Thermal Considerations and Cooling System for the JET Divertor Coils

N Dolgetta, E Bertolini, P Butcher, M Cooke, J R Last,
V Marchese, P Miele, G Sannazzaro, A Tesini.

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

Abstract —**The recently installed and now operational JET divertor coils, have copper conductor and epoxy glass-kapton insulation, but are situated inside the JET vacuum vessel, which can be operated up to 350°C. Despite being insulated, in normal conditions, by the high vacuum, the coils are radiation heated by the surrounding enviroment, and also ohmically by current pulses during operation. The coils are cooled by insulating organic fluid and the copper conductor operating temperature ranges from 10°C to 65°C. The main concern is to maintain the epoxy at a safe temperature and to limit the thermally developed interturn shear stress. The cooling system is designed to limit the maximum differential temperature to 20°C, and it can operate in open and closed loop modes.**

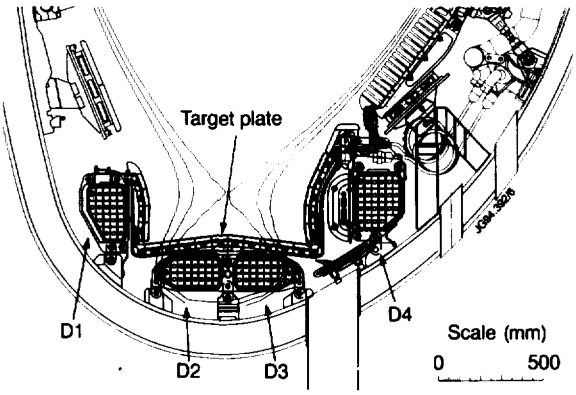

Fig.1. Divertor coils, target plate and cryopump installed in the vacuum vessel

I. INTRODUCTION

The divertor coils and cooling system were installed in 1993 and JET restarted operation in February 1994. Since the restart the thermal performance of the coils has been monitored in order to interpret the measured heat power load to the coils, and the temperatures measured on the Inconel casing. The aim is to estimate if any part of the epoxy-glass may be subjected to temperatures which might undermine its properties as insulating or structural material. Direct measurements of the epoxy temperature are not available. The present Mk1 divertor target plate is supported on the divertor coils, and its alignment ultimately relies on the mechanical stability of the epoxy. Calculations were also made to evaluate faults such as loss of vacuum or failure of the coil cooling system.

The coil cooling system proceeded in parallel to the coil. Measurements on the cooling system enabled the thermal power load to be determined.

II. COIL FEATURES AND ENVIROMENT

The divertor coils, are enclosed in thin Inconel casings (thickness 1.2 mm), which were also their impregnation-curing mould. They are anchored to the vessel by 32 clamps, allowing for radial expansion due to forces and temperature variations. Pads welded on the casing top surface of coils D2 and D3 support the target plate structure. The target plate is generally water cooled at about 70.°C, but operation with uncooled target plate proceeded for several months, and this may still be required for conditioning baking of the vessel. The coils are provided with radiation heat shields over about 75% of their surface (11 layers of polished stainless steel with a nominal 0.1mm spacing and 2.mm from the casing); the remaining 25% being unscreened, in particular the sections at the clamps, pads and coil terminations.

The shields considerably lessen the heat power load, which would otherwise require 50% of the available cooling power. However at the clamps and D2,D3 pads, combined heat radiation and conduction may produce a concentration of heat flux; for this reason the coil assembly includes copper plates, at the top and bottom of the coil, spreading the heat and protecting the ground insulation. Of most concern, from the thermal point of view is, the epoxy that, for structural purposes, fills the gap between casing and electrical insulation or copper plates, which is not protected by this feature.

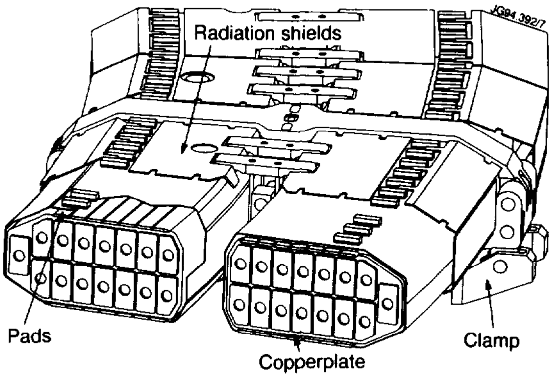

Fig. 2. Divertor coils D2, D3 section

III. THERMAL ASSESSMENT

A. Thermal power load and temperature measurements

Temperature of the casings is monitored, at four points per coil, at two positions (Octant 3 and 6), and at the top and bottom. The thermocouples welded on the casing are 20.mm from the clamps and indicate the temperature at the unshielded part of the casing.

