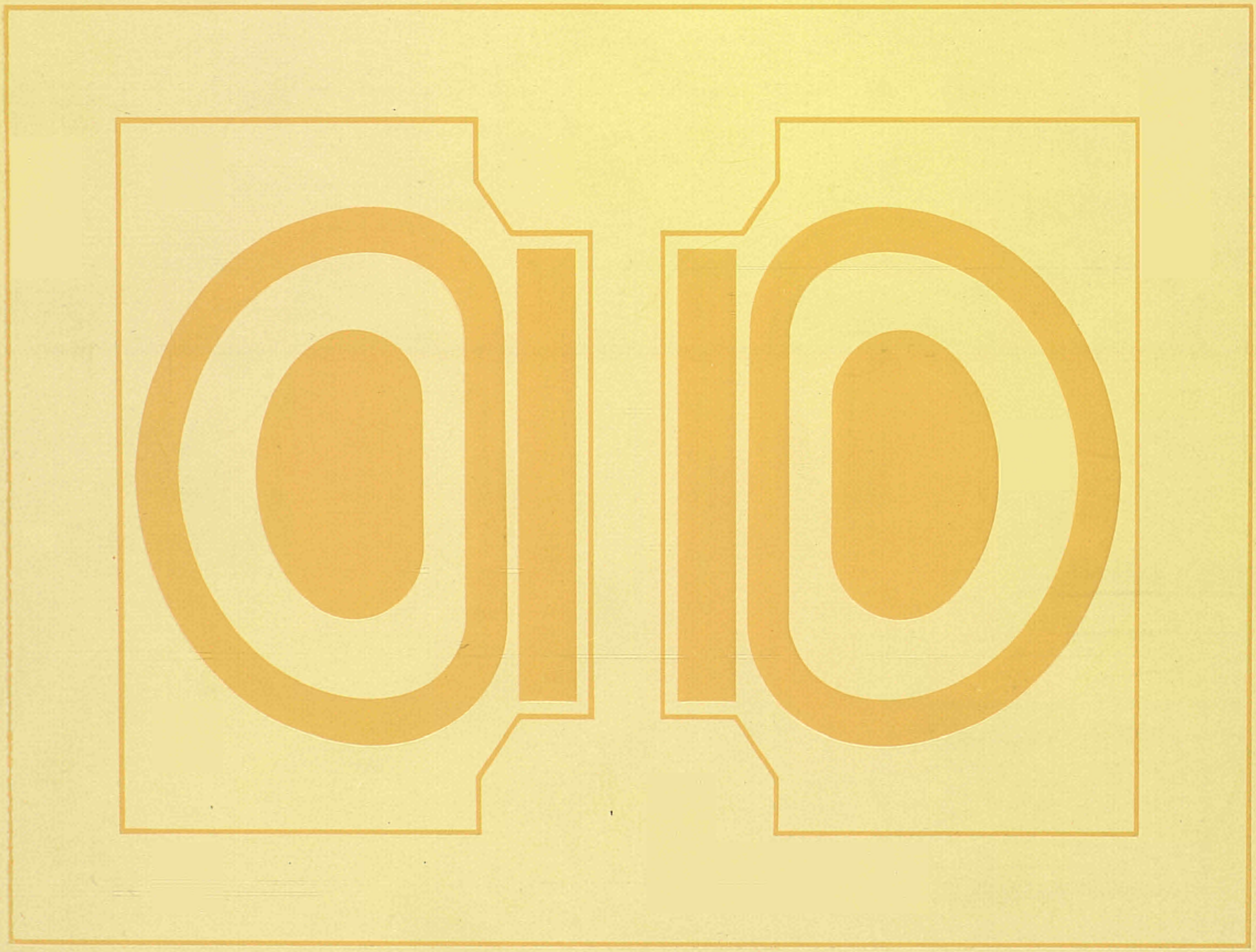
JOINT EUROPEAN TORUS JET

JET JOINT UNDERTAKING

ANNUAL REPORT 1992



S

EUR 15080-EN-C

EUR-JET-AR15

JET JOINT UNDERTAKING

ANNUAL REPORT 1992

MAY 1993

Catalogue number: **CD-NA-15080-EN-C**
for the report **EUR 15080** (EUR-JET-AR15)

Editorial work on this report was carried out by
B.E. Keen and G.W. O'Hara
Prepared and produced by JET Publications Group.

Printed in England

Preface

Preface

I am pleased to report that JET again succeeded in meeting the main targets of its work programme in 1992. It completed Phase III of the Operational Programme on Full Power Optimisation Studies, and embarked upon the new, Pumped Divertor Phase. Preparations for the full D-T phase of operations were also continued. Installation of the systems in the active gas handling building was completed. Significant progress in commissioning was made in exhaust detritiation, gas chromatography and the analytical laboratory. In addition, a series of tests and modifications to improve the performance of the cryodistillation system was carried out.

The final part of the Phase III Programme sought to extend and complete investigations started during the 1991 campaign. In the first two months of the year an extensive programme of experiments was carried out with the plasma current (a major factor in the performance of a tokamak) increased to over 7MA. This is more than double the current used in any other fusion experiment in the world and it was sustained for pulses of over 9 seconds duration. Of fifty 7MA pulses in 1992, there was only one disruption, despite heating powers from the Neutral Beam Injectors and the Radio Frequency Heating Systems of over 28MW. This demonstrates that high reliability at these high currents, similar to those required in a fusion reactor, can be sustained without major problems in operation.

With the completion of Phase III of the planned operation programme two of the four main objectives set out in the original JET design had been fulfilled. These were the demonstration of effective heating methods in near-reactor conditions, and the scaling of plasma behaviour as parameters approached the reactor range. Significant strides were also made towards achieving the two other objectives, namely, studying plasma-wall interactions in near-reactor conditions and studying alpha-particle production, confinement and consequent plasma heating.

In March 1992, the longest and most complex shutdown programme yet undertaken by JET began, ushering in the Pumped Divertor Phase. The aim of this new phase is to demonstrate, prior to the final introduction of tritium, effective methods of power exhaust and impurity control in operational conditions close to those of a fusion reactor. The shutdown is expected to be completed by the end of 1993 and will be used to install the components of the Pumped Divertor, thus totally transforming the interior of the vessel. The shutdown is being undertaken in three stages. Stage 1 involved the removal of components and beryllium decontamination of the vacuum vessel preparatory to the installation of the divertor coils. Stage 2 involves the assembly of the four divertor coils and casings within the vacuum vessel. Stage 3 involves the installation of the Mark 1 inertially cooled divertor, cryopump, RF antennae, limiters and saddle coils. Subsequent operations will then be devoted to studies of controlling impurities, plasma density and exhaust in the divertor configuration.

The scientific results obtained in JET to date are, indeed, impressive. Plasma temperatures, plasma densities and confinement times have now surpassed individually those needed in a reactor but not yet simultaneously. JET is the only machine in the world to have reached this stage. Both ion and electron temperatures of over 150 million degrees C have been achieved at the same time, albeit at a lower density than required in a reactor. In some experiments, ion temperatures of over 300 million degrees C have been reached. Energy confinement times greater than two seconds have been obtained in JET - the only machine where this has been done. Plasma densities have also reached values suitable for a reactor. Simultaneously, JET has achieved, in deuterium plasmas, the equivalent conditions of breakeven and in the preliminary tritium experiments produced 1.7MW of fusion power in the device. These results are important milestones on the road to a fusion rector.

Although JET results are about a factor of 5-6 below simultaneous values of density, temperature and confinement time required in a reactor, knowledge gained within the JET programme enables the parameters of the Next Step to be defined with confidence.

Sufficient knowledge now exists to design a Next Step experimental reactor and this has led to the setting up of the Engineering Design Activities of ITER (International Thermonuclear Experimental Reactor), which is a collaborative effort between the European Community, Japan, the Russian Federation and USA. The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. In July 1992, the ITER Engineering Design Activities (EDA) Agreement was signed by the four parties. In September, the ITER Council nominated Dr. P-H Rebut (the Director of JET) as the Director of the ITER-EDA.

As Chairman of the JET Council, at the time when Dr. Rebut left the Project, I think I have to pay tribute to the outstanding contribution he gave to the advancement of fusion R & D, by conceiving JET and conducting its construction and operation to a success which will remain a milestone in the history of fusion.

A number of other senior JET staff including Dr. M. Huguet (Associate Director of JET and Head of Machine and Development Department) have also been selected for ITER posts. While the Project regrets the loss of the services of such renowned and high calibre staff, it accepts that JET is an obvious and natural source of expertise and experience for the new Project. JET can indeed be proud that its personnel are filling a high proportion of senior posts at ITER.

The success achieved by the Project was marked during the year when the Royal Society in the United Kingdom awarded the Esso Energy Award for 1992 to Dr. P-H Rebut, Dr. M. Keilhacker, Dr. A. Gibson and Dr. M. Huguet for the JET Project and in recognition of its role in the development of nuclear fusion as a potential new energy source. The Award is made each year for outstanding contributions to the advancement of science, engineering or technology in the energy field (see page iv).

JET remains the largest and most powerful fusion experiment in the world. It has the capability for studying problems relevant to reactors and providing information crucial to the design and planning of Next Step devices, such as ITER. The JET Council has supported a proposal from Dr. Keilhacker, the newly appointed Director, to review the Project's scientific programme in order to clarify the major options, objectives, schedules and decision points. The outcome of this review will be considered by the JET Council during 1993. It is clear that JET must continue along the path towards simulating the operation of a fusion reactor and in making unique and essential contributions to the ITER-EDA.

On behalf of my colleagues on the JET Council I wish to express our appreciation to the Host Organisation (UKAEA) and the Associations within the European Fusion Programme on whom the Project relies heavily for support. I would like also to thank my colleagues on the JET Council, and the members of the JET Executive Committee and the JET Scientific Council for their substantial contribution to the Project during the year.

I wish also to thank the whole JET team for their continuing dedication and enthusiasm which, I am confident, will keep JET in the forefront of world fusion research in coming years.

P Fasella
Chairman of the JET Council
May 1993


THE ESSO MEDAL
THE ROYAL SOCIETY

Introduction, Summary and Background

Introduction

The Joint European Torus is the largest project in the coordinated fusion programme of the European Atomic Energy Community (EURATOM), whose long term objective is the joint creation of safe environmentally sound prototype fusion reactors.

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 intended to be 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 throughout the Report.

A more detailed and comprehensive description of the technical and scientific aspects of the JET Project for the same period can be found in the JET Progress Report.

Report Summary

The Report is essentially divided into two main parts:

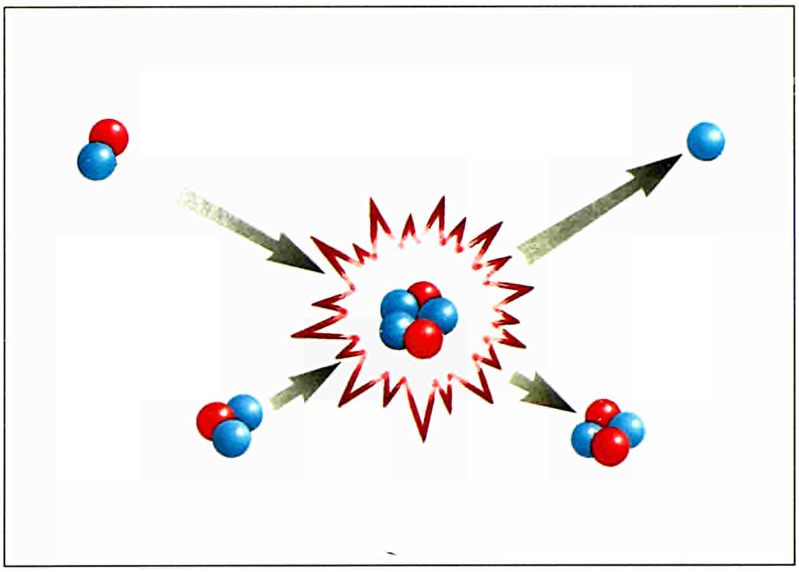
- the scientific and technical programme of the Project;
- the administration and organization of the Project.

The first part of the Report 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 summarise the main features of the JET apparatus and its experimental programme and explains the position of the Project in the overall

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, ^4He) which is also produced in the reaction. In a fusion reactor, a jacket or blanket around the reactor region would slow down the neutrons, converting their energy into heat. This heat could be extracted to raise steam for conventional electricity generation.



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 using fusion reactors, to be maintained at present levels, for several hundreds of years.

Euratom programme. In addition, this relates and compares JET to other large fusion devices throughout the world and confirms its pre-eminent position in fusion research.

The following section reports on the technical status of the machine including: technical changes and achievements during 1992; 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 1992 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 the triple fusion product, 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 scientific part of this Report concludes with a description of the proposed future programme of JET until its planned conclusion.

The second part of the Report explains the organisation and management of the Project and describes the administration of JET. In particular, it sets out the budget situation; contractual arrangements during 1992; and details of the staffing arrangements and 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 30th May 1978, the Council of Ministers of the European Communities decided to build the Joint European Torus (JET) 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 1st June 1978.

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

The Members of the JET Joint Undertaking are Euratom, its Associated Partners in the framework of the Fusion Programme, including Sweden (NFR) and Switzerland, together with Greece, Ireland and Luxembourg, 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 Institutions and the Directorate General of the Commission responsible for Science Research and Development (DGXII).

In July 1988, the Council of Ministers agreed the prolongation of the JET Joint Undertaking to 31st December 1992. A further proposal to prolong JET to 31st December 1996 was submitted to the Council of Ministers in October 1990. At its meeting on 19th December 1991, the Council of Ministers adopted Decisions concerning the Euratom Fusion Programme in the period to the end of 1994 and a modification to the JET Statutes which prolonged its statutory lifetime by four years until 31st December 1996. The extension will allow JET to implement the new Pumped Divertor Phase of operation, the objective of which is to establish the effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies will be pursued before the final phase of full D-T operations in JET.

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 is put 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 $5\times10^{21}m^{-3}$skeV. Typical values for the parameters that must be attained simultaneously for a reactor are:

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

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

Fusion Reactor

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

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

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

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

$$D + D \rightarrow T + p$$

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

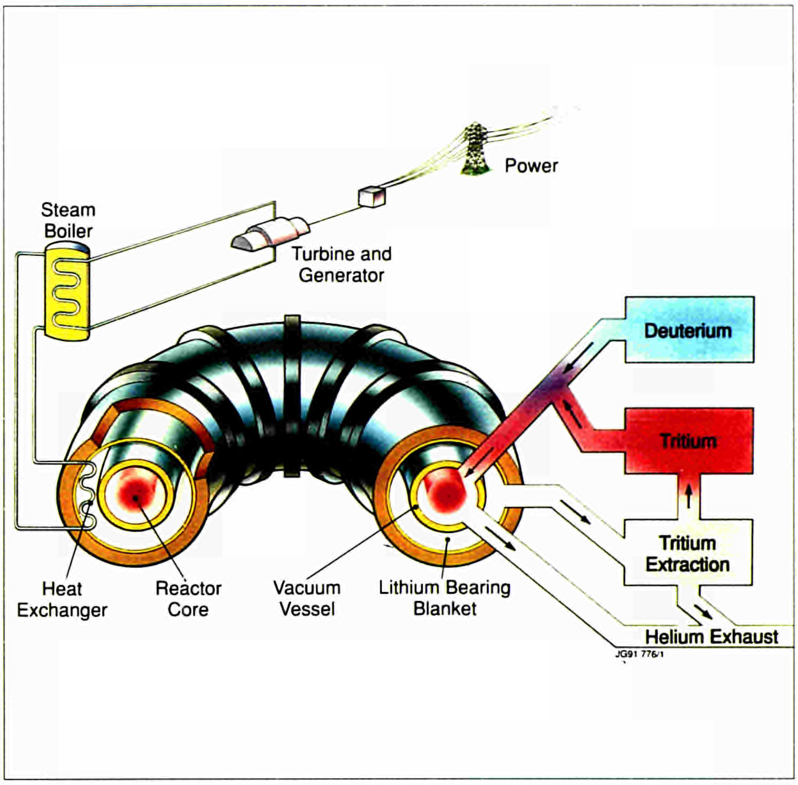
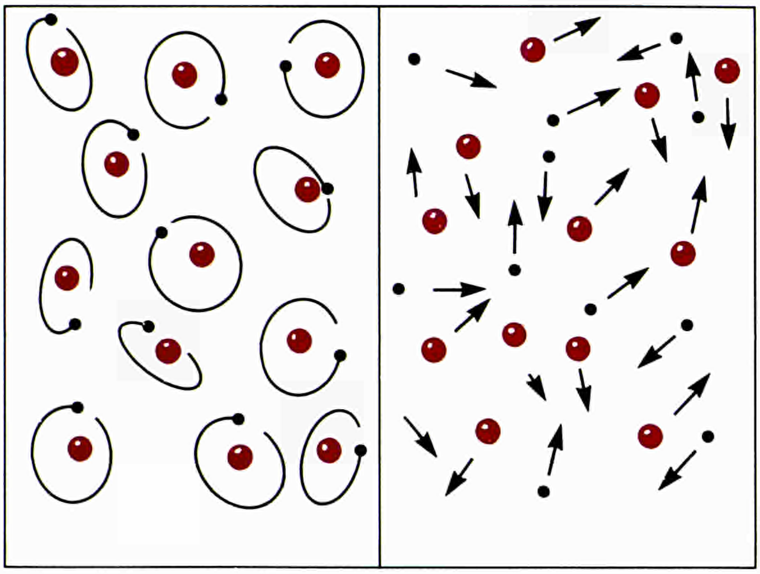


Fig.1: The site of the JET Joint Undertaking, near Oxford in the United Kingdom



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.

Objectives of JET

The original decision of the Council of Ministers in 1978 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 implement this, it was necessary to create and study plasma in near-reactor conditions.

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.

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 presented in Table I.

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

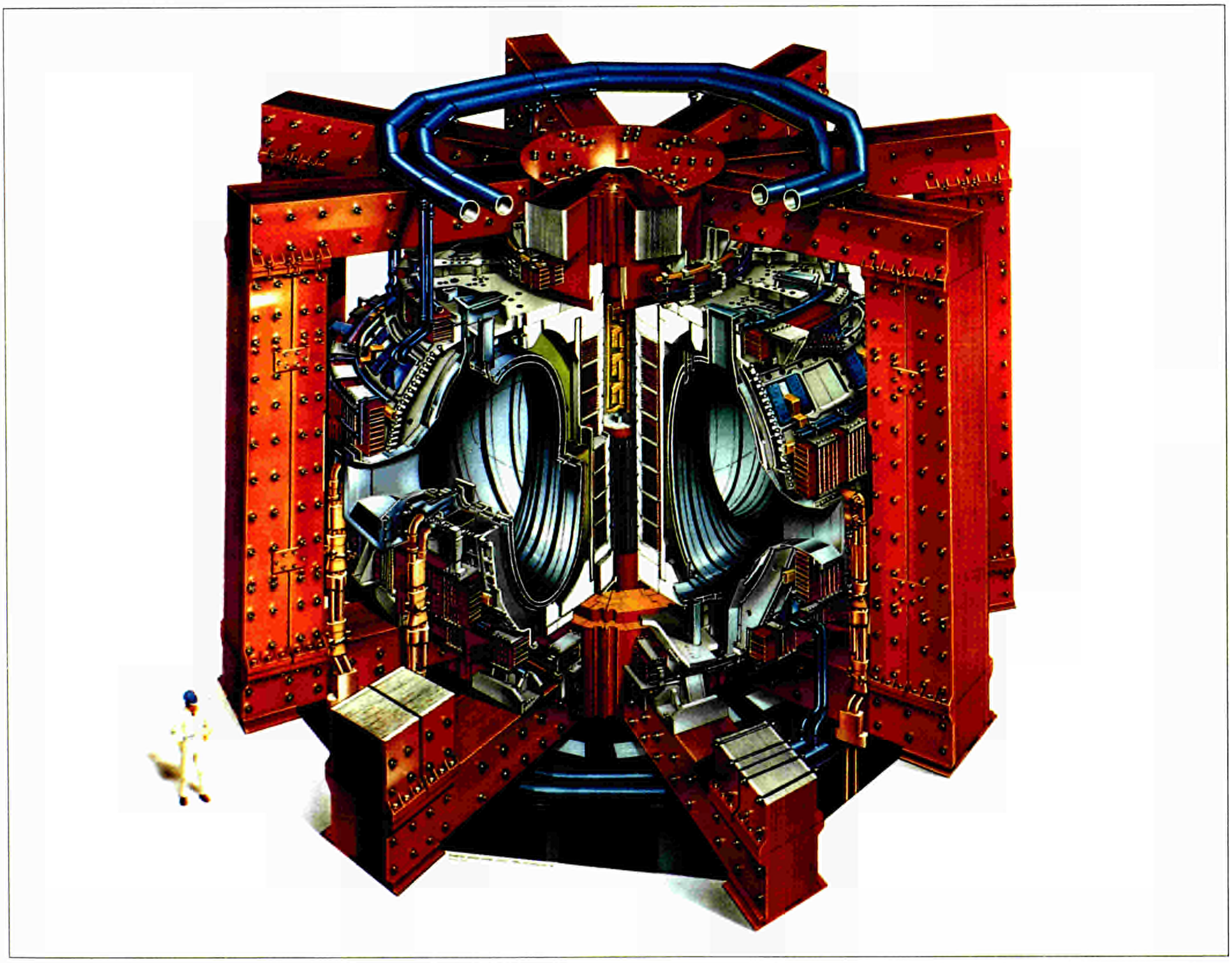


Fig.2: Diagram of the JET apparatus

Table I: Original Design Parameters of JET

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

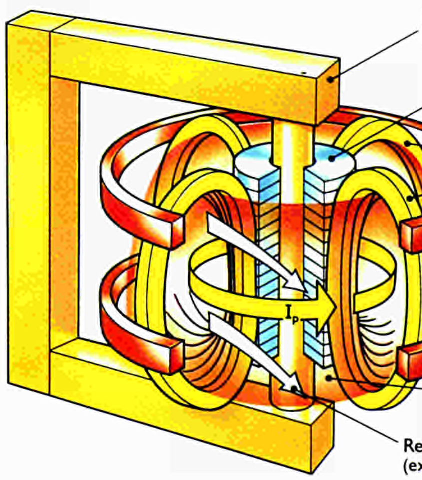
field coils) of the transformer, used to induce the plasma current which generates the poloidal component of the field, is situated at the centre of the machine. Coupling between the primary winding and the toroidal plasma, acting as the single turn secondary, is provided by the massive eight limbed 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 inside the vessel.

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 that the JET machine operates in a pulsed mode. Pulses can be produced at a maximum rate of about one every ten

Magnetic Field Configuration

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.



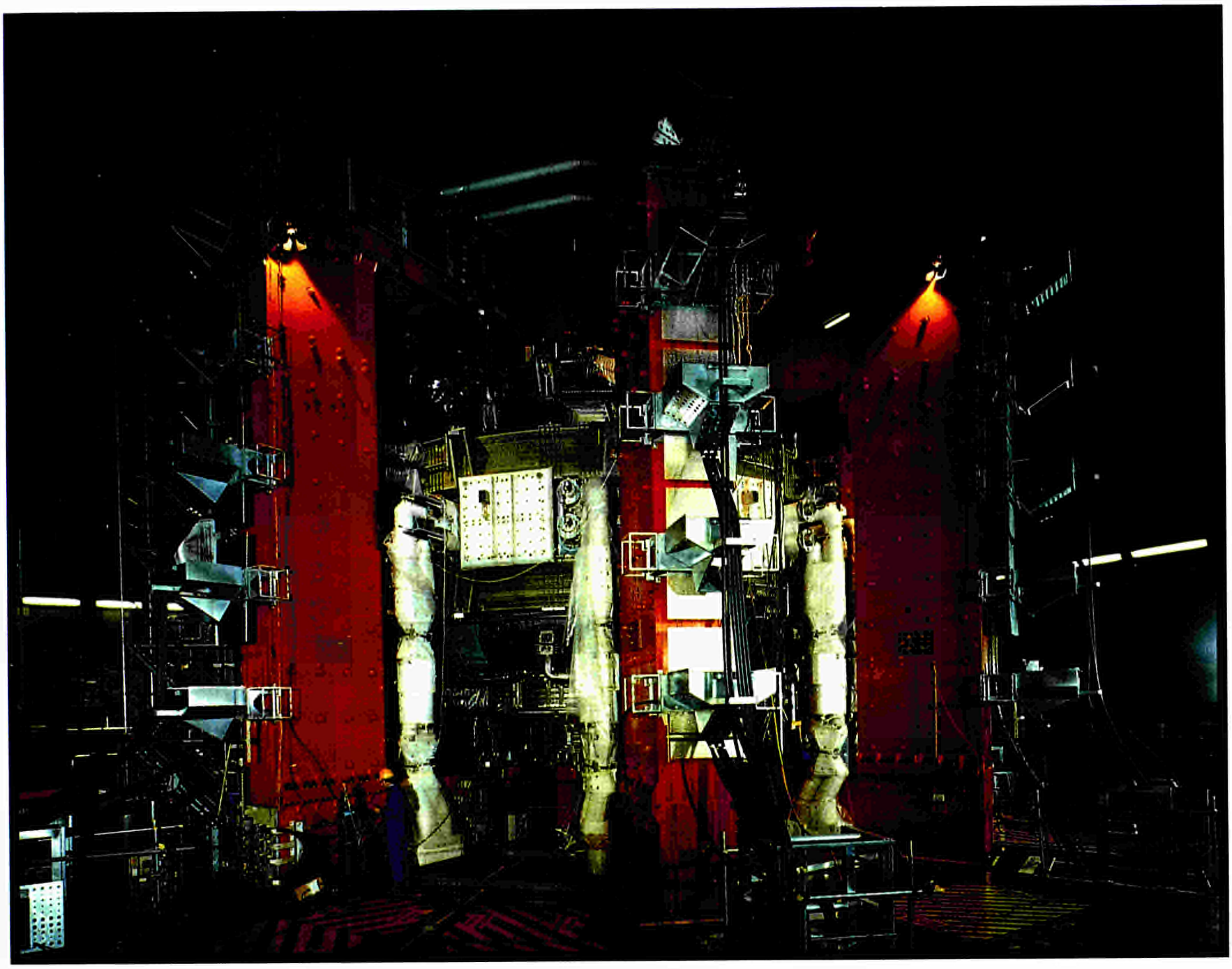


Fig.3: The JET experimental apparatus photographed in May 1983

minutes, with each one lasting up to 60s. The plasma is enclosed within the doughnut shaped vacuum vessel which has a major radius of 2.96m and a D-shaped cross-section of 4.2m by 2.5m. The amount of gas introduced into the vessel for an experimental pulse amounts to less than one tenth of a gramme.

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

The first plasma pulse was achieved on 25 June 1983 with a plasma current of 17000A lasting for about one tenth of a second. The JET Tokamak is shown in Fig.3 just prior to the start of operation in June 1983. This first phase of operation was carried out using only the large plasma current to heat the gas. In 1985, the first additional heating system, employing radio-frequency heating, came into operation and during 1991 reached 22MW of power into the plasma. The neutral beam heating system was brought into operation in 1986, and exceeded its design capability in 1988, with 21.6MW of power injected into the torus.

Experiments have been carried out mainly using hydrogen or deuterium plasmas, although during 1991, experiments were performed in helium-3 and helium-4 and a preliminary experiment was performed using 10% tritium in deuterium. 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 produce significant heating of the plasma. During this phase, the machine structure will become radioactive to the extent that any repairs and maintenance would have to be carried out using remote handling systems.

Heating

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

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

Two main additional heating methods are in general use:

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

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

The Community Fusion Research Programme

All fusion research in Europe is integrated into one *single* Community Programme. Council Decision of 19 December 1991 (OJ No. L 375 of 31 December 1991) defines the long-term aim of the 1990-94 Fusion Programme, embracing all activities undertaken by the Member States (plus Sweden and Switzerland) in the field of controlled thermonuclear fusion by magnetic confinement, as the 'joint creation of safe, environmentally sound prototype reactors'.

A step-wise strategy towards a prototype commercial reactor is envisaged involving a Next Step Experimental Reactor, after JET. The engineering design of such a device is starting in the frame of the quadripartite ITER-EDA (International Thermonuclear Experimental Reactor - Engineering Design Activities) Agreement signed in July 1992; the ITER management structure was also established and the ITER Director (Dr P. H. Rebut) was appointed. The ITER-EDA, to be conducted by the four ITER partners (Euratom, Japan, the Russian Federation and the USA) under the auspices of the IAEA (International Atomic Energy Agency), is expected to last six years and the construction could start in 1998. The design is carried out by a Joint Central Team (JCT) located in three internationally staffed co-centres in San Diego (USA), Naka (Japan) and Garching (EC). The overall objective of ITER is to demonstrate the scientific and technological feasibility of fusion energy for peaceful purposes. A staged approach to ITER operation was agreed, which foresees:

- a basic operation phase for controlled ignited burn of D-T plasmas (1000s inductive pulse length, and ITER design compatible with non-inductive current drive), and functional tests of blanket modules;
- an extended performance phase for tests with higher fluence (target: 1MW/m^2) and the incorporation, if appropriate, of a breeding blanket.

The Next Step should provide the basic data for the engineering of a demonstration fusion reactor (DEMO) capable of producing significant amounts of electricity while taking due account of environmental constraints.

The first priority objective of the Programme is 'to provide the scientific and technological base, to establish the environmental and safety criteria and to prepare industry for the construction of a Next Step device'. For this purpose, a large fraction of the activities, including those on JET and within the Associated Laboratories, are in support of the Next Step. This is also the reason that, together with the Programme Decision, the Council adopted a Decision on a prolongation of the JET Joint Undertaking up to the end of 1996 in order to establish reliable methods of plasma purity control in conditions relevant to the Next Step.

The scientific and technical achievements of the Community Fusion Programme place Europe in the forefront of world fusion research. Following the most successful preliminary tritium experiments on JET in November 1991, constituting an important step forward in fusion research, the machine entered in February a major shutdown expected to be concluded by the end of 1993: substantial modifications were introduced in order to prepare for the (Next Step oriented) 'Divertor Characterisation Phase'. In the Associated Laboratories, new devices became operational: two reversed-field pinches (RFX, the largest in the world, Padova, Italy and EXTRAO-T2 Stockholm, Sweden) early in 1992, and a tokamak (TCV at Lausanne, Switzerland) for the study of plasmas with variable configuration. Operation on ASDEX-Upgrade (Garching, Germany) was interrupted during short periods for new installations. One highlight on the physics side was the progress towards long-pulse operation: with the assistance of non-inductive current drive, it was possible to extend the plasma current for over one minute in JET and TORE-SUPRA (Cadarache, France). The NET Team at Garching pursued its Next Step related activities, and the NET Agreement was modified to take account of Euratom's involvement in the ITER-EDA and to perform longer-term technical developments. In the Joint Research Centre (JRC) (Ispra, Italy), fusion technology activities (mainly safe and advanced materials) were pursued and the commissioning of the tritium handling laboratory (ETHEL at Ispra) started. Finally, in its Communication on the Evaluation of the 2nd Framework Programme (SEC(92) 675 final of 22 April 1992), the Commission noted that the objectives of the Fusion Programme (1988-March 1992) had been reached and that 'the Community is in good position to play an outstanding role in the engineering design of the Next Step'.

The Commission of the European Communities is responsible for the implementation of the Fusion Programme. It is assisted in this task by the Consultative Committee for the Fusion Programme, composed of national representatives. The implementation of the programme is made principally through shared-cost research and technological development contracts in the framework of Contracts of Association with organisations in, or with, Member States (and Sweden and Switzerland); the JET Joint Undertaking; NET and ITER Agreements covering the Next Step activities; shared-cost contracts in the countries having no Associations, and in industry. The Community's JRC, through its own programme, conducts research on specific areas in close coordination with the Fusion Programme.

The Community approach has led to an extensive collaboration between the fusion laboratories. For example, most Associations undertake work for other Associations. The Associations are partners in JET, NET and ITER and carry out work for them through various 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 fully associated with the Programme and enjoy the same rights and responsibilities as Member States. The leading position of the Community Fusion Programme has also made Europe an attractive partner for international collaboration. Apart from the most far-reaching collaboration illustrated by the ITER Project, bilateral Framework Agreements have now been concluded with Japan, USA and Canada. A similar one is under discussion with the Federation of Russian Republics, and contacts have been established with the Republic of Ukraine. There are also eight specific Agreements in the frame of the International Energy Agency, including the cooperation among the three large tokamak facilities (JET in Europe, JT-60 in Japan and TFTR in the USA).

Currently, expenditure on fusion research through the Community is ~200 MioECU per annum. When funding by national administrations and other national bodies is taken into account, the expenditure on fusion from all sources in Europe totals ~450 MioECU per annum. About 1750 professional scientists and engineers are currently engaged in fusion research in Europe. Following the proposal by the Commission for a supplementary financing of the 3rd Framework Programme (OJ No. C. 255 of 1 September 1992), the Council reached, on 31 December 1992, a common orientation regarding a supplementary financing of the Fusion Programme amounting to 110 MioECU in addition to the 458 MioECU already allocated to the current Fusion Programme period (1990-94).

Finally in the Working Document by the Commission (COM (92) 406 final of 9 October 1992) concerning the 4th Framework Programme (1994 to 1998), a declared immediate objective of the

Community Fusion Programme is 'to complete the engineering design of the Next Step after JET in the ITER frame, with supporting R & D in physics and technology'. The participation of European Industry should be fostered, and early qualification of a European construction site for the Next Step will be a priority.

Large International Tokamaks

Now that the ITER Engineering Design Activity (EDA) has started, achievements in tokamak research and, particularly, for the largest tokamaks (Fig.4), have become even more relevant. Table 2 sets out an overview of the large tokamaks, including their main parameters and starting dates. Considerable progress has been made by these tokamaks throughout the world, and these are detailed below.

Peak Performance

The highest peak performance, measured by the triple product of ion density, energy confinement time and central ion temperature ($n_D.\tau_E.T_i$) is still that obtained in JET. However, considerable progress has been made in other devices, particularly in JT-60U and DIII-D. Peak values achieved are set out in Table 3 for these largest tokamaks.

The duration of the high performance phase in these different machines depends on various mechanisms. In JET and TFTR, the wall loading possibly together with certain instabilities related to the high plasma pressure limit the good confinement period. In JT-60U, the high performance appears to be limited by fast relaxations due to the high pressure only. However, wall loading is likely to become a major issue in the next generation of machines.

Table 2: Large Tokamaks operating around the World

Machine	Country	Minor radius a(m)	Elongation κ	Major radius R(m)	Plasma current I(MA)	Toroidal field B(T)	Input power P(MW)	Start Date
JET	EC	1.20	1.8	2.96	7.0	3.5	36	1983
JT-60U	Japan	0.85	1.6	3.2	4.0	4.2	40	1991
TFTR	USA	0.85	1.0	2.50	3	5.2	32	1982
TORE-SUPRA	France	0.80	1.0	2.4	2.0	4.2	22	1988
T-15	CIS	0.70	1.0	2.4	2.0	4.0	-	1989
DIII-D	USA	0.67	2.5	1.67	3.0	2.1	22	1986
ASDEX-U	Germany	0.5	1.6	1.65	(1.6)	3.9	(15)	1991
FT-U	Italy	0.31	1.0	0.92	1.2	7.5	-	1988

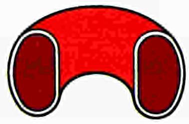
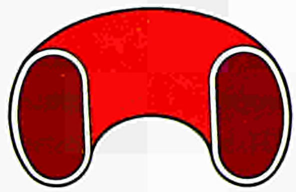
		TFTR	JET	ITER
				
Minor radius	a	0.85m	1.25m	2.8m
Major radius	R	2.5m	2.96m	7.75m
Elongation	κ	1.0	1.8	1.6
Toroidal Field	B	5.2T	3.45T	6.0T
Input Power	P	32MW	36MW	30-200MW
Fusion factor	Q_{DT}	0.25	1.1	30 - Ignition
Plasma current	I	3MA	7MA	25MA

Fig.4: Operating parameters of three large tokamak designs

Advanced Divertor Concepts

It is now clear that a divertor is likely to provide a solution to the problem of impurity production and exhaust, on route to a tokamak reactor. If the target tiles in a divertor receive the full power of an ignited reactor, the power loading would exceed 40 MWm^{-2}, well in excess of acceptable levels of <10 MWm^{-2} (compatible with tile erosion rate and plasma parameters in a reactor). Several forms of advanced divertors are emerging, generally involving closed divertors with large active cooled areas. This then allows for impurity retention as well as a high divertor density, so that most power entering the divertor can be radiated before it hits the target plates and so can be absorbed over a much larger area. In JET, future divertor plasmas heated with 22 MW could be thermally stable, maintained at high density with more than 90% of the power radiated.

DIII-D has obtained promising results with a closed, electrically biased ring divertor at high density. A cryopump will be installed in the near future to allow for 'steady state' operation. TORE-SUPRA in France has demonstrated that an ergodic divertor can efficiently radiate incoming power and retain impurities.

Progress in Technology and Plasma Control

Reliable operation at high current without disruptions has made considerable progress. The highest plasma current of 7 MA has been reached in JET with 28 MW plasma heating for a duration of 8s. MHD activity is carefully avoided by programming the plasma cross-section during the current rise to avoid dangerous rational safety-factors at the plasma boundary. In several cases (TORE-SUPRA and JET), the plasma inductance has been controlled using Lower Hybrid

Table 3: Fusion Products in Large Tokamaks

	JET	JT-60U	TFTR	DIII-D
Electron Temperature				
T_e(keV)	11	12	12	6
Ion Temperature				
T (keV)	18	38	30	7
Duration (s)	1.5	0.8	0.5	0.5
Fusion product				
$n_i T_i \tau_E$ ($\times 10^{20} m^{-3}$keVs)	>9	4.4	3	2

Current Drive (LHCD). DIII-D has compensated the errors in the magnetic fields to allow for low density operation.

Large machines, such as JT-60U and JET, have developed disruption control tools which detect a disruption precursor and then act on plasma parameters to ameliorate further development of the instability. TORE SUPRA (France) and Triam-IM (Japan) have both operated reliably at nominal performance with superconducting toroidal magnetic field coils and have made progress towards steady state operation.

Future Tritium Experiments

The first successful tritium experiment was carried out in JET in 1991. Up to 10% tritium was introduced, which produced a peak fusion power of about 1.7 Megawatts in a pulse lasting for 2 seconds, giving a total energy release of about 2 Megajoules. This was a major step forward in the development of fusion as a new energy source. The next tritium experiments will be carried out in TFTR during the period September 1993 to September 1994. The main aim of the TFTR operation is to produce 5-10 MW of fusion power, and has the further objective of investigating α-particle physics and detecting initial evidence of α-particle heating. Plasmas of 3 MA at 5.2 T, in the so-called supershot regime, will be heated by up to 35 MW of neutral beam injection of 50% deuterium and 50% tritium neutrals and by up to 12.5 MW ICRF heating. The technical aspects of tritium beam operation, tritium retention and handling, and newly developed diagnostics will be evaluated as has been undertaken successfully in the first tritium experiments at JET.

In addition, JET has an option in its 1994 programme to undertake a further preliminary tritium experiment in its new divertor configuration to produce 10 MW of fusion power extended over a 1 second flat-top with the fusion quality factor, Q, in the range 0.7 to 1 (ie 10 MW of fusion power produced by 10 to 14 MW of input power). Further full scale tritium experiments are planned in JET to conclude the project, which is presently foreseen to end in 1996.


HALT
CONT
Ackn Msg
PVC
CC
CB
CA
CD
CE
CF
J1
J2
J3
J4
K1
K2
K3
B1
A1
A2
A3
A3B
A4
A5
Main Menu
Cmnd Ctrl
Show Data
AVC DRCT
MOTION
Free J_St
J_St OFF
Rltv Move
Absl Move
X
Y
R

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 during the remaining operating period of 1992 and the developments and improvements implemented during the major shutdown. In addition, it includes outline planning for the continuation of the shutdown throughout 1993;
- Machine operation during the operating period is summarised in the second section;
- The third section sets out the main details of continuing technical developments on equipment for future installation.

