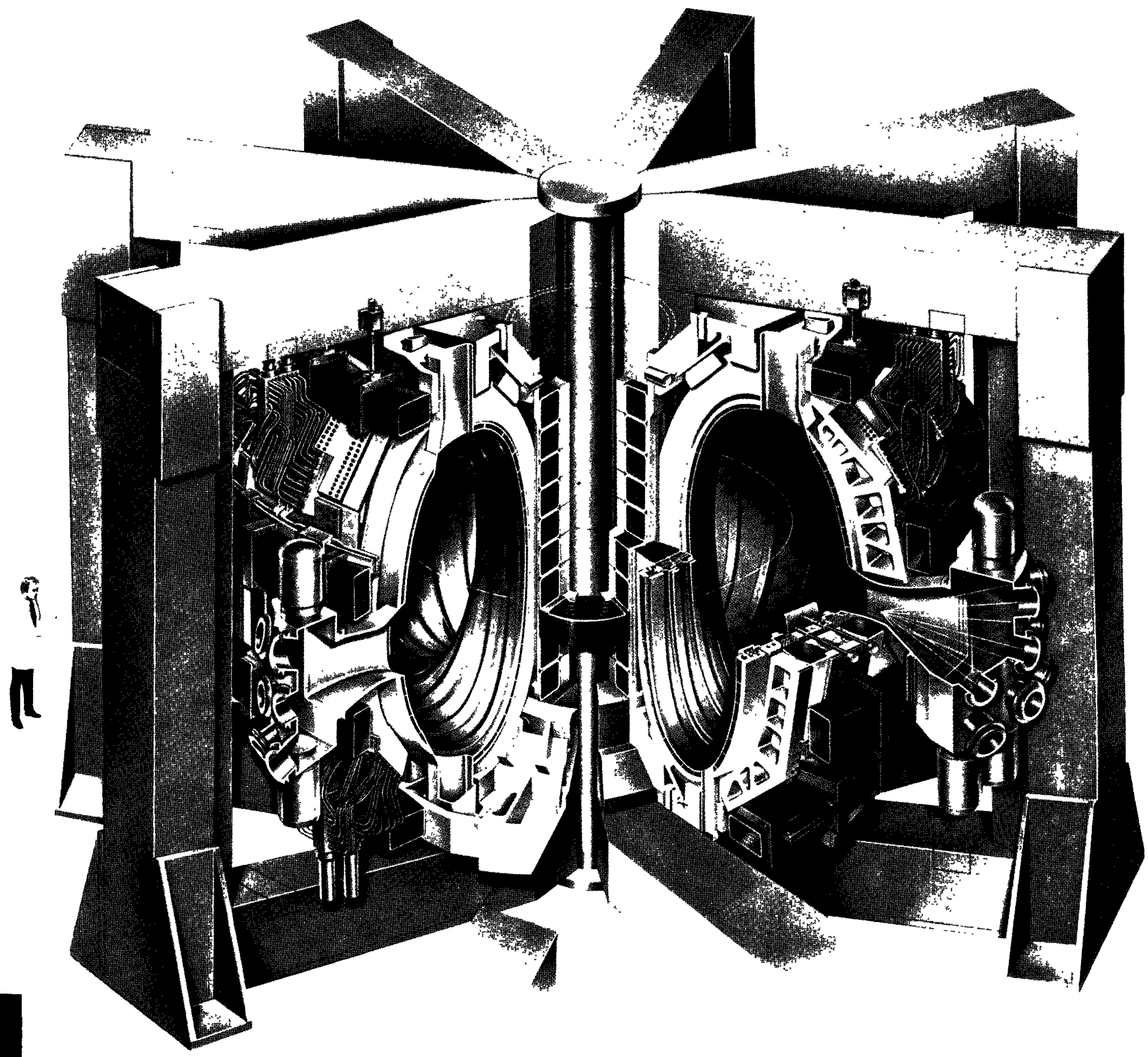
EUR-JET-R7

THE JET PROJECT



JOINT
EUROPEAN
TORUS

Acknowledgements

The JET Design Team is especially indebted to the members of the Associated Laboratories for their valuable work and interest in the project, and especially for their contribution to the JET Workshops. This co-operation between the Design Team and the Associated Laboratories is essential to ensure that JET develops as a true Community project.

The team wishes to acknowledge the collaboration and encouragement of the Directorates of the Associations and of the Commission. The Design Team is grateful for help and advice from the members of the Supervisory Board, and the Scientific and Technical Committee.

The JET Design Team finally takes pleasure in thanking Dr. R. S. Pease and all the members of the Culham Laboratory for their warm welcome and effective help during the design phase of the project.

P. H. Rebut

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The help of the illustrators is particularly appreciated.

The technical sections of EUR-JET-R7 are based upon the detailed design proposal EUR-JET-R5 and on the summary of JET Workshops given in EUR-JET-R6 Enquiries about these documents should be sent to the address below.

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COMMISSION OF THE EUROPEAN COMMUNITIES

Directorate General XII
Fusion Programme

Rue de la Loi, 200

B - 1049 Brussels
BELGIUM

A 1911

EUR-JET-R7
August 1975

THE JET PROJECT

Introduction

In recent years there have been many significant advances in the research program for the utilization of fusion energy which encourage the belief that this important program will have a successful conclusion.

These advances are the reason for the proposed expansion of the fusion research program, both in staff numbers and especially in the scale of the experiments.

There will certainly be an increasingly wide public involvement and interest in this rapidly developing field. It therefore seems appropriate at this time, when the Commission has proposed to the Council the adoption of the Fourth European Fusion Program, in which the Joint European Torus (JET) constitutes a principal part, to prepare this description of JET which is intended for the non-specialist and for industry. To industry, because in the long term, when the current research is successful, industry will have the responsibility for the construction of the fusion reactors; and because in the short term industry will provide the laboratories with many of the large and complicated components of the experiments.

In appreciation of the differing needs of the potential readers we have included both a short section introducing the fusion field and also a more technical section describing the JET apparatus.

The reader may be surprised at the scale of the proposed JET experiment, hundreds of tons of copper and steel and a cost of more than 100 MUC. This is, however, a consequence of the laws of nature which make it impossible in practice to produce and magnetically confine, for an appreciable time, a toroidal thermonuclear plasma having a volume less than many cubic metres. The advances made in fusion research with smaller apparatus are such that the stage has now been reached where a definitive experiment is required with dimensions large enough to permit extrapolation of the results to future reactor designs.

This increase in scale is not peculiar to JET but covers the entire fusion field, and is in evidence throughout the world program. In fact in the U.S.A., U.S.S.R. and JAPAN, machines comparable to the European

Communities JET machine, have been proposed as part of expanded fusion programs.

The dimensions of such an expanded program certainly require, in the European framework, that the member nations should pool their resources. This has been a major aim of the Commission in this field, and the successful initiation of the JET project is evidence of the good progress in this direction. In a relatively short time it was possible to assemble at Culham personnel, from the associated laboratories, representing all the areas of expertise involved in this field. As a result of the effective management of this team, working in close collaboration with the Associated Laboratories, the design has been rapidly and successfully completed.

D. Palumbo

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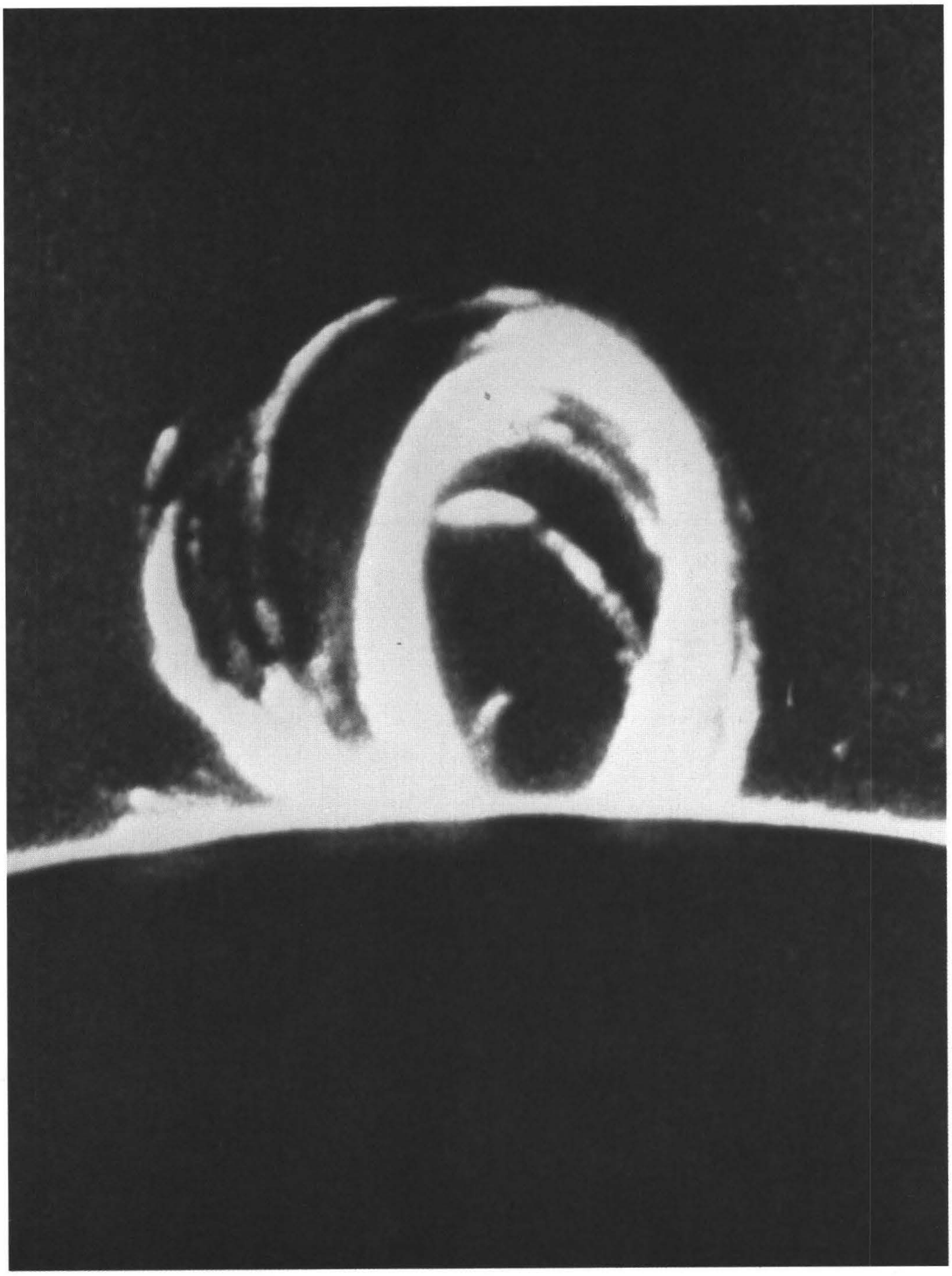


Surface of the sun

Courtesy of the Sacramento Peak Observatory
Sunspot, New Mexico, U.S.A.

I What is JET?

JET (JOINT EUROPEAN TORUS) is an experiment in a program which has the ultimate aim of utilising a new source of energy.

This is the energy released by the fusion of the nuclei of light atoms, the energy source of the SUN.

New sources of energy are required to meet the increasing world energy demands. The increased supply is needed not only because of the increase in world population and in the rapid growth of modern industrialised society, but also because of the need to raise the living standards of the developing countries.

Present day energy production is based mainly on the fossil fuels, oil, coal and natural gas. These fuels cannot supply the needs of the world indefinitely and in any case have such a value as chemicals that as they become depleted they will be too precious to burn simply for the purpose of producing electricity.

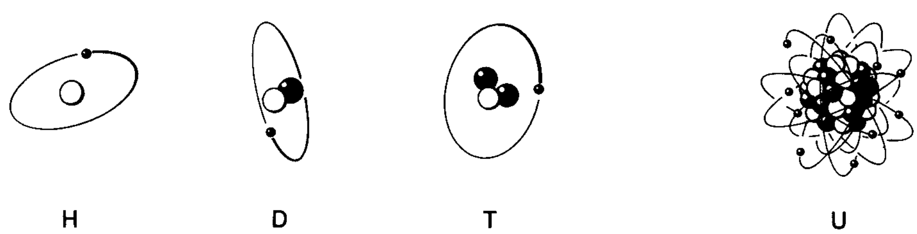
It is desirable to develop for the future as many alternative sources as possible. New sources of energy include nuclear, solar, geothermal, tidal and wind power. Nuclear power in the form of nuclear fission power stations has already made an impact on electricity production in a number of countries. There are however, two possible sources of nuclear energy:

FISSION and FUSION

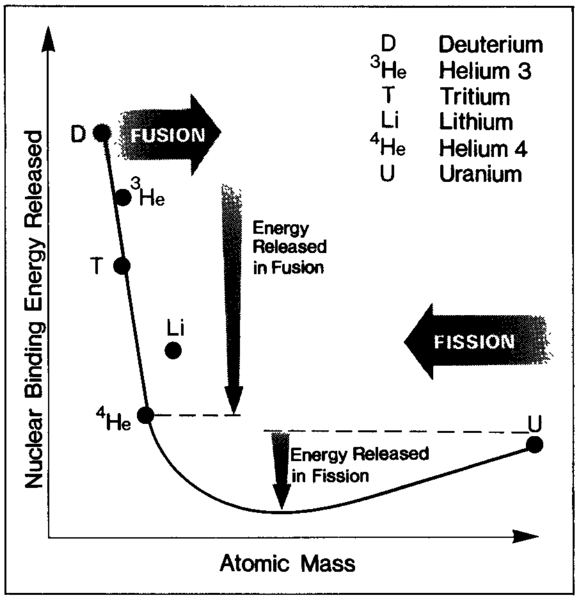
It is proposed to build JET, the biggest experiment in Fusion Research to date, during the period 1976 to 1980. The total Construction Phase Costs, including Commissioning, Buildings and Staff, for JET, amounts to 135 Million Units of Account (MUC; 1UC = 50 Belgian Francs). JET will be a major step forward in the European fusion program to establish fusion as a viable alternative to fission.

2 What is Fusion?

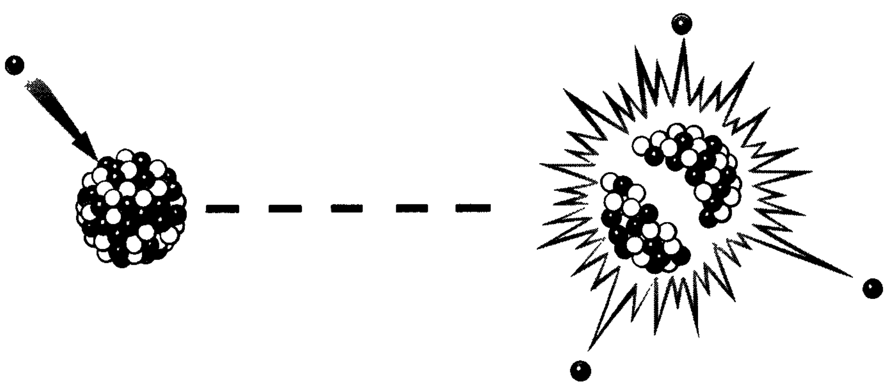
All matter whether it is a solid, a liquid or a gas is made up of millions of tiny particles called atoms. The heart of every atom, called the nucleus, consists of a mixture of two elementary particles called protons (p) and neutrons (n). Orbiting around the nucleus is a swarm of electrons, in number as many as the protons in the nucleus, making the atom look like a very small solar system. The weight of the atom is mainly in the nucleus and corresponds to the number of protons and neutrons. Thus the 'lightest' atom Hydrogen (H) has 1 proton and 1 electron, a heavy hydrogen atom Deuterium (D) has 1 proton, 1 neutron, and 1 electron, while an even heavier hydrogen atom Tritium (T) has 1 proton, 2 neutrons and 1 electron. An example of a very heavy atom is Uranium (^{235}U) which has 92 protons, 92 electrons and 143 neutrons.



Experiments have shown that the forces (binding energy) which hold the nucleus together vary from one type of atom to another. The re-arrangement of the protons and neutrons in certain nuclei into other groupings can lead to the release of large amounts of surplus binding energy (or 'nuclear glue'). This is illustrated in exaggerated form opposite.

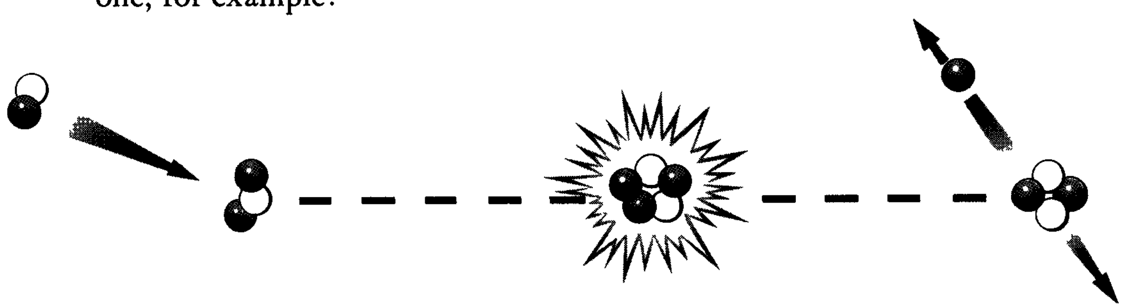


- In the nuclear FISSION process, large nuclei of, for example, uranium and plutonium are split into smaller nuclei by the impact of neutrons. This releases vast amounts of binding energy which can be harnessed and converted into electricity. All present day nuclear reactors work on this principle, for example:



n + U ⟶ Ba + Kr + neutrons + Energy

- The nuclear FUSION process, however, relies on releasing the binding energy by fusing or joining together lighter nuclei to make a heavier one, for example:



D + T ⟶ ^{4}He + n + Energy

There are several possible nuclear fusion reactions involving the light elements as shown in Table 1. The one of greatest interest, because it has a high energy yield and imposes the least stringent conditions, is that between the two types of hydrogen (isotopes), deuterium (D) and tritium (T). These combine to produce the heavier nucleus of helium (^{4}He) and a neutron (n) accompanied by a release of energy. The neutron energy may be converted into heat in a surrounding moderator blanket and thence into electricity by conventional generators.

