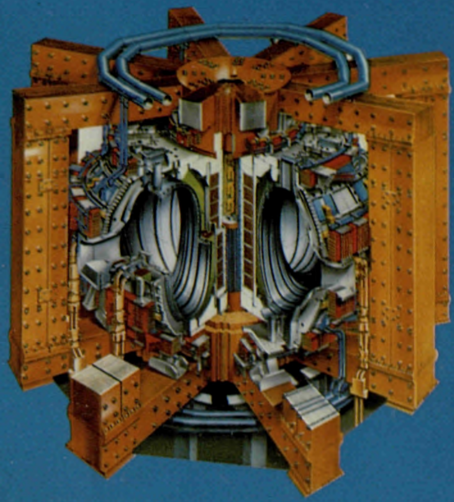
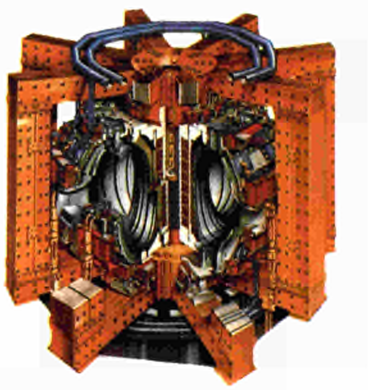


JET

JOINT
EUROPEAN
TORUS

The JET Joint Undertaking

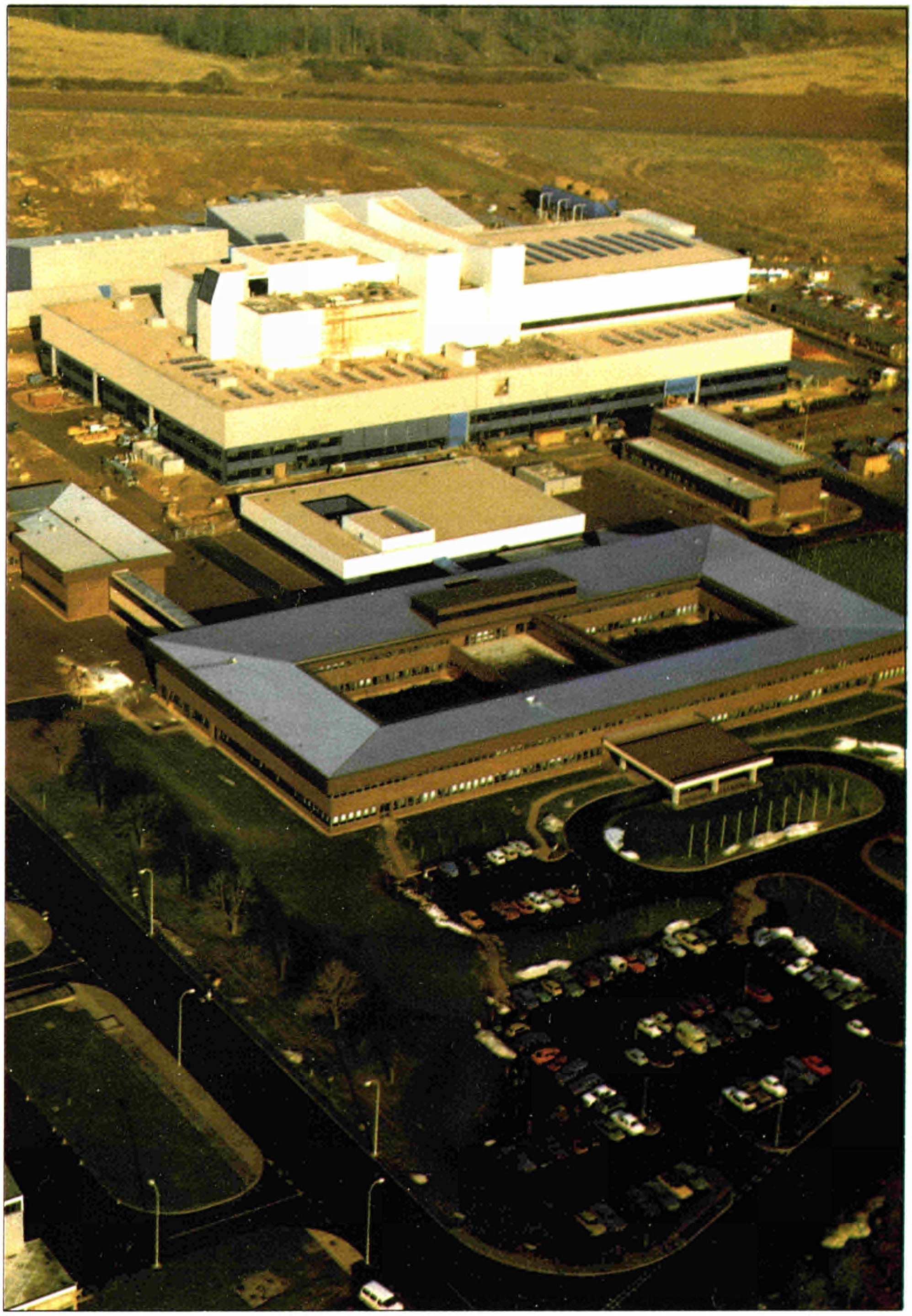


The JET Joint Undertaking
Abingdon
Oxfordshire OX14 3EA
England
Tel: Abingdon (0)235–28822
Telex–837505 JETEUR G

Contents

EUR 8306 EN (EUR-JET-R11) NOVEMBER 1982
Printed in England

JET Joint Undertaking



82-162c

Joint European Torus

JET is the largest single project of the co-ordinated nuclear fusion research programme of the European Atomic Energy Community (Euratom) aimed at proving the feasibility of nuclear fusion as a new energy source.

The experiment is using the tokamak magnetic field configuration and will have a greater performance capability than any other machine of this type in the world. Successful completion of the JET programme will provide essential information on the reactor potential of the tokamak system.

The JET Project

The JET Tokamak

THE aim of the JET project is to build and operate a large tokamak device with overall dimensions of about 15 metres in diameter and 12 metres high. At the heart of the machine there is a toroidal vacuum vessel of major radius 2.96 metres having a D-shaped cross-section 2.5 metres by 4.2 metres. During operation of the machine a small quantity of hydrogen gas is introduced into the vacuum chamber and is heated by passing a very large current (2.6 MA to begin with and 4.8 MA at a later stage) through the gas. This current is produced by transformer action using the massive eight-limbed magnetic circuit which dominates the apparatus. A set of coils around the centre limb of the magnetic circuit forms the primary winding of the transformer with the hot gas or *plasma* acting as a single turn secondary. Additional heating of the plasma is provided by injecting beams of energetic hydrogen atoms into the system and by the use of high power radio frequency waves.

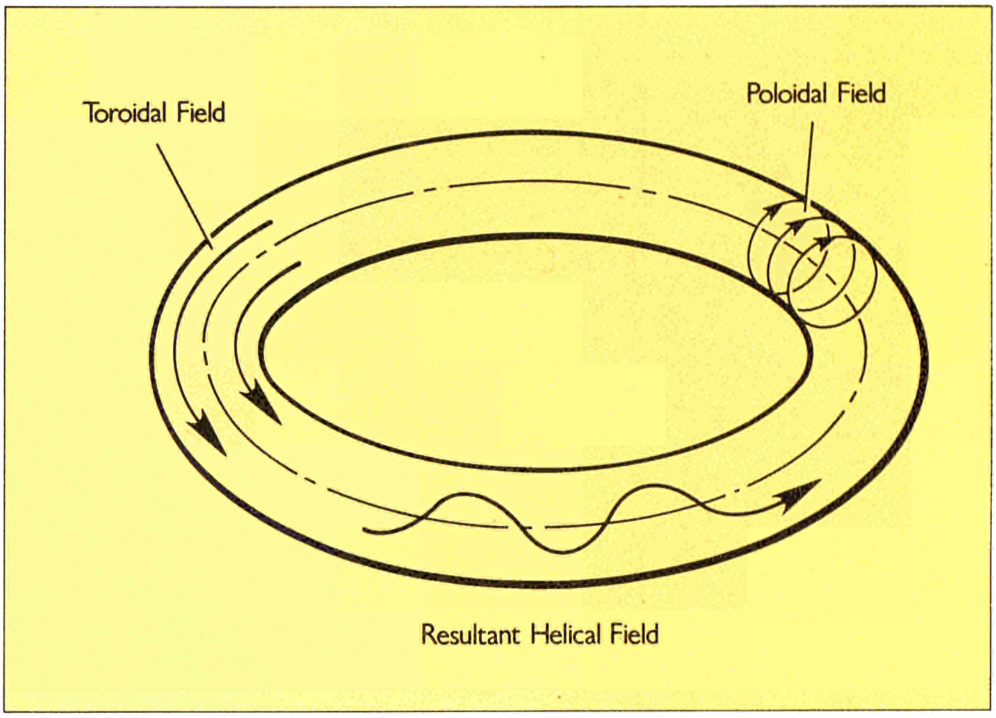
The plasma is confined away from the walls of the vacuum vessel by using a complex system of magnetic fields. The main component of the magnetic field, the so-called toroidal field, is provided by 32 D-shaped coils surrounding the vacuum vessel. This field coupled with that produced by the current flowing through the plasma, form the basic magnetic fields for the tokamak confinement system.

Additional coils positioned around the outside of the vacuum vessel are used to shape and position the plasma. These coils, together with the coils making up the primary winding of the transformer, are called poloidal field coils.

Initial experiments will be carried out using ordinary hydrogen plasmas; towards the later stages of the operation of JET it is planned to operate with deuterium-tritium plasmas so that fusion reactions can occur. Deuterium and tritium are the two isotopes of hydrogen; deuterium is very plentiful but since tritium is not a naturally occurring element it will be manufactured in a future fusion reactor from lithium. Lithium is also very plentiful.

Main JET Parameters

Plasma minor radius (horizontal)	1·25 m	
Plasma minor radius (vertical)	2·10 m	
Plasma major radius	2·96 m	
Flat top pulse length	20 s	
Weight of the vacuum vessel	100 tonnes	
Weight of the toroidal field coils	384 tonnes	
Weight of the iron core	2700 tonnes	
	Basic	**Full Design**
Toroidal field coil power (peak on 13 s rise)	250 MW	380 MW
Total magnetic field at plasma centre	2.8 T	3.4 T
Plasma current:		
circular plasma	2.6 MA	3.2 MA
D-shape plasma	3.8 MA	4.8 MA
Volt-seconds available to drive plasma current	25 Vs	34 Vs
Additional heating power	5 MW	25 MW

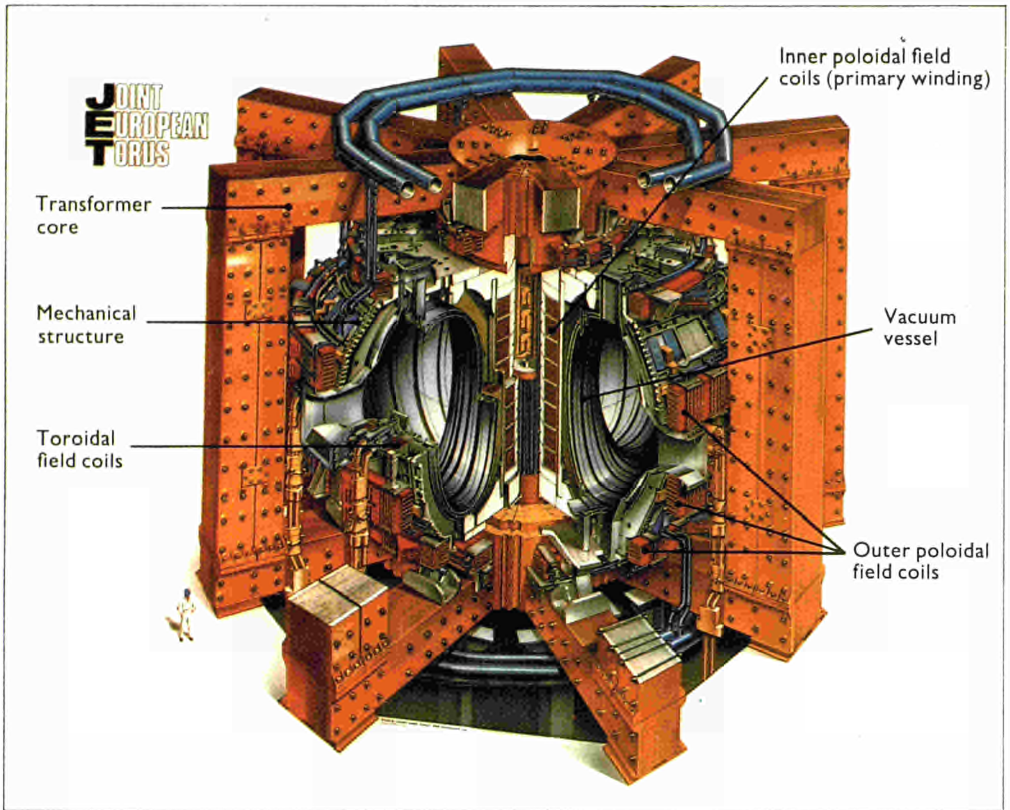


Principal magnetic fields of a Tokamak

Large Scale Tokamaks

Throughout the world there are four large tokamaks at present under design or construction. These are TFTR (USA), JT-60 (Japan), T15 (USSR) and JET (Europe). TFTR is expected to be the first of these four to start operating (December 1982), followed by JET (summer 1983), JT-60 (end 1984) and T15 (1985). Although each of the experiments has a different scientific objective they all represent a major and logical step towards the development of a fusion reactor. JET and TFTR are designed to operate with deuterium and tritium plasmas in the latter part of their programmes, while JT-60 and T15 will operate only with hydrogen plasmas. Thus JET and TFTR hope to create abundant fusion reactions with the consequent release of energetic neutrons.

In a fusion reactor the kinetic energy of these neutrons will be used to heat up a surrounding blanket; this heat will then be used to raise steam so that turbines can be driven to produce electricity in the conventional manner. No provision has been made for such a blanket on JET as this will be the subject of study for the next generation of fusion experiments.



82-348c

Diagram of the JET Tokamak

Objectives of JET

Detailed studies in a series of different sized tokamaks throughout the world have produced a consistent pattern of encouraging results. Plasmas with increasingly higher temperatures have been confined and controlled for progressively longer times. The knowledge gained from these smaller scale experiments indicates that a reactor will need to have large dimensions and a large plasma current.

The essential objective of JET is to obtain and study plasma in conditions and with dimensions approaching those needed in a fusion reactor.

These studies will be aimed at:

1. The study of plasma processes and scaling laws in regions close to those needed for a fusion reactor.
2. The study of the interaction of the plasma with the walls of the torus chamber. This interaction is important because it controls the purity of the plasma which in turn determines the energy lost by radiation.
3. The study of methods of heating the plasma to temperatures approaching those required for a reactor.
4. The study of the behaviour of the energetic α-particles (the nuclei of helium) needed to sustain the plasma temperature and produced as a result of the fusion between deuterium and tritium.

Machine Construction

CONSTRUCTION of the JET experiment started immediately after the Torus Hall was completed in January 1982. The first items to be installed were the large ring manifolds situated in the pit below the machine, and used for supplying the services, such as water, vacuum and hot carbon dioxide, to the machine. The lower horizontal and vertical limbs of the magnetic circuit, which is the heaviest component of the machine, were then moved into position. As the central toroidal structure of the machine is supported by the horizontal limbs, the inner ends are mounted on stanchions in the central pit with the outer ends resting on pads fitted to the Torus Hall floor.

