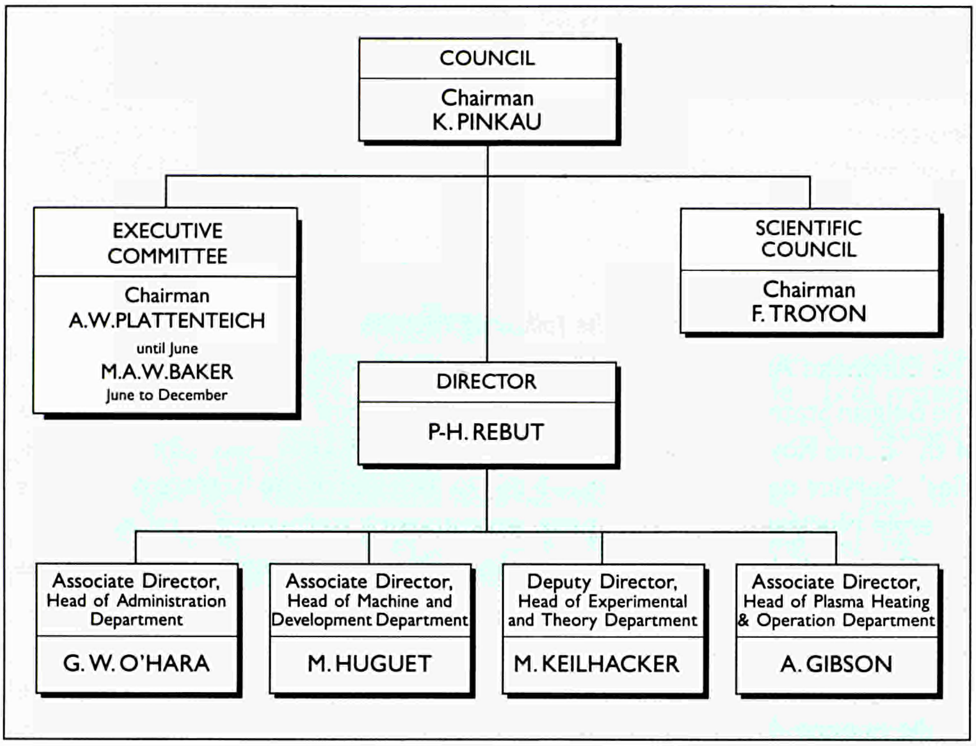

Fig. 43:
Organisation of the JET Joint Undertaking

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 9-10 March, 22-23 June and 19-20 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 six times during the year on 9-10 February, 13 April, 18-19 May, 12 July, 18-19 September and 30 November.

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 four times during the year on 24–26 January, 15 February, 31 May–1 June and 27–28 September.

The main work of the JET Scientific Council in 1989 was to assess and advise the JET Council on:

- The introduction of beryllium into JET; a Thomson scattering diagnostic to measure fast ion and alpha-particle distributions; 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 milestones in the JET programme to 1992 and the consequencies for JET terminating in 1992; the stabilisation of (2,1) modes by magnetic feedback; the New Phase of JET, including proposals for the pumped divertor and the prolongation of JET in support of next step tokamaks.

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.43.

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:

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

Administration

Introduction

The three main aspects of JET's administration—Finance, Contracts and Personnel—are reported on in this section together with the Safety and Public Relations Services.

Finance

The initial budgets for 1989 were approved at 108.17 Mio ECU for Commitments and 115.12 Mio ECU for both Income and Payments. The Commitments and Payments Budgets 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.

During the year, the Project took measures to achieve economies particularly in operating and staff espenditure. These economies were necessary in order to:

- ensure that the Project's required funds up to 31st March 1992 did not exceed the available appropriations resulting from the present Pluriannual European Fusion Programme valid to this date;
- find within the present Pluriannual Programme the initial investment capital required for the New Phase;
- maintain the pattern of decreasing Annual Budgets in real terms.