Technical Achievements

In February, JET completed its planned phase of Full Power Optimization Studies in the machine's original configuration. The machine then entered a major shutdown, which is the longest and most complex shutdown yet undertaken by JET and will lead to a totally transformed interior of the JET vessel. This is expected to be completed by the end of 1993. This shutdown was planned to change a Toroidal Field (TF) coil in Octant No:4 and then to install the components of the pumped divertor and its associated system modifications. These include:

- lower divertor structure with Mark I carbon fibre composite (CFC) target plates (inertially-cooled);
- four internal divertor coils and associated power supplies;
- pumping chamber and cryopump;
- poloidal limiters;
- new ICRF antennae and modified protections;
- full lower hybrid current drive (LHCD) system with modified launcher, grill and protections;
- divertor diagnostics;
- disruption control system using internal saddle coils.

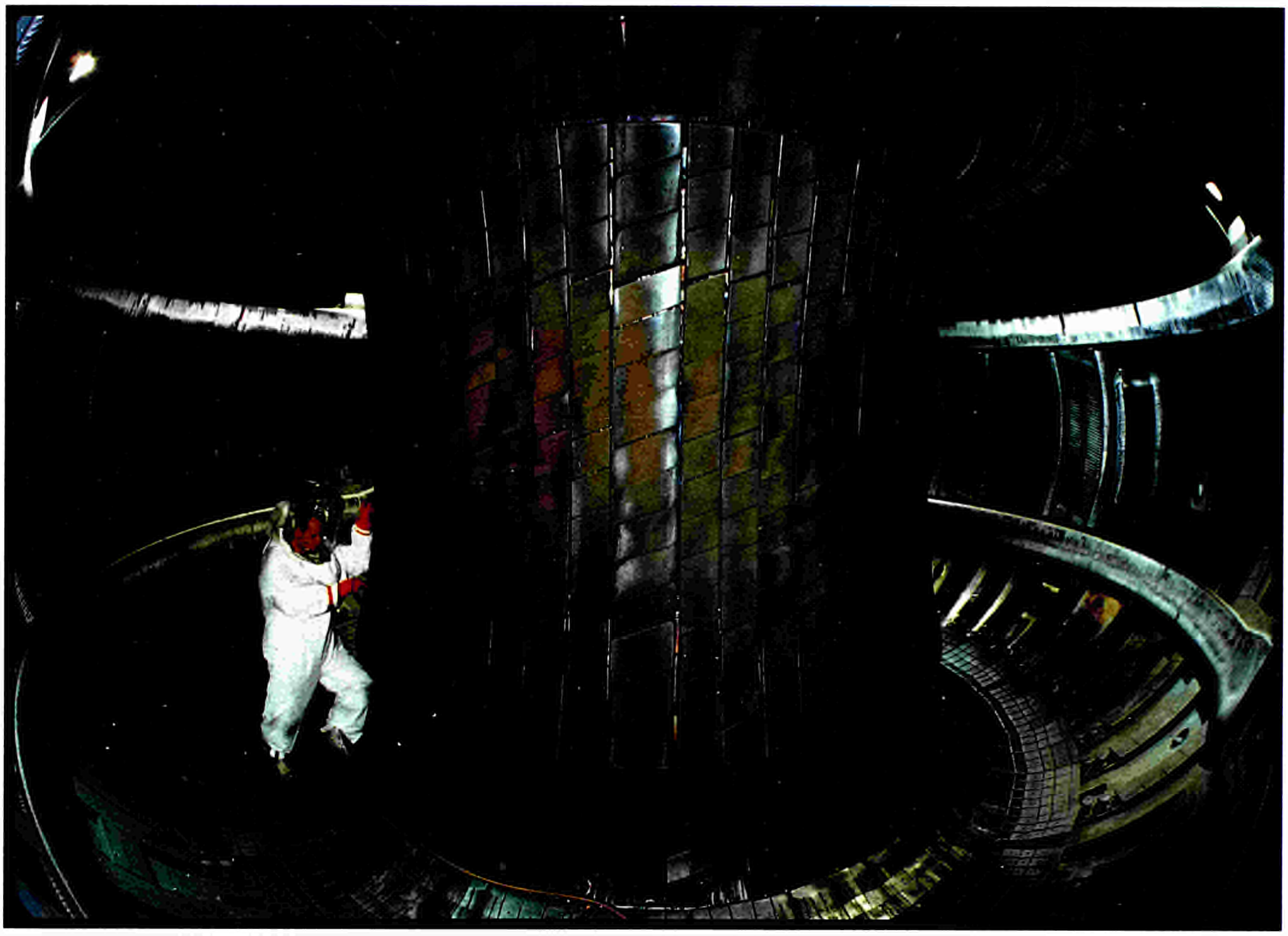


Fig. 5: The interior of the vacuum vessel at the start of the shutdown

The shutdown is being undertaken in three major stages:

- Stage 1 involved the removal of components, replacement of a toroidal field coil, and the preparation of the vacuum vessel for installation of the divertor coils;
- Stage 2 involved the assembly of the four divertor coils and casings inside the vacuum vessel;
- Stage 3 involves the installation of the Mark I intertially-cooled divertor, cryopump, RF antennae, limiters and saddle coils.

The most critical part of the work is that within the vacuum vessel itself. Here, working within a confined space, coupled with the high quality and high accuracy requirements, and the safety restrictions when working in a beryllium, tritium and a radiation environment, means that all the work must be optimized. Each work package must be studied, recorded, practised, planned and organised in minute detail. The components and jigs must be well designed and the tools well tried, effective and easy to use.

The following sections summarise the main technical achievements during 1992.

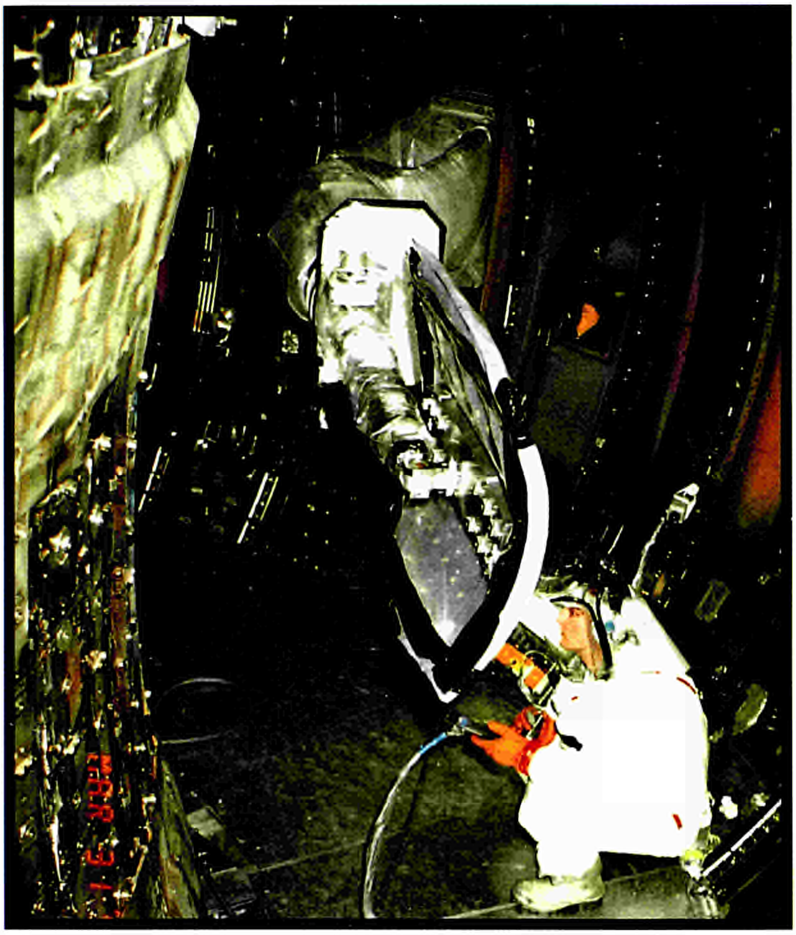


Fig.6: The Remote Handling Boom being used to remove large components from the vacuum vessel

Vessel Strip-Out and Decontamination

At the start of the shutdown, in-vessel activities were influenced by two factors: the tritium-in-air and the beryllium-in-air concentrations. Initially, the tritium-in-air concentration was 86Bq/m^3. This fell to ~10Bq/m^3 at the start of the in-vessel cleaning campaign, and subsequently to <1Bq/m^3. Beryllium-in-air concentrations were strongly dependent upon type of work. Concentrations varied from ~30mg/m^3 after initial vessel opening to below detection level after the vessel wash. Therefore, full airline suits were required only for beryllium, and not for tritium, and were needed for all in-vessel work from March to June 1992.

The state of the interior of the vessel at the start of the shutdown is shown in Fig.5. In the pumped divertor arrangement, only a small number of the existing in-vessel components will be re-used. As a consequence, the first task was the careful removal of all protection tiles, beryllium evaporators, Lower Hybrid wave launcher, Radio Frequency antennae, upper and lower belt limiters and dump plates as well as many in-vessel diagnostic systems (see Fig.6). In all, about 30 tonnes of components were removed from the vacuum vessel.

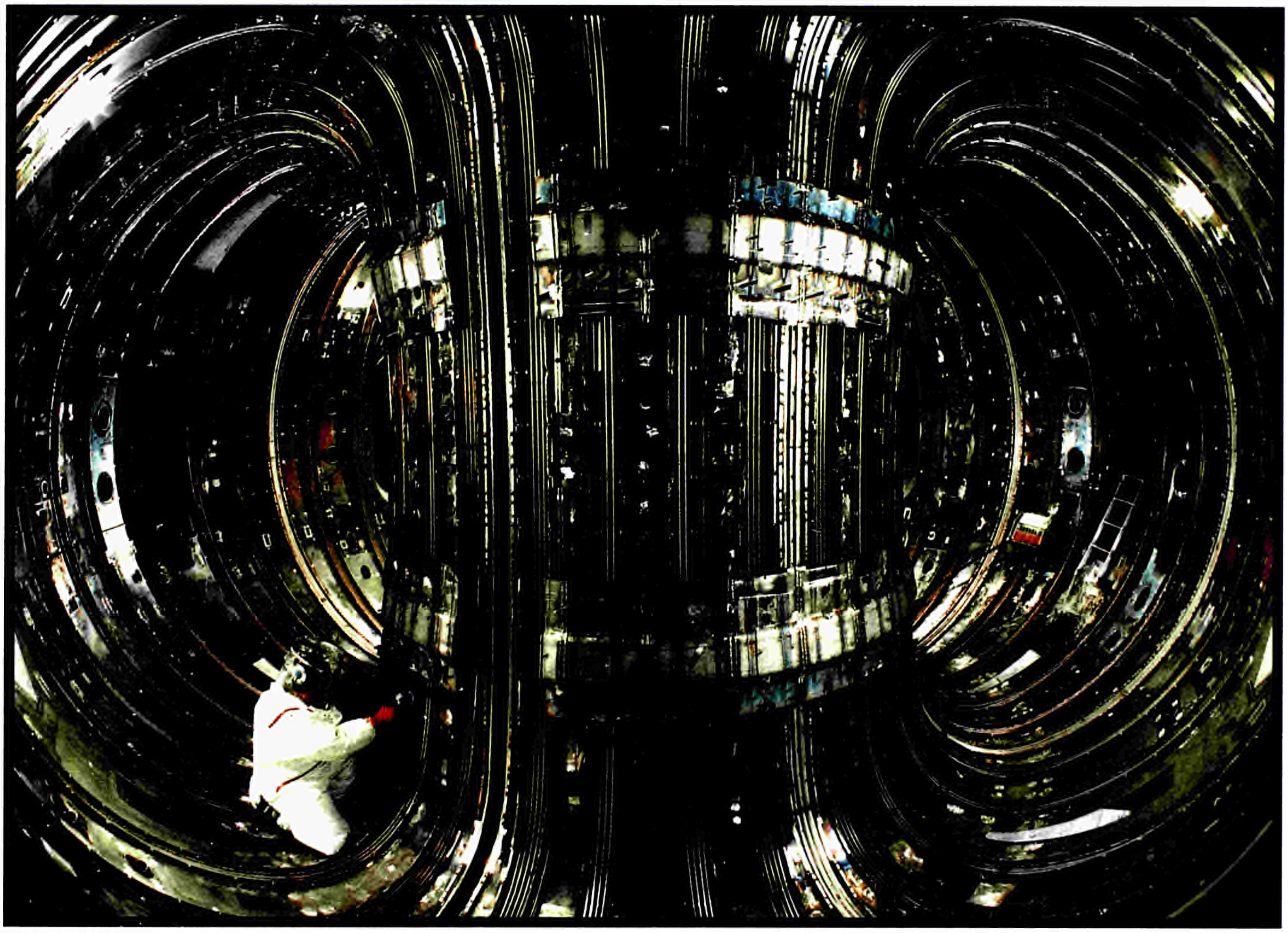


Fig.7: The interior of the vessel following strip-out of components

After many years of operation, the JET vacuum vessel wall had been covered in layers of carbon, beryllium, and metal from accidental melting of components. These layers also contained tritium from D-D reactions and, in particular, from the recent Preliminary Tritium Experiment (PTE). The status of the interior of the vessel at that time

Fig.8: Cleaning the vacuum vessel walls

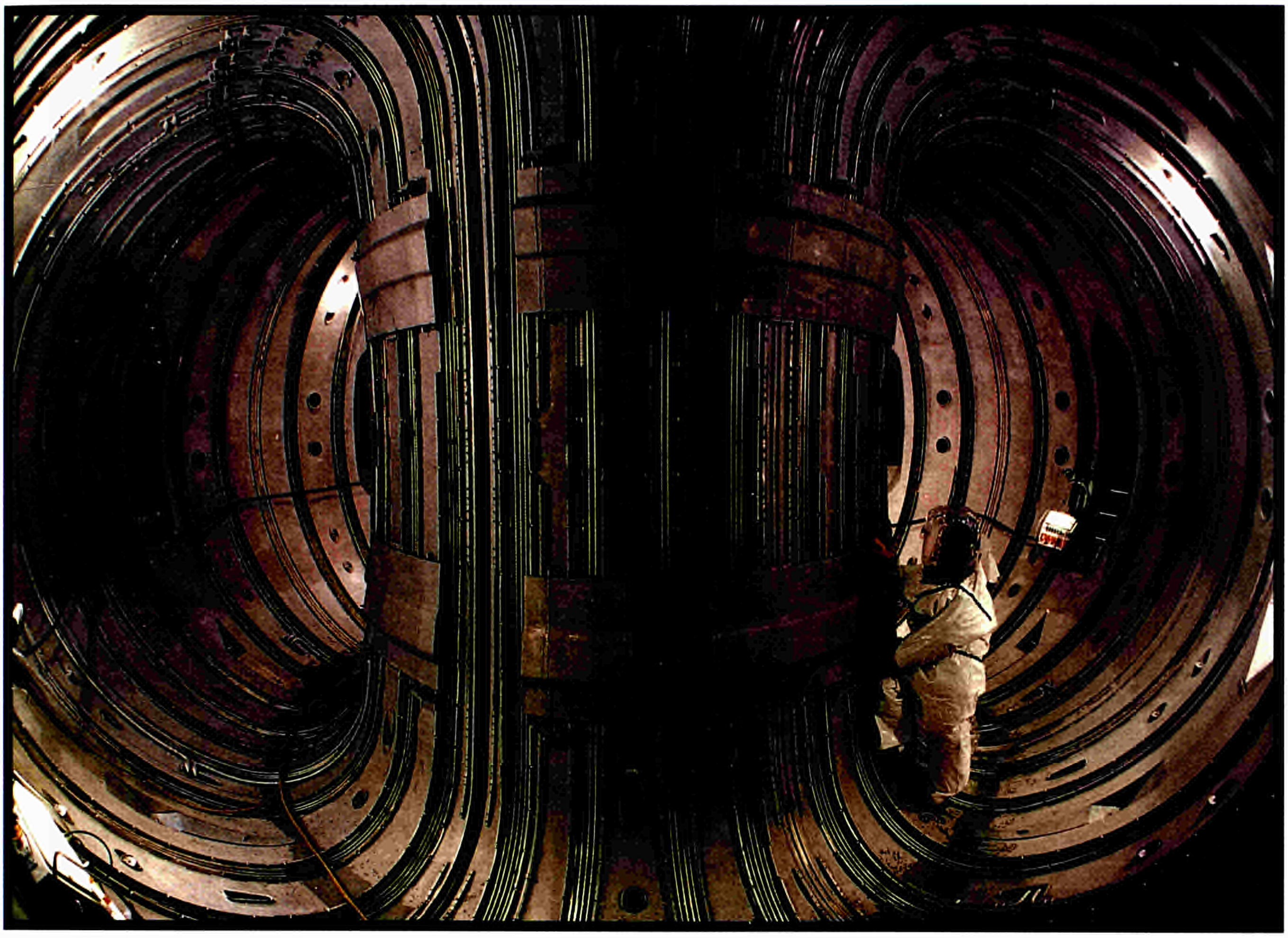


Fig.9: Interior of vacuum vessel after decontamination. The sections of ring removed are where one joint is prepared for octant removal

is shown in Fig.7. These layers needed to be removed before any new attachments could be welded onto the vessel wall. It was clear from the outset that to maintain the proposed timetable, it was necessary to clean the vessel of beryllium and tritium to a level at which it was no longer necessary for in-vessel workers to wear full air-suits.

The cleaning method entailed water blasting the vessel at high pressure with boron carbide abrasive grit (Fig.8). This proved highly effective, fast and had the advantage that any residual material was not expected to be detrimental to operations. The cleaning was accomplished in three weeks and resulted in a vessel (Fig.9) in which the airborne beryllium levels were so low or below the limits of detection that in-vessel work could be performed without requiring respiratory protection.

Toroidal Field Coil Exchange

During the first stage of the shutdown, it was intended to replace one faulty toroidal field (TF) coil (No:4.2) in Octant No:4. As reported in the 1991 Annual Report, a fault had been discovered in Coil No:4.2 in 1990, but, as the fault was of relatively high resistance, operation continued through 1990 and 1991 using the maximum toroidal field

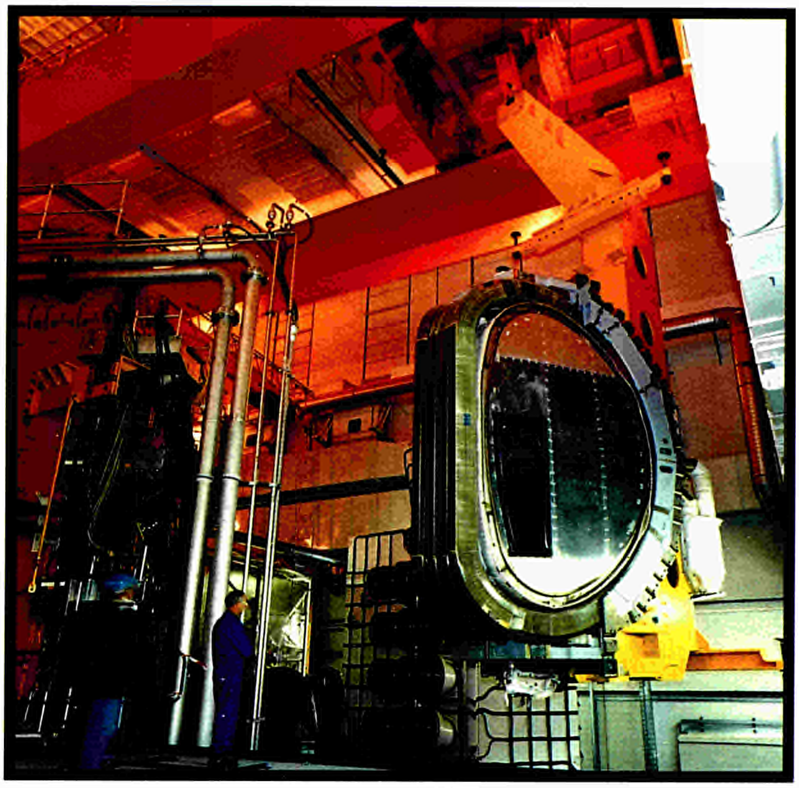


Fig.10: The spare coil fitted to Octant No: 4 ready for replacement in the vessel

Power Supplies

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

An agreement with the Generating Boards 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.

in only a limited number of plasma discharges. The changing of a TF coil required a significant amount of in-vessel work. This involved cutting and removing sections of upper and lower inner restraint rings, cutting and removing a number of horizontal and vertical ports, and cutting joints between adjacent octants. Coil No:4.2 was replaced by a spare and the change was completed by June. Figure10 shows the spare coil for ready for replacement in the vessel.

When the machine was re-assembled after the replacement, the impedance of all the 32 coils was re-checked and a further small fault in Coil No: 4.3 became apparent. This fault was far less severe than the fault in Coil No:4.2. Therefore, it was unlikely to have operational consequences during the next few years. However, in view of the difficuity of changing a TF coil once the divertor coils were installed, it was decided that it would be prudent to replace Coil No:4.3, while the opportunity still existed. The change was successfully completed by August 1992. The consequential delay in the shutdown was limited to eight weeks, by intensive working and by drawing on experience gained in replacing previous coils.

Installation of Divertor Coils

Figure 11 shows a schematic diagram of the positions of the divertor coils relative to the vessel and other coils. Before the divertor coils could be built, a number of components needed to be installed. These included the divertor coil supports which had to be positioned to a very high accuracy (±1mm) and to do this, a previously designed

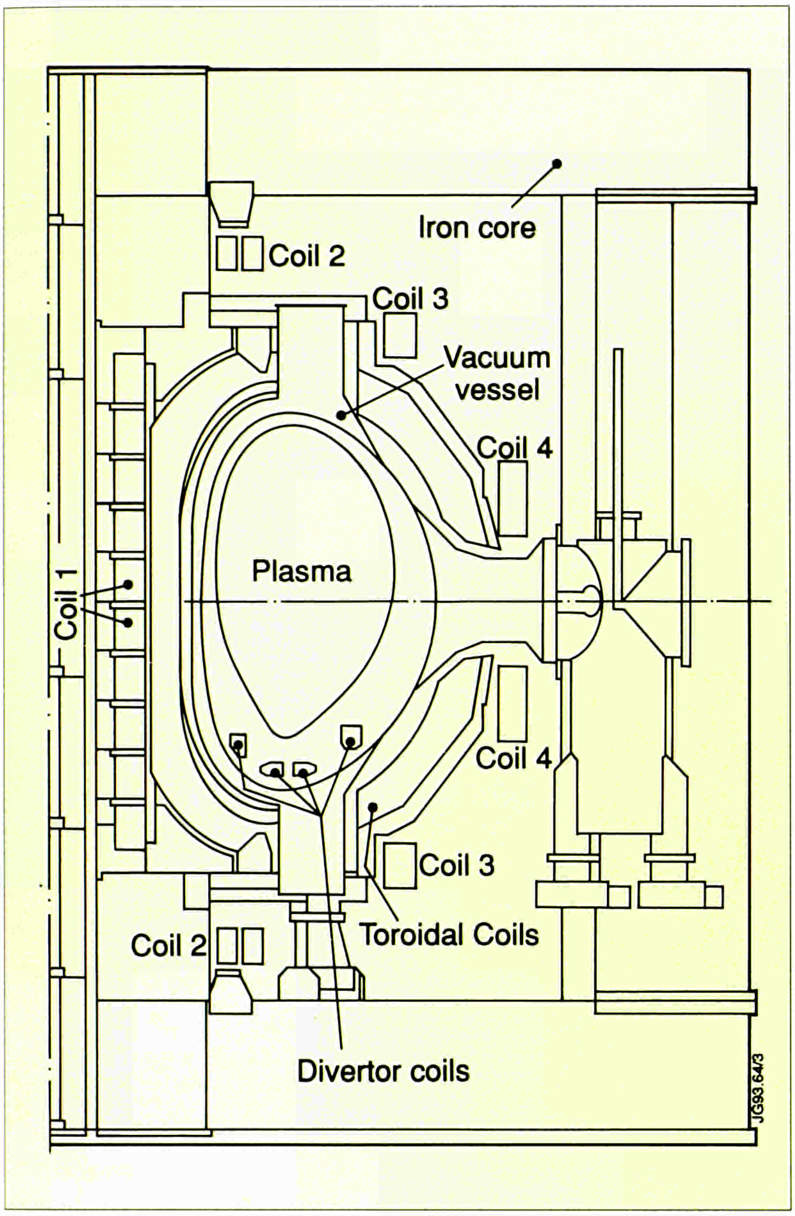


Fig.11: Cross-section of JET showing toroidal, poloidal and divertor coils

and manufactured special master survey ring was installed and used (Fig.12). The variation in profile and position of the vacuum vessel also meant that each block had to be profile machined to suit. The blocks were carefully welded to the wall to ensure alignment.

The copper conductor bars of the divertor coils were pre-formed into half or third turns at the manufacturer's factory and then brazed together to form a coil inside the vacuum vessel. The coil will then be assembled in its inconel case and impregnated with epoxy resin.

Fabrication started at the end of October 1992 and was re-scheduled for completion by the end of April 1993. The work comprised fabrication in situ (using the prefabricated sections) of divertor Coil Casing Nos:1, 2 and 4 followed by storage of the lower part of the casings below floor level and the lids near the vessel ceiling. Fabrication and storage of Case No:3 at this stage would have limited the handling of prefabricated conductor bar sections to such

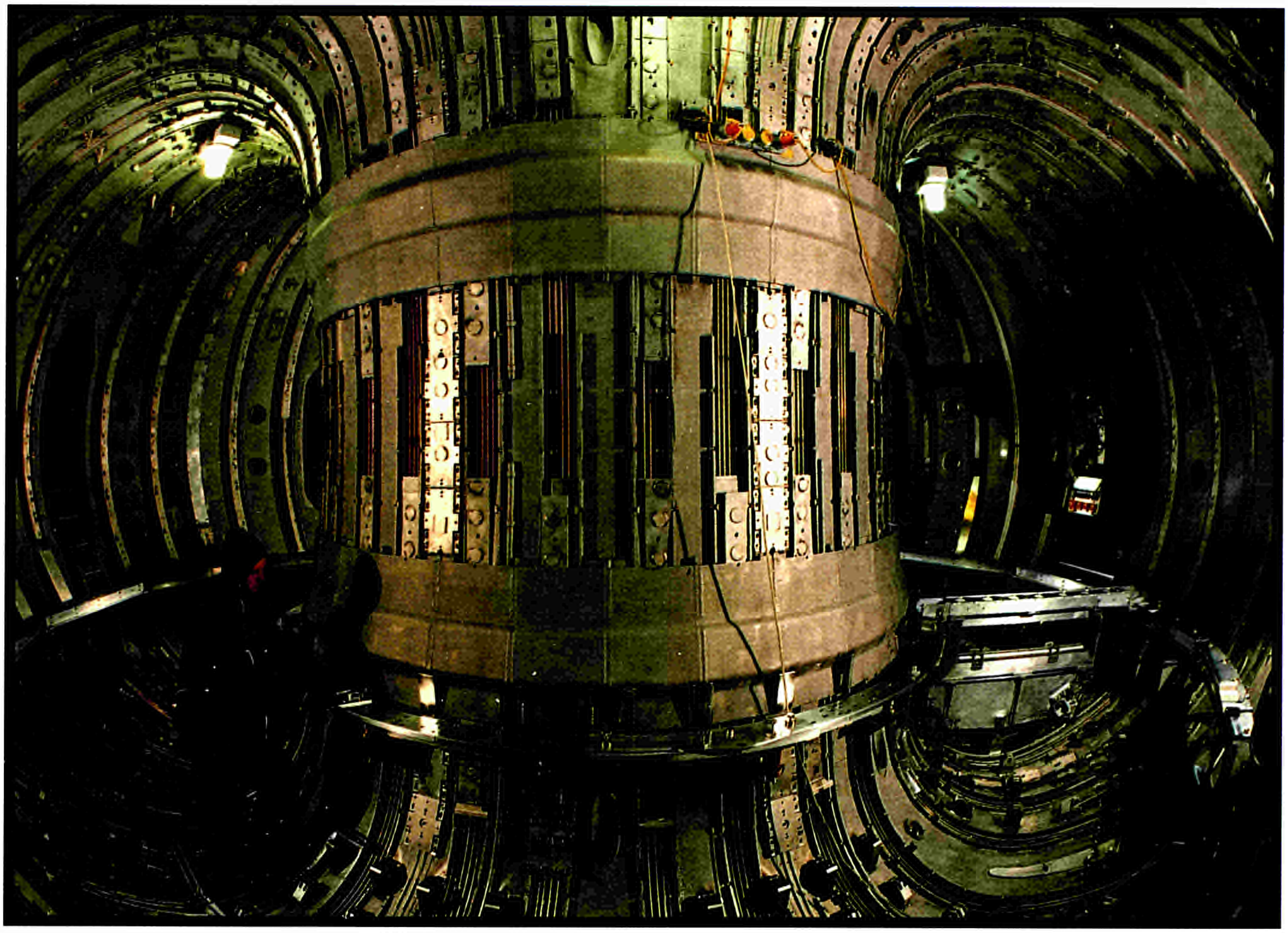


Fig.12: All divertor coil supports are welded in a position defined by the two survey and positioning rings shown

an extent that sections would have had to be cut shorter and would have involved an increased number of brazed joints. Therefore, it was decided to fabricate Case No:3 after completion of brazing. After fabrication of the casings, the coils were formed by brazing prefabricated conductor bar sectors inside the vessel. The brazes were checked by radiography. Following brazing, the coils were wrapped with ground insulation and then encased (see Fig.13). The interspaces were filled with epoxy, and subsequently thermally cured. After completing Coil Nos:1 and 4, Coil Nos:2 and 3 will be fabricated in parallel and Coil Çase No:3 will be built in the vessel following the encasing of Coil No:2. During the brazing campaign, two assembly shifts alternated with two radiography shifts so that work continued for 24 hours per day.

Assembly work started in the vessel in November with Coils No:D1 and No:D4. Some difficulties were encountered in brazing the copper bars in the vessel, which was disappointing since prefabrication tests were excellent. At the end of the year, brazing of Coils No:D1 and No:D4 was half completed, but was still on schedule for completion by April 1993.

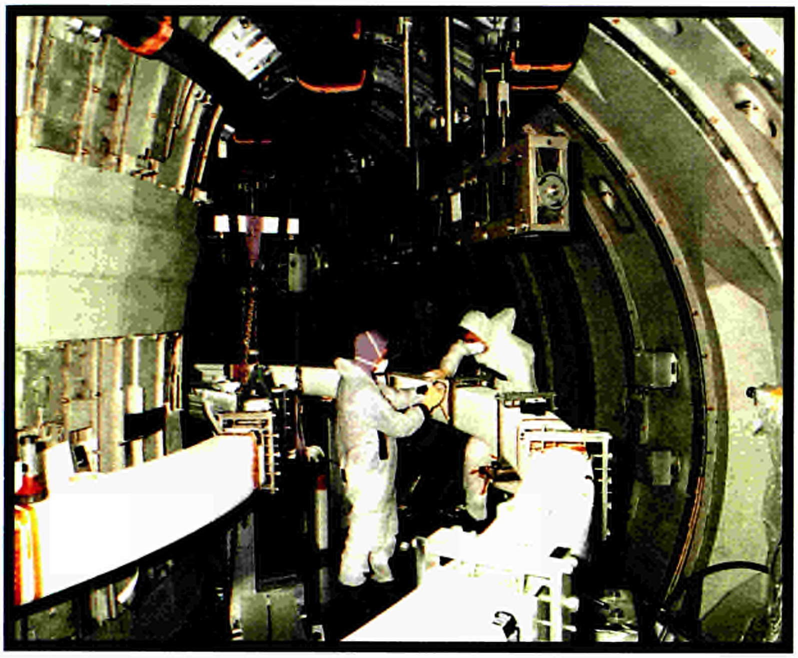


Fig.13: Work on the divertor coils inside the vessel. Above the workers' heads is the motorised lifting beam used during the manufacturing process

Plasma Control

Despite attempts to improve vertical stabilisation, disruptive instabilities frequently lead to loss of vertical position and, consequently, to larger vertical plasma displacements (which can be up to 1m). The associated vertical force acting on the vessel is large at high plasma current and when large shaping currents are applied, such as in single or double-null configurations. The vertical instability produces potentially dangerous forces at in-vessel elements such as protection tiles.

The divertor plasma will be more difficult to stabilise than previous X-point plasmas. Therefore, a new fast radial field amplifier has been installed to provide the required increased performance. The stabilisation principle is similar to that applied previously: the stabilisation uses feedback of the vertical speed of the plasma current centroid, the average amplifier current is maintained at zero by current feedback.

The new system uses direct analogue signal transmission to the plasma position and current control system, independent of other systems. The derivation of the displacement signal is more complex than previously. It includes corrections for current changes in the divertor coils, transmitted from new sensors in the coil busbars, and also a correction due to plasma current changes at a displaced position. The system has been simulated using a simplified model of the plasma and the JET apparatus. In particular, the response on small and large amplitude perturbations was examined. Results and further analysis will be used to prepare the commissioning without and with plasma.

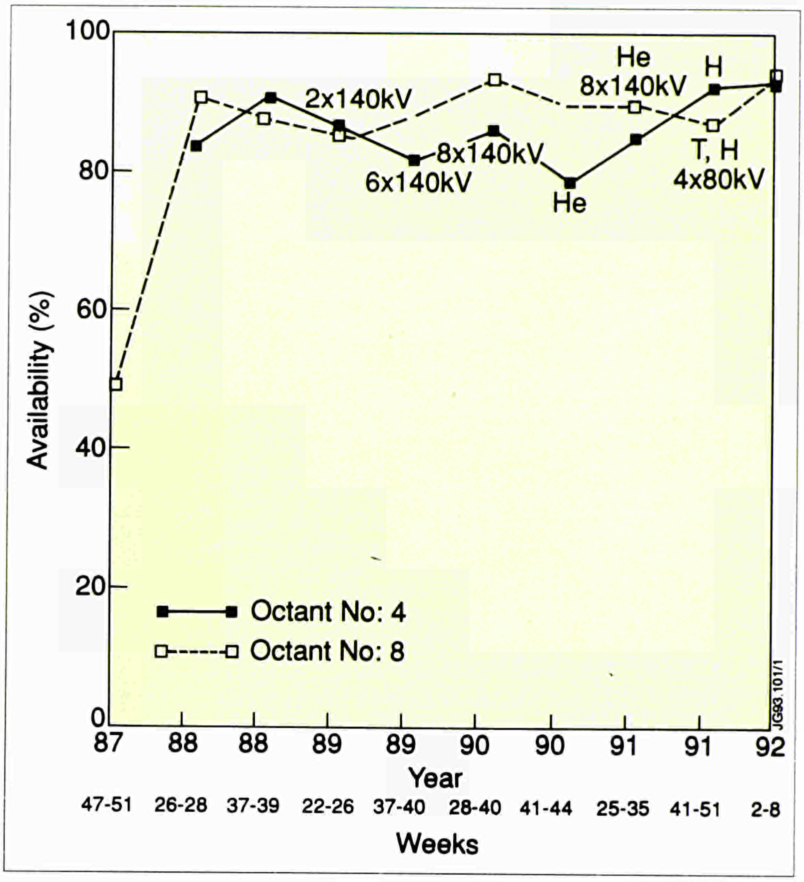


Fig.14: Analysis of neutral beam injector availability

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 1990 one system was substituted with units capable of operating up to 140kV. In addition, this box was also converted to operate with helium (^{3}He and ^{4}He) beams during 1990. 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 up to 10MW of power can be directed.

Neutral Beam Heating System

High power beams from the Octant No:4 and Octant No:8 injectors, using ^{3}He, ^{4}He, H and D, made significant contributions to the overall 1991-92 experimental programme. The range of plasma currents over which injection was performed was extended in 1992, with routine injection at powers of up to 16MW into 7MA plasmas and also into 1.5MA plasmas. 7MA operation was a severe test of the stray-field compensation system and its ability to cancel the substantial stray poloidal field which exists at these high plasma currents. Correct and trouble-free alignment of the neutral beams was maintained successfully throughout the programme. Injection experiments at low plasma currents and toroidal fields down to 1.5MA and 0.9T, respectively, were successfully performed.

Analysis of injector operation over the 1991-92 campaign revealed that high availability and reliability were maintained and in some cases improved upon. The high levels of *reliability* were maintained at over 90% in 1992. Figure 14 shows an analysis of availability for each injector from 1987 to the present. After the first year of operation, availability has been maintained at ~80-90%. The reduction in availability of the Octant No:8 injector at various times reflects its use to bring into operation various new configurations - notably 140kV and helium injection. Subsequent corresponding

Table 4: Neutral Beam Power to JET for Different Species

Beam Species (each box)	Injection Voltage (kV)	Power to JET (MW)	
T	150	11	24
D	80	13	
D	140	7	10
D	80	13	
H	115	3	10
H	70	7	
^{3}He	155	7.5	17.5
^{3}He	85	10	
^{4}He	120	6	18
^{4}He	85	12	

changes to the Octant No:4 injector were incorporated with little or no loss in availability due to experience gained on the first systems.

During the shutdown, the major upgrades and improvements to control and instrumentation subsystems will concentrate on providing simpler and more fail-safe operation for future operation with tritium injection. Experience gained during the preliminary tritium experiment (PTE) proved to be highly valuable in highlighting some of these requirements. An extensive study of injection scenarios was carried out using the various combinations of beam source configurations available. It was decided to equip one injector with eight sources in the 140/160kV configuration and the other with eight x 80kV high-current sources first developed to give increased deuterium power for the PTE. Not only should this configuration result in 20-24 MW for D-T operation, it should also provide very significant power levels in H, D, ^{3}He and ^{4}He. The predicted maximum values of injected power are summarised in Table 4. In all cases, the expected power is in excess of that available during previous campaigns.

Radio Frequency Heating

The ion cyclotron resonance frequency (ICRF) heating system is used for high power centralised heating of the JET plasma and also for Fast Wave Current Drive studies. The wide operating frequency range available (23-57MHz) allows variation in the choice of minority ion species used (H or ^{3}He at present, D in the future D-T phase) and the localised position of the deposited power or driven current.

Radio Frequency Heating

Ion Cyclotron Resonance Frequency (ICRF) heating 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 ICRF heating 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 on antenna located in the vacuum vessel on the outer wall. The eight RF generators produce a maximum output power of 32MW. The net power coupled to the plasma has reached 22.7MW, compared with theoretical limit of 24MW.

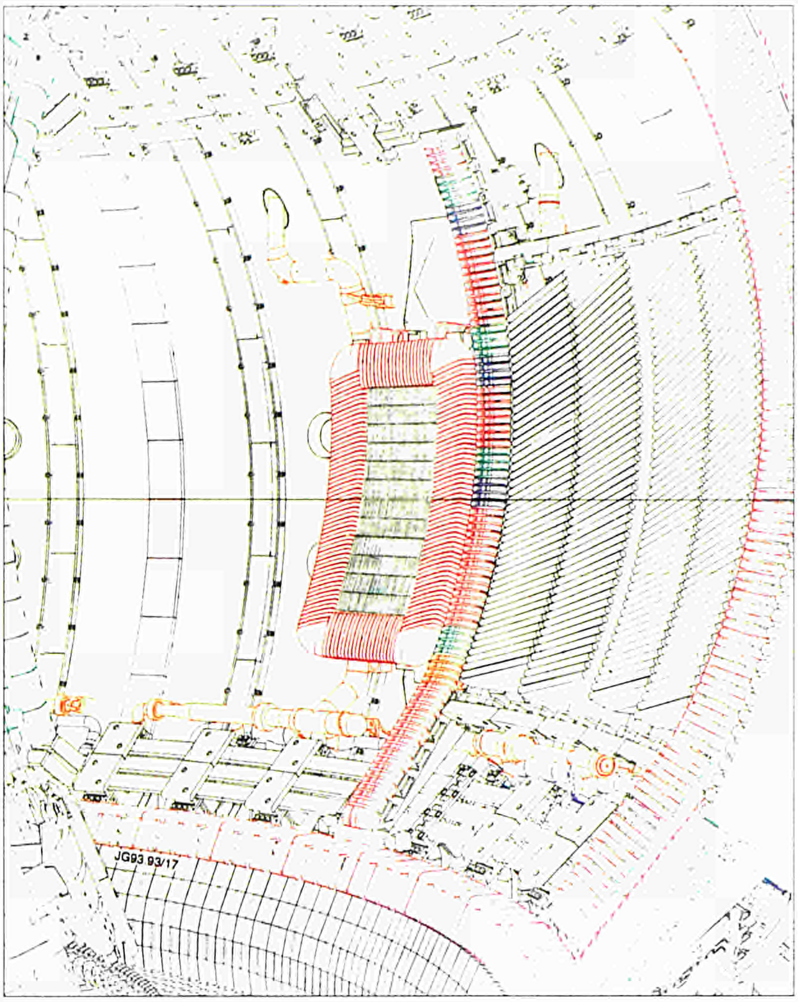


Fig.15: One of the four ICRF heating arrays alongside the LHCD launcher in the divertor configuration of JET

The position is dependent only on the magnetic field and is insensitive to parameters such as density and temperature. The heating system is composed of eight units, each driving the antenna installed 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 maximum design power is 24MW in the plasma (3MW per antenna). However, up to 3.5 MW on one antenna and 22.7MW total coupled power has been achieved. In preliminary experiments, significant effects on plasma behaviour have been achieved by Fast Wave Ion Current Drive.

