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Analysis and Tests in Support of Upgrading the JET Toroidal Field to 4 Tesla

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Analysis and tests in support of upgrading the JET toroidal field to 4 Tesla

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Abstract – **Until 1997 the maximum toroidal field (B) of the JET machine was 3.4 Tesla. When B is raised from 3.4 T to 4 T, in-plane forces rise by 38% and, if the plasma configuration is unchanged, out-of-plane forces increase by 18%. To increase confidence in the ability of the coils to withstand higher fields after 14 years of operation, several new analyses and tests have been made. They include review of test data to set allowable stress and force limits, new detailed finite element models of critical parts of the coil, tests of mechanical strength and elastic properties of insulation systems of used coils and comparative mechanical tests of used and unused coils.**

I. INTRODUCTION

The JET toroidal field (TF) coils [1] (Fig. 1) are "D" shaped so that the toroidal field causes essentially tensile stresses in the coils. Each toroidal coil is subject to a net inward force which is reacted along the straight section by the inner poloidal coils (P1). Both the tension in the toroidal coils and the inward force on the inner poloidal coils are proportional to B^2, where B is the toroidal field.

The poloidal field causes out-of-plane forces on the TF coils, which increase linearly with B. These forces are reacted by fluted inner cylinder along the straight section, by the ring and collar teeth at top and bottom and by shell casting on the outer part of the coil.

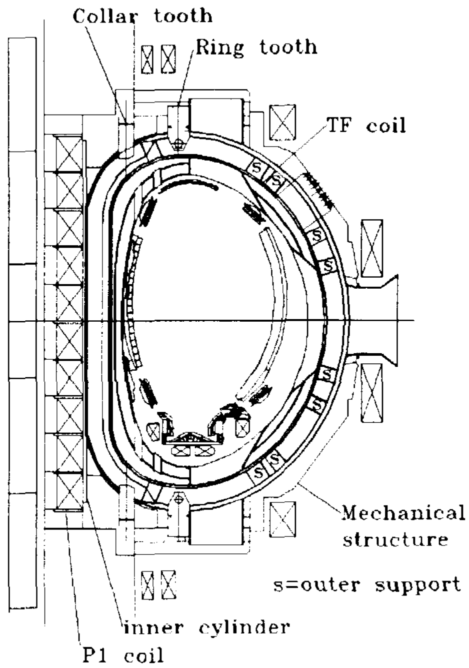

Fig. 1. The JET machine showing toroidal and poloidal coils and support positions for out-of-plane forces

The temperature rise of the coils and thermal stresses will not be affected because a slightly shorter pulse will be used to keep constant I^2t.

II. STRESSES IN THE COILS

A. Electromagnetic forces

The toroidal field is calculated by a 3D Biot Savart magnetic code and the poloidal field by a 2D finite element plasma equilibrium code (MAXFEA). Fig. 2 shows the normal magnetic field along a TF coil periphery for a typical plasma.

B. Stress Analysis

Stress in the coils due to the electromagnetic forces has been analysed using several finite element models, which are summarised in the table.

Type of element	Number of elements	Used for	Typical. calculation time (secs)
Beam	136	routine analysis of plasma scenarios	2
Brick	2176	check of beam model, analysis of test	42
Local	35000	stress concentrations, effect of cracks	1100
Hybrid	46000	stress concentrations	5100

1) Beam model. The coil is represented by 136 beam elements with axes in the winding direction of the coil and properties approximating the cross sectional properties of the coil winding. This model is useful for quick calculations of operational conditions. Fig. 3 shows tensile stresses in the TF coil conductor for a typical plasma calculated using the beam model. The tensile force in the coil is constant so the average tensile stress only changes at changes in coil cross-section.

