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Brazing of the Tore Supra Actively Cooled Phase III Limiter*

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Abstract

The head of the water-cooled Tore Supra Phase III Limiter is a bank of 14 round OFHC copper tubes, curved to fit the plasma radius, onto which several hundred pyrolytic graphite (PG) tiles and a lesser number of carbon fiber composite tiles are brazed. The small allowable tolerances for fitting the tiles to the tubes and mating of compound curvatures made the brazing and fabrication extremely challenging. The paper describes the fabrication process with emphasis on the procedure for brazing. In the fixturing for vacuum furnace brazing, the tiles were each independently clamped to the tube with an elaborate set of "window frame" clamps. Braze quality was evaluated with transient heating tests. Some rebrazing was necessary.

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1. Introduction

As plasma confinement experiments have become larger with more power added to their plasmas, removing this power has brought significant new technical challenges for the fusion program, specifically the need for actively cooled components for primary heat removal. The mission of Tore Supra, a large tokamak located at CEN (Commissariat a l'Energie Nulcaires de Cadarache) in France, is to study plasma confinement during long pulses. Tore Supra's requirement for heat removal differs from most other tokamaks which operate with shorter pulses.

In collaboration with CEN, the Fusion Technology Department of Sandia National Laboratories, has designed, fabricated and installed a series of outboard moveable limiters in Tore Supra. During its early operation, Tore Supra ran short pulses with the Phase I and then the Phase II limiter. Heat was simply absorbed by these "inertially cooled" limiters and conducted away or radiated between plasma shots. Longer pulses required a design with active cooling and the result was the Phase III Outboard Moveable Pump Limiter, installed in Tore Supra in March 1993. The design goals include steady state removal of 2 MW, incident heat fluxes as high as 10 MW/m^2 on the face and 30 MW/m^2 on the leading edge. Details of the design have already been reported[1-4].

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2. Phase III Outboard Pump Limiter Configuration

The Phase III limiter module is mounted at Tore Supra's mid-plane and the radial location can be manipulated between shots. The limiter head is a bank of 14 water-cooled copper tubes. Figure 1 shows the piping and a few of the several hundred tiles. Figure 2, a cross section of half of the limiter head, shows the shape in the toroidal direction. The limiter's shape spreads the heat load to equalize the burnout limit for the tubes. The poloidal curvature fits a plasma radius of 75.4 cm. The central eight tubes have tiles brazed on both the front and back faces. The back surface of the limiter deflects particles that pass behind the limiter's leading edge toward the pumping duct. The design maximizes pumping by having the limiter's leading edge as far as possible into the plasma while still maintaining a manageable heat load.

3. Fabrication

Figure 3 shows several stages during fabrication and assembly. Oxygen free (OFE-HIT C101) copper tubes, drawn to sizes ranging from 0.72 to 1.6 cm inside diameter and annealed were bent into the broad "m" shape (Fig. 3a) using standard tube bending techniques. Any ovality was corrected by removing material during hand finishing since a true tube radius was needed for the braze surface. Digitized data describing the "m" shapes of the tubes were obtained for use in machining the tiles as the tubes were inspected for conformance.

Piping, except for the tubes themselves, is 316 low cobalt stainless steel (SS). The SS/Cu transition occurs in inertially welded transition couplings which were welded (Cu/Cu) to the tubes prior to brazing.

The tiles were cut to the proper width but oversized in height. Excess material was removed later, during machining of the surface contours. Each set of 46 rough cut tiles (one side of one tube), separated by 1 mm graphite spacers, was clamped together in a machining fixture and then a semi-circular groove (braze surface) was cut. The tool path followed any small "wobbles" prescribed by the digitized data on the shape of the corresponding tube (except for the leading edge tubes, which fit into a strongback; see Fig. 2). Mating of compound curvatures was problematic. Great care was taken to match tiles to the tubes. The allowable tolerances for fitting the tiles to the tubes prior to brazing were typically 0.09 mm down to 0.03 mm in key locations.

