UPGRADING THE JET TOROIDAL FIELD TO EXCEED 3.45 TESLA

J. R. Last, E. Bertolini, M. Buzio, P. Presle, T. Raimondi, V. Riccardo

JET Joint Undertaking, Abingdon, Oxon, OX14 3EA, UK

The JET toroidal field can be raised from the present level of 3.45 T with acceptable stresses in the toroidal (TF) and poloidal (PF) coils. The paper describes analysis of operation of the coils at fields up to 4 T.

1. INTRODUCTION

The JET toroidal field coils [1] are "D" shaped so that the toroidal field causes only 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 the mechanical structure; along the straight nose section by the fluted inner cylinder, on the outer parts of the coil by the outer shell casting and at top and bottom by collar and ring teeth.

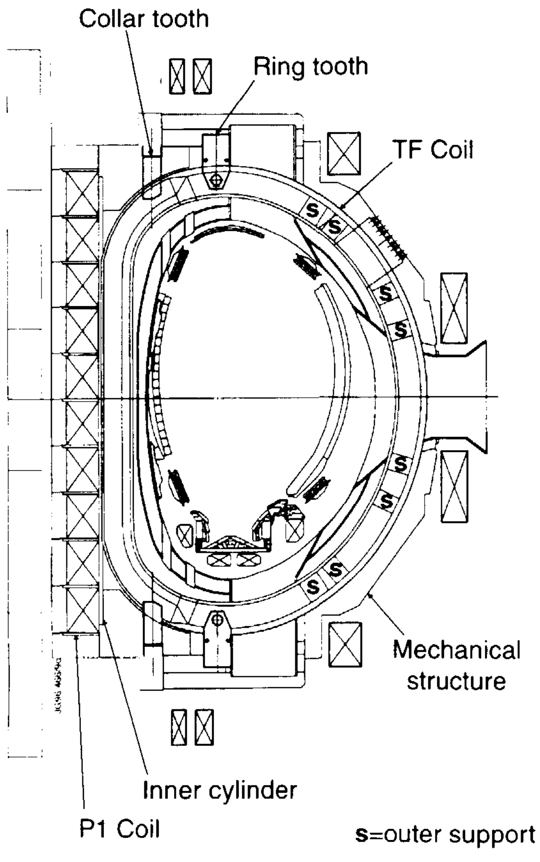

Figure 1. The JET machine showing toroidal and inner poloidal coils

Allowable stresses for the coil materials, based on test values, and allowable forces on the support structure have been established. Operational stresses and forces on the TF coils for plasma configurations of interest at 4 T have been calculated and are within these allowables. A slightly shorter pulse will be used so the temperature rise of the coils will not be changed and thermal stresses will not be affected.

2. STRESSES IN THE TF COILS

2.1. General

The toroidal field causes tension in the D shaped toroidal coils and an inward force which is reacted by the P1 coils. The poloidal field causes out of plane forces which are reacted by the mechanical structure.

2.2. Allowable stresses and forces

For the copper conductor the allowable stress is based on the minimum of $^2/_3$Sy and $^1/_2$Su, where Sy and Su are the yield and ultimate stresses of the material, as shown in Table I.

Table I. Allowable stresses in copper conductor		
All stresses in MPa	Copper conductor	Brazed joints
Tests		
Yield stress (Sy)	198 to 273	100
Ultimate stress (Su)	237 to 296	180 to 210
Allowables		
Primary stress	119	67
Primary + bending stress	154	87
Primary + secondary stress	178	100

Tests on the coil insulation show shear strengths of typically 45 MPa at room temperature and 33 MPa at operating temperature. This gives a basic allowable shear stress of 15 MPa with some increase for secondary stresses and local stress concentrations.

The strength of the outer part of the mechanical structure far exceeds expected out of plane loads. However a critical region for both the structure and coils is the ring and collar tooth region. The allowable forces in this region are given in Table II.

Table II. Allowable forces at coil supports			
	Max. force	Stress in tooth material	Force limited by
Collar tooth	50 tonnes	600 MPa	shear stress in coil
Ring tooth	75 tonnes	275 MPa	tooth bolts

2.3. Operational stresses and forces

Forces and stresses have been calculated for plasma configurations of interest at 4T and are listed in Table III. The table shows that coil stresses are all within allowable limits. This is because plasmas for use at 4 T have been specifically designed to limit the out of plane forces on the coils. Thus the maximum allowable out of plane forces, as Table II, will not be increased for operation at 4 T.

