Received by OSTI
CONF-880929--11
Paper submitted to SNL
After publication - D. Croessmann
APR 0 7 1989
SAND 89-0670C
SAND--89-0670C
DE89 009325

TORE SUPRA GRAPHITE INNER FIRST WALL

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TORE SUPRA is a fairly large tokamak (R = 2.350 and r = 0.800) and has an original goal to withstand a large power removal (25 MW) during a 30 seconds long pulse / 1 /. One of the main energy removal system is the inner first wall which was originally designed for the following aims :

- protect the inner side of the vaccuum vessel from normal plasma operation (participates to the plasma power removal) and against disruptive events (plasma energy quench and current decay),
- act as a toroidal belt limiter during steady state operation and plasma start up,
- protect the vacuum vessel from the shine through of the neutral beam injectors and act as a beam dump for short shots.

In order to match those different goals the design choice was oriented towards an actively cooled graphite wall capable to sustain an 1 MW/m^2 continuous heat flux. As for all other inner components, a pressurized water circuit (3.5 MPa) is used to remove the heat load and to bake out the vessel up to 240°C. A stainless steel square tube with a circular inner channel (see figure 1) was choosen because of the moderate heat flux and the vacuum compatibility. Geometrical dimensions (tube diameter and length) and the water flow where adjusted for a 0.4 MPa pressure drop with an 80°C water temperature increase on the whole wall.

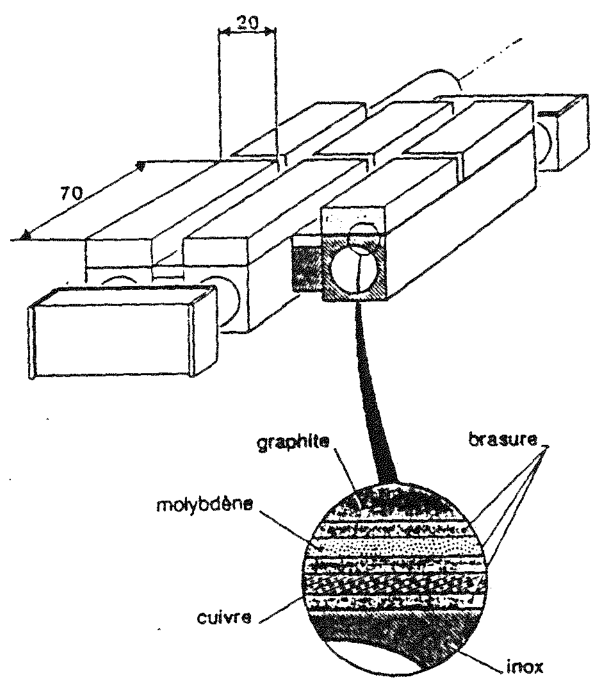

FIGURE 1
Inner first wall design concept

The 150° poloidal extension of this wall allows to cover 23 m^2 of the inner vessel ; but only the graphite, which represent a 12 m^2 area for ther 8700 brazed tiles can be in contact with the plasma. The remaining space is filled by the stainless steel spacers and plates welded to the coolant lines.

The poloidal curvature of this wall was adjusted to give a 35 mm scrape off at the ends of each sector (θp = + - 75°) for a

R = 2.360 and r = 0.800 m plasma which is pushed against the equatorial plane of the inner first wall.

The design concept is based on square stainless steel tube protected by brazed graphite tiles (see figure 1). Stainless steel may have a low heat transfer coefficient but it is sufficient for the desired heat flux. The main advantages of this material are the good weldability, deformation capability, high electrical resistivity and is well known for tokamak fabrication. The graphite is high density grade from Le Carbonne Lorraine (Gennevillier, France) named 5890 PT.

As other components this wall is hydraulically divided into six modules having each an separate inlet and outlet through the vacuum vessel. One module is also divided in six individual sectors, each of 10° toroidal extension and being feeded in parallel. One sector is composed of 9 stainless steel tubes (roughly 2.2 m long) welded 3 by 3 (one groupe of 3 formes the elementary concept seen in figure 1) and connected in serie.

The brazing studies were started by C.E.A. and then jointly developed with the company Vide et traitement for this application. The brazing joint was studied to ensure a good bonding beetween all materials, to lower the stresses in the graphite and to accomodate the thermal expansion differents by plastic deformation (a sketch of this joint is visible on figure 1). A good brazing quality requieres a 0.1 MPa minimum pressure on the components at the melting temperature and during the cool down of the structure. Therefore a brazing jig was studied and build for this purpose.