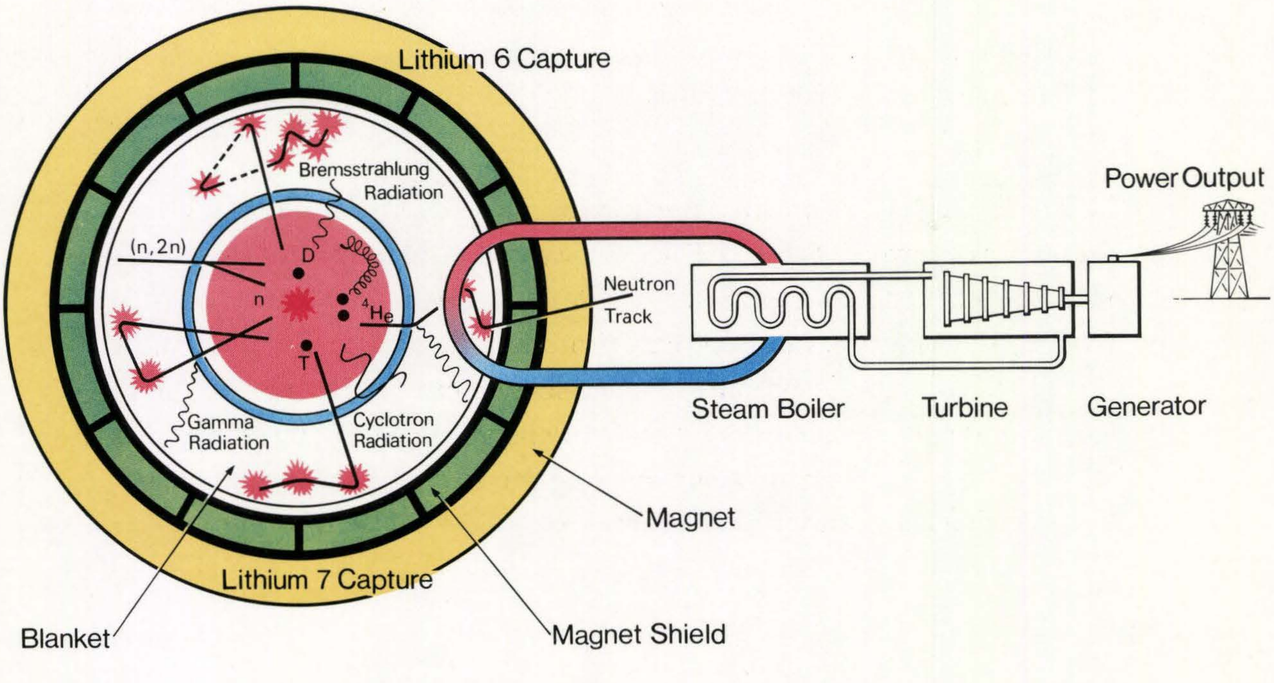
Table 1 Fusion Reactions

D + D	$\rightarrow$	^{3}He	+ n +	5.2	$\times 10^{-13}$	Joules
D + D	$\rightarrow$	T	+ p +	6.4	$\times 10^{-13}$	Joules
D + T	$\rightarrow$	^{4}He	+ n +	28.2	$\times 10^{-13}$	Joules
D + ^{3}He	$\rightarrow$	^{4}He	+ p +	29.4	$\times 10^{-13}$	Joules

Although deuterium, which occurs in water, is extremely plentiful, tritium is not a naturally occurring element and it must therefore be manufactured. Possible breeding reactions are shown in Table 2. Tritium may be manufactured in a lithium blanket, which surrounds the fusion region, as illustrated in the figure. Neutrons produced by the deuterium/tritium reaction are then captured by the lithium to yield tritium and helium.

Table 2 Tritium Breeding Reactions

^{6}Li + n $\rightarrow$ T + ^{4}He	+ 7.7	$\times 10^{-13}$	Joules
^{7}Li + n $\rightarrow$ T + ^{4}He + n	− 4.0	$\times 10^{-13}$	Joules



D-T Fusion Reactor

3 Why Fusion?

The energy needs of the world in the future are so great that all sources of energy should be seriously studied. The present understanding is, however, that only nuclear energy – FISSION and FUSION – can meet the long term needs of Europe. Thus the advantages of fusion are seen mainly in a comparison with fission. It must be emphasised that, given the magnitude of the energy problem, one should think of the systems as complementary rather than as alternatives. Research on fission reactors points to the likelihood of breeder reactors being successful as the basis of generating stations. Fusion is at present at a much earlier stage but offers the possibility of several long-term advantages.

(1) Fusion is intrinsically cleaner because the ultimate fusion products (mainly helium) are non-radioactive and harmless. The radioactivity produced by neutron irradiation in the structural materials of the fusion reactor may at worst, depending on the structural materials used, be comparable with that in a fission reactor.

(2) The amount of fuel in the reactor zone is expected to be so small that there is no prospect of a dangerous nuclear runaway. The nuclear heat produced after a shutdown does not present a serious problem. Safeguarding against the misuse of the system is easy. The tritium processing may be undertaken on site; this eliminates the dangers associated with the offsite transportation of radioactive fuel. The time to replace the tritium fuel, by breeding in the blanket, is small.

(3) Of the principal fuels for the D–T reactor, deuterium and lithium, deuterium is extremely plentiful and the known reserves of high grade lithium ore have an energy content comparable with the reserves of uranium and thorium. Further lithium may be extracted, though at higher cost, from widely distributed low grade ores and from the sea.

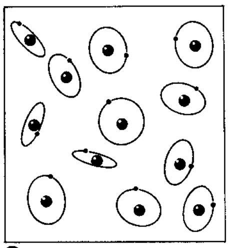
4 Conditions for Fusion

Fusion reactions are difficult to achieve because the deuterium and tritium nuclei each have a positive electric charge and therefore strongly repel one another. Fusion will only occur if the nuclei approach each other at very high velocities, sufficient to overcome their mutual electrostatic repulsion.

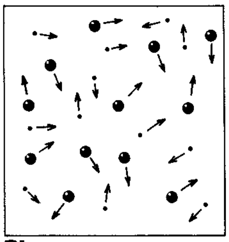
HEATING

Abundant fusion reactions can be obtained by HEATING the gaseous deuterium–tritium fuel to a temperature of 100 million degrees or above. Already at considerably lower temperatures than this the gas becomes IONIZED – that is, the electrons are dislodged from the atoms. In this state the separate electrons and nuclei move freely.

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. It is often referred to as the 4th State of Matter, solid, liquid and gas being the other three. In nature plasma occurs in the sun, stars, aurora and in the tails of comets. Plasma is the glowing material in fluorescent lights, circuit breakers, etc.



Gas



Plasma

CONFINEMENT

In order to obtain more energy out than is put in it is necessary to CONFINE the plasma for long enough so that sufficient fusion reactions can take place. The required CONFINEMENT TIME (τ) for a 100 million degree plasma depends upon the DENSITY (n). The requirement, known as the LAWSON CRITERION, is that the product $n\tau$ is greater than about $10^{14} cm^{-3}$ s, thus at a density of 10^{14} particles per cubic centimetre ($10^{14} cm^{-3}$) the particles must be confined on average for about 1 second. At lower densities the confinement time would have to be longer.

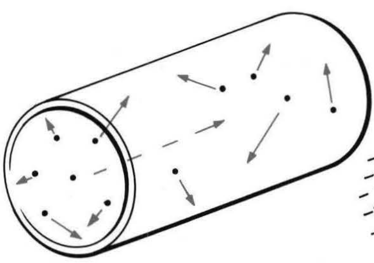
Summary of Conditions for Fusion
TEMPERATURE ~ 100 000 000 degrees
DENSITY X CONFINEMENT TIME greater than 10^{14} cm^{-3} s.

5 Confinement of a Plasma

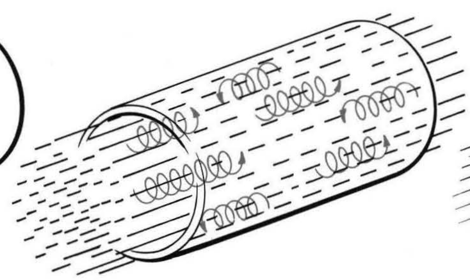
High temperature plasmas have a natural tendency to expand unless restrained in some way, since the individual particles, electrons and nuclei which constitute the plasma are moving at very high speeds (typically a few million kilometres per hour). Fusion plasmas in the Universe – the sun and the stars – are held together by large gravitational forces. Gravitational forces, however, are too small for apparatus of a terrestrial scale.

On earth we must find some way to confine hot plasma, but in a more convenient sized module.

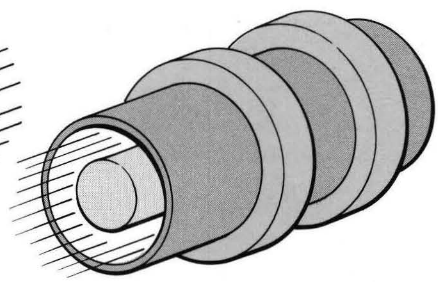
The plasma must be confined in a non-material container, since no matter can withstand the high temperatures without vaporising and cooling the plasma by contamination. This in turn must be contained within some material container, a high vacuum vessel, so that the composition of the plasma can be controlled.



Without Magnetic Field



Charges in a Magnetic Field



Plasma in a Magnetic Field

MAGNETIC CONFINEMENT

Plasma is a very good conductor of electricity and it can be influenced by magnetic fields. Magnetic confinement has been under investigation for over 25 years, and is the approach to be used in the JET experiment. The charged particles which constitute the plasma follow helical paths around the magnetic field lines, and may therefore be isolated from the material walls. They are contained in the magnetic bottle while they are heated and react.

A number of comments can be made about magnetic confinement.

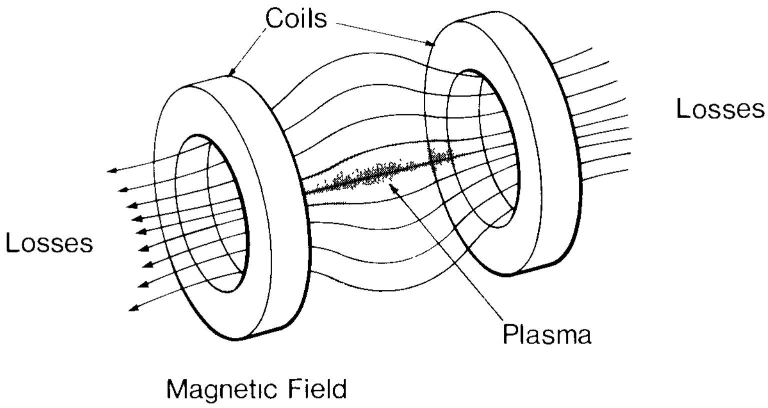
- There is a wide variety of possible 'magnetic bottles' and over the last 25 years many configurations have been tried.

- Some arrangements of plasma and magnetic field are UNSTABLE, that is the plasma can escape from the magnetic bottle much more rapidly than by simple diffusion.
- The simplest arrangement is straight and OPEN ENDED. By increasing the fields at the ends we can reflect some particles back and forth (MIRROR) but the end losses appear at present to pose severe difficulties for a fusion reactor.
- To eliminate the ends the field lines are bent to close on themselves within the vacuum container. This is known as a TOROIDAL MAGNETIC FIELD (B_{TOR}). Unfortunately, the plasma drifts sideways to the wall in this field system. The drift can be overcome by the addition of a second field around the minor diameter – POLOIDAL MAGNETIC FIELD (B_{POL}) – which gives the resultant field a twist and provides compensating drifts.
- A promising magnetic confinement system of this type is the TOKAMAK in which the poloidal magnetic field is produced by a current I_p flowing through the plasma itself. The plasma is the secondary winding of a transformer. JET is a TOKAMAK.
- Other systems use external coils to produce the extra field (Stellarator), or have different ratios of the two fields (Pinch Devices).
- Due to collisions particles can transfer from one field line to a neighbouring one and cross the field. This process is called DIFFUSION.
- An important feature of the diffusion process is the rapid increase in confinement time obtained with increase in the scale of the system.

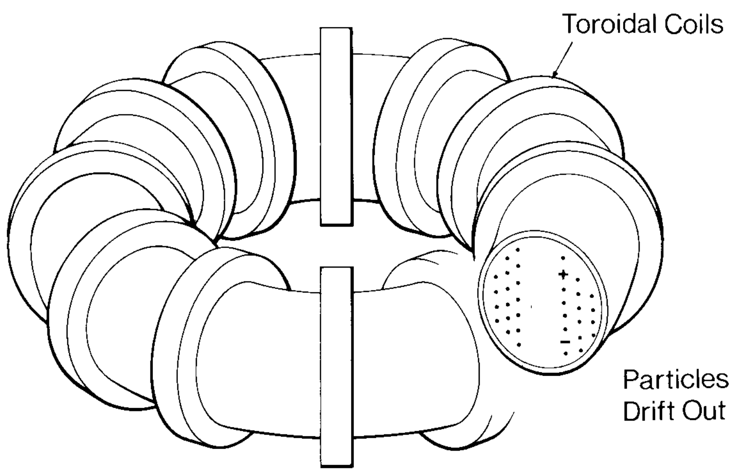
INERTIAL CONFINEMENT

In this alternative approach, beams of laser light or very energetic electron beams are shot symmetrically onto a small spherical hydrogen target. The beams heat and compress the target and its inertia holds it together long enough for the thermonuclear reactions to take place. The confinement times are relatively short and the ultrahigh densities required are produced by the compression.

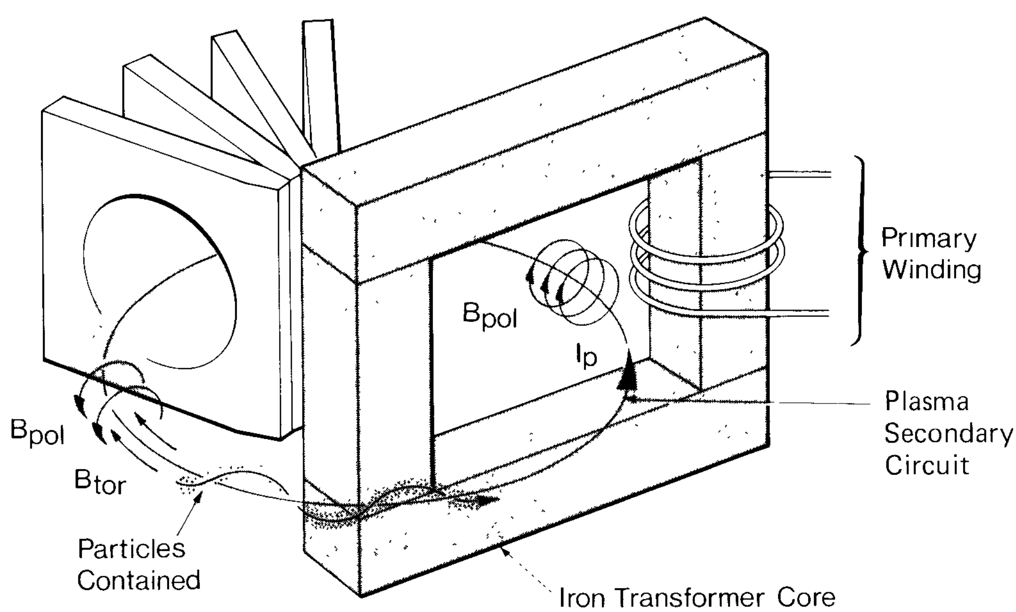
MIRROR MAGNETIC FIELD



TOROIDAL MAGNETIC FIELD



TOKAMAK



6 Heating of a Plasma

In a reactor the α-particles (the nuclei of helium ^4He produced by the fusion of deuterium and tritium) will provide the heat to sustain the plasma temperature. The α-particles will be trapped by the confining magnetic fields and will slow down by collisions with the plasma particles, heating them. In present experiments, which work at temperatures too low for significant fusion heating, other methods must be used. This will also be the case during the start-up of a reactor when the temperature has to be raised to the fusion level.

OHMIC HEATING

The main heating method in Tokamaks and in many other magnetic confinement devices is the Ohmic or Resistive heating due to currents flowing in the plasma. This heating is similar to that in an electric heater element or in a light bulb.

A problem with the application to plasmas, when the currents are steady, is the decrease in plasma resistance as the temperature rises. The losses on the other hand, for example by radiation, generally increase with temperature. The temperature reached when the losses balance the heating is therefore limited.

