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JET Reliability Assessment for 4T Operations and the DTE1 3.8T Experience

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ABSTRACT

The design value of the toroidal magnetic field (TF) for JET is 3.4 T. Operations were limited to this value until late 1997, when it was raised to 3.8 T. It is planned to further increase it to 4 T. This increase follows an in-depth reassessment of the critical components, namely the TF coils, the Mechanical Structure (MS) and the vacuum vessel (VV).

1. INTRODUCTION

The reliability assessment comprises both analytical and experimental work.

The analytical work resulted in the development of a new FE model of the TF coil [1] which accounts for the different material properties of the epoxy insulation and copper, and predicts peak localised stresses. The bolts in the mechanical structure that supports the TF coils have also been reassessed. In addition, the coil thermal stresses have been analysed in detail. In the calculations related to the VV, the main vertical port (MVP) FE model [2] has been upgraded.

In the experimental work on the TF coils, the fatigue behaviour of the brazed joints in the conductors and the strength of the epoxy insulation including the effect of radiation have been measured. Further fatigue measurements of the Inconel 600 used for the VV have also been undertaken.

2. ANALYTICAL WORK ON THE TF COILS

The TF coils see stresses which depend on the TF current only or on the combination of TF current and the poloidal field (PF). Membrane and bending stresses in the copper are within allowable limits for the material. Only critical areas of high stress are discussed here.

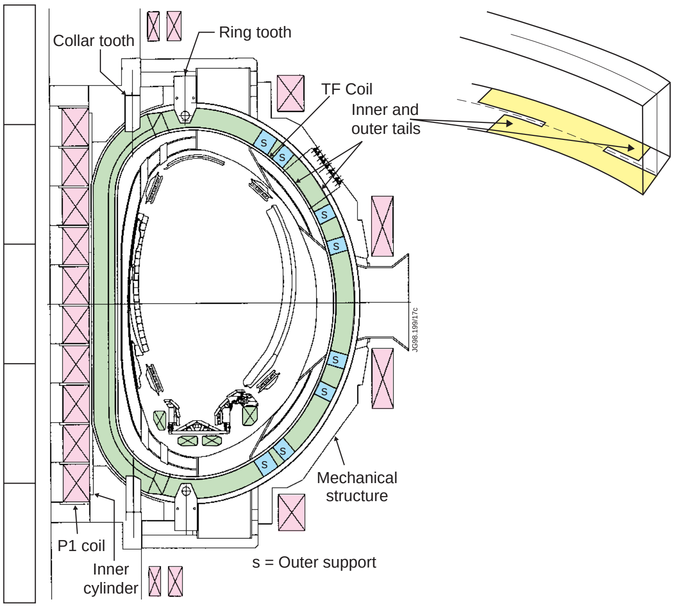

Fig. 1 TF coil cross section

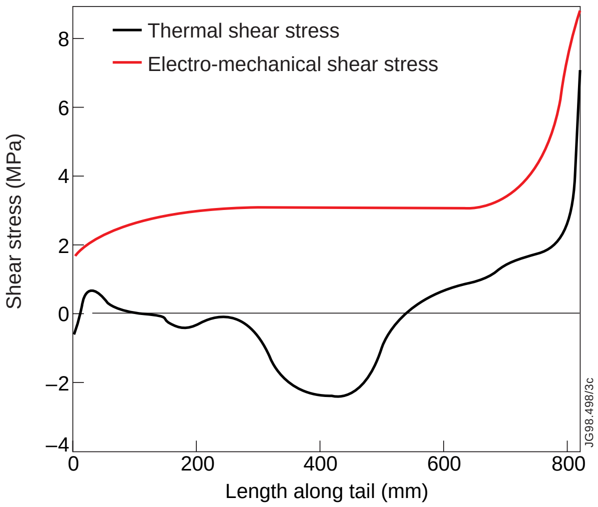

Fig. 2 Stress distribution along the tail of the coil.