After the smallest of the lower set of three outer poloidal field coils had been installed the lower ring and collar of the mechanical structure were placed into position and the upper ring and collar supported above it on four pillars. Four sections of the inner cylinder were then attached to the ring and collars to allow the first four machine octants to be installed. After these had been fitted the pillars were removed, the other sections of the inner cylinder fitted and the remaining machine octants installed. Each octant of the inconel vacuum vessel was then welded to its neighbour. The coils resting on the magnetic circuit limbs were raised into position and the outer poloidal field coil system completed with the fitting of the upper three coils.

82-T-520c/2

Assembly of the magnetic circuit

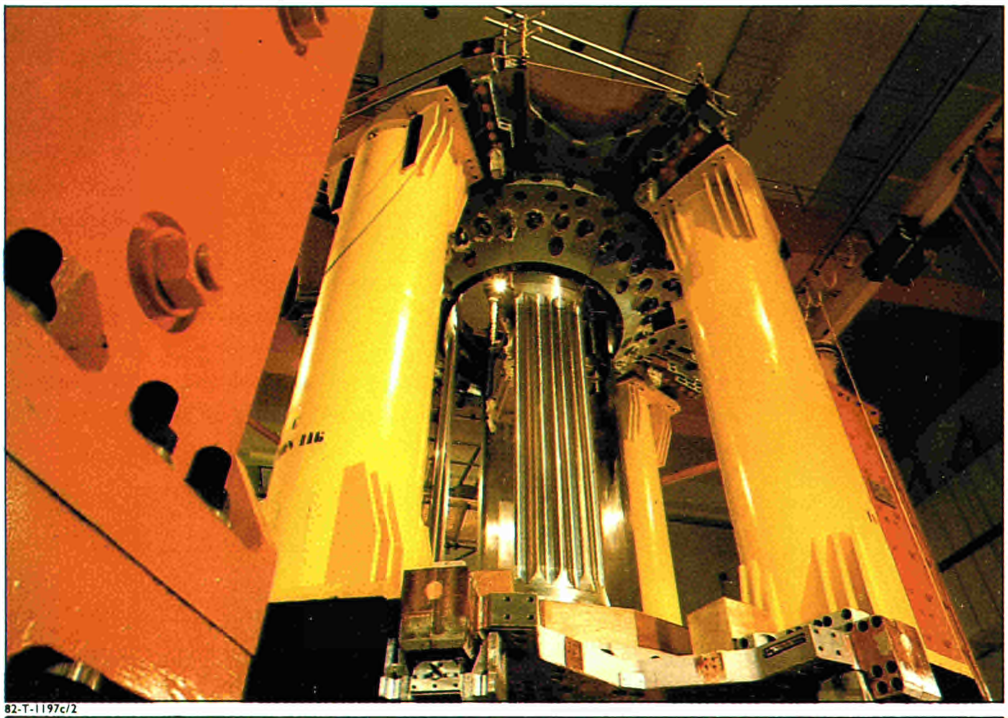
82-T-835c/4

Transfer of an outer poloidal field coil to the Torus Hall

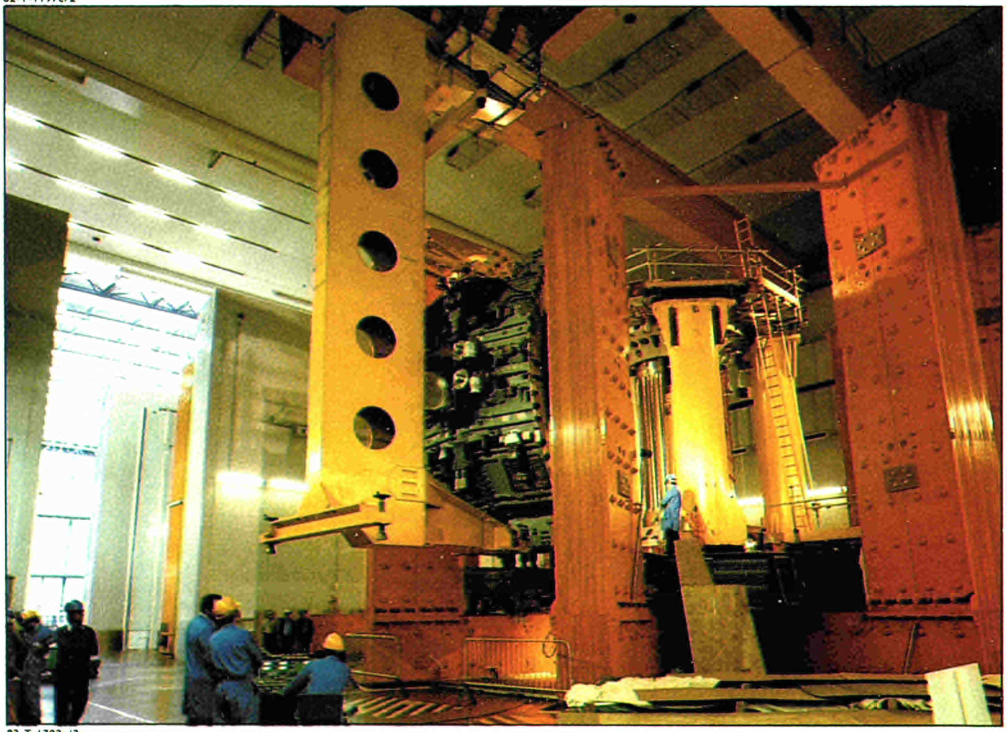
82-T-220c/9

Fitting of the service manifolds in the central pit

While the octants were being installed the eight inner poloidal field coils were built up into a stack and lowered into the inner cylinder. The magnetic circuit was then completed with the installation of the upper horizontal limbs and centre piece.
During the construction of the machine the service ducts and pipework were installed in the basement and wings of the building. With construction of the basic machine completed the additional work needed to connect the services onto the machine was carried out making it ready for DAY ONE operation.


82-T-1197c/2

Inner cylinder and upper ring and collar of the mechanical structure


82-T-1702c/2

Machine octant installation

Machine Components

COMPONENTS for the JET experiment were manufactured by industry throughout Europe and then transported to the Culham site. In the JET Assembly Hall some of these components were built-up into larger units before being incorporated into the machine. Other items, such as the magnetic circuit, were moved directly to the Torus Hall for installation.

Machine Octant Assembly

Among the items built up in the Assembly Hall were the eight wedge-shaped machine octants which make up the central toroidal structure of the machine. Each octant is built from four toroidal field coils, a one-eighth section of the outer mechanical structure and a vacuum vessel octant.

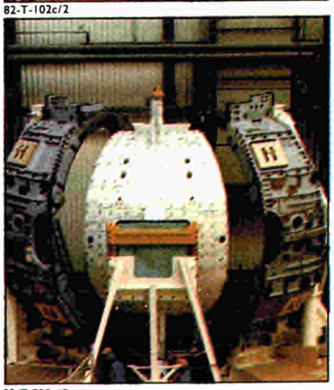
The assembly procedure for each octant was started by separating the one-eighth section of the mechanical structure into two pieces longitudinally. Each piece was then fitted separately into a jig so that two of the D-shaped toroidal field coils could be lowered into grooves machined on the inside surface of the shell. The coils were then locked into position and the unit, weighing approximately 45 tonnes, was lifted onto one of the movable side tables of the assembly fixture. This procedure was repeated with the other section of the mechanical structure.

An octant of the vacuum vessel was then mounted on to the central table of the fixture and the outer tables moved inwards, so that the toroidal field coils and mechanical shell enclosed the vacuum vessel. The two sections of the mechanical structure were then bolted together to form a completed machine octant.

Each octant was transferred in turn to the Torus Hall on a large C frame which supported the machine octants by attachments on the outer sections of the mechanical structure.

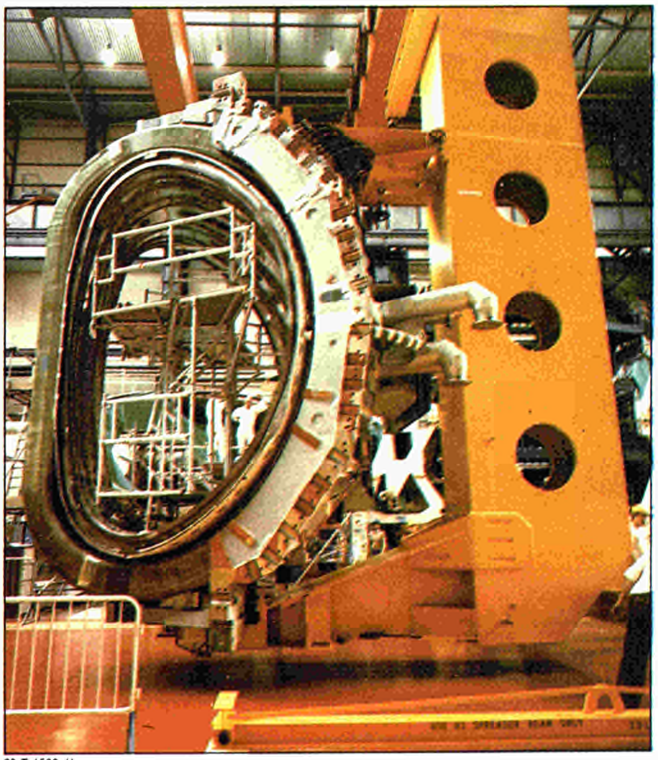
Installation of a toroidal field coil into the outer shell

82-T-102c/2



Octant assembly fixture

82-T-798c/5



A completed machine octant

82-T-1500c/1

Vacuum Vessel

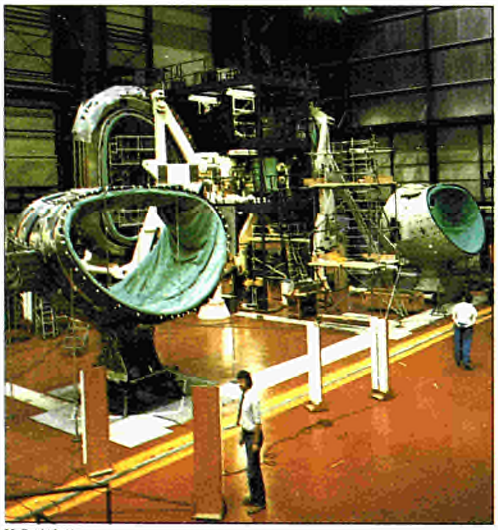
To maintain the plasma conditions required for studies on the JET experiment it is necessary to establish a very high vacuum in the plasma container. Under normal conditions the attainable vacuum is limited by the continuous evolution of gas from the vacuum chamber walls. To reduce this outgassing it is necessary to bake the whole vacuum vessel at 500°C for several hours. This process drives the gas from the walls and subsequently enables high vacuum conditions to be obtained. In addition, precautions are taken to ensure that all the internal surfaces are kept scrupulously clean during manufacture and assembly.

The vacuum vessel is made up from eight sections or octants, each of these being assembled from five rigid pieces and four sets of bellows. After all the sections of the vacuum vessel are incorporated into machine octants and installed on the machine, they are welded to each other in such a way that the welds can be easily opened later using remote handling techniques if necessary. The total length of high quality welds needed in the manufacture of the vacuum vessel exceeds 4 kilometres and the required leak rate must be less than 10^{-8} millibar-litres per second. This means in more familiar terms that it would take more than 3000 years for one litre of air to penetrate into the system.

To enable the complete vacuum vessel to be baked in situ the octants are constructed as double-walled chambers and hot carbon dioxide gas is passed through the interspace. The large horizontal and vertical ports on the vacuum vessel are heated using electrical heating elements attached to their outside surfaces. These heating methods are necessary to obtain a base pressure of 10^{-10} torr which is required to minimise the level of impurities in the plasma.

The bellows joining the rigid sections are incorporated to increase the electrical resistance of the vacuum vessel and thus ensure that the plasma current flows through the gas and not through the walls of the chamber. Because the bellows are made from relatively thin material, protective shields are used to ensure that they do not come directly in contact with the plasma.

82 T 799c/9



82-T-1613c/1

Vacuum vessel ready for assembly into a machine octant

Preparation of vacuum vessel octants

Under operating conditions energetic particles and radiation from the plasma interact with the walls of the chamber releasing impurities. To reduce this problem a series of plates, called limiters, is supported a few centimetres away from the vacuum vessel wall. The limiter material is chosen so that plasma interactions cause less contamination to be released.

Major radius of vessel centre	3 metres
Vessel diameter in horizontal direction	2.63 metres
Vessel diameter in vertical direction	4.18 metres
Width of vessel wall (rigid sector)	18 centimetres (typical)
Total weight	100 tonnes
Volume	190 cubic metres
Bellows material	Inconel 625
Rigid sector material	Inconel 600 or Nicrofer 7216

Toroidal Field Coils

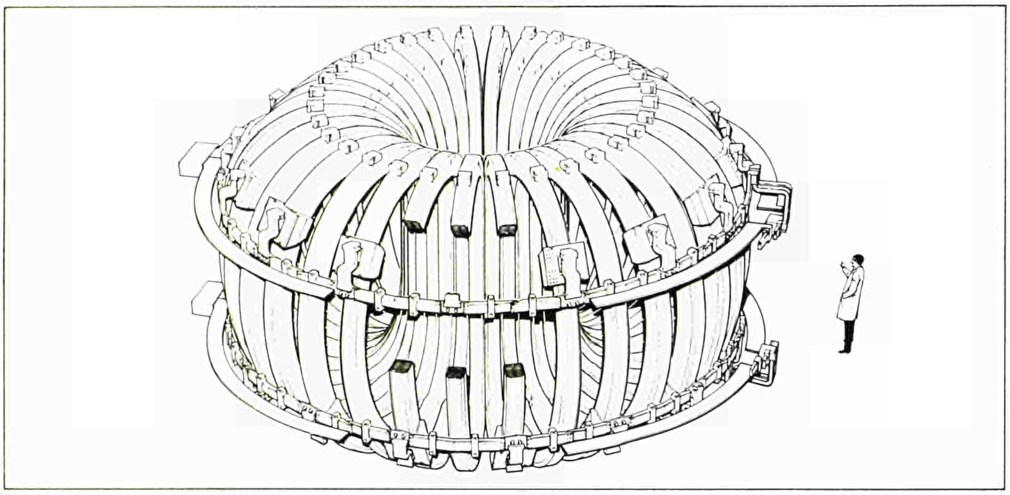
The toroidal field is one of the important components making up the complex magnetic field configuration used on tokamaks for confining the plasma.

On JET, the toroidal field is produced by 32 identical coils evenly distributed around the torus. The large number of coils has been chosen to achieve the required uniformity of the field, which is important for confinement of the plasma. The set of coils can maintain a magnetic field of up to 3.4 Tesla for between 10 and 20 seconds once every 10 minutes. To achieve this field an electric current of 66,000 amperes is circulated through the coils. Each coil, which weighs 12 tonnes, is made up from 24 turns of heavy copper bar, insulated with glass tapes and vacuum-impregnated with epoxy resin. During operation, the temperature of the copper increases from 20°C up to 80°C in 20 seconds. To cope with this temperature rise, a very efficient cooling system is used which consists of water circulating through channels in the centre of the copper conductors. The total flow of water required to cool the 32 coils is 700 litres per second.

