Mechanical and Material Problems of JET

P.H. Rebut
JET Joint Undertaking,
Abingdon, Oxfordshire 0X14 3EA, United Kingdom

Abstract

A major part of the controlled fusion research programme is at present devoted to tokamak experimental devices. The aim of the large tokamaks, e.g, JET (EURATOM) and TFTR (USA) which are under construction, is to obtain and study plasma under conditions approaching those required in a thermonuclear fusion power-producing reactor. The performance of these toroidal machines depends critically on their size, their toroidicity and the values of magnetic fields employed.

It is clear that the characteristics are limited by the mechanical properties of the materials used in the construction of the tokamak. A basic feature of the JET design from the start has been the attempt to minimise the stresses in its different elements, viz., the toroidal field coils, the mechanical structure, the vacuum vessel etc.

The JET operating conditions are :

(i) pulsed magnetic field operation for 20 s duration every 10 minutes.

(ii) up to 10^{20} neutrons (of energy 14.5 MeV) per pulse once deuterium-tritium plasma is studied. This should produce a radiation dose up to 10^{8} - 10^{9} rem. These conditions require that the materials used have suitable fatigue and radiation resistance properties.

I - THE BASIC TOKAMAK

To gain a clearer understanding of the problems involved in the design of the Joint European Torus (JET), it is useful to describe the basic tokamak concept on which JET is based. The elements of a tokamak will be described with the aid of a cutaway view of JET (fig. 1).

The working gas (e.g hydrogen and/or its isotopes) is fed into a toroidal vacuum vessel (1) which has been evacuated to a high vacuum. The toroidal magnetic field generated by a current in a set of discrete coils (4) placed around the torus, is established. A change of current flowing in the inner poloidal field coils (7) which are tightly wound around the major axis of the toroidal system is effected, and this causes a change of magnetic flux linking the vacuum vessel thereby inducing a toroidal electric field. A transformer core may be used to assist this coupling of magnetic flux and acts as a magnetic circuit (8). The induced electric field is sufficient to ionise the gas within the vacuum vessel and, if it is maintained, will drive a toroidal current in the plasma. This plasma current is essential to tokamak operation as the associated poloidal magnetic field, together with the poloidal field produced by current flowing in the external conductors (6) completes the field necessary to confine the ionized gas (plasma) which has been produced. The induced plasma current also heats the toroidal plasma column and although the thermal load on the vacuum vessel is reduced by the confining magnetic field, special limiter plates (2) are used to define the thermal contact of plasma and wall.

The external poloidal field coils produce a control field which can position and shape the cross-section of the toroidal plasma column. Nevertheless, to protect the thinner sections of the vessel from damage which might arise in an uncontrolled motion of the plasma column, protective poloidal plates (3) could be used. The size of the magnetic fields and currents required in the electromagnetic system lead to large mechanical forces which must be resisted and, in particular, the toroidal field coil set has to be supported in some way either by individual coils casings or by a complete mechanical structure (5). If the mechanical structure surrounds the coil set and vacuum vessel, adequate access must be provided to service the coils (9) and the vacuum as well as to heat and study the behaviour of the plasma (10).

II - THE JET DESIGN

Two main principles guided the JET design :

(i) the use of design solutions involving established technology. This was to improve reliability and to reduce cost.

(ii) the employment of modular systems. This feature would clearly simplify manufacture but also facilitate the assembly, disassembly and maintenance of the device. This led to a machine which consists of eight essentially identical and self-consistent sections (octants) each one of which contains a vacuum vessel octant, four D-shaped, toroidal field coils and one octant of

the external mechanical structure.

The achievement of the JET objectives, in terms of plasma parameters obtained, indicated high plasma current (3-5 MA) and the dimensions (and toroidicity) were chosen to maximise this current, given mechanical constraints due to magnetic field (see below) and cost.

The main JET parameters are given in Table I and the detailed design and its evolution is described in reports (1), (2), (3).

Deuterium-tritium operation is an integral part of a successful JET programme. The machine will become radioactive, making scheduled and unscheduled interventions possible only with remote handling systems. Therefore, it was essential right from the beginning of the design to maintain good access for such systems as well as for additionnal heating and plasma diagnostics equipment. To consider some of the mechanical and material problems of JET more closely, three major systems will now be discussed.

III - TOROIDAL FIELD (TF) COILS

Each of these 32 coils is D-shaped and consists of two pancakes each with 12 turns (Fig. 2). The toroidal field ($\sim$ 3 T) and the coil current ($\sim$ 53 - 67 kA/turn) combine to produce large stresses within each coil. The in-plane, bending moments on such a coil are substantially reduced by shaping it appropriately, and the D-shape approximates the natural, pure-tension coil form.