New ICRF antennae are being installed in JET during the shutdown, designed to take advantage of the new shape of the divertor plasmas and to achieve enhanced coupling. The new antennae (A2 design) are radially deeper and, to obtain the desired radiated spectrum, are toroidally wider (see Fig.15). In addition, to avoid interaction between side protections of these antenna and the edge of the tangential neutral beams, the antennae are being relocated in the torus and grouped into four pairs (see Fig.16). This also allows improved radiated spectra to be obtained from the four conductors

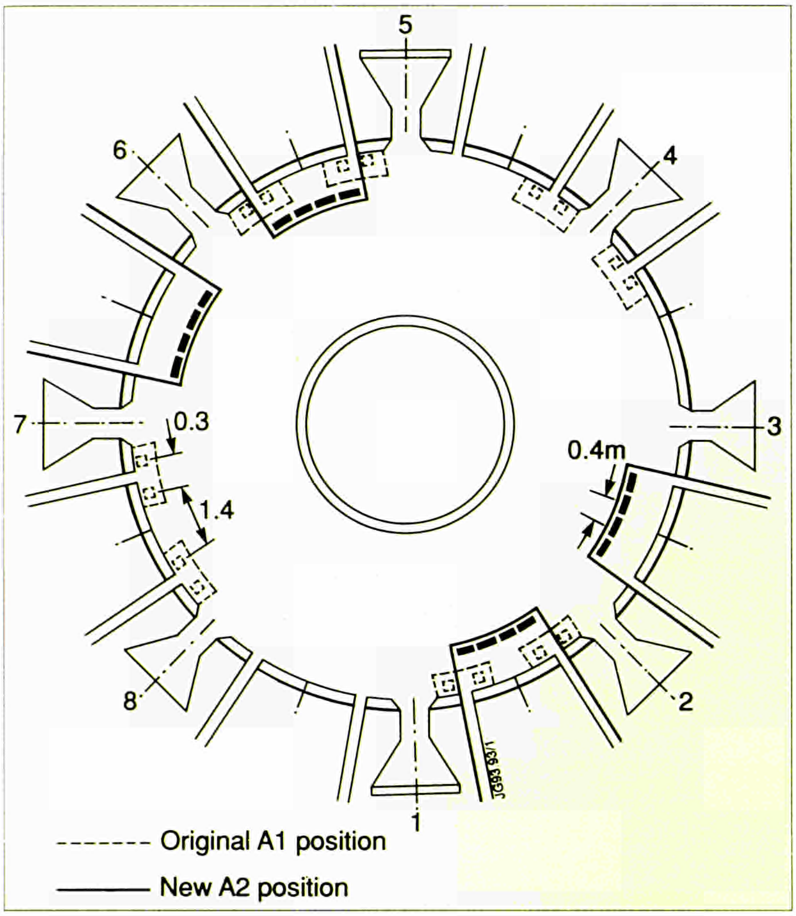


Fig.16: Original ICRF antenna and the new antenna (A2) positions in JET

formed by the 'array' of two adjacent antennae, to give enhanced FWCD performance.

The RF transmission line system design has remained substantially unmodified since its initial installation. About half of the existing system is now being re-routed to connect to the new antenna positions. The generator cooling systems and 33kV supplies have been regrouped into new pairs that correspond to the new antenna configuration. In addition, a new tritium containment secondary gas barrier is being included near to the antenna end of the transmission lines.

Lower Hybrid Current Drive

The final Lower Hybrid Current Drive (LHCD) system (12MW at 3.7GHz) is intended to drive a significant fraction of the current flowing in the plasma, by direct acceleration of the plasma electrons through interaction with lower hybrid waves. This should stabilise sawtooth oscillations, thereby increasing the central electron temperature and improving overall JET performance. This will be the main tool in JET for controlling the plasma current profile. A prototype system consisting of two launching units (one built by CEA Cadarache, France, and the other built by JET) fed by a total klystron power of 4MW was operated during the 1991/92 campaign. Up to

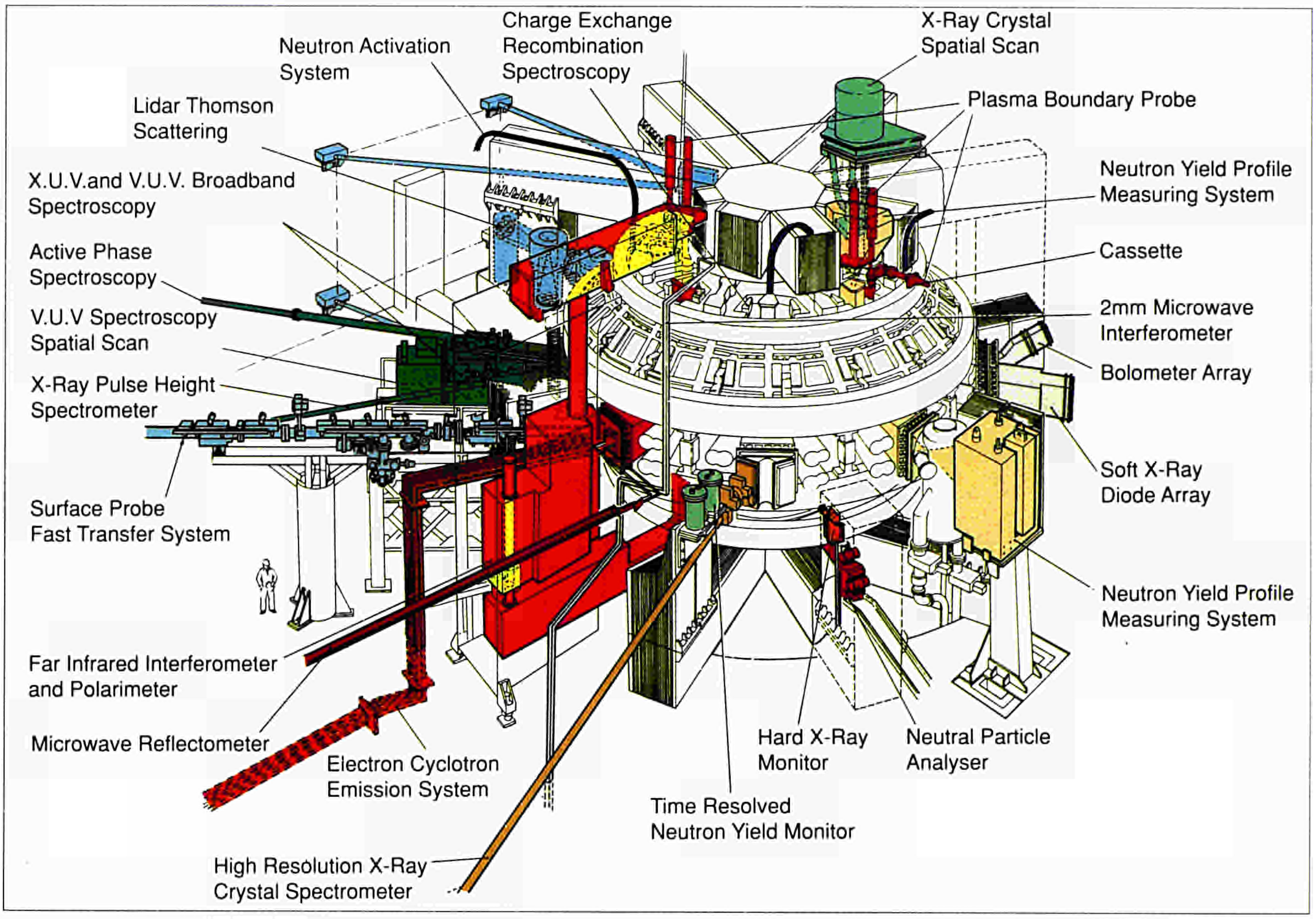


Fig.17: General layout of diagnostics in the JET machine

2.3MW of LHCD was coupled to the plasma, and full current drive was demonstrated in a 2MA low density plasma. Towards the end of the campaign, 1.5 MW of LHCD power was applied during the ramp-up of a 7MA plasma pulse. This altered the current profile, reducing the internal inductance of the plasma. As a result, the transformer flux swing required to establish the 7MA current was reduced by 2V-s, enabling the plasma pulse flat-top to be extended. To follow the plasma boundary, the LHCD launcher was moved back as the plasma current developed using the launcher's real time position control system. The prototype LHCD launcher (LO) has now fulfilled its role in providing engineering, operational and physics experience of LHCD on JET.

Diagnostics

The location of the JET measuring system (or diagnostics) is shown in Fig.17 and their status at the end of 1991 is shown in Table 5. Operational experience has been good and most 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. A number of new systems are in preparation or in the design stage for

Table V
Status of JET Diagnostics Systems, December 1992
Existing Diagnostics

System	Diagnostic	Purpose	Association	Status
KB1	Bolometer array	Time and space resolved total radiated power	IPP Garching	Modified
KC1	Magnetic diagnostics	Plasma current, loop volts, plasma position, shape of flux surface, diamagnetic loop, fast MHD	JET	Upgraded
KE3	Lidar Thomson scattering	T_e and n_e profiles	JET and Stuttgart University	Upgraded
KF1	High energy neutral particle analyser	Ion energy distribution up to 3.5MeV	Purchased from Ioffe St Petersburg	Upgraded
KG1	Multichannel far infrared interferometer	$\int n_e ds$ on six vertical chords and two horizontal chords	CEA Fontenay-aux-Roses	Modified
KG3	Microwave reflectometer	n_e profiles and fluctuations	JET and FOM Rijnhuizen	Modified
KG4	Polarimeter	$\int n_e B_p ds$ on six vertical chords	JET and CEA Fontenay-aux-Roses	Upgraded
KH1	Hard X-ray monitors	Runaway electrons and disruptions	JET	
KH2	X-ray pulse height spectrometer	Monitor of T_e, impurities, LH fast electrons	JET	
KK1	Electron cyclotron emission spatial scan	$T_e(r,t)$ with scan time of a few milliseconds	NPL, UKAEA Culham and JET	Modified
KK2	Electron cyclotron emission fast system	$T_e(r,t)$ on microsecond time scale	FOM Rijnhuizen	
KK3	Electron cyclotron emission heterodyne	$T_e(r,t)$ with high spatial resolution	JET	Upgraded
KL1*	Limiter viewing	Monitor hot spots on limiter, walls, RF antennae, divertor target tiles	JET	Upgraded
KL3	Surface temperature	Surface temperature of target tiles	JET	Upgraded
KM1	2.4MeV neutron spectrometer	Neutron spectra in D-D discharges, ion temperatures and energy distributions	UKAEA Harwell	
KM3	2.4MeV time-of-flight neutron spectrometer		NFR Studsvik	Modified
KM7	Time-resolved neutron yield monitor	Triton burnup studies	JET and UKAEA Harwell	
KN1	Time-resolved neutron yield monitor	Time resolved neutron flux	UKAEA Harwell	
KN2	Neutron activation	Absolute fluxes of neutrons	UKAEA Harwell	Modified
KN3*	Neutron yield profile measuring system	Space and time resolved profile of neutron flux	UKAEA Harwell	Upgraded
KN4	Delayed neutron activation	Absolute fluxes of neutrons	Mol	
KR2	Active phase neutral particle analyser	Ion distribution function, $T_i(r)$	ENEA Frascati	
KS1	Active phase spectroscopy	Impurity behaviour in active conditions	IPP Garching	
KS2*	Spatial scan X-ray crystal spectroscopy	Space and time resolved impurity profiles	IPP Garching	
KS3	H-alpha and visible light monitors	Ionisation rate, Z_{eff}, impurity fluxes from wall and limiter	JET	Upgraded
KS4	Charge exchange recombination spectroscopy (using heating beam)	Fully ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Modified
KS5	Active Balmer α spectroscopy	T_D, N_D and $Z_{eff}(r)$	JET	Modified
KS6*	Bragg rotor X-ray spectrometer	Monitor of low and medium Z impurity radiation	UKAEA Culham	Upgraded
KS7*	Poloidal rotation	Multichannel spectroscopic measurement of poloidal rotation	UKAEA Culham	Modified
KT2*	VUV broadband spectroscopy	Impurity survey	UKAEA Culham	Upgraded
KT3	Active phase CX spectroscopy	Full ionized light impurity concentration, $T_i(r)$, rotation velocities	JET	Modified
KT4*	Grazing incidence+visible spectroscopy	Impurity survey	UKAEA Culham	Upgraded
KX1	High resolution X-ray crystal spectroscopy	Central ion temperature, rotation and Ni concentration	ENEA Frascati	
KY3*	Plasma boundary probes	Vertical probe drives for reciprocating Langmuir and surface collector probes	JET, UKAEA Culham and IPP Garching	Modified
KY4	Fixed Langmuir probes (X-point belt limiter)	Edge parameters	JET	Modified
KZ3*	Laser injected trace elements	Particle transport, T_i, impurity behaviour	JET	Upgraded
Kγ1	Gamma rays	Fast ion distribution	JET	Modified

* Not compatible with tritium

JG93.131/1

Table VI
Status of JET Diagnostics Systems, December 1992
Diagnostics under Construction

System	Diagnostic	Purpose	Association	Status
KB3D	Bolometry of divertor region	Power balance of divertor plasma	JET	Mechanical interface manufacture in progress. Final tests of detector element in progress. Procurement of electronics and data acquisition in hand.
KB4	In-vessel bolometer array	Time and space resolved radiated power	JET	Manufacture in progress. Final tests of detector elements in progress. Procurement of electronics and data acquisition in hand.
KC1D	Magnetic pickup coils	Plasma geometry in divertor region	JET	Manufacture in progress.
KD1D	Calorimetry of Mark I divertor targets	Power balance of divertor plasma	JET	Thermocouple installation awaiting delivery of target tiles.
KE4	Fast ion and alpha-particle diagnostic	Space and time resolved velocity distribution	JET	Under construction
KE7	Lidar Thomson scattering	Higher spatial resolution, n_e and T_e in plasma edge	JET	Design
KE9D	Lidar Thomson scattering	T_e and n_e profiles in divertor plasma	JET	In-vessel design complete, procurement in progress.
KG6D	Microwave interferometer	$\int n_e dl$ along many chords in divertor plasma	JET	In-vessel waveguide design complete, procurement in progress.
KG7D	Microwave reflectometer	Peak n_e along many chords in divertor plasma	JET	In-vessel waveguide design complete, ex-vessel microwave design and mockup experiments in progress.
KG8	E-mode reflectometer	Measurement of density profiles in edge and SOL	JET and CFN/ISTLisbon	Design
KJ3	Compact soft X-ray cameras	MHD instabilities, plasma shape	JET	Under construction
KJ4	Compact soft X-ray camera	Toroidal mode number determination	JET	Under construction
KK4D	Electron cyclotron absorption	n_eT_e profile along many chords in divertor plasma	JET	In-vessel waveguide design complete. Ex-vessel microwave design and mockup experiments in progress
KM2	14MeV neutron spectrometer	Neutron spectra in D-T discharges, ion temperatures and energy distributions	UKAEA Harwell	In installation
KM5	14MeV time-of-flight neutron spectrometer		NFR Gothenberg	In installation
KT1D	VUV spatial scan of divertor	Time and space resolved impurity densities	JET	Under construction
KT5D	Toroidal view visible spectroscopy of divertor plasma from Octant No: 7 mid-plane	T_z and V_z, ion temperature and toroidal velocity of impurities	JET	Design in progress. Optics components defined and procurement in progress.
KT6D	Poloidal view visible spectroscopy of divertor plasma using a periscope	Impurity influx, 2-D emissivity profile of lines	JET	Periscope and in-vessel components installed Design of other components and optics in progress
KT7D	VUV and XUV spectroscopy of divertor plasma	Impurity influx, ionization dynamics	JET	Spectrometer in manufacture, mechanical design in hand, procurement of electronics and data acquisition in hand.
KY4D	Langmuir probes in divertor target tiles	ne and Te in the divertor plasma	JET	Thermocouple installation awaiting delivery of target tiles
KY5D	Fast pressure gauges	Neutral flow in divertor region	JET	Manufacture in progress
KY6	50kV lithium atom beam	Parameters of the scrape-off-layer plasma	JET	Source under test. Telescope in manufacture.

JG93.131/2

operation in the divertor phase or in the active D-T phase. Table 6 sets out the list of additional diagnostics under construction.

Temperature and Density Measurement

The LIDAR Thomson scattering system operated reliably until the end of the experimental campaign giving accurate measurements of electron density and temperature profiles on most plasma pulses. The construction of the new 4Hz ruby laser system to improve the repetition rate was completed and the laser was extensively tested at the manufacturers and again on installation at JET. The roof laboratory was extensively modified so that the new laser and the existing lasers (the 0.5Hz LIDAR laser and the original laser for the single point scattering system) could all be accommodated.

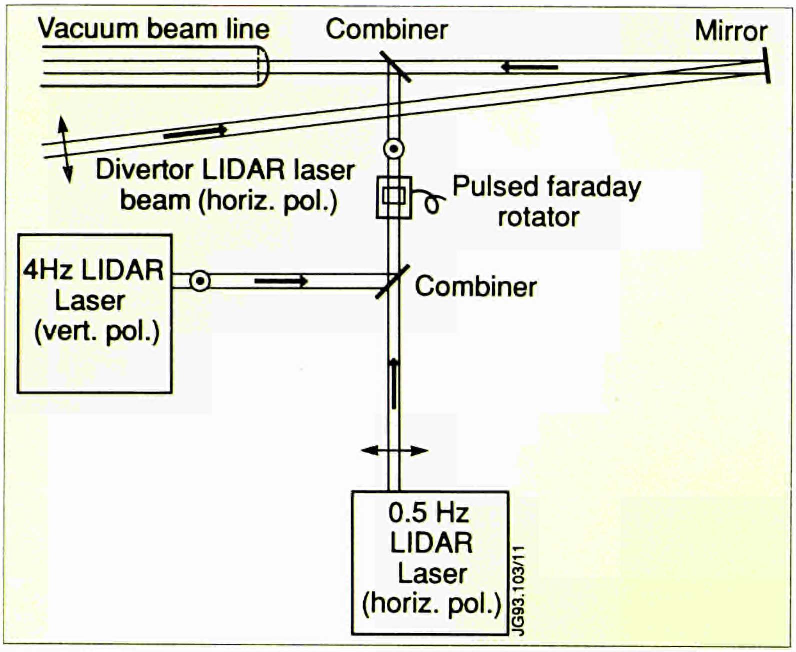


Fig.18: Schematic of the system for combining the beams from the two lasers on the main horizontal LIDAR system with the beam from the laser on the divertor LIDAR system

A scheme for combining the beam from the existing 0.5Hz LIDAR ruby laser and the new 4Hz laser beam along the same beam path is being developed (see Fig.18). The lasers are set up with orthogonal polarizations. A mirror which reflects vertical and transmits horizontal polarised ruby laser light is used to combine the two beams. A pulsed Faraday rotator, triggered synchronously with the 0.5Hz laser, flips this beam polarization into the vertical plane. The divertor LIDAR laser is also combined along the same beam path using another polarization selective mirror. A similar mirror in the vicinity of the floor penetration separates the standard and divertor input beams and directs them down their respective paths to the torus. The spectrometer is being modified to improve the low temperature limit of the standard LIDAR system. The angle of the first filter in the spectrometer is being changed to extend the lowest measurable temperature from 200eV down to 50eV, for more accurate edge temperature resolution.

The multichannel reflectometer probes the JET plasma along a major radius in the mid-plane with electromagnetic radiation propagating in the ordinary mode through the plasma. It operated routinely throughout the experimental campaign and provided measurements of the edge electron density profile and measurements of density transients and fluctuations. A new method of sweeping the source frequency has been developed for operating the reflectometer and processing the data. The procedure yields density profiles in which the position of the probed density layers is known absolutely to ±3cm. Movement of the density layers can be monitored with millimetre accuracy. The measurement accuracy is

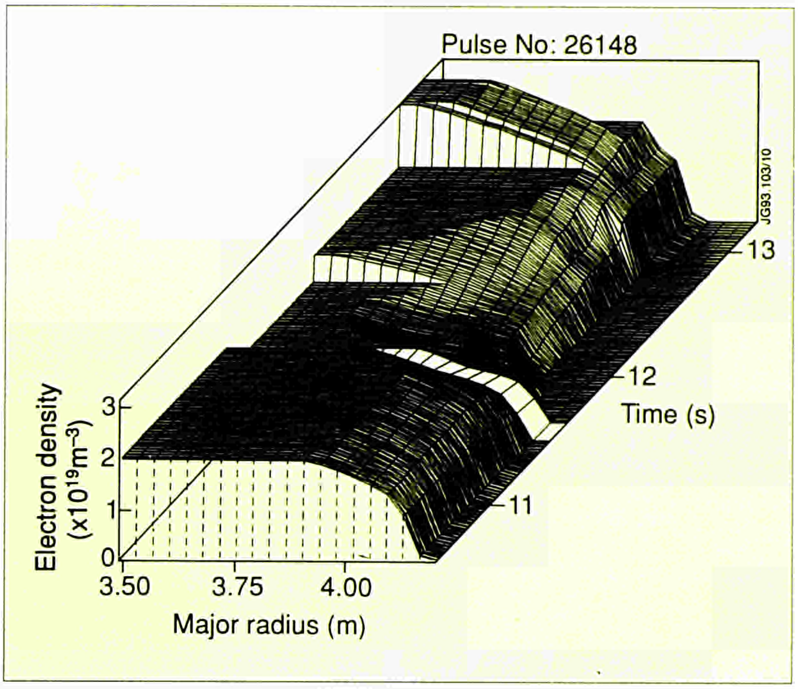


Fig.19: Density profiles measured with the multichannel reflectometer. The changes in the density profile associated with the formation of the X-point at 11.5s and the onset of the H-mode at 12.0s are clearly visible

so high that it is necessary to correct for the change of the position of the probed density layer due to the finite sweep time of the source, and for relativistic modifications of the plasma refractive index. An example of measured density profiles is shown in Fig.19.

Comparisons have been made of density profiles measured with the reflectometer with profiles measured with the LIDAR Thomson scattering system and with the multichannel far infrared interferometer. Usually the profiles agree (Fig.20(a)) but under some conditions there is an apparent systematic difference with the edge of the interferometer profile being at smaller values of the major radius than the reflectometer and LIDAR profiles (Fig.20(b)). The position of the edge of the interferometer profile is determined by a reconstruction of the magnetic flux contours from independent measurements with the magnetics diagnostic and is believed to be accurate to ±1cm. Investigations are in progress to try to determine the cause of this discrepancy.

The three instruments in the electron cyclotron emission (ECE) measurement system, the Michelson interferometer, the grating polychromator and the heterodyne radiometer, continue to provide routine electron temperature data on almost all JET pulses. From the measurements, the electron temperature is obtained with good spatial and temporal resolutions. At the beginning of the shutdown, modifications and upgrades of some of the ECE instrumentation were initiated. The in-vessel ECE antennae were being modified to accommodate upward vertical displacement (~0.3m) of the plasma centre which will result from the new plasma configuration. The fan

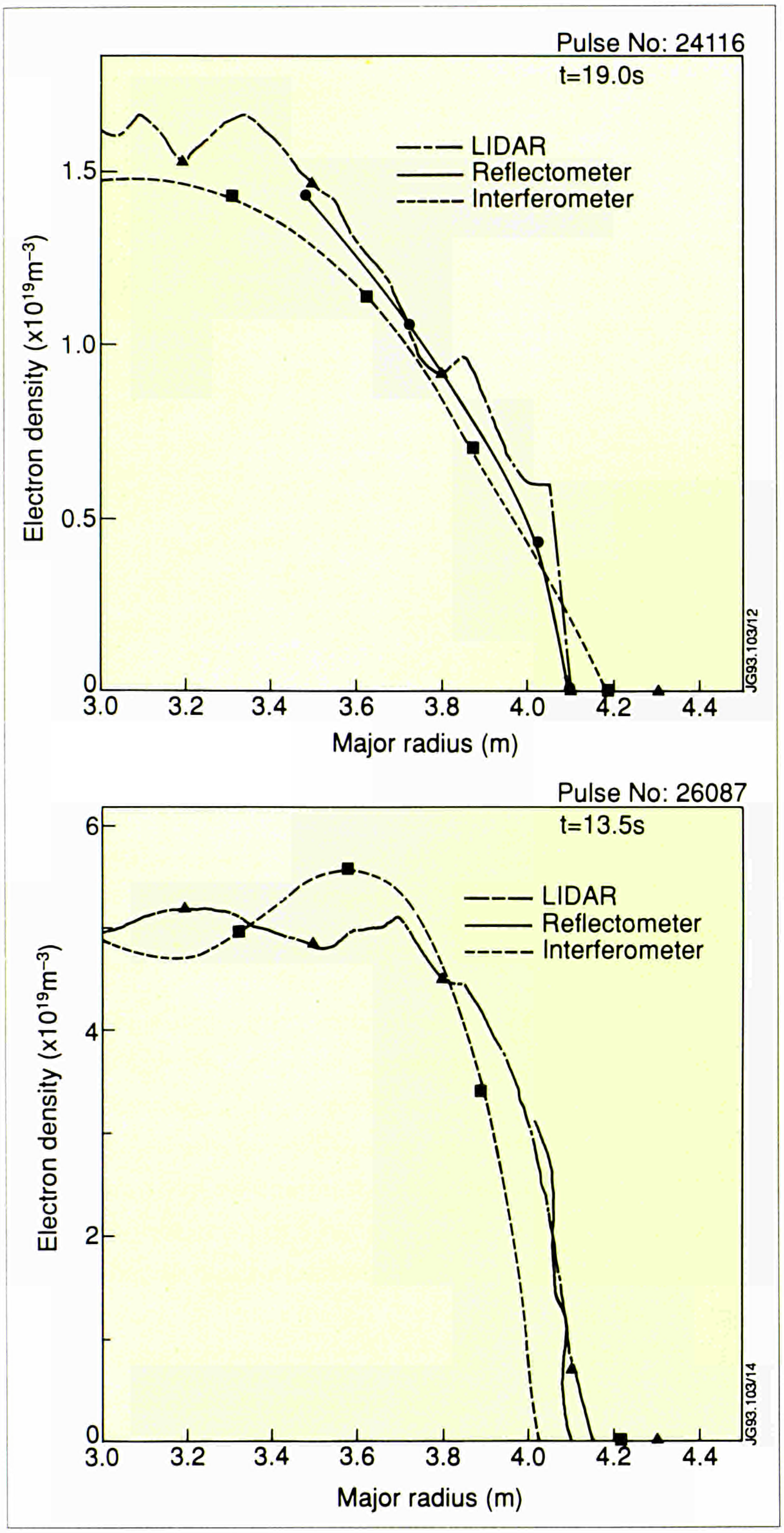


Fig.20: Density profiles measured with the reflectometer compared with those measured by LIDAR Thomsom scattering and the far infrared interferometer. The profiles usually agree within the measurement uncertainties as shown in (a), but in some cases significant differences exist as in (b)

array of six antennae which view the whole poloidal cross-section has been removed, and will be replaced with three antennae viewing around the new mid-plane location plus a fourth which will have an oblique line-of-sight through the plasma centre. This new

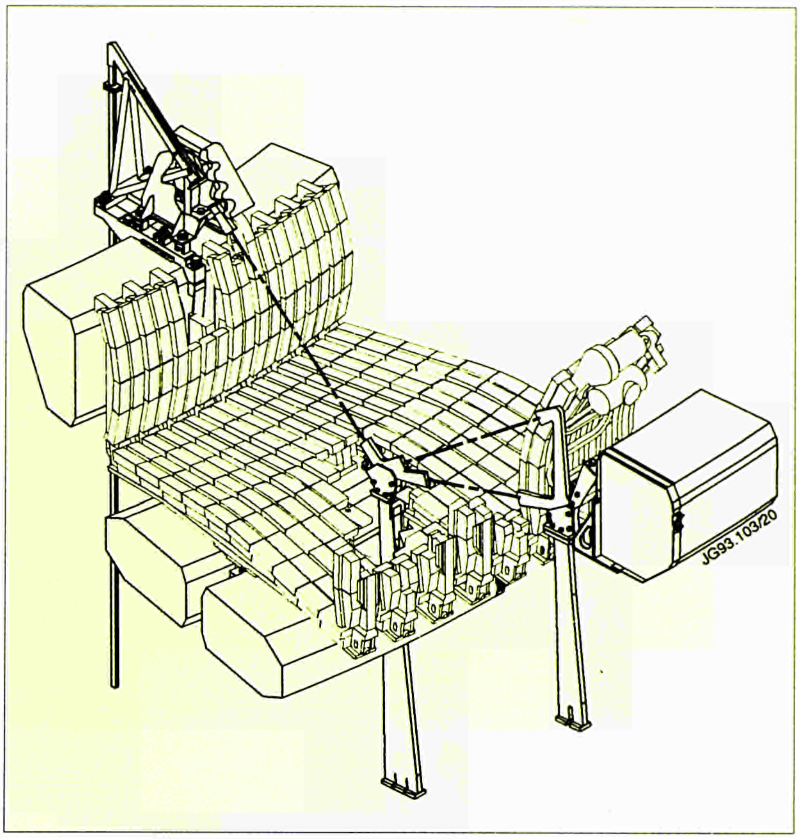


Fig.21: Three-dimensional view of the pumped divertor showing the location of microwave diagnostic antennae, and their sightline across the divertor plasma. The six antennae are arranged as three pairs, giving two lines of transmission through the outboard divertor channel plasma, and one on the inboard side

arrangement will allow several instruments to make simultaneous measurements on sightlines through the plasma centre. The windows on the vacuum vessel are being changed to double windows so that the system will be fully compatible with the D-T phase.

A LIDAR Thomson Scattering system and an integrated set of microwave diagnostics is being prepared to measure the electron density and temperature of the plasma in the pumped divertor region. The design of the LIDAR system is almost complete and several of the most important components have been manufactured and are currently under test. Tests have been conducted of some of the in-vessel components and possible optical coatings for use at the elevated vessel temperatures (~ 400°C). These have shown that it is not possible to use dielectric coatings in the vessel and so it will not be possible to use a mirror to steer the input laser beam. Instead, the beam will be steered by internal reflection in a quartz prism. Tests with a high power laser have shown no damage at the expected energy level. The in-vessel collection mirrors will probably be near surface silver mirrors with a protective coating over the silver.

The microwave system will consist of a dual frequency interferometer, a multi-frequency 'comb' reflectometer and an electron cyclotron absorption diagnostic. Due to limited access in the divertor region, the three systems will share a common set of waveguides and antennae. There will be three sightlines through the divertor plasma, two on the outboard side and one on the inboard side (Fig.21). The 'comb' reflectometer will be used for estimating the peak electron density in the divertor plasma. A prototype 'comb' reflectometer has already been used to estimate the peak density in the X-point region of JET. The maximum probing frequency in reflection was determined by the level of fluctuations on the reflected symbols. However, results showed that this method is not always reliable, as changes in the plasma (e.g. L- to H-mode transitions, or movements in the reflecting layers) can introduce changes in the fluctuation level, which can be confused with changes due to the onset of reflection. To avoid this problem, the instrument will use phase sensitive detection principles.

Boundary Measurements

New Langmuir Probes have been designed for the new divertor geometry. The probe tips will be located in the gaps between target elements and supported in an isolated holder. The tips are shaped to give optimum collecting area and correct orientation to the average field line direction. Tips can easily be installed, exchanged and adjusted in height. There will be two coarsely spaced poloidal sets of eleven probes approximately matching the positions of the magnetic measurements in the divertor module.

In addition, an array of 40 triple probes is planned which will cover the most probable locations of the two strike zones. The triple probes will allow continuous observation of the plasma parameters, plasma density, electron temperature and floating potential. The triple probes should prove invaluable for fast measurements (10kHz) during ELM activity.

The long stroke fast scanning probe will be maintained for the new experimental phase. Tests during the last operation period showed that the CFC probe head is extremely robust. The second stationary probe has been redesigned so that it can also have a long stroke fast scan capability. This probe can carry a variety of heads. It can expose rotating collector probes and sophisticated retarding field analysers or a plasma ion mass spectrometer.

CCD cameras equipped with filter carousels (CI, CII, CIII, OIII, BeI, BeII, and H_α/D_α) are considered essential to observe general discharge behaviour and more importantly to assess the loading of the target plates. The targets will be observed at two toroidal positions (Octant No: 5 and No: 8) from the top and tangentially from the pumping port in Octant No: 1 (wide angle survey camera).

For the observations in the visible and near UV part of the spectrum, two black and white CCD cameras and one colour CCD camera (wide angle view) together with appropriate interference filters will be used. All cameras are being modified to allow either remote or automatic control. In addition, a five-channel photon flux detector will be installed on a vertical port, to measure photon fluxes at five different wavelengths as a function of the major radius and time. This system features high spatial ($\delta R \leq 3$mm) and moderate time resolution ($\delta t \leq 20$ms). Two linear CCD arrays will be used to study fast events.

Density profile measurements in the scrape-off plasma can be made using an energetic neutral lithium beam. As the beam traverses the boundary layer, it is attenuated, mainly due to ionization by electron impact, and the neutral lithium atoms are excited to higher energy states. The beam attenuation profile can be deduced from measurements of the spatial profile of intensity of spectral emission, from which the electron density profile over the beam penetration distance may be obtained. Detailed design of the diagnostic and its operating system for the divertor phase have been completed successfully. Simulations show, that for the presently commissioned Li-beam diagnostic system, edge densities up to 4×10^{19}m^{-3} may be recovered.

Impurity Analysis

JET plasmas offer a variety of mixtures of light impurities in the hot plasma core for analysis by various spectroscopic means. Radial profiles of the effective ion charge, Z_{eff} are determined from Abel inverted profiles of the multi-chord visible Bremsstrahlung signals and simultaneous measurements of main light impurities by charge exchange spectroscopy. The dilution factor (the ratio of deuterium density to electron density, n_D/n_e) is derived from the density of electrons and light impurities. The available XUV and VUV spectroscopic data was analysed to give line intensities, elemental radiated power components and impurity concentrations. This allowed an assessment to be made of the global impurity behaviour in JET.

The radially scannable VUV spectroscopy diagnostic consisted previously of two dual-chrome spectrometers, which looked vertically and horizontally into the upper divertor region. The scan was provided by two-faced rotating mirrors running at a maximum speed of 5Hz and provided a minimum time resolution of 100ms. Each spectrometer has two 10-channel detectors, which allowed the measurement of a spectral line profile over a wavelength range of up to 5Å. The diagnostic was mainly aimed towards divertor investigations. A major change and upgrade of the diagnostic is now underway to match the demands of the pumped divertor phase and to provide a higher time resolution (~25ms) and better spectral coverage up to 15Å.

Table 7: Neutron Diagnostic Systems

System	Measured quantities
Time resolved neutron yield monitor Fission chambers and Silicon diodes	Measures instantaneous neutron emission strength. Distinction between D-D and D-T neutrons necessary for triton burnup and low-level tritium diffusion studies
Activation system Due to new in-vessel components, reliable response calculations possible only for the upper irradiation end inside the vacuum vessel.	Determines absolute neutron yields and hence calibration of time-resolved neutron yield monitors for D-D and D-T neutrons.
2-D neutron camera (D and D-T plasmas) Upgrade essential for operation with >1 MW fusion power. This diagnostic should be in place by end of 1993.	Measures radial neutron intensity distributions in two directions, the absolute neutron yields, and permits tomographic reconstruction of neutron emission. Study of triton burnup in D-plasmas, to investigate fast particle confinement and to determine n_D/n_e ratios.
Neutron Spectrometers (radial and tangential) 2.5 MeV neutrons, available. 14 MeV neutrons, being installed.	Measurement of neutron energy spectra; separation of thermal and beam-plasma contributions. Identifies neutron production from ICRF-heated particle interactions with impurities. Determines n_D/n_e ratios in D plasmas and n_{fuel}/n_e ratio in D-T plasmas.

A new instrument, a Bragg rotor X-ray spectrometer was fully commissioned before the end of 1992 operations. This has two independent sections; a hexagonal rotor gives full spectral coverage between 0.1nm and 10nm to monitor all likely impurities, while a small array of multilayer mirrors and crystals gives good time resolution of representative lines of the main impurities for routine radiated power analysis.

Neutron Measurements

The neutron diagnostic systems summarized in Table 7 are all expected to be operational at the start of the next campaign. The philosophy underscoring the deployment of these diagnostics is that there will be no clear separation between the operational phase that uses deuterium from that with deuterium-tritium mixtures. Instead, lengthy periods of deuterium operation interspersed with low level tritium usage may be anticipated, followed by the main tritium period. The neutron diagnostics of D-D operation must therefore remain available, in parallel with those specifically for D-T operation.

The time-of-flight 2.5MeV neutron spectrometer is being moved from its position in the Roof Laboratory above Octant No:8 to above Octant No:5. Since the plasma axis for high performance divertor plasmas will be located near 2.90m, instead of 3.25m, it has been necessary to modify the collimation. The 14MeV spectrometer is

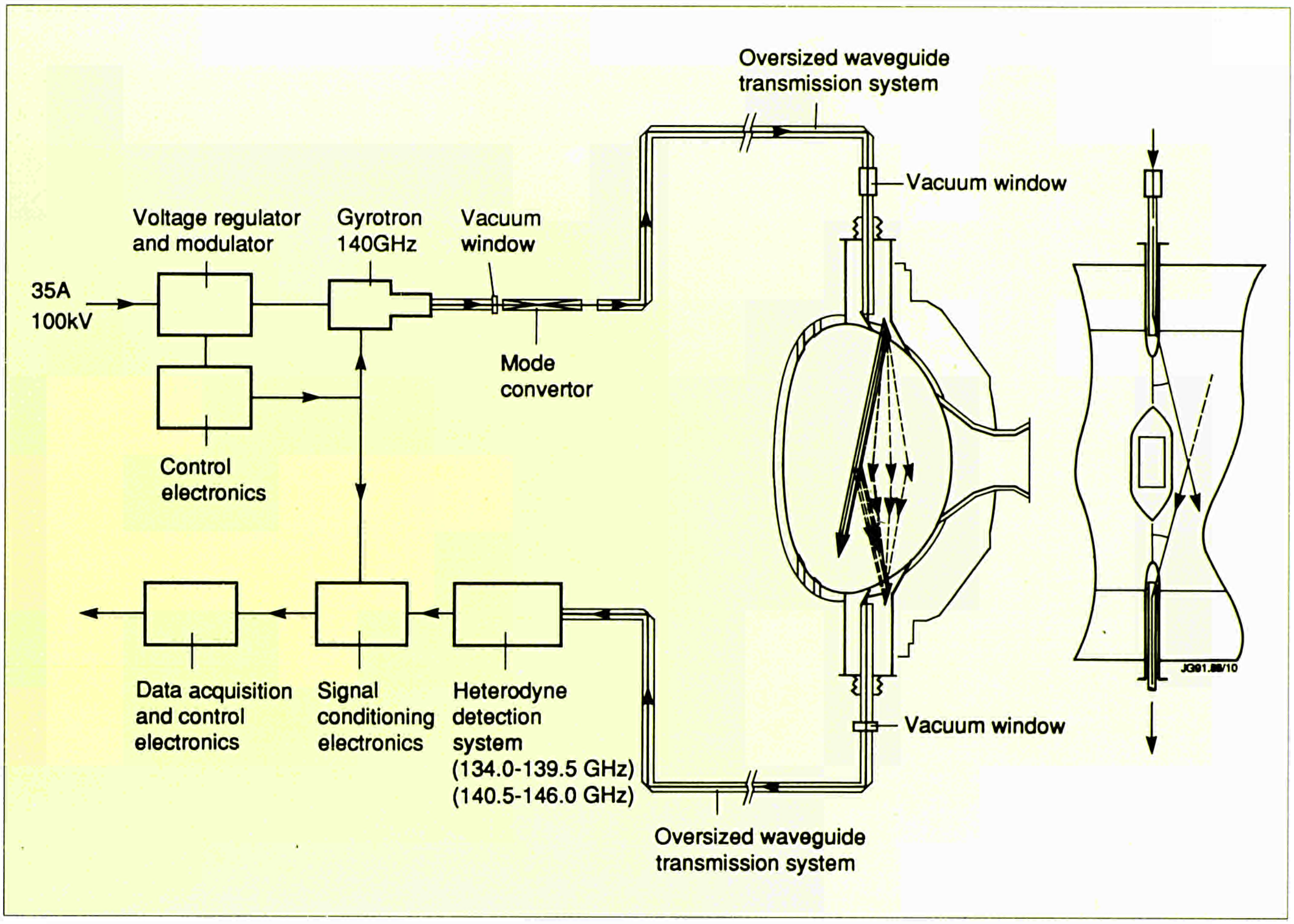


Fig.22: Schematic of collective scattering system for measuring spatial and velocity distributions of fast ions including alpha-particles

being installed in Octant No:8. A tandem-radiator spectrometer is to be installed, using the beam-line formerly occupied by the Surface Probe Fast Transfer System and thereby avoiding the need for constructing a massive but moveable radiation shield for deployment within the Torus Hall.