Additional heating methods are therefore needed. Among those which have been used are

NEUTRAL INJECTION

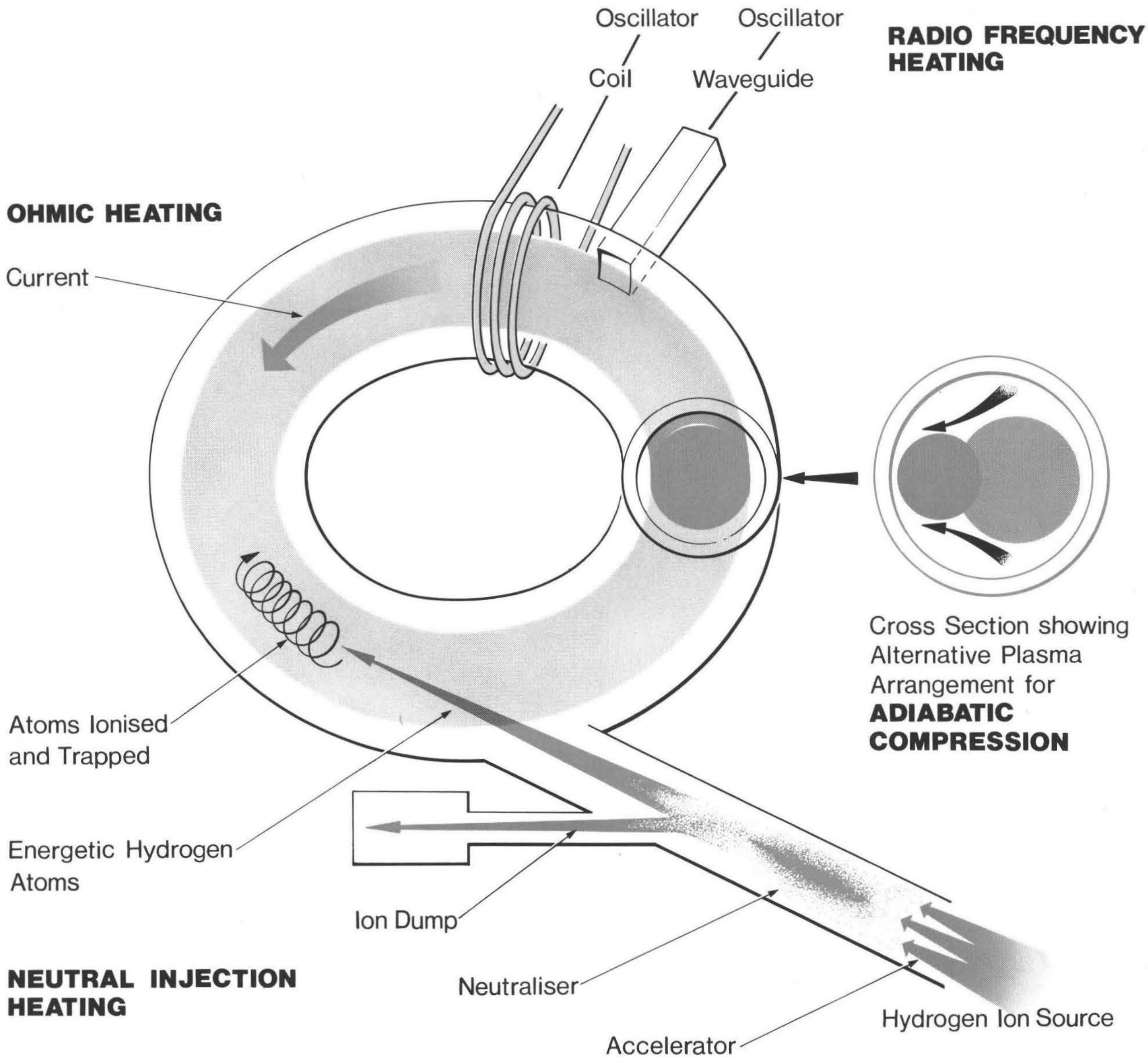
Hydrogen atoms are injected with very high speed. They are electrically neutral and cross the magnetic field, where they are ionized by the plasma and are then trapped by the magnetic field. They may then be confined by the field, and slow down transferring their (kinetic) energy to the plasma by collisions, thus heating it.

RADIO FREQUENCY HEATING

High frequency oscillating currents are induced in the plasma by external coils or waveguides. The frequencies are chosen to match regions where the energy absorption is very high (resonances). In this way large amounts of power may be transferred to the plasma.

ADIABATIC COMPRESSION

The magnetic field is raised rapidly; as a consequence the plasma is compressed and heated. This may be achieved by moving the plasma to a region of stronger magnetic field.



In present Tokamaks temperatures of more than 10 million degrees have been reached with ohmic heating. Neutral injection and radio frequency heating have been successfully applied; in both cases with power levels of about 100 kilowatts the temperature rise was about 2 million degrees. Temperatures have been more than doubled by adiabatic compression.

All these methods will be used in JET.

7 The Tokamak Confinement System

This type of confinement system was first developed in the U.S.S.R., and has the general form shown in the figure opposite. This figure reflects the choice of design options made for the JET Tokamak.

The main components of the Tokamak and their respective functions are listed below.

- The plasma is contained in a ring-shaped vacuum vessel – TORUS. The vacuum is maintained by external pumps. The plasma is created by letting in a small puff of gas, inducing some ionization and then driving a current in it to ionize it completely and heat it.

- The plasma is confined by a MAGNETIC FIELD. This field is the combination of the TOROIDAL FIELD produced by a set of TOROIDAL FIELD COILS which link the torus, and the weaker POLOIDAL FIELD produced by the current flowing in the plasma (see section 5).

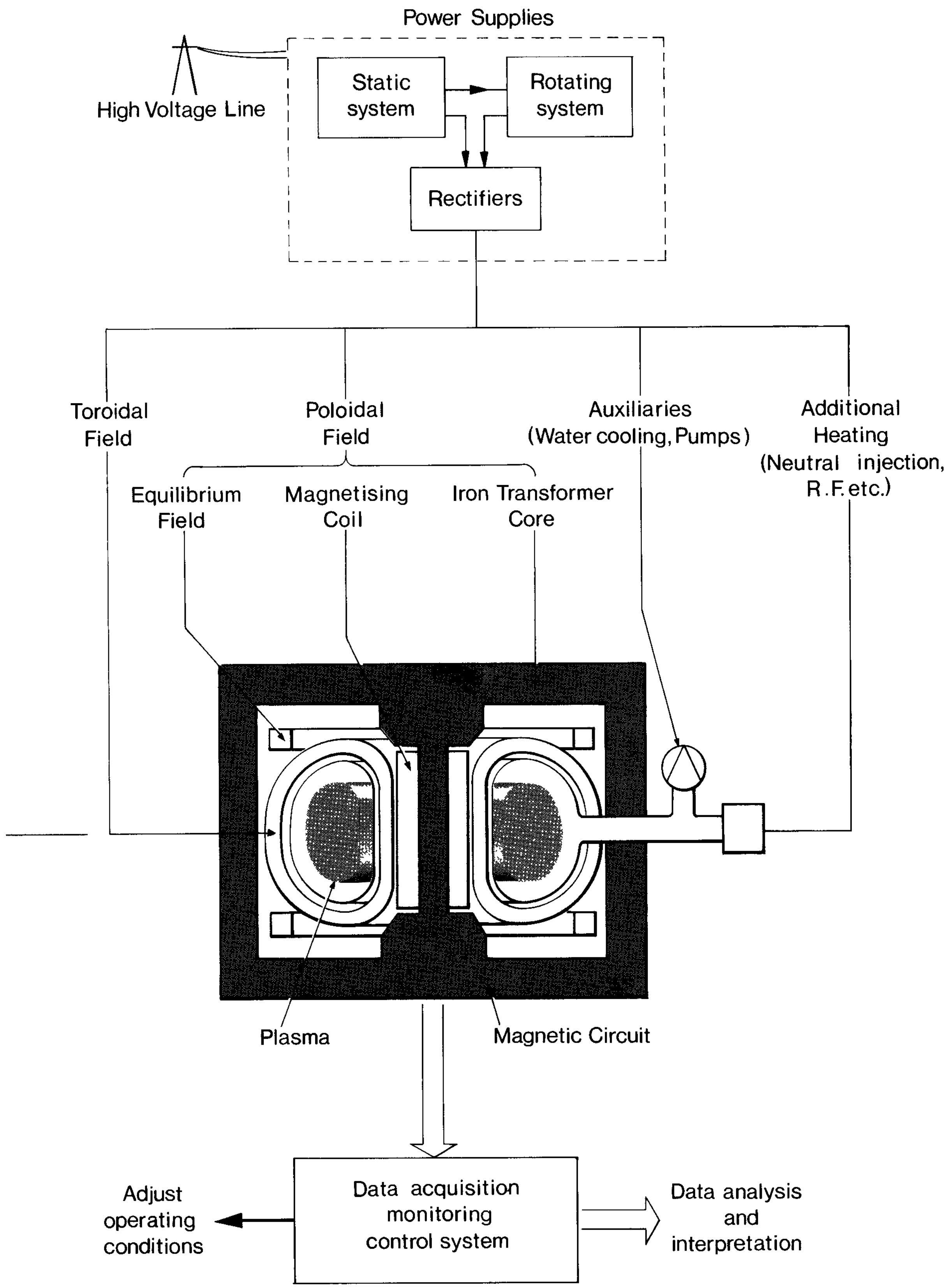
- The PLASMA CURRENT is induced by a transformer, of which the plasma is the Secondary Winding. The Primary Winding of the transformer and the subsidiary Equilibrium coils, which give the fine control of the position and shape the plasma, are called POLOIDAL FIELD COILS.

- Large POWER SUPPLIES are used to generate the strong magnetic fields (up to 100 kilogauss) and large plasma currents (up to 400 000 amperes in present Tokamaks).

- Powerful ADDITIONAL HEATING systems are used to augment the heating of the plasma current (see section 6).

- The coil and plasma currents and plasma content and density are in general pre-set by the CONTROL SYSTEM. Fine adjustments may however be made by using FEEDBACK SYSTEMS which are controlled by measurements on both the apparatus and the plasma i.e. DIAGNOSTICS.

- In present Tokamaks, the plasma is maintained for up to about 0.5 seconds (25 times the energy confinement time). The repetition rate is typically once every 1 to 20 minutes.



A Representative Tokamak System

8 The World Tokamak Program

Tokamak research, initiated in the U.S.S.R., is now a major part of the world fusion effort.

The Tokamak is a relatively simple device for the production and confinement of large volumes of high temperature plasma at a density level relevant to reactors. It is therefore of interest not only as the basis of a fusion reactor, but also as a workhorse for the investigation of areas of general importance to the fusion program.

Thus there are Tokamaks which are designed to extend the scaling of the plasma confinement parameter ($n\tau$) and temperature (T) towards the reactor regime and there are others which will investigate specific problems such as heating, plasma shaping and plasma cleanliness.

These roles are represented in the wide range of machines, existing and under construction, of which some examples are given in Tables 3 and 4.‡

Table 3 Representative* Parameters (Characteristics) of Existing Tokamaks

Device	Country	I_p (kA)	R_o (m)	a (m)	B_{TOR} (kG)	$\hat{T}_e$ million deg.	$\hat{T}_i$ million deg.	$n\tau_E$ (cm^{-3} s)
T–3	U.S.S.R.	90	1.00	0.17	25	20	6	$\sim 3 \times 10^{11}$
T–4	U.S.S.R.	180	1.00	0.17	50	20	10	$\sim 3 \times 10^{11}$
ORMAK	U.S.A.	200	0.80	0.23	18	12	4	$\sim 2 \times 10^{11}$
ST	U.S.A.	130	1.09	0.13	40	22	8	$\sim 2 \times 10^{11}$
ATC†	U.S.A.	80–200	0.88–0.35	0.17–0.11	20–25	10–25	3–8	$\sim 10^{11}$
TFR‡	FRANCE	400	0.98	0.20	60	30	12	[illegible]
PULSATOR‡	F.R.G.	80	0.70	0.12	28	[illegible]		[illegible]
ALCATOR	U.S.A.	160	0.54	0.095	60	18	6	10^{12}

* These numbers represent normal operation rather than maximum capability

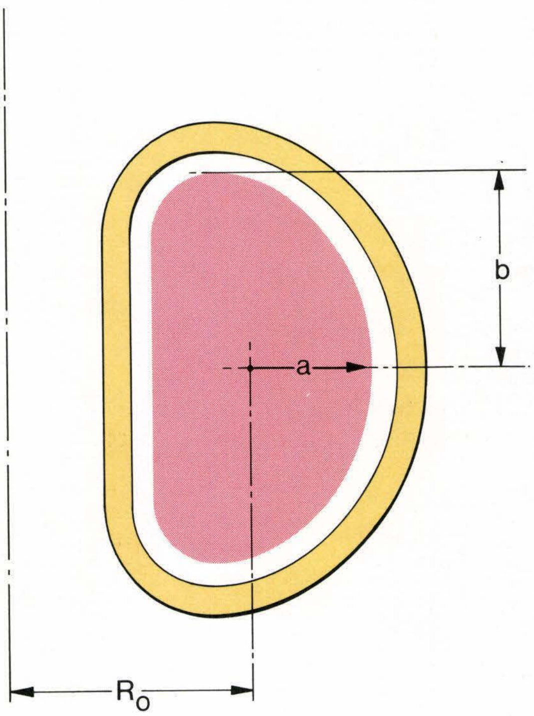
† The two values refer to initial and compressed states

‡ Work performed in association with Euratom

Table 4 Principal Tokamaks under Construction

Device	Country	I_p (MA)	R_o (m)	a(m)	B_{TOR} (kG)
DITE°	U.K.	0.28	1.12	0.23	28
PLT	U.S.A.	1.4	1.30	0.45	46
FT°	ITALY	1.0	0.83	0.21	100
T–10	U.S.S.R.	0.8	1.50	0.35	50
PDX	U.S.A.	0.50	1.40	0.45	50
ASDEX°	F.R.G.	0.50	1.54	0.40	30
DOUBLET 3	U.S.A.	2.5–5.0	1.40	0.45 ; 1.50 (a ; b)	26(42)

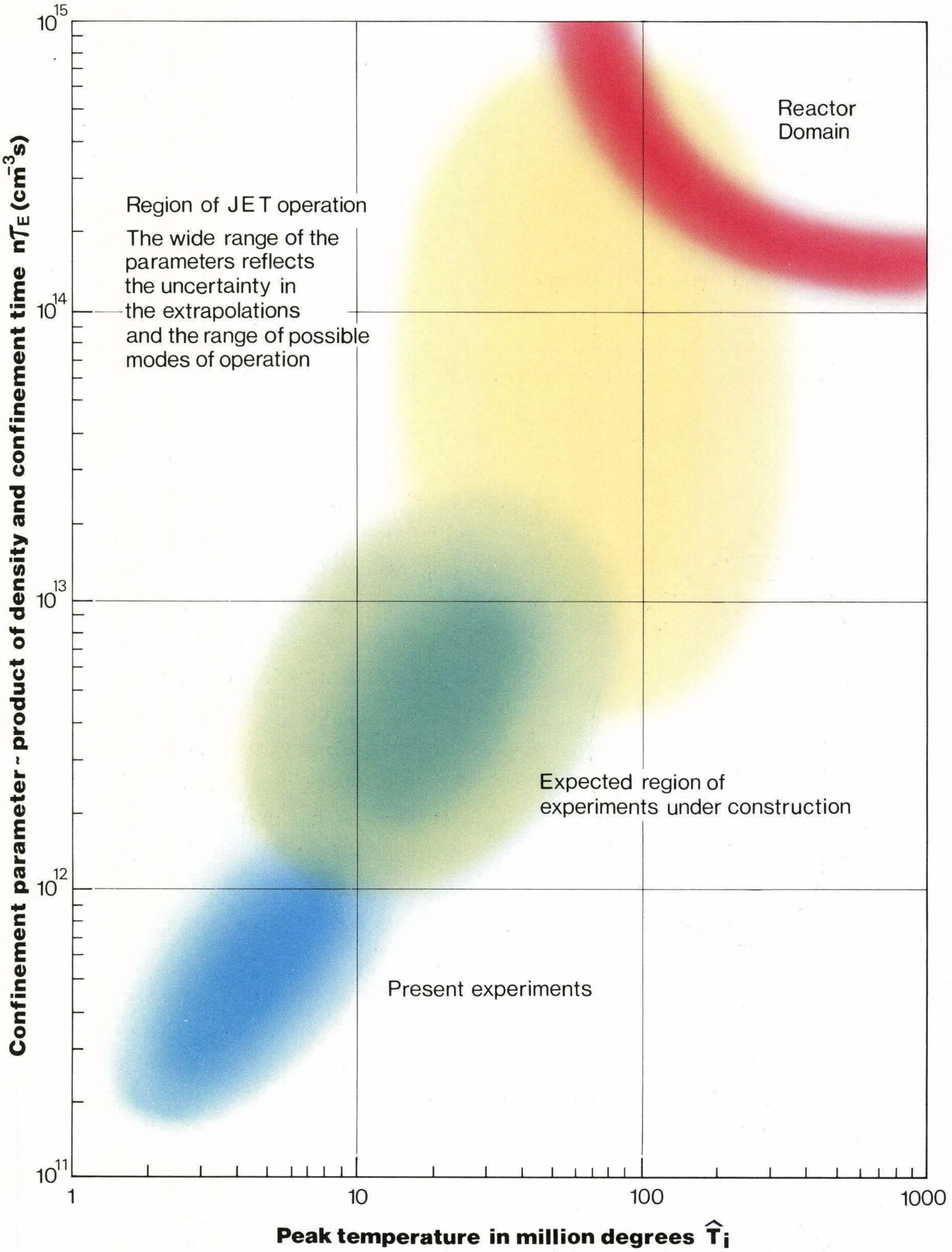
‡A glossary of symbols and units is given at the end of this document.