The straight side of each coil is subjected to large centring forces (up to 1800 t) and these are supported, in the first instance, by a central column which forms an inner part of the mechanical structure. The forces are ultimately taken up by the set of 8 inner poloidal field coils, and to limit the stresses in these coils to acceptable value(3kg/mm^2)they are mounted on steel support rings.
For the TF coils manufacture, a copper conductor of cross-section approximately 4000 mm^2 is extruded and drawn in a half-hard state into bars of 15 m length (Fig. 3). The conductor is cooled by water passing through the two cooling channels and each turn is insulated one from the other by glass fibre and epoxy resin which is vacuum impregnated. The resin will withstand a radiation dose of about 10^9 rad. Each turn is grooved so that there are interturn keys which reduce the damaging effect of shear stress on the insulation.

The bars are braze welded together to form the pancake conductor and each joint has an ultimate tensile stress of 20-22 kg/mm^2, but a reduced fatigue limit of 17.5 kg/mm^2 after 10^5 cycles, and 15 kg/mm^2 after 2.5 x 10^5cycles. Nevertheless, the design limit of 10 kg/mm^2 (reached only in the straight coil section where the cross-section is reduced) should guarantee a machine life of 10^5 pulses. Techniques were employed to ensure efficient, reliable and reproducible silver brazed welds.

Production of these coils is well advanced and in January 1981, 24 coils had already been delivered to the JET site (Fig. 4).

IV - MECHANICAL STRUCTURE

This 450 t structure is designed to withstand the complex system of forces in the tokamak for a large number (10^5) of pulses. It consists essentially of three parts (Fig. 5).

(i) an external shell surrounding the TF coils,
(ii) a ring and collar both top and bottom. The ring provides side supports for each TF coil and connects the external shell to
(iii) an inner cylinder. The straight section of each TF coil fits into a vertical groove in this column which also transmits the large centring forces.

The chief function of the structure is to withstand the large out-of-plane tilting moment on each coil produced by the interaction of the TF coil currents and the poloidal field. Such torques can be as high as 20000 tm and correspond to large shearing forces.

The external mechanical structure is made of a spheroidal graphite, cast iron material which is austenitic (nonmagnetic) so as not to interfere with the electromagnetic operation of the tokamak . This material has a high ductility and good fatigue characteristics. Each octant is electrically insulated one from the other, and special hexagonal keys transmit the shear.

The necessity to insert many openings into the external structure to provide access to the vacuum vessel and plasma results in exceedingly complex stress patterns which, of course, change significantly from one form of machine operation to the other. Detailed 3-dimensional, finite element calculations (Fig. 6) for a variety of conditions including faults were performed. Fatigue tests of the octant joints and of the castings were carried out. Manufacture of all parts of the mechanical structure is well advanced (Fig. 7).

V - VACUUM VESSEL

The vacuum vessel is a double-walled structure made up of alternate rigid (box-like) and thin flexible (bellows)sectors which are welded together (Fig.8). Each vacuum vessel octant consists of four rigid sectors and four bellows sectors.Each octant is welded to the next by a U-type joint.The vessel can be baked at high temperature (up to 500° C) by passing hot gas through the wall interspace. The vessel is D-shaped which allows maximum use to be made of the toroidal field for stable plasma containment.

This vessel must withstand : atmospheric pressure when under vacuum (20 t per rigid sector), its own weight (108 t) and pulsed electromagnetic forces (up to 10 t per rigid sector due to the build-up of the toroidal field. Once again, the requirements of access to plasma make the detailed calculation

of mechanical and thermal stresses under many different conditions, rather complex.

The toroidal structure provides a parallel electrical path to the plasma and so carries induced toroidal eddy currents, which in normal operation can reach 400 kA. In fault conditions (disruptions) the vessel current can be of the order of the total plasma current (3-5 MA). The bellows' sectors are inserted to reduce the induced eddy currents as they provide a "lengthened" resistive path to the applied inductive voltage. The vessel has a toroidal electrical resistance of . 52 m Ω which is large compared to that of the hot plasma. The large volume (190 m^3) vessel must be built to ultra-high vacuum standards (base pressure 10^{-10} - 10^{-9} torr), and is made of high nickel content stainless steel (inconel). This material was chosen because of its good mechanical properties at the baking temperature, because of its favourable outgassing rates under high vacuum, and because of its high electrical resistivity.