Commitments

Of the total appropriations in 1989 of 128.85 Mio ECU (including 20.68 Mio ECU brought forward from previous years), 90.86 Mio ECU was committed and the balance of 37.99 Mio ECU was available for carrying forward to 1990.

The details of the commitment appropriations available (Table 10) and of the amounts committed in each Phase during the year (Table 11) are summarised as follows:

- In the extension to Full Performance Phase of the Project 8.41 Mio ECU was committed leaving commitment appropriations not utilised at 31 December 1989 of 12.70 Mio ECU to be carried forward to 1990.
- In the Operational Phase 82.45 Mio ECU was committed leaving a balance of 25.29 Mio ECU to be carried forward to 1990.

Income and Payments

The actual income for 1989 was 117.31 Mio ECU to which was added 0.12 Mio ECU available appropriations brought forward from previous years giving a total of 117.43 Mio ECU; this total compares with the 1989 Income Budget of 115.12 Mio ECU; the excess of 2.31 Mio ECU is carried forward to be offset against future contributions of Members. Of the total payment appropriations for 1989 of 128.37 Mio ECU payments made were 106.39 MioECU and 0.04 MioECU was transferred to income leaving a balance of 21.94 MioECU which was transferred to the Special Reserve Account to meet commitments outstanding at 31 December 1989. (Payments are summarised in Table 11.)

TABLE 10: COMMITMENT APPROPRIATIONS FOR 1989

	Mio ECU
Initial Commitments Budget for 1989	108.17
Uncommitted amounts available from previous years	20.68
	128.85
Commitments made during the year	90.86
Balance uncommitted in 1989 available for use in 1990	37.99

TABLE 11: COMMITMENTS AND PAYMENTS FOR 1989

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	21.11	8.41	17.44	13.77
Phase 3 Operational				
Title 1 Project Investments	21.34	10.07	16.99	14.52
Title 2 Operating Costs	43.02	37.52	45.75	37.66
Title 3 Personnel Costs	43.38	34.86	48.19	40.44
Total Phase 3	107.74	82.45	110.93	92.62
Project Total—all phases	128.85	90.86	128.37	106.39

Contributions from Members

The budget for Members' contributions was 114.00 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 13 gives the percentage contribution from Members for 1989.

Bank Interest

During the year funds are normally received on a quarterly basis in respect of Members' contributions and intermittently in respect of other items. Funds which

TABLE 12: INCOME AND PAYMENTS FOR 1989

	Mio ECU	
Income		
Budget for 1989		115.12
Income received during 1989		
(i) Members' Contributions	114.00	
(ii) Bank Interest	3.25	
(iii) Miscellaneous	0.06	
(iv) Unused Appropriations brought forward from 1987	0.12	
Total Income		117.43
Excess of budgeted income carried forward for off-set against Members' future contributions		2.31
Payments		
Budget for 1989		115.12
Amounts available in the Special Account to meet outstanding commitments at 31 December 1988		13.25
Total Available Appropriations		128.37
Actual payments during 1989	106.39	
Amounts from Special Account transferred to income	0.04	106.43
Unutilised appropriations at 31 December 1989 carried forward in the Special Account to meet outstanding commitments at that date.		21.94

TABLE 13: PERCENTAGE CONTRIBUTIONS TO JET FOR 1989

Based on the Euratom Participation in Associations' Contracts for 1988

Member	%
Euratom	80.0000
Belgium	0.2553
CIEMAT, Spain	0.1050
CEA, France	2.1478
ENEA, Italy	1.8576
Risø, Denmark	0.0773
Luxembourg	0.0016
KFA, FRG	0.7056
IPP, FRG	2.2771
KfK, FRG	0.7535
NFR, Sweden	0.1317
Switzerland	0.4053
FOM, Netherlands	0.4069
UKAEA	10.8753
	100.0000

are progressively required for the discharge of commitments and therefore are placed on deposit account at market interest rate. During 1989, earned interest amounted to 3.25 Mio ECU.

