Mechanical Design Assessments of Structural Components and Auxiliaries of the Joint European Torus

L. Sonnerup

*JET Joint Undertaking, Fusion Technology Division, Culham Laboratory,
Abingdon, Oxon, OX14 3EA, U.K.*

Abstract

The general design of the Joint European Torus (JET) is briefly described. The loads on its major structural components, at normal operation, and in cases of plasma instability and/or disruption, are discussed. The way these components have been assessed and optimised in relation to their loads is presented. A short account of mechanical design problems of auxiliary equipment is given. Finally, the state of operation of JET and its implications for the mechanical design at the time of the conference will be summarized.

The mechanically most important components of the JET device are the support structure of the toroidal magnet, the vacuum vessel, the coils of the magnets and the pedestals supporting the weight of the torus. These components all participate in resisting and transmitting the primary forces during operation.

1. Introduction

The basic principles of nuclear fusion of hydrogen isotopes and magnetic confinement of a hydrogen plasma, forming the scientific basis for the Joint European Torus (JET) experiment, have been summarized in the report *The JET Project* (1) published by the JET Joint Undertaking in 1978 and will not be repeated here.

The JET machine is a magnetic confinement system of the Tokamak type where the plasma is contained in a torus shaped vacuum vessel (fig. 1,2). Outside the vessel is a set of coils encircling the minor periphery of the vessel. These coils produce the magnetic field in the toroidal direction. The additional poloidal field, necessary to stabilize the major radius of the ring-shaped plasma, is produced by a current flowing in the plasma itself. This current is induced via transformer action by a pulse through the set of coils in the centre of the machine, the primary winding of the JET transformer. The plasma acts as the secondary winding of the transformer. The plasma current also produces the basic resistive heating of the plasma. This pulsed mode of operation is an important feature in relation to the mechanical design of the structural components of JET.

The vacuum vessel is a torus with a D-shaped cross section (fig. 2). It consists of so called rigid sectors joined together by bellows units. The structure of the vessel is a thin walled, double skinned shell. The rigid sectors give the shell sufficient stiffness and stability whereas the bellows units facilitate assembly of the torus and have sufficiently reduced material cross section (ie high electrical resistance) to prevent a

large current being induced in the vessel during the operational pulse.

The vacuum vessel and the toroidal field coils are housed in the main JET support structure (fig. 1,3). This structure (fig. 3), usually referred to as the Mechanical Structure, is the backbone of the machine, supporting also the external poloidal field coils for plasma shape and position control (fig. 1). The structure is designed as a closed shell to provide a high torsional strength and stiffness, necessary to resist electromagnetic tilting forces on the toroidal coils. The gravitational forces from the weight of the structure itself, the coils, the vacuum vessel and other attached components are transmitted to the eight horizontal limbs of the transformer core which in turn rest on the heavily reinforced floor of the Torus Hall.

To facilitate assembly and to allow repair or exchange of components, the JET machine has been designed in eight modules, octants (fig. 1,2,3). Each major structural component was therefore first assembled into octants. Four toroidal field coils, a vacuum vessel octant and a shell octant of the mechanical structure (fig. 3) were then put together to form a machine octant. The torus was built from these octants by inserting them into the internal mechanical structure (fig. 3) which in turn in its centre encloses the primary winding of the transformer (fig. 1).

Fig.1. The JET Tokamak

Fig.2. The JET Vacuum Vessel

2. Primary Forces and Stresses during Operation

The significant loads on the various components of the machine stem from the interaction of magnetic fields and electrical currents, such as currents in the coils of the magnets and induced eddy currents. The latter are particularly prominent in the vacuum vessel. The vacuum vessel, in addition, is of course under external atmospheric pressure during operation. The electromagnetic forces rise from zero to their particular current maximum levels during each operational pulse of the machine. The mechanical forces and stresses in the structural components are therefore pulsating and thus creating a fatigue loading condition. In the event of plasma disruption or instability, very rapid changes of the acting forces occur, introducing an additional dynamic load component.

2.1 The Toroidal Field Coils

The forces on the toroidal field coils are of two kinds. Firstly, the magnetic pressure of the toroidal field tends to expand the coils and, due to the toroidal geometry, produce a net inward force on each coil. This force could be up to 1800 tonnes at full field. Secondly, the poloidal field interacts with the coil current to produce lateral forces (in the toroidal direction) on the coils, equal in magnitude but opposite in direction for the top and bottom half of each coil. The net result is a tilting moment on each coil tending to turn the vertical plane of the coil into a horizontal position. In the design of the toroidal field coils extensive finite element calculations have been used to assess in particular the shear stresses in the internal layers of the glass epoxy insulation. The design and manufacture of these coils were reviewed in 1983 by Huguet et al (2).