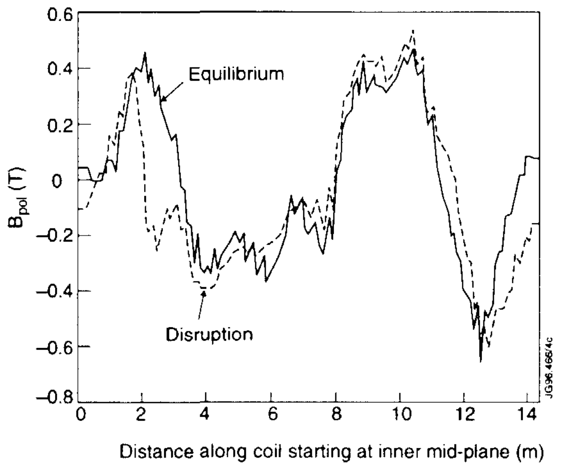

Figure 2. Normal magnetic field along TF coil periphery for 6 MA plasma

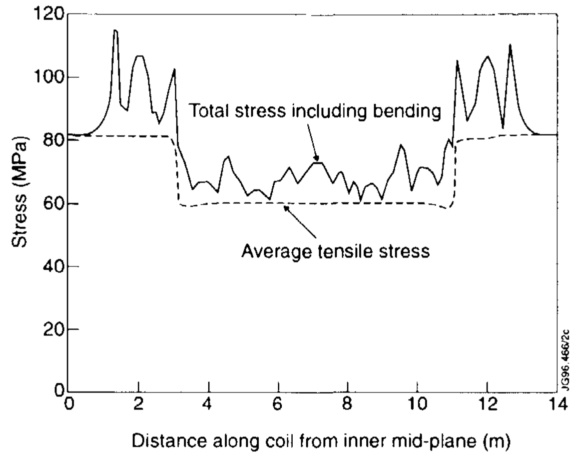

Figure 3. Tensile stresses in the TF coil conductor for 6 MA plasma at 4T

Figure 2 shows the normal magnetic field for the 6 MA plasma in Table III, calculated using the JET Maxfea equilibrium code. Figures 3 and 4 show stresses due to the same field calculated using a 136 element Abaqus beam model.

The tensile force in the coil is constant so the average tensile stress only changes at changes in coil cross-section. 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. It also depends on the support positions. Similarly the shear stress is composed of in-plane and out-of-plane shear and torsional shear.

Table III. Forces and stresses in the TF coils at 4 T. with typical plasmas			
Plasma description	simulation of ITER plasma, ρ^* scaling	5 MA, high q95, high ICRF coupling	6 MA scenario
Plasma current (MA)	4	5	6
Shear Stress [in the insulation] in MPa			
inter-pancake at nose	8.9	10.0	10.4
inter-turn at collar tooth, top [peak]	8.4	17.3	17.2
inter-turn at collar tooth, bottom [peak]	5.7	14.4	15.4
Tensile Stress [in the copper] in MPa			
total at nose	108	113	114
primary + bending at brazed joints	72	76	76
primary at brazed joints	60	60	60
MS Teeth Support Forces [out-of-plane] in tonnes			
collar tooth, top	-23.2	-48.1	-47.8
collar tooth, bottom	16.0	40.0	42.6
ring tooth, top	*52.6*	*50.6*	*57.7*
ring tooth, bottom	*-66.0*	*-61.6*	*-70.1*
The table gives the maximum stress or force for equilibrium or disruption conditions. Normally the maxima occur in equilibrium, except for the values in *italic*, which are for disruption conditions.			

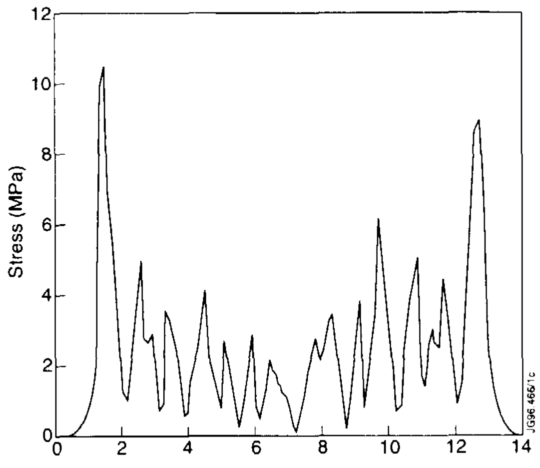

Figure 4. Shear stress in the TF coil insulation for 6 MA plasma at 4T

2.4. Further Analysis

The following points are being studied further.