The cooling system is used for the thermal power load measurements since, in steady state conditions, the power is given by:

$$Q = \dot{m}C\Delta T$$

$\dot{m}$ *Coolant mass flow,* C *Coolant thermal capacity,* ΔT *differential temperature.*

To assess the power scaling and the main heat transfer mechanism to the coils, measurements were performed with the vacuum vessel at several temperatures, in steady state conditions, between 150°C and 250°C (with no target plate cooling). To confirm the above result the cooling system was stopped for 1 hr. leaving stationary coolant in the coil (vessel at 250°C). A temperature increase of 10°C of coil and coolant was observed at the restart of the cooling flow, consistent with the measured thermal power and coil mass. A loss of vacuum in vessel would increase the thermal power load to the coils. Tests were performed, to assess the effect of a vacuum loss up to 1 bar of air in vessel, considering that in the past JET experience, in the worst event, pressure rose up to 400.mbar. Gases H_2, and N_2 were injected in flowing and stationary conditions, up to 10 mbar pressure, with the vessel at 150°C and, 250°C respectively. The effects on the coolant differential temperature, due to the increased heat power, are shown in Fig.3 for coil D4. In this case 10.mbar N_2 was maintained in vessel for four hours (from 0 to 4 hrs) to reach stationary conditions, then reistablishing the normal high vacuum. The differential temperature appears to double, while the undershoot at 10.hr is due to fluctuation in the coolant inlet temperature. Tests were repeated with the cooled target plate (vessel at 250°C), although, thermal power loading, failure of the cooling system, and vacuum loss pose less serious damage.

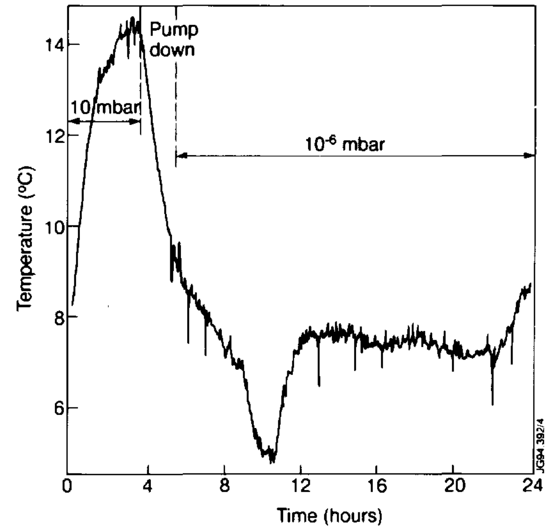

Fig.3. D4 Coolant differential temperature during 10.mbar N_2 injection in vessel

B. Interpretation and modelling

A model representative of the casing shielding non uniformity has been developed; parameters have been determined so as to obtain consistency between the measured power and temperatures. The measured thermal power load dependence with the vessel temperature scales as the radiation law. Casing surfaces screened by the heat shields contribute marginally, about 10% of the heat power load to the coil. Their equivalent emissivity is about 0.01, a factor of about 1/20 compared to the unshielded casing surfaces. The underlying epoxy is in all cases less than 5°C higher than the coil copper. The radiative power is essentially transmitted through the unshielded casing parts, where the underlying epoxy is about 30°C higher than the coil copper. Measurements and model predictions, in high vacuum, are in agreement if the emissivity assumed is 0.3, compared to the nominal value for polished Inconel of 0.15. This is conceivable considering the blackening effect on the surface due to glow discharge conditioning and plasma operation. Molecular conduction is the main means of heat transfer across the interspace between casing and epoxy, estimated at about 20W/°Cm^2, compared to radiation $\simeq$5W/°Cm^2. This interspace, which is pumped down to $\simeq$0.1 – 1.mbar, was formed during resin polymerisation. The clamp conductive contribution appears negligible, possibly due to a low pressure on the contact between casing-clamp, and in the pins linking the clamp to the vessel. The contact pressure, depending on coil and target plate weight, but also on the deflection profile of vessel could not be defined beforehand. The epoxy layer underlying coils D2,D3 pads is the most critically affected by the vessel temperature, because of the observed, larger than expected, heat conduction from the target plate graphite tiles to the supporting Inconel structure. Also the graphite tiles bulk temperature may increase to hundreds of degrees higher than the vessel temperature with repeated pulsed plasma operation. With an uncooled target plate, operation proceeded with maximum vessel temperature up to 250°C, and the pads underlying epoxy is estimated to have reached $\simeq$180°C. The effect on the epoxy disappears with a cooled target plate. Baking and operation with the target plate uncooled have now been restricted to a maximum vessel temperature of 200°C, while, with target cooled, this temperature will be allowed to rise to 320°C.