Brazing of the tube/tile assemblies is discussed in the next section. After brazing, each tube assembly consisted of oversized tiles brazed to the tubes and separated by 1 mm (unbrazed) graphite spacers. Shaping of the plasma side and deflector side contours was done on each assembly (Fig. 3a) before their placement on the limiter. The tool followed the spline along the length of the tube and cut the full breadth of each tile.

The final placement of the tubes was a delicate operation. Alignment was monitored with a coordinate measuring machine (Fig 3b) that accurately tracked the coordinates of a stylus at the end of a computerized arm. Each tube was joined, using metallic shrink-to-fit couplings, to nipples extending from the upper and lower headers, or to separate inlet/outlet lines, already welded in place in the limiter module. (A stainless steel sleeve overlaps joining pipe ends and, when activated by heating, "memory metal" collars compress each end of sleeve.) The couplings were selected because they produce only small mechanical deflections of the joint. There was also concern whether a welding head could be used effectively in the tight space between the nipples. Prototypic joints were successfully tested and the assembly passed a helium leak test under vaccuum and a static water pressure test at 1050 psi (7.2 MPa) prior to shipment. In pressurization tests of the assembled module at CEN, to pressures of 610 psi (4.2 MPa) and at temperatures up to 145 C, some joints leaked. All joints were repaired by reheating and moving the collars and then welding the sleeves in place. The excellent welding in these replacements was done by the Tore Supra staff.

4. Brazing Procedure

The greatly different thermal expansion coefficients of pyrolytic graphite (PG) and copper, by more than an order of magnitude for PG perpendicular to the c-axis, and the high brazing temperature necessary make PG-copper a difficult combination to braze. However, their high thermal conductivities were needed in this application. The service temperature for a braze joint approaches 600° C for at a "hot spot" (150% nominal heat load, 2 MW overall, 140°C water inlet, 4.3 MPA). While, in theory, a lower braze temperature could mitigate some problems associated with brazing of PG and copper, choices are limited for high temperature reactive metal brazes for joining graphite and copper and copper-silver brazes (e.g., TiCuSil and CuSil ABA) were preferred.

At the braze temperature, a tube's length has grown by 1 cm and the oversized tiles and a large tube have grown in height by 0.3 mm. Independent, spring-loaded "window frame" clamps maintained pressure between each tile and the tube while accomodating the thermal expansion of the assembly (Fig. 4). Sandia's Thin Film, Vacuum and

Brazing Department did the brazing in a cold wall, resistively heated, graphite element vacuum brazing furnace. The chamber typically was evacuated to 1-2x10^{-7} Torr (1.3-2.7 Pa) at 25° C prior to ramping up the furnace. Outgassing in the low 10^{-5} Torr range was maintained to 500° C where the furnace was held until the pressure decreased to the low 10^{-6} Torr range. To reduce evaporation of silver from the braze material, the chamber was back-filled with argon to a pressure of about 750 mTorr prior to the final ascent to the braze temperature.

Foils of TiCuSil (68.8% Ag, 26.7% Cu and 4.5% Ti) and CuSil ABA (63% Ag, 1.75% Ti balance Cu), typically 0.05 mm (actually 0.002 in), were used as braze material. Thinner foils (0.025 mm) were also used as needed. Where extra fill in the joint was needed, a copper foil was interleaved between braze foils. Brazes with TiCuSil were done at 855°C and brazes with CuSil ABA were done at 830°C. The furnace was shut off after thermocouples on the tubes and tiles equilibrated at the braze temperature. The time at or near the braze temperature was 10-15 minutes, depending on the mass of the tube. For several tubes, defective brazes or cracked tiles were replaced and the new tiles brazed. TiCuSil was used for some rebrazes. The later rebrazes used CuSil ABA. In rebrazing before the final contours were cut, the entire tube was reclamped in the brazing fixture. Partial fixturing and CuSil ABA were used for replacements done after the final contour had been cut.

5.0 Testing of Braze Quality

The quality of brazes was evaluated using transient heating tests. The surface temperatures of tiles were monitored with an infared (IR) camera as hot water passed through a tube assembly initially at 30° C.

