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WALL PROTECTION IN JET

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JET JOINT UNDERTAKING
Abingdon, U.K.

JET has operated initially with graphite limiters and Inconel walls. An inspection after twelve months of operation showed damage to the inner wall, mainly due to runaway electrons. About 1 kg of Inconel was melted. To inhibit this source of metal contamination of the plasma - metal droplets were deposited on the limiters - 20 m^2 of graphite tiles were installed at the inner wall. They will also act as protection against beam shine-through as soon as neutral injection becomes available.

This paper describes the wall damage observed, the design and operational limits of the graphite protection and discusses the future plans.

INTRODUCTION

The presence of a hot plasma close to the material walls of a vacuum vessel requires special conditioning procedures[1] and a suitable choice of the wall and limiter material in order to minimise the impurity influx into the plasma. The impurity production processes are well known[2,3] but their relative importance is not fully understood. One of the main aims of JET is to study this problem[4] and to find means to reduce the impurity influx to such an extent that radiation and dilution processes in the plasma core become sufficiently small to reach reactor-near conditions.

Initially JET operated with Inconel walls and graphite limiters. The conditioning procedure was mainly glow discharge cleaning. After a short period of operation it was observed that the graphite limiters were the main source of high-Z contamination. Metals from the walls accumulated on the limiter and were released into the plasma. Possible sources of this contamination were the glow discharge cleaning process where hydrogen atoms, being accelerated in the sheath potential of about 300V sputter wall material, the normal plasma operation when sputtering occurs by charge exchange neutrals, and abnormal operation conditions such as disruptions. It was observed that in JET during a disruption the plasma moved to the inside wall. The voltage spike associated with a disruption drives run-away electrons which hit the inner wall. From the

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simultaneously observed photo-neutrons it could be estimated that melting and evaporation of the inconel heat shields should occur.

To eliminate this source of limiter contamination by metals it was decided to install graphite heat shields at the inner wall. At the same time this gave the opportunity to investigate the plasma behaviour with a completely low-Z machine, by covering the rest of the vessel with a carbon layer[3]; the parts of the vessel prone to damage by disruptions being covered by graphite tiles.

DAMAGE ON THE INCONEL PROTECTION

The inner wall consists of rigid sectors, bellows assemblies and octant joints[5]. They are protected by heat shields and protection plates (Inconel 600). This is illustrated in fig. 1 (top) where a cross-section of the midplane of the inner wall is shown. The damage is localized to heat shields and protection plates mainly centred around the midplane of the machine (fig. 2).