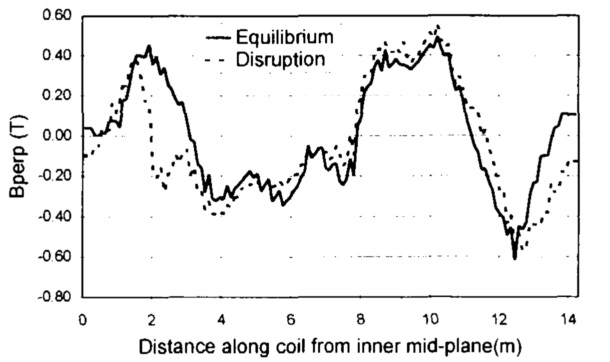

Fig. 2. Normal magnetic field along TF coil periphery for 6 MA plasma. This field determines the out of plane force on the coil.

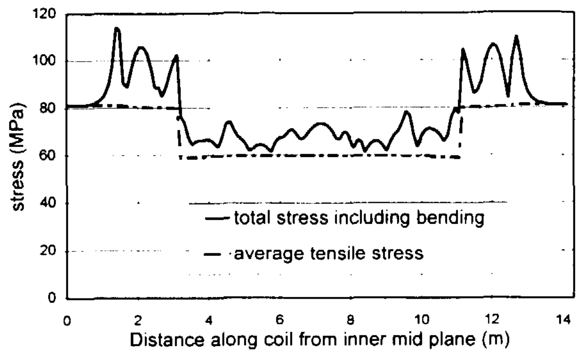

Fig. 3. Tensile stresses in the TF coil conductor for 6 MA plasma at 4 T

The total tensile stress includes bending stress. There are small in-plane bending stresses due to deviations from the perfect theoretical shape but most of the bending is due to out-of-plane forces.

2) Brick model. The coil is represented by brick elements (Fig. 4), which enable the properties of the coil winding, in particular its shear stiffness to be represented more accurately than with the beam model. This model was used to check the beam model and analyse load tests on complete coils.

3) Local models. Regions with complex or high stress distributions are represented in considerable detail with explicit modelling of copper and insulation. Boundary conditions approximate the effect of the rest of the coil.

Three calculations have been made using local models.

- The stresses at the end of an inter-turn crack in the collar region have been calculated to determine whether inter-turn cracks are self limiting. As the crack is made longer, the stresses reduce suggesting that a crack would not grow.
- Calculations have been made on the effect of extensive delamination in the collar region. These show that, even if the coil was completely delaminated (i.e. only the inter-turn key was available to transmit shear forces between conductors) over a length of 200 mm, stresses and deflections would be acceptable.
- The interconnection between the two coil pancakes has been investigated using a local model. This shows bending stress in the copper and shear stress in the insulation both within acceptable levels.

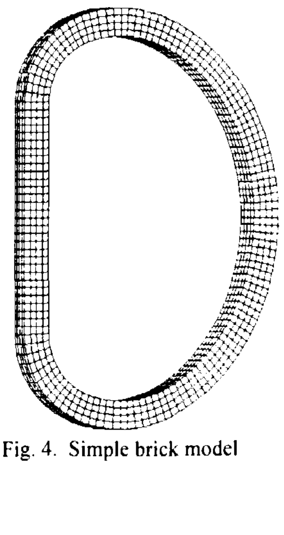
Fig. 4. Simple brick model

4) Hybrid model. This combines the properties of overall and local models. Most of the coil is modelled coarsely with beam elements, while regions of interest are modelled in detail with 3D brick elements (Fig. 5). The detailed regions are equivalent to the local models studied previously and the coarsely meshed region provides accurate boundary conditions for the detailed region.

A calculation made in 1988, using average properties for a copper and insulation mixture, showed that 50 tonnes collar tooth force corresponds to 17 MPa peak or 15 MPa average stress in the coil. This calculation has been repeated using the more detailed hybrid model, where the insulation is modeled explicitly.

The new calculation has shown that the shear stress in the insulation is a function of the shear modulus of the insulation (Fig. 6). The maximum shear stress varies between 9 MPa if G = 1.2 GPa and 12 MPa if G = 4 GPa. Note that even with the higher value of G the maximum shear stress is less than the previous value and that at higher temperatures G will reduce. The reduced G will lead to lower stresses which will compensate for the reduced strength at higher temperature (see section IIIA).