- Stress analysis of collar region using new model to determine peak and average shear stress. This will be compared with previous JET analyses.
- Crack propagation in collar region to determine whether inter-turn cracks are self limiting.
- Effect of delamination in collar region to show that the coil can operate safely with partial failures.
- Further assessment of relevance of previous tests.

3. STRESSES IN THE P1 COIL

3.1. General

The inward load of the TF coils (proportional to B^2) is transferred to the P1 coil, which is in turn supported by a steel ring. The division of forces between coil winding and support ring depends on

- the elastic properties of each
- the initial state of stress (the coil is pre-stressed at room temperature)
- temperature of P1 coil (as the coil heats the copper carries a larger proportion of the load)
- current in P1, which balances the TF force.

In principle the P1 coil is axisymmetric so there are no primary shear stresses. Secondary stresses are caused by internal features (such as conductor joggles and terminals) and by temperature gradients.

3.2. Allowables

The materials and construction methods used for the P1 coil are similar to the TF coils so similar allowables are applied for copper and insulation. The additional element in P1, the steel support ring (Fe 86%, Cr 13%, other elements <1%) has an allowable primary stress of 240 MPa and a total allowable stress including secondary stress of 360 MPa.

3.3. Analysis

A comprehensive analysis of the P1 coil was made in 1989, when JET plasma current was increased from 5 to 7 MA. This analysis included global and local finite element models of the coil, support rings and internal features (Figure 5).

Because of the large number of independent variables (poloidal field, toroidal field, poloidal current and temperature) which affect P1, the number of load combinations is very large. It is impractical to run every load case through the FE code, so unit load cases were run for Bz, Br, dBz/dr, dBr/dz, external radial and vertical pressure, coil/ring interference and temperature distributions (function of time and current). Pulse scenarios were then constructed using these unit load cases.

Operation at 4 T has been studied using the unit load cases developed in 1989. This analysis has shown that the P1 coil temperature is one of the most critical features for high field operation, because a raised temperature in P1 transfers load from the coil support ring to the coil itself. It is therefore necessary to limit the pulse I^2t for the P1 coil to 28.10^9 A^2s. This value gives acceptable stresses and not limit proposed plasma operations. The relationship between P1 and TF current also has to be controlled, because the forces due to the poloidal field balance the inward pressure due to the TF coils. This relationship is illustrated in Figure 6.

3.4. Further Analysis

Although primary stresses are acceptable further work is needed to determine the relevance of stress concentrations indicated by the FE analysis.

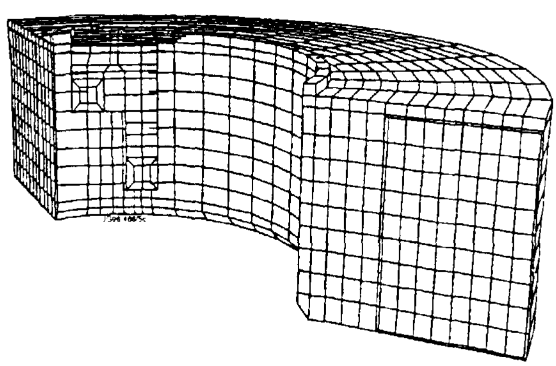

Figure 5. Global finite element model of P1 coil

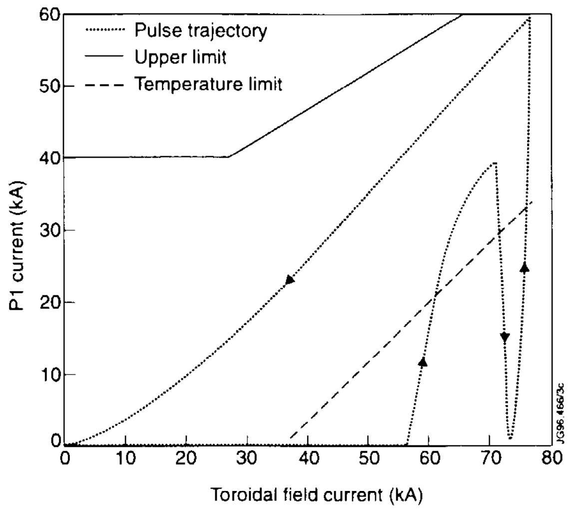

Figure 6. Safe operating region for P1 coil. The P1 current has to be below the upper limit and above the temperature limit when the coil is hot. The pulse trajectory crosses the temperature limit in the early part of the pulse but this is acceptable because the coil is cool at this time.