At the present time the highest values of $n\tau$ and T in the world have been achieved in the laboratories associated with Euratom. JET is a logical extension of this work as a part of the continuing European Tokamak program. It should not only raise $n\tau$ and T well towards the reactor regime but also contribute significantly in such areas as plasma-wall interaction and plasma heating. It will be joined by other large Tokamaks which are proposed by the other countries with large fusion programs, TFTR (U.S.A.) and JT–60 (Japan). In the U.S.S.R. an even bigger machine, T–20, is proposed. This is expected to go into operation after JET and the others. The machine parameters are shown in Table 5.

Table 5 Proposed Large Tokamaks

Device	Country	I_p (MA)	R_o (m)	a(m)	b(m)	B_{TOR} (kG)
JET°	E.E.C.	2.6(4.8)	2.96	1.25	2.10	27.7(34.5)
TFTR	U.S.A.	2.5	2.48	0.85	0.85	52
JT–60	JAPAN	3.0	3.0	1.0	1.0	50
T–20	U.S.S.R.	6.0	5.0	2.0	2.0	35



Possible Performance Data for JET

9 Objectives of JET

Detailed studies in the present, relatively small Tokamaks have produced a consistent pattern of encouraging results. Plasmas with increasingly high temperatures have been isolated and controlled for progressively longer times. The knowledge gained from small scale apparatus shows that higher temperatures and longer confinement times can only be achieved in large machines with large plasma current.

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

These studies will be aimed at defining the parameters, the size and the working conditions of a Tokamak reactor. The range of values of ($n\tau$) and (T) expected in JET are indicated opposite.

Under these conditions the following studies will be made:

(1) The study of plasma processes and scaling laws into regions close to those needed in a thermonuclear reactor.

(2) The study of the behaviour of energetic α-particles (the nuclei of helium ^4He) produced by the fusion of deuterium and tritium. In a reactor, the α-particle energy will sustain the plasma temperature.

(3) The study of methods of heating the plasma to temperatures at which in a reactor the energy released in fusion reactions would sustain the plasma.

(4) The study of the interaction of the plasma with the torus walls. This is important because the effects of impurities (driven from the walls) on the plasma and the lifetime of the walls in a reactor are still unknown factors.

(5) The study of general factors, such as plasma start-up, and plasma shaping, which are important to the viability of a Tokamak reactor.

10 Main Parameters of JET

The Tokamak design described here is the culmination of studies initiated by the Joint European Torus Working Group in 1972, and undertaken by the JET Design Team (October 1973–1975) working in close collaboration with the Associations.

The design philosophy has been to achieve the JET objectives with a machine based as far as possible on well-established engineering techniques. Within this frame-work, great attention has been paid to achieving the most cost-effective design.

- The main parameter is the plasma current which not only heats the plasma but also provides the poloidal magnetic field. Experimental and theoretical investigations have confirmed that both T and $n\tau$ increase with this current. A plasma current of 3 million amperes, in basic operation, has been chosen. This level will permit a significant scaling from earlier Tokamaks and should provide good containment of the energetic fusion α-particles.

- The level of current permitted by stability considerations depends upon the aspect ratio (R_0/a) of the torus, the strength of the toroidal magnetic field, and the size of the plasma. The most cost-effective design to meet the JET objective is found to be a fat torus with an aspect ratio of about 2.4 with a major radius of about 3 metres.

- The maximum toroidal magnetic field at the centre of the plasma which may be achieved at this aspect ratio, with low technological risk, is about 30 kilogauss.

- The toroidal field coils which have the lowest mechanical stress are D-shaped in profile and this shape has been chosen for JET. In addition this shape is a desirable feature because of the interest in investigating non-circular cross section plasmas.

The performance of JET will be increased in stages by the addition of more powerful power supplies.

Main Parameters of JET

Plasma minor radius (horizontal)	a	1.25 m	
Plasma minor radius (vertical)	b	2.10 m	
Plasma major radius	R_o	2.96 m	
Plasma aspect ratio	R_o/a	2.37	
Plasma elongation ratio	b/a	1.68	
Flat top pulse length		20 s	
Weight of the vacuum vessel		80 t	
Weight of all the toroidal field coils		380 t	
Weight of the iron core		1500 t	
		Basic	Extended*
Toroidal field coil power (peak on 13 s rise)		245 MW	380 MW
Total magnetic field at plasma centre		27.7 kG	34.5 kG
Plasma current:			
– circular plasma		2.6 MA	3.1 MA
– D-shape plasma		3.9 MA	4.8 MA
Volt-seconds available to drive plasma current		25 Vs	34 Vs
Additional heating power		4–10 MW	~25 MW

*Additional funds will be required for the extended performance. The schedule for the extension is discussed in section 13.

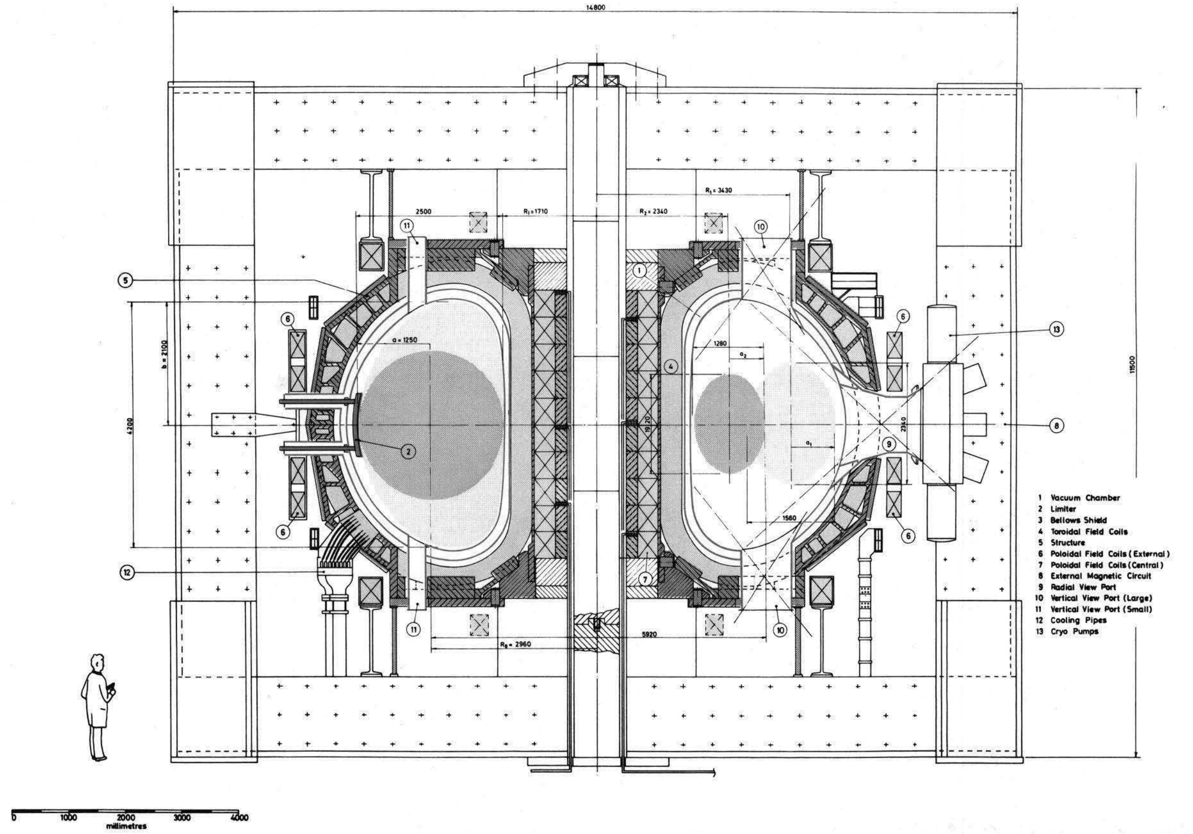
11 Description of the JET Apparatus

The general form of a Tokamak is discussed in section 7. Some general information on the components of JET is presented below.

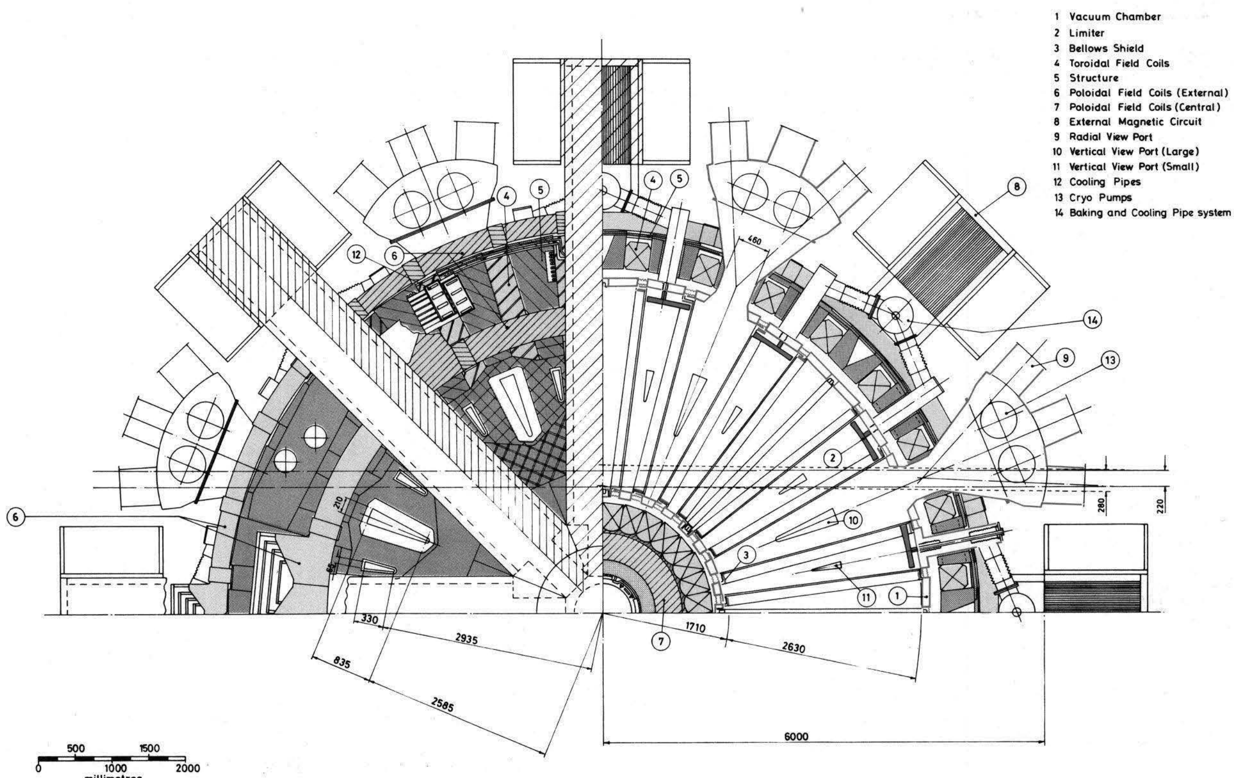
- The vacuum vessel – TORUS – is made of eight stainless steel sections, which are welded together. The total weight is 80 tonnes – see section 11.1.
- There are 32 TOROIDAL FIELD COILS made of water-cooled copper conductors, total weight 380 tonnes – see section 11.2.
- The POLOIDAL FIELD COILS are also constructed of water-cooled copper, total weight 80 tonnes. The transformer efficiency is improved by an eight-limbed IRON CORE, weight 1500 tonnes – see section 11.2.
- The POWER SUPPLIES are a combination of power from the network and motor generator flywheel sets. The initial capacity will be an average power 180 MW energy dissipated per pulse (20 s), 3600 megajoules – see section 11.3.
- ADDITIONAL HEATING will be provided by Neutral Injection, Radio Frequency Heating and Adiabatic Compression. Initially at a level of 4 MW – see section 11.4.
- The CONTROL CIRCUIT and DIAGNOSTICS will be linked by computers which will provide fast feedback control of the plasma and apparatus and will assist in analysis of the measurements between pulses – see section 11.5.

With apparatus the size of JET, changing a part or repairing a failure is a time-consuming process. Consequently special provision must be made to permit efficient assembly and dismantling and components must be reliable, thus

- The design of the apparatus is modular
- Large single units are made from sets of identical smaller components, suited to serial production.
- The poloidal field coils are outside the toroidal field coils eliminating undesirable topological links.
- Only essential parts have been retained on the apparatus itself; wherever possible, auxiliary equipment has been kept outside the torus hall.



The JET Apparatus – Elevation



The JET Apparatus – Plan

11.1 VACUUM SYSTEM

In order to minimize the plasma loss arising from interactions with background gas particles, the plasma is contained in an ultra-high vacuum system.

The JET vacuum chamber is composed of a series of box sections joined together with thin flexible bellows, the whole made of high nickel content stainless steel. This structure is able to withstand the forces of atmospheric pressure, 20 tonnes on each of the 32 rigid sectors, and those associated with the currents induced during the rise of the toroidal magnetic field, an additional 10 tonnes per sector.

The inner walls of the vacuum chamber must be extremely clean (a base pressure of 10^{-10} torr is specified) to minimise the level of impurities released from it. This is obtained by using a completely welded structure, which may be baked to 500°C to remove gas from the walls. Discharge cleaning by bombardment with low energy plasma particles will also be used.

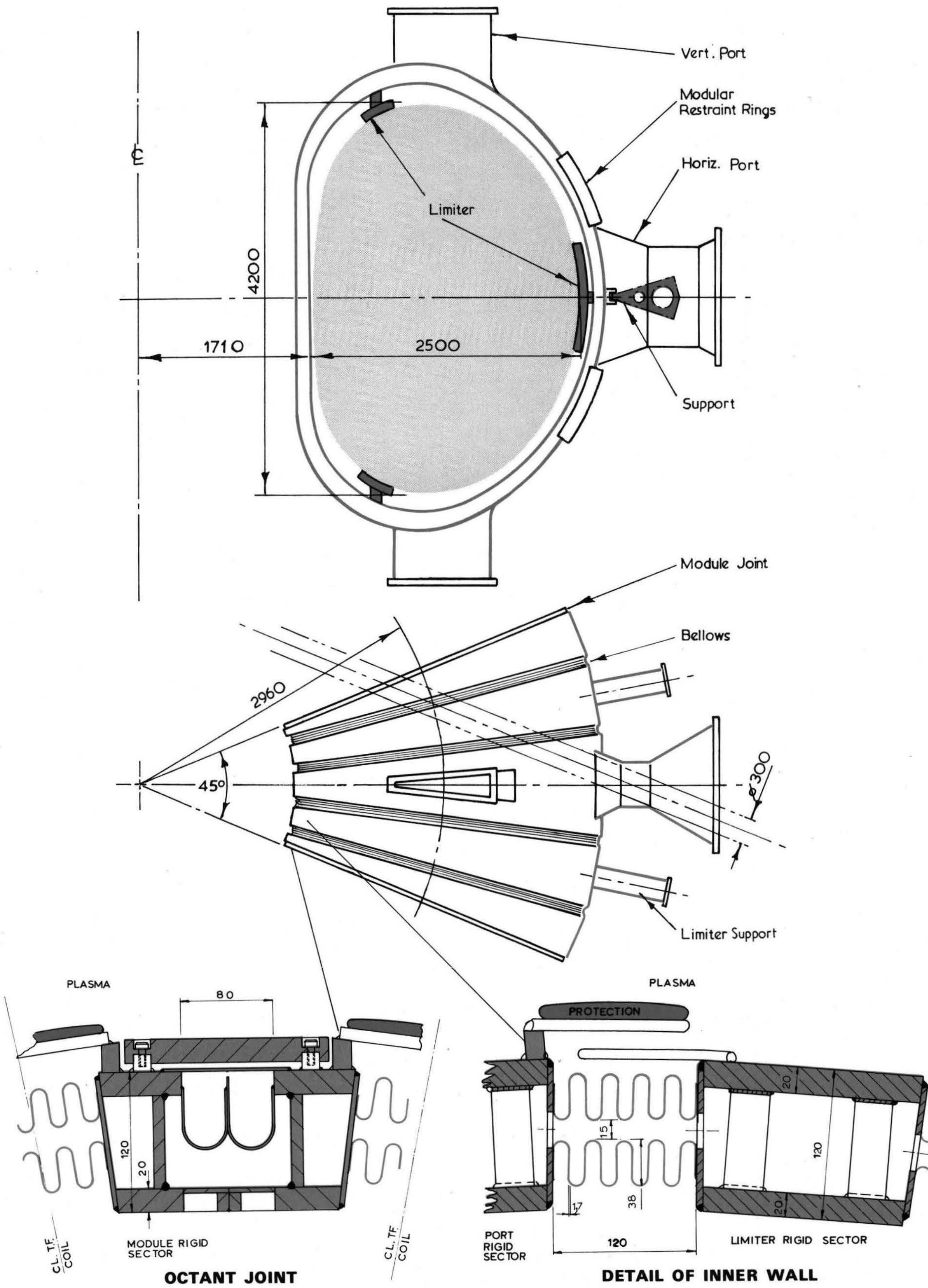
The chamber is in eight sections, and the welds between sections are designed to be easily opened to facilitate remote handling.