Winding of the copper conductor into the coil's D-shape

79-355c

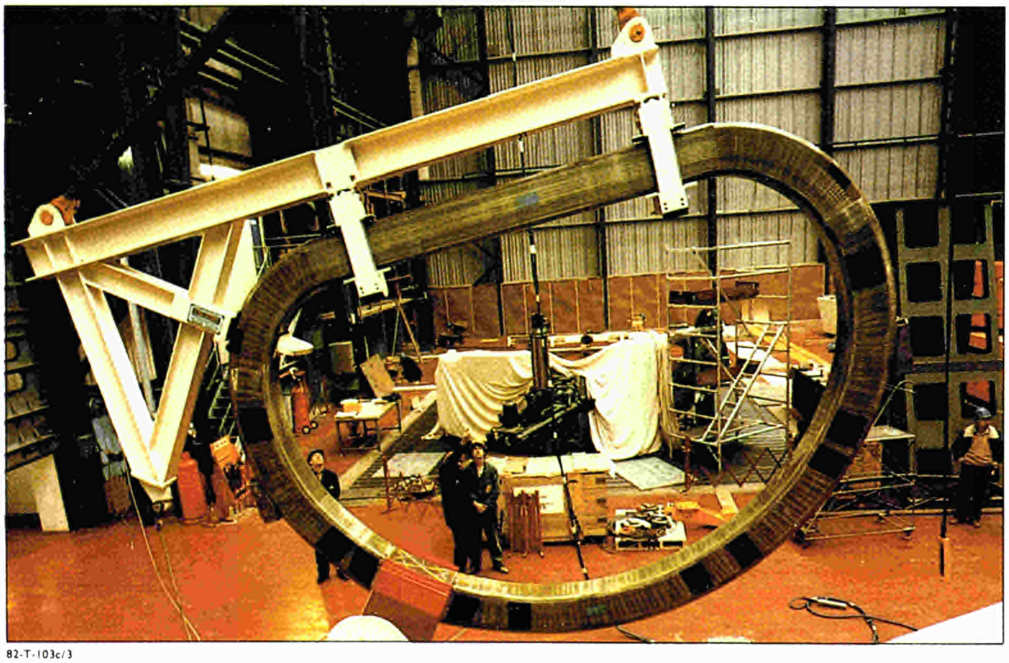
The magnetic field exerts a magnetic pressure which tends to expand the coils and produce very large mechanical forces. For example, each coil is pressed towards the centre of the machine with a force of 2000 tonnes. To minimise the mechanical bending stresses resulting from the internal magnetic pressure the characteristic D-shape coils have been chosen. This is the equilibrium shape that the coils would naturally assume when subjected to the forces due to the magnetic field if they were totally flexible and free to deform.



79-910

The toroidal field coil system

	Basic performance	Extended performance
Toroidal field at plasma centre line	2.8 Tesla	3.4 Tesla
Duration of pulse	30 seconds	20 seconds
Maximum current in conductor	53,000 Amp	66,000 Amp
Resistive power dissipated	180 MW	280 MW
Cross section of copper conductor	3900 mm^2	
Weight of one coil	12 tonnes	
Overall height of one coil	5.68 metres	
Overall width of one coil	3.86 metres	
Weight of complete magnet (32 coils)	384 tonnes	



82-T-103c/3

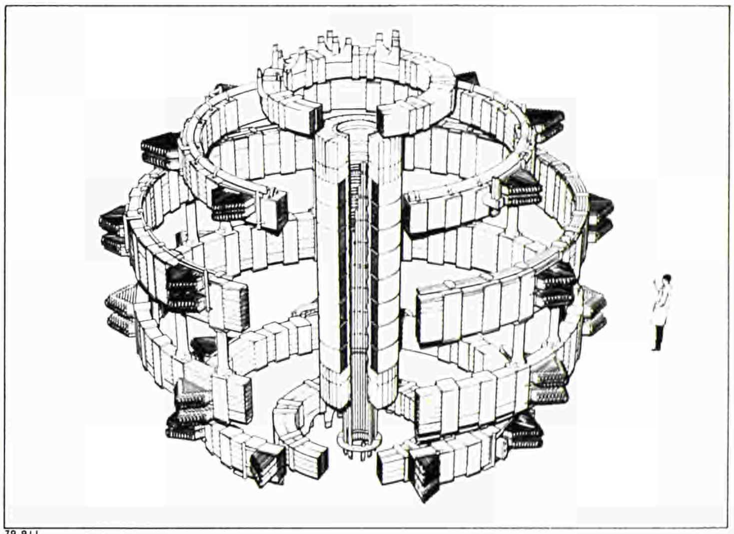
A completed toroidal field coil ready for assembly

Poloidal Field Coils

The other major component of the magnetic field for confining the plasma is produced using the poloidal field coils. There are two types, the inner (No. 1) poloidal field coils situated at the very centre of the machine and the outer (Nos. 2, 3 and 4) coils mounted around the exterior of the mechanical shell.

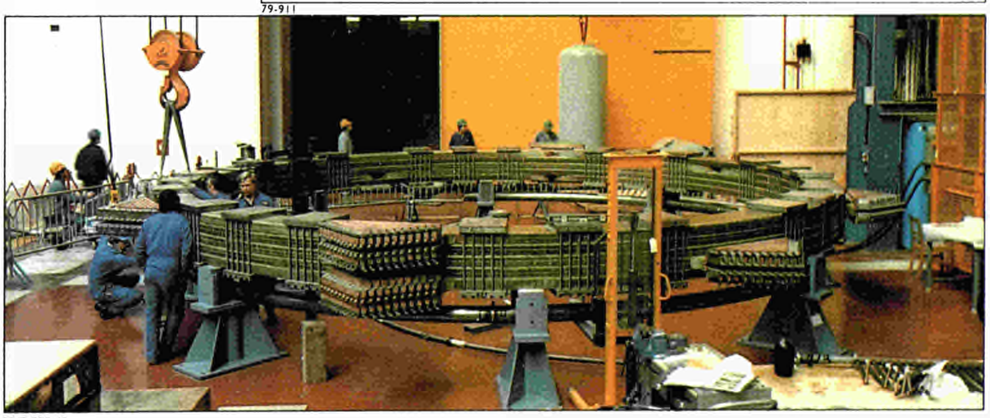
The 8, essentially identical, inner coils make up the primary winding of the transformer for generating the plasma current needed to produce the poloidal magnetic field. This current initially reaches 2.6 million amperes and in the later stages of the experiment will be increased to 4.8 million amperes.

The six larger diameter outer coils, spaced almost equally around the mechanical shell, are used to prevent the plasma from escaping either in the radial or vertical direction. By creating a magnetic barrier, the position and shape of the plasma cross-section can also be controlled.



The Poloidal field coil system

79-911



A completed outer coil with water manifolds and electrical bus bars

82-T-795c/9

	Coil No. 1	Coil No. 2	Coil No. 3	Coil No. 4
Number of coils	8	2	2	2
Outer diameter (metres)	2	5	8	11
Weight per coil (tonnes)	11	18	45	80
Total weight (tonnes)	90	36	90	160
Maximum current (amperes)	40,000	45,000	45,000	45,000
Maximum voltage to earth (volts)	20,000	20,000	20,000	20,000
Duration of pulse (seconds)	20	20	20	20

In the poloidal field coils the electric conductor is a heavy copper bar wound into a circular shape and cooled by means of water flowing through channels in the copper. Since the two largest outer coils are 8 and 11 metres in diameter respectively, they could not be transported from the factory as complete units. Because manufacture on site would have been far too expensive, they were built up in small sections and then transported to Culham for assembly. Each coil was assembled from a number of layers or pancakes with each layer made up from two semi-circular pieces.

82-T-458c/1

Assembly of one of the large outer coils from half pancakes

Mechanical Structure

The interaction of the electric current flowing in the toroidal field coils with the magnetic fields, created by the poloidal coils and the plasma current, gives rise to very large mechanical forces. These forces act laterally on the toroidal field coils trying to push the upper and lower halves in opposite directions and thus rotate them into a horizontal plane. The overall effect of these forces on all 32 coils is to produce a twisting moment around the axis of the machine.

The forces developed are resisted by the mechanical structure, which is a tightly fitting metallic shell surrounding the toroidal field coils. For ease of assembly and manufacture the mechanical structure is split into a number of components including the inner cylinder, upper and lower ring and collars and the external shell. The external shell is split into eight identical sectors and provides the mechanical backbone for the machine octants. Each toroidal field coil is tightly shimmed into grooves on the inside of this external shell.

The centre section of the mechanical structure consists of the inner cylinder having 32 flutes machined into its outer surface which locate the vertical limbs of the toroidal field coils. At the base and at the top of the cylinder there are the lower and upper ring and collars onto which the assembled machine octants are bolted.

Problems encountered during the design of the structure were related to the fatigue effects due to the expected life of 100,000 cycles and also to the stress concentration around the openings needed for access to the plasma and to the coil terminals. The connecting joints between octants presented a special problem as they have to carry very high mechanical shear loads of up to 120 tonnes per metre as well as providing electrical insulation. To overcome this problem a special design of insulated shear key was developed.
Most major components of the mechanical structure are made from a non-magnetic ductile cast iron (austenitic nodular cast iron). The development work on this material, which was carried out specifically for JET, has shown that it is a cheap alternative material to stainless steel with excellent mechanical properties. Nevertheless, the manufacture of these castings has presented a major challenge for industry because of their large size, complexity of shape and the very high level of quality required. Three and a half years were required to produce the castings, the welded components and to complete the complex and accurate machining operations.

Maximum twisting moment around the axis of the machine	20,000 tonnes metre
Maximum torsional deformation of shell (between upper and lower ring)	4 mm
Material for inner cylinder	Stainless steel 304
Material for ring and external shell	Austenitic nodular cast iron
Total weight of mechanical structure	approx. 470 tonnes

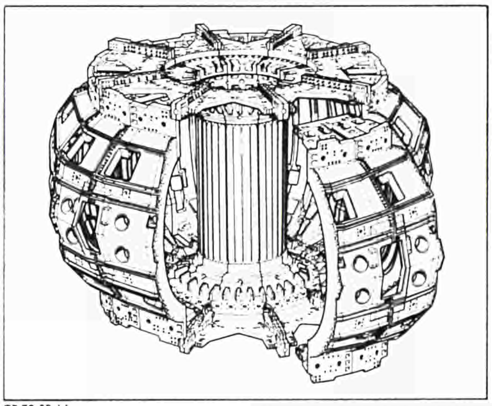
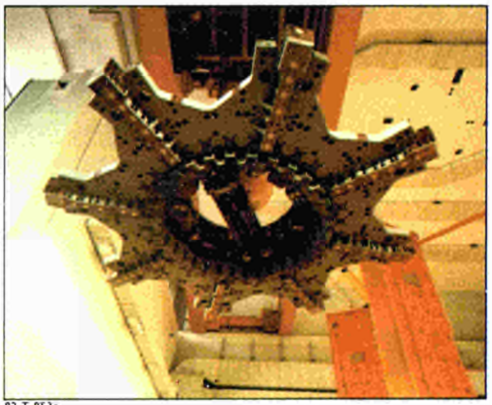


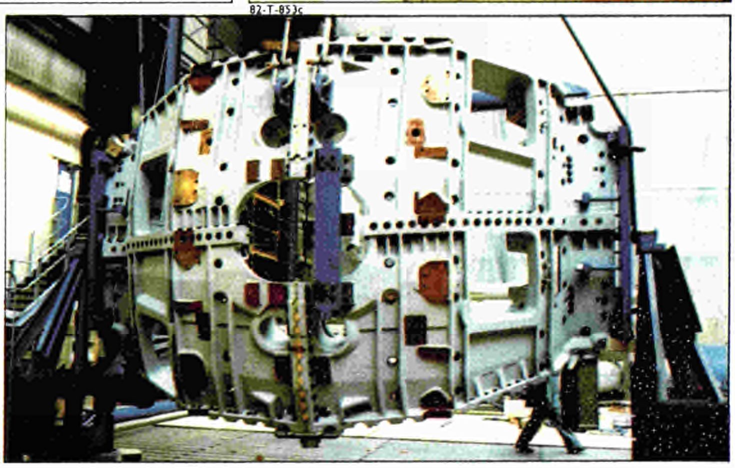
Diagram of mechanical structure

CR 78-32-14



The lower ring & collar

82-T-853c



An octant of the external shell

82-M-26c/12

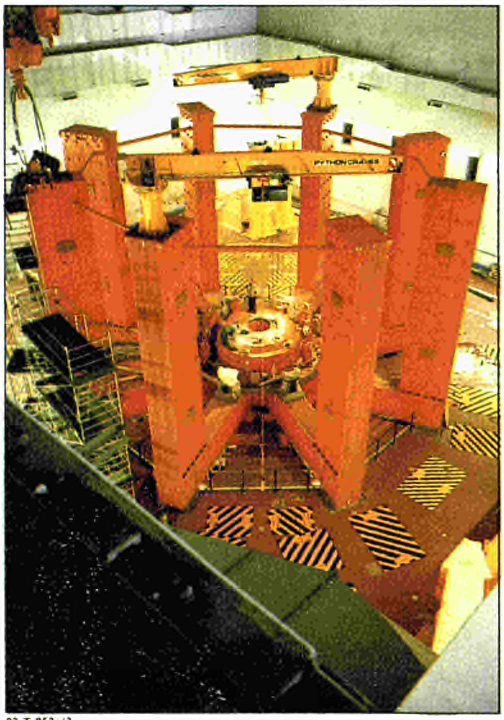
Magnetic Circuit

The large plasma current, needed to produce the poloidal magnetic field and for initial heating of the gas, is induced by transformer action. The primary winding of the transformer is the inner (No. 1) poloidal field coil situated at the centre of the machine and the plasma acts as the single turn secondary winding.

As in an industrial transformer, the efficiency of the coupling between the primary and secondary windings is improved by the use of an iron magnetic circuit to provide a well-defined and easy path for the magnetic flux. On the JET machine the magnetic circuit has a central core, where the magnetic field is very high, and eight external branches for the return magnetic flux. Each branch is built up from a lower and upper horizontal limb and two vertical limbs. The external branches also reduce the amount of stray magnetic field around the outside of the apparatus, which is extremely important for the satisfactory operation of the additional heating and diagnostic systems located in this region.

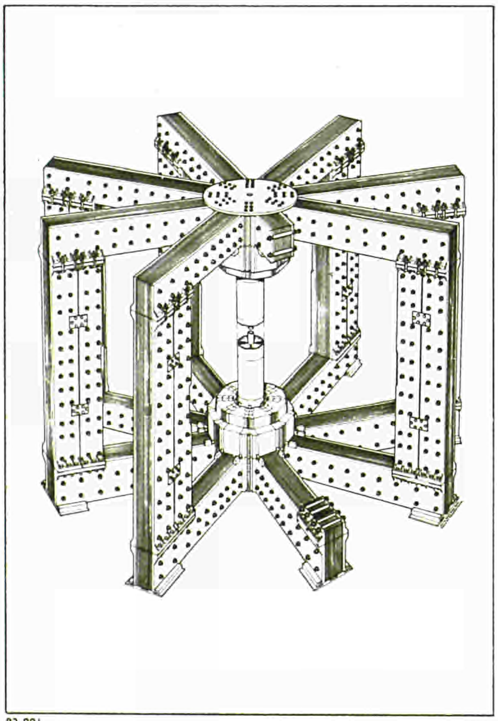
The optimisation of the shape of the JET Tokamak leaves very little space for the central core of the magnetic circuit, so that here the iron is highly magnetically saturated and the field reaches 8 Tesla, whereas in the remainder of the magnetic circuit the field is less than 2 Tesla. The limbs of the magnetic circuit are constructed in a similar way to that used for industrial transformers, that is using thin magnetic steel sheets clamped together between thick flanges.