The temperatures of tiles with braze voids or cracks lagged behind the temperatures of adjacent well bonded tiles. Temperature lags were correlated with flaw sizes based upon detailed 2-D heat transfer analyses and flaws observed during repairs. These results will be reported in the future.

The tests were performed using the high temperature, high pressure flow loop with 120°C water at about 2.07 MPa (300 psi) at Sandia's Plasma Materials Test Facility. Flow rates were in the range of 1.6-1.8 m^3/h (7-8 gpm) for the smaller tubes and about 2.3 m^3/h (10 gpm) for the large tubes. The respective flow velocities were 10-12 and 3.2 m/s.

Typically, bad tiles were easy to detect and had temperature lags in the range of 10-20° C depending upon the size of the tiles. When such tiles were removed, braze voids of roughly 50% of the joint area were found. The observed braze voids seemed to be of three basic types, as indicated in Figure 5. Probable causes of the voids are: (edge void) slight rocking of the tile in the braze fixture; (center void) improper fit due to interference along the sides after expansion of the copper tube; (side void) improper fit with the volume of the joint greater than the available braze material so that only a portion of the joint filled.

5. Problems with the Braze Joints

The original design for the Phase III limiter called for PG brazed to dispersion hardened copper using compliant layers (e.g. soft copper or copper sponge) between the tiles and the tubes to reduce residual stresses from brazing. As a semi-circular brazed PG/Cu joints cools, the copper tries to shrink away from the PG. A PG tile and a center tube starting in good contact at 850° C (but not brazed) would have a radial gap would be about 1 mm at room temperature. When the residual stresses are too large, as with the dispersion hardened copper tubes, cracking occurs in the PG (Fig. 6), usually adjacent to the braze joint.

Several techniques were tried, including pure (soft) copper plasma sprayed on the tubes, a slotted soft copper layer and, a composite construction with tunsgten fiber winding around the tubes to constrict thermal expansion. Materials development and characterization were done by Sandia's Departments of Physical & Joining Metallurgy, Mechanical and Corrosion Metallurgy and Ceramic Processing Science. Although improvement was evident with these innovative techniques, a reliable method to produce braze joints without cracking the tiles was never realized, and the design was modified to use (thicker) soft copper tubes. Yielding of the tube during cooling can reduce residual stresses, but even with soft copper tubes, cracking of long PG tiles near the ends of the tubes forced the use of carbon fiber composite for some long tiles.

While the use of C101 copper mitigated the earlier problem of tile cracking, other issues arose. The soft copper had less structural rigidity than would have been present with dispersion hardened copper tubes. The structural rigidity of the head was enhanced by strapping the tubes together with Inconel wires.[5]

Another problem was severe cracking in the walls of at least some tubes. One large tube (2E) was rejected because of cracks through the wall. Figure 7 is an SEM photo of the inside surface of Tube 2E in a region where surface cracks were found. After cracking was found in a replacement leading edge (small) tube, a general problem was suspected.

The ongoing investigation will be reported in the future. Some initial observations are given here.

Figures 8a and 8b are micrographs of the braze joint in Tube 2E. The large grain size of the copper is evident. There is gross diffusion of material at the interface between the copper and the braze. The dark copper rich regions (pro-eutectic copper) formed first as the braze zone solidified from the copper toward the graphite. The light colored two-phase region is eutectic copper-silver. Figure 8b shows a large crack.

Our working hypothesis is that such cracks initiated during the cool down by high temperature creep rupture processes. Grain boundary sliding can be expected because of the high homologous temperature (>0.8) and may be inferred from the nature of the intergranular cracks. A relatively low equi-cohesive temperature* can be expected with the large-grained microstructure and (presumed) large angle grain boundaries. Some wavy grain boundaries, associated with grain boundary adjustment during high temperature creep, were observed.

The two failed tubes, both rebrazed, had through-wall cracks near the ends of the tubes. While it is not clear that this location, or the rebrazing itself, is significant since other rebrazed tubes did not fail and our observations are still incomplete, crack formation may be worse near the ends for two reasons. First, most tiles are nearly perpendicular to the tube but near the ends, as the tube curves, the braze joints are longer (see Fig. 3b). For these tiles the longitudinal constraint was larger and there was somewhat greater longitudinal stress in the copper.