From an electrical viewpoint, the vacuum vessel must not short-circuit the plasma. The bellows sections are included in order to increase the electrical resistance to a level high compared to the resistance of the plasma.

A series of protective shields prevents the plasma from touching the bellows. In addition, a series of plates a few centimetres inside the plasma wall defines the plasma boundary: these are known as LIMITERS. Various materials, with good thermal properties, ranging from tungsten and molybdenum to ceramic compounds of boron and carbon are being investigated for use as limiters.

Access to the plasma for additional heating and diagnostics is provided by large radial and vertical ports in the same radial plane.

The high vacuum is obtained by using turbo-molecular pumps for the initial pumping and liquid helium cryopumps for the pumping to very low pressure (high vacuum).



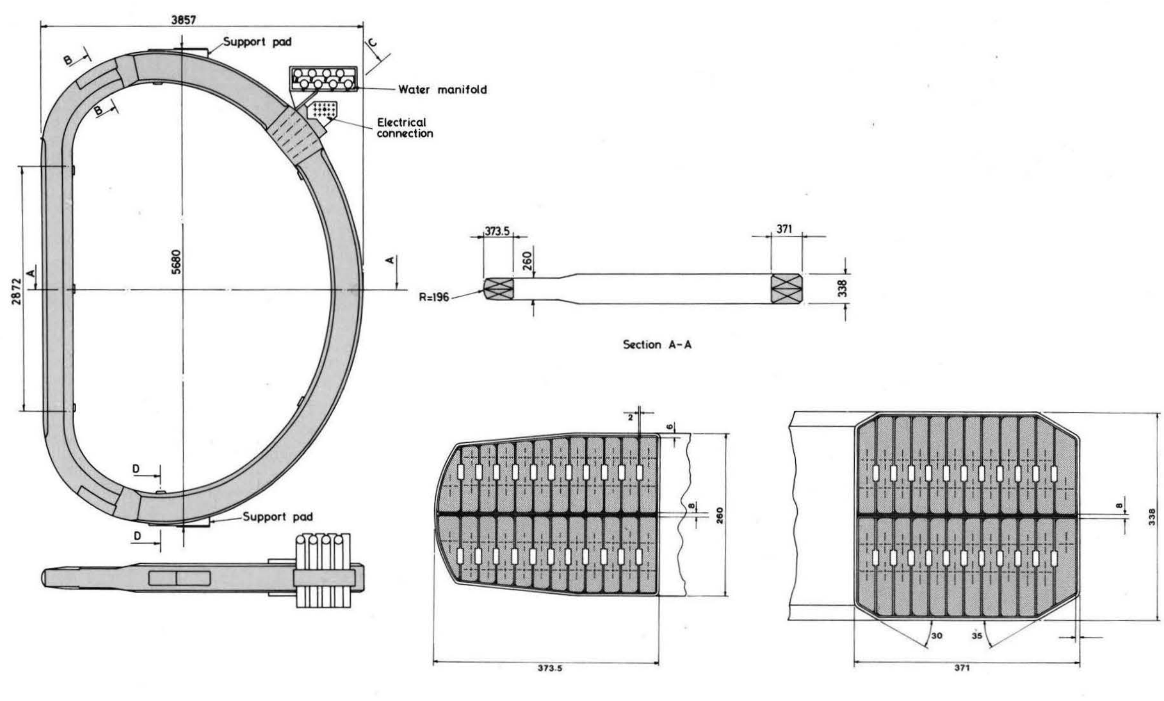
General Lay-Out of the Vacuum Vessel Octant

11.2 MAGNETIC FIELD SYSTEM

TOROIDAL FIELD SYSTEM

The toroidal magnetic field is produced by 32 D-shaped coils which link the torus. These water-cooled copper coils produce a toroidal magnetic field of about 30 kilogauss at the plasma centre. The field will be maintained for about 20 seconds, in each pulsed operation of the machine.

The shape of the coil is one which minimises the mechanical stresses. A mechanical structure supports these coils against the forces arising from the interaction of the poloidal and toroidal field systems. The centering force of 1800 tonnes per coil is supported by the central column.



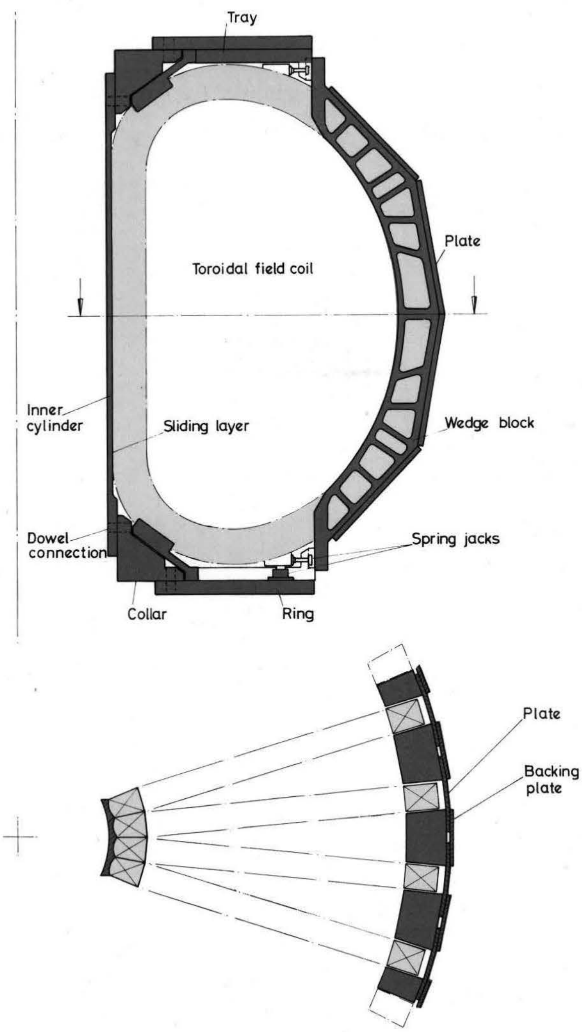
PARAMETERS OF ONE TOROIDAL FIELD COIL

Overall height	5.68 m
Overall width	3.86 m
Weight	12 t
Copper cross-section per turn: (average)	
inner part of coil	2700 mm^2
outer part of coil	3900 mm^2
Insulation thickness between turns	2 mm
Insulation thickness between pancakes	8 mm
Ground insulation thickness	6 mm

PARAMETERS OF THE TOROIDAL FIELD SYSTEM

Total resistance before a pulse (25° C)	61 mΩ
Total resistance after a pulse	67 mΩ
Total inductance	0.66 H
Inductance of one coil alone	4.4 mH

		Basic performance	Extended performance
Total Ampere turns	(MA)	41	51
Magnetic field at R_o = 2.96 m	(kG)	27.7	34.5
Nominal current	(kA)	53.4	66.4
Peak voltage (for adiabatic compression)			
between turns	(V)	12	12
between pancakes	(V)	288	288
versus ground	(kV)	±4.6	±4.6
Resistive power	(MW)	175	270
Equivalent square wave pulse duration	(s)	30	20
Energy dissipated per pulse	(GJ)	5.3	5.4
Magnetic energy stored	(GJ)	0.94	1.45



Mechanical Structure Design

The poloidal field coils mounted outside the toroidal field coils, have two main functions:

(a) To act as the primary windings for the transformer, of which the plasma is the secondary winding. This is the primary function of the coils wound around the iron core.

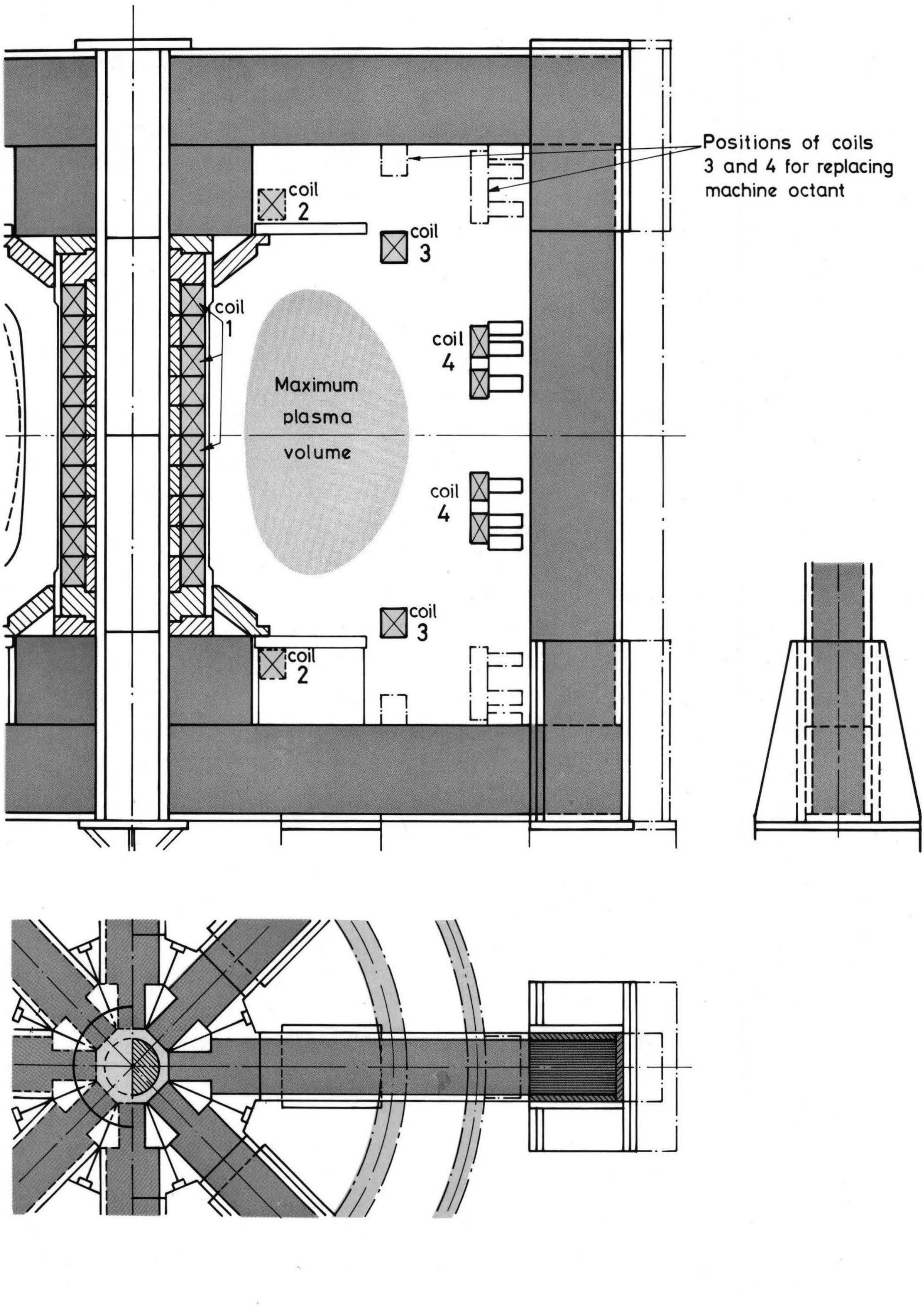
(b) To shape, position or compress the plasma. These are the primary functions of the coils wound around the outer part of the system.

A secondary function of these coils is to act like a copper shell and through induced eddy currents to suppress rapid motion of the plasma.

The addition of the massive iron core, with its eight return limbs, improves the efficiency of the transformer coupling and keeps to a minimum the power supplies required for establishing and maintaining the plasma current. In addition the return limbs give a significant reduction in the magnetic field outside the apparatus (stray field). This latter function is extremely important for the neutral injection and diagnostic systems.

Poloidal Field Coils – Physical Parameters and Performance Data

Coil Type No.		1	2	3	4
Designation		Inner	Inner	Outer	Outer
Conductor cross section (C.S)	mm× mm	44 × 44	44 × 44	29 × 29	29 × 52
Cooling hole diameter	mm	15	15	12	12 × 22
Mean diameter of coil	m	1.81	4.3	7.88	10 49
Total C.S. area including insulation	m^2	0.157	0.161	0.174	0.227
Total C.S. area of copper	m^2	0.111	0.093	0.087	0.122
Weight of copper/coil	t	5 7	10	20.2	35 9
Weight of insulation/coil	t	0.4	1.2	2.8	4.2
Number of coils required		10	2	2	2
Max. current density in copper	MA/m^2	19.3	19.3	1.62	10.2
Max. current/conductor	kA	34	34	11.8	13
Effective pulse length	s	20	20	20	20
Adiabatic temperature rise	°C	40	40	31	12
Total water flow l/s (all coils)		24.5	5.6	55.2	90.2
Max. voltage between terminals of each coil	kV	8	7	20	20
Max. voltage to earth	kV	20	20	20	20
Max. hoop stress in copper	kg/mm^2	5.9	–	0.67	2.0
Max. external pressure	kg/mm^2	3	0	0	0
Max. axial force/coil (magnetic)	t	1500	–	220	100



General Arrangement of the Poloidal Field System

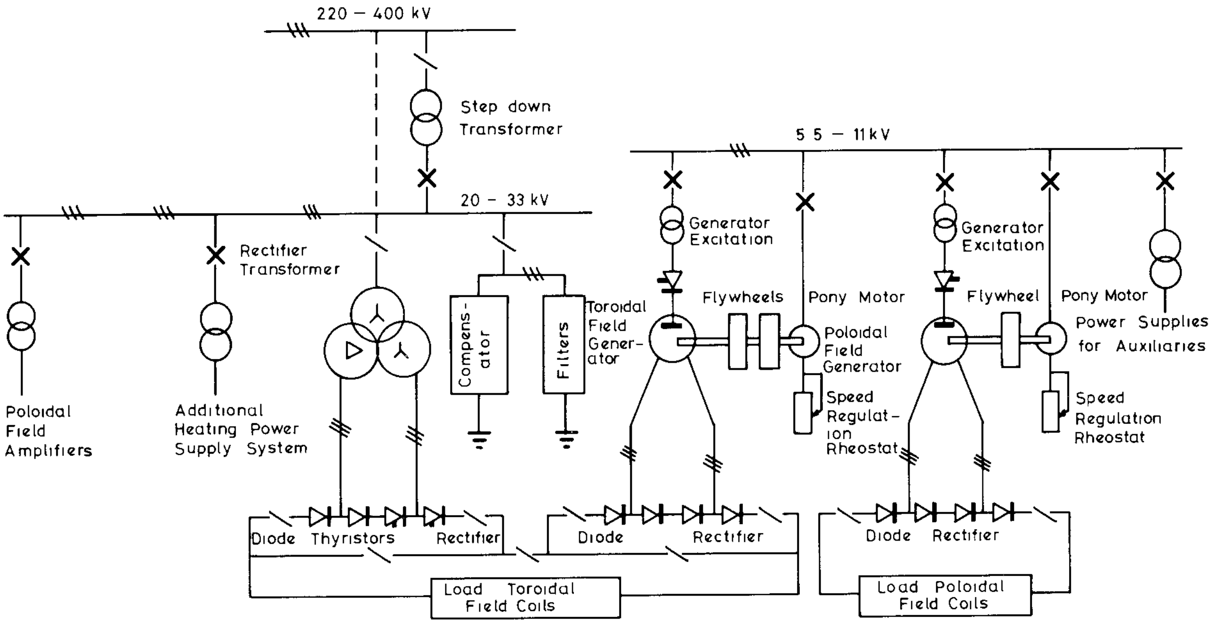
11.3. POWER SUPPLIES

JET will operate in a pulsed mode, with a pulse length of up to 20 seconds, every 5 to 15 minutes. During this short pulse, very large peak electrical powers are required. It is proposed that the multi-megawatt pulses should be provided by a combination of power from the local network (static system) and from motor generator flywheel sets. The precise distribution between these alternative sources depends upon the site chosen for JET. An indication of the general form of the supplies is given in the figure below.