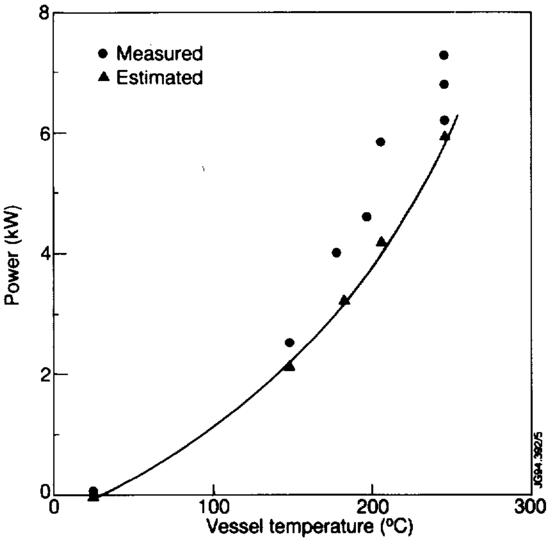

Fig.4. Thermal power load and model prediction for D4

In case of a considerable water leak to the vessel, or vacuum loss, heat transfer to the coil, would increase by molecular gas conduction at first and then by convection. Decay in the effectiveness of the radiation shields, spaced 0.1mm apart, is an important effect, with the radiative power to the coils increasing also at pressure as low as $\simeq$0.1mbar during glow discharge conditioning. Test results of in vessel gas up to 10.mbar pressure, were in agreement with predictions, considering natural convection and shields loss of effectiveness. Procedures, in some cases requiring to lower the vessel temperature at 20°C/hr, were laid down to safe guard the coils, in case of failure of target or coil cooling.

IV. Cooling system

A. Design parameter

The cooling system is designed for the following requirements.

- Limit the thermally developed shear stress in the interturn insulation
- High cooling rate
- High electrical resistance coolant
- Limit the pressure of the cooling circuit and flow velocity

Shear stress is developed in the interturn insulation due to the thermal gradient between turns and the coil spurs. This has been estimated to be of the order of 0.5 MPa/°C, resulting in 10.MPa for a temperature difference of 20°C, between adjacent turns. This is to be compared with a shear stress at breaking of 45.MPa, for specimen at 20°C, and of 22.MPa at 80.°C. During cycled operation, the maximum differential temperature of the coil parallel cooling channels (2 for D1,D2, D3, and 3 for D4) is limited to 20°C by limiting the coil measured differential temperature to 15°C, and so maintaining the shear stress to < 10 MPa. The largest I^2t allowed is 21.10^{9}A^{2}s, corresponding to a flat top of 40.kA for 8.s, and a temperature increase of 47°C; in this most demanding case the estimated cooling time is 60.min..

The coolant choice was CFC113, as for the JET TF coils, an organic insulating fluid, which would prevent the coils from developing interturn faults in case of an internal leak through a brazed joint. Besides this remote possibility, CFC cooling provides an insulation resistance to earth > 1MΩ, a factor more than

100 times higher than water, resulting in sensitive detection of any change in the coil insulation to earth. On the other hand CFC has only 30% of the heat capacity of the equivalent water volume, requires special handling procedures, and in the event of a leakage the cooling system may have to be stopped, unless secondary containment is provided. Pressure in the circuit is limited to 18.Bars, compared to a bursting test pressure of fitting and hoses of 250.Bars; flow velocity is limited to 3 m/s, to avoid erosion .