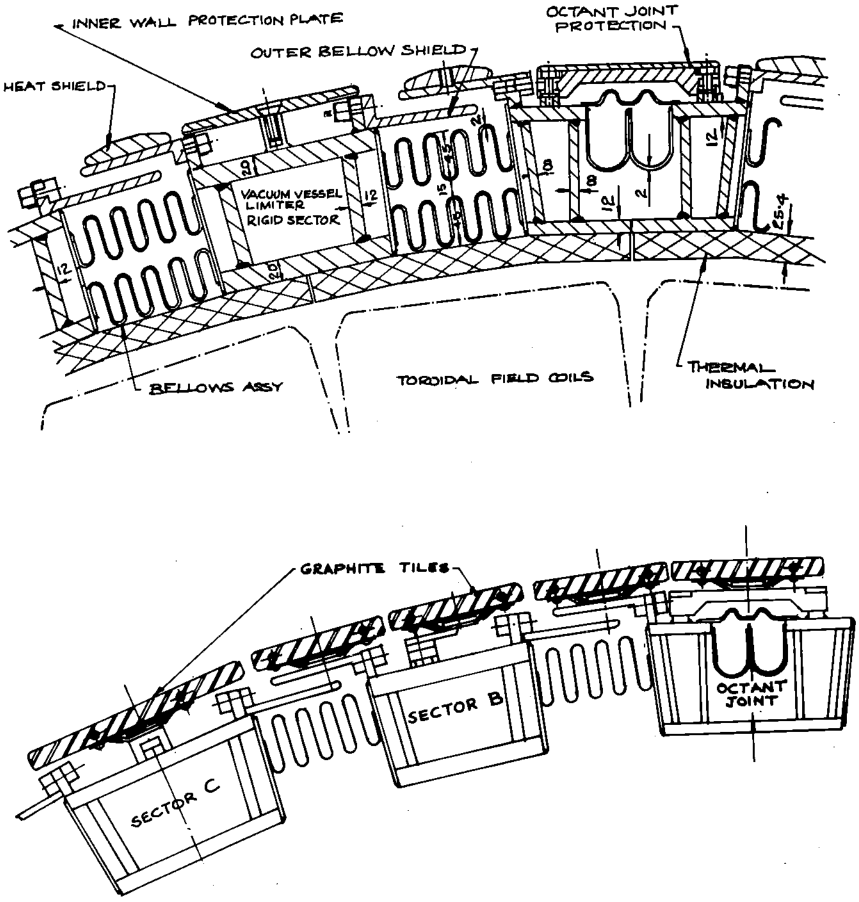

Fig. 1 Inner wall protection.
top: Inconel
bottom: Graphite

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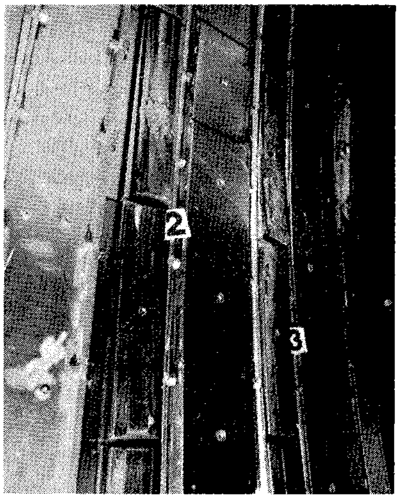

Fig. 2 Example of wall damage.

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Two distinctly different types of damage were found. The first one is characterised by a thin (<0.1mm) melted layer which extends along the edge of the protection plates. Depending on the position in the machine, the damage is on the left hand side (electron side) for locations above the midplane, at the ion side for locations below, and at electron or ion side at the midplane.

The melted areas were non radioactive, they are associated with a carbon deposit of about 100nm thickness. The damage of this type seems to be caused by plasmas leaning against the inner wall for a short time.

The second type of damage (fig. 2,3,4) is more severe. It consists of melted zones (shallow craters) of semi-circular shape, sometimes more than 1mm deep. The melt appears to have moved radially from a centre which in most cases is located at the edge of the tile. This indicates that neither eddy currents nor gravitational forces are responsible for this motion. Assuming a volumetric energy deposition, e.g. runaways, it appears more likely that the melt is driven by high internal pressure caused by heating of residual gases in the metal or by internal evaporation of metal.

The damage is almost exclusively on the inner wall protection plates adjacent to octant joints on that side of the plates which points to the octant joint.

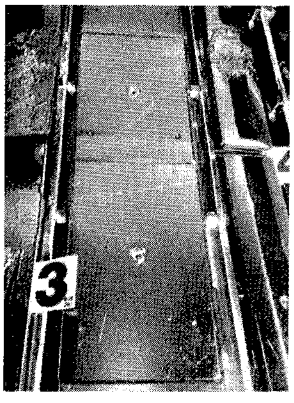

Fig. 3 Example of wall damage.

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Fig. 4 Examples of wall damage.

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Table 1. Size distribution of damaged areas.

Size distribution	Number of events
0 – 5cm²	10
5 – 20cm²	29
20 – 50cm²	9
> 50cm²	3

Due to the design of the supports of the protection plates there exists an angle of about 4° between the plates and the circular track of runaway electrons, leading to an intersection.

There is much less damage found on the heat shields since tilting of these shields does not shift the leading edge to the same extent towards the plasma as for the protection plates.