Weight of heaviest single piece	100 tonnes
Total weight of magnetic circuit	2,700 tonnes
Overall height of circuit	11.5 metres
Overall outer diameter	15 metres
Maximum field in iron (central core)	8 Tesla



82-T-852c/3

Erection of the vertical limbs in the Torus Hall



82-801

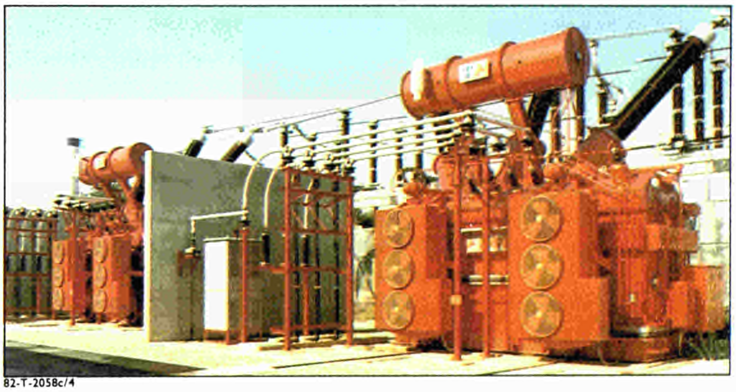
Diagram of the magnetic circuit

JET Power Supplies

THE peak electrical power required for JET during each operational pulse exceeds 700 MW. As the Central Electricity Generating Board limits the power which may be drawn directly from the grid, the major part of this power is provided by two flywheel generators.

Incoming Power Supply

The JET power supply system uses two incoming high voltage lines. The pulse power is drawn from the 400 kV supergrid and is transformed down to 33 kV and fed to the JET loads by up to 15 circuit breakers. Additional power for large motors, pumps, air compressors etc. is taken from the 132 kV grid line and distributed around the site at voltages between 11 kV and 415 V.

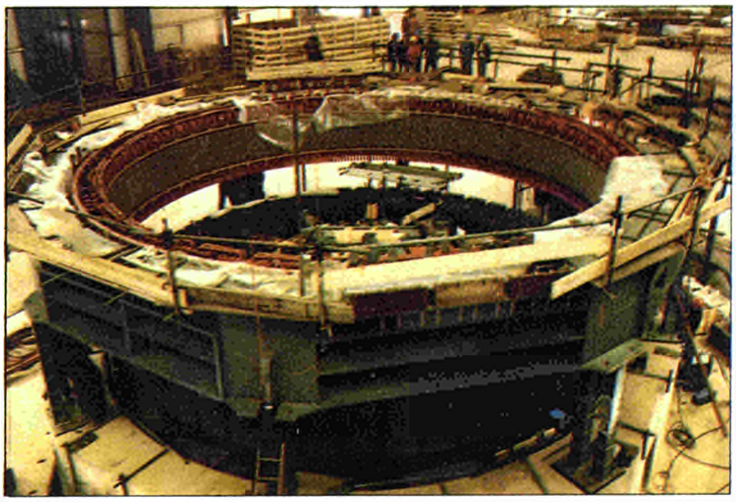


82-T-2058c/4

The 400 kV to 33 kV transformers.

The Flywheel Generators

Two large flywheel generators provide the base power to the two principal JET loads – the toroidal and poloidal field coils. Each of these vertical shaft generators can provide 2600 megajoules of energy. They are identical and are capable of delivering 400 MW of pulse power. Each rotor, weighing 775 tonnes, is accelerated between pulses by a 8.8 MW pony motor to a speed of 225 revolutions per minute. Normally when power is needed for the operation of JET the rotor windings are energised, the rotational energy of the flywheel is converted into electrical energy and the rotor slows down to half speed. The power from each generator is rectified using four diode rectifier stacks before it is delivered to the loads.



81-T-2846c

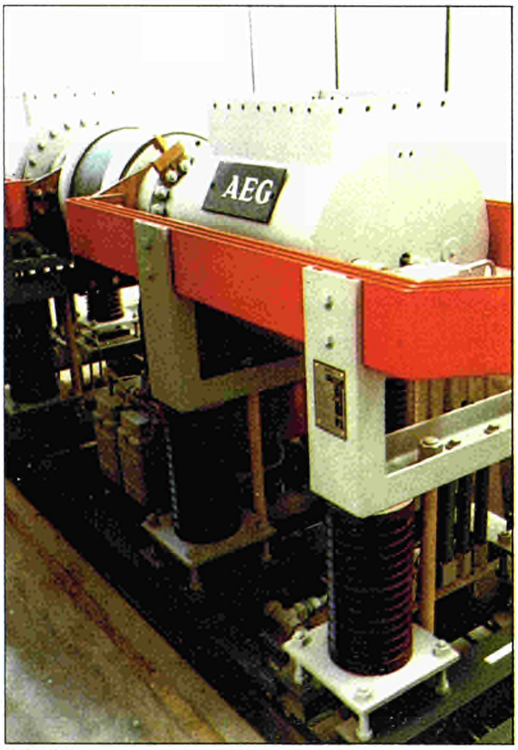
Flywheel generators under construction

Toroidal Field Power Supply

The 32 toroidal field coils are powered by one of the flywheel generators augmented by a grid supply. Up to 225 MW of power is provided from the grid supply to enable the toroidal field coils to be pulsed for longer periods than the poloidal coils.
The power from the grid system is rectified using capsule thyristors mounted onto water-cooled heat sinks. Filter networks are incorporated into the circuits to prevent interference being fed onto the grid system.

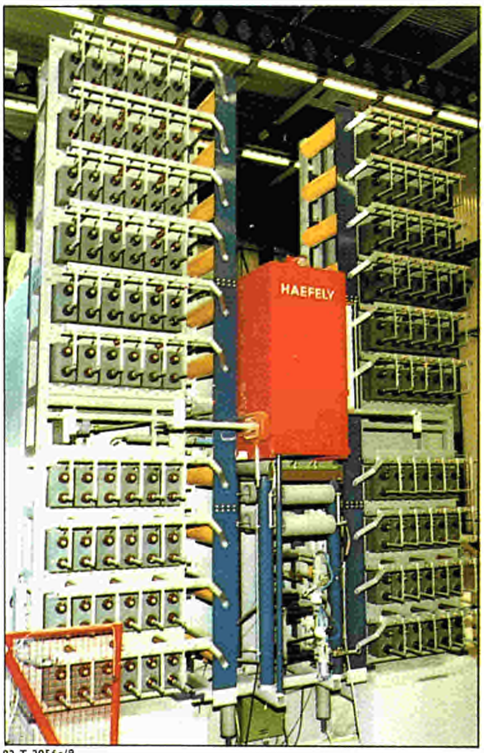
Poloidal Field Power Supply

The second flywheel generator provides the power for the inner poloidal field coils. A specially designed system uses very fast air-blast circuit breakers to interrupt up to 80 kA of direct current in the coils to produce the initial high voltage for ionising the gas. This system also allows the coil connections to be reversed enabling the maximum flux change in the JET iron transformer core to be utilised.
The outer poloidal field coils, used for shaping and controlling the radial and vertical movements of the plasma, are supplied with 125 MW of power from the grid. This power supply system must be capable of responding rapidly so that movements of the plasma can be corrected.



82-T-1977c/1

One of the fast air blast circuit breakers used to interrupt the poloidal pulse.



82-T-2056c/9

One of the 30 kV capacitor banks also required for interrupting the poloidal field coil pulse.

Neutral Injection Power Supply

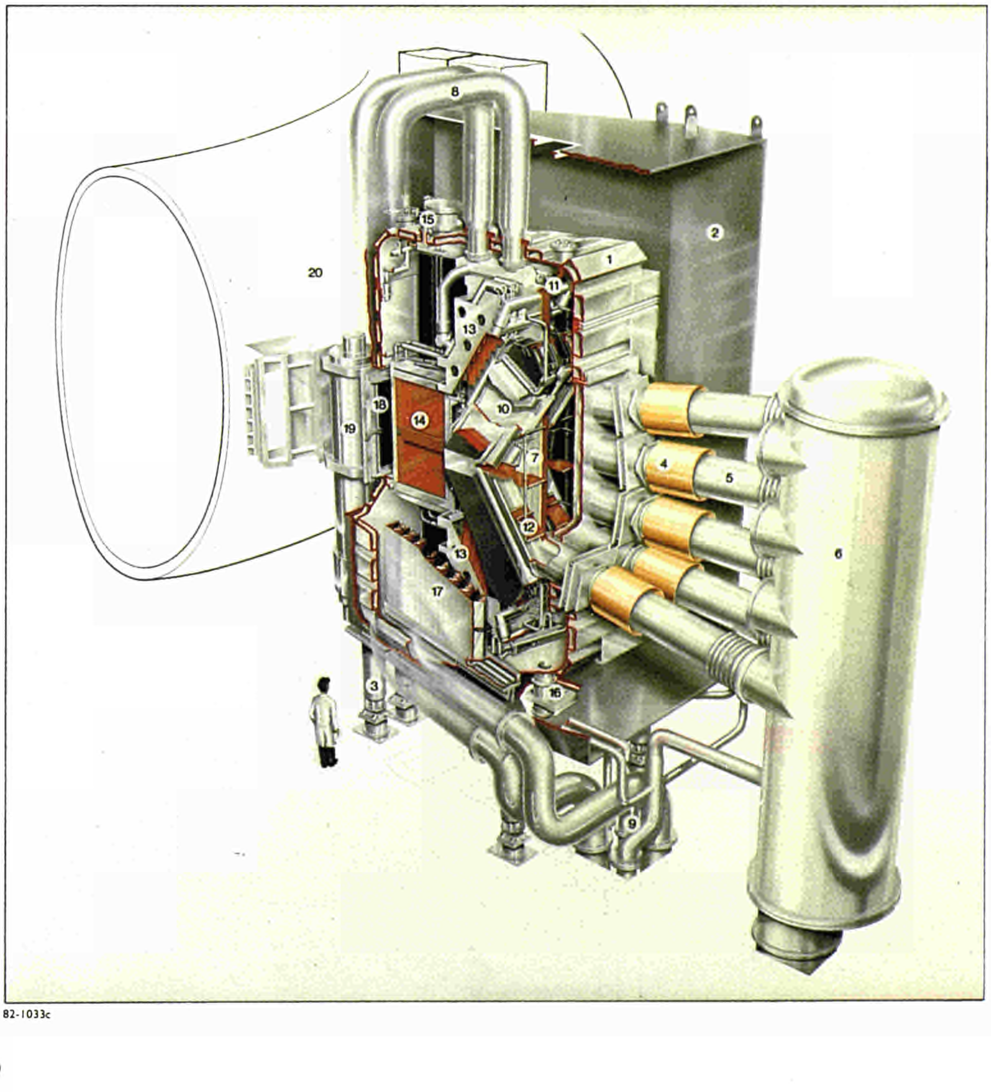
The neutral injectors, for additional plasma heating, require 60 MW of power from the 33 kV system. Most of this power is used to drive the accelerating grids of the neutral injectors. The power to these accelerator grids is regulated and switched by large tetrode valves. The system is controlled to within ± 1% of the required voltage by rapid switching in times of less than 10 microseconds.

Additional Heating

INITIAL heating of the gas on the JET experiment is carried out using the plasma current which also produces the poloidal magnetic field. Unfortunately, as the plasma resistance decreases with increasing temperature, resistive heating by the plasma current becomes increasingly less effective at higher temperatures. To reach temperatures high enough for abundant fusion reactions to occur, additional heating methods must be used. Two additional heating methods are being used on JET, neutral injection heating and radio-frequency heating.

Neutral Injection Heating

Neutral injection heating is achieved by injecting an intense beam of energetic neutral atoms across the confining magnetic field into the plasma. There the neutral particles are ionised and confined by the magnetic field. The resulting energetic (supra-thermal) ions give up their energy to the bulk plasma via collisions thus increasing its temperature. The technique of neutral injection heating has been successfully demonstrated on several of the present generation of tokamaks and plasma temperatures in excess of 75 million degrees have been achieved.



82-1033c

Schematic of Neutral Injection System

1 Vacuum Tank
2 Magnetic Shielding
3 Support Structure
4 PINI Beam Source
5 High Voltage Termination
6 High Voltage Tower with Snubbers
7 Central Support Column
8 Main Cooling Pipes
9 Coolant Supply Lines
10 Bending Magnet with Cooled Liner
11 Magnet Electrical Supply Cables
12 Fractional Energy Ion Dump
13 Full Energy Ion Dump
14 Calorimeter
15 Calorimeter Drive
16 Turbomolecular Vacuum Pump
17 Cryopump System
18 Fast Shutter
19 Rotary Valve
20 JET Torus

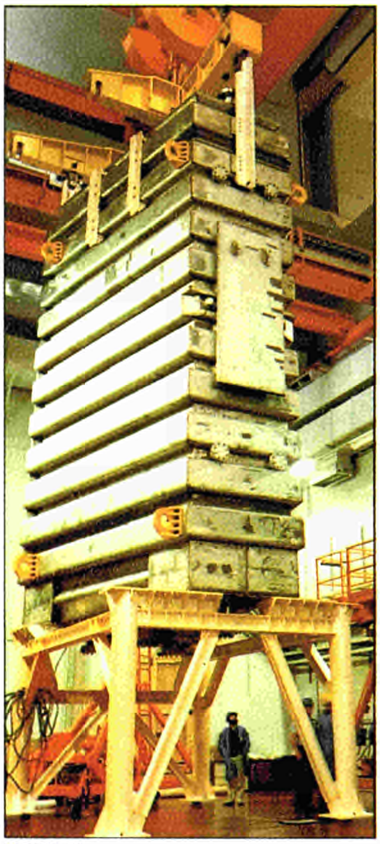
Although the basic physics of both the production of energetic neutral beams and the subsequent interaction with the plasma are well understood, injection requirements for JET have required a substantial extension of technology in terms of total power and pulse duration.

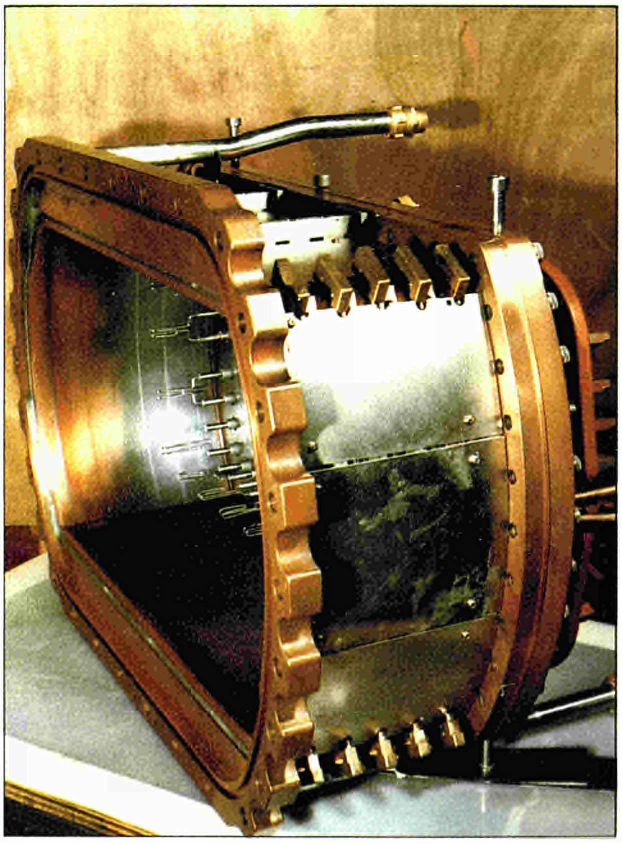
Joint Design Team

In order to meet these requirements a joint design team was formed drawing mainly upon expertise in the Associated Laboratories of Fontenay-aux-Roses (France) and Culham Laboratory (UK). This joint team was responsible for the development of the physics and technology needed to meet the required specifications. The Culham Laboratory's contribution is orientated towards the development of high power 80 keV hydrogen beams with long pulse duration, while Fontenay applies itself to the problems associated with deuterium beams and higher voltage operation.