A major upgrade is being planned for the neutron profile monitor to provide: improved radiation shielding (for D-T operation), remotely adjustable collimation, and provision for three in-line detectors within each collimation channel. The number of channels and their viewing directions will remain unchanged. With these modifications, it will be possible to follow the programme without need for physical access to the profile monitor to exchange detector boxes or collimation in accordance with the programme. It will also be possible, for the first time, to study simultaneously fast electron currents generated through operation of the LHCD system and the effects on the neutron emission profiles.

Fast Particle and Alpha-Particle Studies

The high energy neutral particle analyzer (NPA) instrument, purchased from the AF Ioffe Physical-Technical Institute, St. Petersburg, Russia, operated during 1992. Consisting of eight energy channels with common mass selection, it measures fluxes of H, D, ^{3}He and ^{4}He atoms and their energy spectra in the range 0.5-3.5 MeV. These ions arise from hydrogen and helium minority ICRF heating, or from fusion reactions. The ions then neutralize by charge-exchange with low energy atoms, or by recombination, forming MeV atoms which exit the plasma. The low energy atoms are from injected neutral beams, or from recycling. At the end of the campaign, the prototype device was returned to undergo further tests and recalibration using a cyclotron beam source. An instrument suitable for deployment during D-T operations is in manufacture, for installation in 1993.

A system to measure the velocity and spatial distributions of fast ions, including α-particles in the D-T phase, continued commissioning during 1992. The system is based on collective scattering of radiation with a frequency of 140GHz generated by a powerful gyrotron source. The principal system is shown in Fig.22. During 1991, commissioning of the system had to be discontinued before the end of plasma operation due to technical difficulties. The 60kW, 140GHz gyrotron, on loan from the USDoE developed a vacuum leak in the window. Difficulties were also experienced with the power supplies and drives to the steerable mirrors mounted inside the vacuum vessel. Therefore, it was not possible to carry out the planned preliminary scattering experiments. Nevertheless, many technical systems were tested and useful experience gained.

At the beginning of the shutdown, a programme of technical improvements was initiated. Also, substantial modifications are now necessary to make the system compatible with the new divertor geometry. New in-vessel steerable mirrors for launching and receiving the radiation are being designed. The received radiation will be transmitted to the detection waveguide run using small diameter corrugated waveguide specially shaped to go around the divertor coil. The vacuum windows will be replaced by double disk windows and will be mounted vertically to avoid contamination. With the new divertor geometry, the in-vessel components can no longer be supported externally independent from the vacuum vessel. Instead these will be mounted on the vessel wall.

Technical difficulties were experienced in the manufacture of the high power (400kW) gyrotron and have delayed the delivery of this tube. However, a short pulse (100ms), high power prototype gyrotron has been loaned to JET as part of the collaborative agreement with the USDoE and will be used for initial system commissioning. The diagnostic will be operated and controlled from the Control Room with a central control system. In operation, the diagnostic will generate a substantial quantity of data and the software to process and analyse the data using the central computer is being developed.

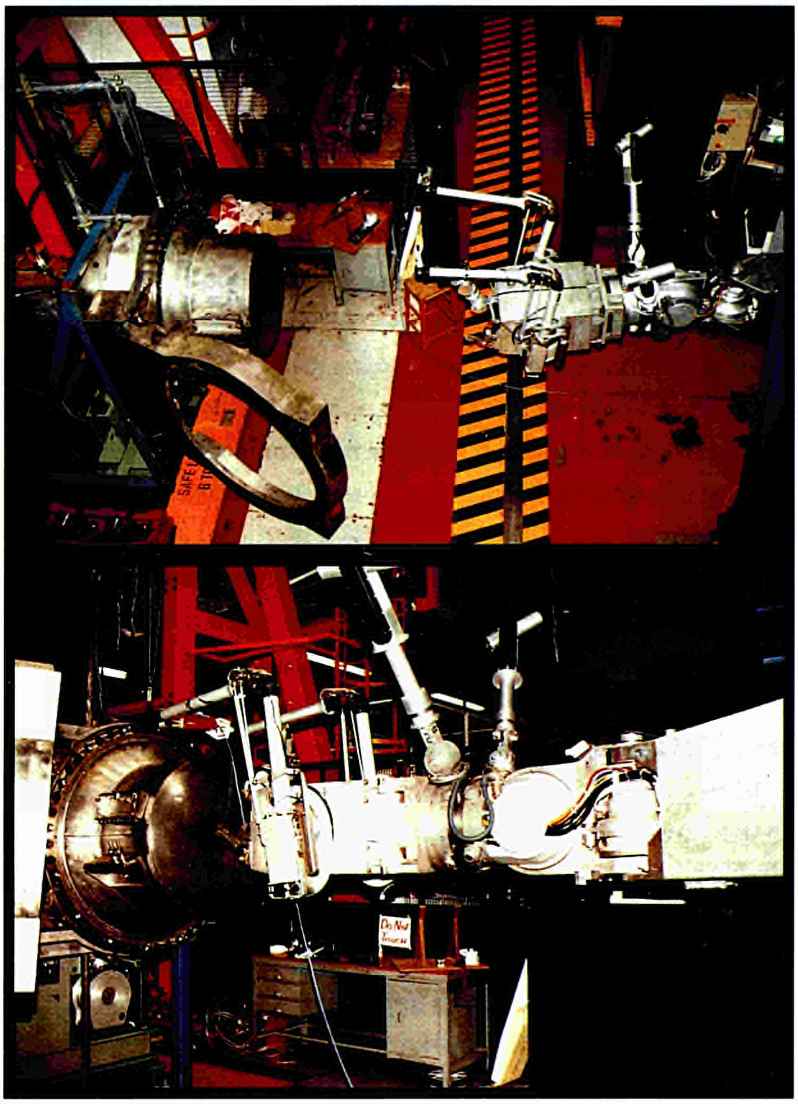


Fig.23: MASCOT IV (a) at start of mock-up; and (b) poised to begin unbolting operation

Remote Handling

The main objective of the remote handling programme is to prepare for the introduction of tritium into JET, which will generate a large number of D-T fusion reactions, with a high flux of 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 be 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.

To gain experience, remote handling equipment is being deployed during shutdowns, in hands-on or semi-automatic mode. Whilst the use of remote handling equipment during shutdowns provides an excellent testing ground for the effectiveness and reliability of equipment, it also means that as a consequence of the associated manpower effort, only limited effort has been available for development of full remote handling procedures. Therefore, it is now envisaged that the remote handling for the D-T phase will concentrate on a few essential ex-vessel and in-vessel operations, including gaining remote entry into the vacuum vessel using the telescopic articulated remote mast (TARM) and the articulated boom with special end effectors or the MASCOT IV manipulators. The latter would allow, to a certain extent, carrying out non-planned activities inside and outside the vacuum vessel.

During March 1992, the articulated boom was used to remove 82 large components from within the torus. Many of these components could only be removed after cutting them free and over 132 cuts were made inside the torus. After removal of equipment from the vessel in the first part of the shutdown, the boom underwent extensive upgrading and modification. It has been totally rewired with insulated cables of low halogen and low smoke material. It is designed for enhanced flexibility, and the total number of joints has been increased from five to six. Following the installation of new actuators and reinforcing plates the boom has been recommissioned for higher speed reducing the insertion time in the vessel to nine minutes from the "pick-up" point.

Improvements to the MASCOT manipulator have been achieved especially in the man-machine interface, computer aided teleoperation and grippers to increase speed and reliability. The man-machine interface has been made more friendly and manually driven, and the documentation has been clarified. The computer aided teleoperator has been improved to bring sampling time for constraint and weight compensation to below 10ms. Figure 23 shows the MASCOT manipulator applying an impact wrench to port-holes during trials on a mock-up of the main vacuum vessel flange.

Waste Management

The responsibilities of the Waste Management Group include the provision of the infrastructure in JET for waste handling (radwastes and beryllium-contaminated wastes) and the provision and maintenance of respiratory protection and equipment. Five controlled area facilities, which are all equipped to handle components and materials activated and contaminated with tritium and beryllium, have been operated in support of the 1992 shutdown. Wastes generated in these areas are disposed of either as beryllium or low level radioactive waste. These facilities are all ventilated through plant operated in accordance with an Authorisation from the UK Department of the Environment.

The Torus Access Cabin (TAC) was installed on the machine at the start of the shutdown in an extended configuration with an enlarged operations box and improved facilities for the transfer of components in ISO-freight containers. The access and change facili-

Fig.24: In-drum compactor

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 micro-processors) 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 transmitted to the IBM mainframe computer for detailed analysis. A summary of information from the JET pulses is held in the JET Survey Data Bank.

ties were also improved to allow for quicker entry and exit. Up to six operatives were able to work concurrently in pressurised suits with a modified breathing air supply system. The ventilation plant for the torus and the TAC was extensively modified to take account of the potential tritium levels following the preliminary tritium experiment. However, tritium levels within the vessel were very low (below the limit of detection on hand-held monitors) and pressurised suits were primarily required to protect against the beryllium hazard.

The TAC provided trouble-free support to the in-vessel programme throughout 1992 and, in the initial three month period, there were ~1400 suited entries, representing over 5000 man-hours spend in airsuits inside the vacuum vessel. Following the removal of first wall components and decontamination of the vessel, it was possible to change the classification of the vessel and dispense with the use of airsuits.

During the shutdown, the two beryllium handling facilities in the Assembly Hall were integrated into one area with a new materials airlock. A new tritium compatible ventilation system was commissioned, which also serves other areas in the Assembly Hall, including that used for the octant toroidal field coil change.

The new Waste Handling Facility was commissioned in January for the start of the shutdown. Principal operations conducted in the area include: sorting and sampling of materials, in-drum compaction of compressible wastes (Fig.24) and preparation for disposal and packaging of component wastes. Initial work concentrated on

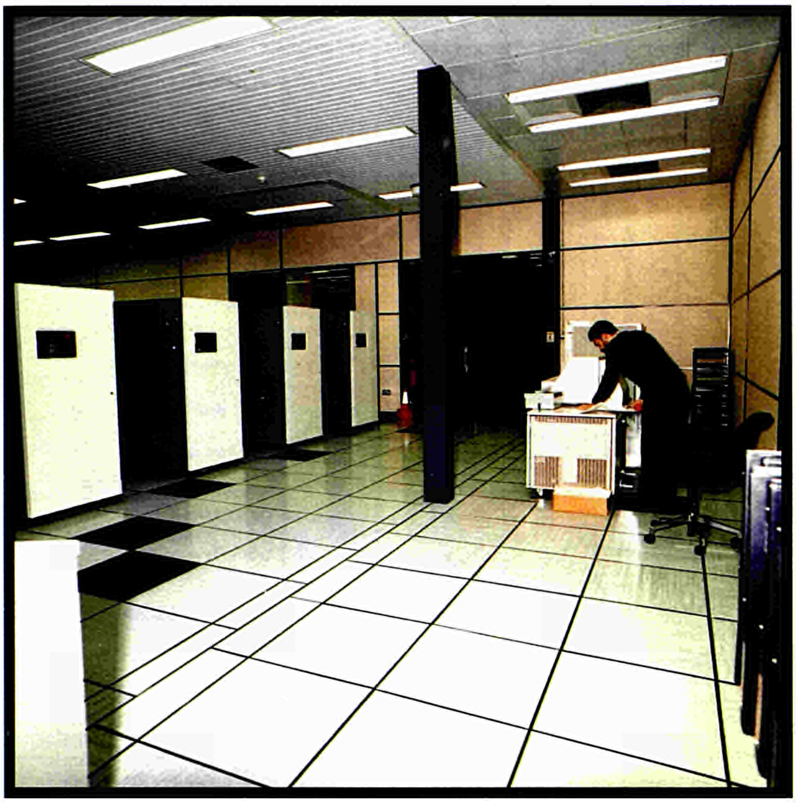


Fig.25: Installation of IBM mainframe computer in the new JET computer room

secondary wastes consisting mainly of disposable clothing and housekeeping waste. By mid-November, 110 drums of compacted waste had been prepared for disposal. Progress was also made on the disposal of wastes accumulated during earlier shutdowns.

Control and Data Management

The JET Control and Data Acquisition system, CODAS, is based on a network of minicomputers. It allows centralised control, monitoring and data acquisition of JET. The various components of JET have been logically grouped into subsystems, such as Vacuum, Toroidal Field, Lower Hybrid system, etc. Each subsystem is controlled and monitored by one dedicated computer interfaced to the machine and its diagnostics, through CAMAC instrumentation and EUROCARD-based signal conditioning. Embedded front-end intelligence is implemented through CAMAC-based microprocessors for real-time applications. The actions of the various computers are coordinated by a supervisory software running in the Machine Console computer.

During 1992, the main effort was devoted to moving CODAS to a UNIX environment. The structure of the system is similar. The CAMAC interface is retained and the Man Machine Interface (MMI) is upgraded to use Windows.

The JET Computing Service has operated since June 1987 and the central computer was upgraded in 1990 from an IBM 3090/200E to an IBM 3090/300J with three processors, two vector facilities and 256 MBytes of memory (128MB central and 128MB expanded). The

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.

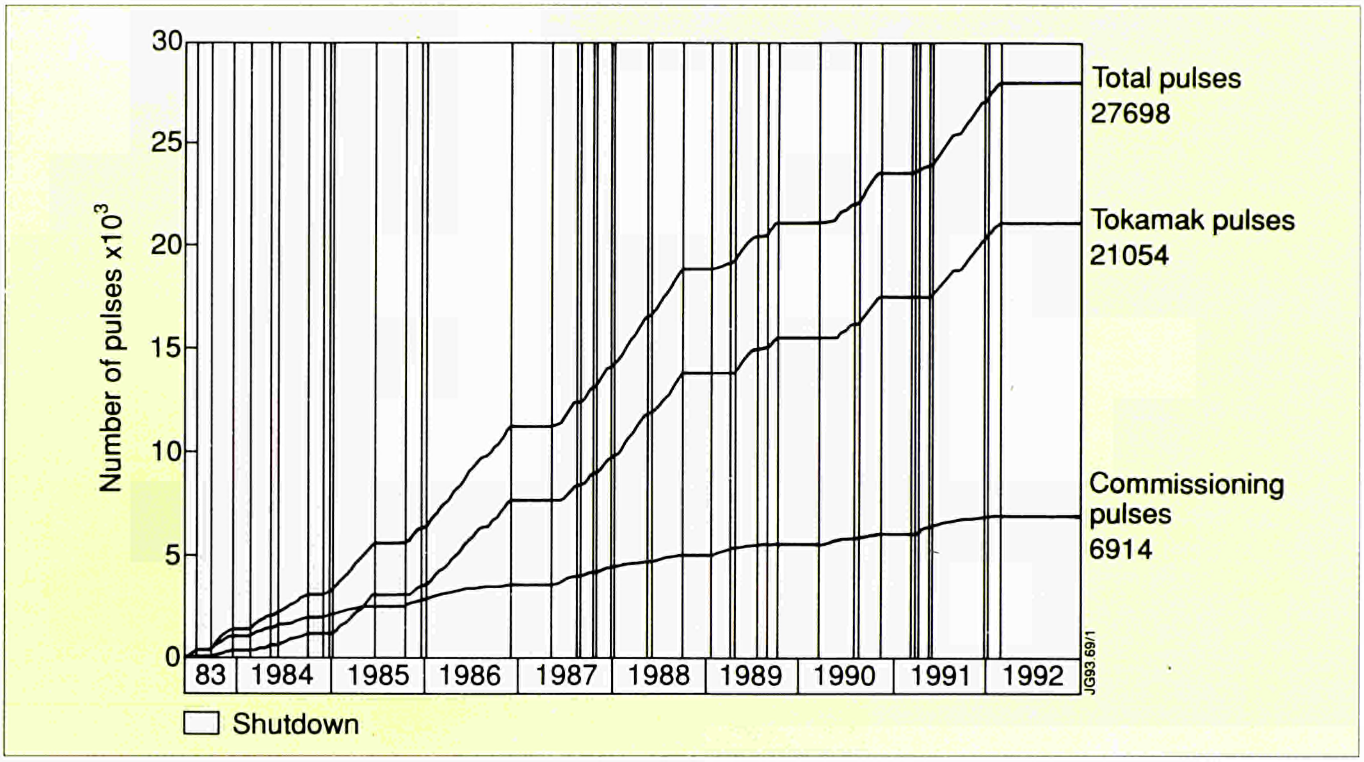


Fig.26: Cumulative totals of JET pulses - 1983 to 1992

upgrade permitted a significant growth of mainframe computing workload, most critically in the areas of data processing, CAD work from the Drawing Office, interactive (TSO) work and mechanical and electrical design studies. These improvements have significantly enhanced the Project's Design and Data Processing capabilities.

The IBM computer was previously based at the UKAEA Harwell Laboratory. However, by virtue of the reduced physical size of the UNIX equipment, a detailed study proved the feasibility of re-organising the Computer and Control Room arrangements and of allocating 250m^2 to house the IBM3090 on the JET site. The move the equipment took place over the weekend of 17th July 1992, with minimal interruption, and service was restored to users before midday on the Monday (Fig.25).

Summary of Machine Operation

As planned, operation in 1992 was for a period of only the first seven weeks of the year. Due to the small time available and due to severe restrictions on plasma performance limiting the neutron activation of the vessel (to facilitate subsequent in-vessel work during shut-down), special attention was given to planning many of the experimental studies. As a consequence, many magnetic field configuration and protection circuit changes had to be performed.

The overall operation was successful and resulted in an average of 135 pulses per week, which was a considerable improvement over the 100 pulses per week during 1991. On one particular day (2-shifts),

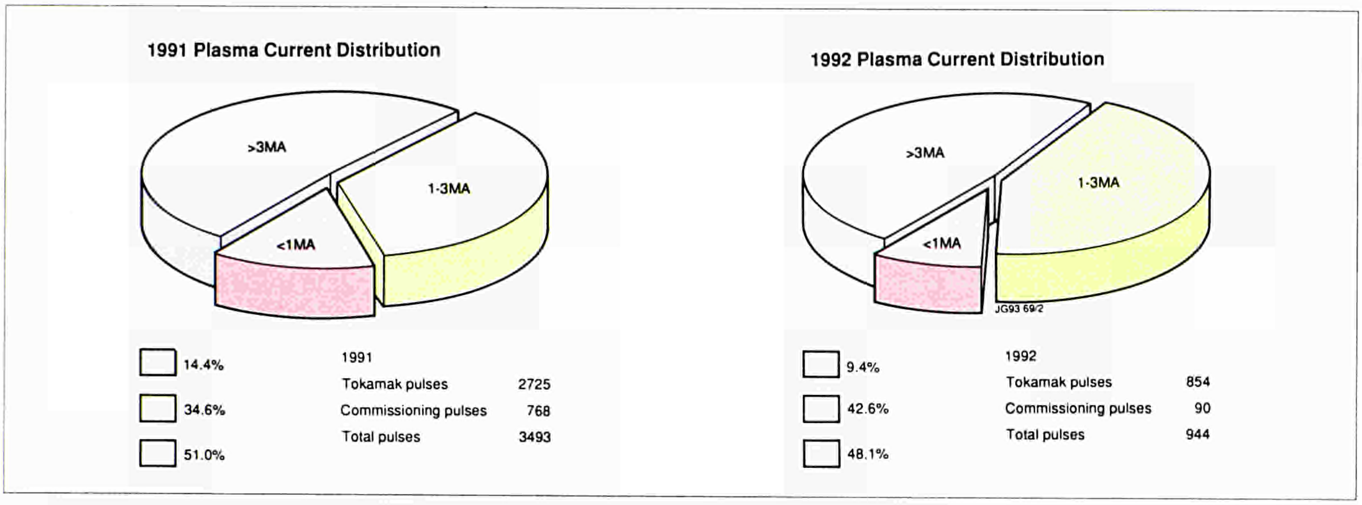


Fig.27: Comparison of numbers of pulses and distributions of plasma currents for 1991 and 1992

52 pulses were achieved. High-current operation was resumed and in a period of two days nearly fifty 7MA current plasmas were reliably produced. The effects of high current disruptions had been much reduced by improved protection control arrangements.

Two events significantly hampered operations:

i) a rupture of a diagnostic bellows, due to a control circuit commissioning error, which vented the vessel almost to atmospheric pressure and the repair and recovery caused a six day loss of operation;

ii) a water leak from the NB Testbed effected the cooling of torus components and control cubicles of the NB injectors. This caused a further 1.5 days loss of operation.

In spite of these problems, the reliability and performance of subsystems was good and allowed effective use to be made of the time available.

During this period, the vacuum exhausts of the torus and neutral beam injector boxes were carefully monitored for tritium, following the preliminary tritium experiments in November 1991.

Organisational arrangements for operation (Task Forces H, I and P) remained similar to 1991 operation. The experimental programme time during 1992 was distributed as follows:

Task Force H:	High Performance	21.6%
Task Force I:	Impurity Transport and Exhaust	43.1%
Task Force P:	Physics Issues	35.3%

The number of pulses in 1992 was 944, bringing the total number of pulses to 27968 (see Fig.26). The percentage of commissioning pulses in 1992 (less than 10%) was half that in 1990 or 1991. The plasma current distribution (Fig.27) for 1992 compared with 1991 shows a reduction in the fraction of small plasma currents (<1MA) and high currents (>3MA), and an increase in medium currents (1-3MA).

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 shutdown periods. 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 is the main method of decoupling the plasma currrent and temperature profiles in JET. The main objectives of current drive and profile control are:

- to suppress sawtooth 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 (and efficiency) required for non-inductive operation of large tokamaks.

The JET LHCD system will be powered by 24 klystrons operating at 3.7GHz to produce a total power of 12MW. The launcher will produce a narrow wave spectrum with a parallel wave index which can be varied from 1.4 to 2.3. 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 8.

The system is being installed in JET in two stages. The first prototype stage was tested during the 1991/92 campaign. The first

Table 8: Parameters of the JET LHCD System

	Prototype	Final
Frequency	3.7GHz	3.7GHz
No. of Klystrons	8	24
(launched) Power (max)	3.5MW	10MW
Launcher waveguides	128	384
Multijunction phasing	90°	90°
Central $N_{//}$	1.8	1.8
Range in $N_{//}$	1.4-2.3	1.4-2.3
Width of $N_{//}$ spectrum	0.4	0.2
Phase accuracy	10°	10°
Directivity	70%	80%
Density limit	$8\times10^{20}m^{-3}$	$8\times10^{20}m^{-3}$
Power Handling	$4\text{-}5kWcm^{-2}$	$4\text{-}5kWcm^{-2}$
(Estimated) drive current		
(in ICRF heated plasmas)		
at $n_e = 2 \times 10^{19}m^{-3}$	2MA	(5MA)
at $n_e = 4 \times 10^{19}m^{-3}$	(1MA)	(2.5 MA)

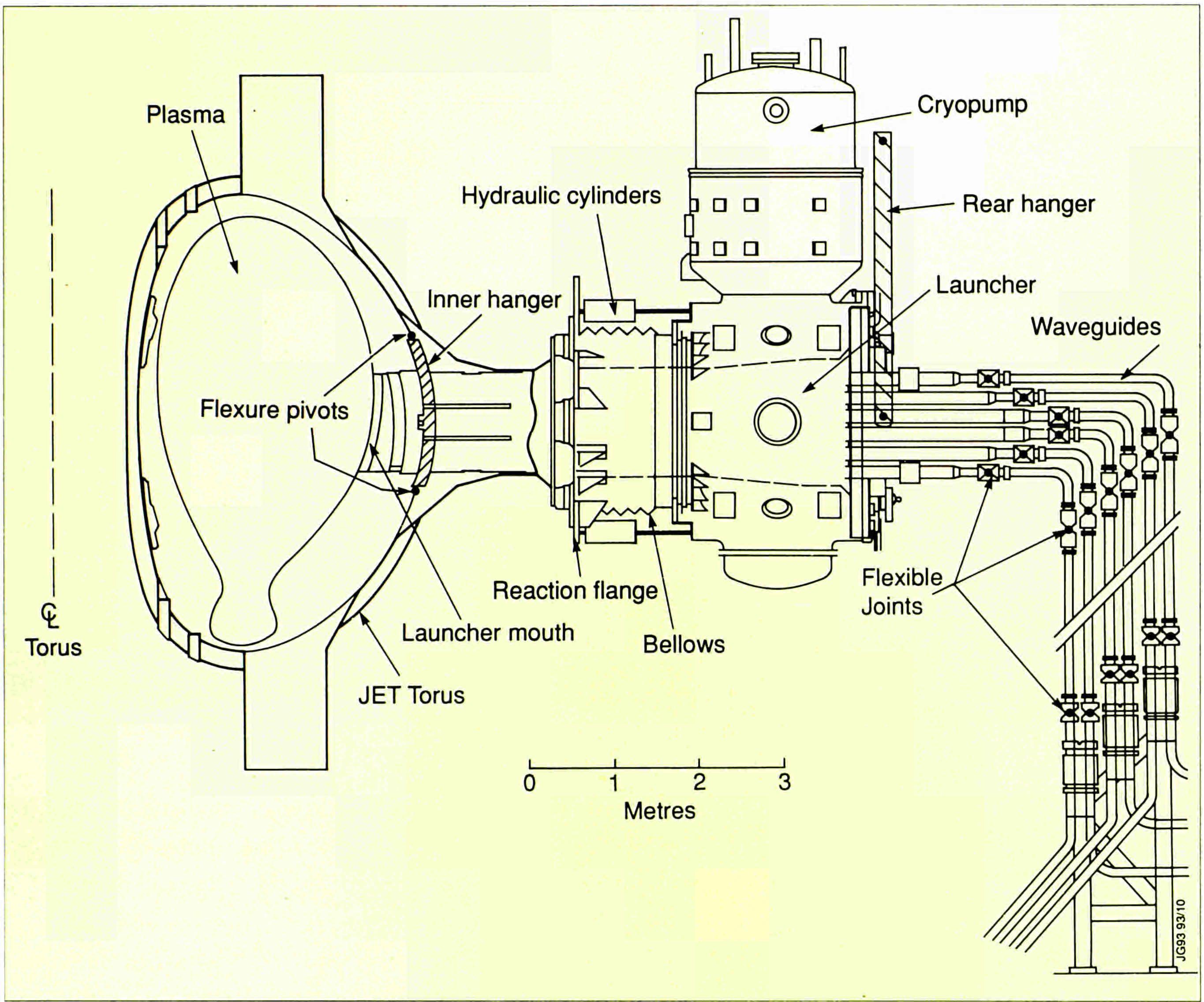


Fig.28: Elevation of the lower hybrid launcher

stage was composed of two prototype launchers, one built using the same technique as foreseen for the final system (LOP) and one built by CEA Cadarache, France, using the technique developed for TORE-SUPRA (LOC). The prototype launcher comprising one third of the number of waveguides of the full system was tested on the torus. Figure 28 shows a cross-section of the system on JET.

The prototype LHCD system operated for a total of 12 months (over a 2 year period) up to February 1992. The total available generator power was 4.8MW. The achieved generator power on LOP was 2MW compared with an installed capability of 2.4MW, with 1.75MW coupled to the plasma. LOC managed 1.5MW generator power with 1.2MW coupled to the plasma, prior to major air leaks elsewhere in the torus, but only achieved 600kW generator power after the air leaks. Plasma pulses of one minute duration were obtained with 1MW of LHCD power applied for 50s.

The prototype system has fulfilled its role in providing engineering, operational and physics experience of LHCD on JET. The new

Fig.29: A view of the forty-eight vacuum windows connecting the LHCD waveguides to the rear of the launcher.

full-size launcher is now being prepared for installation. This will be capable of launching 10MW into the plasma. Based on the results with the prototype system, this should allow full current drive of a 4MA plasma.

The full-size launcher was originally designed for the plasma profile of the belt limiter configuration. Following a decision in 1990 to install the launcher after installation of the pumped divertor, the shape of the grill mouth was modified to match this plasma. During 1992, the procurement of the modified components was completed and the launcher fully assembled. This launcher incorporates 48 multijunction units each having eight waveguides at the grill to give a total of 384 waveguides. The power from 24 klystrons is coupled to the grill via 48 vacuum windows. Figure 29 shows the launcher assembled on the testbed. the windows may be replaced using remote handling tools. A cryopump of 85,000ℓs^{-1} is being prepared for installation on top of this launcher. The fully assembled launcher is shown in Fig.30. The total mass of the launcher is ~15 tonnes.

Pellet Injection

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

Fig.30: View of the L1 launcher prior to its installation in the Testbed

speed pellets, in order to penetrate beyond the q=1 surface to the plasma centre. So far in JET, measurements have only been carried out in a limited velocity range up to 1500ms^{-1}.

As mentioned in the 1991 Annual Report, JET had planned to implement, for the divertor and later phases of JET operation, a repetitive high-speed pellet launcher system - the Advanced Pellet Launcher (APL). This would have been alongside an intermediate-speed repetitive pneumatic launcher, JPL II, as a replacement for the launcher (JPL I) used during the 1991/2 campaign, built by Oak Ridge National Laboratory (ORNL), USA. In addition, there would be a low-speed pellet centrifuge. Due to the budgetary situation at JET and in the USA, the APL will now not be pursued for financial reasons.

After only a short period of operation following the preliminary tritium experiment, the repetitive pellet launcher, (JPL I) was de-commissioned and returned to ORNL for refurbishment and further use in USA. For the next operational period in 1994, two pellet launching devices are now foreseen. The first device is a high-speed (4kms^{-1}) single-shot pneumatic launcher, employing two-stage gun drivers and delivering pellets through the pellet injector box (PIB) vacuum interface to the torus. There will be two of these high speed launchers. The second device is a new mechanical low-speed pellet centrifuge. A schematic view of both devices is shown in Fig.31.

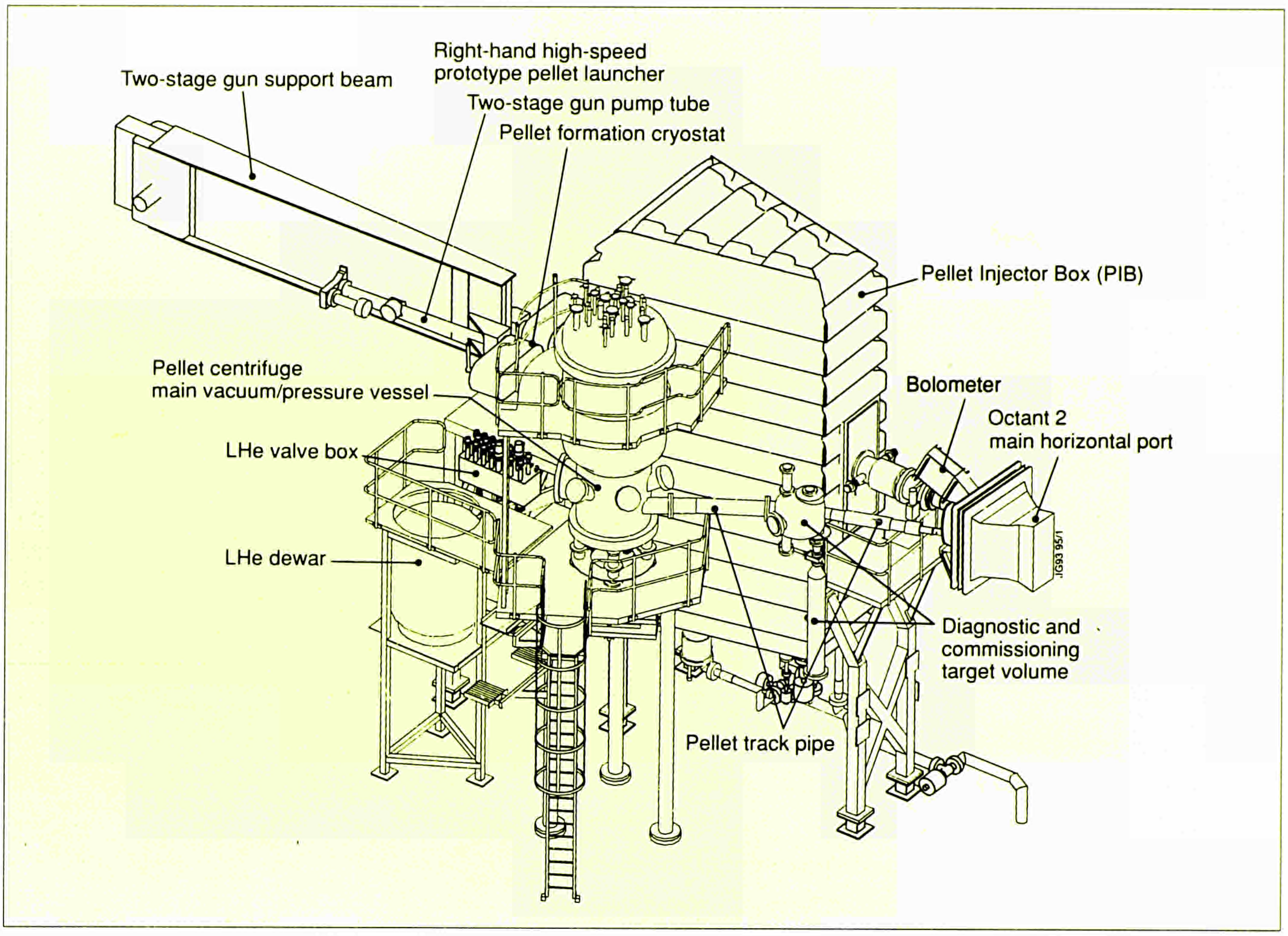


Fig.31: Pneumatic and centrifuge pellet injectors

This high-speed prototype launcher accelerates sabot supported 6mm deuterium pellets to speeds up to 4kms^{-1} by using two-stage light gas gun driver technology for deep central plasma fuelling purposes. Sabots are small plastic pistons, set behind the deuterium pellets to protect them from the hot driving gas. These sabots, needed for pellet velocities in excess of about 3kms^{-1} and being accelerated with the pellet, are made from two halves of equal mass, which split after leaving the barrel due to aerodynamic forces and can be eliminated from the pellet path by a shear cone.

Two prototype launchers, the second being a mirror image of the first, are under preparation for the next experimental period to be installed side by side at the rear of the Pellet Injector Box in the Torus Hall. The two-stage gun of the second launcher is commissioned and the cryostat is in a late state of assembly (incorporating modifications from the commissioning of the first one).

The pellet centrifuge is to provide a source of deuterium particles at varying depths beyond the recycling layer and with it a minimum recycling flow into the divertor. The injection parameters chosen are pellet sizes of 1.5-3mm with repetition frequencies up to 40s^{-1} at speeds of 50-600ms^{-1} for long pulses approaching one minute. At the upper end, this provides up to 1000mbarℓs^{-1}

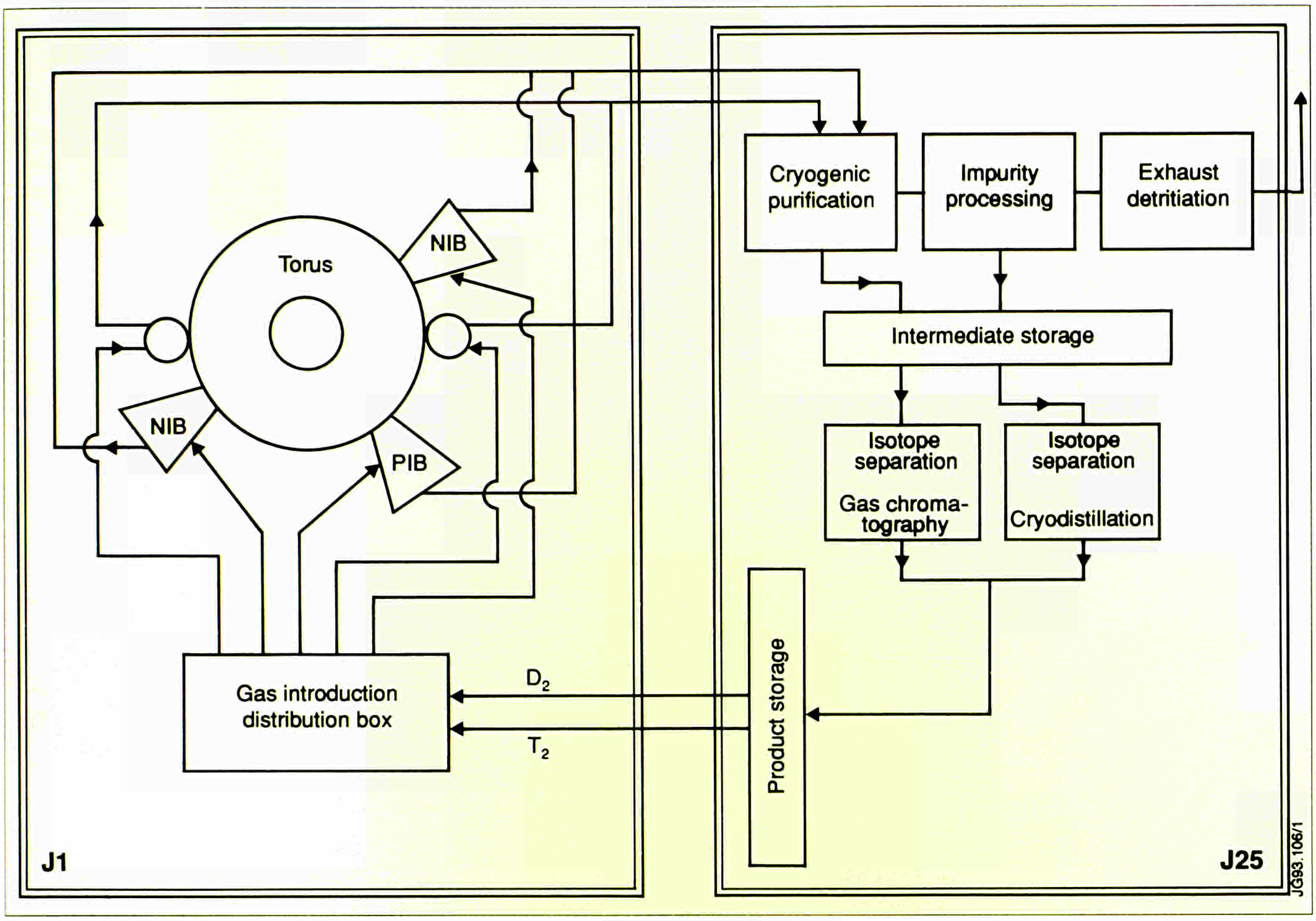


Fig.32: Block diagram of functions of Active Gas Handling System

of gas flow regardless of pellet speed and the penetration depth variation is over a factor of 12. The plan is to position the centrifuge at Octant No:2 midplane, alongside the pneumatic pellet injector. The detailed design of the vacuum vessel, the centrifuge and the cryopump, needed to absorb the gas load evaporated from the pellets during acceleration and guidance, has been finalised. Advice has been given on implementation of the pellet centrifuge in JET by IPP Garching, Germany under an Article 14 contract.