The bellows sectors have been made by a mechanical rolling process and the dimensional tolerances necessary to ensure a high-quality, vacuum-tight weld to the rigid sector are of the order of a mm over lengths of 4 m. Progress with the rigid sectors has been more difficult and involved full-scale gas flow tests. Nevertheless, a prototype octant (Fig. 9) has been assembled and will undergo intensive leak and thermal stress tests at 600° C (in a large oven).

Protective shields ensure that the thin bellows sectors are not inadventantly thermally loaded by the plasma. The limiter plates (Fig. 10) which define the plasma/wall thermal contact have been designed to withstand pulsed loads of up to 10 MW/m^2. The techniques for cooling the limiters and the identification of the materials required to withstand the thermal load (yet introduce as little impurity (non-hydrogenic) material as possible to the plasma), have necessitated a significant testing programme. These limiters are made of copper chromium and cooled by using the hypervapotron (controlled nucleate boiling) technique developed by Thomson CSF. For sputtering reasons, the surface is covered with an explosively-bonded pure nickel surface layer. The thermal stresses and the fatigue are among the most severe problems in this element.

VI - FINAL COMMENT

The above examples have given some idea of the mechanical and material problems of JET. These features make JET, in dimensions and form and in many areas of technology, more similar to proposed reactor designs than any other tokamaks built or under construction.

REFERENCES

/ 1 / The JET Project - Design Proposal EUR 5516 e (1976)

/ 2 / The JET Project - Scientific and Technical Developments 1976, EUR 5781 e (1977)

/ 3 / The JET Project - Scientific and Technical Developments 1977 and 1978 (to 1 June) EUR - 6831 en (1980)

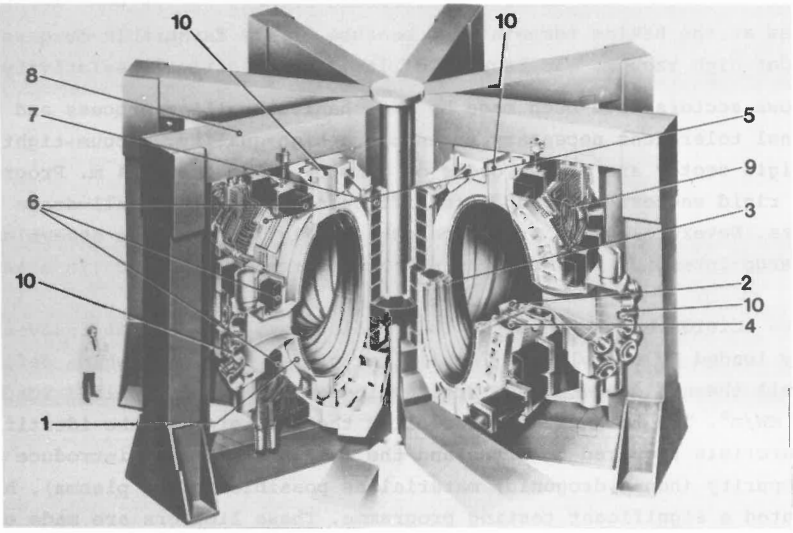


Fig. 1 The JET apparatus :

Key-/

(1) Vacuum vessel (double wall)

(2) Material limiter defining the outer plasma edge

(3) Poloidal protective shields to prevent the plasma touching the vessel

(4) Toroidal field magnet of 32 D-shaped coils

(5) Mechanical structure

(6) Outer poloidal field coils

(7) Inner poloidal field coils (primary or magnetising windings)

(8) Iron magnetic circuit (core and eight return sections)

(9) Water and electrical connections for the toroidal field coils

(10) Vertical and radial ports in the vacuum vessel.