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* Slip will be easy but the coordination of slip systems from one large grain to the next will be constrained and the stress needed to force coherent deformation across grain boundaries will be relatively high compared to the strength of the grain boundaries.

Second, the cold work in forming the tighter bend at the ends is somewhat greater than for the large radius bend in the center. A gross measure of cold work, equal to the tube radius plus half the wall thickness divided by the bend radius, is about 14% near the ends versus 1% near the middle for a large tube (2E) and 6% versus 0.5% for a small tube. But one would expect to see the primary effects from the cold work done in bending on grain growth during the first braze cycle.

In the rebrazed microstructure, one might look for more grain growth due to the additional time at the braze temperature, plus effects of the altered parent state, specifically, deformation and residual stresses from the first braze cycle and constraint by the brazed PG tile during heating. It is not obvious that any of these should have an effect unless there is significant plastic deformation during the cool down of the first braze cycle. The unconstrained thermal contraction would be about 1.5%, so some plastic strain can be expected. If, during the cool down of the first braze cycle, some plastic strain occurs in the region of greatest constraint (adjacent to the braze joint), then there will be a hysteresis during the rebraze cycle and this region will be under stress as the tube heats up, which may promote additional grain growth. A more complete evaluation will be reported in the future.

6. Conclusions

The Phase III Limiter is both a major accomplishment and already out-of-date. When it was designed, PG was the only form of graphite that had very high thermal conductivity and was commercially available (but in thicknesses of one centimeter or less). A design evolved with the tubes as structural support for a "necklace" of thin tiles. With the high conductivity carbon fiber composites (CFC) now available, a different design would likely evolve today. CFC armor, not limited in unit size, could provide its own structural support, perhaps even with internal cooling channels. There is a wealth of new technology to use in the next generation of actively cooled plasma facing components as well as severe engineering challenges in developing reliable and effective components.

Acknowledgements

The authors appreciate helpful discussions with Bob Watson of Sandia's Fusion Technology Department regarding stresses in braze joints and cracking of pyrolytic graphite tiles and with John Davis of MacDonnell Douglas Aerospace Corporation regarding copper metallurgy as well as the efforts of Paul Freschour of Sandia's Fusion Technology Department in preparing tubes for brazing and the assistance of Bonnie McKenzie and Fred Greulich in the metallographic observations.

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Figure Captions for paper ICFRM/T009 by Nygren

Figure 1. Phase III Outboard Pump Limiter Piping with copper tubes (light gray), stainless steel piping (dark gray), tiles (black). Only a few tiles shown.

Figure 2. Horizontal cross section, half the Tore Supra Phase III Outboard Limiter

Figure 3. Assembled tube before cutting of surface contours (3a) and photo of tube installation (3b).