Unused Payment Appropriations from Earlier Years

0.12 MioECU of unused payment appropriations arising in 1987 and held for reduction of Members' future contributions was transferred to income in 1989.

Summary

Table 14 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1989, which have yet to be audited. The final audited accounts will be published in due course.

TABLE 14: SUMMARY OF FINANCIAL TRANSACTIONS AT 31 DECEMBER 1989

	Mio ECU
Cumulative commitments	1016.7
Cumulative payments	963.9
Current commitments	52.8
Of which carried forward on reserve account	21.9
Amount available from 1988 and 1989 due to be set off against future contributions from Members	2.6

Contracts

Contract Activity

133 tender actions covering supply, service and personnel requirements were issued in 1989, 11,343 contracts were placed which represented an increase of 25% in volume terms against 1988. Of the 68 Major contracts (value greater than 75,000 ECU) placed, a significant proportion were for tritium related capital plant and for services.

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 1989, was 6.5 MioECU.

5440 minor contracts (value between 500 and 75,000ECU) were issued in 1989. A Direct Order System which allows technical groups to process thier own orders for values at 500ECU and below was introduced in the early part of 1989 and is working satisfactorily. This system, while maintaining adequate financial and administrative control, provides a faster and more efficient way for ordering low value goods and services than heretofore. 5835 orders were placed in this way over a nine month period. These accounted for 63% of all orders placed while their aggregate value amounted to 2.8% of the total value of all orders, including amendments, in that period.

Imports and Export Services

Contracts service is also responsible for the import and export of JET goods. The total number of imports handled in 1989 was 1070 while the total exports amounted to 350. There were also 894 issues of goods to UK firms. The total value of issues to all countries for the year was 6.5 MioECU.

Administration of Contracts

The distribution of contracts between countries is shown in Tables 15 and 16. Table 15 includes all contracts with a value of 10,000 ECU and above, placed prior to 1984 together with all contracts placed during the period 1984-89. Table 16 is an allocation of 'high-tech' JET contracts, which is based on the figures shown in Table 15 but excludes all contracts below 5,000 ECU and contracts concerning civil works, instillation, pipework, consumeables including gases, maintenance, operations and office equipment (including PCs.)

TABLE 15: ALLOCATION OF JET CONTRACTS

Country	Total of kECU Values	% of Total
UK	349,475	51.35
FRG	132,800	19.51
France	66,413	9.76
Italy	43,207	6.35
Switzerland	37,161	5.46
Denmark	10,487	1.54
Netherlands	9,395	1.38
Belgium	7,979	1.17
Sweden	5,871	0.86
Ireland	374	0.05
Others	17,488	2.57
Totals	680,650	100.00

TABLE 16: ALLOCATION OF JET "HIGH-TECH" CONTRACTS

Country	Total of kECU Values	% of Total
UK	117,695	30.20
FRG	113,689	29.16
France	51,895	13.31
Italy	38,220	9.80
Switzerland	29,368	7.53
Denmark	9,676	2.48
Netherlands	7,019	1.80
Belgium	4,420	1.13
Sweden	4,113	1.05
Ireland	330	0.08
Others	13,491	3.46
Totals	389,916	100.00

Personnel

Recruitment and Complement

The recruitment of team staff was again a major activity of Personnel Service during 1989. As a result 45 new team staff joined the Project during the year, a significant increase compared to previous years. Few of the staff recruited had already been employed by the Associations (including the UKAEA) before joining JET. The cooperation of the Associations in undertaking to employ such staff at the end of their JET appointments has been an important factor in making the recruitment exercise a success.

A welcome development during 1989 was the increase in the number of contract staff applying for JET team posts. This resulted in 13 contract staff being recruited to team posts during the year. This development together with tighter divisional budgets resulted in a reduction of contract staff over the year from 274 to 242.

Table 17 shows posts filled against the approved complements and Fig.44 shows the distribution of team staff by nationality.