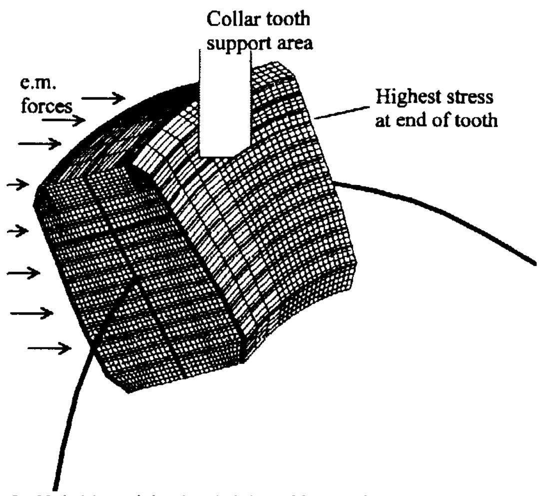

Fig. 5. Hybrid model using brick and beam elements. A small part of the coil near the collar tooth is modelled in detail.

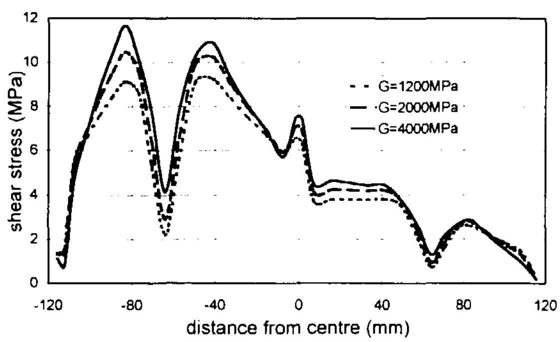

Fig. 6. Shear stress in inter-turn coil insulation at collar tooth end (along line AA on Fig. 7) for three values of shear modulus

C. Allowable stresses

Results of analysis are assessed in terms of allowable stresses in the coil materials and support structure. These allowable stresses are based on QA and test data from the original coil manufacture contract reinforced by recent tests on used coils and coil parts and are summarised in the table.

Component	Primary stress MPa	Primary + secondary stress MPa
Copper conductor	120	180
Brazed joints	67	100
Epoxy glass insulation	15	15

The strength of the outer part of the mechanical structure far exceeds the expected out-of-plane loads. However, a critical region for both the structure and coils is the ring and collar tooth region. Therefore, in assessing plasma scenarios, the forces on these teeth are kept within predefined limits.

III. Tests on Coils and Coil Components

This section describes tests made recently on used and spare coils and on samples cut from used coils. The object was to compare data from used production coils with pre-production test data.

A. Shear strength tests on insulation

Tests were made on samples taken from a coil that had been operational in the machine for 6 years. The coil was cut into cross sectional slices and shear test samples cut from the slices as shown in Figs. 7 and 8

The two types of samples gave similar results. Fig. 9 shows the effect of temperature on the shear strength of the insulation and Fig. 10 shows fatigue tests.

These tests on small samples are unusual in that they were made on a used coil made by industrial methods, whereas most tests are done on new laboratory made samples. It is unrealistic to expect to achieve laboratory results in industrial conditions. The results achieved are therefore remarkably good.