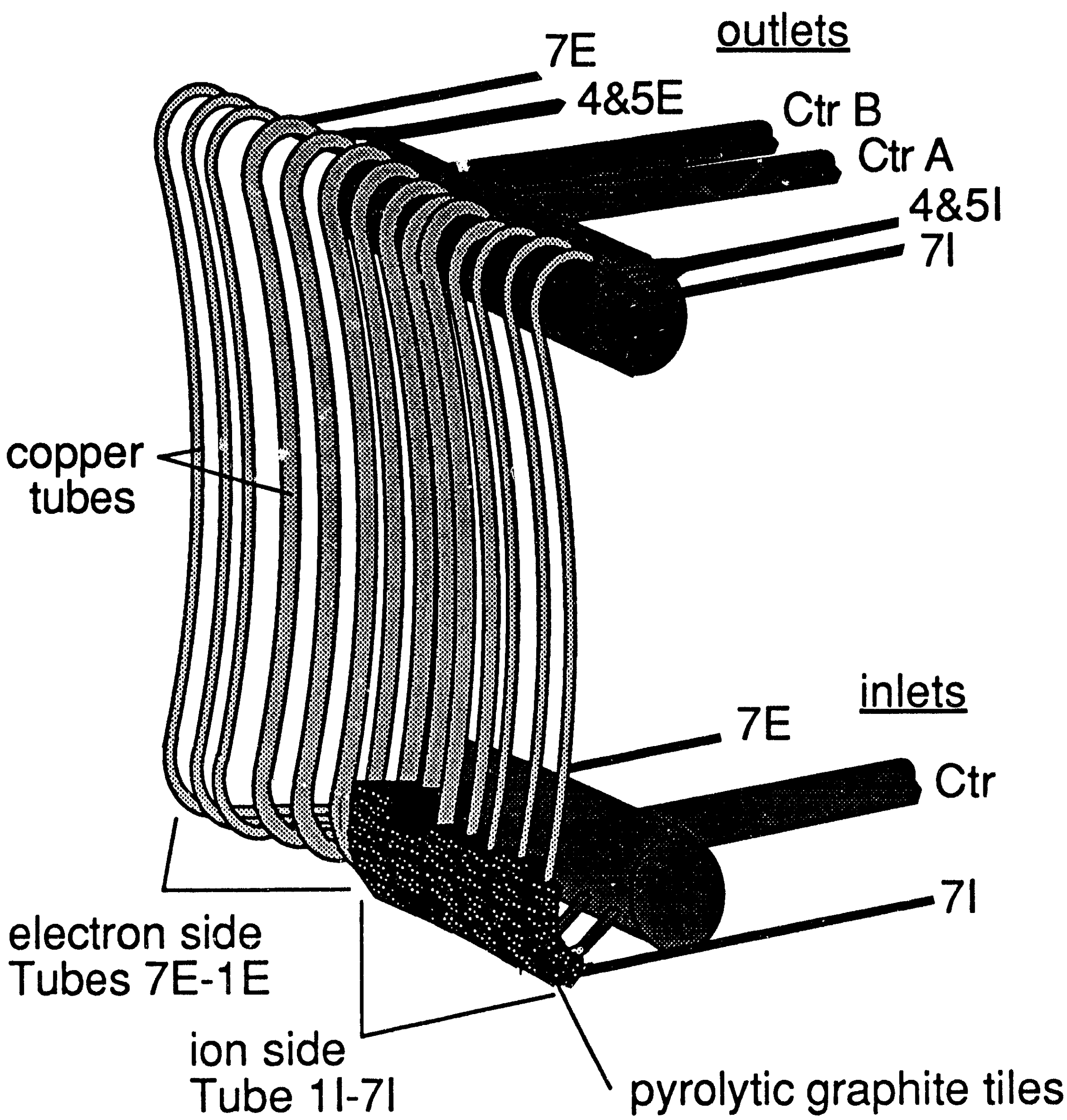
Figure 4. Brazing fixture with "window frame" clamps holding tiles on a portion of the tube.

Figure 5. Types of braze voids (light areas).

Figure 6. Typical crack sites for brazed "saddle-type" PG tiles.

Figure 7. SEM photo of cracks on inner wall of Tube 2E.

Figure 8. Micrographs of Tube 2E section: grain size in tube wall (a) and braze zone (b).



ICFRM6/T009 Fig. 1. single column

Figure 1. Phase III Outboard Pump Limiter Piping with copper tubes (light gray), stainless steel piping (dark gray), tiles (black). Only a few tiles shown.