TABLE 17: POSTS FILLED AGAINST COMPLEMENT

(situation as at 31 December 1989)

	Complement	In Post
Team Posts		
Temporary Euratom Staff	191	164
UKAEA Staff	260	208
DG XII Fusion Programme Staff	19	11
	470	383
Contract Personnel	210	*242
TOTAL	680	625

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

Euratom Staff

24 Euratom staff took up appointments during the year of whom 8 were already employed by an Association; 7 staff left the Project of whom 2 returned to employment with an Association. There were no movements of DG XII staff during the year. The number of Euratom staff in post at the end of 1989 was 175 including 11 from DG XII.

UKAEA Staff

During the year, 21 new staff were assigned to JET by the UKAEA of whom 4 had been employed by the UKAEA at the time of their selection. However, 20 UKAEA staff also left the Project during the year of whom 3 returned to the Authority. The number of UKAEA staff in post at the end of the year was 208. Many of these staff were not employed by the UKAEA before joining the Project

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 1989, the allowance was paid to 172 staff which was similar to last year.

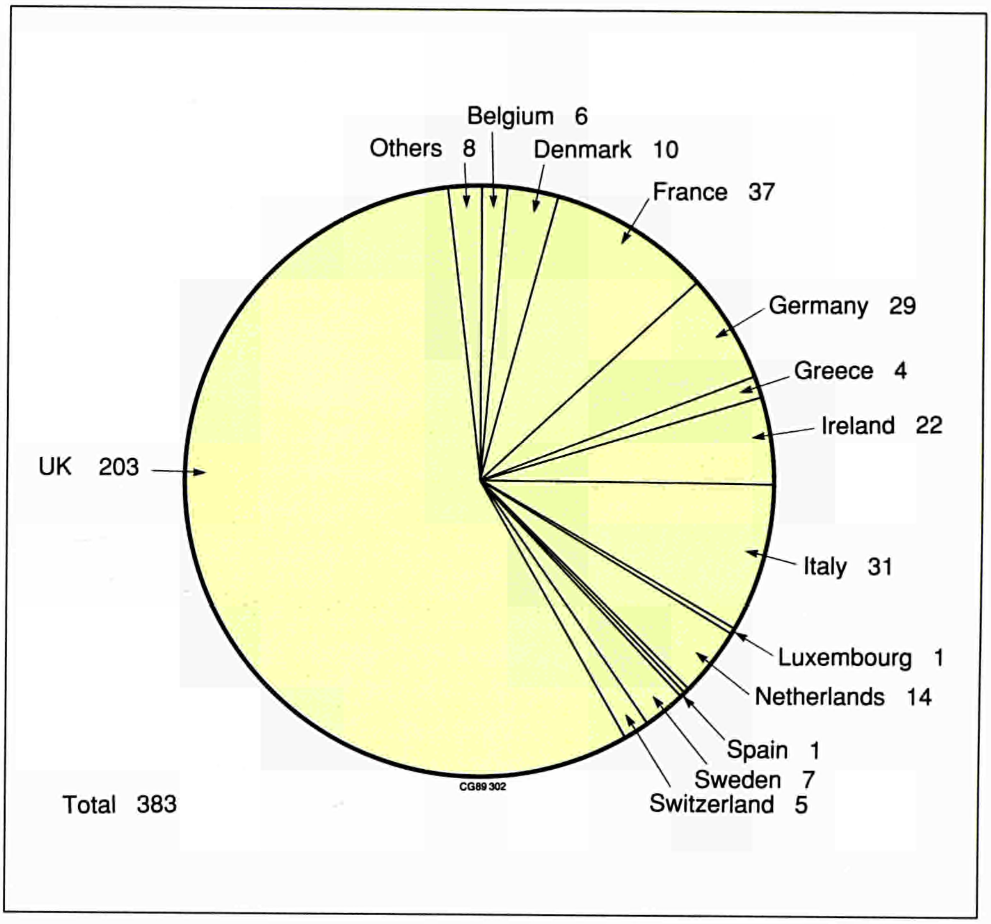

Fig. 44:
Composition of team staff by nationality

Control and Monitoring of Personnel Costs

At the beginning of this year, personnel budgets were introduced for Divisions and Services, and the salaries and mission costs of team staff and contractors have been charged to these budgets on a monthly basis. The Personnel Service has monitored this expenditure and issued monthly Divisional reports of expenditure together with a forecast incorporating expected trends and changes in the personnel strength over the year. This has contributed to improved accountability within Divisions and Services, and increased interest in achieving economies wherever possible.

Assigned Associate Staff

During 1989, the total number of staff assigned to JET from Associate Laboratories fell to 40 compared to 66 during 1988. The total contribution (including an estimated 12 man-years from the UKAEA) was 32 man-years, a reduction of 6 man-years compared to 1988, due largely to a decrease in the number of short-term appointments following the introduction of economy measures. The average duration of assignments increased slightly from 0.4 man-years in 1988 to 0.5 man-years in 1989. Table 18 shows the contribution made by the partners to the Project as a whole and Table 19 shows the contribution made to Divisions within the Project.

Liaison with JET Partners

Contact between JET and the Associated Laboratories continued to be maintained during the year, mainly for recruitment of team staff and