Tritium Handling

Following the extension of the Project to the end of 1996, the Active Gas Handling System (AGHS) will be required to be fully operational before the start of the full D-T phase of JET scheduled for 1996. Installation of the systems in the Active Gas Handling building have been completed. The function of these systems is to collect exhaust gases from the torus, to remove impurities and to separate pure deuterium and tritium for storage for re-injection through neutral beam, pellet or torus gas introduction as required. The functions of the Active Gas Handling System are shown in Fig.32. During 1992, significant progress in commissioning was made in exhaust

Fig.33: Gas chromotography equipment

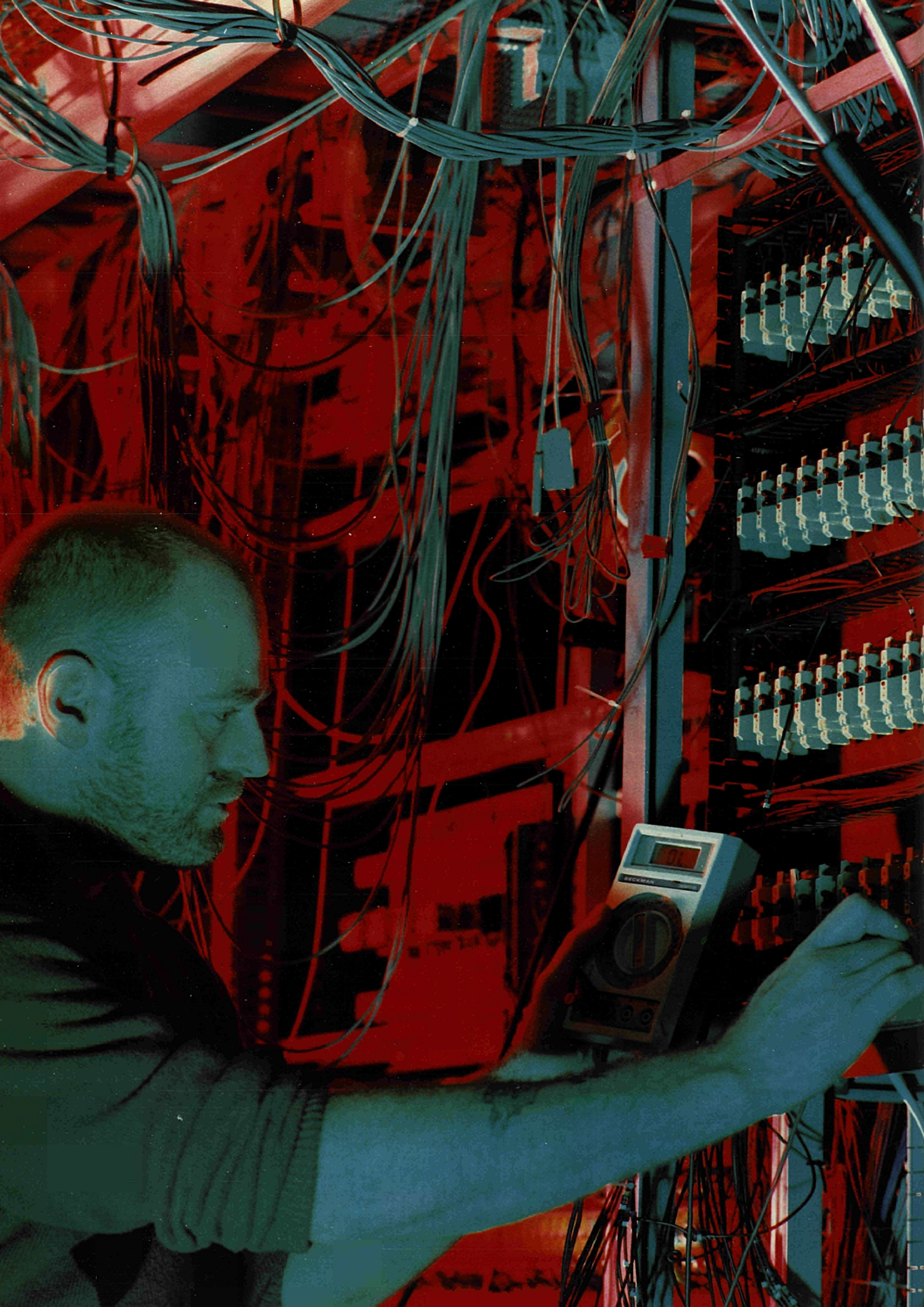
detritiation and gas chromatography (see Fig.33). In addition, a series of tests and modifications to improve the performance of the cryodistillation system were carried out.

An analytical laboratory was designed as a central facility for the Active Gas Handling System with the purpose of analysing all gas species exhausted by JET and treated in the different subsystems of the plant. A special gas chromatograph was built for the detection of the six hydrogen molecules, helium, carbon monoxide, carbon dioxide, methane and higher carbon hydrides, nitrogen, oxygen and water. The separation of the gas species is carried out via commercially available packed columns. A series of tests were carried out to confirm that the required performance was achieved, and all gas species were detected and separated.

All the Design Safety submissions for the Active Gas Handling System have been issued to the Safety and Reliability Directorate (SRD) of the UKAEA. Apart from minor issues which can readily be resolved, the design of the system has been accepted as meeting UKAEA standards. Effort is now concentrated in producing the justification documents, which will permit active commissioning to begin. As well as providing an overall assessment of the accidental risk from the plant, these will deal with issues of operational safety management.

For the torus system, SRD have specified that a rigorous hazard analysis methodology should be used to identify any hazards arising from the design and operation of the machine in the D-T phase. Work has started with a series of Hazard and Operability studies (HAZOPs), which will be used to identify those systems which require a detailed safety justification involving Failure Mode and Effect Analysis (FMEA) and Fault Tree analysis.

In accordance with the Authorisations issued by the Department of the Environment, careful monitoring of the effect of the Preliminary Tritium Experiment in November 1991 has continued. This confirms that the experiment has had negligible environmental impact.

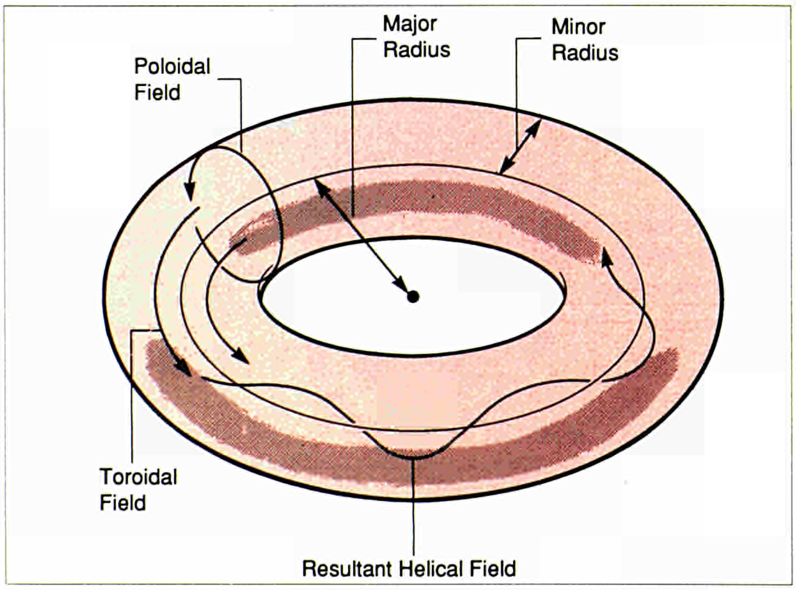

BECKMAN

Scientific Advances during 1992

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 such that the product ($n_i\tau_E T_i$), exceeds the value $5\times10^{21}m^{-3}skeV$. Typical values for these parameters which must be attained simultaneously in a reactor, are given in Table 9.

With ohmic heating alone in JET, temperatures of 3keV and 4keV for the ions and electrons, respectively, densities of $4\times10^{19}m^{-3}$ and energy confinement times of 1s are the limits that have been achieved. These parameters were obtained simultaneously during one discharge and result in a fusion product of $1.2\times10^{20}m^{-3}skeV$. However, higher peak values of electron and ion temperature have been reached using additional radio frequency heating and neutral beam heating and combinations of these methods. Even so, these substantial increases in temperature were associated with a reduction in the energy confinement time as the heating power was increased. Thus, gains in plasma temperature have been partly offset



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 vary and usually decrease with increasing minor radius. The number of turns a field line must traverse around the major direction of the torus, before closing on itself, is denoted by the safety factor, q. Of special importance are the positions where q is numerically equal to 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 plasma current value. 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 elongated plasma cross-section rather than circular. This enables larger plasma currents to be carried for given values of magnetic field, major radius and 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.

by degradation in energy confinement time. The fusion product values obtained have not shown the full gains anticipated over conditions with ohmic heating only. However, a substantial increase in the values of the fusion product has been achieved, by operating in the so-called magnetic limiter (X-point) configuration. During the 1991/92 campaign, values of 9-10x10^{20}m^{-3}skeV were obtained using up to 16MW of additional heating.

Table.9: Reactor Parameters

Central Ion Density, n_i	2.5x10^{20}m^{-3}
Global Energy Confiement Time, τ_E	1-2s
Central Ion Temperature, T_i	10-20keV
Fusion Product, $(n_i\tau_E T_i)$	5x10^{21}m^{-3}skeV

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 temperature up to 30keV, energy confinement times up to 1.8s and central densities up to 4x10^{20}m^{-3}.

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 acceptable high confinement

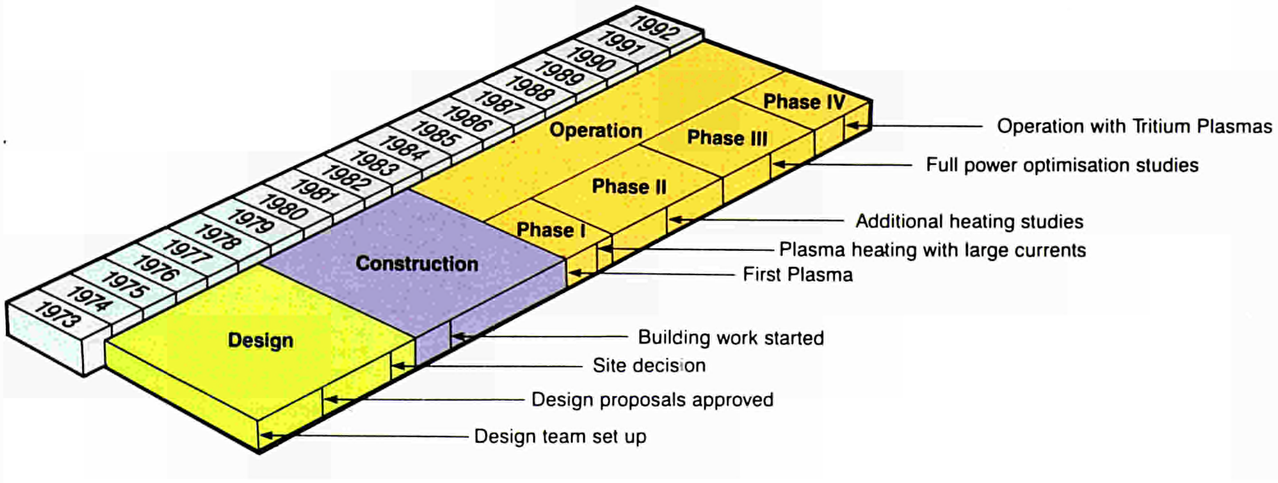


Fig.34: The original overall JET programme.

time. These conditions should ensure that sufficient alpha-particles are produced with deuterium-tritium operation so that their confinement and subsequent heating of the plasma can be studied.

The original scientific programme of JET was divided into four phases as shown in Fig.34. 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, Phase IIA, had been completed. The machine then entered a planned shutdown for extensive modifications and enhancements before the second part of the Additional Heating Studies, Phase IIB, which started in June 1987. The objective of this phase, from mid-1987 until late-1988, was to explore the most promising regimes for energy confinement and high fusion yield and to optimise conditions with full additional heating 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 heating power exceeding 20MW at 80kV. 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 and was completed in early 1992.

The 1991/92 experimental programme was executed by three Task Forces, with the programme objectives divided, as follows:

Task Force H: High Performance

(involving progression to full performance in material limiter and magnetic limiter configurations with currents up to 7MA, with high energy content and including progression to the highest fusion product, long pulse operation, steady state conditions and exploration of operational limits, etc.)

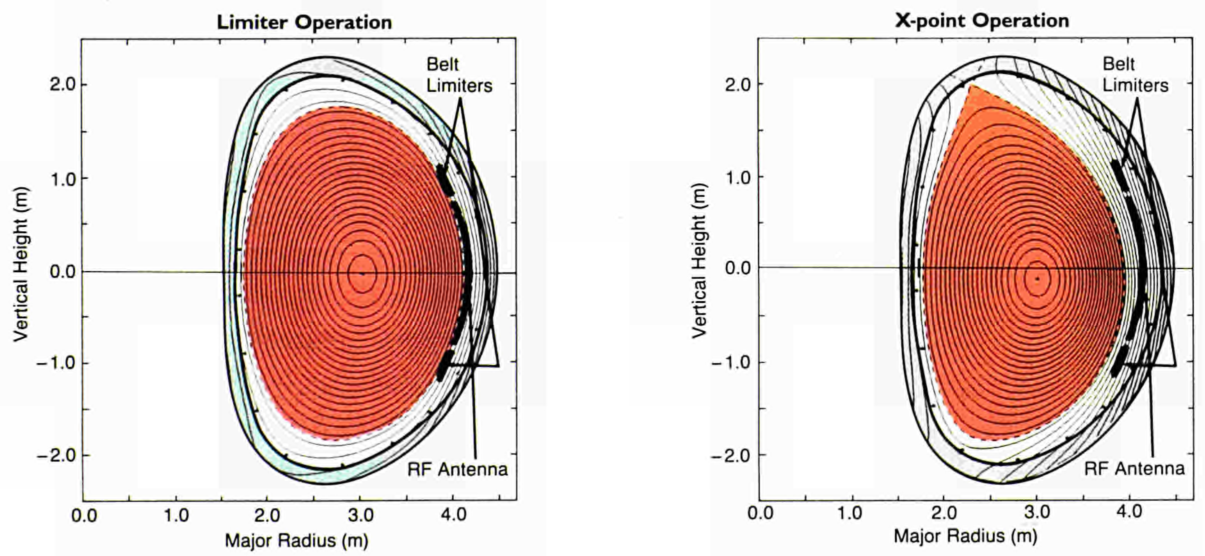
Operating Modes

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 material 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 (or magnetic limiter) 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 the High (H)-mode of operation.



Task Force I: Impurity Transport and Exhaust

(involving optimization of plasma purity and studying exhaust phenomena, and including studies of divertor physics and edge effects; impurity retention, erosion and redeposition; control of boundary instabilities, etc.)

Task Force P: Physics Issues

(involving studies of control and optimization of plasma profile effects (using LHCD, RF, NB and pellet injection, etc.) and optimization of heating effects, especially electron heating. This included particle and energy transport studies in transient conditions; disruption and sawtooth stabilisation; high beta regimes; α-particle and fusion simulation studies; and issues related to Next Step devices.

Main Scientific Results

The 1992 experimental campaign essentially sought to extend and complete the experimental investigations addressed during the 1991 campaign. As outlined in the 1991 Report, the major themes of the programme during 1991-1992 were:

- introduction and exploitation of new facilities;
- optimization of plasma performance;
- advancing understanding in key certain areas of tokamak physics, such as: physics of the H-mode; energy transport and confinement; and transport of particles and impurities;
- establishing the basis for Pumped Divertor and Next Step physics (including a Preliminary Tritium Experiment);
- to complete certain experiments relevant to the belt limiter configuration.

Since many of the experiments relevant to the first, second and fourth themes were completed in the 1991 campaign, these had a lower priority in the 1992 experiments. This permitted more time to be allocated to experiments designed to improve physics understanding in several areas and to experiments aimed at completing the programme of studies utilizing the belt limiter. Nevertheless, significant advances in pumped divertor and Next Step issues were also made.

The major constraint on the programme during this period was the requirement to limit neutron production, in order to minimize vessel activation for the start of the major 1992/93 shutdown. Since much of the vessel activation had been contributed by the first tritium experiment, inevitably neutron production had to be strictly controlled. While this limited the duration of experiments at the highest power levels, it did not prevent significant advances being achieved in several areas. This review concentrates on those areas where significant new results were obtained during 1992.

The scientific results in these areas are described in the following sections, under the headings: Density Effects; Temperature Enhancement; Energy Confinement Studies and Impurities.

Density Effects

Disruptions and Density Limits

In most tokamaks, disruptions can occur under certain circumstances. Disruptions are dramatic events in which plasma confinement is suddenly lost, followed by a complete loss of current in the plasma. Disruptions pose a major problem for tokamak operation as they can impose a limit on 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.

Extensive and detailed studies of disruptions in JET have been undertaken. The complicated pattern of behaviour of fast disruptions in JET is now reasonably well understood. The early phase of development is associated with MHD instability, current re-distribution, a negative voltage within the plasma and energy loss. In fast disruptions, this is followed by a sudden plasma cooling, now thought to be due to a massive localised influx of impurity. The increase in resistivity leads to the release of the trapped negative voltage followed by a large positive voltage. It is the associated electric field in the plasma which can produce a large current of runaway electrons.

With carbon limiters, large runaway currents are produced. With X-point configurations, the currents are less and with beryllium limiters there are generally few runaway electrons. In some discharges, the runaways carry a large fraction of the original current for a considerable time. These runaway electrons have energies of tens of MeV and the current is located at a small major radius. They are generally stably confined but are subject to sudden unexplained loss. While they are confined, they lose energy by synchrotron radiation, but since the electrons are relativistic, the current persists. Typical behaviour is illustrated in Fig.35 from a disruption at 1.8MA.

Once the runaway regime has been reached, the energy of the runaways increases rapidly. Calculations show that energies up to 36MeV are reached in 12ms, in agreement with the characteristic rise time seen in the hard X-ray signal. After a substantial runaway current is produced, the loop voltage drops to around zero and the hard X-ray signal then shows a smooth decay. This signal is believed to originate in bremsstrahlung radiation from the runaways.

Effort has also been devoted to development of techniques for avoidance of disruptions, or for the minimisation of their consequences. A substantial advance was made in this respect through

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 magnetic surface where q=2.

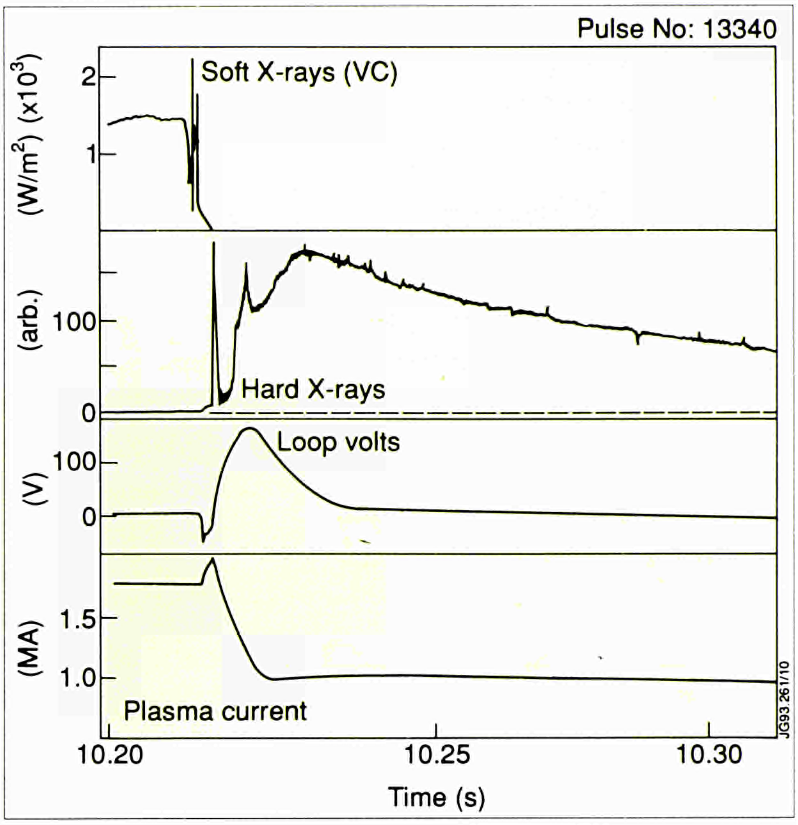


Fig.35: The time development of the soft and hard X-rays, the loop voltage and plasma current, following a disruption

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 solid 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, to provide a pumping mechanism for removing particles so that the density can be reduced below the critical limit.

improvements to the Plasma Fault Protection System (PFPS). Early detection of precursors to major disruptions has enabled measures to be taken (reduction of plasma current, elongation and of heating power) to minimize impact of the resultant disruption on the torus.

Of fifty pulses at 7MA plasma current during 1992, there was only one with a disruption. In this case, a stationary mode precursor was detected by the PFPS system and the current shaping the elongated plasma was ramped down to zero before the start of the current quench. As a result, the vertical position was well controlled down to about 2MA. The resulting force on the vessel was only 200kN (~20tonnes). The vessel forces arising from this 1992 7MA disruption are compared in Fig 36 with one in 1990 causing vessel damage. The benefit is clearly obtained reliably, and in the 1992 7MA case reduced the vessel forces from 400 tonnes to only 20 tonnes. No vessel damage resulted and the 7MA programme continued.

A particular disruption instability is that caused by the growth of large amplitude n=1 'locked' modes as the internal separatrix (X-point) is formed. The poloidal and toroidal field coils generate small error fields, that is components of magnetic field which are not axisymmetric. These error fields cause disruptions if the plasma density drops below a minimum value at low edge safety factor, q(a).

Experiments were carried out in which the total error field was dominated by that from vertical field coils. The plasma density was

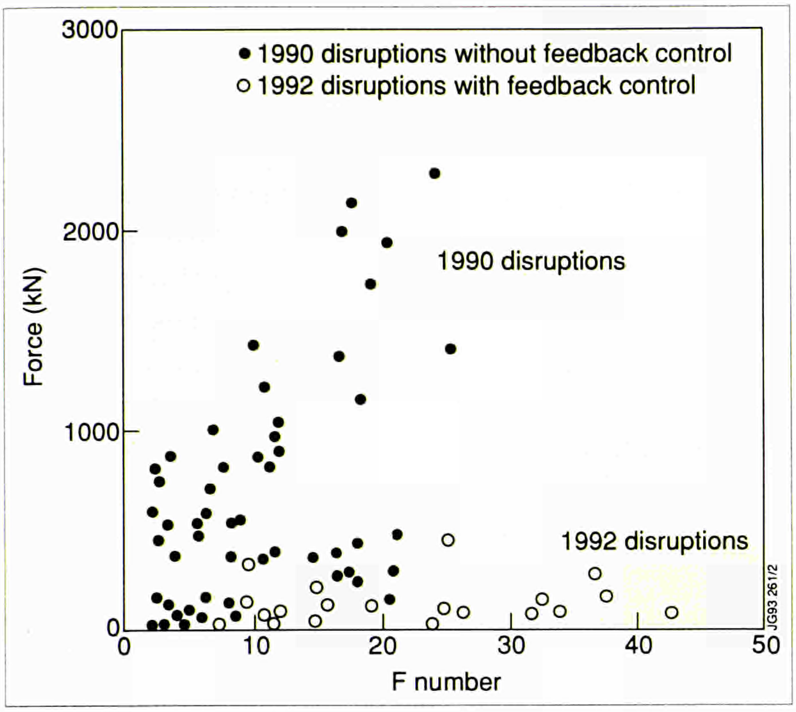


Fig.36: Vertical forces on the vacuum vessel during disruptions versus a measure of the vertical destabilisation force on the plasma (F number). The triangles show the normal case whereas the circles show the effect of ramp down action of the current following detection of the disruption precursor

ramped down slowly and the minimum density for each plasma was taken as the density immediately before growth of a helical perturbation of the magnetic field. This was performed in two cases, when the predominant error field was ~1 Gauss and when it was 0.4 Gauss. Plasmas with various values of safety factor on the last closed flux surface, q(a), were produced by varying the toroidal field. The results from both configurations of the vertical field coils are shown in Fig.37 and it is seen that error fields below 0.4 Gauss are required for safe operation.

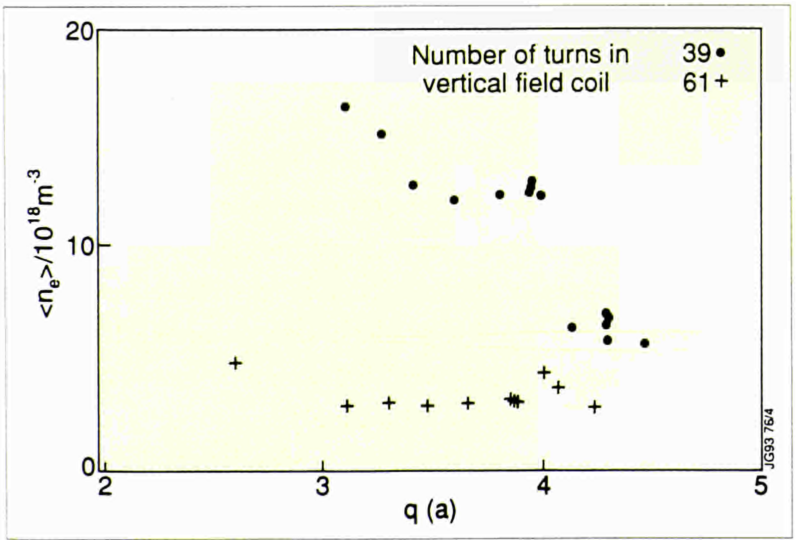


Fig.37: Measurement of the minimum density for the two configurations of the vertical field coils, as a function of q(a)

Plasma Fuelling

Efficient fuelling of a reactor plasma is an important aspect, particular in a divertor configuration. To understand the interrelationship between plasma fuelling, divertor plasma density and main plasma density recycling, as well as the role of the material surfaces, fuelling studies were carried out. Comparisons were made between discharges where the location of the external gas fuelling source was changed from the plasma mid-plane to the divertor region. In other experiments, the plasma configuration was changed from limiter to divertor and the resulting density variations were studied. Additional studies comprised discharges with central particle fuelling by pellet injections or neutral beam injection.

The experimental results were analysed by means of an extended particle balance model, where plasma particles which hit the material surfaces were assumed either to diffuse into the material or to leave it by recombination into molecules. Those leaving the surfaces were assumed to fuel the main plasma, however, only with an efficiency of less than unity, while the complementary remaining ones returned to the surface. Results of the analysis showed that for a given external fuelling flux, the plasma density and the magnitude of the recycling flux depended in a non-linear fashion, on the pumping capability of the material surfaces.

For gas fuelling, particle consumption and recycling fluxes did not depend on the poloidal location of the gas valve. If pellets or beams rather than gas fuelling was used, both recycling fluxes as well as particle consumptions were reduced.

Analysis showed that besides the external fuelling sources, the strength of the recycling source for plasma fuelling had to be taken into consideration. This depended on the fuelling and pumping efficiencies. In gas fuelling experiments under quasi-steady state, the recycling flux dominated over the external flux and contributed most to the plasma fuelling such that the poloidal differences in the fuelling efficiencies of external gas sources became unimportant. To explain the results due to pellet and neutral beam fuelling, the assumption of an increase of fuelling efficiency alone was not enough, but an increase of the average particle confinement time due to deep penetration of neutrals into the plasma had also to be taken into account. For non-steady state conditions, the analysis showed that increases of the plasma density transiently lead to an increase of passive pumping and so temporarily caused a relative decrease of the recycling flux, unfavourable for impurity reduction.

Generally, the analysis explicitly indicated that, to maximise recycling fluxes whilst pumping is required during quasi-steady state, the smallest possible pumping should be established, a low fuelling efficiency for recycling particles should be achieved (baffling) and shallow fuelling (gas) should be used. Small fuelling efficiencies will invariably increase particle consumption. If gas is externally fuelled into the divertor region, then the recycling flux becomes independent of pumping efficiency due to similar fuelling efficiencies for recycling and external particle fluxes. Baffling of neutrals is a way of controlling the recycling flux.

Temperature Enhancements

Sawtooth Oscillations

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

The consequences of the sawtooth instability are detrimental in two respects. This instability flattens the central plasma temperature and density, and it can expel energetic particles (injected by neutral beams, accelerated by 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 can be achieved by injection of lower hybrid (LH), radio-frequency (RF) waves or neutral beams into the plasma. In addition, a spontaneous stabilization process was discovered during heating experiments in JET, which has resulted in the production of long sawtooth-free periods (called 'monsters').

This has simulated extensive experiments to clarify the underlying stabilization mechanism, and has led to the development of the idea that sawteeth can be stabilized by a population of energetic particles which are accelerated by ICRF waves or by NB injection. This theory predicts that stabilization is associated with a peaked profile of fast particles within the q=1 surface, but that the m=1 mode becomes more unstable as the q=1 radius expands, as can occur due to resistive diffusion of the current profile.

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 sawteeth, which occur on the q=1 surface, this high current density region would be squeezed or pinched inwards. Selective heating outside 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 (called Lower Hybrid Current Drive (LHCD)).

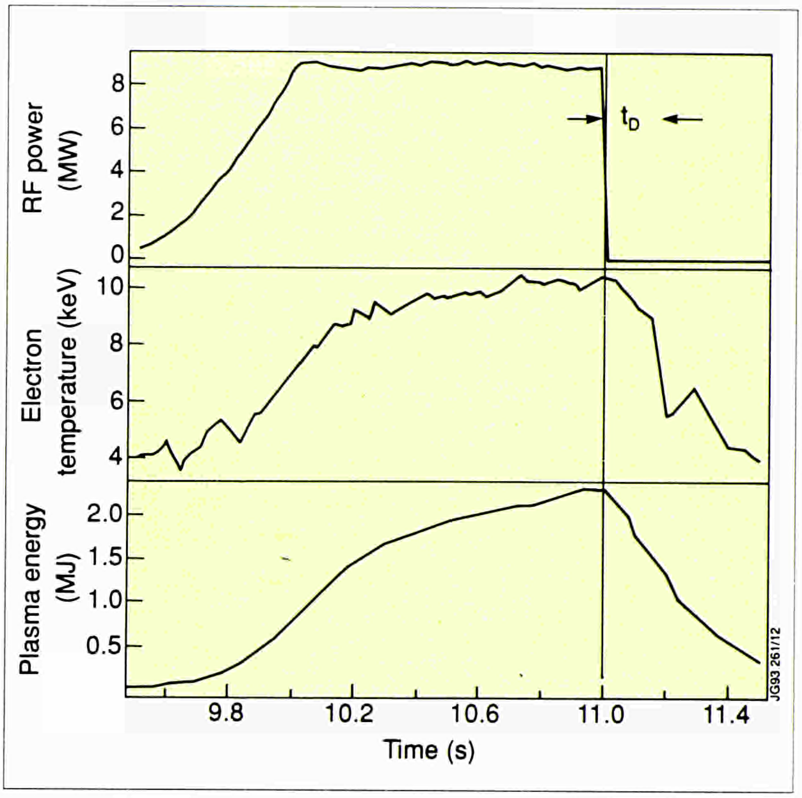


Fig.38: Switch-off of ICRF power showing delay (t_D) to a monster sawtooth crash shown by the collapse of the electron temperature and the plasma energy

To test these aspects of the theory, a series of discharges were performed in which the sawtoothing was suppressed by the application of ICRF power on-axis. The ICRF power was switched off at different times during the sawtooth suppression interval, and the time delay for a sawtooth to occur after switch-off was measured as shown in Fig.38. To relate the experimental observations to theory, measurements of the evolution of the q=1 radius and of the fast particle content were used to construct a model of the behaviour of these critical quantities during the ICRF pulse. On this basis, these experiments showed that the behaviour of the delay from RF switch-off until the sawtooth collapse was consistent with that expected from the fast particle stabilization theory.

High Power Heating

The main sources of high power additional heating in JET are the power introduced into the plasma from neutral beam injection and from the ion cyclotron resonance frequency (ICRF) heating system.

The two neutral beam injectors on the JET machine inject high energy neutral beams into the plasma tangential to the torus from diametrically opposite positions at Octant No: 4 and Octant No: 8. Originally, both injectors operated at 80kV energy and in 1988 deposited up to 21.6MW power in the plasma. During 1989/90, the Octant No: 4 system was converted to 140kV operation with deuterium beams and during 1991, the Octant No: 8 system was similarly

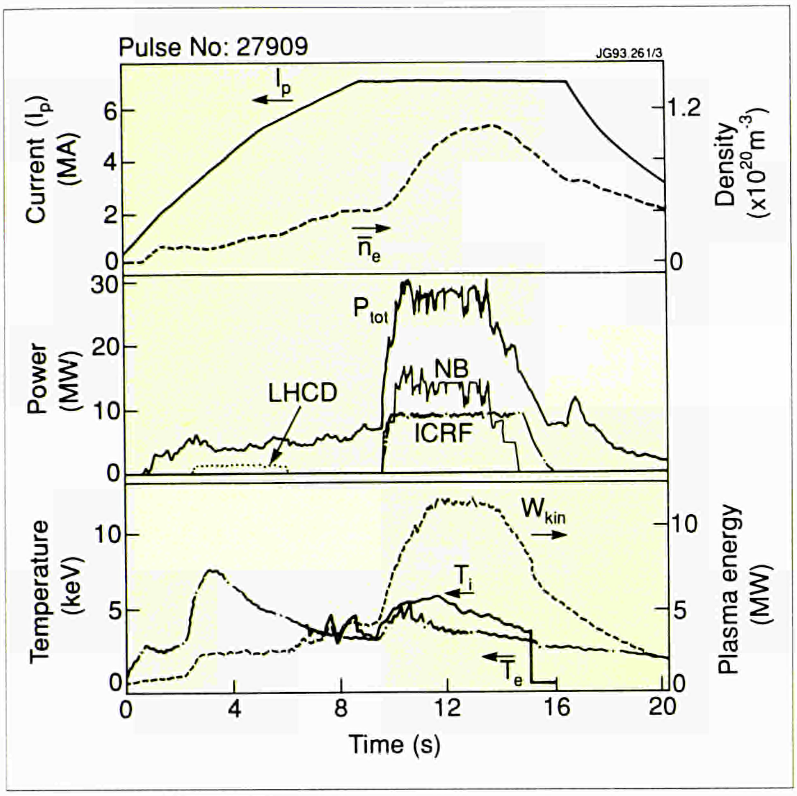


Fig.39: A 7MA dicharge with 28MW of additional heating, in which the introduced power produces in excess of 12MJ of energy in the plasma

upgraded. This provides greater penetration of the neutral beams into denser plasmas and deposits more power near the plasma centre. However, when operating both systems at 140keV, the total power was reduced to 16MW of beam power. The high power beams have been used for injection of H, D, ^{3}He and ^{4}He neutrals into JET plasmas.

The ion cyclotron resonance frequency (ICRF) heating system is used for highly localized heating of JET plasmas. The wide frequency band (23-57MHz) allows variation in the radial 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. A maximum ICRF power of about 22MW for 1.75 seconds has been coupled to the plasma.

During 1992, a programme with 7MA plasma current in deuterium discharges was undertaken, with high power heating. Over fifty discharges were reliably achieved. Figure 39 shows an example of high power heating at 28MW applied to a 7MA plasma. The power was made up of 12MW ICRF heating together with 16MW of neutral beams. Although, the electrons and ion temperatures only reached ~6keV, the density was high (~10^{20}m^{-3}) and the heating was sufficient to allow the plasma stored energy to reach ~12MJ under steady conditions. This is comparable to the best H-mode results achieved transiently on JET at lower current and power.

Lower Hybrid Current Drive

The Lower Hybrid Current Drive (LHCD) system (12MW at 3.7GHz) is intended to drive a significant fraction of the current flowing in the plasma, by direct acceleration of the plasma electrons through interaction with lower hybrid waves. This should stabilize sawtooth oscillations, thereby increasing the central electron temperature and improving overall JET performance. This will be the main tool in JET for controlling the plasma current profile. A prototype system consisting of two launching units (one built by CEA Cadarche, France, and the other built by JET) fed by a total klystron power of 4MW was used during the 1991/92 campaign.

Encouraging results have been obtained with the prototype system. Full current drive in almost steady-state conditions has been achieved. At low electron temperature of T_e ~1keV, 0.4MA was driven by LH alone with 1.5 MW of coupled power. At higher temperatures of T_e~5keV, during the application of ICRF power, 2MA current was maintained at plasma densities of ~2.5x10^{19}m^{-3} and 2.8T toroidal magnetic field. Close to 2MW of LH power have been coupled to a 1MA discharge, in conjunction with 3MW of ICRF power, maintaining the full plasma current for 4s. Flux savings of ~2V-s resulted from application of ~1.5MW of LH power during the low density current ramp-up phase of 7MA limiter plasmas allowing an extension of the current flat-top by 2 seconds to a total of 9 seconds. Installation of the full LHCD systems should increase the power in the plasma to ~10MW, which should increase the potential of achieving full current drive of 4MA plasmas.

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

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

where W_k is the kinetic energy and P_t is total input power to the plasma without subtracting radiation losses. The values of τ_E reported are such that $(dW_k/dt) << P_t$ and so are quasi-stationary.

Material Limiter Configuration

Energy confinement times up to 1.8 seconds have been attained in JET ohmically heated discharges. However, the temperatures achieved

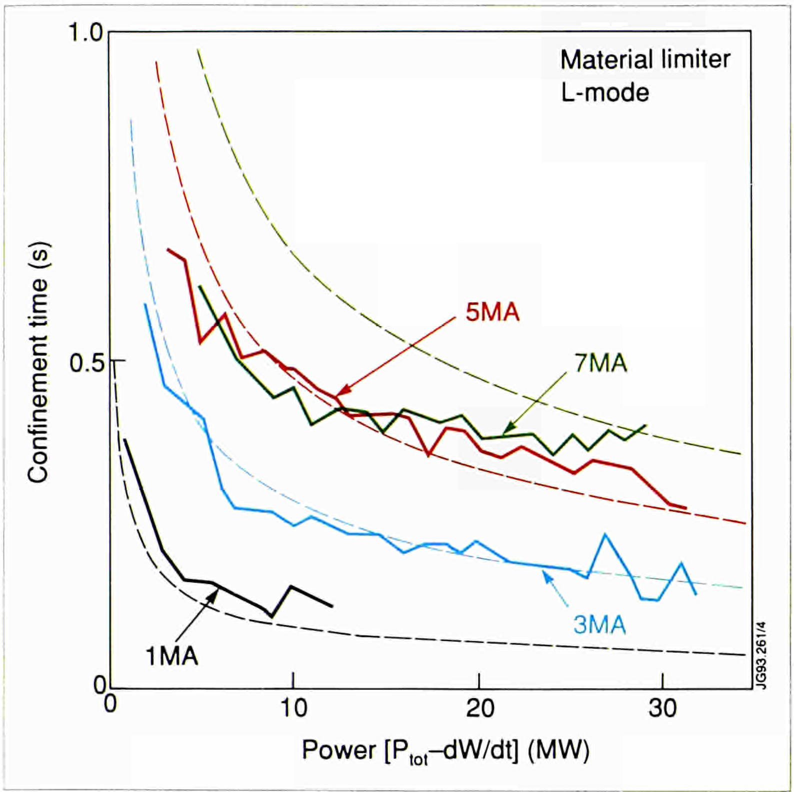


Fig.40: Confinement time as a function of input power for material limiter conditions, for different plasma currents

are too low to achieve fusion reactor conditions, so that it is important to provide additional heating.

Energy confinement times on JET fall with increasing heating power independent of the type of heating, whether neutral beam injection, radio frequency heating or a combination of the two methods, with both carbon and beryllium limiters. However, with a beryllium first-wall improved density control is achieved due to higher wall pumping and the impurity content (and plasma radiation) is reduced. These factors allow higher plasma densities and result in improved fuel concentrations (n_D/n_e), which permit improved fusion performance.

The decrease of energy confinement time with increasing heating power in material limiter cases is shown in Fig.40. The energy confinement time shows only a weak dependence on density, but improves favourably with increasing plasma current. The global energy confinement time results have been fitted to results from thirteen tokamaks worldwide (including JET) by a simple power law relationship. The ITER and L-mode scaling law still remains valid and is given by

$$\tau_E(\text{ITER89-P})=0.048\, A^{0.5} I_p^{0.85} T^{1.2} a^{0.3} \kappa^{0.5} (n/10)^{0.1} B^{0.2} P^{-0.5}$$

where A is the atomic number, I_p(MA) is the plasma current, R(m), is the major radius a(m) is the minor radius, κ is the elongation, B(T) is the magnetic field, n(10^{19}m^{-3}) is the density, and P(MW) is the total input power.