Finite elements calculations backed up with thermal tests have shown that the graphite surface temperature should not exceed 1200°C for a 2 MW/m^2 incident heat flux. The time constant of this concept is 15 seconds and steady state is reached before 25 s. Critical heat flux calculations also backed up by tests showed that the wall can be safely operated under a steady incident heat flux of 1.5 MW/m^2 on the whole sector with a 150°C inlet water temperature (total tubes lengh - 20 m). Some local subcooled boiling can appear but this is not the principal cooling mechanism. The main limitation comes from the fatigue of this joint induced by the residual stesses and the plastic deformation of the compliant layer. Thermomechanical tests done under a 1.8 MW/m^2 electron beam lead to a partiel failure after 1000 cycles. This had initiated in the braze material and had propagated in the graphite tile. The fatigue curves of graphite allow us to conclude that at the design heat flux of 1 MW/m^2, a 10000 cycles life is expected.

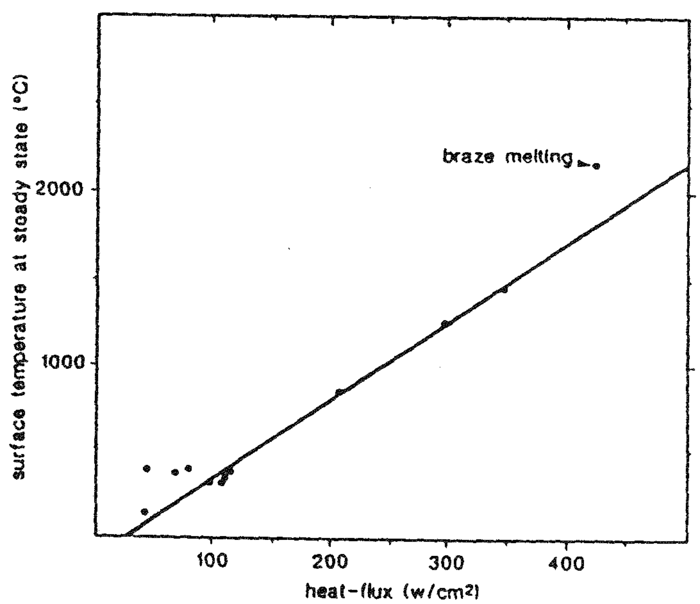

FIGURE 2

Electron beam test of thermal behaviour on a inner first wall moke-up

TESTING

In order to assess the design many moke-ups where build and tested in different configuration. The main thermal tests where done in the electron beam facility at Sandia National Laboratories in Albuquerque (N.M., U.S.A) and the results are described in a other paper in this conference / 2 /. The maximum steady state heat flux attained before braze melting was 3.5 MW/m^2 (see figure 2) ; other results were quoted before.

FABRICATION

All the stainless steel used in this fabrication is either of a 316 or 304 type, both are always low cobalt grades (less than 500 ppm). The special square tube with an circular cooling channel was made by Vallourec and came out as strait 2.2 m long tubes with high tolerances on all dimensions. Then they were put to length and localy machined before welding them 3 by 3 with spacer in-between. The front and back faces were milled for flat references. The poloidal curvature was done by bending at each locally machined array. Three groupes of 3 tubes were then assembled on a jig reproducing the toroidal curvature and welded on specially machined (with ϕ and θ angles) spacers. All water connections were donne before the final machining of the sides facing plasma on a 3 D milling machine which could reproduce the toroidal surface with brazing compatible tolerances.

All the graphite tiles were machined in CL 5890 PT graphite blocks to a 70-20-10 mm rectangular shape and then baked out at 2000°C in a vacuum furnace for complete outgasing.

To avoid non wetting of the stainless steel by the brazing alloy, each wall sectors was electroplated with copper on the brazing faces. Special high temperature jigs were build to keep the wall sector curvature during furnace operation and to hold a pressure on every tiles being brazed. First operation was a solution annealing of the parts at 1050°C coupled with a braze material deposit on local highly stressed area to prevent liquid metal cracking by the brazing alloy used for the graphite bonding. This procedure was choosen due to the appearance of leaks in the stainless steel tubes after the tile brazing. The leaks were related to a copper-silver induced cracking at high temperature (850°C) in stress concentrated areas.