The Neutral Beam Injectors for JET

The neutral injection for JET is provided by two systems, each capable of delivering 5 MW of power to the plasma. Each neutral beam injection system uses eight plug-in neutral injectors (PINIs), with each injector capable of providing an equivalent hydrogen beam current of 60 amps at an energy of 80 keV. At a later stage in the experimental programme the voltage will be increased to 160 kV using deuterium beams.





Neutral injector box being prepared for testing

The bucket-type plasma source of the JET prototype PINI after its first operation

82-T-1990c/11

Radio Frequency Heating

For this method of heating, high power electromagnetic waves are radiated from antennae on the walls of the vacuum vessel. Power is coupled into the plasma by selecting the frequency of radiation (25 — 55 MHz on JET) to be equal to that of an ion species gyrating around the magnetic field lines at the centre of the plasma. At this Ion Cyclotron Frequency the ions are accelerated and leave the resonant region at the centre to give up their energy to the bulk of the plasma.

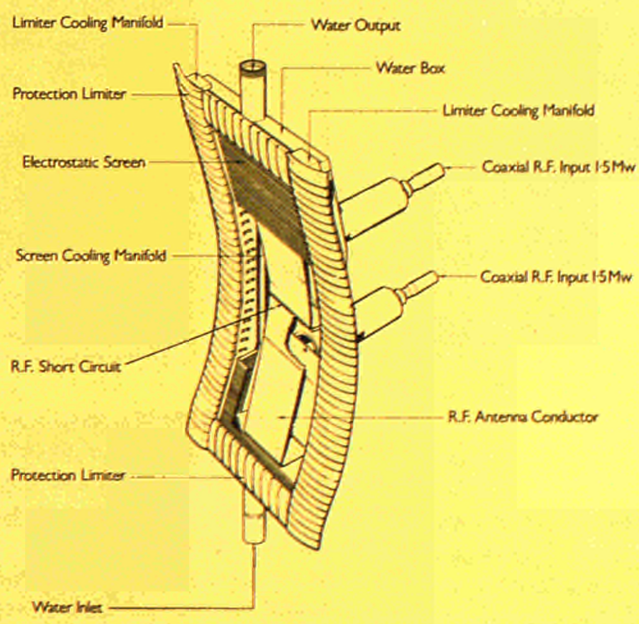
On the TFR tokamak at Fontenay-aux-Roses up to 2 MW of RF power has been coupled to the plasma, raising its temperature by more than 10 million degrees Centigrade without any apparent limitation due to the plasma density.

The ICRF heating system for JET has been evolved with the help of the Associated Laboratories involved in this research.

Ten RF generators will be used to produce the 30 MW of power required. The power from each generator is coupled into the upper and lower halves of an antenna by two 230 mm co-axial transmission lines. About 50% of the 30 MW of generated RF power will be coupled into the plasma. The generators situated in the north wing of the main building will use large tetrode electronic tubes, each one capable of providing 1.5 MW of radio-frequency power.

Development of the antennae presents a technological challenge as they are situated close to the plasma and are thus subjected to high mechanical and thermal stresses, high RF voltages and must also be capable of being installed remotely.

The 10 antennae will be distributed almost equally around the torus and they will be incorporated into the limiters attached to the walls of the vacuum vessel.



JET ICRF Heating Antenna

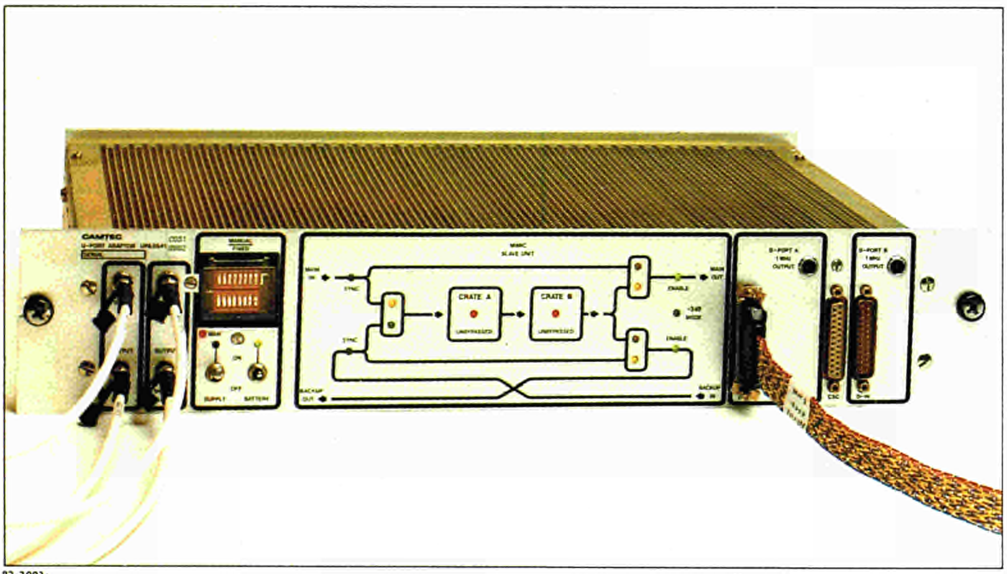
Control Room

JET uses a computerised Control and Data Acquisition System (CODAS) to provide a flexible, easy and safe method of operating the experiment. This requires the interfacing and processing of more than 10,000 digital and 1,500 analogue signals.

Control System

Control and monitoring of the experiment is carried out using a network of 25 Norsk Data ND-100 and ND-500 mini-computers. The hierarchical structure of the control system reflects the way JET is made up from sub-systems (poloidal field, toroidal field etc.). Each computer is responsible for monitoring and controlling a part of the JET experiment with the overall supervision being performed by the two console computers. Any transfer of information between computers is carried out via the two communication computers. A real time data base holds a description of the JET experiment in the CODAS computers and forms the basis of all control and monitoring operations.

Signals between the JET machine and CODAS are taken via one of about 70 CODAS cubicles that contain interfacing electronics conforming to the CAMAC standard. Information is transferred between the computers and the cubicles situated around the site via 19 fibre-optic loops (Serial Highways) at a rate of 5 million bits per second.



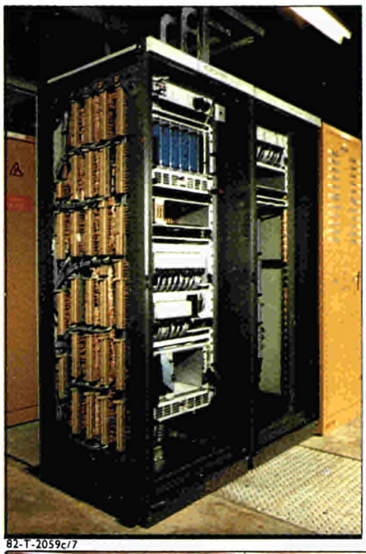
82-2093c

"Serial highway U-port adapter"

Data Acquisition

Acquisition of experimental data from the diagnostic equipment on the experiment requires in excess of 1 million items of data to be gathered during each pulse. The computers and interface electronics for the control and monitoring of the experiment are also used for data acquisition.

Filing of experimental data is performed by the largest computer in the Control Room, an ND-560, so that experimentalists can gain easy access to the information. The experimental data is then transferred to the Culham Laboratory's large computers for permanent archiving and more detailed evaluation.



Codas cubicle for controlling the 132kV power supply system for JET

82-T-2059c/7

Operator console

82-1102c

Interior of the computer room in the control building

81-T-1593c/3

Computer operators and experimentalists can communicate with the control system either via the two main consoles in the Control Room or through a number of mobile consoles. The following facilities can be used with these units:

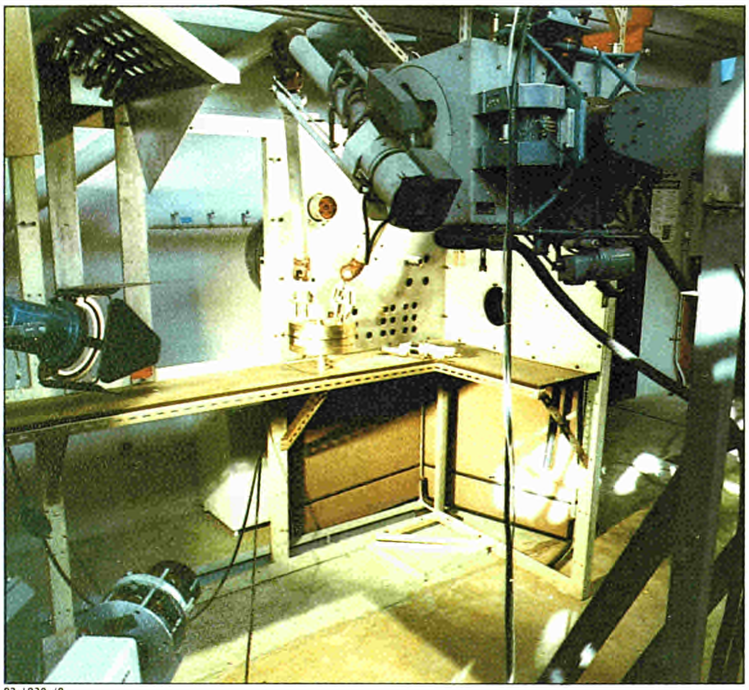
1. Touch sensitive panels replacing conventional push buttons.
2. Colour television screens for displaying mimic diagrams of the JET systems, processed data in a graphical form or closed circuit television pictures.
3. Trackerballs, to allow identification of points on the screen, thus providing additional facilities to the touch sensitive panels.
4. Keyboards and display screens.
5. Black and white screens for closed circuit television pictures and high resolution graphic displays.

The control and interlock functions for JET are normally taken care of by the CODAS system. To ensure the safety of both personnel and the machine basic back-up interlock functions are provided by the Central Interlock and Safety System (CISS) which can automatically revert equipment into a safe state or inhibit JET pulses in the absence of abnormal conditions or computer failures.

Remote Handling

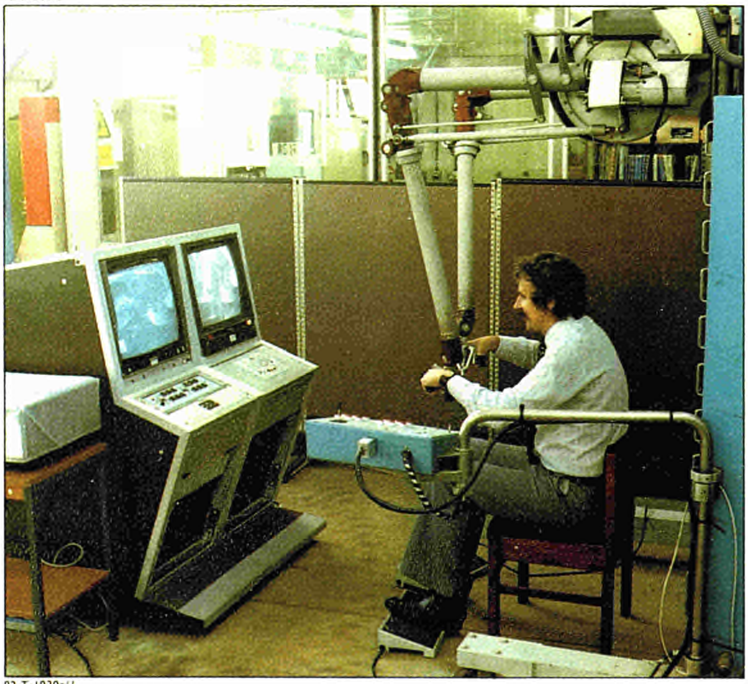
DURING the last stages of the JET project high energy neutrons produced by the fusion reactions will activate the machine structure. This will severely restrict or inhibit the access of personnel to the machine area. Any operations that need to be performed on the machine, such as inspection of the interior of the vacuum vessel for damage caused by the plasma or maintenance of auxiliary equipment, will have to be done by using remote handling techniques.

Because of the wide variety and unpredictable nature of the operations needed, servomanipulators will have to be used. Each manipulator uses a master unit in the accessible area with a slave unit working in the radioactive area. Movements carried out on



82-1930c/8

Mascot slave unit



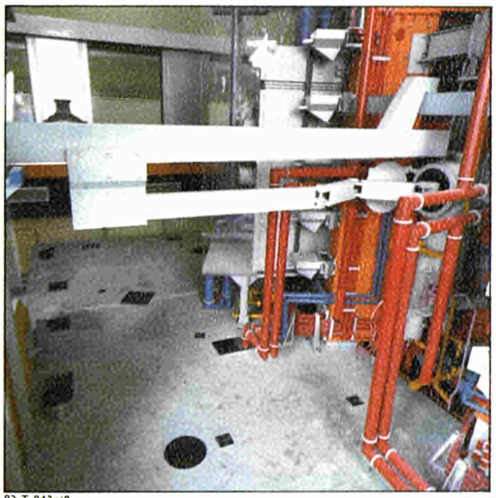
82-T-1930c/1

Mascot master unit

the master unit by the operator are followed by the slave which reflects back the forces exerted by the manipulator to give some feel to the operator. These units will be supplemented by special power tools, welding torches etc, while any heavy lifting will be done by the 150 tonne crane which has been designed for smooth and programmable movements. Complex transport systems using robotic techniques will position the manipulators within the working areas. Tests are being carried out with a Mascot servomanipulator to determine whether the various operations needed are feasible. A one-tenth scale model is used to evaluate access problems and to ensure that the design of components is compatible with the remote handling techniques. Design recommendations, such as those relating to the specially designed vacuum and water flanges, and any standards that are particularly relevant for remote operations, are included in a remote handling manual.

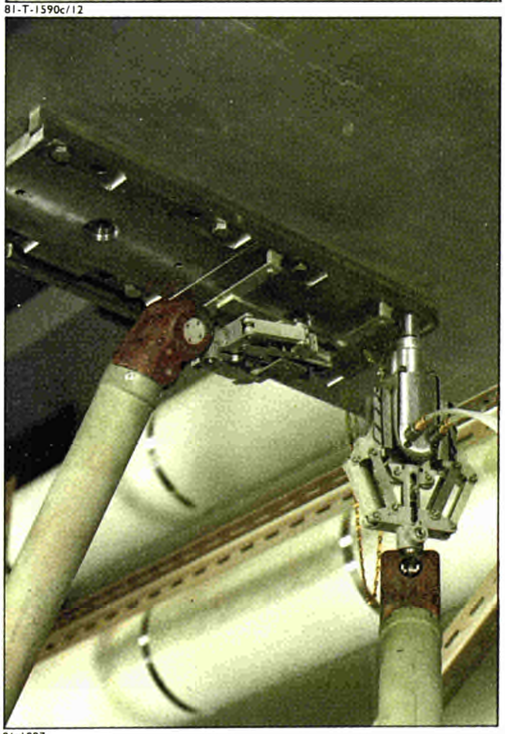
81-T-1590c/12

1:10 model of floor mounted manipulator disconnecting the flange of a turbopump. Sufficient degrees of freedom allow reaching behind obstacles. Computerised approach is essential.