TABLE 18: CONTRIBUTION FROM ASSOCIATED LABORATORIES DURING 1989

Associated Laboratory		Man-Years
UKAEA	(UK)	12.0
IPP	(Federal Republic of Germany)	6.5
FOM	(The Netherlands)	3.3
NFR	(Sweden)	3.2
CEA	(France)	1.8
CIEMAT	(Spain)	1.6
JNICT	(Portugal)	1.3
CRPP	(Switzerland)	1.0
Risø	(Denmark)	0.5
KFA	(Federal Republic of Germany)	0.5
ENEA	(Italy)	0.3
TOTAL		32.0

TABLE 19: ASSIGNED ASSOCIATED STAFF WITHIN THE PROJECT

Division	Man-Years
Experimental Division I	16.7
Experimental Division II	9.3
Theory Division	2.6
Radio Frequency Heating Division	1.7
CODAS	1.0
Fusion Technology Division	0.6
Experimental & Theory Department	0.1
TOTAL	32.0

assignment of temporary staff in support of Task Agreements. Arrangements for the temporary recall of their staff continued to operate satisfactorily with the partners and annual staff assessment reports on their staff continued to be made available to them by the Project.

Beryllium Working

Following the JET Council's agreement, beryllium working in controlled areas was introduced during the year. The rights of staff to compensation for injury arising from working with beryllium were established in consultation with the two employers. JET team staff who are registered beryllium workers have been informed of their rights under the conditions of service of their employer. At the year end, a proposal by the UKAEA to make a special bonus payment to UKAEA staff in JET who are required to work with beryllium was being considered.

Shift Work

During the three main periods of machine operation, there were 86 days of double-shift working and 20 days of extended day work in 1989. 111 staff 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. Following the start of Saturday shift working, a special shift allowance was introduced by the UKAEA, payable according to the number of shifts worked on a Saturday, in recognition of the atypical pattern of working for UKAEA staff.

Overtime

Recorded overtime averaged 250 hours per week, or the equivalent of 6 man-years of effort. For economy reasons, Sunday overtime was reduced to a minimum and this contributed to an overall reduction of 50% during the year compared to 1988.

On Call

To provide emergency cover during 1989, on-call rosters were maintained for the 5 subsystems of the JET machine. 18 staff each working an average of 7 weeks undertook this on-call duty. In addition, two on-call systems were introduced for the October 1989 shutdown.

Visiting Scientists

During the year, 10 Visiting Scientists worked at the Project for varying periods. This represents a 38% reduction on the 1988 figure mainly due to a reduction in Divisional budgets. To counteract this decline, Visiting Scientists will be funded centrally by the Project in 1990.