4. TESTS

4.1. Small sample tests

The materials data base will be improved by destructive tests on one of the TF coils which was found to have an inter-turn fault. Cross sectional slices have been cut out of one of these coils, as shown in Figure 7. These slices have been examined to determine the condition of the coil insulation. The insulation is in good condition but there is some evidence of inter-turn delamination. This delamination is partly due to in-built stresses which are released when the coil is cut but could also be due to stresses in operation.

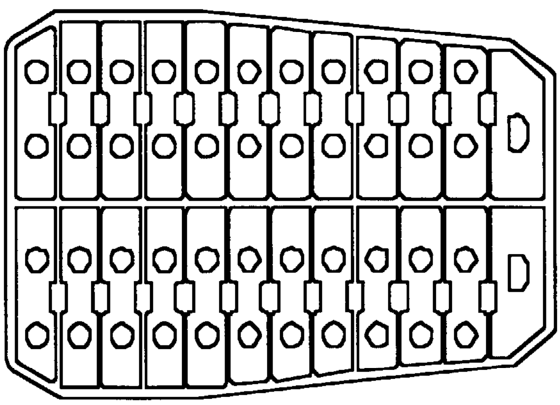

Figure 7. Cross-section of TF coil

Mechanical test samples will also be cut from the slices as shown in Figure 8. The elasticity of the side supports is designed to ensure that the sample fails in shear rather than combined shear and tension. The test sample is designed to measure the strength of both the inter-turn insulation and of the key. A typical force/deflection graph is shown in Figure 9. The first two steps in the graph occur

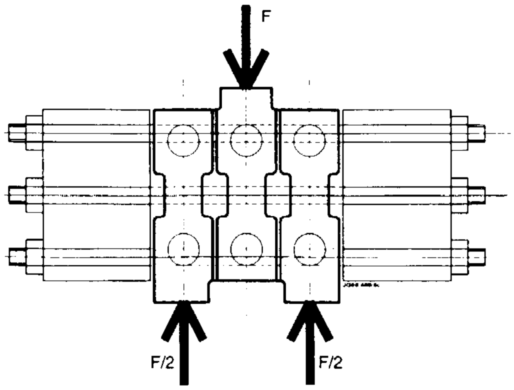

Figure 8. Test sample for measurement of inter-turn shear strength.

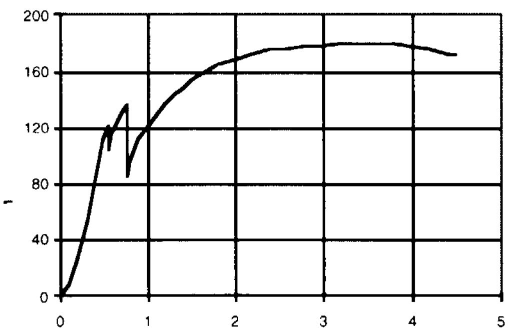

Figure 9. Typical force/deflection graph for sample in Figure 8

when the two sides of inter-turn insulation fail. The load then transfers to the key. Further deflection is due to plastic flow of the copper adjacent to the key.

4.2. Tests on complete coils

Force/deflection tests will also be made on coils that have been used in operation and an unused spare coil. The object is to determine whether the coils have deteriorated mechanically during operation.

A test machine is available, which can apply 3 point bending loads, either in the plane of the coil or perpendicular to the plane. Loading conditions will be chosen which give allowable peak stresses at locations of interest. Fatigue tests will also be made on the coil that is no longer required for operation.

5. CONCLUSIONS

Initial assessment shows that it should be feasible to increase the toroidal field in JET. Further analysis and tests will be made to validate the initial assessment.

REFERENCES

1. M. Huguet, K. Dietz, J.L. Hemmerich, J.R. Last, The JET Machine: Design, Construction and Operation of the Major Systems. Fusion Technology, January 1987 - Vol. 11, No. 1