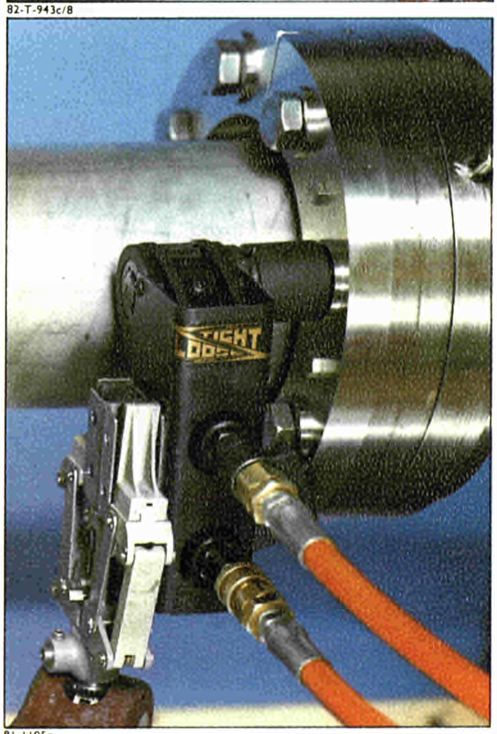
82-T-943c/8

1:10 model of the articulated arm designed to support either the "limiters" or a servomanipulator for in-vessel work.



81-1097c

Replacement tests with a Mascot servomanipulator of 1st wall plates: one arm supports the plate while the other positions a vessel on the "captive" bolts.



81-1105c

Servomanipulator disconnects a R.H. flange with a hydraulic wrench.

The JET Buildings

THE largest building on the site houses at one end the JET apparatus within the massive concrete walls of the Torus Hall and at the other end the Assembly Hall. Linking these two regions are the intermediate access cell and hot cell, which form with the Torus Hall the main reinforced dense concrete structure necessary for absorbing neutrons resulting from the fusion reactions between deuterium and tritium.

Before construction could start on this building an impervious flexible cut-off wall had to be installed around the area to stabilise the ground water which is only about 1 metre below the surface. The wall was built from a non-hardening flexible material made up of bentonite and cement.

Because the total weight of the Torus Hall, access cell and hot cell is approximately 83,000 tonnes, a 3 metre thick concrete raft foundation was built in two layers to counteract differential settlement. The top of this raft is screeded and forms the basement floor 6 metres below the ground floor level of the Torus Hall. The outer walls of the Torus Hall are 2.5 metres thick and lined on the inside with 300 mm thick boronated concrete blocks to provide radiation shielding. The roof structure weighs about 5,000 tonnes and has a span of 37.5 metres. It is constructed from post-stressed concrete beams 1.5 metres wide and 2.4 metres deep so that it can be dismantled at a later stage. Both the floor and roof have been treated with boronated screeds.

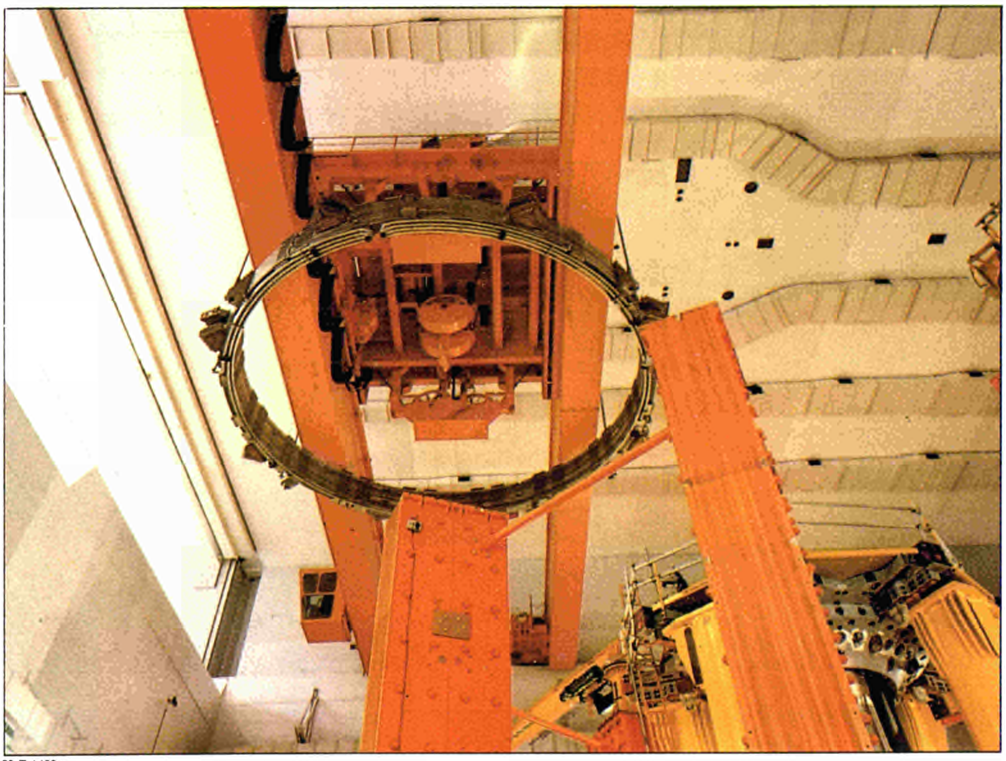
80-485c

Basement area during construction

Construction of the Torus Hall roof

80-2823c

Large machine components can be moved between the Assembly Hall and Torus Hall by a 150 tonne crane. So that the environmental integrity of the building is maintained large movable shielding beams and doors have been installed either side of the intermediate access cell. Each shielding beam, which weighs approximately 1000 tonnes, is 39 metres long, 1.25 metres thick and 9 metres high and can be raised into deck housings above roof level by hydraulic jacks in about 30 minutes to allow the crane to pass through. The large doors below the movable beams allow the movement of heavy components or vehicles. These doors, which weigh approximately 400 tonnes each, are 5.5 metres wide, 16.5 metres high and can be opened in about 8 minutes. A similar door divides the intermediate access cell from the hot cell. Radiation shielding is provided below the Torus Hall by the 1 metre thick floor, the 3 metre

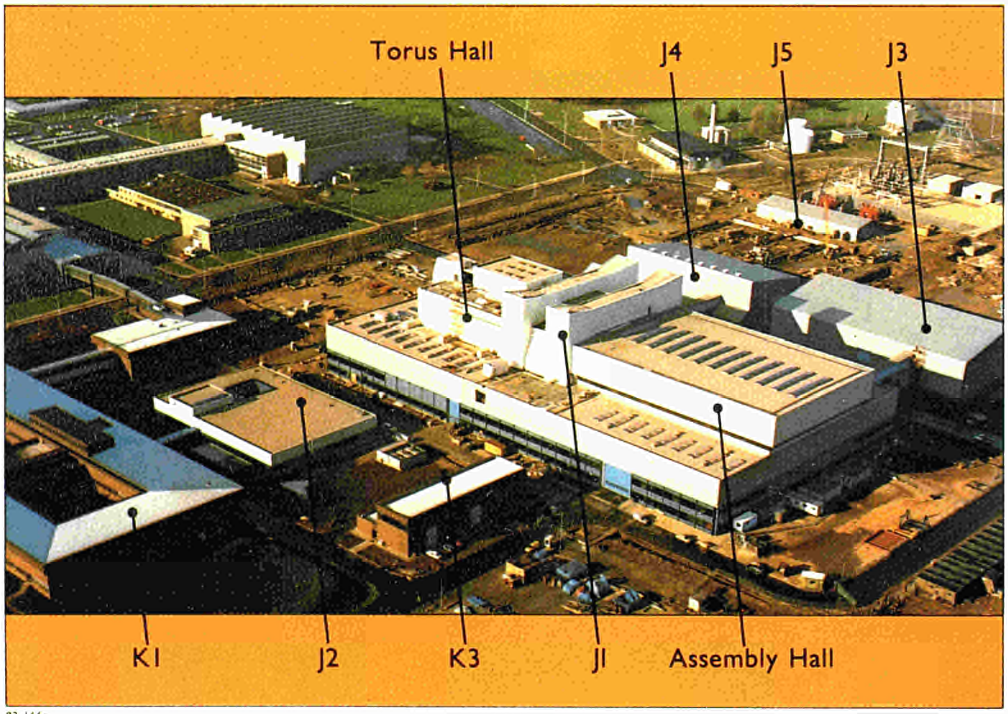


The 150 tonne crane transferring one of the largest outer poloidal field coils to the Torus Hall

82-T-1452c

thick foundation slab and the double walled system in the basement. The walls, floor and ceiling all contain service and diagnostic ports and the laboratory on the roof is used for diagnostic equipment. Normally the Torus Hall operates below atmospheric pressure and has an air change 3 times every hour. The 150 tonne crane runs the full length of the building from the Assembly Hall to the Torus Hall. The two main beams are each 37 metres long and weigh 50 tonnes. Besides the main 150 tonne hook the crane also has a 25 tonne capacity hook and a four rope lift with load balancing for lifting the poloidal field coils. The crane can be operated either from the cab, which is lowered to a position below the beam and then rotated through 180°, or from a mobile plug-in control unit on the ground. For later phases of the experiment the crane control system will be linked into the computer for remote operation.

The Assembly Hall which is founded on concrete piles, is built from a steel framework covered in sheet cladding. On the north, south and west sides of the building are steel frame wings used for diagnostics and support services.
South of the Torus and Assembly Halls are the control building (J2) from where the machine is controlled and monitored, K1 containing offices and small laboratories and K3 used for remote handling and high vacuum development. There are two other buildings, situated to the north of the site, for JET power supplies; J4 contains equipment for the rectification and filtering of power from the 400 kV supergrid, whilst J3 houses the two flywheel generators. Also to the north of the site are the J5 building housing switchgear associated with the control of the stepdown transformers linked to the national grid and the cooling towers for the water recirculation system needed for cooling the magnetic field coils.



Aerial view–January 1982

82-166c

JET Scientific Programme

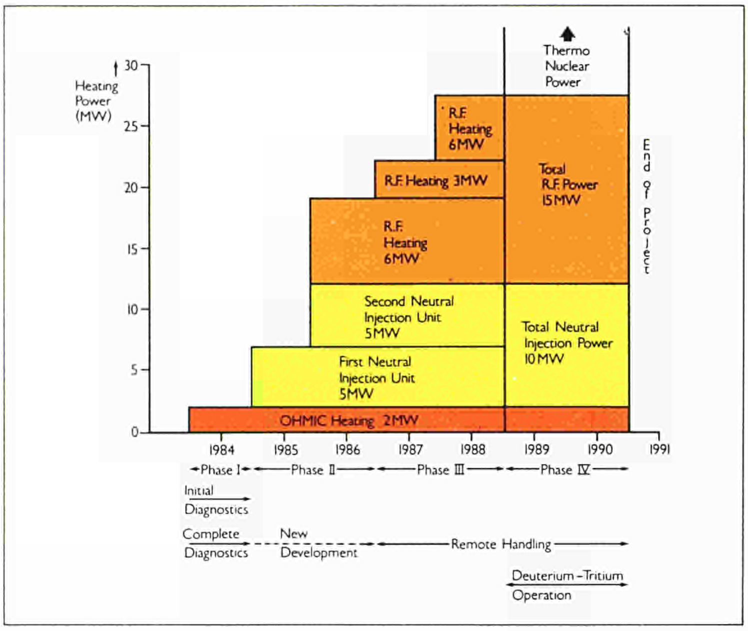
THE aim of the JET project is to obtain a plasma with a size, density and temperature comparable to the values needed in an eventual power producing reactor. This means producing a plasma with a diameter of about 2 metres, a density of 100 million million atoms per cubic centimetre and a temperature of 100 million degrees centigrade. Achieving these parameters on JET will be a major step forward, but many other difficult problems will have to be overcome before an economic fusion reactor can be built. The physics of plasmas is very complicated and not completely understood and it is therefore not certain that the JET apparatus will be able to produce plasmas with these parameters. The machine was designed between 1973 and 1975 and progress on smaller machines since then has confirmed the underlying ideas. JET is now considered to be the most advanced machine of its type in the world and is likely to remain so for at least a decade.

The plasma in a tokamak, such as JET, is heated by the very large electrical currents of up to 4.8 million amperes. Unfortunately this is totally inadequate to achieve the plasma temperatures required for nuclear fusion. Additional heating systems will therefore be added to JET over a number of years using two different methods:

1. The injection into the plasma of highly energetic neutral atoms (Neutral Injection heating) and
2. The coupling of high power electromagnetic radiation to the plasma (Radio Frequency heating).

The total power into the plasma will increase in discrete steps up to 25 megawatts.

The envisaged programme is that JET will start operating in 1983 with the modest plasma heating (2-3 megawatts) provided by the plasma currents and will continue in this way for about a year, learning how to use the equipment and adding diagnostic equipment to measure the plasma behaviour. A mean plasma temperature of about 5 million degrees at modest densities is expected. Between 1984 and 1987 new heating systems will be progressively added onto the machine, starting with 5 megawatts of additional heating and finishing with a total capacity of 25 megawatts. After each annual step increase in heating power the machine will be run for about nine months to establish its performance. At full power an average temperature of 50 million degrees at rather higher densities is expected. If this can be achieved the machine will then be operated with a deuterium tritium plasma. The additional power deposited in the plasma by thermonuclear reactions would then cause the temperature to rise towards the required 100 million degrees. In the extremely optimistic case of ignition the external heating systems could be turned off and the plasma temperature would continue to rise until the end of the pulse. At the other extreme, the pessimistic result would be that the plasma will not reach high enough temperatures to justify the use of tritium. Whatever the outcome JET will provide valuable and definitive information on the possibilities of fusion power development.