Consultants

8 Consultants were engaged to advise the Project on a range of topics from magnetic configuration and plasma control to the improved control of remote handling equipment.

JET Fellowships

During the year, 15 grantees worked at JET under the Fellowship Scheme - 11 physicists and 4 engineers. 11 of the Fellowships were awarded for post graduate or post-doctoral research projects while 4 JET Fellows undertook research for PhD degrees.

In October 1989, the JET Council agreed to revise the limit on the number of JET Fellowships and a further 6 candidates have been selected to take up Fellowships early in 1990 as a result.

3 Fellowship holders were recruited to Euratom posts in the JET team following completion of their Fellowships.

Exchange of Personnel

Exchanges of personnel under the Tripartite Agreement between JET, JT60 in Japan and TFTR in USA, took place during the year. Altogether 5 JET team members undertook assignments with the other projects for the periods ranging from 6 weeks to 6 months and 6 members of the other laboratories worked at JET for up to 18 weeks.

The Bilateral Agreement between the United States Department of Energy and the European Atomic Energy Community in the field of controlled thermonuclear fusion has enabled 43 months of manpower to be contributed by US Laboratories under agreement for specific collaborative areas of work.

The Co-operation Agreement between the Commission of the European

Communities and the People Republic of China has continued to provide grants for 2 Chinese scientists to continue their work at JET during 1989.

Student Assistants

Students from nine EEC countries worked at JET during 1989 but as a result of the budgetary restrictions at the beginning of the year, there was a marked decrease in the number of appointments, especially of short-term students. The number of students during 1989 totalled 56, compared with 110 students in 1988. Long-term students, i.e. those with contracts for longer than 14 weeks, made up 66% of the total and the average length of appointment was approximately 4 months. 40% of the students appointed worked in the Experimental and Theory Department.

2 students were also accepted by the Project under the Commission's 'Comnet' grant scheme which provides grants to enable students to take up industrial training outside their own country.

Staff Training

During the year, 26 staff members were recalled by their parent Associations for training and 9 staff continued to pursue part-time courses either through day-release or the Open University.

The JET Induction Programme for new staff was reviewed and the bimonthly course was discontinued in favour of an introductory session for new staff on an individual basis according to their work activity.

Safety training procedures were also reviewed and towards the end of 1989, a safety training programme was introduced comprising four standard basic courses compulsory for all staff, supplemented by specialist safety training as required by the nature of the work. The first new basic safety courses were attended by 46 team staff and 7 contract staff. A comprehensive training programme was organised for secretaries and typists in the use of word processors.

Language tuition in English was given to 14 team members and to 49 team members in other community languages.

Staff Representation

During 1989, four official meetings took place between the JET management and the Staff Representatives Committee at which various topics on working conditions ranging from working with beryllium to machine operation shifts were discussed.

Missions

The number of missions undertaken by JET staff during the year totalled 2335 of which 49% were in the United Kingdom and 47% in other EEC countries. The average duration of a mission in the UK was 1 day and 2.2 days elsewhere. Overall, there was a reduction of 20% in the number of missions undertaken in 1989 compared with 1988.

Economy class air travel was introduced as an economy measure. Additional economies were achieved when Personnel Service took over responsibility for use of taxis and hire cars; altogether a 30% reduction in the cost of missions was achieved during the year.

General Administration

A number of services previously provided by Culham Laboratory, under the Host Support Agreement, were taken over by the Personnel Service. At the end of the year, these services were being reviewed with the aim of improving efficiency and reducing costs.

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 Operations Safety Assessment Panel. The UKAEA Culham Laboratory and JET Joint Health & 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 1989.