From the geometrical observations and from the radioactivity of the melt zones (10-50nC/kg) it is concluded that the damage results from run-away electrons. These are produced during disruptions by the associated spike in the loop voltage. At the same time the plasma is driven to the inner wall and the runaway electrons deposit their energy at locations which intersect with the plasma. The total number of events is approx-imately 50, the size distribution is given in Table 1. Most of these events (40) were found to be located in the midplane, 10 below and one above.

Due to the following uncertainties it is difficult to calculate the total amount of material melted or the energy deposited:

In several cases the damage from several events are overlapping. Due to the distortion of the protection resulting from the first impact, edges sticking out received several impacts of runaway electrons.

The temperature of the melt is not known. From the appearance of the resolidified melt it could be close to the boiling point for some events or close to the melting point for others.

The amount of debris fallen off was determined by measuring the volume of a replica of the crater, but melt resolidified on the tile can only be estimated from the thickness of a coarse grain structure apparent on optical micrographs.

With these uncertainties the damage resulting from a single event resulted in melting between 4-30 g and the deposited energy was $6 \times 10^3 - 5 \times 10^4$J. This has to be compared with calculations[6] of the amount of melted material from the yield of photo-neutrons (1.1×10^{15}). A total amount of 5000 g of melted material was calculated. This is about 5 times higher than the above estimate. The main uncertainty in this calculation is due to the fact that the energy of the runaways as well as the cross-section for producing photoneutrons is only known approximately.

GRAPHITE PROTECTION TILES

After having established that one source of the limiter contamination by metals was the runaway interaction with the inner wall it was decided to have a material other than Inconel in contact with the plasma. This material should have the following properties:

- low density to spread the energy deposition by runaways over a large volume
- high specific heat to minimise the temperature increase
- high melting or sublimation temperature
- low-Z to minimise the effects of plasma contamination
- high resistance against thermal stresses, i.e. low modulus of elasticity and expansion coefficient and high values of permitted tensile and compression stresses.

The thermal conductivity is of less concern as the disruptions occur typically on a time scale of 10-100ms and thermal diffusion can be neglected compared with the penetration depth of high energy electrons.

One obvious choice was graphite, using the same material as for the limiters (CL5890PT, manufactured by Le Carbone Lorraine). The penetration depth of runaway electrons (5-30 MeV) is 15-80mm. They have grazing incidence on the surface and as their energy loss is about constant for the energies considered, a nearly uniform heating of the surface layer of the protection tiles can be expected. For the energies found for melting the Inconel protection (5×10^4J) a temperature rise of 1000°C can be derived for the surface. This is well below the sublimation temperature and thermal stresses remain low.

The design of the graphite tiles is shown in fig. 1. The Inconel protection is replaced by V-shaped carriers into which the graphite tiles are assembled. The graphite has an Inconel attachment plate having fingers which slide over the V-shaped carriers. The graphite tiles of 20mm thickness have two holes into which attachment rods (Inconel 600) are fitted with a clearance of 0.3mm. The attachment plate is screwed by four bolts to the attachment rods. A spring washer (Inconel 718) allows for thermal expansion between the graphite and the screws (Inconel 600). A spring (Inconel 718) is fixed to the carrier (Inconel 600) which counteracts undesirable movements of the tile assembly. Stop screws (Inconel) on the carrier which slide into a slot in the tile assembly allow for correct positioning of the tiles.

The protection was installed on the inner wall covering a height of 2m (fig. 5). The slots between the tiles are not horizontal to avoid plasma penetration.