JET Scientific Programme

JET Diagnostics

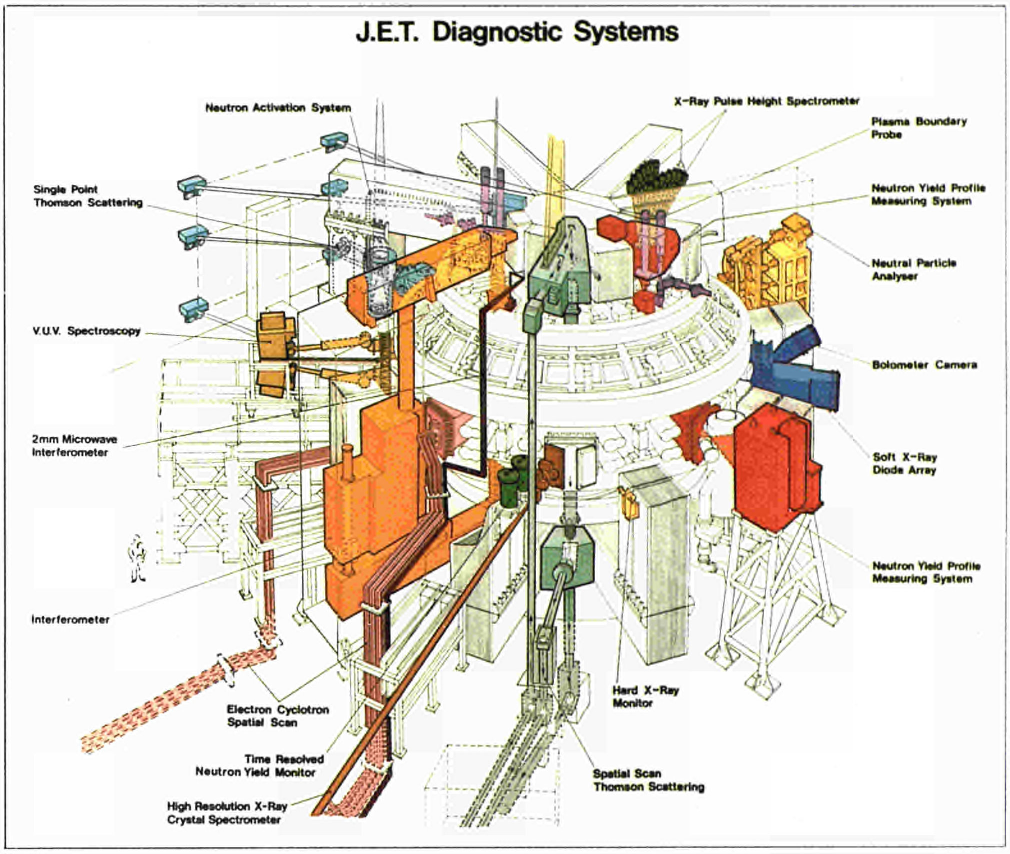
EXPERIMENTAL information about the properties of a plasma is obtained by making quantitative observations of the physical processes which can occur within the plasma. These processes are:

1. Collisions between plasma ions and neutral atoms, electrons and the impurity atoms (C, O, Ni, Cr, Fe) originating from the walls of the vacuum vessel.
2. Interaction between plasma particles and electromagnetic waves and emission by the plasma of electromagnetic energy.

The diagnostic systems on JET measure the properties of the plasma and are designed to yield all relevant parameters simultaneously in one single pulse. Most of the diagnostic systems have many channels to allow the parameters to be measured throughout the plasma volume. The high plasma temperature and the long duration of the pulse exclude measurements involving physical contact between the sensor and the plasma. Only passive and active beams of particles, light and electromagnetic radiation are being used.

For the preparation of the diagnostics JET relies on the expertise of the Associated Laboratories in all the member countries. Only diagnostic systems virtually integrated with the machine itself are prepared by the JET team.

The philosophy underlying the JET diagnostics is that they must be able to operate for the whole experimental life of the machine. Because of the radiation problems during the deuterium-tritium phase the receiver/transmitters are located outside the biological shield, so that the systems can be easily maintained and repaired. The large distance between the machine and this area causes in many cases very large alignment or signal transmission problems.



Schematic of JET diagnostics

82-1684c

Among the more important diagnostics being used on JET are:

1. Magnetic diagnostics – A system of small coils and larger single loops, closely integrated with the vacuum vessel wall, picks up the magnetic field and fluxes outside the plasma. From these measurements plasma loop voltage, plasma current and the position of the plasma in the vessel can be derived.
2. Interferometers – Electrons in the plasma cause microwave or infrared waves to be delayed with respect to an external reference beam. Thus this diagnostic enables values of the electron density to be obtained. The main interferometer has 7 vertical and 3 horizontal channels and the mirrors for reflecting the beams onto the detectors are located behind the environmental shield.
3. Spectrometers – The type, density and temperature of energetic atoms in the plasma determines the wavelength and intensity of emitted light. By measuring these two parameters spectroscopy plays a major role in the understanding of plasma behaviour.
4. Thomson Scattering – High intensity pulsed laser light is scattered by electrons into specific directions. The intensity of this light depends on the electron density and its change in wavelength on electron temperature. Single point Thomson scattering looks at the light scattered through 90° and is the most reliable method to date for obtaining local values of electron density and temperature. The source and detectors are again located outside the environmental shield and there are severe alignment problems due to the large distances involved.

5. Neutral Particle Analyser – Neutral particles in the plasma are in thermal-equilibrium with the ions and because they are uncharged can easily escape from the magnetic confinement. The plasma ion temperature can therefore be determined by measuring the energy of escaping neutral atoms.
6. Bolometer – This detector essentially measures a broad spectrum of radiation representing the main radiation energy loss from the plasma. It consists of a thin foil with an absorber that receives the radiation and heats up. Coupled to this foil is a temperature-sensitive resistor which measures the thermal variation.
7. X-Ray Measurements – X-rays emitted by the plasma enable information about temperature, density and impurity content to be made. Special solid state detectors are employed in the soft x-ray diode array. This diagnostic is especially useful for observing fluctuations of the temperature but as the sensors are located close to the plasma, they will probably not be useful during the active phase.
8. Plasma Boundary Probe – Interactions between the plasma and the vacuum vessel can be determined by analysing wall material exposed to the plasma. Clean samples of wall material are exposed to the plasma from a special vacuum-tight container. After the exposure to one or more pulses the samples are removed and analysed using surface analysis techniques.
9. Neutron Measurements – Neutron diagnostics are planned because neutrons are produced as a result of fusion reactions occurring within the plasma. Observation of the intensity and energy distribution of these neutrons enables a direct measure of the reaction rate and consequently the density and temperature of the reactants.

JET Theory

Role of Plasma Theory

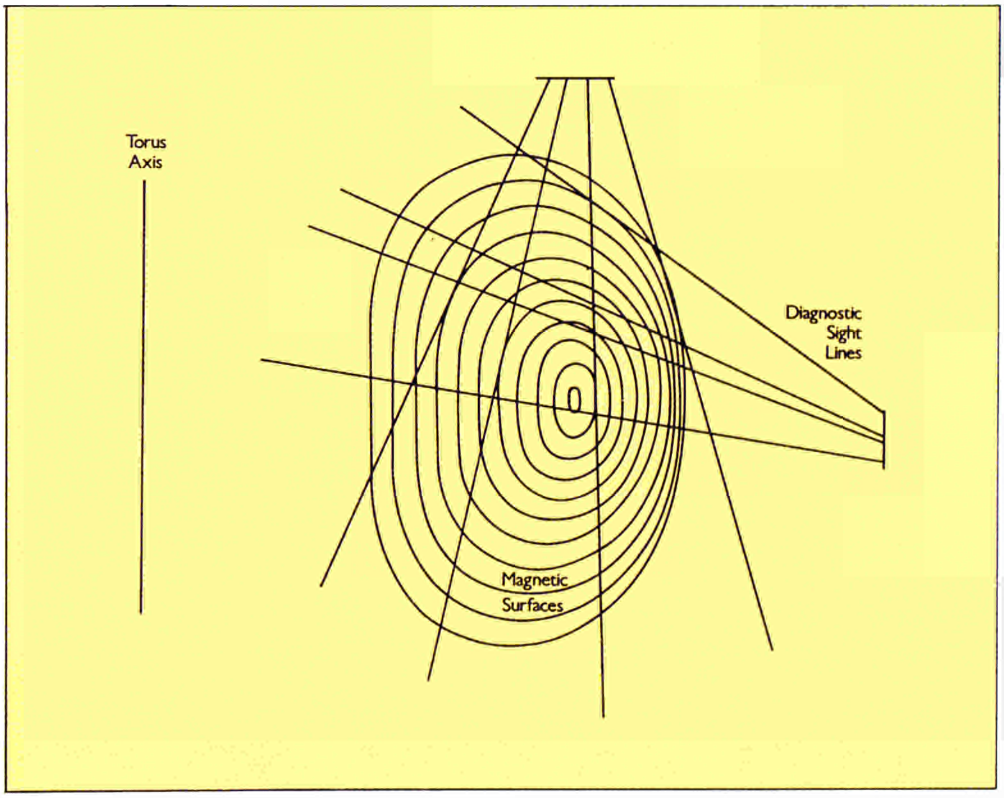
NO scientific or technical work is possible without a theory, ie a conception of what one is trying to establish. A theory in physics must be capable of providing a qualitative conception of the physical mechanisms, as well as making quantitative statements on the system under consideration. For example, the theory explaining how and why a plasma is heated by an electrical current flowing through it must also contain a mathematical procedure to give the temperature in degrees that can be achieved with a certain current.

Compared with a simple system such as a body falling under gravity or an electrical current passing along a wire, a plasma is a vastly more complex system. Instead of dealing with just one moving body or one electrical current, it is necessary to deal simultaneously with typically 10^{13} (= 10,000,000,000,000) electrically charged particles in each cubic centimetre of the huge JET volume (150,000,000 cm^3), moving in magnetic and electric

fields and strongly influencing each other's orbit. These basic features also require plasma theory to include and interconnect numerous fields of classical physics (such as mechanics, hydrodynamics, electrodynamics, statistical mechanics, atomic physics, optics etc.) including many of their concepts and mathematical procedures.
Simple formulae or short calculations are usually not applicable because they oversimplify the theory, or are much too inaccurate. On the other hand, a theory, which includes simultaneously all the effects which could be important, would require a computer larger and faster than those presently available (eg the Harwell computer centre's IBM and CRAY machines). Finding feasible compromises between these extremes is one of the main tasks of plasma theory.

Plasma Theory within JET

There exist theories on how to produce plasmas in fusion reactors. Some of these theories are rather vague, while others are capable of making reasonably accurate predictions. A major goal of the JET experiment is to check and improve present theories in order to build up a more accurate and true theory. Many of the observable quantities on JET do not coincide directly with those occurring in the above theories. In the figure, showing a cross-section of a computed JET plasma, the desired quantities are, for example, plasma temperature and density on the curved lines (magnetic flux surface lines). The measured light signals, however, emerge from the plasma along the indicated straight lines. Thus complicated calculations are necessary to combine and reduce the measured signals to useful quantities.



Plasma Probing Beam Arrangement

Researchers all over the world are working on fusion plasma theory, with new mechanisms of plasma behaviour constantly being identified, new mathematical methods invented and new relevant data obtained from other plasmas. JET theoreticians need to keep abreast of these latest developments so that they can be applied to explain the observations on JET.
Since theoretical hypotheses and methods can be transported much more easily than experimental apparatus, the theory groups in the Associated Laboratories are expected to give strong support to the JET theoreticians. An important role for the JET team is to keep these groups informed of recent JET results, pointing out problems relevant to JET for them to study.

Data Analysis

1. Analysis Between Pulses – A partial analysis of data is made immediately after each pulse (on the local ND-500 computer) to guide the experimentalists on the choice of parameters for the next pulse. Only a small portion of the data (magnetic loop signals) is utilised and rough estimates obtained for the plasma β (ratio of plasma pressure to magnetic field pressure), average energy containment time τ_e and the safety factor q (a measure of plasma stability). These results are displayed some 20 seconds after each pulse in several locations within the diagnostic area and then stored for future use.

2. Full Off-line Analysis – A full analysis of the data from one or a sequence of similar pulses is carried out off-line on the CRAY computer at Harwell. First, the plasma shape, which is determined by the configuration of the magnetic surfaces, needs to be calculated.
   Plasma density, particle and heat sources on these surfaces can then be calculated from experimental measurements. By exploiting particle and energy balance equations, the particle and heat fluxes for electrons and ions can be obtained as a function of space and time. Finally, a full statistical analysis is carried out to reveal correlations and scaling laws. It is anticipated that up to 100 pulses per week can be analysed.

Theoretical Models

Theoretical models are developed and adapted so that the dominant plasma phenomena in JET can be explained. Models are used, which incorporate reasonable simplifications, but allow a sufficient number of interactive physical effects to be taken into account, to determine groups of important physical phenomena including:

1. Equilibrium and stability of the plasma in the magnetic field.

2. Transport of particles, momentum and energy within the plasma (diffusion, heat conduction, turbulence etc).

3. The effect of neutral beam injection, application of RF fields and fusion-produced α particles for plasma heating.

4. Energy losses by radiation due to impurities released by interactions of the plasma with the chamber walls.

Future Predictions

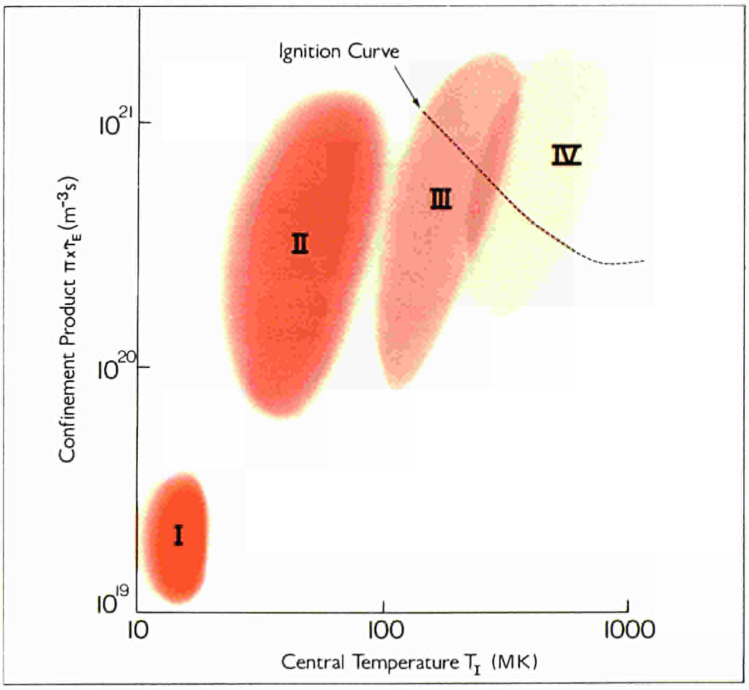
These models are used to form a consistent theory of a tokamak plasma. All of the quantitative knowledge on such a plasma will finally be contained within a set of properly interconnected computer programs (codes). These codes should be able to *describe* with sufficient accuracy plasmas already produced and *predict* the plasma behaviour under technical conditions not yet obtainable, such as the advanced operation of JET and ideally those needed for fusion reactor plasmas.

This involves the use of sophisticated numerical methods as most models require the solution of large systems of non-linear differential and algebraic equations for which the effective numerical procedures are not readily available.

Whenever measurements are available (from JET or other tokamaks) they will be compared with computations using the codes that have been developed and the models adjusted, if necessary, to describe these plasmas properly and help to understand the mechanisms involved.

The main use of these codes, however, is to extrapolate present knowledge for planning the future operating programme of JET and for future tokamak experiments.

The performance of magnetic confinement systems is measured by the confinement products (particle density n × energy confinement time τ_e) and the ion temperature T_i at the centre of the plasma. Preliminary predictions for the performance of JET are shown on the diagram for the various phases of operation (I–IV). Ignition occurs if the amount of energy produced from fusion reactions exceeds the energy loss from the plasma. According to these predictions JET could ignite in phases III–IV. The extent of the shaded areas shows that a great deal of study still remains to be done before firm predictions can be made about the performance of JET.