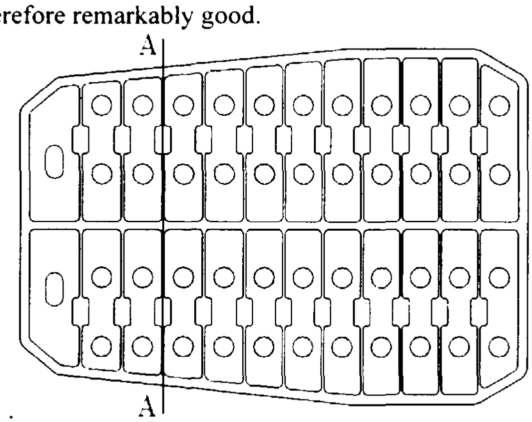

Fig. 7. Typical cross-section of TF coil. High shear stresses occur along AA at the collar tooth (see Fig. 6)

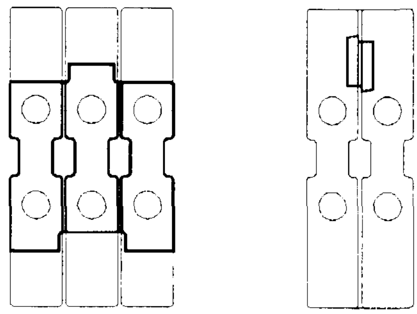

Fig. 8. Double and single shear test samples cut from cross section.

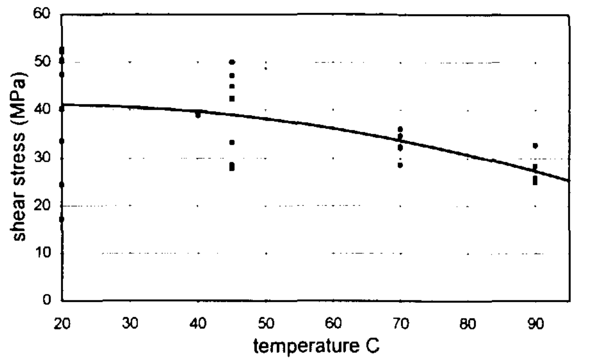

Fig. 9. Static shear strength as a function of temperature (double shear specimens)

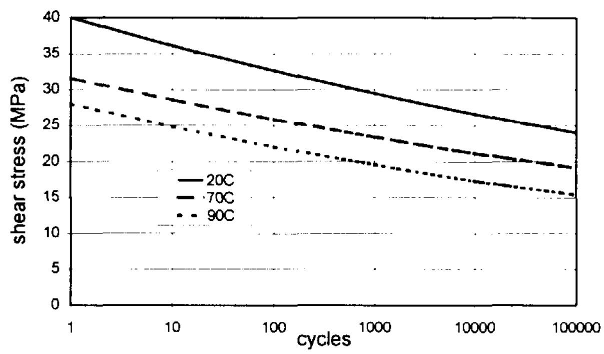

Fig. 10. Shear strength versus number of cycles at 20,70 and 90°C (double shear specimens)

B. Measurement of shear modulus of insulation

F.E. analysis (section II) showed that the shear modulus (G) of the insulation affects the calculated (and real) stresses. G was therefore measured using the samples described above and also using an Iosepescu shear sample. First measurements indicate G between 1 and 2 GPa.

C. Tensile tests on brazed joints

Each coil has 48 brazed joints (2 per turn). The brazed joint region of a coil was completely dismantled and all brazed joints X rayed. The X ray test revealed defects of varying size and was used as a basis for selecting joints for tensile testing. The joints were tested statically and in fatigue and the results are shown in Fig. 11.

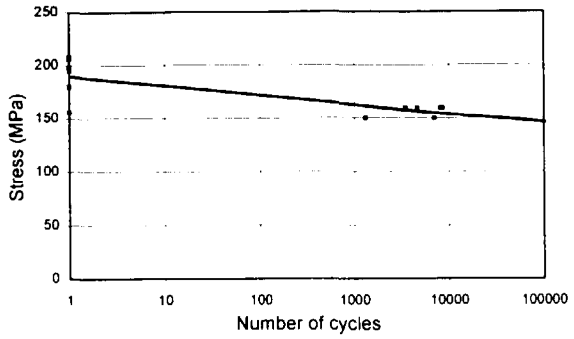

Fig. 11. Tensile stress versus number of cycles for brazed joints showing static and fatigue measurements

Although the defect size estimated from X ray measurements was only approximate, a correlation between strength and defect size was found, as illustrated in Fig. 12. Note that, even with the largest defect, the required life (20,000 cycles) can be achieved with a stress exceeding the allowable..