The TF current alone produces in-plane magnetic and thermal loads. In most areas of the coil, thermal stresses in the conductor and in the epoxy are moderate, but relatively large local thermal and mechanical stresses are at the tapered conductor terminations (tails) of the coil (Fig. 1). The thermal shear stress at the tip of the tail depends linearly on the energy dissipated, proportional to $I^2(t)dt$ (called I^2t); the mechanical shear stress depends on I^2, where I is the TF current. At the end of the TF flat top of a 4 T pulse using the maximum I^2t (112 10^9 A^2s), the mechanical shear stress is 9 MPa and the thermal shear stress is 7 MPa. These stresses add to a maximum of 16 MPa. Fig. 2 illustrates the predicted thermal and mechanical stresses at the tail in these conditions. There are also high peak thermal gradients in the area of the inlet/outlet manifold which occur long after the end of the pulse: e.g. 100 s after the end of a pulse the thermal tensile stresses in the copper are ~47 MPa but only ~10 MPa at the end of the TF current flat top, when the mechanical total stress is ~60 MPa. The copper stresses are small compared with the combined allowable stress in the region, 178 MPa. The epoxy stresses are also small, 4 MPa, compared with the allowable values.

The TF current together with the poloidal magnetic field normal to the coil produce out-of-plane loads, whose intensity and distribution depend on the PF currents and on the plasma behaviour. These loads are of particular concern in the regions of the collar tooth and of the ring tooth supports (Fig. 1). Their peak can occur either during the equilibrium or after a disruption. Sometimes the forces increase in a disruption, but such events are rare. Slow increases are caused by a sudden drop in β_p, which shifts the current distribution pushing the out-of-plane loads to the inward side of the coils and increasing the load in the collar region. Fast increases or spikes may follow a substantial Vertical Displacement Event (VDE). In addition, since the PF coils are left free-wheeling after the disruption, these loads may increase because of the residual current flowing in the PF coils some seconds later.

The collar tooth out-of-plane support covers only part of the coil surface (Fig. 1), causing a peak in the inter-turn shear stress up to 9 MPa in the epoxy insulation. A new detailed FE model is used to predict localised peak stresses in this region [1]. In the ring tooth region, the pre-loaded M27 bolts clamping the tooth to the MS are the critical items. With their nominal pre-load of approximately 270 kN/bolt, the bolts see practically no dynamic loads even for the severest of disruptions. However, assuming conservatively a loss of pre-load to a value of 200 kN/bolts, these bolts will operate in fatigue when the ring tooth assembly sees loads in excess of

560 kN. A fatigue assessment of the severest of disruptions with a maximum load of 675 kN (ring tooth maximum allowed force) in the bolts assembly, resulted in at least 3500 permitted disruptions.

3. EXPERIMENTAL WORK ON THE TF COILS

The shear modulus of the fibre-glass/epoxy insulation (G) is a critical parameter for the stress distribution between copper and insulation. The higher the G, the higher the shear stress in the insulation. Original stress calculations assumed G=4 GPa. Measures of G using the Iosepescu method [1], which generates pure shear and reduces errors due to copper or support deformations, have confirmed this value at room temperature, but it falls to 1.2 GPa at higher temperatures, 90^0C.

During the DTE1 campaign the TF coils have seen radiation with ~1 kGy. Tests with γ radiation indicated no deterioration in the strength of the epoxy up to 10 kGy. Tests on brazed joints showed that the endurance limit was greater than the working stress at 4 T [3]. Comparative mechanical stiffness tests between a spare and a used coil showed that used coils had not deteriorated [3].

4. VACUUM VESSEL

A dynamic lumped parameters model [2] has been used to predict transient forces that act on the VV during disruptions. In addition, peaked dynamic forces, which may result from an uneven toroidal distribution of halo currents, have been analysed. The JET machine is stiff and, even for a large toroidal peaking factor, small dynamic force factors are excited, due to the long natural period of the VV. The contribution of the Neutral Beam Boxes (NBs) was also included in the analysis. This analysis showed that the NBs shift slightly the frequency response of the VV, the VV displacements are reduced (~20%) while the effect on critical stresses is marginal [4].