Table 1 Divertor coil cooling system capacity, $\Delta T=15^{\circ}C$

	Coil	D1	D2	D3	D4
Main flow	Flow rate (m^3/hr)	3.96	4.32	5.04	7.92
	Pressure (bars)	6.0	7.4	10.8	13.1
	Cooling (KW)	22	24	28	43
Emergency flow	Flow rate (m^3/hr)	1.47	1.42	1.24	1.90
	Pressure (bars)	1.0	1.0	1.0	1.0
	Cooling (KW)	8	8	7.5	10.5

JG94.392/1

B. Cooling system layout and operation

The main cooling system, individual to each divertor coil, is connected in parallel to the TF coils system, providing a resevoir of cold fluid at 5.Bars, and avoiding the need for new heat exchangers. The main cooling system schematic and components is shown in Fig.5.

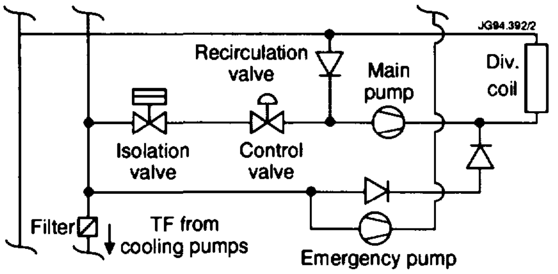

Fig.5. Cooling circuit diagram for one divertor coil (repeated for each coil).

During operation in closed loop, the control valve is closed before the start of the power pulse, setting the cooling to full recirculation; following the pulse the valve is automatically operated to control the differential temperature to 15°C. The design ensures that the fluid leaving the coil reaches the recirculation path in less than 10.s. In case the differential temperature of 20°C is exceeded, during open loop operation or failure of the control, the isolation valve closes forcing the flow to full recirculation.

An "Emergency cooling system" is also installed, in parallel and with common pump for the four coils, operating only in open loop mode, capable of extracting the thermal power load to the coil and limited operation.

Early operational experience, in open loop mode, showed a cooling time of the coils longer than expected. Due to the large heat load, the outlet coolant temperature of the heat exchanger, in common to TF and Divertor coils, would increase, after a pulse, to 30°C, limiting the cooling rate of the Divertor coils. A new dedicated heat exchanger, cooling the fluid from the TF system to the Divertor coils is being considered. Full commissioning in closed loop mode is now to preceed.

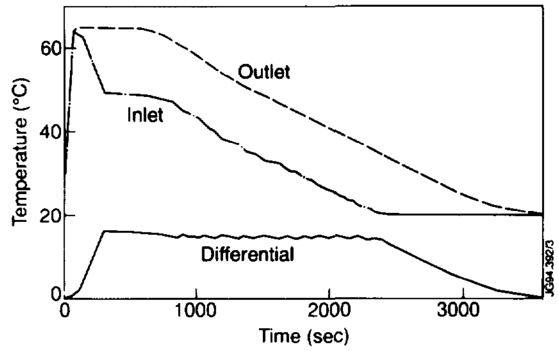

Fig.6 D4 Cooling evolution for high I^2t pulse

V. CONCLUSION

The divertor coils performance and vessel temperature, have gradually been increased after having established safe thermal conditions for their operation.

Present restrictions will be reviewed and possibly relaxed with the Mk2 divertor configuration as the critical pads on D2, D3 coils will not be in contact with the target plate.

REFERENCES

[1] J.R. Last et al, "The JET divertor magnetic configuration and coil design.", Proceeding of the 16th Symposium on Fusion Technology, London 1990.

[2] N. Dolgetta et al, "JET Divertor Coils Manufacture, Assembly and Testing.", Proceeding of the 13th International Conference on Magnet Technology, Victoria, British Columbia, 1993.

[3] M. Cooke et al, "Organic Cooling Fluids for the JET Toroidal and Divertor Field Coils", presented at the 15th Symposium of Fusion Engineering, Hyannis, Massachusetts 1993.