Energy Confinement

Energy confinement in tokamaks when the plasma is bounded by a material limiter generally degrades as the input power to the plasma increases. The result is that the energy confinement time, τ_E falls approximately as the square root of the input power. This regime is said to exhibit L(low)-mode confinement. In plasmas with a magnetic limiter (that is with an internal magnetic separatrix or X-point), a transition can occur above a certain threshold input power to a regime in which the energy confinement time is increased by a factor of two or more greater than in the L-mode situation. This has been called H(high)-mode confinement. However, a similar degradation with input power is observed.

In addition to the improved energy confinement time, enhanced particle confinement is observed and the temperature and density close to the separatrix can increase substantially, resulting in the formation of plasma profiles with an edge 'pedestal'. The precise conditions for the transition into the H-mode vary with plasma parameters. For example, the threshold power for the transition increases at least linearly with the toroidal magnetic field. In recent years, the H-mode transition has also been observed in plasmas with a material limiter, although the power threshold is usually significantly higher than in magnetic limiter (X-point) plasmas.

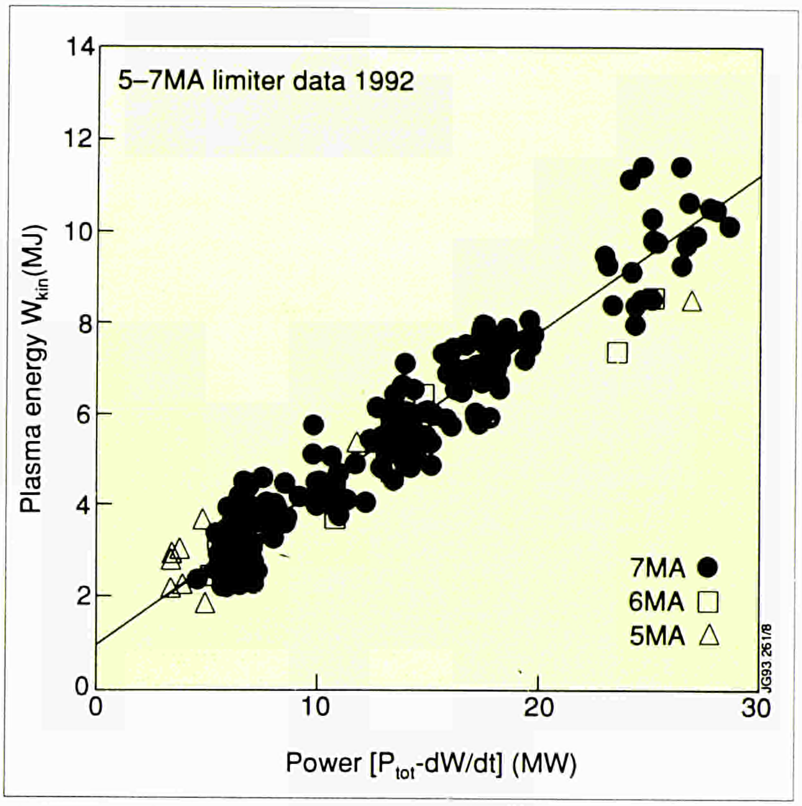


Fig.41: Thermal stored energy plotted against loss power for 5,6 and 7MA plasmas from the 1992 campaign

During 1992, long pulse full and half power discharges were run at 5, 6 and 7MA plasma current. The data from these pulses have been incorporated into Fig.40. The thermal stored energy from these pulses is shown in Fig.41 plotted versus power. At the highest power, the global thermal energy confinement time was τ_E=400ms. The 5,6 and 7MA data were similar at moderate power, but the stored energy at 7MA was significantly higher at full power reaching ~12MJ. The confinement times achieved at 7MA are similar to those at 5-6MA, due to sawtooth degradation and increased impurity content. The latter might be avoided by better density optimization.

Most scaling laws of energy confinement predict that the energy confinement time τ_E scales as $A^{0.5}$ where A is the atomic mass of the ion species. However, such a dependence is difficult to justify on theoretical grounds. The dependence of energy confinement in JET on the plasma ion species was studied by means of a full global and local transport analysis of a series of discharges with fixed geometric configuration, plasma current and toroidal field, but with different ion species H, D and ^3He.

Figure 42 shows the total and thermal energy confinement time as a function of density. The thermal energy confinement time in deuterium is ~15% larger than in hydrogen at all densities. This difference is somewhat larger in total energy confinement times due to larger fast ion component with deuterium injection, but it does not exceed 25%. No significant difference was observed in thermal

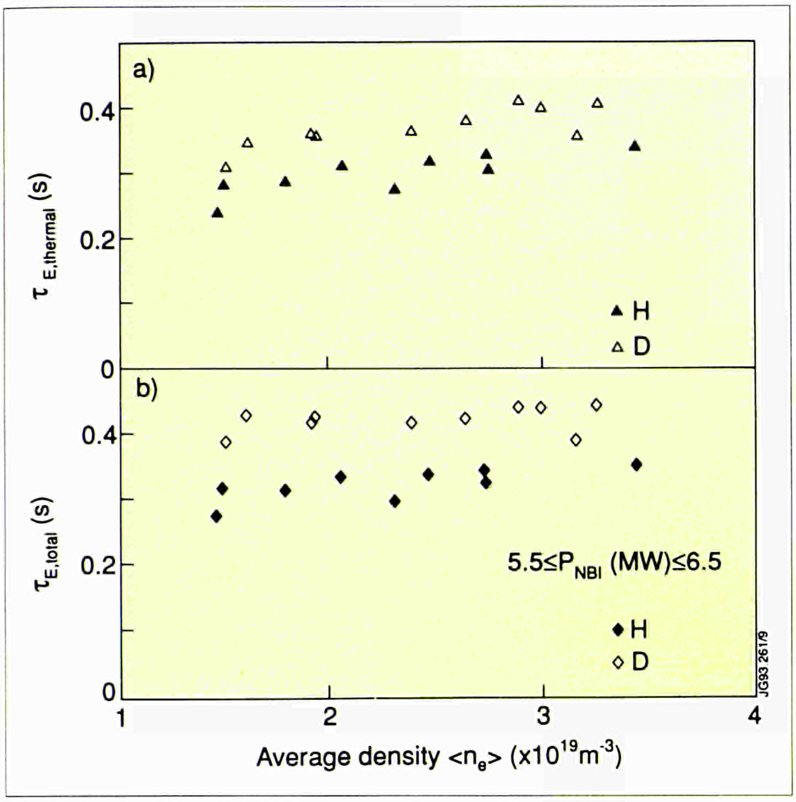


Fig.42: (a) thermal energy confinement time and (b) total energy confinement time versus volume thermal and average density

energy confinement time or in particle confinement time of D and ^{3}He discharges. In summary, JET results point to very weak dependence of the thermal energy confinement time on ion species ($\tau_E \propto A_i^{0.2\pm0.1}$) and do not support the hypothesis used in most scaling laws of a square root dependence on the isotope mass, A_i.

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. With heating applied above a certain threshold power value, a transition occurs to an improved plasma confinement (H-mode) regime, which depends upon the toroidal magnetic field. Fundamental characteristics include a rise in energy content and plasma density. An increase in electron temperature also occurs near the separatrix, which produces a pedestal in the temperature profile, and a flatter density profile with a steep gradient near the separatrix. The energy confinement time in the H-mode exceeds that with limiter discharges (L-mode) by more than a factor of two, as shown in Fig.43.

Energy confinement predictions for H-mode operation in Next Step tokamaks require a scaling law based on tokamaks of different dimensions. Throughout 1991/92, JET has continued to add new data to the H-mode database for global confinement scaling at the

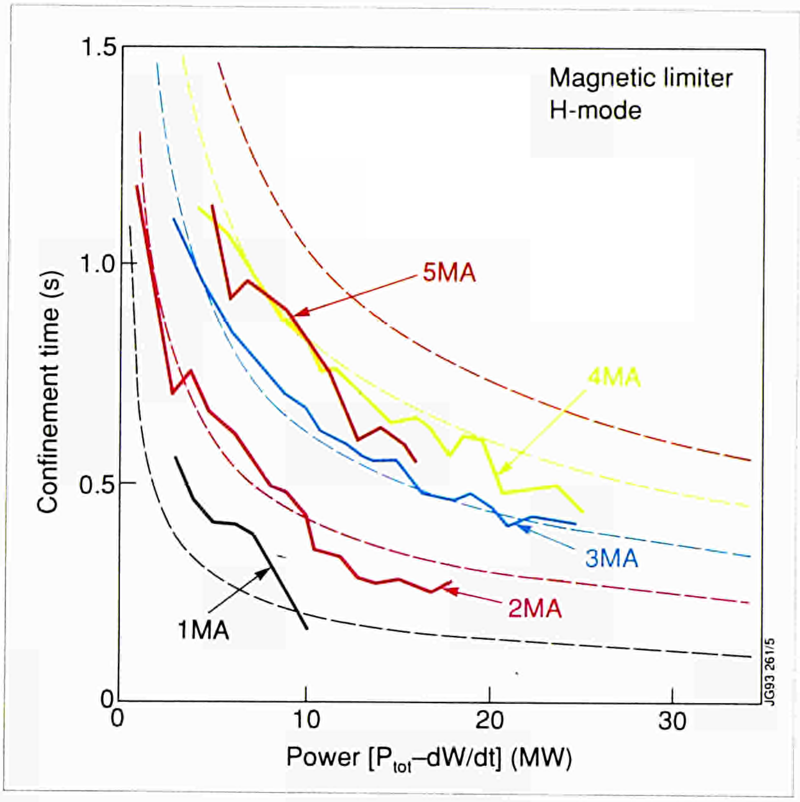


Fig.43: Confinement time as a function of input power for magnetic limiter conditions, for different plasma currents

MARFE

A MARFE (Multifaceted Asymmetric Radiation From the Edge) is a toroidally symmetric band of cold, highly radiating plasma which normally forms at the plasma inner wall. It can occur when the plasma edge density is high and results from of an imbalance between the power flowing along magnetic field lines in the edge and the power lost locally due to radiation. A MARFE grows rapidly, on a timescale of ≈10-100 milliseconds, but it can persist for several seconds. In some cases, the MARFE leads to a disruption, but in others the main consequence is a reduction in the edge density.

request of the ITER Project. The work is performed as a combined effort from JET and from other tokamaks (DIII-D (General Atomics, USA), ASDEX (IPP Garching, FRG), JFT2M (JAERI, Japan), PBXM and PDX (PPPL, USA)). The database now contains measurements from a variety of heated H-modes (ECH, ICRH and neutral beams). The fit to the data set gives:

$$\tau_E(\mathrm{ITER92H\text{-}P})=0.032\, I_p^{0.95} B_T^{0.20} P^{-0.65} A^{0.45} R^{1.9} \kappa^{0.65} n^{0.3} a^{0.05}$$

where τ_E(s) is the energy confinement time, I_p(MA) is the plasma current, P(MW) is the loss power, A is the atomic number, R(m) is the major radius, κ is the plasma elongation, n($10^{19}m^{-3}$) is the density, and a(m) is the minor radius.

During 1992, H-mode plasmas were obtained in double-null X-point configuration at plasma currents up to 5MA, further extending the H-mode database, particularly with respect to confinement scaling. However, the configuration formed at 5MA showed that the magnetic null-point was located about 10cm outboard of the surface of the X-point dump-plates. Despite the marginal nature of this X-point configuration, H-modes with ELM-free periods were nevertheless obtained. Figure 44 summarises the global confinement data of these H-modes in the range 3-5MA. The 5MA data confirms the previously observed trend that the increase of confinement with current eventually saturates.

During the series of hot-ion H-mode experiments completed during the 1991/92 campaign, a new enhanced confinement

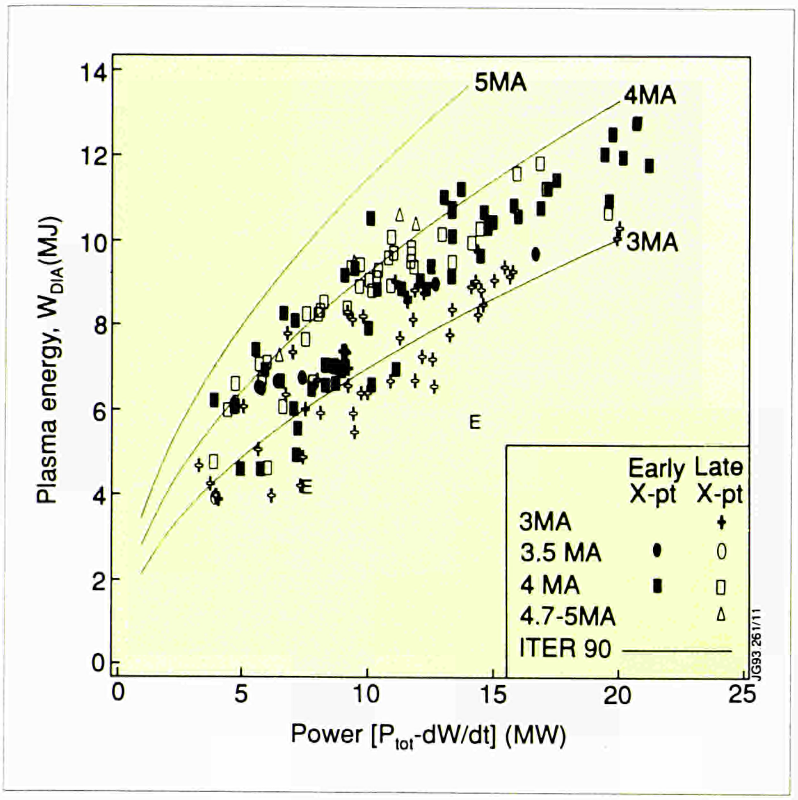


Fig.44: Stored energy versus power for double null X-point 3-5MA H-modes, during ELM-free periods. Solid curves are predictions of ITER scaling law

regime was found. The new regime is similar to the VH-mode seen in DIII-D, with values of the confinement time about twice the usual ITER H-mode scaling and exceeds a factor three above the L-mode scaling expression. This improved confinement follows a second transition during the H-mode. The transition is clearly visible and is usually coincident with the disappearance of ELMs during the H-mode. The high confinement is associated with reduced energy transport near the edge. The improvement in confinement from L-mode to H-mode coincides with the development of steep gradients in the temperature and density profiles near the edge. The improvement in confinement from H-mode to VH-mode is a consequence of the broadening of the steep gradients. Figure 45 shows the confinement time for the VH-mode plotted versus the ITER(92H-P) scaling for values taken at currents of 1, 2 and 3MA.

An ELMy period is often observed before the transition to VH-mode. In this ELMy period the gradients in the interior increase before the broadening of the edge gradients occurs in the VH-mode phase. The existence of steep edge pressure gradients and significant edge currents during the VH-mode phase indicate that these discharges may have access to and may enter the second stable region of ballooning instability modes at the plasma edge. Calculations on some of the high performance discharges show that this is indeed possible.

ELM

An ELM (Edge Localized Mode) is an edge instability which occurs in the high confinement (H-mode) regime. It affects a narrow region in the plasma edge and leads to a loss of particles and energy from the edge on a timescale ≤1 millisecond and therefore is a rapid, but transient, instability. However, ELM's can occur as repetitive instabilities which cause a reduction in the time-averaged energy and particle confinement time.

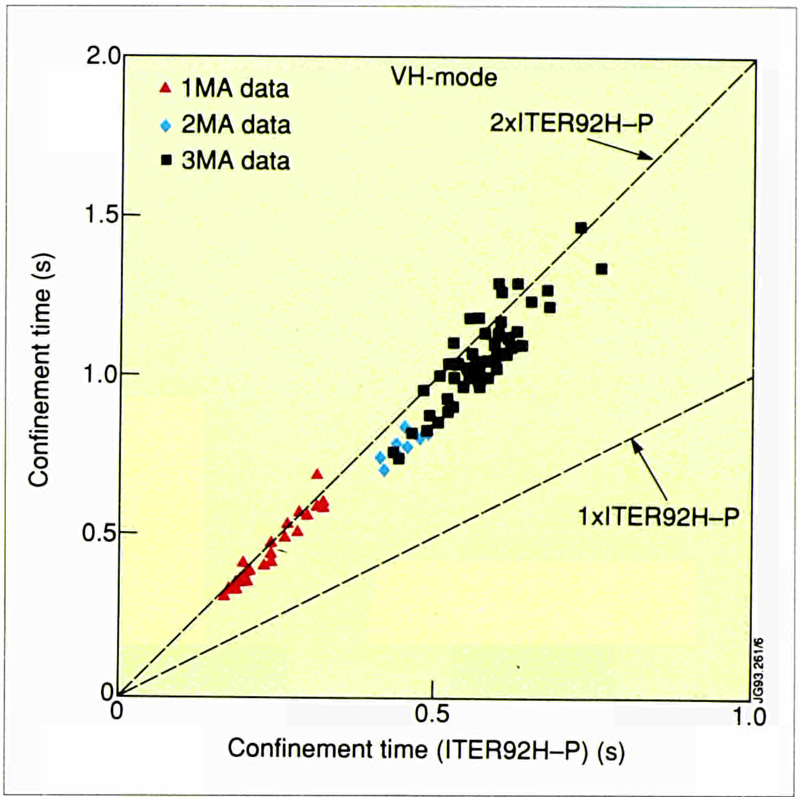


Fig.45: Confinement time for the VH-mode plotted versus the ITER(92H-P) scaling for values taken at currents of 1, 2 and 3MA

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 in the plasma would cause this value to be increased. In JET, Z_{eff} is generally in the range from 1.2-3.*

Major energy losses can result from two radiation processes:

- *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;*
- *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.

Impurities

Impurities present a major problem in tokamaks 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, with a corresponding fall in thermonuclear yield;
- reductions in the density limit.

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.

During 1991/92 an assessment was made of the global impurity behaviour in JET. Frequent metallic influxes occurred throughout the campaign. This contrasted with 1990 operations in which chlorine was a significant contaminant and where nickel and chromium influxes were observed only at the end of the campaign, after displacement of some protective X-point tiles. In 1991/92, the most common influxes were nickel and chromium, the main constituents of inconel. In addition, some iron influxes were observed and, less frequently, those of aluminium, copper and zinc.

During operations, it was not possible to determine the source of the nickel and chromium, the most serious of the metallic contaminants. Investigations suggested a number of possible sites. It was

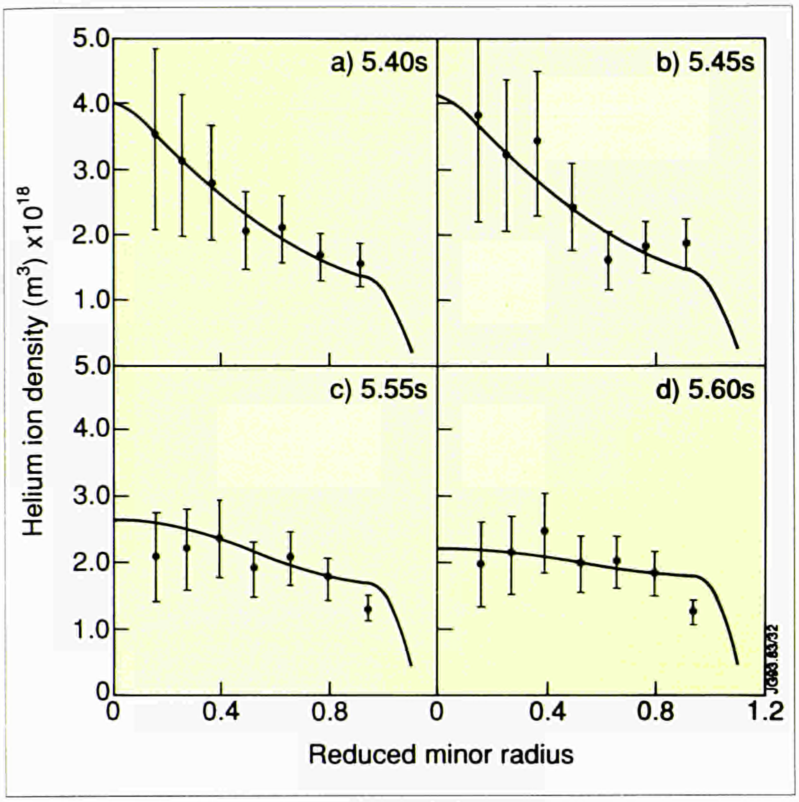


Fig.46: Helium ion density profiles in a typical L-mode discharge. Helium fuelling ends at 5.5s. The solid curves are simulations using an impurity transport code

concluded that many of the releases came from secondary sources, which had resulted from the previous deposition of materials released from a primary source. Subsequently, confirmation was provided by an analysis of a number of inner wall tiles which indicated that these were covered by a film many millimetres thick and containing ~1% of calcium, chromium, iron and nickel. The primary source is thought to be exposed pipes on the inner wall of the machine that were eroded during operations.

Of the low Z elements, beryllium and carbon were routinely observed. These impurities originate in the plasma-facing components. During the limiter phase of a pulse, this connection can be seen in that there is a correlation between the low Z impurity dominant in the plasma and the distance of the plasma from the appropriate limiter. Throughout most of the operations, the use of beryllium as a getter for oxygen maintained the latter concentrations at ~0.1-0.4%. However, towards the end of 1991/92 campaign, higher levels of oxygen were observed. At times, these rose to values of ~0.5-1%.

Measurements have shown that particles are intrinsically much better confined than energy. The recognition that the consequent helium ash accumulation threatens long pulse operation of a D-T tokamak has made investigation of helium confinement and removal an important issue for ITER. Not only must the fuel concentrations be controlled, but impurities must be screened and helium must be efficiently exhausted to prevent fuel dilution. Exploration of these questions has been undertaken. Using 130keV NB helium atoms as a central source in the plasma, the evolution of the resulting fully-ionised helium ion density profiles has been measured, where L- and H-mode plasmas were compared at similar input power levels. Local measurements of the helium density profile were derived from active charge exchange recombination spectroscopy (CXRS), although the complexities of analyzing the emission spectrum were considerable and the resultant uncertainties great. Nevertheless, it was observed that, in L-mode discharges, the helium density profile could be simulated using a diffusion coefficient of 0.3±0.1 m^2s^{-1} (see Fig.46). However, the decay of the helium density profile following the termination of central helium fuelling, required a diffusion coefficient, which was a factor of 4-5 larger. The source of this discrepancy is not understood, but the non-stationary plasma conditions may be relevant. In H-modes, it was not possible to establish a helium density profile with measurable peaking, indicating that particle fluxes in the bulk plasma must be large. Therefore, in such a situation, helium exhaust is expected, to be dominated by edge transport, which cannot be addressed adequately in the present JET configuration. However, the active pumping expected to be available in the divertor phase should permit a more thorough investigation of this question.

Progress Towards a Reactor

Next Step Related Issues

A number of experiments have been carried out on certain issues of particular relevance to Next Step devices. These are described below:

Toroidal Field Ripple Experiments

Establishing the acceptable amplitude of toroidal field ripple for a tokamak reactor is fundamental to the design of a Next Step tokamak. By operating JET with 16 (rather than 32) toroidal field coils, it was possible to compare plasma performance with theoretical predictions, particularly in relation to fast particle confinement. Experiments were performed in L- and H- mode, using ICRF and NB heating in plasma configurations with 16 and 32 coils. In the former case, the edge toroidal field ripple was 15%, while in the latter it was less than 1%.

In L-mode plasmas with 16 coils, central ion heating with NB injection was reduced relative to plasmas with 32 coils and the efficiency of ICRF heating fell significantly as the minority ion resonance was moved to larger major radius. Both effects led to a significant degradation of energy confinement with 16 coils com-

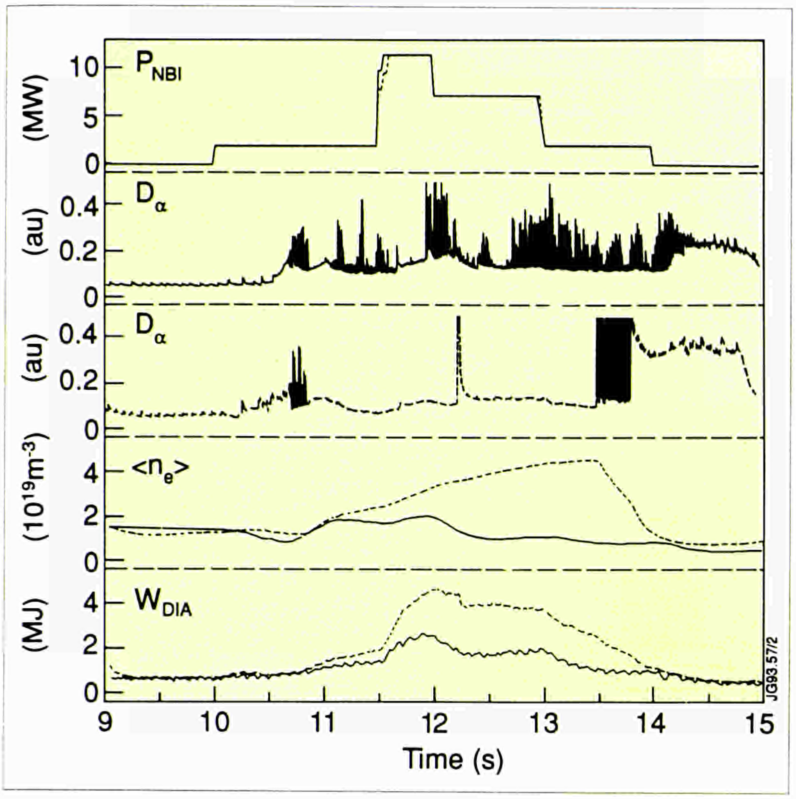


Fig.47: Comparison of H-mode discharges with 16 (solid traces) and 32 (dashed traces) coils. the plasma energy (W) obtained the high ripple (16 coils) core is substantially reduced

pared to the 32 coil case. The reduction of fast particle confinement due to the enhanced ripple was in line with expectations and fast ion spectra were in agreement with theoretical predictions.

A striking difference in H-mode behaviour between the 16 and 32 coil cases was also observed as shown in Fig.47. Whereas, with 32 coils, ELM-free H-modes with high energy confinement would be achieved readily at NB powers of 1.5MW, only ELMy H-modes could be obtained with 16 coils, even at NB powers as high as 12MW. The energy and particle confinement of these H-modes was significantly poorer than in the 32 coil plasmas. These findings confirmed that high ripple cannot be tolerated in any future tokamak reactor.

Pumped Divertor Studies

Considerable efforts have been made during the campaign to establish an experimental database for the validation of the modelling of the Pumped Divertor. A key experiment has been the attempt to establish a 'gas target', or radiative divertor plasma. The requirement for such an approach arises from the excessive power densities, in excess of $10MWm^{-2}$, to which divertor targets in Next Step Devices will be exposed unless a substantial fraction of the power efflux is radiated. The constraints on bulk plasma impurity concentration, plasma density and MHD stability imply that most of this radiation will have to occur outside the separatrix, that is in the divertor.

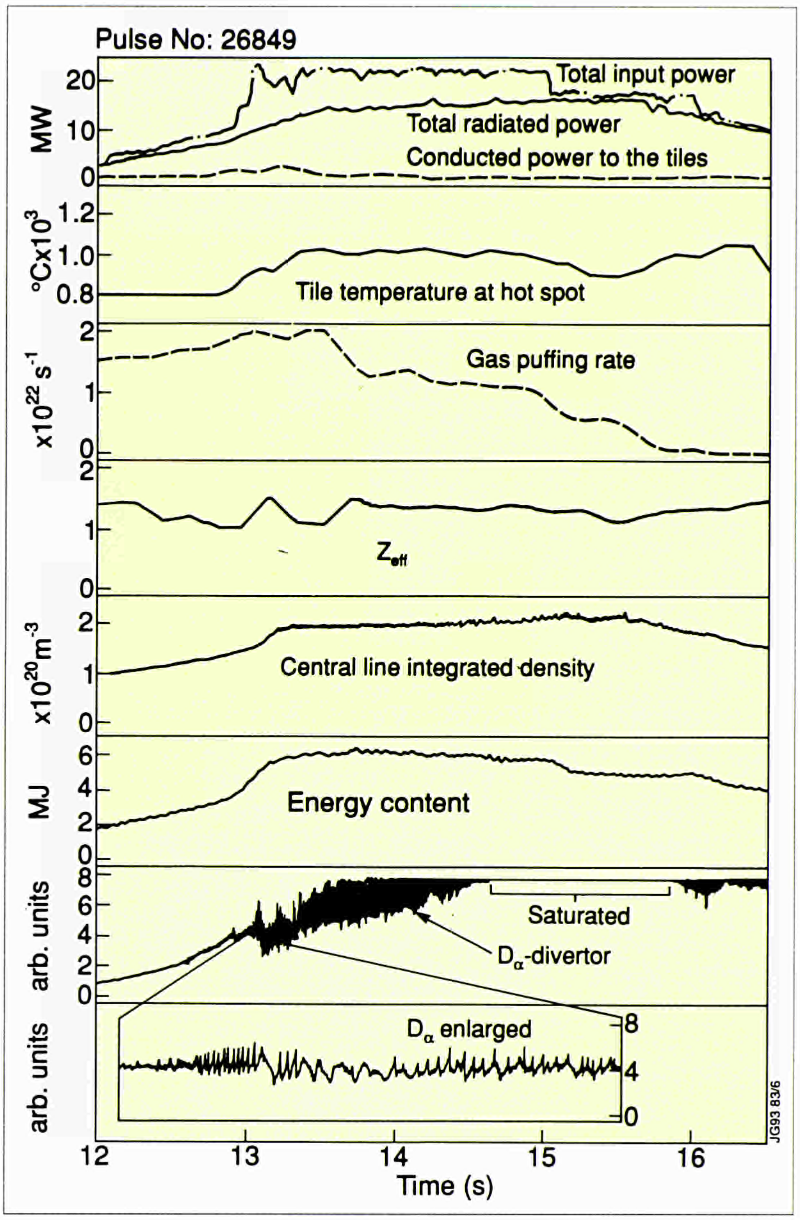


Fig.48: Radiative divertor discharge with 22MW input and 1.0MW conducted power on the target tiles. Quasi-steady state operation is demonstrated

The most successful attempts to establish a radiative divertor utilized the beryllium target in a single-null X-point configuration. In most experiments, a preprogrammed gas-puff was applied from the start of additional heating and was increased with increasing heating power. The regime could be maintained in a stable state with less than 1MW of power conducted to the divertor if the gas-puff rate was subsequently reduced to that required to replace particles lost by wall pumping. Quasi-steady state operation was demonstrated at powers of up to 22MW and for pulse lengths of up to 4 seconds (see Fig 48). In a more advanced scenario, a control loop was established using thermal radiation from the divertor target to maintain the gas-puff rate. This permitted the gas target regime to be brought under feedback control. The demonstration of this regime is of major significance for the development of reactor-relevant scenarios. However, it has not yet been possible to combine the radiative divertor with high confinement H-modes, since the bulk plasmas either remained in the L-mode or exhibited ELMy H-mode behaviour with a confinement enhancement factor of 1.4.

Analysis of Preliminary Tritium Experiments

The first tokamak discharges in D-T fuelled mixtures, undertaken in November 1991, was a most significant achievement. Tritium was introduced, into hot-ion H-mode discharges, from two neutral beam sources delivering 1.5MW within a total of 14.3 MW heating. This produced a tritium concentration of about 11% at the time of peak performance, when the total neutron emission rate was $6 \times 10^{17} s^{-1}$. The neutrons came about equally from beam plasma and thermal processes. These levels were equivalent to total fusion releases (α-particle and neutrons) of 1.7MW peak power and 2MJ energy.

Further analysis of the data from the preliminary tritium experiment has continued throughout 1992. It has led to a coordinated series of papers, which will be published in the Nuclear Fusion journal during 1993.

The following subjects have been covered:

- Neutron Emission Profile Measurements during the Tritium Experiments;
- Release of Tritium from the First Wall;
- Particle and Energy Transport during the PTE;
- Ion Cyclotron emission Measurements during the Deuterium-Tritium Experiments;
- Discharge Termination of High-Performance Discharges.

New information has been obtained in the following areas.

Ion Cyclotron Emission Measurements

During experiments, where combined deuterium and tritium neutral beam injection generated D-T fusion power, ion cyclotron emission (ICE) was detected. The spectra contained superthermal, narrow, equally spaced emission lines which corresponded to successive cyclotron harmonics of deuterons or α-particles at the outer mid-plane. The emission intensity increased in proportion to neutron flux. This indicated that fusion α-particles, and not beam ions, provided the free energy for generating the emission. This constituted the first detection of emission from confined α-particles in a fusion experiment. In pure deuterium discharges, ICE was generated by primary D-D fusion products: The most likely single candidate driving the ICE was the 3MeV fusion proton.

The JET ICE database, which now extends over a range of six decades in signal intensity, shows that the time-averaged ICE power increased linearly with total neutron flux (Fig.49). The rise and fall of

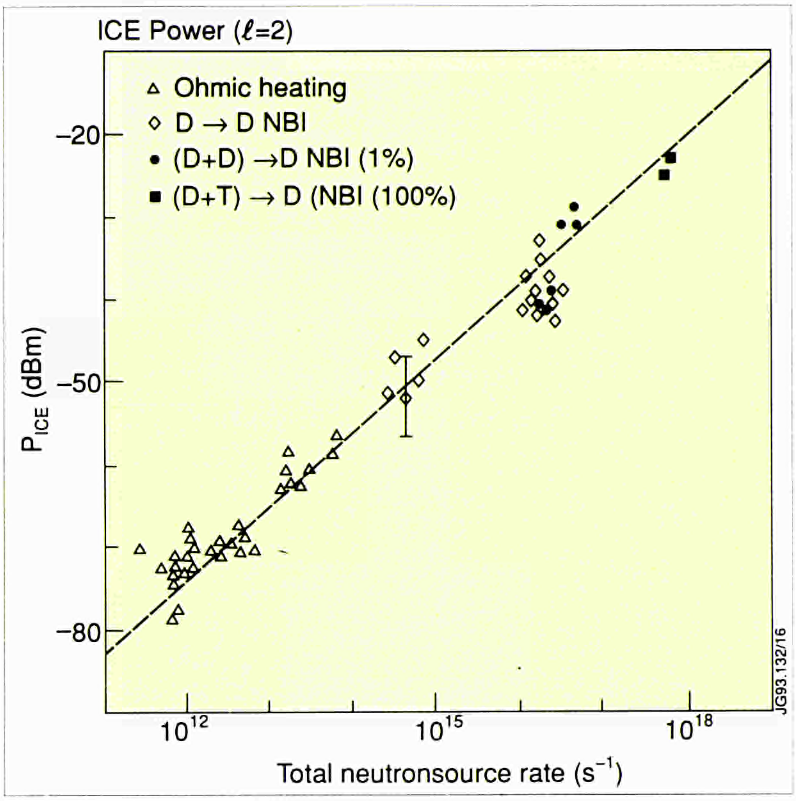


Fig.49: Correlation between ion cyclotron emission intensity P_{ICE} and total neutron emission rate R_{NT} for ohmic and NB heated discharges. The frequency corresponds to the second harmonic of the deuterium or alpha-particle ion cyclotron frequency evaluated at the outer mid-plane plasma edge

the neutron flux during a time-evolving D-T discharge was closely followed by that of the emission intensity, which was delayed by about the α-particle slowing-down times (~0.5s). This feature is well-modelled by code simulation of the density of deeply trapped α-particles reaching the plasma edge. Calculations revealed a class of fusion products, born into trapped orbits in the core plasma, which made orbital excursions of sufficient size to reach the outer mid-plane edge. There, the energetic α-particle or fusion proton velocity distribution was both anisotropic and was potentially unstable to relaxation at multiple ion cyclotron harmonics. These measurements show how ion cyclotron emission provides a unique diagnostic for confined fusion alpha-particles.

Release of Tritium from the First Wall

During the experiment, an estimated 2×10^{12}Bq(1.1×10^{21} atoms) of tritium were injected into the vacuum vessel. A series of experiments was performed whose purpose was to deplete the torus of tritium, to compare the effectiveness of different methods of tritium removal, and to obtain a quantitative understanding of the processes involved. The effectiveness of the cleaning procedures was such that the normal tokamak programme was resumed one week after the experiment and routing of exhaust gases to atmosphere after two

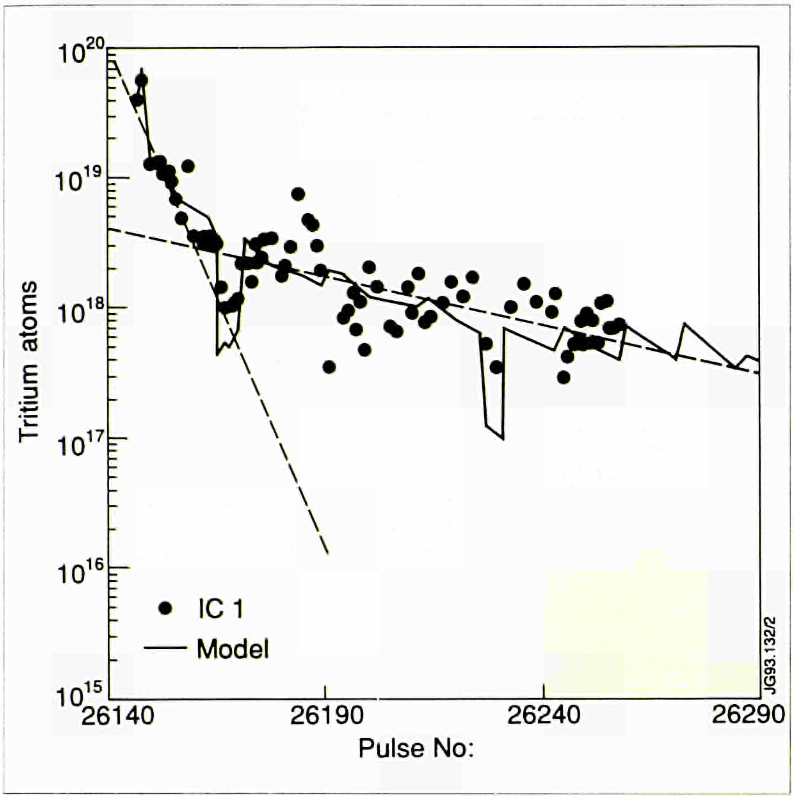


Fig.50: Number of tritium atoms released from the vessel as a function of Pulse No. The PTE shots were Pulse Nos: 26147 and 26148. Data are integrated over the first 560s of outgassing after the pulse. The solid curve is prediction of a model and dashed lines are the results of a simple two-reservoir model for the wall

weeks. The release of tritium from the vessel was found to scale with the deuterium release from the vessel, suggesting that dilution and mixing of the hydrogen isotopes in the vessel walls is important.

The experiment offered a unique opportunity to study the isotopic exchange processes in a large tokamak and to follow the release rate over nearly four orders of magnitude in concentration. The primary objective of removing most of the tritium was successfully accomplished. The tritium inventory was reduced to 3.4×10^{19} atoms at the end of the operations (i.e. 3% of the injected tritium).

High density, disruptive tokamak discharges were found to be the most successful plasma pulses for tritium removal. Purges with deuterium gas were also effective and have the advantage of operational simplicity. Helium discharges, on the other hand, resulted in low tritium release from the vessel walls. After about two weeks operation, the tritium level was sufficiently low that evacuation into the sealed-off backing line could be discontinued and use of the conventional backing pumps resumed (see Fig.50). It was demonstrated that the tritium release rate could be predicted using data from hydrogen to deuterium changeover experiments. The physical mechanisms necessary to describe the hydrogenic uptake and release from the torus were identified.