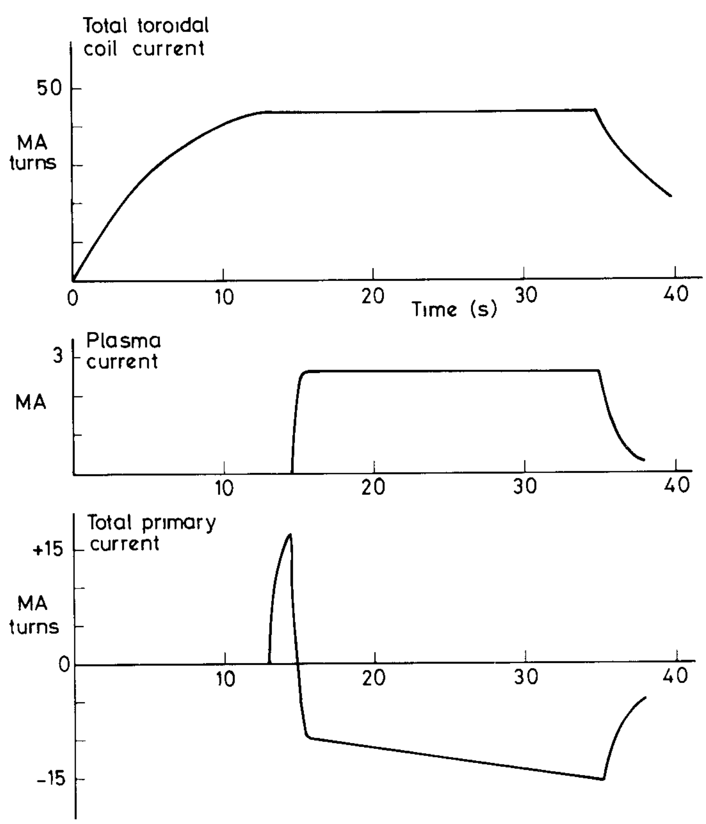
> *The toroidal field system* is supplied through a combined scheme made up of a static unit which supplies up to 80% of the energy and a motor generator set which supplies up to 60% of the power. The energy stored in the coils will be 940 to 1450 megajoules* and the energy dissipated during the constant field period (20 seconds) 3600 to 5600 megajoules*. The average power applied will be 180 to 280 megawatts*.

> *The poloidal field system* is supplied by a motor generator set which provides a high voltage at the pulse start (zero current) and a high current at lower voltage subsequently. The amount of energy per pulse is about 1/5 of that in the toroidal system. The maximum power will be 160 to 230 megawatts*, to be applied in slightly less than one second. An indication of the time variation of currents is given in the schematic diagram opposite.

*The ranges reflect the extension from basic to extended performance (see section 10).



Jet Main Power Supply Scheme



Time variation of representative plasma
and coil currents

11.4 ADDITIONAL HEATING SYSTEMS

The initial heating in JET is provided by the ohmic heating of the toroidal current. This should raise the temperature to the region of 10 million degrees. A problem with this method of heating is the way in which the plasma resistance decreases as the temperature rises, while the losses, owing for example to radiation, increase.

To achieve the objectives of JET and make full use of the great flexibility of the apparatus, the ohmic heating will be supplemented by additional heating.

The methods used will be those discussed in section 6.

- NEUTRAL INJECTION. Hydrogen nuclei will be accelerated up to 80 000 volts and then converted back to atoms in a neutraliser. These atoms cross the confining magnetic field and transfer their energy to the plasma. Deuterium atoms at energies up to 160 000 volts will also be used.

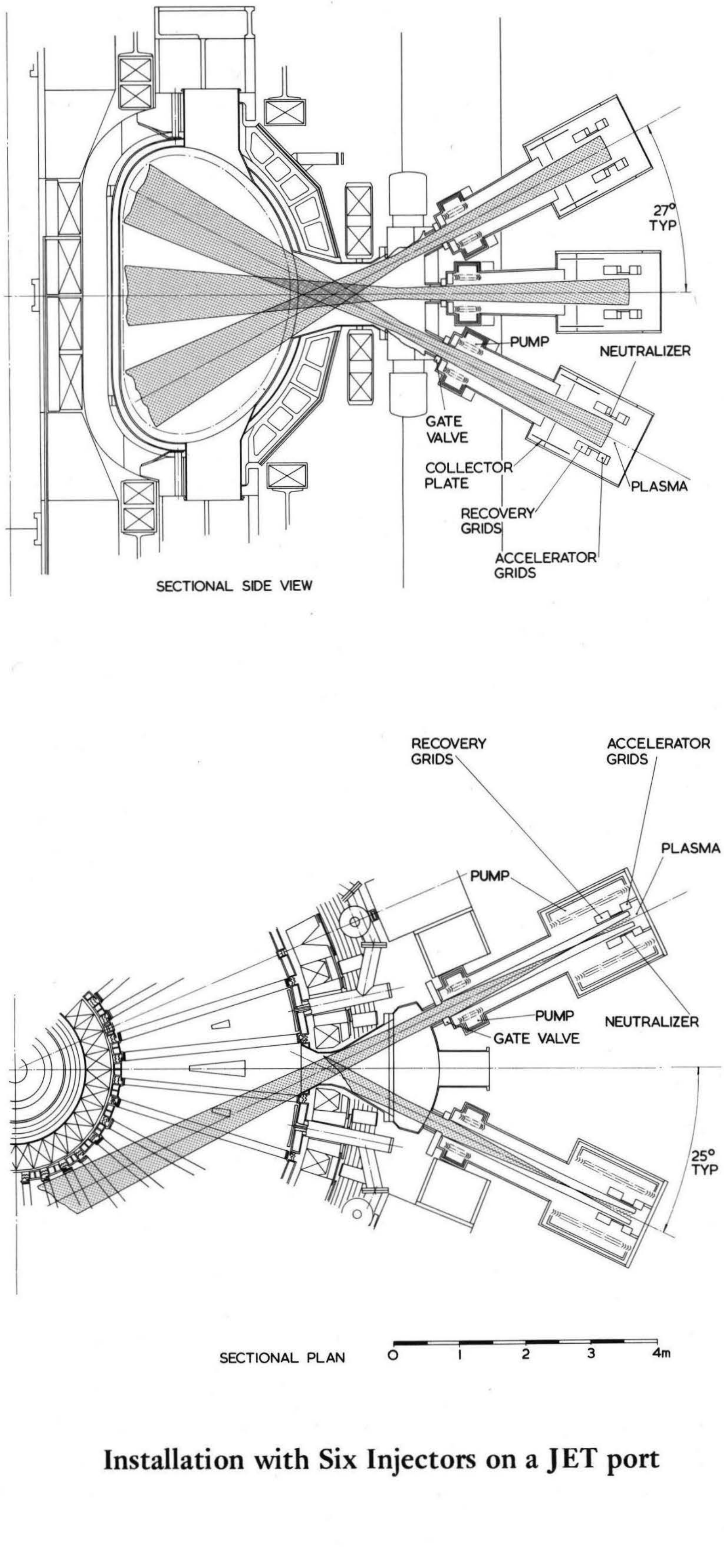
- RADIO FREQUENCY HEATING. Use will be made of the resonances at the 'Lower Hybrid Frequency' (about 1000 MHz) and the region of oscillatory frequency of the ions in the magnetic field 'Cyclotron Frequency' (about 5 to 50 MHz).

- ADIABATIC COMPRESSION. The plasma will be started in the outer region of the torus, and will be preheated by injection or radio frequency heating. It will then be moved rapidly to the inner part of the torus where the toroidal field is stronger. The resultant compression will heat the plasma.

On present experiments significant temperature rises, more than 2 million degrees, have been obtained with these methods using about 100 kilowatts of power.

On the larger JET plasma relatively more power will be needed and 4 megawatts of heating will be applied initially. This will subsequently be raised in stages to 10 and then 25 megawatts. These power levels should raise the plasma temperature to more than 50 million degrees.

- The power supplies, initially with 25 megawatts capacity (finally about 50 megawatts) will be constructed of a number of units, each of about 60 000 volts. These units will be stacked to provide the range of voltages, up to about 200 000 volts required by the various heating methods.



Installation with Six Injectors on a JET port

11.5. DIAGNOSTICS and CONTROLS

The main control of the apparatus will be on a preset basis, with some measure of self-adjustment in the circuits. However, the fine control and operation in the event of a fault will be directed from the analysis of measurements made on the apparatus and plasma.

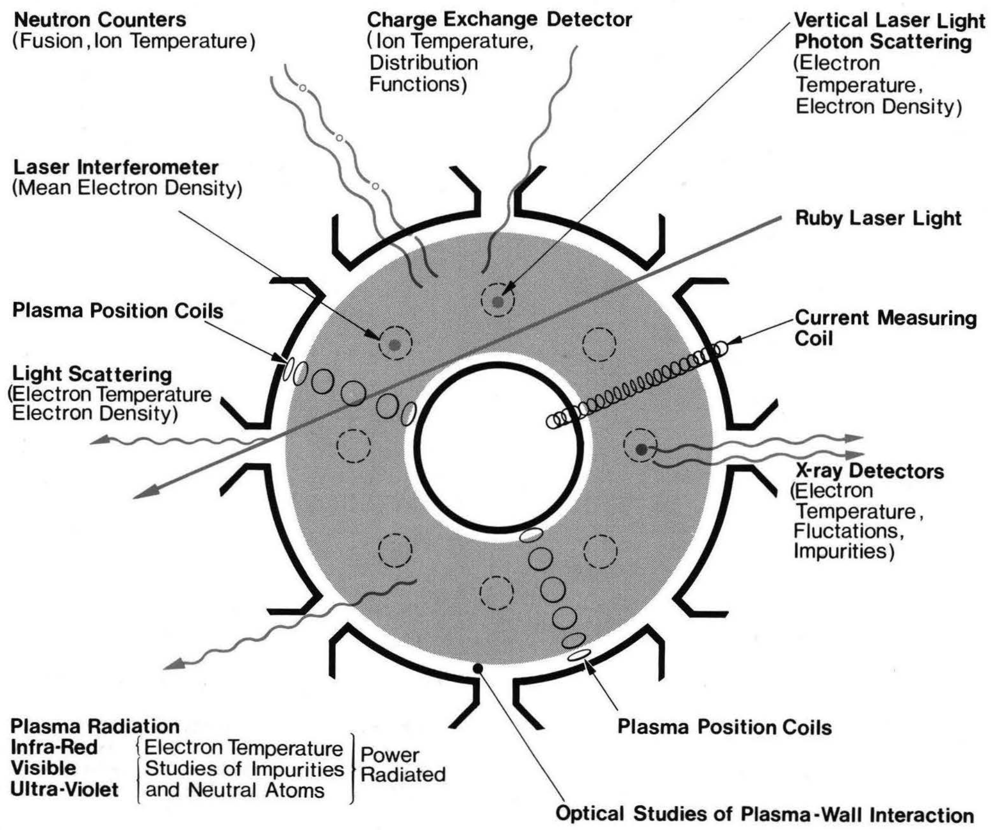
On the apparatus, voltages and currents, the hydrogen gas pressure, stresses and temperatures in the coils and vacuum vessel, and the cooling water flow will be measured.

On the plasma, the current, voltage around the plasma, the plasma position and shape, density, temperature, radiation and impurity level will be measured. Material diagnostic probes may not be used because the hot plasma will damage them and they in turn will contaminate the plasma. Consequently the measurements depend upon detecting the external effects of the plasma.

Passive diagnostics involve:

Radiation. X-rays, ultra-violet, visible, infra-red and microwave radiation emitted by the plasma will be analysed.
Particles. Charge-exchanged atoms and neutrons released by fusion will be studied.
Fields. The changes in electric and magnetic fields will be analysed.

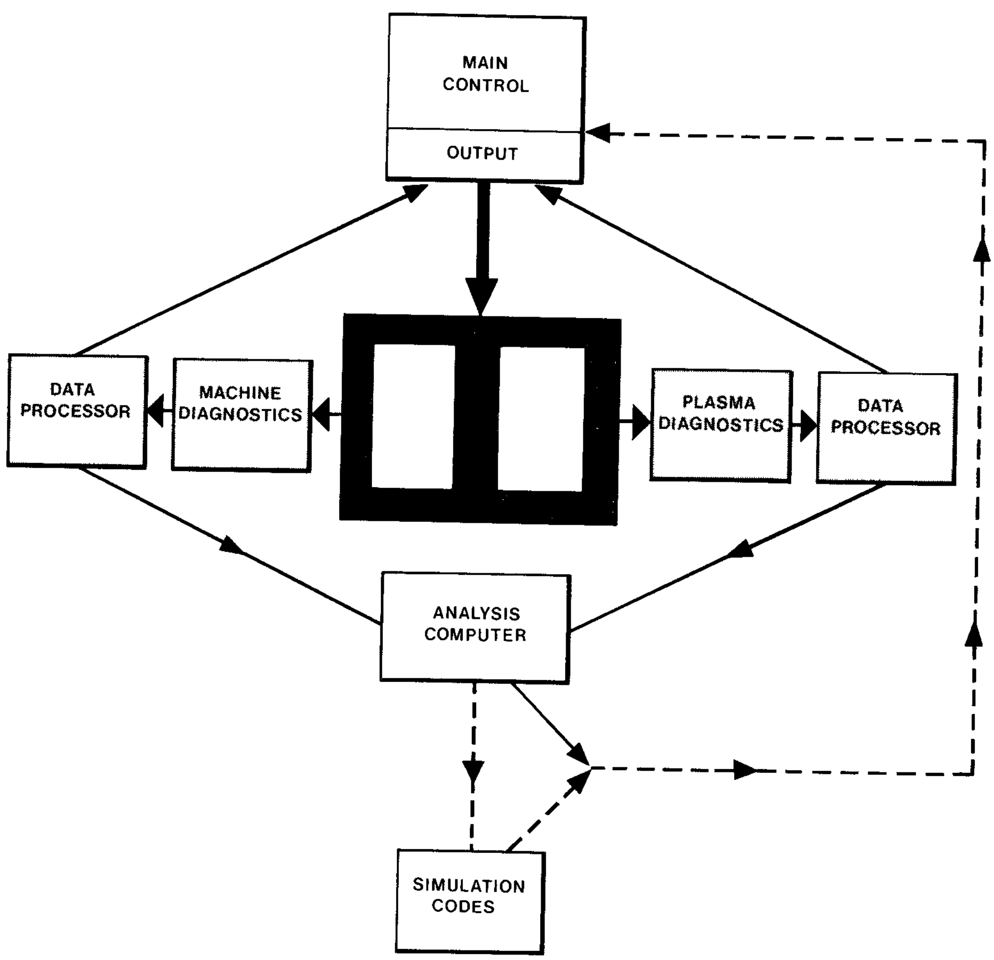
Active diagnostics include the study of laser beam light scattered by the plasma and the study of beams of atoms fired into the plasma.



Diagnostics

All this information will be handled by data processing units (including computers). This will be done on a fast enough time scale, that action can be taken to prevent damage (as for example if a coil overheats), or to adjust the plasma position to reduce the heat loading on the limiters. On a slightly slower time scale, the data from a pulse will be analysed so that there is time to consider the implications for subsequent pulses.

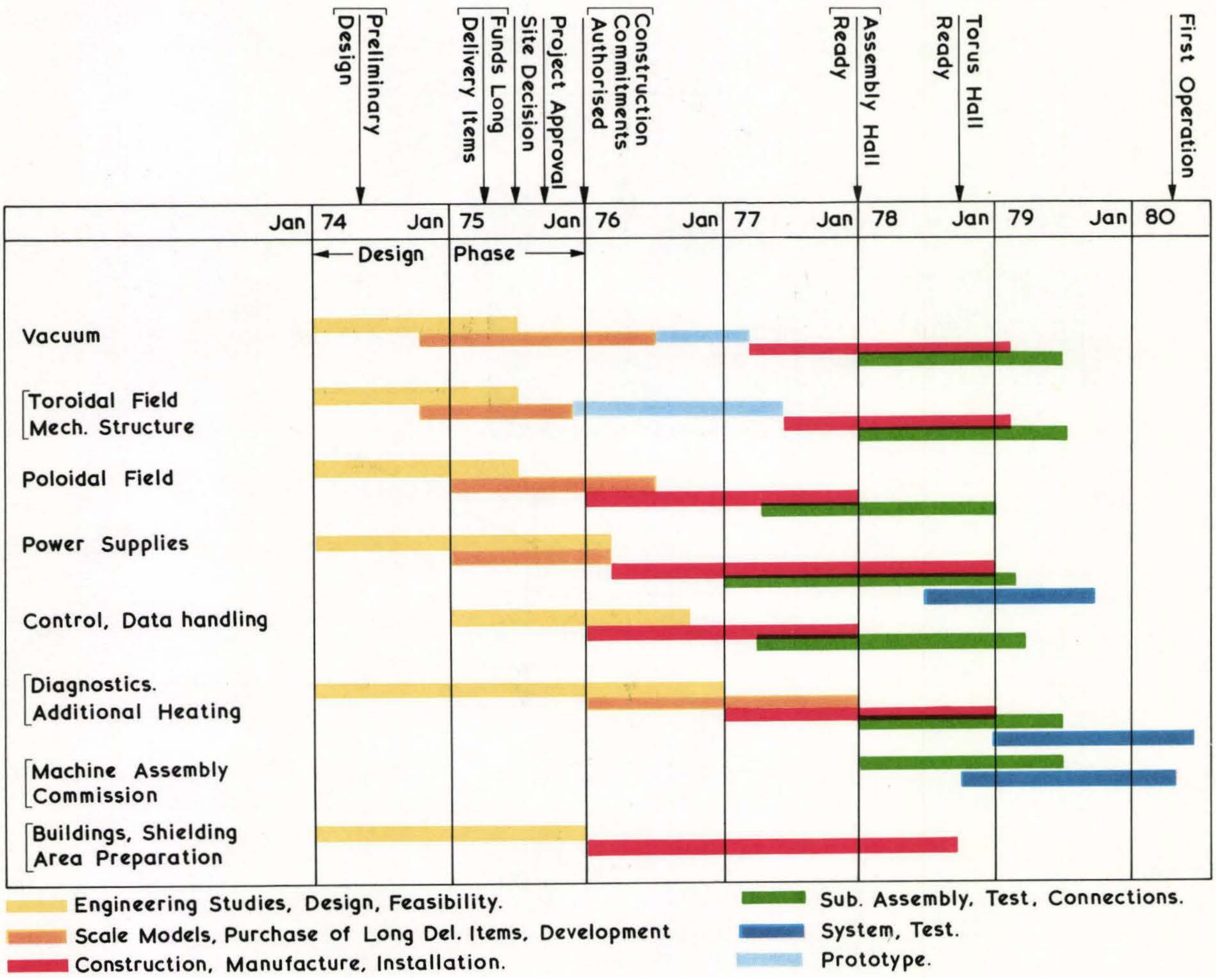
In addition, this data will be introduced into computer programs that simulate the plasma (make a mathematical model of the plasma.) This allows values to be inferred for parameters that are not measured and checks the self-consistency of the data.