Material fatigue tests on Inconel 600 gave results consistent with the ASME fatigue curve, notwithstanding defects were found in the fatigue specimens, which came from the original batch of 16 mm Inconel 600 plates. These defects are the result of inclusions generated during the manufacturing process (rolling/cooling). Inclusions are not present in plates thinner than 16 mm, as those used in the critical area of the Main Vertical Port / Vacuum Vessel (MVP/VV) interface.

Improvements in the FE modelling of the geometry of the critical MVP/VV interface and the use of the measured rather than the specified yield strength of the material, resulted in acceptable strain for the severest disruptions, even if a stress concentration factor of 1.5 is included to accommodate weld defects. Thus the strain should not exceed 0.5% during the 4 T experimental campaign.

5. EXPERIENCE AT 3.8 T

At the end of the 1997, campaign 172 pulses have been performed above 3.45 T. The plasma disrupted in 20 of these pulses, but only 9 with an initial plasma current higher than 3 MA. The largest rolling motion [2] swing was 3.4 mm, produced by a 3.8 MA disruption, and no sideways displacement larger than 2 mm have been recorded. Consequently the life consumption of the VV during these pulses has been negligible. For comparison, the upper boundary of sideways displacements, scaling with the product I_pB_T [4], would have given a projected displacement of 11 mm at 4.2 MA and 3.8 T.

The typical mechanical stresses on the copper of the TF coils produced by a 3.8 T pulse are well within the allowable values [5]. The out-of-plane forces have been kept within the allowable values by restraining the allowed plasma shapes to limit the transverse field at critical regions of the coils. A reasonable estimate of the force acting on the collar and the ring supports, which in their turn determine the peak shear stress on the inter-turn insulation and the loads on the bolts, is given by the product of the transverse flux (measured by loops mounted on the coil) and the TF current. This product is constantly monitored. During the 3.8 T campaign the force on the ring supports has always been below 85% of the allowable value. In equilibrium and disruption, the force on the collar has been close to its allowed value, which is conservative in terms of both epoxy and bolt stresses. The increase in the toroidal field requires the exploitation of much of the available I^2t. The area most affected by this step forward in performance is the insulation at the tip of the tail. However, this peak stress does not occur in the bulk of the coil and should not affect its functionality. There have been >50 pulses above 15 MPa, which is the maximum stress achieved during 3.4 T pulses.

6. SCENARIOS AT 4 T

The introduction of the Gas Box divertor requires the MarkII-A plasma configurations to be adapted to the new geometry. Only the out-of-plane loads depend significantly on the plasma scenario. Since the operations will restart with the septum and the vertical plates in place, the X-point has to be raised. The plasma shape of the MarkII-A high-performance plasmas has not changed dramatically, but the divertor flux expansion can not be maintained and lower triangularity decreases. The proposed high-performance configurations (Optimised Shear at 4 MA, ELM-free H-mode at 4.3 MA and ELMy H-mode at 5 MA) can be run at 4 T without exceeding the limits on the forces and stresses on the TF coils, both in equilibrium and in disruption.

7. CONCLUSIONS

Advanced FE models used to simulate the TF coils and the VV have been extended to account more accurately for static and transient load conditions.

Localised peak thermal and mechanical stresses in the complex composite structure of the coils and their supports can be predicted and compared with strength values adjusted for temperature effects.

The VV dynamic analysis was also upgraded to account for the contribution of the NBs and possible higher modes of vibration.

The analytical investigations coupled with measurements of material strength indicate that JET has consumed a modest fraction of the life of its critical components and that, with suitable control of operating limits, it is able to withstand typically a thousand 4 T and 5 MA pulses and hundreds of disruptions.

8. ACKOWLEDGEMENTS

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