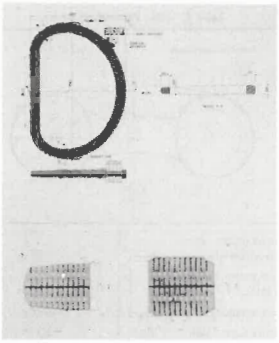


Fig. 2 Shape and dimensions of a toroidal field coil

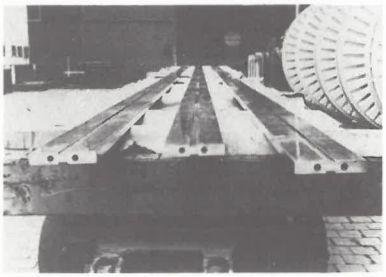


Fig. 3 Copper conductor for the toroidal field coils

Fig. 4 Some of the completed toroidal field coils at the Jet site

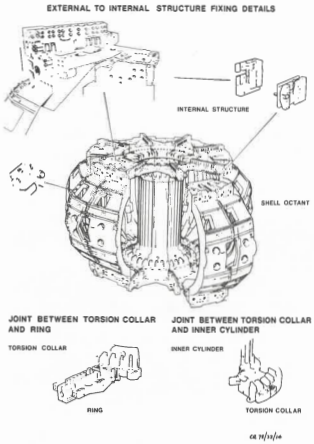


Fig. 5 The mechanical structure - external to internal fixing details

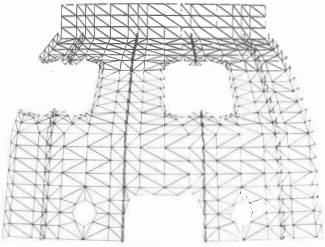


Fig. 6 Mesh used for the finite element analysis of the external shell. For clarity only the external surface of the shell has been represented.

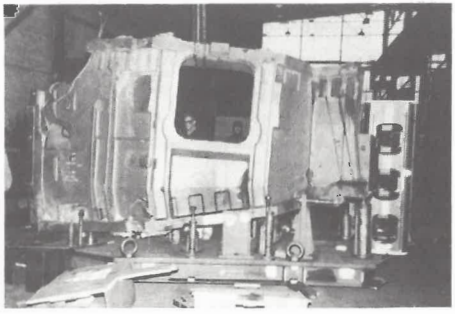


Fig. 7 External shell casting at the factory

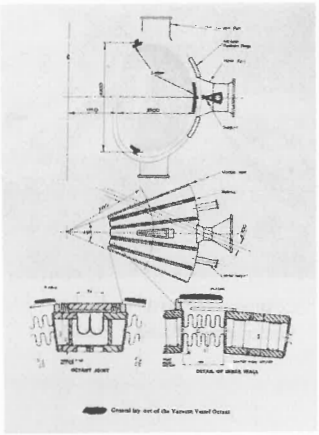
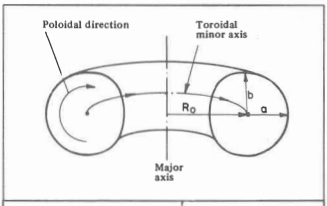


Fig. 8 General layout of the vacuum vessel (line diagram)

Table I Main Parameters of JET



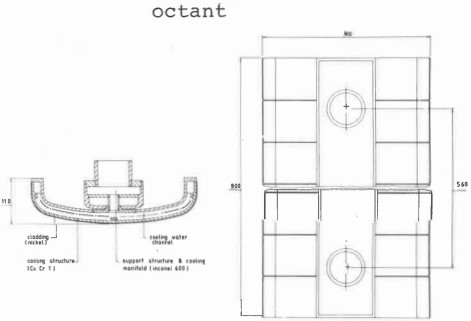
Plasma minor radius (horizontal)	a	1·25m
Plasma minor radius (vertical)	b	2·10m
Plasma major radius	R_0	2·96m
Plasma aspect ratio	R_0/a	2·37
Plasma elongation ratio	b/a	1·68
Flat top pulse length		20s
Weight of the vacuum vessel		68t
Weight of all the toroidal field coils		384t
Weight of the iron core		2567t

	Basic*	Extended*
Toroidal field coil power (peak on 13s rise)	250MW	380MW
Total magnetic field at plasma centre	2·77T	3·45T
Plasma current:		
– circular plasma	2·6MA	3·2MA
– D-shape plasma	3·8MA	4·8MA
Volt-seconds available to drive plasma current	25Vs	34Vs
Additional heating power	10MW	~25MW

*Basic performance refers to that mode of operation characterised by the parameters given. A staged increase of the power supplies will make possible the mode of operation referred to as extended performance. Additional funds will be required for the extended performance.

Table 1 Main parameters of JET

Fig. 9 Prototype vacuum vessel octant



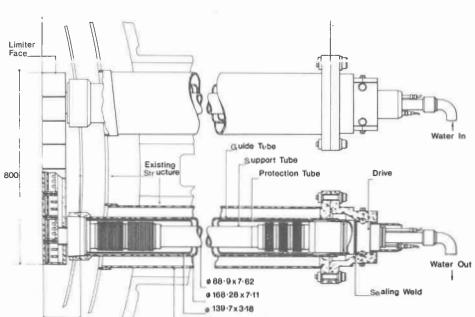


Fig. 10 General layout of the limiter plate assembly