The 1988/89 shutdown was completed in April with a total collective radiation dose of approximately 0.14 man-Sv, of which 37% was accrued in 1989. Neutron yield per pulse continued to rise during 1989 but operations were controlled to limit the activation of the vacuum vessel to levels not exceeding 35 μSv/h during interventions. The 1989/90 shutdown started in October and the collective dose from in-vessel work up to the end of December amounted to approximately 0.03 man-Sv. The total collective dose for the Project during 1989 was approximately 0.13 man-Sv. Beryllium evaporators were installed during the final stages of the 1988/89 shutdown and beryllium was evaporated onto the first wall in late May. All interventions and shutdowns following evaporation have been subject to rigorous safety precautions against inhalation of beryllium dust. During 1989, in-vessel work was largely performed in full pressurised suits. This led to some logistical problems and delays in the July intervention but these were largely resolved by the start of the 1989/90 shutdown.

The Tritium Operations Safety Assessment Panel is chaired by the Head of Joint Safety Services, with members from JET, Joint Safety Services, the UKAEA Safety & Reliability Directorate, and the UKAEA Harwell Laboratory. 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 met. The formal arrangements for liaison between JET, the UKAEA Safety & Reliability Directorate and Culham Laboratory continue. 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 JET Co-ordinating Staff Unit with members drawn from JET, Joint Safety Services and the Site 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

Fusion made a major impact upon the media and the general public as the 'cold fusion' controversy caught the public attention around the world. Interest remained at a high level from March to August. Many requests were received by JET from press, radio and television for expert views and comment on the various claims and for information on the progress of fusion projects such as JET. The Director and staff were interviewed for television and radio, and television crews from Italy, Norway, Spain, and the United Kingdom and Federal Republic of Germany visited the Project. These provided good opportunities to publicise the excellent progress made by JET.

Of greatest importance was the Press Conference in November at which the Director announced JET's latest achievements. Four television crews, three radio reporters, fifteen journalists and two press photographers attended the Conference, with press packs being sent to another twelve journalists. The Director' statement to the media and a Press Release were given a further wide distribution in Member countries through the JET Information Network. Twelve television and radio interviews were given by the Director and senior staff. Media interest in consequence was extremely high throughout Europe.

Visits of groups of schools, universities, professional bodies and the general public continued at a high level, and about 200 groups comprising over 3,200 visitors were given presentations and guided tours around the JET facilities. Notable visitors included:

Dr. Marilies Flemming, Austrian Federal Minister for the Environment;
Academicians V I Goldanski and V I Trevilof, USSR Academy of Sciences;
Sir John Kendrew, Chairman of the Board of Governors, JRC Ispra;
Baron Hermann von Richthofen, FRG Ambassador to the UK;
M. Curien, French Minister of Research and Technology;
Dr. Heinz Riesenhuber, Minister for Research and Technology, Federal Republic of Germany

Lectures continued to be given on JET and nuclear fusion by invitation to outside events. JET exhibited at the Stockholm Technical Fair and also provided a JET display to the Abingdon Town Council for their exhibition at Argentan, France.

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 - Laboratorium voor Plasmafysica, Ecole Royale Militaire - Koninklijke Militaire School) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the UBL); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studie-centrum 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* *R. Aymar*	
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	*A. Bracci* *R. Andreani* *P. Longo*	*(to March)* *(from March)*
The Hellenic Republic (Greece)	*A. Katsanos*	
The Forskningscenter Risø (Risø), Denmark	*H. von Bülow* *J. Kjems*	
The Grand Duchy of Luxembourg (Luxembourg)	*J. Hoffmann* *J. P. Zens*	
The Junta Nacional de Investigação Cientîfica e Tecnológica (JNICT), Portugal	*J. A. da Costa Cabral* *Mrs M. E. Manso*	
Ireland	*D. Byrne* *F. Turvey*	
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* *H. Wilhelmsson*	*(to December)*
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*	*(to December)*

Secretary: J. McMahon, JET Joint Undertaking.