The data obtained has enabled a much better understanding of

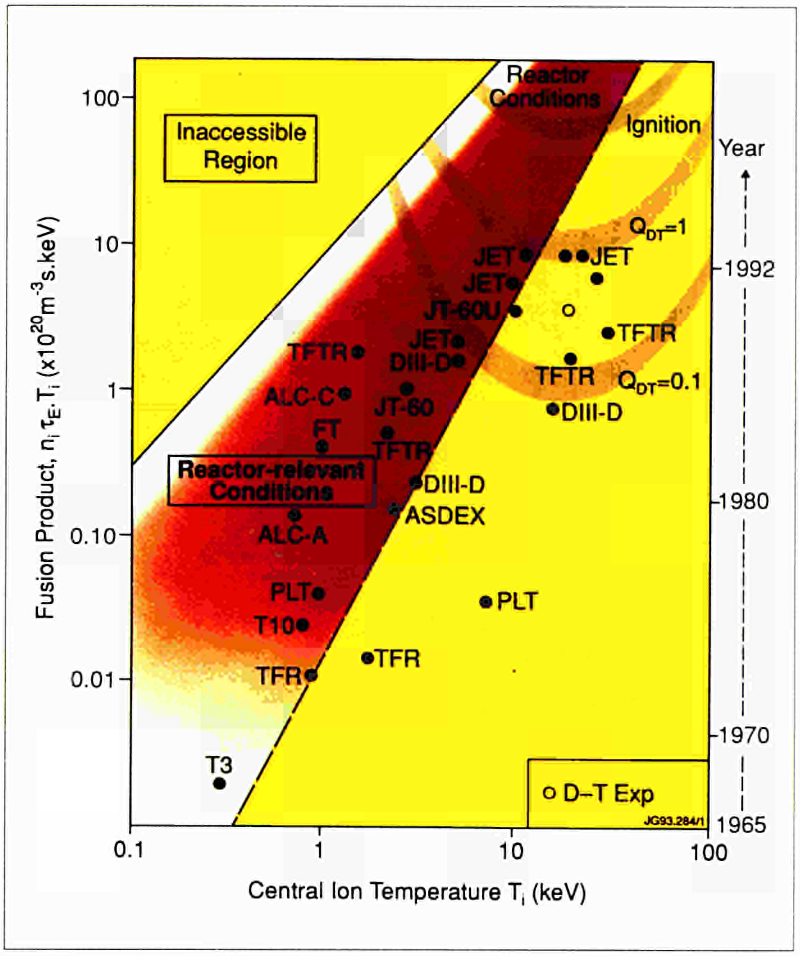


Fig.51: Fusion product ($n_D \tau_E T_i$) versus central ion temperature, $T_i(0)$, for a number of machines worldwide in the period 1965-1992

the principal processes occurring. This should enable the behaviour of tritium in the full D-T phase to be predicted with some confidence. However, since the rates of physical processes are dependent on material properties, the absolute values of the model parameters will change if the vessel materials are changed. Therefore, an isotope exchange experiment with hydrogen and deuterium is necessary to validate the model parameters for different machine conditions.

High Performance in JET

During the 1991/92 campaign, significant progress was made in determining the conditions required in a fusion reactor. By using tritium, it had been possible to check predictions made in previous years concerning the power output and to assess whether the thermonuclear Q in JET with a D-T mixture were actually valid. In particular, the tritium experiments enabled detailed checks of computer codes used in predictions of D-T performance. The outcome was that, indeed, the previous code predictions of Q_{DT} close to breakeven have been fully justified. During 1992, further analysis of the high performance discharges obtained during the first tritium series of experiments was completed. The overall picture was unchanged with the hot-ion H-mode plasma having the highest Q_{DD} ($5x10^{-3}$) and the extrapolated Q_{DT} was 1.14.

In early 1992, a series of 7MA limiter L-mode plasmas with high power combined ICRF and NB heating was developed. Although these pulses achieved a high stored energy (~12MJ), the triple fusion product ($n_D T_i \tau_E$) was less than $1.4x10^{20}m^{-3}$keVs at a temperature of 4.5keV. The main problem encountered was that high impurity levels gave rise to a low deuterium concentration, n_D/n_e<0.5.

The actual preliminary tritium experiment pulses had a somewhat lower Q_{DT} than the highest values obtained. The actual equivalent value Q_{DT} was 0.46. This was due to the reduced value of the fusion product ($n_D T_i \tau_E$) in these particular pulses caused by the early onset of the "carbon bloom". The fusion product values of the high performance pulses in both impure deuterium and in the D-T pulses are compared in Fig.51 with data from other machines to illustrate the progress that has been made over the last 30 years.

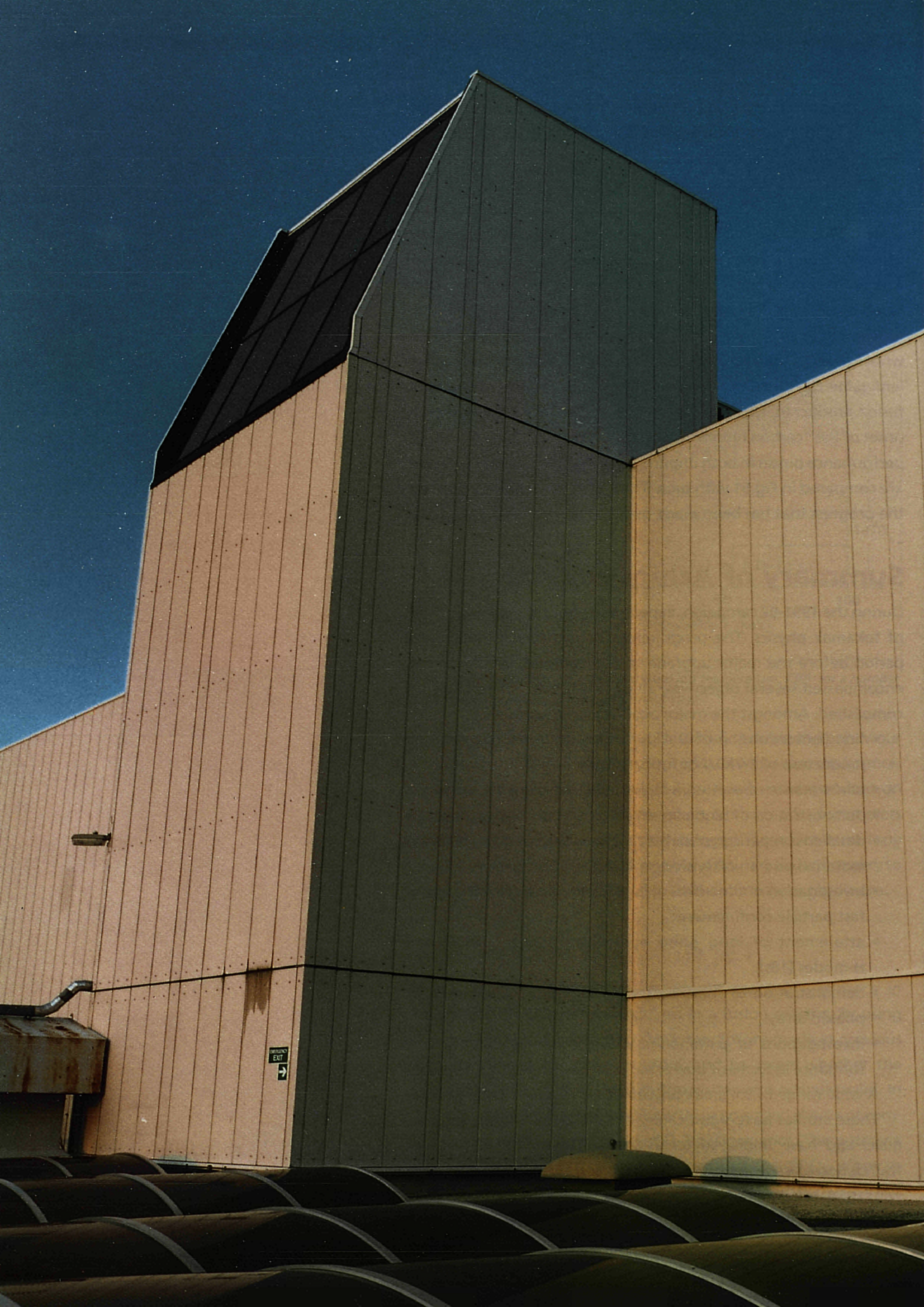
Summary of Achievements

During the 1991-92 campaign, experiments ranged over wide areas of tokamak physics. The programme for this final experimental period before the major upgrade to the pumped divertor phase, encompassed several objectives, all of which were successfully accomplished. Amongst the major achievements were:

- first demonstration of the use of tritium in a tokamak and production of 1.7MW of fusion power;
- performance of extensive high power experiments at 7MA;
- demonstration of high current AC operation of the tokamak;
- detailed comparison of carbon and beryllium as divertor target materials and an extensive exploration of divertor physics;
- investigation of the effect of large field ripple on thermal and fast particle confinement;
- attainment of long pulse operation in both L-(60s) and H-modes (18s);
- demonstration of minority ion current drive using an ICRF phased array:
- investigations of parameters which influence divertor performance in terms of power handling and impurity screening..

A wide range of tokamak physics issues were also addressed:

These studies have significantly advanced knowledge of tokamaks and have improved technological capabilities, laying the foundation of a successful transition to the new phase of JET, which will exploit the pumped divertor to address key questions relating to control of heat and particle exhaust and of impurity influxes.


EXIT

Future Programme

Introduction

In 1978, the original objectives of JET were set out in the JET Design Proposal, EUR JET-R5, as follows:

'The essential objective of JET is to obtain and study a plasma in conditions and dimensions approaching those needed in a thermo-nuclear reactor. These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor. The realisation of this objective involves four main areas of work:

i) the scaling of plasma behaviour as parameters approach the reactor range;

ii) the plasma-wall interaction in these conditions;

iii) the study of plasma heating; and

iv) the study of alpha-particle production, confinement and consequent plasma heating.

The problems of plasma-wall interaction and of heating the plasma must, in any case, be solved in order to approach the conditions of interest.

An important part of the experimental programme will be to use JET to extend to a reactor-like plasma, results obtained and innovations made in smaller apparatus as a part of the general tokamak programme. These would include: various additional heating methods, first wall materials, the control of the plasma profiles and plasma formation.'

At the start of 1992, the Project had almost completed its planned Phase III - Full Power Optimisation Studies. The general objectives of the experimental programme were to optimise performance and to explore the domain of high performance plasmas, studying aspects of plasma physics and engineering including: profile and heating effects; exhaust phenomena; and divertor edge physics. Priority was given to study of the power and energy handling capability of newly installed plasma facing components in regimes relevant to the Next Step and to the New Phase of JET.

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; and*
4. *Alpha-particle production, confinement and consequent plasma heating.*

Extensive studies had been made in the first and third areas of work of JET's objectives: reactor relevant temperatures (up to 30keV), densities (up to $4x10^{20}m^{3}$) and energy confinement times (up to 1.8s) had been achieved in separate discharges. The second area of work had been well covered in the limiter configuration for which JET was originally designed. However, the highest performance JET discharges had been obtained with a 'magnetic limiter', (or X-point configuration). The duration of the high performance phase of these discharges exceeded 1.5s; this was achieved by careful design of the targets and specific operation techniques, but is limited, ultimately, by an unacceptably high influx of impurities, characterised by a rapid increase in electron density, effective ionic discharge and radiated power (referred to as the 'bloom').

The fourth area of work had been started by earlier studies of energetic particles produced as fusion products or by ion cyclotron resonance heating (ICRH). It was addressed further during 1991 by the first tokamak plasma experiments in deuterium-tritium mixtures. The high performance achieved in deuterium discharges, together with the experience gained in making substantial modifications to JET in a beryllium environment and with significant vessel activation, gave confidence that an experiment with about 10% tritium in the plasma could be performed and would provide data that could be used to plan an effective campaign of deuterium-tritium experiments in 1996.

During 1991, the JET Council had approved the policy of a stepwise approach to the introduction of tritium in advance of the full D-T phase of JET operations. As a first such step, after having obtained all necessary regulatory approvals, JET successfully carried out a preliminary tritium experiment (PTE-1) in November 1991 (as already described). A release of fusion energy in the megawatt range in a controlled fusion device had been achieved for the first time in the world.

The most recent experiments on JET achieved plasma parameters close to breakeven values for about a second, resulting in large bursts of neutrons. However, in spite of the 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 near-breakeven conditions could be maintained is due to poisoning of the plasma by impurities (the "bloom"). This has further emphasised the need to provide a scheme of impurity control suitable for a Next Step device.

At its meeting on 19 December 1991, the Council of Ministers adopted Decisions concerning the Euratom Fusion Programme in the period to the end of 1994 and a modification to the Statutes of JET, which prolonged its statutory lifetime by four years until 31

December 1996. The extension will allow JET to implement the new Pumped Divertor Phase of operation, the objective of which is to establish the effective control of plasma impurities in operating conditions close to those of the Next Step. This programme of studies will be pursued before the final phase of full D-T operations in JET.

During 1992, a large proportion of JETs effort was devoted to shutdown work for the new pumped divertor phase of operations. The first stage of the shutdown in 1992 involved removal of components and replacement of faulty toroidal magnetic field (TF) coils. The second stage involves assembly of the four divertor coils and casings inside the vacuum vessel and this was in progress at the end of the year. It is believed to be the first time that full manufacture and assembly of coils has been undertaken in such a confined space, and the work is being done to demanding standards to ensure the highest reliability during subsequent operations. Intensive design and procurement activities for the pumped divertor components to be installed in the third stage of the shutdown have continued.

JET Strategy

Present achievements show that the main objectives of JET are being actively addressed and substantial progress is being made. The overall aim 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. 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 quantities 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 involves the following:

a) Increasing the Central Deuterium Density, $n_D(0)$, by:
- injecting deuterium pellets and high energy deuterium 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) Increasing 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 regions, 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 (24 MW, ICRH, and 20MW, NB);

c) Increasing the Energy Confinement time, τ_E, by:
  - increasing to 6MA the plasma current in full power, H-mode operation in the X-point configuration;

d) Reducing the impurity content, by:
  - using low Z first-wall material (such as beryllium) to decrease the impurity content;
  - controlling new edge material by using the pumped divertor configuration.

In parallel, preparations for the full D-T phase of operations have continued. In particular, JET has completed installation of all the main components of the active gas handling system and commissioning is underway. At the end of the shutdown, JET will be in a position to begin its programme of operations to demonstrate effective methods of power exhaust and impurity control in operational conditions close to those envisaged for ITER before the final phase of full D-T operations. ITER relevant studies will provide stimulation to JET and JET's results will make an important contribution to the development of the ITER design. The following sections describe such studies underway on advanced divertor systems.

Advanced Divertor Studies

Introduction and Overview

The present pumped divertor programme consists of two phases. In the first (Mark I), inertially-cooled target blocks of carbon fibre composite (CFC) or beryllium are mounted on a water-cooled support structure to speed cooling between discharges. The second version, for installation in 1995, was based upon actively-cooled copper elements to which thin beryllium plates were brazed ("Hypervapotrons") to permit thermally steady state operation at high powers.

During 1992, an ad hoc Advanced Divertor Study Group was set up to study the question of possible improvements to the pumped divertor, for the purpose of optimising its performance and reliability. At that time, the Mark I design was nearly finished, but the Mark II design was only partly completed.

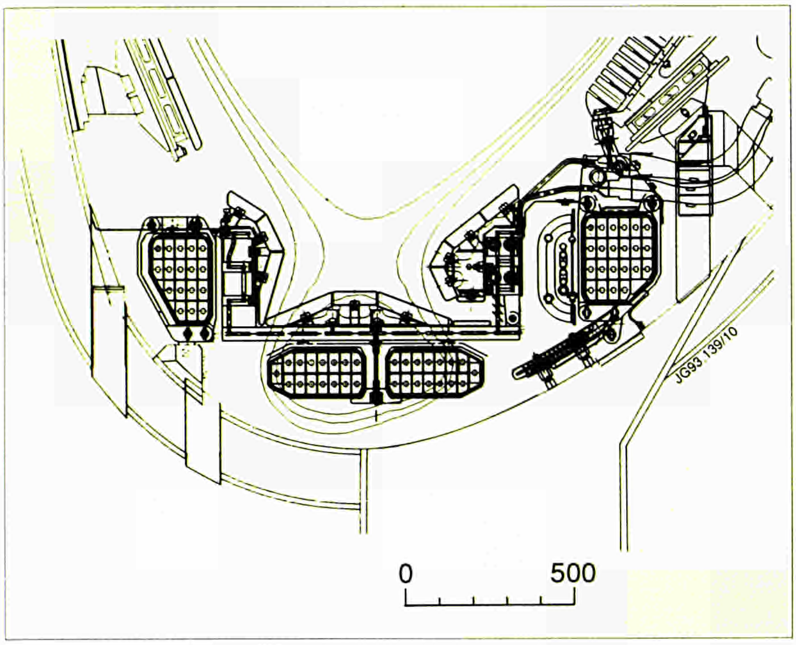


Fig.52: Cross-section of the inertial Mark IIA divertor

The study was motivated by two factors:

(a) it was generally accepted recently that "conventional" divertors, wherein the SOL power flows directly to the target plates, would lead to unacceptably high heat loads in Next Step devices. The exhaust power should be distributed over a much larger divertor surface area than can be obtained by simply tilting the plates, and radiation and charge-exchange processes were the leading candidates for accomplishing this. The Mark I divertor geometry, which was to have been taken over directly into the hypervapotron-based Mark II phase, is not well suited to achieving such divertor conditions, principally because it is too "open";

(b) there was continuing concern about the reliability of brazing beryllium plates to copper hypervapotrons, and the severe risk to the programme, especially in the D-T phase, which a failed braze would imply.

The Study Group was detailed to study both the physics and engineering of various divertor designs, within the constraints imposed by the JET schedule.

The three main functions which a divertor should perform can be summarised as:

- handle the heat load (power exhaust) at acceptable erosion rates;
- control impurity content in the main plasma by reducing sources and retaining impurities in the divertor;
- remove helium ash.

The divertor plasma parameters (n_e, n_i, T_e, T_i, ..) depend most sensitively on two quantities, the power crossing the separatrix (P_{sol}) and the mid-plane separatrix density (n_b). For fixed power, divertor

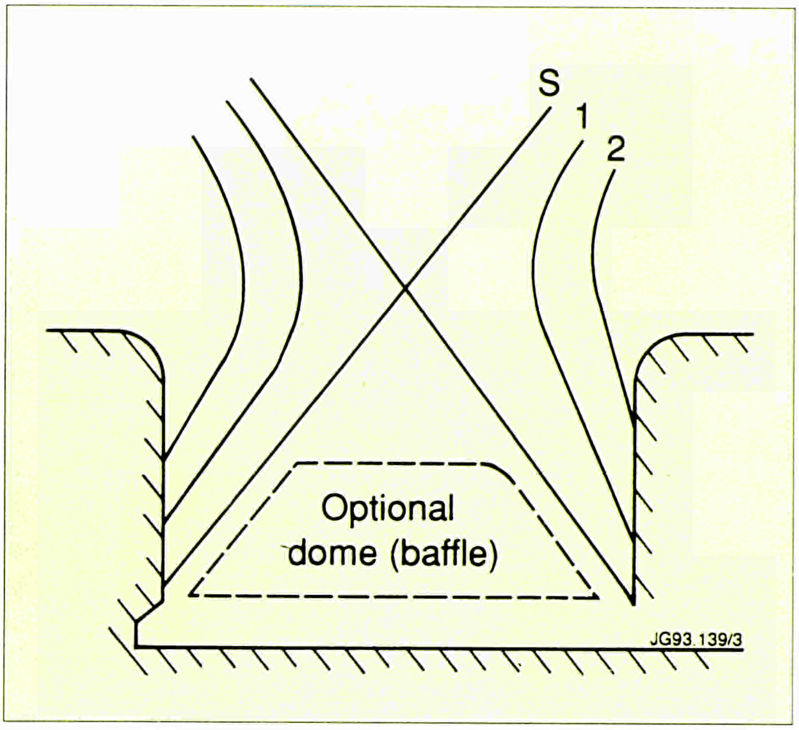


Fig.53: Vertical target divertor with optional baffle

performance improves dramatically as the midplane density is raised. However, when both variables are fixed, the divertor geometry itself can play a major role. Generally speaking, the more "closed" the divertor, the higher its plasma density and the lower its temperature, contributing to improved performance.

The effects of divertor geometry can be divided into two categories. Firstly, there is the purely geometric effect of increasing the wetted area, upon which the conducted power falls, by tilting the plates relative to the poloidal flux surfaces. The second effect arises from the fact that by tilting the plates, the recycling neutrals can be directed either towards the private flux region, in "vertical target" designs, or towards the divertor sidewalls, in "domed horizontal target" designs. Examples of these generic target geometries are shown in Figs.52 and 53. In either case, fewer neutrals, respectively, head directly back towards the main plasma than is the case for divertors with targets oriented orthogonally to the poloidal flux surfaces. More importantly, the distribution of ionisation sources in the divertor is dramatically altered by tilting the plates. This can lead to a major redistribution of plasma profiles in the divertor, which in turn can lead to enhanced volumetric losses from radiation and charge exchanges. Pumping performance can also be enhanced, particularly when "pumping baffles" are introduced.

Divertor Geometries

The geometry of Mark I (see Fig.54(a)) (and the original Mark II hypervapotron design) is relatively wide, U-shaped trough with nearly vertical sides. It was designed to accommodate a large family of equilibria and to permit high amplitude sweeping. Due to the 1cm gaps between narrow (3cm) tiles, and relatively poor alignment tolerances achievable, it has a small toroidal utilisation factor, and sweeping would be required for all but modest power inputs. The geometry is very "open" for most equilibria of interest, which may limit access to the high recycling/atomic physics regime. However, elevated X-point equilibria having their strike zones on the vertical side walls can probably be produced, permitting investigation of "vertical target" divertor geometries at modest powers and currents.

The basic concept of the Mark II proposal is to use a rigid, toroidally continuous, water cooled base structure upon which target/baffle structures of various designs can be mounted. The rigid base allows for good tile alignment and thus permits the sue of large tiles, with small incidence angles, resulting in large wetted areas. The wetted area depends on the particular magnetic equilibrium chosen, but is typically a factor of four or more larger than in Mark I, virtually eliminating the need for sweeping.

The degree to which the divertor geometry can be optimised in JET is restricted by the geometry of the lower part of the vessel, including the divertor coils, which cannot be changed due to time constraints. Specifically, the divertor floor cannot extend below the top of the case around the lower divertor coil pair, so that the divertor "depth", distance from the X-point to the bottom of the divertor plasma channels, is limited by X-point heights.

For this limited X-point to divertor floor distance, a true "deep-slot" design is not possible. The divertor geometry closest to this design, referred to as Mark IIA (see Fig.54(b)), is of the "domed horizontal target" type, shown in Fig.53. Relative to Mark I, the target is tilted upwards in the centre. This serves the dual purpose of increasing the wetted area and redistributing the re-cycled neutrals, which tend to come off the targets perpendicularly. In addition , the side walls are brought in, in this version, to about the 2cm line.

A deeper, "slot-like" divertor can also be envisaged if the magnetic axes of the equilibria are allowed to rise to about 50cm above the midplane. This version of the divertor is referred to as Mark IIB (see Fig.54(c)). In this version, the targets are nearly vertical side walls, and the high "centre dome" is inserted to reflect neutrals back into the lower part of the divertor plasma. It can easily incorporate openings for pumping or gas puffing, either near its base, or higher up, to test various ITER-relevant ideas on enhancing charge-exchange and radiation losses. Using vertical targets, rather than an orthogonal one at the bottom of the slot, increases the wetted area

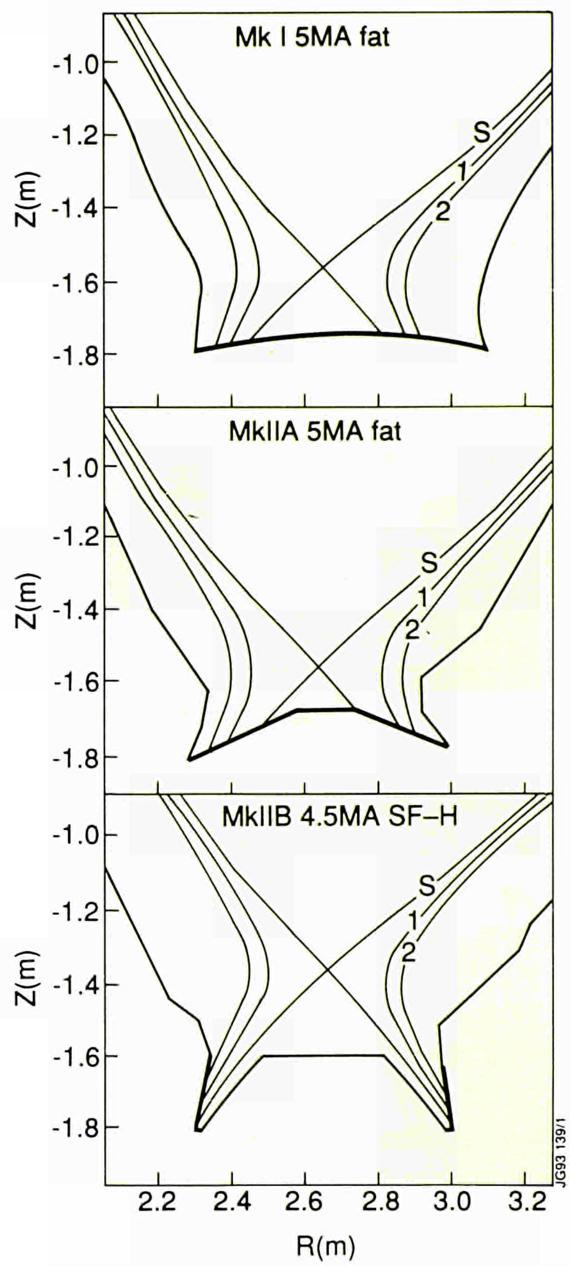


Fig.54: Geometries used for simulations

and thus keeps heat loads to manageable values even for high power, low density pulses, for which it is difficult to radiate large fractions of the SOL power.

Code Predictions of Divertor Performance

The performance of Mark I and versions of Mark II has been simulated using a full 2-D model. The geometries are shown in Fig.54. Mark IIA is a domed horizontal plate design, and Mark IIB is a vertical slot, which fits raised X-point equilibria. The simulations, while preliminary, all tend to confirm that a closed divertor will function more effectively than an open one, which can be deduced from analytical divertor models. Although closing the divertor means reducing the SOL flow outside the divertor, the gains in power exhaust performance, through entrance into the high recycling/atomic physics regime, and the improved impurity behaviour seem to more than offset the effect of the reduced flow.

The Mark II configurations, while differing from each other in performance, outperformed the more open Mark I in nearly every respect, at fixed input power and SOL midplane density. Mark IIA produced a relatively uniform plasma across a broad target, and is clearly a great improvement over Mark I. It is a relatively conservative design, which will be further optimized by moving the sidewalls closer, and perhaps increasing the height of the centre dome.

Mark IIB is an example of a family of deeper slot geometries which is considered more "ITER relevant". Such geometries can be investigated in JET by raising the X-point. Mark IIB performs well in terms of divertor particle inventory, peak density, radiation per impurity atom, hydrogen radiation, and charge-exchange losses. However, the rather hot, rarefied outer layers of the divertor plasma allow the escape of more impurities than the "outward facing" designs such as Mark IIA.

From the limited number of simulations performed so far with the full multi-species version of the code, it seems that radiation from sputtered impurities will always be small for a high recycling, low temperature divertor. This suggests that injected impurities will be needed.

Divertor optimization is a difficult problem involving many factors. Further work will be undertaken on optimization of the "deep" version of Mark II. This will include investigation of high dome- and unbaffled-vertical target designs, as well as of the effect of puffing and pumping opening in the divertor walls. Simulation of helium transport in the SOL and divertor for the various candidates will also be addressed.

Technical Conceptual Design

A technical conceptual design has been developed. This has a toroidal continuous structure, as shown in cross-section in Fig.52, (with the Mark IIA tile geometry), and could be assembled inside the machine from 48 sections, each compatible with vessel entry. A continuous structure also significantly simplifies the attainment of mechanical stability. Although the forces due to halo currents may be large, the inherent rigidity of a continuous ring enables the support structure to withstand these forces internally. Each module is made up from a 4cm thick baseplate and two 10cm thick fabricated sidewalls. The modules are pre-assembled during manufacture with dowel locations to form a complete ring, which then enables very accurate tile locations. The inherent stiffness of the sidewall structure allows hinged corner joints, thereby leaving a reasonably large pumping gap open to the cryopump.

A substructure is used to support the tiles according to the chosen divertor geometry. Each tile would be attached by a single spring-loaded central bolt and supported on corner pads. Each module is fitted with its own tile carrier, but adjacent tiles share corner support pads, so that tile-to-tile step accuracy is dependent only on the tolerance of tile thickness. Replacement of a damaged tile is carried out by exchanging a complete carrier, an operation which can be performed by remote handling.

Cooling of the support structure is required to prevent overheating of the divertor coil epoxy. Present designs of the coil and heat shields can withstand radiation from a 350°C surrounding structure, as required for bake-out. The required cooling is modest. The power handling capability of this design has been significantly improved, relative to Mark I, by maximising the total wetted area. The poloidal wetted length is increased by inclining the target plates to the poloidal flux surfaces, while the toroidal length is increased by using carefully aligned large tiles with small inter-tile gaps.

The Mark I, hypervapotron Mark II, and inertially-cooled Mark II can all be swept, with a resultant gain in power handling which is approximately proportional to the field angle of incidence. For a 4° angle, a factor of ~3 gain could be achieved. The Mark I and hypervapotron Mark II were designed to rely upon sweeping, while for most equilibria and plasma powers of interest, inertial Mark II can operate without sweeping. In addition, the inertial Mark II is expected to produce larger volumetric power losses, further increasing its advantage over the older designs.

Conclusions

The Study Group recorded the following conclusions:

- To the extent possible, the divertor should be "closed", (i.e. it should allow as few as possible of the neutrals recycling from the target plate to escape from the "divertor region" below the X-point). Closing the divertor leads to higher density and lower temperature in the divertor. This reduces impurity production, enhances impurity retention, and facilitates access to the "atomic physics" regime where radiation and charge exchange are increased, decreasing the conducted power load to the plates. In addition, the wetted area should be made as large as possible by reducing the angle of incidence of the field line on the target to the limit allowed by target alignment tolerances;
- Only minor changes, specifically with respect to final machining of the target blocks to maximize their effective wetted area, could be made to the Mark I design due to time constraints;

- An inertially cooled version of Mark II, offering high performance (relative to Mark I), flexibility, and minimum risk could be built in about the same time schedule as the hypervapotron-based Mark II. It would allow testing of recent divertor concepts, and could be designed to form the basis for an extended programme.

The inertial Mark II divertor proposed to replace the original hypervapotron design has several innovative features. It is based on a water-cooled, rigid, toroidally continuous floor-and-sidewall structure upon which large tiles can be mounted with a high degree of alignment, permitting small magnetic field line incidence angles with corresponding large wetted area. The design is such that the divertor geometry, which plays a crucial role in divertor performance, can be readily changed by an exchange of tiles and tile holders, requiring only a relatively short machine intervention. Inertial Mark II divertor has a heat handling capacity which meets or exceeds that of the hypervapotron design for pulse lengths of 5-10s at high power, depending on plasma conditions. It can accommodate either beryllium or CFC tiles, allowing investigation of the two leading candidate target materials for Next Step devices.

A technical conceptual design has been developed which has large wetted area to eliminate the need for sweeping. It allows various target plate geometries to be tested, with only a short machine intervention required to change the configuration. This permits the investigation of the effect of geometry on divertor performance, leading to optimization of a Next Step divertor.

Future Plans

The JET Programme is divided into phases governed by the availability of new equipment and fitting within the accepted life time of the Project. Phase I (Ohmic Heating Studies) was completed in September 1984, and Phase II (Additional Heating Studies) in October 1988. Phase III (Full Power Optimization Studies) ended in February 1992. The scientific aims of Phase III were to obtain maximum performance in limiter configuration (currents up to 7MA) and to optimize X-point operation (currents up to 7MA) including a comparison of H-modes in X-point configuration using beryllium (lower X-point) with carbon (upper X-point) dump plates. The programme to 1996 is shown in Fig.55.

JET future plans are dominated by the insertion of a new phase of the Project (Phase IV: Pumped Divertor Configuration and Next-Step Oriented Studies). This phase is subdivided into a Divertor Characterization Plasma and a Full Tritium Compatibility Phase. The final Full Tritium Compatibility Phase, is now scheduled to start in

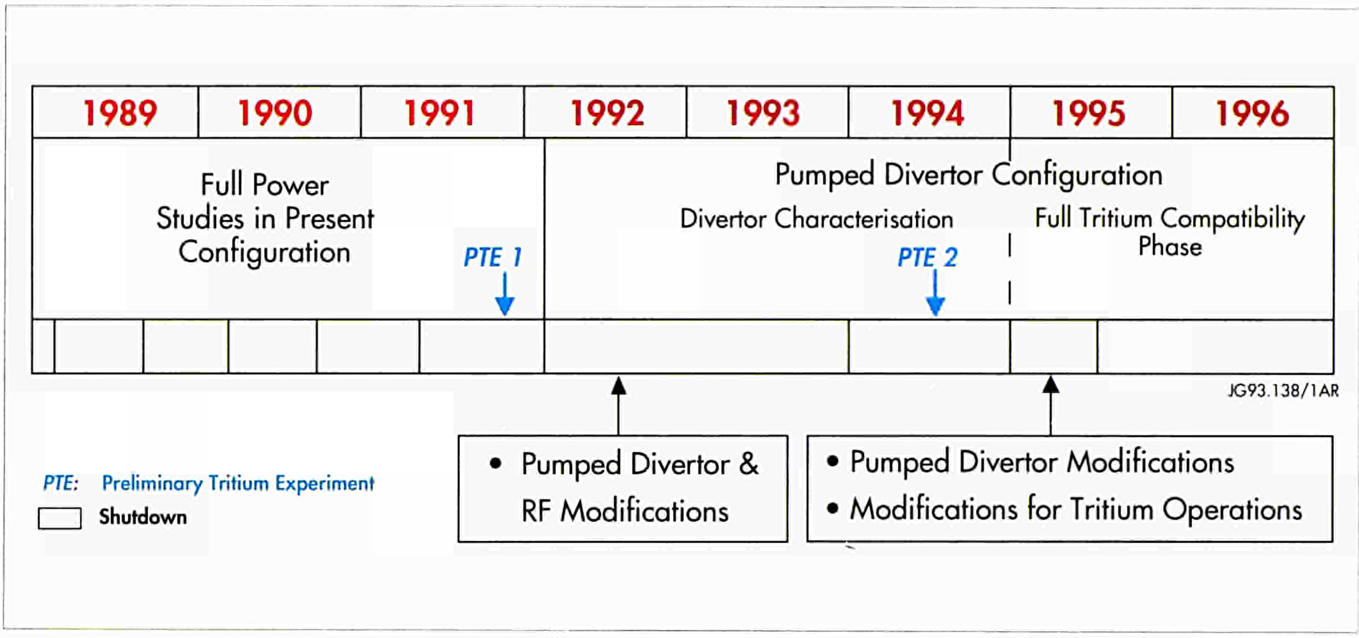


Fig.55: JET Programme Schedule: 1989-1996

1995. This new phase has now been formally approved and has extended the lifetime of the Project by four years to the end of 1996.

The aim of the phase is to demonstrate, prior to the introduction of tritium, effective methods of impurity control in operating conditions close to those of a Next-Step Tokamak with a stationary plasma (10 - 60s) of 'thermonuclear grade' in a single-null axisymmetric pumped divertor configuration. This configuration can only be achieved in JET by using divertor coils internal to the vessel.

Following approval by the JET Council of the stepwise approach to the introduction of tritium in advance of the full Tritium Phase, a first preliminary tritium experiment (PTE-1) was carried out and successfully completed in November 1991. A second tritium experiment (PTE-2) is scheduled for the first half of 1994 at a point, yet to be determined, when divertor operation has been well established, but in time to allow the necessary period of radioactive decay before the following shutdown. The information derived from these preliminary tritium experiments will provide a safer approach to the full tritium phase and will help to optimize the active handling and waste management arrangements.

More information on the future phases of the Project are indicated below.

New Phase (first part):
Pumped Divertor Configuration - Phase IVA (Divertor Characterization Phase) (February 1992 - December 1994)

In February 1992, the Project entered an extended shutdown to install the components relevant to the new pumped divertor. This will be concluded by the end of 1993. This is involving intensive in-vessel work to install the following equipment:

- lower divertor structure with Mark I carbon target plates (inertially cooled);
- pumping chamber and cryopump;
- internal divertor coils and associated power supplies;
- poloidal limiters;
- new ICRF heating antennae (A2);
- full lower hybrid current drive (LHCD) system with modified launcher;
- divertor diagnostics;
- high-speed pellet launcher (for plasma core injection);
- centrifuge pellet launcher (for plasma edge injection);
- disruption control system using internal saddle coils.

The single-null X-point pumped divertor configuration should enable JET to progress towards extended high power operation with 40MW additional heating using neutral beam and ICRF power (e.g. plasma currents of 6MA for up to 3s, 3MA for up to 5s). The control of disruptions using saddle coils system and the control of sawteeth using the full power LHCD systems should also be studied.

Experiments during the subsequent operating period in 1994 will concentrate on establishing and characterising plasma behaviour in the pumped divertor configuration. The programme will focus on:

- establishing reliable operation in the new configuration;
- studying the control of impurities, plasma density and exhaust, and power loading on the target plates; and
- assessing power handling using the full range of ancillary equipment.

The centrifugal pellet injector will be used for repetitive fuelling. In addition, the prototype fast pellet injector should deliver one pellet per tokamak discharge.

At the end of the shutdown, the RF capabilities of JET will have been enhanced significantly with the installation of the A2 antennae and of the full LHCD launcher. The exploitation of these systems in a range of heating and current drive scenarios will also be an integral part of the programme during this phase.

CFC divertor target plate tiles will be installed for the first period of operation with the Mark I divertor (inertially-cooled plates). Initially, this will allow a more rapid characterisation of plasma behaviour and build-up of high performance in the divertor configuration, particularly at low density. When pumped divertor operations are well established, a decision will be taken on whether to replace the CFC tiles with beryllium tiles during a short intervention.

A second Preliminary Tritium Experiment (PTE-2) is provisionally scheduled to take place (subject to the necessary formal approvals) about halfway through the operating period. A decision whether or not to proceed with this experiment, together with its timing and objectives, will be taken at a later date in the light of the early experience of operation in the new pumped divertor configuration. Account will also be taken of the evolving R & D needs of the overall European Fusion Programme.

At this stage, it appears likely that PTE-2 could also involve a full scale application of the tritium handling system at JET. Such a demonstration well in advance would help to optimise the active handling and waste management arrangements for full D-T operations and would be of importance in establishing technological aspects of the Next Step.

Preparations for D-T operations will continue during this period, including finalisation of remote handling tests and commissioning of the Active Gas Handling System with tritium (subject to consent by the approving bodies).

New Phase (second part): Pumped Divertor Configuration - Phase IVB (Full Tritium Compatibility Phase) (January 1995 - December 1996)

The second part of the new phase will start with a major shutdown scheduled for early in 1995. The main in-vessel task will be to install the Mark II divertor. As presently conceived, this would involve replacing the inertially-cooled divertor target plates with actively-cooled hypervapotron elements, which should allow the divertor to accept the incident power level from operation with full plasma heating in steady state. In addition, it should be possible to install other enhancements aimed at improving performance in the new configuration or for the D-T experiments (e.g. enhanced pellet injection or fuelling system, modification to LHCD or additional heating systems). In parallel, ex-vessel activities would focus on bringing all the systems and subsystems to fully tritium compatible status.

Operations would resume in mid-1995 and the use of tritium would start near the end of 1995, subject to the approval of the JET Council and to the necessary official consents. Decisions on the precise programme of experiments during this phase will be taken at a later date, in the light of experience during the characterisation phase (including the possible PTE-2) and of the Fusion Programme needs at that time. The general plans envisage the re-establishment of pumped divertor operation and experimental progress towards reliable stead-state operation at high heating power. The experimental programme will be directed at the physics of alpha-particle production, confinement and heating. Key additional information will be generated from the experience of tritium operations on a reactor relevant scale - tritium retention, remote maintenance and plasma diagnostics with large neutron and gamma backgrounds. This experience of D-T operation in a reactor scale tokamak should provide information essential for ITER design and construction.

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'Études 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 Investigaçao Cientifica 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

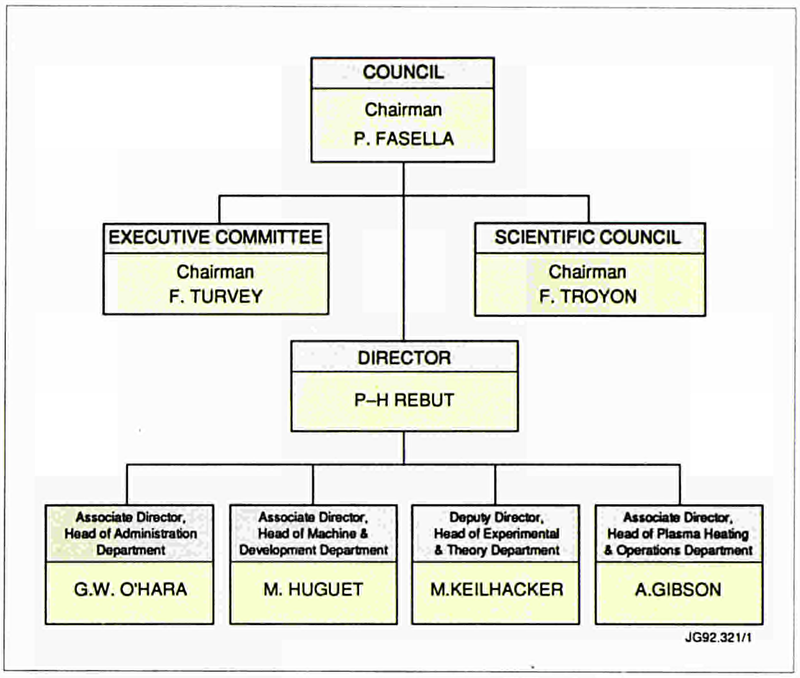


Fig. 56: Overall Project Structure

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.58).