Predicted Performance for Various Phases of JET Operation

JET Organisation – Summarised

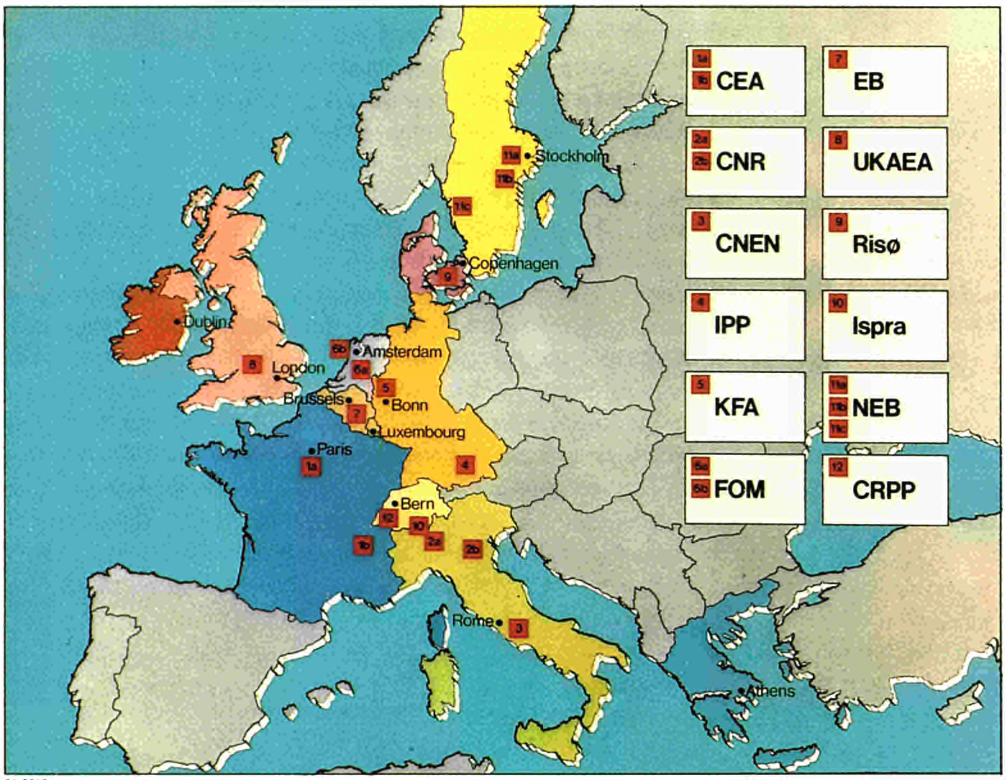
The JET Joint Undertaking

THE JET Joint Undertaking was established for a period of 12 years beginning on 1 June 1978 to construct and operate the Joint European Torus (JET). JET is the largest single project of the co-ordinated nuclear fusion research programme of the European Atomic Energy Community (Euratom).

Members

The members of the JET Joint Undertaking are Euratom, all its associated partners of the fusion programme with Luxembourg and Ireland.

On the 28 January 1982, Greece applied to join the JET Joint Undertaking.



81-3015c

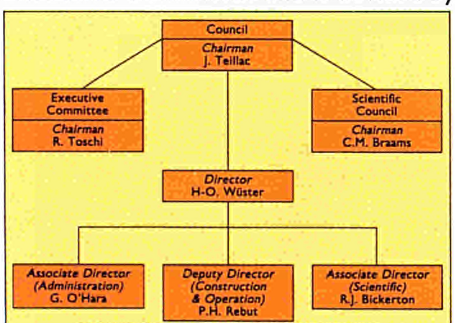
Location of the organisations associated with the Euratom fusion programme

1 Commissariat à l'Énergie Atomique, France. Centre d'Etudes Nucléaires de
1a Fontenay-aux Roses
1b Grenoble
2 Consiglio Nazionale delle Ricerche, Italy
2a Milan
2b Padua
3 Comitato Nazionale per la Ricerca e per lo Sviluppo dell'Energia Nucleare e delle Energie Alternative, Italy (formerly CNEN)
4 Max-Planck Institut für Plasmaphysik Garching, Federal Republic of Germany
5 Kernforschungsanlage Jülich GmbH, Federal Republic of Germany
6 Stichting voor Fundamenteel Onderzoek der Materie, the Netherlands
6a Nieuwegein
6b Amsterdam
7 État Belge, École Royale Militaire et Université Libre de Bruxelles, Belgium
8 United Kingdom Atomic Energy Authority, Culham Laboratory, United Kingdom
9 Risø National Laboratory, Risø, Denmark
10 Centro Commune Ricerche, Ispra, Italy
11 Energiforskningsnämnden (EFN), Sweden
11a Stockholm
11b Studsvik
11c Gothenburg
12 Confédération Suisse, Centre de Recherches en Physique des Plasmas, Lausanne, Switzerland

Management

The JET Joint Undertaking is governed by Statutes which were adopted by the Council of the European Communities on 30 May 1978.

The organs of the Joint Undertaking are the JET Council and the Director of the Project. The JET Council is assisted by a JET Executive Committee and is advised by a JET Scientific Council.



ORGANISATION OF THE JET JOINT UNDERTAKING

JET Council

Each member of the Joint Undertaking is represented on the JET Council. The JET Council is required to meet at least twice yearly and elects its chairman from among its members. The Council is responsible for the management of the Joint Undertaking.

Staff

The project team is formed partly from personnel assigned to the Joint Undertaking from the Associated Laboratories and partly by staff from the UKAEA – the Host Organisation

Number of Project Team staff by nationality
August 1982

Belgium	8
Denmark	6
France	35
FRG	31
Ireland	7
Italy	22
Luxembourg	1
Netherlands	9
Sweden	15
Switzerland	2
United Kingdom	152
Total	288

The Host Organisation

It was decided that the JET 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 the Host Organisation to the Project. The Host Organisation provides technical, administrative and general services for the Joint Undertaking and in addition provides staff for the Project Team.

Finance

The expenditure of the Joint Undertaking is borne by Euratom (80%) and the UKAEA (10%); the remaining 10% is shared between all Members having Contracts of Association in proportion to the Euratom financial participation in the total costs of the Associations.

Cost of JET 1977–86 (at 1982 prices)

	MECU
Basic performance construction phase	312.1
Extension to full performance	156.45
Operational Phase	158.2
Total	626.75

Allocation of 1981 budget fundings to Members based on 1978 Euratom/Association participation

Member	%
Euratom	80.000
Belgium	0.178
CEA, France	1.914
ENEA, Italy	0.871
CNR, Italy	0.116
Risø, Denmark	0.070
Luxembourg	0.009
KFA, FRG	0.961
IPP, FRG	3.373
Sweden	0.148
Switzerland	0.370
FOM, Netherlands	0.488
UKAEA, UK	11.502
	100.000

Involvement of Industry

Many large scale and long term research programs are undertaken initially in Government Research Laboratories.
In the early phases of these programs Industry usually plays a supporting role in providing tools for the research. The involvement of Industry, however, becomes more active and the participation increases as the goals are approached, and finally, in the exploitation of the research, Industry plays the major role.
According to the Treaty an important mission of the Community is to encourage this involvement of Industry in the nuclear program, with the aim of producing a vigorous European Nuclear Industry.
In the fusion program, and in particular in Europe, the participation of Industry, in the past, has been in a supporting role. The large fusion experiments such as JET have required a much stronger involvement by Industry.
In the JET Design Phase various study contracts and orders for long delivery items were placed after calls for tender from firms in all member states of the Community.
During the JET Construction Phase there has been even closer collaboration as most of the JET components were manufactured by Industry. It has also become necessary to employ consulting engineering firms especially in the areas of power supply construction, very heavy engineering component manufacture and large scale project control. With this involvement it is hoped to ensure that European Industries will have a long term competitive position in this important and exciting new field.

Analysis of the values of major contracts as at end 1981

	ECU	% of Total
UK	74,611,935	41.41
FRG	41,881,501	23.24
France	20,568,233	11.42
Italy	19,828,718	11.00
Switzerland	9,858,797	5.47
Denmark	4,588,505	2.55
The Netherlands	4,075,414	2.26
Belgium	3,243,868	1.80
Sweden	607,136	0.34
Others	911,718	0.51
	180,175,825	100.00

1 ECU = £0.549 (29 Sept 1982)

Nuclear Fusion

MATTER is built up from millions of tiny particles called atoms. At the heart of each atom is a nucleus containing a mixture of positively charged protons and uncharged neutrons. Negatively charged electrons orbit around this central core making the atom similar to a very small solar system.

The energy required to bind together the protons and neutrons in the nucleus varies from one element to another. When a nuclear reaction occurs, resulting in a change in the number of protons and neutrons contained within the nucleus, then one element is changed to another and some binding energy can be released. One type of reaction where this occurs is when elements join or fuse together to form heavier ones – NUCLEAR FUSION.

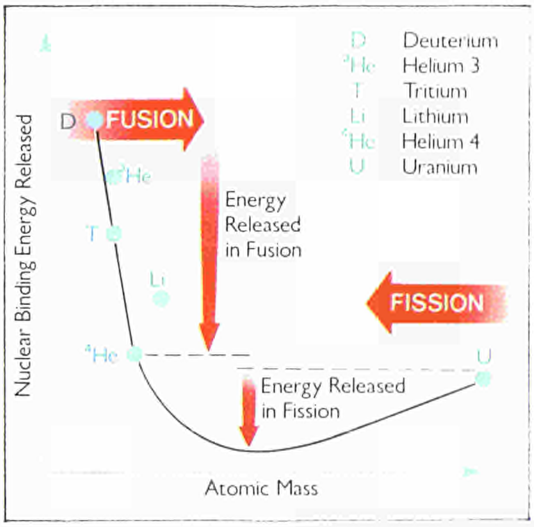
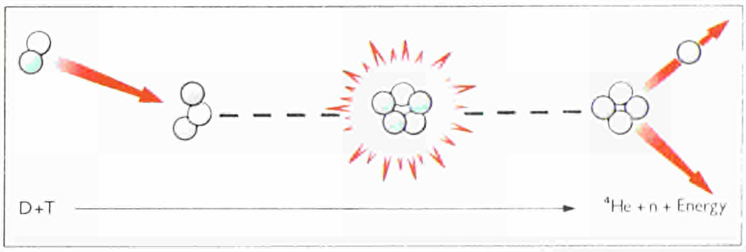


Illustration of the Energy which can be released by Nuclear Reactions

There are several possible fusion reactions involving the light elements, but the one of greatest interest, because it has a high reaction rate and imposes the least stringent conditions, is that between deuterium (D) and tritium (T), the two heavy isotopes of hydrogen. The heavier element helium (He) and a neutron are produced from the reaction combined with the release of energy.



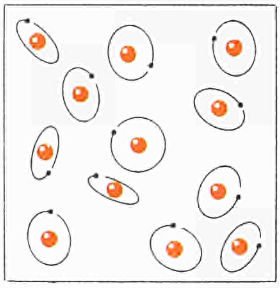
The Deuterium-Tritium Fusion Reaction

Although deuterium is extremely plentiful, as it can be obtained from ordinary water, tritium is not and must be manufactured. This can be done by using the neutrons produced in the fusion reactions to bombard a blanket containing lithium, resulting in the formation of tritium and helium gas. Thus, although the fusion reactions occur between the nuclei of deuterium and tritium the consumables used in this fusion process are deuterium and lithium. Lithium, like deuterium, is a widely available element.

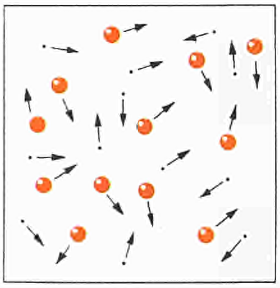
Fusion Reaction	$D + T \rightarrow {}^4He + n + 28.2 \times 10^{-13}$ joules
Tritium Breeding Reactions	${}^6Li + n \rightarrow T + {}^4He \quad + 7.7 \times 10^{-13}$ joules ${}^7Li + n \rightarrow T + {}^4He + n - 4.0 \times 10^{-13}$ joules
Overall Reaction	$D + Li \rightarrow 2\,{}^4He$

Conditions for Fusion

Fusion reactions are difficult to achieve because the deuterium and tritium nuclei each has a positive electric charge and therefore strongly repel one another. To enable the nuclei to come close enough together, so that fusion reactions occur, the nuclei must be given sufficient energy to overcome their mutual electrostatic repulsion. This may be achieved by heating the gaseous fuels to very high temperatures. As the temperature is increased the gas becomes ionised – that is the electrons are stripped away from their parent nuclei – resulting in a mixture of positively and negatively charged particles. The physical properties of such an assembly of particles are so different from those of a normal gas that it is given a special name – PLASMA.



Gas



Plasma

At temperatures around 100 million degrees centigrade abundant fusion reactions occur in a deuterium-tritium plasma releasing large amounts of energy.

Heating

Plasmas can be created and heated by passing very large currents through the gas, but to get the temperatures needed for fusion reactions to occur additional heating methods, such as the injection of energetic atoms or the use of radio frequency waves, must be employed.

Confinement

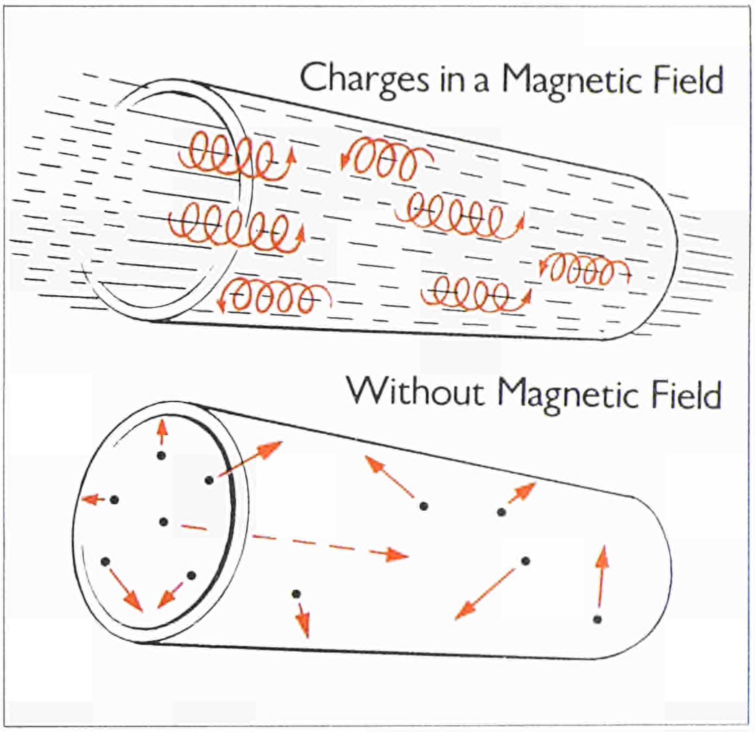
In addition to heating the fuels to very high temperatures it is essential for power generation that the energy produced from fusion reactions exceeds the amount of energy required to run the system.

To satisfy this condition sufficient hot fuel must be confined in isolation from the container walls for a long enough period of time. This requirement or Lawson Criterion ($n \times \tau_e$) as it is known, is expressed as the product of fuel density (n) and confinement time (τ_e) and must exceed 10^{20}s m^{-3} for the deuterium-tritium reaction.

High temperature plasmas have a natural tendency to expand unless restrained in some way. As no matter can withstand the high temperatures without vaporising and cooling the plasma by contamination, the plasma must be confined in a non-material container. Fusion plasmas in the universe – the sun and stars – are held together by large gravitational forces. These, however, are too small to be used with apparatus of a terrestial scale.

Because the plasma is a mixture of charged particles it can be influenced by magnetic fields and investigations have been going on for over 30 years to try and find the most suitable magnetic field configuration for the reactor criteria to be satisfied.

In practical terms using the magnetic confinement approach to fusion means that the high temperature fuels need to be held at densities of 10^{20} particles per cubic metre for periods in excess of 1 second.



The JET experiment has been designed to approach the plasma conditions needed for a reactor. It is using one of the most promising magnetic confinement systems that has been developed – the TOKAMAK.*

Summary of Conditions for Fusion
TEMPERATURE >100,000,000 degrees (Celsius)
DENSITY × CONFINEMENT TIME greater than 10^{20}s m^{-3}

*The word tokamak is derived from the Russian for toroidal magnetic chamber.