APPENDIX II

The JET Executive Committee

Member	**Representative**
The European Atomic Energy Community (EURATOM)	*J. P. Rager* *P. J. Kind*
The Belgian State acting for its own part (Laboratoire de Physique des Plasmas - Laboratorium voor Plasmafysica, Ecole Royale Militaire - Koninklijke Militaire School) and on behalf of the Université Libre de Bruxelles (Service de Chimie-Physique II of the UBL); and of the 'Centre d'Étude de l'Energie Nucléaire' (CEN)/'Studie-centrum 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 (to May)* *R. Gravier (from May)*
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	*R. Andreani (to March)* *A. Coletti (from March)* *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	*J. Bonfirm* *F. Serra*
Ireland	*F. Turvey (Vice-Chairman)* *D. Kearney (to March)* *D. Taylor (from March)*
The Kernforschungsanlage Jülich GmbH, Federal Republic of Germany (KfA)	*V. Hertling* *A. W. Plattenteich (Chairman to June)*
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	*K. Tichmann*
The Swedish Natural Science Research Council (NFR) Sweden	*E. Hellstrand* *G. Leman*
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)	*M. A. W. Baker (Chairman June to December)* *D. M. Levey* *W. M. Lomer*

Secretary J. McMahon, JET Joint Undertaking.

APPENDIX III

The JET Scientific Council

Members appointed by the JET Council:

F. Troyon (Chairman)
EURATOM-SUISSE Association
Centre de Recherches en Physique
des Plasmas
Ecole Polytechnique Fédérale
21 Avenue des Bains
CH-1007 Lausanne, Switzerland

R. Aymar
EURATOM-CEA Association
Département de Recherches sur la
Fusion Contrôlée
Centre d'Études Nucléares Cadarache
Boîte Postale No.1
F-13115 St Paul lez Durance, France

F. Engelmann
NET Team
Max-Planck-Institut für Plasmaphysik
D-8046 Garching bei München
Federal Republic of Germany

D. Gambier
EURATOM-CEA Association
Département de Recherches sur la
Fusion Contrôlée
Centre d'Études Nucléares Cadarache
Boîte Postale No.1
F-13115 St Paul lez Durance, France

K. Lackner
EURATOM-IPP Association
Max-Planck-Institut für Plasmaphysik
D-8046 Garching bei München
Federal Republic of Germany

L. Pieroni
EURATOM-ENEA Association
ENEA Centro di Frascati
Casella Postale 65
I-00044 Frascati/Roma, Italy

D. C. Robinson (Secretary)
EURATOM-UKAEA Association
Culham Laboratory
Abingdon, Oxfordshire, OX14 3DB
United Kingdom

A. Samain
EURATOM-CEA Association
Département de Recherches sur la
Fusion Contrôlée
Centre d'Études Nucléares Cadarache
Boîte Postale No. 1
F-13115 Saint Paul Lez Durance, France

F. C. Schüller
EURATOM-FOM Association
FOM Instituut voor Plasmafysica
'Rijnhuizen'
Postbus 1207 – Edisonbaan 14
NL-3430 BE Nieuwegein
The Netherlands

D. R. Sweetman
EURATOM-UKAEA Association
Culham Laboratory
Abingdon, Oxfordshire, OX14 3DB
United Kingdom

F. Waelbroeck (until June 1989)
EURATOM-KFA Association
Kernforschungsanlage Jülich GmbH
Institut für Plasmaphysik
Postfach 1913
D-5170 Jülich 1
Federal Republic of Germany

F. Wagner
EURATOM-IPP Association
Max-Planck Institut für Plasmaphysik
D-8046 Garching bei München
Federal Republic of Germany

R. Weynants
EURATOM-EB Association
Laboratoire de Physique des Plasmas
de l'École Royale Militaire
Avenue de la Renaissance 30
B-1040 Brussels, Belgium

G. Wolf
EURATOM-KFA Association
Kernforschungsanlage Jülich GmbH
Institut für Plasmaphysik
Postfach 1913
D-5170 Jülich 1
Federal Republic of Germany

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

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