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 for:

- Nomination of the Director and Senior Staff of the Project with a view to their appointment by the Commission or the Host Organisation as appropriate;
- Approval of the annual budget, including staffing, as well as the Project Development Plan and the Project Cost Estimates;
- Ensuring 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 25th-26th March, 17th-18th June, and 14th October 1992. 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 13th-14th February, 23rd April, 9th July, 17th September, 29th-30th October and 10th-11th December 1992.

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 Scientific Council met once during the year on 13th-14th May. Its main work during 1992 was to assess and advise the JET Council on:

- The JET programme to the end of 1996;
- JET-US collaboration on Fast Wave Current Drive experiments.

In addition, it reviewed the results of the experimental campaign that ended in February 1992.

During 1992, the JET Council appointed Prof. K. Lackner in succession to Prof. F. Troyon as Chairman of the JET Scientific Council with effect from 1st July 1992. The full membership was also renewed from 1st July and this is detailed in Appendix III.

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.58.

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 on 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 three groups. One contains Scientific Assistants who assist and advise the Director on scientific aspects of JET operation and future development. Another 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 Leader of the Publications Group. A third section contains the Press and Public Relations Group.

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 four groups (Machine Operations Group, Physics Operations Group, Data Management Group and Health Physics 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 beam 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 and Lower Hybrid (LH) systems during the different stages of their development to full power. The Division also participates in studies of the physics of RF heating and Lower Hybrid Current Drive.

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 measurement, 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 of JET performance by computer simulation, interpretation of JET data and 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* is responsible for the design, construction, installation, operation and maintenance of the tokamak electromagnetic system and of plasma control. The area of responsibility encompasses the toroidal, poloidal and divertor magnets, mechanical structure, methods for controlling plasma position and shape and all power supply equipment needed for magnets, plasma control, additional heating and auxiliaries;

(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, bakeout 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

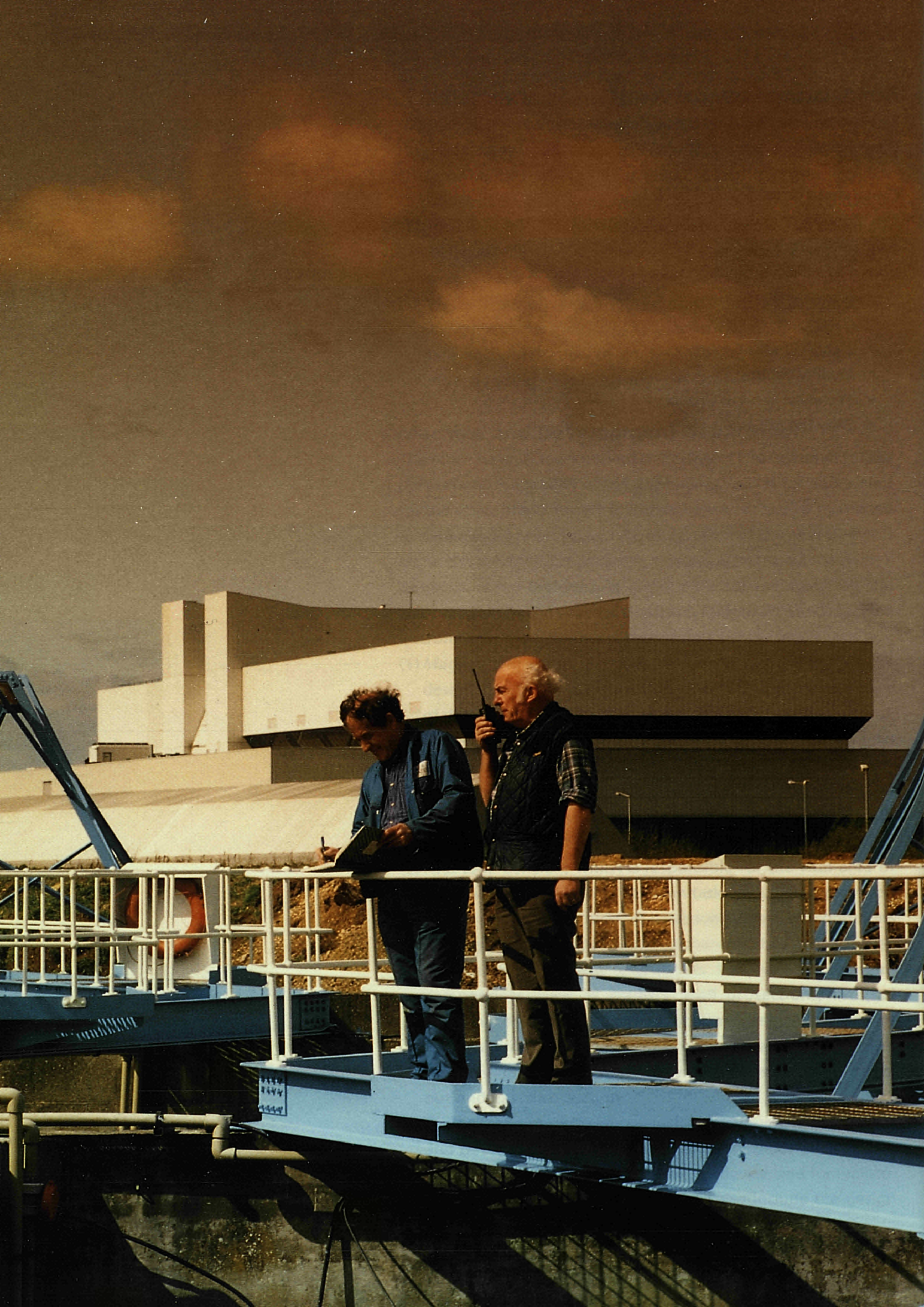
The Administration Department is responsible for providing Contracts, Finance and Personnel services to the Project.

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 five Groups:

- Safety Group;
- Health Physics Group;
- Quality Group;
- Technical Services Group;
- Drawing Office.



Administration

Introduction

The three main aspects of JET's administration - Finance, Contracts and Personnel - are reported on in this section. In addition there are contributions on Safety, Public Relations, and Publications Group.

Finance

The initial budgets for 1992 were approved at 92.39 MioECU for Commitments and 106.20 MioECU for both Income and Payments. The Commitments and Payments Budgets each are divided into two phases of the Project - Extension to Full Performance and the Operational Phase; subdivisions distinguish between investment, operating, and personnel costs, each with further detailed cost codes.

The Commitments, Payments and Income Budgets included 0.20 MioECU for specific work for the European Fusion Programme.

Due to budgetary problems within the European Communities budget the JET budget could not be adopted until late in the year. For this reason the JET Council imposed financial restrictions on the Project which remained in force for most of the year.

Commitments

Of the total appropriations in 1992 of 111.24 MioECU (including 18.85 Mio ECU brought forward from previous years), 88.57 MioECU was committed and the balance of 22.67 MioECU was available for carrying forward to 1993. 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 1.14 MioECU was committed leaving 6.21 MioECU commitment appropriations not utilised at 31 December 1992, to be carried forward to 1993;
- In the Operational Phase 87.43 MioECU was committed leaving a balance of 16.46 MioECU to be carried forward to 1993.

Table 10: Commitment Appropriations for 1992

	MioECU
Initial Commitments Budget for 1992	92.39
Amounts brought forward from previous years	18.85
	111.24
Commitments made during the year	88.57
Balance of appropriations at 31 December 1992 available for use in 1993	22.67

Table 11: Commitments and Payments for 1992

Budget Heading	Commitments		Payments	
	Budget Appropriations MioECU	Outturn MioECU	Budget Appropriations MioECU	Outturn MioECU
Phase 2 Extension to Full performance				
Title 1 Project Investments	7.35	1.14	7.30	5.70
Phase 3 Operational				
Title 1 Project Investments	11.12	7.30	16.35	12.09
Title 2 Operating Costs	41.05	37.97	45.29	39.50
Title 3 Personnel Costs	51.72	42.16	55.00	49.67
Total Phase 3	103.89	87.43	116.64	101.26
Project Total - all phases	111.24	88.57	123.94	106.96

Income and Payments

The actual income for 1992 was 104.70 Mio ECU to which was added 2.95 Mio ECU available appropriations brought forward from previous years giving a total of 107.65 Mio ECU. This total includes 0.02 Mio ECU arising from Specific Fusion Research work against a budget of 0.20 Mio ECU. The shortfall in income of 0.18 Mio ECU was offset by a corresponding reduction in the available Payments Budget. The excess of other income over budget totally 1.63 Mio ECU is carried forward to be offset against future contributions of Members.

Table 12: Income and Payments for 1992

	MioECU	
Income		
Budget for 1992		106.20
Income received during 1992		
(i) Members' Contributions	101.00	
(ii) Bank Interest	3.06	
(iii) Miscellaneous	0.10	
(iv) Unused Appropriations brought forward from 1990	2.95	
(v) Transfers from the Special Account	0.52	
(vi) Income for Specific Fusion Research	0.02	
Total Income		107.65
Income in excess of budget carried foward for off-set against Members' future contributions	1.63	
Shortfall of Income for Specific Fusion Research reducing available payment appropriations	(0.18)	
Payments		
Budget for 1992	106.20	
Amounts available in the Special Account to meet outstanding commitments at 31 December 1991	17.74	
Reductions in appropriations corresponding to shortfall of income for Specific Fusion Research	(0.18)	
Total Available Appropriations for 1992		123.76
Actual payments during 1992	106.96	
From Special Account transferred to income	0.52	
Unutilised appropriations at 31 December 1992		107.48
carried foward in the Special Account to meet outstanding commitments at that date		16.28

The total payment appropriations for 1992 of 123.94 MioECU were reduced by 0.18 MioECU due to the shortfall in income from Specific Fusion Research work; the payments in the year amounted to 106.96 Mio ECU and 0.52 MioECU was transferred from the Special Account to income. The balance of 16.28 MioECU was transferred to the Special Reserve Account to meet commitments outstanding at 31 December 1992. (Payments are summarised in Tables 11 and 12).

Contributions from Members

The budget for Members' contributions was 101.00 MioECU funded as follows:

- 80% from the general budget of the European Atomic Energy Community (Euratom);

Table 13: Percentage Contributions to JET for 1992

(based on the Euratom Participation in Associations' Contracts for 1991)

Member	%	MioECU
Euratom	80.0000	80.80
Belgium	0.1934	0.19
CIEMAT, Spain	0.2424	0.24
CEA, France	1.9135	1.93
ENEA, Italy	2.2347	2.26
Risø, Denmark	0.0745	0.07
Luxembourg	0.0019	0.00
JNICT	0.0883	0.09
KFA, Germany	0.6547	0.66
IPP, Germany	2.1154	2.14
KfK, Germany	0.7606	0.77
NFR, Sweden	0.1985	0.20
Switzerland	0.4908	0.50
FOM, Netherlands	0.3329	0.34
UKAEA	10.6984	10.81
	100.0000	101.00

- 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 contributions from Members for 1992

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. Therefore, the Project has funds which are not immediately required for the discharge of its commitments; these funds are placed on deposit accounts at market interest rates. During 1992, earned interest amounted to 3.06 Mio ECU.

Table 14: Summary of Financial Transactions at 31 December 1992

	MioECU
Cumulative commitments	1316.2
Cumulative payments	1278.0
Unpaid commitments	38.2
Amount carried forward in the Special Account	16.3
Amount available from 1991 and 1992 for set off against future contributions from Members	2.9

Appropriations from Earlier Years

The unused payment appropriations and excess income over budget of 2.95 Mio ECU arising in 1990 and held for reduction of Members' future contributions were transferred to income in 1992.

Summary

Table 14 summarises the financial transactions of the JET Joint Undertaking as at 31 December 1992, which have yet to be audited. The final audited accounts will be published in due course.

Contracts Service

Contracts Activity

157 tender actions covering supply, service and personnel requirements were issued in 1992 and 16,505 contracts were placed. Of the 93 major contracts (value > 75,000ECU) placed, a significant proportion were for pumped divertor related plant and for services. 4,222 minor contracts (value between 600 and 75,000 ECU) were issued in 1992. 11,990 Direct Orders (value 0 to 600 ECU) were issued in the year (73% of total orders placed) whilst their aggregate value amounted to only 4% of the total value of all orders in that period.

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 1992 was 9.6 MioECU.

Imports and Exports Services

Contracts Service is also responsible for the import and export of JET goods. 1,151 imports were handled in 1992 while the total exports amounted to 328. There were also 931 issues of goods to UK firms. The total value of issues to all countries for the year was £8,011,745.

Stores Organisation

The bulk of JET material is procured on a "just in time" basis and the Stores Organisation provides a receipts and delivery service for this material to the Project. The total number of such receipts in 1992 amounted to 17,315.

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 1984-92. Table 16 is an allocation of "high-tech" contracts, which is based on the figures shown in Table 15 but excludes all contracts below 5,000 ECU and contracts covering civil

Table 15: Allocation of JET Contracts

Country	Total of kECU Values	% of Total
UK	473,051	52.95
Germany	157,551	17.63
France	85,290	9.54
Italy	54,622	6.11
Switzerland	41,550	4.65
Denmark	12,725	1.42
Netherlands	16,280	1.82
Belgium	10,986	1.23
Sweden	6,515	0.73
Ireland	877	0.10
Others	34,150	3.82
TOTALS	893,597	100.00

Table 16: Allocation of JET "High-Tech" Contracts

Country	Total of kECU Values	% of Total
UK	126,372	25.99
Germany	142,679	29.34
France	75,596	15.55
Italy	48,823	10.04
Switzerland	33,602	6.91
Denmark	7,437	1.53
Netherlands	15,196	3.13
Belgium	5,024	1.03
Sweden	4,352	0.89
Ireland	330	0.07
Others	26,844	5.52
TOTALS	486,255	100.00

works, installation, pipework, consumables (including gases), maintenance operations and office equipment (including PCs).

Personnel Service

During 1992, the work of Personnel Service was concerned with staffing, conditions of service, recruitment, training and general administration.

Recruitment and Staffing

The recruitment policy established in the latter part of 1991 continued in 1992. This restricted recruitment to essential cases, with the aim of reducing the size and cost of the JET team. Only five recruits joined the team in 1992 (4 AEA, 1 Euratom). Furthermore, JET Management decided not to renew the assignments of 10 UKAEA and 13 Euratom team members at the end of 1992, and most of these staff left the Project during or at the end of the year. However, one was redeployed within the JET team and three others were subsequently granted temporary extensions of their assignments. 23 team members left through normal turnover which was a little higher than in 1991 (21). As a result of these factors, the number of team posts filled declined by 37.

Reorganisation

A major reorganisation of JET's management structure was planned during 1992 to take effect when the new JET Director formally took up his position. After the JET Council had nominated or renominated Associate Directors, Department, Division and Service Heads in June and October 1992, action was taken to select new Group Leaders and to fill vacancies resulting from internal transfers. Most posts in the new structure were filled by existing JET team members. The composition of Team Staff by nationality is shown in Fig.57.

Assignments to the JET Team

Following the decision of the Council of Ministers in December 1991 to prolong the JET Project, reassignments of staff had to be arranged. 397.5 personnel (168 Euratom and DG XII and 229.5 AEA staff including 11 part-timers) were reassigned for two years with the expectation that their assignments would be extended further to 31 December 1996 provided the Project receives adequate funding for 1995 and 1996. The assignments of a further four staff (3 Euratom and 1 AEA) were extended for a shorter period, giving an overall total of 401.5 posts filled.

Table 17: Posts Filled against Complement

Team Posts	Complement	Posts Filled (31.12.91)	Posts Filled (31.12.92)
Temporary Euratom Staff	191	181	163
UKAEA Staff	260	249.5	230.5
DG XII Fusion Programme Staff	19	8	8
TOTAL	470	438.5	401.5

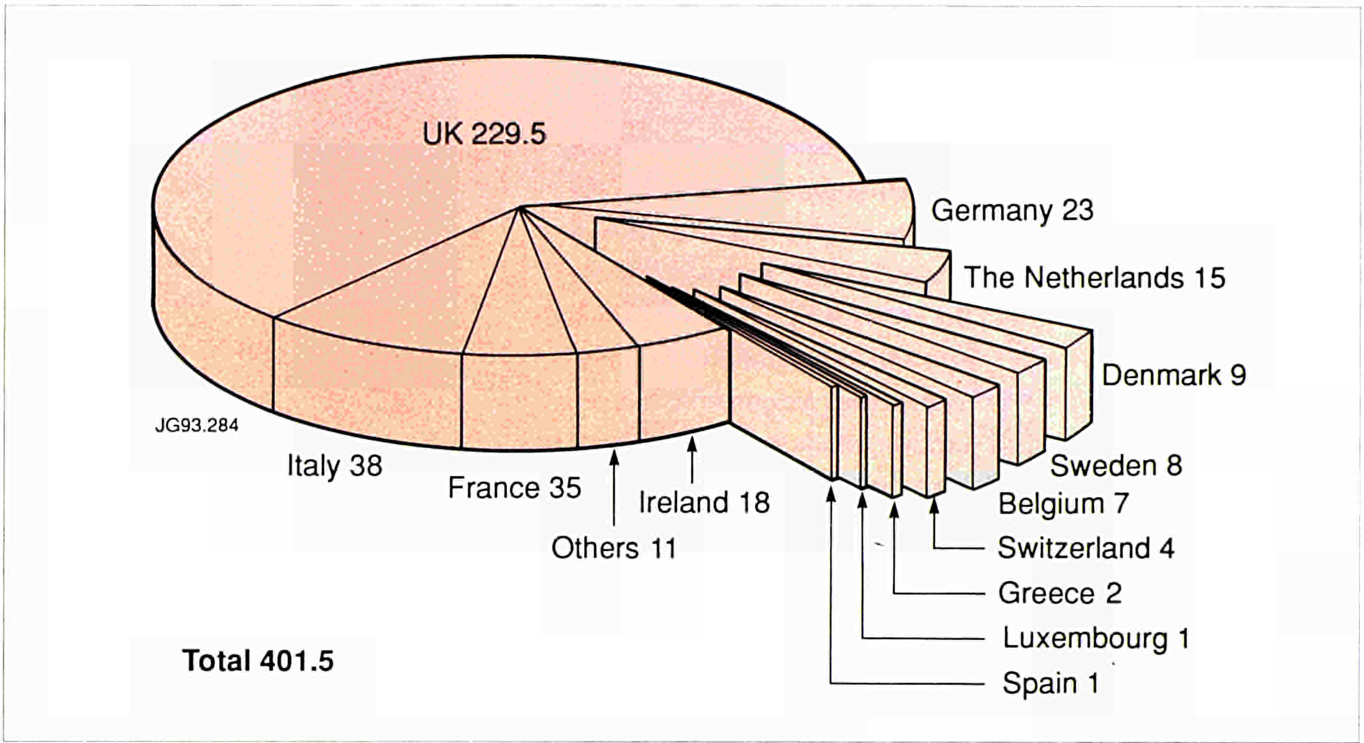


Fig.57: Composition of Team Staff by nationality

The JET Council asked that the terms of guarantee of employment or re-employment of Euratom staff at the end of this extended assignment should be explicit, acknowledged by staff concerned and full details made available to JET as well as to the Commission. All renewed 'return tickets' were received on time for the Director to reassign staff before the end of 1992.

Conditions of Service

The UKAEA Retention of Experience Allowance was again paid to a large proportion of UKAEA staff at JET. It is expected that the scheme will be reviewed during 1993.

Matters relating to working conditions at JET were considered jointly by JET management and the Staff Representatives Committee at two meetings during the year. Topics covered included staff reductions, JET promotion procedures, and assignments to ITER.

Industrial Action

A series of one-day strikes was organised by the Trade Unions/Staff Associations representing the UKAEA team members during the year in pursuit of their claim for equal pay and conditions with their Euratom colleagues. Six hundred and sixty full staff-days were lost in a series of one-day strikes between June and August. The European Parliament considered the UKAEA staff's petition concerning their claim and the Commission agreed to set up a Panel of Wise Men to review remuneration arrangements at similar institutions. Their report, published in September 1992, gave rise to discussions

Table 18: Contributions from Associated Laboratories during 1992

Associate Laboratory		Man-Years
UKAEA	(UK)	14.0
IPP	(Germany)	5.3
NFR	(Sweden)	2.1
Risø	(Denmark)	0.1
ENEA	(Italy)	0.6
CEA	(France)	0.2
FOM	(The Netherlands)	0.4
CIEMAT	(Spain)	0.8
EPFL	(Switzerland)	0.4
JNICT	(Portugal)	1.0
	TOTAL	24.9

Table 19: Assigned Associate Staff within the Project during 1992

Department	Man-Years
Experimental and Theory	20.8
Machine and Development	2.3
Plasma Heating and Operations	1.8
TOTAL	24.9

between the unions, the Commission, the employer (UKAEA) and JET management towards resolving the dispute.

Students

Eighty-six students were selected to work at JET during 1992 and appointments were made through a local employment agency. Departmental quotas from the budget were allocated following the 1991 pattern, but reflecting the tight financial constraints at JET and the aim to improve the balance between engineering students (who have been under-represented in the past) and science students. A large majority of the students were in their later years of study. Students were recruited from all member states except Luxembourg.

Fellows

During 1992, 25 Fellows worked at JET, of whom 19 were scientists and 6 were engineers. The research projects undertaken were at both post-graduate and post-doctoral level.

In October 1992 a new Fellowship scheme to be administered under the regulations of the Human Capital and Mobility Programme, was introduced by the Commission. This scheme is designed to encourage the training and mobility of young researchers, especially at post-doctoral level.

Assigned Associated Staff

The decline in numbers of staff assigned to JET from the Associated Laboratories continued in 1992. This was to be expected due to the long shutdown of the machine which commenced in March 1992. The contribution for 1992 was 24.9 man-years compared with 27.8 man-years in 1991. Tables 18 and 19 show the contributions under the scheme from the Associations in 1992, together with the distribution of the Assigned Associated Staff within the project.

Training

Although slightly lower than during 1991, training activity at JET continued at a high level, with 80% of team members being involved in a least one training activity during the year. Much emphasis was again placed on safety training, with around 2650 attendances on safety courses. A high proportion of these were contractors working on the Project during the shutdown period who required basic safety induction training, although a significant amount of effort was also devoted to training in hazardous materials, with a total of 168 man-days being spent on radiation protection, and beryllium and tritium safety.

Attendance on short-term courses to obtain or up-date specialist skills increased during 1992, with much of this effort concentrated on courses in UNIX and C software required for the later stages of the machine operation. By the end of 1992, in-house language tuition was confined to English only, but a scheme was introduced in the Autumn to support team members studying other Community languages plus Swedish at local Adult Education Colleges.

General Administration

Following a proposal by the Director, subsequently approved by the JET Council, a new telecommunications system was purchased to replace the Culham site facility which previously served JET and had become obsolete. The new system covering telephones and on-site pagers (bleeps) was installed and became operational in May 1992 under JET's sole responsibility. It is expected to provide a more efficient service and to yield financial savings and improved management information.

The management of office and laboratory space has been greatly improved by the introduction of a computer-aided design facility containing all the information necessary to carry out efficiently inventories and reallocations, for example to reflect new organisational structure.

The number of missions on JET business increased this year by 30% from 2676 to 3479, reflecting efforts to complete tasks during the shutdown (eg contractual discussions). Missions undertaken by JET Team staff for ITER have increased significantly.

Site security passes are required by all personnel on site and in 1992 about 1700 were issued by Personnel Service to long-term contractors and visitors (a similar number to last year).

JET hosted 11 meetings of governing and advisory bodies, for which Personnel Service co-ordinated all transport and accommodation arrangements.

Safety

Organisation and Committees

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 Group provides a general safety service, including training, monitoring, co-ordination and planning. Special attention was paid to training with particular emphasis on the long shutdown. The Health Physics Group provide a comprehensive radiological protection and occupational hygiene service, dosimetry service, beryllium analysis and environmental monitoring, both on- and off-site.

There are currently four committees on safety-related matters:

- *The JET Safety Policy Board*, chaired by the Director, meets once a year to review safety policy and define new actions;
- *The JET Health and Safety Committee*, chaired by the Head of Administration Department, which consists of representatives of management and staff and reviews all matters which affect the health and safety of all employees on the JET site. It receives reports of Safety Audits, inquiries into accidents, and accounts of activities of the other JET Safety Committees;
- *The JET Fusion Safety Committee*, chaired by the Head of Coordinating Staff Unit and includes non-JET members, keeps under review the safety aspects of the Project during design, commissioning and operation, arising from the use of tritium;
- *The JET Safety Working Group*, chaired by the Head of Coordinating Staff Unit with members from JET and the Host Patrol Service, continued to review all aspects of day-to-day safety.

Health Physics

The divertor shutdown started in February and in-vessel access commenced on 1 March. The radiation dose rate in-vessel (~90µSv/h) was higher than at the beginning of previous shutdowns - this was a direct and foreseen result of the First Tritium Experiment. As a consequence dose management was necessary and some staff were 'rotated' out of in-vessel work, during April, when their doses in the calendar year approached 5mSv. The collective dose in 1992, due to in-vessel work in the divertor shutdown was 0.201 man-Sv: the total collective dose for the project for 1992 was 0.223 man-Sv.

Tritium contamination encountered within the vacuum vessel was significantly lower than forecast, and a urine sampling campaign indicated that no measurable intakes of tritium occurred during 1992 (airborne tritium in-vessel did not exceed 100 Bq/m^3 during periods of in-vessel access). Surface contamination was generally in the range 4-70 Bq/cm^2, though locally 7.6 kBq/cm^2 was measured at (the ^{3}H injection port) Octant No:8. Low levels of tritium (~ 100-200 Bq/ℓ) were encountered in some of the water cooling circuits on the machine; this arose by permeation of tritium through the pipework within the vessel.

Exposure to airborne beryllium at JET continues to be monitored by personal-air-sampling. Analysis of 12,374 samples during 1992 indicated that more than 99% of these assessments were below the UK's occupational exposure standard of 2µg/m^3 (8 hour time weighted average), and compliance with the Control of Substances Hazardous to Health Regulations 1988 was demonstrated.

Press and Public Relations

In the wake of the successful experiments involving deuterium-tritium plasmas in November 1991, both public and media interest in the Project continued at a high level throughout the current year. A further boost to the general interest in fusion research was given in July by the signing of the agreement setting up the ITER Engineering Design Activity in the three co-centres at San Diego, USA, Garching, Germany and Naka, Japan.

On the political front, a number of politicians from various countries visited the site for briefings on JET's achievements and future plans. Most notable of these was the President of the Commission of the European Communities - Mr. Jacques Delors. This visit was covered by seven television crews and around 30 journalists, radio reporters and photographers. Mr. Delors, after his tour of JET, praised the JET Team for their successes both as a scientific experiment and as a collaborative community venture.

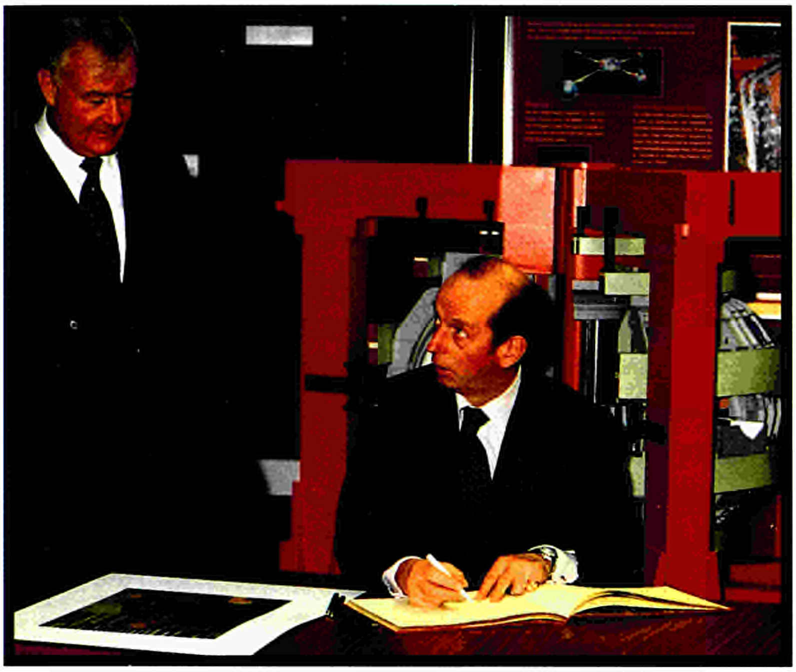


Fig.58: Visit of HRH, the Duke of Kent to JET on 30th November,1992

At other times in the year there were visits by members of the Budget's Committee of the European Parliament, a party of German MPs, the Swedish Minister for Education, Mr. Per Unckel, UK MP's Mr. Kevin Barron and Mr. Simon Coombs and local MEP Dr Caroline Jackson.

Among the more distinguished visitors to JET were His Royal Highness, The Duke of Kent (Fig.58), the Italian Ambassador, Mr. G Attolico and the Secretary General of the Commission of the European Communities, Mr. David Williamson.

In addition to the media coverage for the visit of Mr. Delors, during the year 14 television or film crews from Chile, France, Germany, Italy, Portugal, Russia and the UK shot sequences of the JET machine and recorded interviews for documentaries and news items on nuclear fusion. A similar number of radio interviews were given by JET staff, including a two-hour live programme on local radio, in which eight staff of different nationalities talked about their experiences of living and working in the UK. JET staff also gave interviews during the year to a number of journalists from the UK, Canada, Norway, Spain and Sweden.

Professional organisations, university and school students and local groups continue to take a keen interest in the Project. Nearly 200 such groups, not only from the European Communities but also from further afield, were given conducted tours of the JET laboratories and many invited lectures were given to groups unable to visit the site. In July, a delegation of senior Chinese scientists and engineers from the South Western Institute of Physics paid a four-day visit to JET.

JET continues to foster good relations with the local community through meetings of a Local Liaison Committee, an annual reception and site visits of interested groups.

The four technical Directors of JET - Drs Rebut, Keilhacker, Gibson and Huguet - were awarded the 1992 UK Royal Society - Esso Energy Award, for JET and its role in the development of nuclear fusion as a potential new major energy source. This prestigious award is made annually for 'outstanding contributions to the advancement of science, engineering or technology in the energy field'. The award is to promote a more efficient use of existing energy sources and to stimulate the development of new ones. The award (see page iv) was presented at a special meeting and dinner at the Royal Society, London, UK in November, at which Dr. Keilhacker gave a lecture on Energy for the 21st Century: A Perspective on Nuclear Fusion.

Publications Group

The Publications Group provides a Graphics, Phototypesetting, Photographic and Reprographics service for the Project. The Group is lead by the Publications Officer, who is also responsible for the clearance, production and distribution of all JET documents. In addition, the Group arranges JET attendance at major International Conferences, and prepares papers and posters for these Conferences and Meetings.

Conferences

The number of Conferences attended by JET Representatives during 1992 was fewer than in 1991, but JET still provided major contributions to a number of meetings, as follows:

- 10th International Conference on Plasma Surface Interactions, Monterey, USA, 30th March - 3rd April 1992, (1 Invited Paper, 2 Oral Contributions and 18 Posters);
- 19th European Conference on Controlled Fusion and Plasma Physics, Innsbruck, Austria, 29th June - 3rd July 1992 (3 Invited Papers, 6 Oral Contributions and 39 Posters);
- 17th Symposium on Fusion Technology (SOFT-17), Rome, Italy, September 14-18 1992, (2 Invited Papers, 2 Oral Contributions and 23 Posters);
- 14th IAEA Conference on Plasma Physics and Controlled Nuclear Fusion Research, Würzburg, Germany, 30 September - 7 October 1992, (2 Invited Papers, 8 Oral Contributions and 2 Posters);
- 34th Annual Meeting of the American Physical Society - Division of Plasma Physics, Seattle, USA, 16-20 November 1992, (1 Invited Paper and 7 Posters).

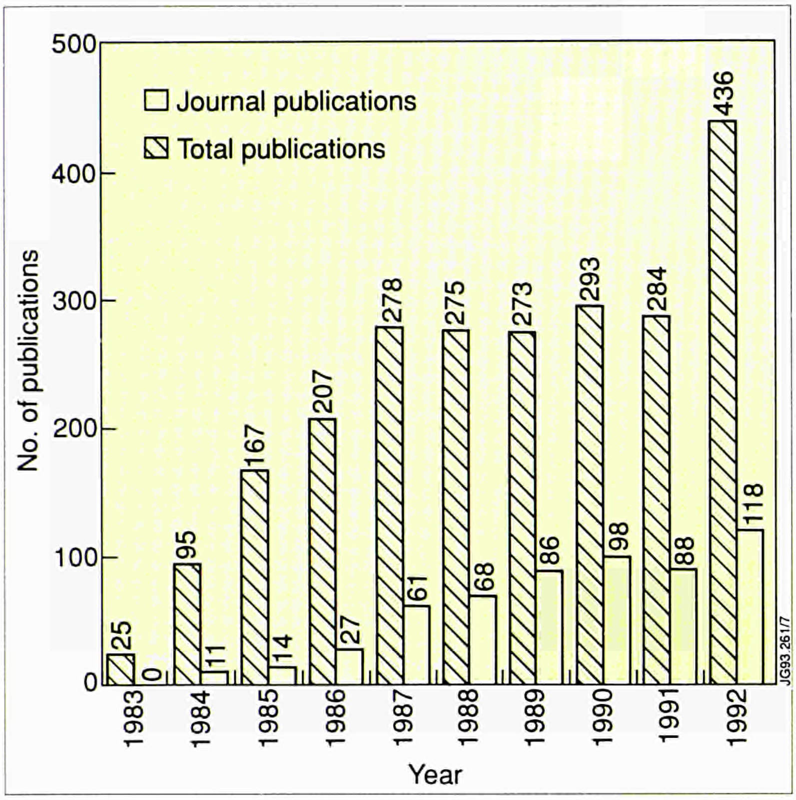


Fig.59: JET Publications 1983-1992

In total, the Group prepared 169 Papers and 113 Posters for presentations to nine different Conferences throughout the world. Arrangements were also made by the Group for 178 participants to attend these major meetings during the year.

Publications

The Publications Office is responsible for the clearance and production of all JET presentations (including Journal Papers, Reports, Conference Papers, Poster Contributions, Lectures, etc.). Throughout 1992, over 440 publications were cleared for external presentation.

During the year 436 documents were published from the Project and the full list is included as an Appendix to the 1992 JET Progress Report. This total included 13 JET Reports, 102 JET Preprints, 11 JET Internal Reports, 1 JET Technical Note and 7 JET Divisional Notes. All these documents are produced and disseminated by the Group on a wide international distribution. The variation of the total number of JET publications and the number of journal publications throughout the period 1983-1992 is shown in Fig.59. In total, the Group produced 3361 new illustrations and figures and 3100 photographs for publications and other disseminated material during 1992.

APPENDIX I
The JET Council

Member	Representative
The European Atomic Energy Community (EURATOM)	P. Fasella (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	J. Tachon (to October) D. Escande (from October) R. Aymar
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	R. Andreani C. Mancini
The Hellenic Republic (Greece)	A. Katsanos
The Forskningscenter Risø (Risø), Denmark	H. von Bülow (Vice-Chairman from March) J. Kjems
The Grand Duchy of Luxembourg (Luxembourg)	J. Hoffmann Mrs. S. Lucas
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	C. Varandas Mrs. M.E. Manso
Ireland	M. Brennan F. Turvey
The Kernforschungsanlage Jülich GmbH*, Federal Republic of Germany (KfA)	G. von Klitzing
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	K. Pinkau
The Swedish Natural Science Research Council (NFR), Sweden	M.O. Ottosson (to September) G. Leman (from September) H. Wilhelmsson
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)	J.R. Bretherton D.R. Sweetman

Secretary: J. McMahon, JET Joint Undertaking

* name changed to Forschungszentrum Jülich GmbH in January 1990.

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
Commissariat à L'Énergie Atomique (CEA), France	C. Gourdon (Vice-Chairman) (to March) C. Samour (from March) R. Gravier
Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative (ENEA), Italy	A. Coletti M. Samuelli
The Hellenic Republic (Greece)	A. Theofilou
The Forskningscenter Risø (Risø), Denmark	Mrs. L. Grønberg V.O. Jensen
The Grand Duchy of Luxembourg (Luxembourg)	R. Becker
The Junta Nacional de Investigação Científica e Tecnológica (JNICT), Portugal	J. Bonfim F. Serra
Ireland	F. Turvey (Chairman) D. Taylor
The Kernforschungsanlage Jülich GmbH*, Federal Republic of Germany (KfA)	V. Hertling
The Max-Planck-Gesellschaft zur Förderung der Wissenschaften e.V. Institut für Plasmaphysik (IPP), Federal Republic of Germany	K. Tichmann (to February) C. Halfmann (from February to September) Mrs. I. Kramer (from September)
The Swedish Natural Science Research Council (NFR), Sweden	G. Leman (Vice-Chairman from March) L. Gidefeldt (from September)
The Swiss Confederation	A. Heym P. Zinsli (to September) L. de Faveri (from September)
The Stichting voor Fundamenteel Onderzoek der Materie (FOM), The Netherlands	A. Verhoeven L.T.M. Ornstein
The United Kingdom Atomic Energy Authority (UKAEA)	D.M. Levey (to September) T.J. Elsworth (from September) D.C. Robinson

Secretary: J. McMahon, JET Joint Undertaking

* name changed to Forschungszentrum Jülich GmbH in January 1990.

APPENDIX III
The JET Scientific Council

Members appointed by the JET Council:

F. Troyon (Chairman and Member until 30th June 1992)
EURATOM-SUISSE Association
Centre de Recherches en Physique des Plasmas
Ecole Polytechnique Fédérale
21 Avenue des Bains
CH-1007 Lausanne, Switzerland

R. Aymar (until 30th June 1992)
EURATOM-CEA Association
Orme des Merisiers
Centre d'Études Nucléaires de Saclay
F-91191 Gif-sur-Yvette, France

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

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

M. Gasparatto (from 1st July 1992)
EURATOM-ENEA Association
ENEA Centro di Frascati
Casella Postale 65
I-00044 Frascati/Roma, Italy

A. Grosman
EURATOM-CEA Association
Département de Recherches sur la Fusion Contrôlée
Centre d'Études Nucléaires Cadarache
Boîte Postale No.1
F-13108 St. Paul lez Durance, France

T. Hellsten
EURATOM-NFR Association
Royal Institute of Technology
Department of Fusion Plasma Physics
S-10044 Stockholm, Sweden

F. Hofmann (from 1st July 1992)
EURATOM-SUISSE Association
Centre de Recherches en Physique des Plasmas
Ecole Polytechnique Fédérale
21 Avenue des Bains
CH-1007 Lausanne, Switzerland

K. Lackner (Chairman from 1st July 1992)
EURATOM-IPP Association
Max-Planck-Institut für Plasmaphysik
D-8046 Garching bei München
Federal Republic of Germany

P. Lallia
DG-XII, Commission of the European Communities
200, Rue de la Loi
B-1049 Brussels, Belguim

D. Moreau
EURATOM-CEA Association
Département de Recherches sur la Fusion Contrôlée
Centre d'Études Nucléaires Cadarache
Boîte Postale No.1
F-13108 St. Paul lez Durance, France

D.C. Robinson
EURATOM-UKAEA Association
AEA Technology
Culham Laboratory
Abingdon, Oxfordshire, OX14 3DB
United Kingdom

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

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

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

R. Weynants
EURATOM-EB:BS Association
Laboratoire de Physique des Plasmas/
Laboratorium voor Plasmafysica
Ecole Royale Militaire/Koninklijke Militaire School
Avenue de la Renaissancelaan, 30
B-1040 Brussels, Belgium

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

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