D. Mechanical tests on complete coils

1) Tests on prototype coil in 1988.

Two types of test were made in 1988. Test 1 simulated the typical magnetic loading of the coil in the region of the collar support. Test 2 examined the behaviour of the coil at the entry into the flute of the inner cylinder. Forces and stresses of more than twice the present allowable values were applied with no detectable effect.

Recent calculations have confirmed that stress concentrations such as those occurring at the collar teeth are mainly determined by the locally applied force rather than the remote boundary conditions. These tests were therefore valid tests of the coils under local operational stress conditions.

2) Tests on used and unused coils in 1996/97

The object was to compare the mechanical stiffness of used and unused coils to see if coils had been affected by operation. An unused spare coil was compared with a coil that had been used on the machine for 7 years.

The coils were subjected to in-plane and out-of-plane bending. Stresses and deflection calculations for all proposed tests were made to determine the forces

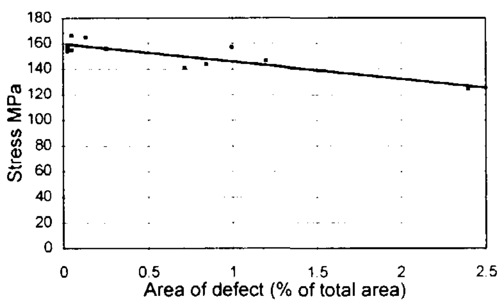

Fig. 12. Stress for life of 20,000 cycles versus brazed joint defect size. (Total cross sectional area is 3923 mm^2)

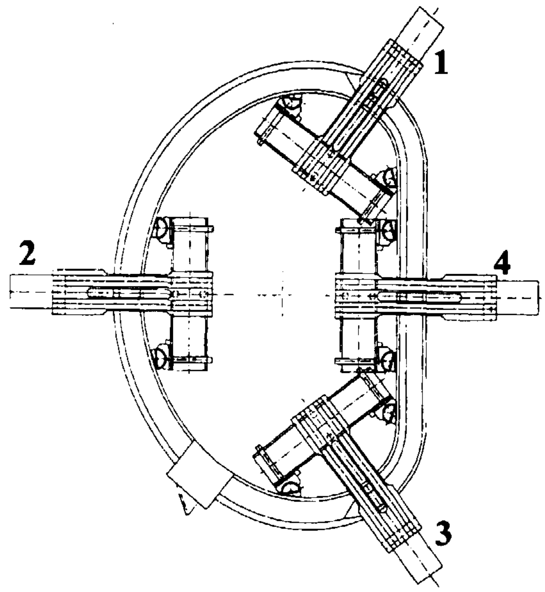

Fig. 13. Positions of testing machine. The machine applies a central load which is reacted on either side.

required to give suitable stress levels (i.e. significant but not excessive).

In plane test positions are shown in Fig. 13. The tests showed that the used coil had stiffness within 8% of the unused coil. The coil deflections were also compared with a finite element brick model. The shear modulus of the insulation was adjusted and gave a best fit to the measurements with G between 1 and 2 GPa.

IV. CONCLUSIONS

The coils can be assessed in terms of out of plane and in plane force systems.

Increase of maximum stress due to out of plane forces can be avoided by controlling the plasma shape so that the transverse poloidal field in critical regions is reduced, when the toroidal field is raised. However the analysis and tests reported give confidence in the coils' ability to withstand high out of plane forces.

In plane forces cause tension in the coil winding, which increase ($\propto B^2$) at higher field. Stresses in the copper conductor are well below acceptable levels and quality of the copper is very consistent. Quality control is more difficult for brazed joints.. However recent tests have shown that even the worst joints can withstand operation at 4 T with good safety margins.

ACKNOWLEDGEMENTS

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