All the different foils and innerlayers (ticusil, copper and molybdenum) composing the braze joint were mechanically cut, cleaned and stored in dry air. The copper coating of each sector had to be brushed in order to remove the air oxydated layer. Preparation of the brazed part was done on the jig, in a clean room and within a short delay to diminish the air oxydation problems. After brazing each sector was cleaned to remove all braze material excess (see figure 3).

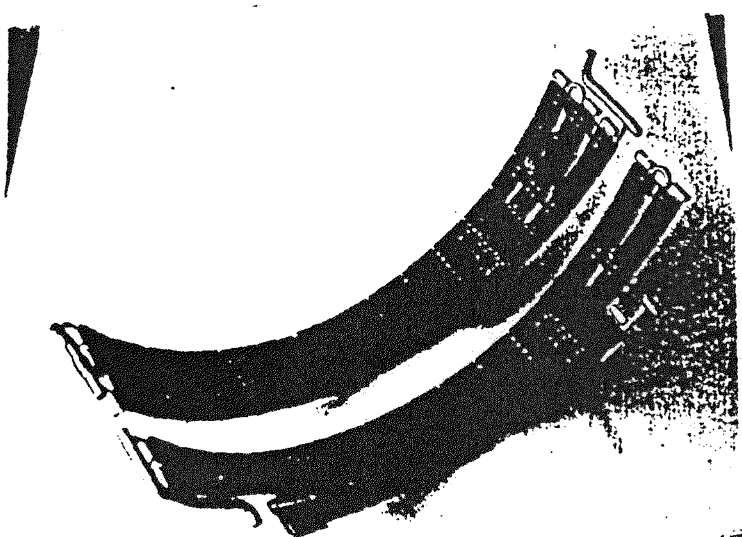

FIGURE 3
Inner first wall sectors ready for installation in the vessel

INSPECTION

Each inner first wall sector was individually controled for the geometrical dimensions which had to be :

1) for the surfaces receiving the graphites tiles, 0.05 mm flatness and 3.2 µm roughness.
2) for general geometrie, a space definition within + - 2 mm.

These controles where done on a surface plate with the adequate tools.

A helium leak test was done after every weld on the water circuit and a final global one at 200°C for the final part acceptance.

The graphite to stainless steel brazing joint of every tile was inspected by an infrared (IR) method. An IR camera was pointed at a group of 30 tiles and water was flowed in the tube. The thermal response of the surface (ie the isothermal profile of each tile) was recorded and analysed by comparison of the other tiles response in the same group. Two types of defects where identified :

1) clear delay in the heating of the tile which was representative of a major crack. Those tiles where chopped of. The remaining graphite was still sufficient to protect locally the stainless steel.
2) slight delay in the heating of the tiles. Those were marked and will be closely followed during operation.

A maximum of 100 tiles on 8700 brazed were faulty over the whole fabrication.

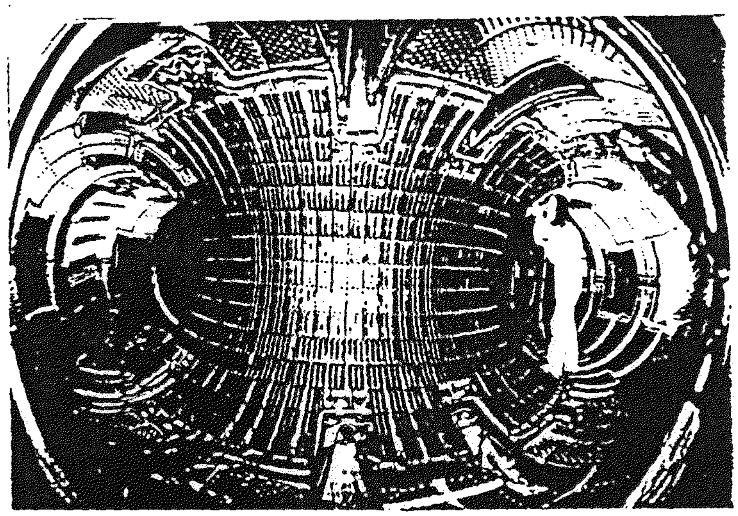

FIGURE 4
In vessel assembly-final welding on the inner first wall manifold

IN VESSEL ASSEMBLY

A complete prealignment by laser beam was done on the main supports of each sector in order to have a ± 2 mm positionning of the whole wall (the assembly is detailed in a other paper presented in the same conference, see réf. 3). The sector where introduced one by one and bolted in place on the support with very little handling. A final adjustement of the end supports was done before welding of the manifolds (see figure 4).