2.2 The Mechanical Structure

The tilting forces of the toroidal coils constitute the major load acting on the mechanical structure. They result in a total torque (around the vertical axis) which at a plasma disruption could rise to about 20,000 ton-metres. The torque is transmitted from the top to the bottom half of the structure and is fully developed in its horizontal

mid-plane (fig. 3). The distribution of internal forces in the shell, resulting from this torsional load, has had a considerable influence on the design of the joints of the structure, as has the pulsating character of the load. The shell also has many openings for access to vacuum vessel and toroidal coil connections. These openings give rise to stress concentrations and thus the risk of fatigue cracks forming. The stress pattern around such openings has therefore been carefully investigated, both theoretically and experimentally, and the level of stress assessed in relation to fatigue and crack propagation values for the material.

In fig. 4 the principal stress pattern in the external shell of the mechanical structure due to the torsional load is demonstrated. The simulation was obtained by means of the photoelastic technique and consisted of a plane photoelastic model with a distribution of openings (black areas) corresponding to that of a shell octant (fig. 3). The plate was loaded in shear by a specially designed load frame as indicated in fig. 4. The severe stress concentrations near the re-entrant corners of the rectangular openings are clearly visible in the form of a high density of photoelastic fringes. Near the top of the photo a crack (arrow) has developed from such a corner to the edge of the plate. These regions of the shell have therefore been heavily reinforced and as large a radius as possible has been chosen. The main opening in the centre of the shell octant has in fact a semi-circular shape of its upper and lower rim and not the straight edges and small corner radii shown in fig. 3. This is particularly important since this area has to resist the fully developed torque between the top and the bottom of the structure.

The distribution of forces and stresses in the mechanical structure has been determined by finite element calculations for certain critical load conditions (including plasma disruptions) and the design adjusted to accommodate high internal (shear) forces in certain areas. In particular the distribution of shear forces along the joints of the shell segments has been assessed carefully to ensure that the density of shear dowels is sufficient. Details of the design and manufacture of the mechanical structure as well as the distribution of loads, joint forces and stresses were reported in 1980 by Sonnerup et al (3).

Fig.3. The JET Mechanical Structure

Fig.4. Stress pattern in plate with openings subject to shear load

Fig.5. FE-model for stress analysis of the vacuum vessel

2.3 The Vacuum Vessel

The primary load on the vacuum vessel is a combination of electromagnetic forces due to induced eddy currents and the atmospheric pressure on the outside of the vessel. This loading results in both a compressive hoop force in the vessel and shear forces between the rigid sectors due to tilting actions, similar to those for the toroidal coils. To resist the hoop force, the vessel has two ring shaped reinforcements on the outside of the torus bridging the bellows units. The shear forces are transmitted by the bellows units unaided. For the vacuum vessel, a main concern has been to obtain acceptable stresses in all the welded joints under these load conditions, so that no leaks would develop due to fatigue cracks in joints. The condition of a vertical plasma instability can introduce further forces on the vessel in the vertical direction. These forces are of an impact nature and will be partly absorbed by the inertia of the vessel and partly resisted by special supports on the ports of the vessel.

The vessel has a high degree of symmetry (fig. 2) and during normal operation the loads on the vessel are either symmetrical or anti-symmetrical with respect to the symmetry planes of the vessel. The loads are also self-equilibrating so that no net forces are created on the vessel. For purposes of stress calculations at such normal loadings, a total of sixteen vertical symmetry planes plus the horizontal mid-plane can be assumed and only a typical segment corresponding to $1/64$ of the whole vessel or $1/8$ of a vessel octant needs to be considered. The results of such finite element calculations were presented in 1979 by Streibl et al (4) who also considered the transient response and stability against buckling of the vacuum vessel at plasma disruptions.

In the event of a vertical plasma instability, however, the loads are no longer

symmetrical with respect to the horizontal mid-plane and net vertical forces, tending to push the vessel either up or down, arise. These forces are located above only or below only of the mid-plane (as the case may be) and have to be resisted by supports at the main ports of the vessel, ie at eight positions around the torus. This immediately reduces the available symmetry to eight vertical planes; four through the eight main ports and four midway between these planes. As a result, stress calculations for this situation have to be performed on a larger portion of the vessel corresponding to 1/16 of the whole vessel or 1/2 of a vessel octant. Such a finite element model is shown in fig.5.

2.4 Auxiliary Equipment

Problems of vibrations have had to be considered for, in particular, experimental equipment attached to the machine or supported on the floor near it. For example, a large amount of elastic energy is stored in the primary winding of the transformer during the initial phase of an experimental pulse, and then released over a very short time. As a result the winding sends a shock wave through the Torus Hall floor on which it rests. Sensitive measuring equipment has to be isolated from such shocks.

Thermal stress problems occur in certain components exposed to heat radiation from and contact with the plasma, such as limiter plates on the inside of the vacuum vessel wall. Also some parts of the neutral injection system are subject to very severe thermal gradients. In some of these cases peak stresses up in the plastic range are unavoidable.

3. Final Comments

This presentation aims at highlighting the load conditions and design assessments for the major structural components of the JET machine. In the space available it is not possible to cover all aspects of these assessments or all areas where extensive mechanical analysis has been undertaken. It should, however, be pointed out that for all sensitive regions of the design, the mechanical problems have been solved by a combination of analytical/numerical calculations and testing. The tests have ranged from conventional material testing to full scale functional tests of components.

4. References

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