12 JET Construction Phase

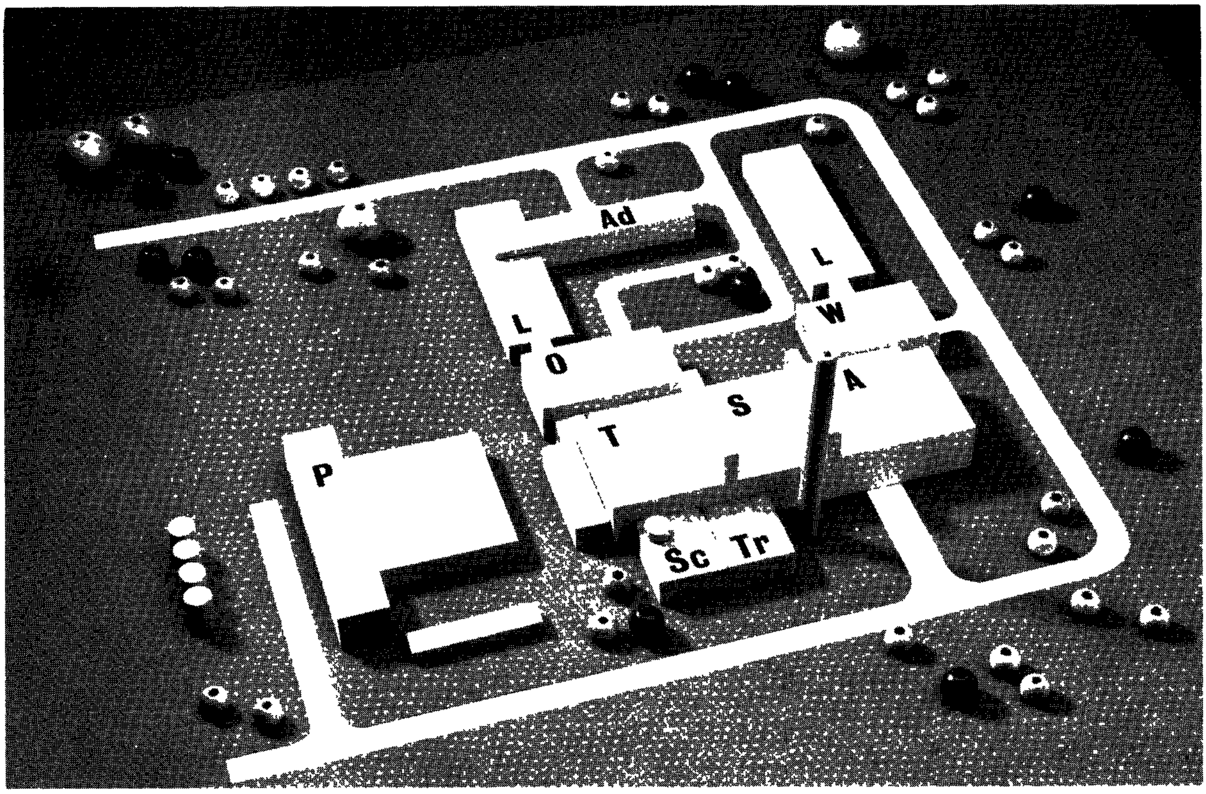
- The Construction Phase of JET should start in 1976 and will continue for a period of about five years. Some design work will of course continue during this phase and some aspects (modification, preparation for the operation with tritiun) will extend into the Experimental Phase. The time scales involved for the various components are shown in the time bar chart.

- The Experimental Phase will start in 1980 provided that decisions concerning the site and the build-up of the Construction Team can be taken before the end of 1975.



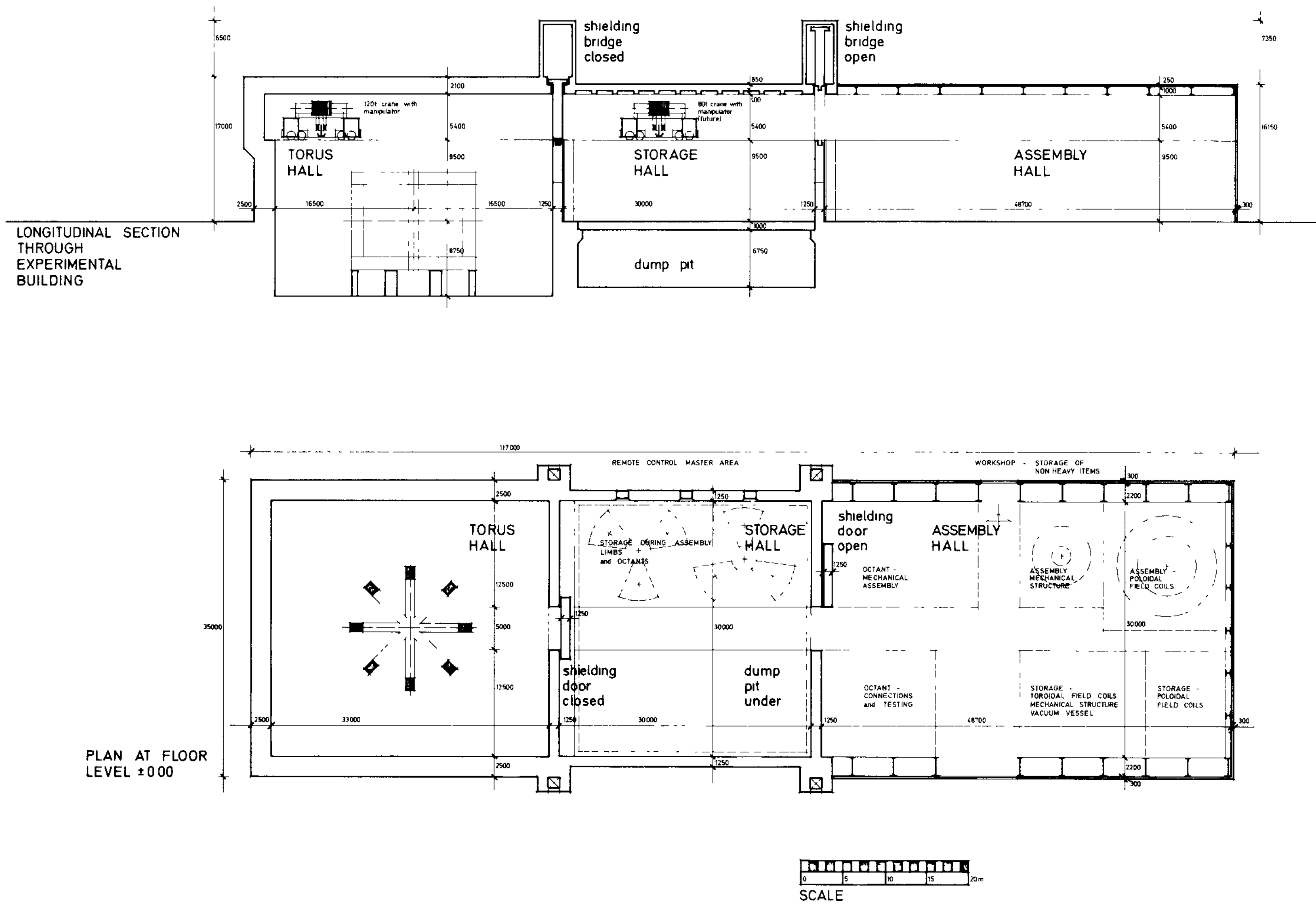
Time Bar Chart for JET

- An overall view of a possible site layout is shown below. More detailed drawings of the Experimental Buildings are shown overleaf.



A	Assembly Hall	S	Storage Hall
Ad	Administration Support	Sc	Support Cell
L	Laboratories	T	Torus Hall
O	Operations Wing	Tr	Tritium Room
P	Power House	W	Workshop

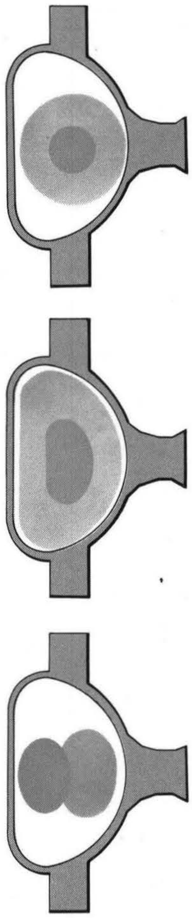
Possible JET Site Layout



Possible Experimental Building Section and Plan

13 JET Experimental Program

A significant feature of the JET design is the flexibility, which permits the use of a wide range of plasma configurations and modes of operation, with large current (greater than 1 million amperes) and large radius (greater than 0.5 metres). This will play an important role in the making of the studies described in section 9. There are two basic modes, one involving a fixed plasma shape, the other involving the major radius compression of a reduced size plasma. In both modes a wide range of configurations, involving circular or elliptical (D-shaped) cross section plasmas, are possible as illustrated.



As a general strategy it is intended to realise the objectives by a program of phased exploitation. This is described below and summarised in the table.

Outline of Experimental Program

1980 1981	1982 1983	1984
Phase I: Exploratory Studies	† Phase II: Improvement of Plasma Performance	Phase III: Fusion Studies
• establish a range of operating conditions • scaling studies • work up to maximum plasma current for installed power supplies including use of D-shaped cross-section • examine additional heating • investigate impurity effects • establish limits of operation • decide on future power supplies • decide whether the divertor is needed	(some of the following will be attempted) • extend power supplies • examine heating methods using internal structures • increase heating power • fit divertor if necessary • try new limiter or wall materials	• attempt fusion experiments (a) non-Maxwellian beam-plasma methods, maybe with compression (b) self-heating if possible

† if results from Phase I are extremely favourable

Phase I Exploratory Studies.

This phase will begin in the final stages of the machine commissioning to establish operating regimes at low plasma currents. Over a period of months the plasma current will be raised to the 3 million amperes level and non-circular plasmas will be studied. A decision will then be taken as to whether to order further power supplies for later phases of operation.

- The experimental results will be compared with the predictions of plasma simulation computer codes, which in turn should indicate optimum regimes of operation.

- A range of heating methods including neutral injection, radio frequency heating and adiabatic compression will be assessed.

By the end of the phase the possible range of parameters – density, temperature, containment time, etc., for the available power supplies and heating methods, will have been established.

Phase II Improvement of Plasma Performance.

The program for this phase will depend on the outcome of Phase I. At one extreme, if very favourable plasma parameters are obtained it will be possible to go directly to Phase III; at the other extreme, Phase II will contribute the bulk of the experimental program and will involve the exploration of heating and impurity control for future experiments.

It may be necessary to enhance the power supplies or to install a modified vacuum vessel for impurity control. For example, a special wall might be introduced or an additional field system (divertor) to divert impurities away from the plasma might be added.

Phase III Fusion Studies.

The object of experiments in this phase will be to establish the behaviour of plasmas which include a significant level of 'fast' particles produced by fusion reactions in the plasma. The heating, diffusion and pressure of the fast fusion particles will modify the plasma equilibrium.

Discharges with appreciable fusion power generation may be produced with plasma temperatures greater than 50 million degrees. The fusion reactions take place in collisions involving the more energetic plasma nuclei. Alternatively they may be produced by injecting the energetic particles, by neutral injection, into a lower temperature plasma, e.g. by the injection of energetic deuterons (160 000 volts) into a tritium plasma, or into a plasma of ^3He.

Except in the case of deuteron injection into a ^3He plasma there will be a large release of neutrons and the consequent activation problems will severely restrict access to the machine and may well limit operation to only a small number of discharges. Consequently the experimental program for this phase will have to be very carefully planned so that the maximum information is obtained from each discharge.

Method of Working.

JET is planned to be the principal Tokamak in the Euratom Fusion Program from 1980 onwards. Clearly the success of the experiment will depend on the active support of scientists in the Associations. It is foreseen that the JET experiment, carried out as a joint venture of the Associations, will benefit from many individual investigations carried out by teams of scientists visiting the JET site for periods of several months, using equipment developed in their own laboratories. Such work has already begun in the field of plasma heating. During the operating phase it is foreseen that the JET project will involve the following:

- A European Program Committee to determine the general line of experiments and the relative priorities.

- A resident European JET Team; (1) to run the experiment, (2) ensure program continuity, (3) collect, interpret and distribute the data obtained on JET, and (4) take responsibility for maintenance, safety and to undertake modifications to the apparatus.

- A formal body to certify the acceptability and safety of equipment proposed for use on JET.

- A number of Visiting Teams of Specialists from the Associations to develop and use specialist dignostic techniques.

- Theoreticians on site and in their own laboratories working on problems relevant to JET.

14 European Collaboration in Fusion Research

Fusion research started around 1950 in a number of European countries. Cooperation between these countries was initiated first through exchanges of information. As the work progressed, the true European dimensions of the program were appreciated and the advantages to be gained from sharing the effort became apparent, a closer collaboration was sought.

The first European 5-year program for Plasma Physics and Fusion Research was a part of the initial program, when in 1958 the European Atomic Energy Community (EURATOM) was established. This has since been followed by a number of pluriannual programs, adopted by the COUNCIL of the European Communities on the proposal of the COMMISSION of the European Communities.

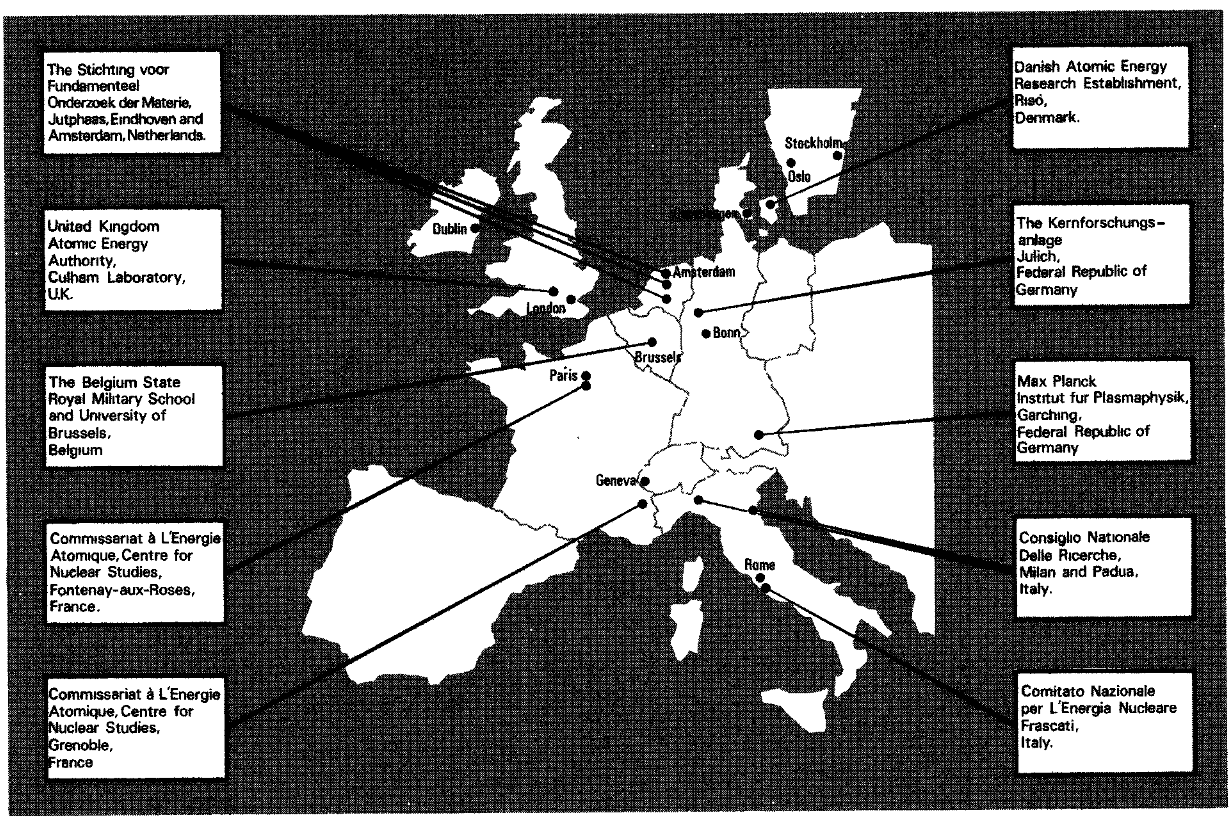
According to the EURATOM Treaty the Commission is responsible for the implementation of the program. The Commission decided that, given the existence of the national programs, the goal of a united European Fusion Program could most readily be achieved through CONTRACTS OF ASSOCIATION with the laboratories already existing or being built up.