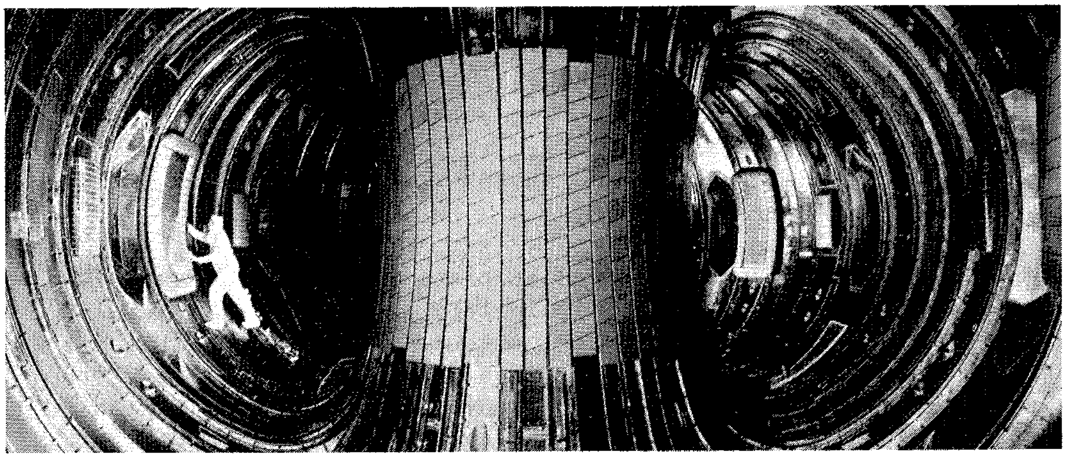

Fig. 5 Inner wall protection by graphite.

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The operational experience after six months of operation was excellent. Virtually no damage was observed and this even after a period during which the total dose of photoneutrons exceeded 10^{16} and disruptions up to a current level of 4.5 MA occurred.

PROTECTION AGAINST BEAM SHINE-THROUGH

In addition to the task of acting as a protection against runaways, the graphite tiles have to take the heat load (500 W/cm^2 for 10s) during Neutral Injection which occurs when at low plasma density a fraction of the beam particles impinge on the inner wall.

The present design is completely adequate for this purpose as tests in the JET Neutral Injection system have demonstrated[7]. Heat loads of 1 kW/cm^2 were applied for eight seconds duration. Only when the power was increased to 1.5 kW/cm^2 for 2s, the test tile developed a crack during the second pulse. Three dimensional stress calculations have shown that a graphite tile without any support (i.e. no holes which act as stress amplifier) can support 1.5 kW/cm^2 for 10s. The holes increase the stress by a factor of 2.8. For a load of 1 KW/cm^2 for 10s duration the stresses remain below 40 M Pa for tension and below 110 M Pa for compression. These values are the upper limit for the graphite used.

In case of firing the Neutral Beam with no plasma in the machine, e.g. immediately after a disruption, peak loads of 2.5 kW/cm^2 will occur. The present design requires that the beam must be switched off within 0.2s after such an event to avoid damage to the tile. If there was no stress amplification this time could be extended to about 1.3s.

In principle the inner wall protection should be able to withstand one event during which the unattenuated beam hits the inside wall. It is evident that this cannot be achieved with the present design. It will be necessary to either reduce the thickness of the tiles by 5-10mm and to develop a new support which does not increase thermal stresses or to employ a different type of graphite (carbon fibre reinforced) together with a modified support.

FUTURE DEVELOPMENT

One source of limiter contamination by metals was successfully eliminated by covering the inside wall of the vacuum vessel by graphite tiles. The operational experience was good, virtually no damage was observed after 6 months of operation. Together with carbonization of the vessel radiation levels as low as 35% could be achieved for the first few weeks of operation.

This good performance degraded as other sources of "explosive" evaporation developed, which led again to the formation of metallic droplets on limiters and inner wall protection. In particular melting of the Inconel surface of heat shields at the top and bottom of the machine occurred during experiments studying the effects of highly elongated plasmas, vertical instabilities, and separatrices inside the vessel. The resulting damage shows a pattern similar to that earlier observed for the inner wall under runaway impact.

The octant joint protection will now be replaced by graphite in such a way that eight poloidally closed rings are formed. In addition the graphite already installed will be taken out and cleaned. During the shutdown end of 1986 all heat shields for the bellows protection will be replaced by graphite.

As soon as additional heating becomes available the inner wall protection will also act as protection against beam-shine through. The present design will have to be modified to cope with loads of 2.5 kW/cm^2 for up to 10s.

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