Finally, in adopting the present 5-year program the COUNCIL decided that the program should be part of a long term cooperative project embracing all work carried out in the Member States in the field of Fusion and Plasma Physics. It is designed to lead in due course to the joint construction of prototypes with a view to their industrial scale production and marketing.

Up to now, the Commission has concluded such contracts with:

AEK	– The Atomenergiekommissionen Denmark (Laboratory at Risø).
CEA	– The Commissariat à l'Energie Atomique (Laboratories at Fontenay-aux-Roses, Saclay and Grenoble).
CNEN	– The Comitato Nazionale per l'Energia Nucleare (Laboratory at Frascati).
CNR	– The Consiglio Nazionale delle Richerche (Laboratories at Milan and Padua).
EB	– The Etat Belge (Laboratories of the Ecole Royale Militaire and the University of Brussels).
FOM	– The Stichting voor Fundamental Onderzoek der Materie (Laboratories at Jutphaas, Amsterdam and Eindhoven).
IPP	– The Max-Planck-Institut für Plasmaphysik (Laboratory at Garching).
KFA	– The Kernforschungsanlage Jülich GmbH (Laboratory at Jülich).
UKAEA	– The United Kingdom Atomic Energy Authority (Laboratory at Culham).

Fusion Research in the European Community



The subject matter of each individual Contract of Association, a pluriannual program, is agreed after discussion in the COMMITTEE OF DIRECTORS and a recommendation of the LIAISON GROUP to the Contracting Parties. These programs form part of a Community-wide long term collaboration with the aim of the joint construction of large experimental facilities.

The execution of these programs is supervised by the STEERING COMMITTEE of the individual Association.

In the framework of these contracts the Commission contributes to the expenditure of the Association by about 24% (or about 44% for certain experiments of priority interest), participates through representatives in the different management boards in the preparation and execution of the programs and seconds scientists to the laboratories for collaboration with the national staff.

A contract concerning the important exchange of personnel (MOBILITY CONTRACT) allows national laboratories to second their staff to other national laboratories, the costs of these secondments being reimbursed by the Commission.

The program is open to cooperation with countries outside the E.E.C., in particular other European countries. In this respect negotiations for cooperation with Sweden are well advanced.

14.1. EUROPEAN COLLABORATION IN THE JET DESIGN

HISTORY

Encouraging results with various relatively small Tokamaks have led to proposals for large Tokamak facilities, to extend the parameter range close to the conditions needed in a thermonuclear reactor. It soon became clear that the realisation of such a machine would involve large personnel and financial requirements, and would best be achieved by a joint effort of the Partners.

After preliminary discussions in the Tokamak Advisory Group in 1971 the Liaison Group set up a JOINT EUROPEAN TORUS WORKING GROUP to prepare various design concepts and compare them from the point of view of technology, cost and construction time. On the basis of this work the Liaison Group in 1973 recommended the setting up of a Team to design a 3 MA Tokamak.

LEGAL BASIS

The basis for the realisation of the JET Design was a PROGRAM DECISION of the Council of the European Communities in 1973, incorporating the JET Design Project into the presently running 5-year-program.

In implementation of this decision a JET DESIGN AGREEMENT covering the Design Phase from October 1973 to December 1975 was concluded between the PARTNERS, that is between the contracting parties of the Association Contracts.

The MOBILITY CONTRACT was amended in order to take into account the specific requirements of the JET Design Phase.

ORGANISATION

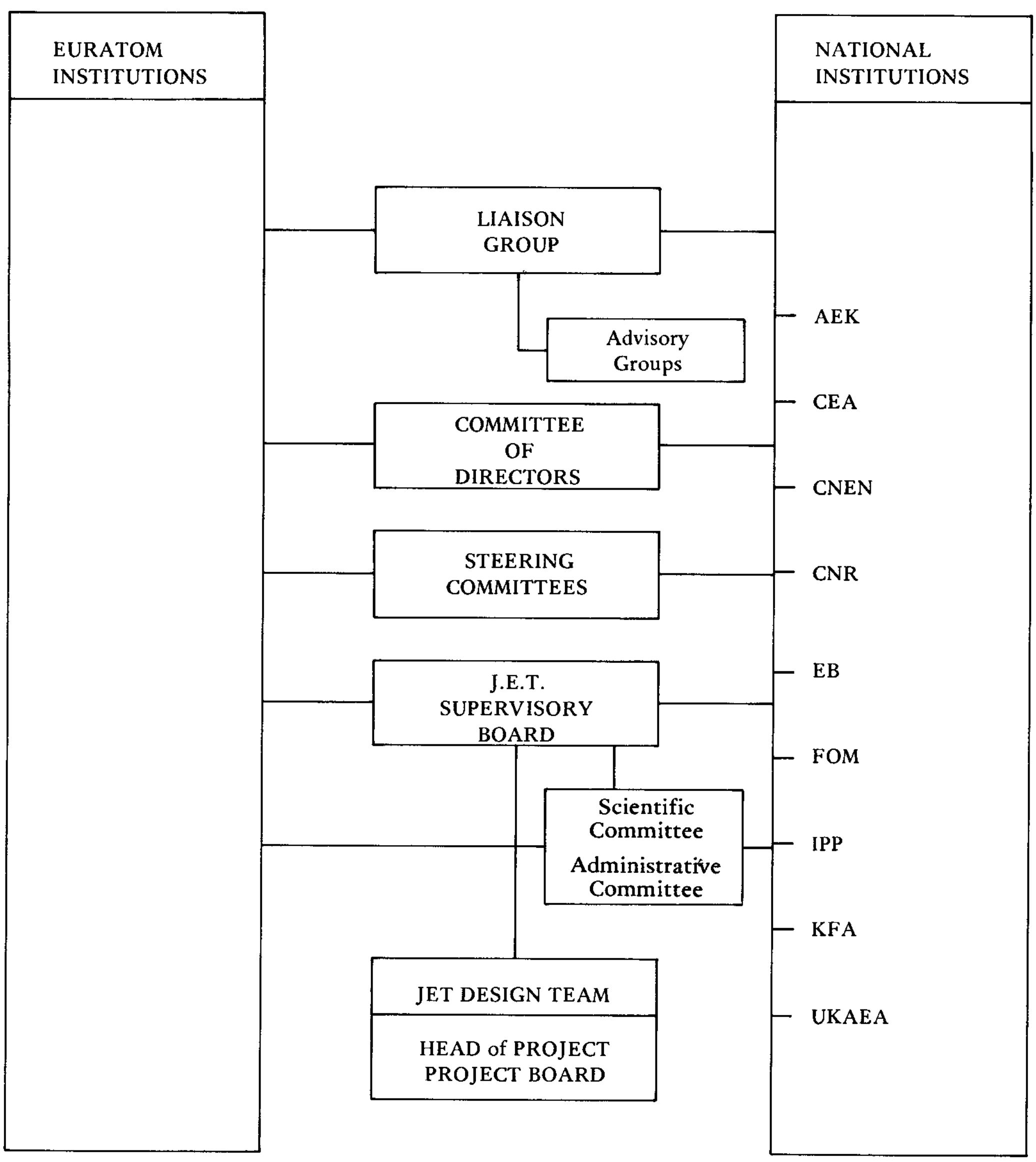
Within the framework of the overall organisation of European collaboration in Fusion Research the Partners set up a SUPERVISORY BOARD which represents all the Partners and ensures on their behalf the proper implementation of the Design Agreement. This Board has approved secondments of the Head of Project, of the Administrator, set up a Project Board and decided the staff strength of the Design Team. In close contact with the Committee of Directors the Board decides between the main technical options for the Design proposed by the Head of Project and approves contracts above 50,000 U.C.

The Board is assisted by a Committee for Scientific and Technical matters as well as a Committee for Administrative matters, both of which advise the Board.

The execution of the program agreed upon in the Design agreement was assigned by the Partners to a JET DESIGN TEAM, which was set up in October 1973 and centred at the UKAEA Culham Laboratory acting as host laboratory.

The Team is directed by a HEAD OF PROJECT who is responsible to the Supervisory Board for the execution of the work and who has power of decision for any operation required for the implementation of the work except where the Design Agreement specifies otherwise.

The implementation of the successive stages of the work as well as contracts up to 50,000 U.C. are approved by a PROJECT BOARD, composed of the Head of Project and five Group Leaders.



THE FUNDS FOR DESIGN

The following funds necessary for the implementation of the JET Design Project are provided by the JET Design Agreement and the Mobility Contract as upper limits:

TYPE OF EXPENDITURE	Total Ceiling (MUC*)	Commission Share	Association Share
NATIONAL STAFF: SALARIES	1.2	0.3	0.9
EXPATRIATION ALLOWANCES, etc., travel of JET team members	1.25	1.25	–
EURATOM STAFF	0.3	0.3	–
CONTRACTS WITH ASSOCIATIONS to execute specified work required for JET	3	1.32	1.68
CONTRACTS WITH THIRD PARTIES (Industry, etc.) to execute specified work or to supply certain long delivery items	3	3	–
HOST LABORATORY EXPENSES	0.45	0.34	0.11
	9.2	6.51	2.69

* MUC = Million Units of Account.
1 Unit of Account equals 50 Belgian Francs.

THE WORK OF THE DESIGN TEAM

The Design Team, internationally composed and supported by Host Laboratory staff, is organised in 7 groups as shown in the introduction.

In November 1973 the Team issued an outline design and first set of dimensions in the Report 'Preliminary Description' (EUR-JET-R1), followed in April 1974 by the Report 'First Project Proposal' (EUR-JET-R2) and in July 1974 by a first cost estimate for the project (EUR-JET-R4).

On the basis of a positive response from the JET Supervisory Board and after discussion in the Committee of Directors and the Liaison Group the Partners accepted the JET parameters outlined in EUR-JET-R2 and the cost estimates contained in EUR-JET-R4 as a basis for continuing design.

By June 1975 the final report required by the JET Design Agreement (EUR-JET-R5) was issued. The work of the Team as well as the results of over 100 contracts with the Associations and Industry about specific problems resulted in a detailed design of the whole facility and includes specifications, calculations and drawings of the various prototypes allowing immediate calls for tender. The report also contains detailed cost estimates and planning schedules for the various stages of supply, construction and tests as well as a program for the operational phase.

14.2. EUROPEAN COLLABORATION IN JET CONSTRUCTION

Upon a recommendation of the Partners on the basis of this report, the Commission may propose to the Council the construction of the JET facility within the next pluriannual research and training program of the Community in the field of Nuclear Fusion and Plasma Physics.

THE FUNDS FOR CONSTRUCTION

The proposal of the Commission to the Council includes funds for JET during the 5 years from 1976 to 1980 of 135 million Units of Account (MUC; 1 UC = 50 Belgian Francs) at March 1975 prices for the following items:

TYPE OF EXPENDITURE	Amount (MUC)
THE JET DEVICE (comprising Mechanical structure, Toroidal field magnet, Core and outer coil support structure, Poloidal field windings, Vacuum vessel, Limiter, Miscellaneous, Spares, Transport).	29.1
AUXILIARY SYSTEMS (comprising Pumping and Cooling systems, Assembly and Maintenance systems, Additional Heating systems)	9.0
POWER SUPPLIES (for Toroidal and Poloidal field systems; Auxiliary power supplies)	22.5
CONTROL, MONITORING, DATA ACQUISITION (comprising Computers and peripherals, Control station and connections)	3.5
DIAGNOSTICS	3.5
OPERATING BUDGET (Preparation of the operation phase, Test and commissioning of the device, Provision for modifications)	8.9
BUILDINGS (Assembly hall and Torus hall, Power supplies areas, Cooling tower, Rental auxiliary buildings)	15.3
MANPOWER (Team for construction phase and preparation of operation phase, Overheads, Travel)	31.9
RESERVE	11.3
	135

THE MANPOWER

Building JET efficiently requires a careful distribution, control and monitoring of the work. Although the legal form of JET and its detailed organisation are at present still under discussion, one can distinguish three main groups contributing to the Project.

1. The JET Construction Team

Provision of Team members will be shared between the Partners, a larger share being provided by the Host Partner. The Team might also use manpower on a rental basis under its direct control, mainly for assembly work.

The required man-years have been estimated and are split into various categories as shown below:

Calendar Year	1976	1977	1978	1979	1980
Man-Years JET Construction Team (1398 MY total)	108	206	325	374	385
Engineers	26%	19%	14%	13%	12%
Physicists	9%	6%	6%	9%	14%
Draughtsmen	30%	20%	11%	9%	10%
Technicians	17%	24%	32%	32%	32%
Clerical, secretaries	18%	19%	16%	15%	14%
Industrials	0%	12%	21%	22%	18%

2. Groups working inside the Associations

Work to be shared between JET and the Associations in the area of physics, diagnostics and additional heating will progressively increase as the project moves towards its operating phase.

The following number of professional man-years additional to those shown above were estimated to be required in the Associations:

Year	1976	1977	1978	1979	1980
PMY	35	50	60	60	50

3. Groups working under the Control of Industry

This includes staff belonging to or hired by contractors to complete orders on site (e.g. assembly of buildings, hardware of the device and its power supplies).

LEGAL BASIS

For the realisation of the JET Project a PROGRAM DECISION of the Council on the proposal submitted by the Commission is now required.

The execution of such a decision will need arrangements between the Partners such as for instance those covered by the present MOBILITY CONTRACT, incorporating provisions as to the conditions of service as well as to the sharing of funds for JET staff.

Additional arrangements will also be required. The basic rules governing the JET collaboration could be set forth in a JET CONSTRUCTION AGREEMENT.

ORGANISATION

In order to ensure the possibility of continuous transition from the Design Phase to the Construction and Experimental Phase the Partners have already consulted and agreed on a MANAGEMENT STRUCTURE.

This structure provides for a PROJECT TEAM directed by a HEAD OF PROJECT, who is responsible for directing the execution of the project.

A MANAGEMENT COMMITTEE shall assure the effective management of the Project by developing the guidelines and controls under which the Project is directed by the Head of Project.

A JET COUNCIL, meeting once or twice a year, shall advise on the overall general management and prepare matters needing a decision of the Council of the European Communities.

Other important issues like the conditions of service, the sharing of funds and the site of JET are under discussion.

15 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. Within the next phase of the program, however, the large fusion experiments and especially experiments of JET-size will require a much stronger involvement of Industry.

Already in the JET DESIGN PHASE various study contracts and orders for long delivery items have been placed, after calls for tender from firms, in all member states of the Community.

During the JET CONSTRUCTION PHASE an even closer collaboration with Industry will be required since by far the majority of the JET components will be manufactured by Industry. To a certain extent it may also become necessary to employ consulting engineering firms, especially in the areas of power supply construction, very heavy engineering components and large scale project control. In this way it is hoped to ensure that European Industries will have a long term competitive position in this exciting new field.

Symbols and Units

SYMBOLS

R_o	– major radius of the plasma
a	– minor radius of the plasma in the median plane
b	– half height of the plasma
B_{TOR}	– toroidal magnetic field on the plasma axis
B_{POL}	– poloidal magnetic field of the plasma
I_p	– plasma current
$\hat{T}_e$	– peak electron temperature
$\hat{T}_i$	– peak ion temperature

UNITS

The standard units are sometimes inconveniently small and it is common practice to use a prefix to define a larger unit.

k means 1000 times, as in kG (kilogauss)
M means 1 000 000 times as in MW (megawatt)
G means 1000 million times as in GJ (gigajoule)

An abbreviated way of writing a large number is in powers of 10, e.g.
3 000 000 A = 3.0×10^6 amperes of current = 3 MA
1/10 000 000 000 torr=10^{-10} torr pressure
100 000 000 000 000 cm^{-3} = 10^{14} particles per cubic centimetre.

Quantity	Unit	Symbol	Comment
Energy	joule	J	1 million joules – 1 MJ will raise about 2 litres of water from room temperature to the boiling point.
Time	second	s	
Power	watt	W	1 watt = 1 joule of energy used per second. A community of about 1 million people in an industrialised country uses an average power of about 1000 MW.

			To produce 1000 MW for one day we must burn about 9000 tons of coal or 5000 tons of oil or in a fusion reactor about 125 grams of deuterium and 400 grams of lithium.
Temperature	degrees Celsius or Centigrade		Plasma temperatures are often quoted in electron volts (eV). The relation between temperature (random energy) and the directed energy of a charge accelerated through a potential of 1 volt is 11 600 degrees = 1 eV.
Density	number of particles per cubic centimetre	cm^{-3}	$10^{14} cm^{-3}$ means 100 000 000 000 000 particles per cubic centimetre.
Vacuum Pressure	torr		Atmospheric pressure is 750 torr. At room temperature a pressure of 1 torr corresponds to a particle density of about 3.5×10^{16} particles per cubic centimetre. At 10^{-10} torr there are 3.5×10^{6} particles cm^{-3}.
Dimensions	metres centimetres	m cm	
Current	amperes	A	An electric heating element supplied at 100 V and carrying a current of 10 A provides 1000 Watts of heating.
Voltage	volts	V	
Magnetic field	gauss	G	The very weak magnetic field of earth has a maximum value of about 0.4 G. A typical bar magnet has a field near the end of about 5000 G = 5 kG.
Weight	tonnes	t	1 tonne = 1000 kilograms = 1000 kg.
Force	tonnes	t	1 t force is the force exerted by a 1 tonne weight due to gravity.