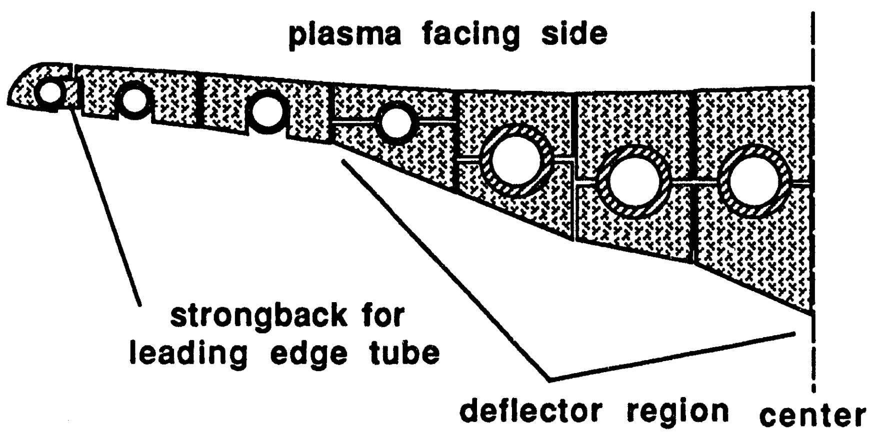


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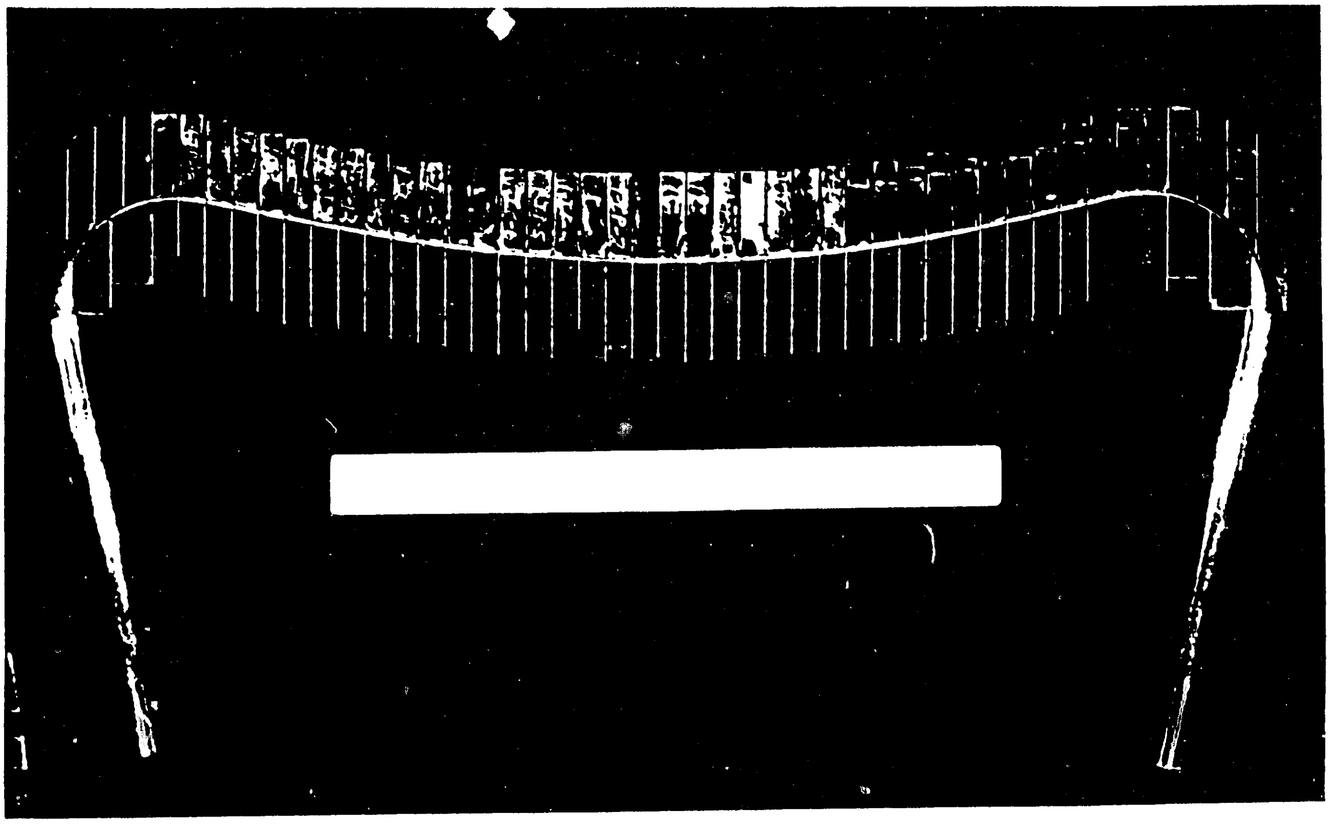
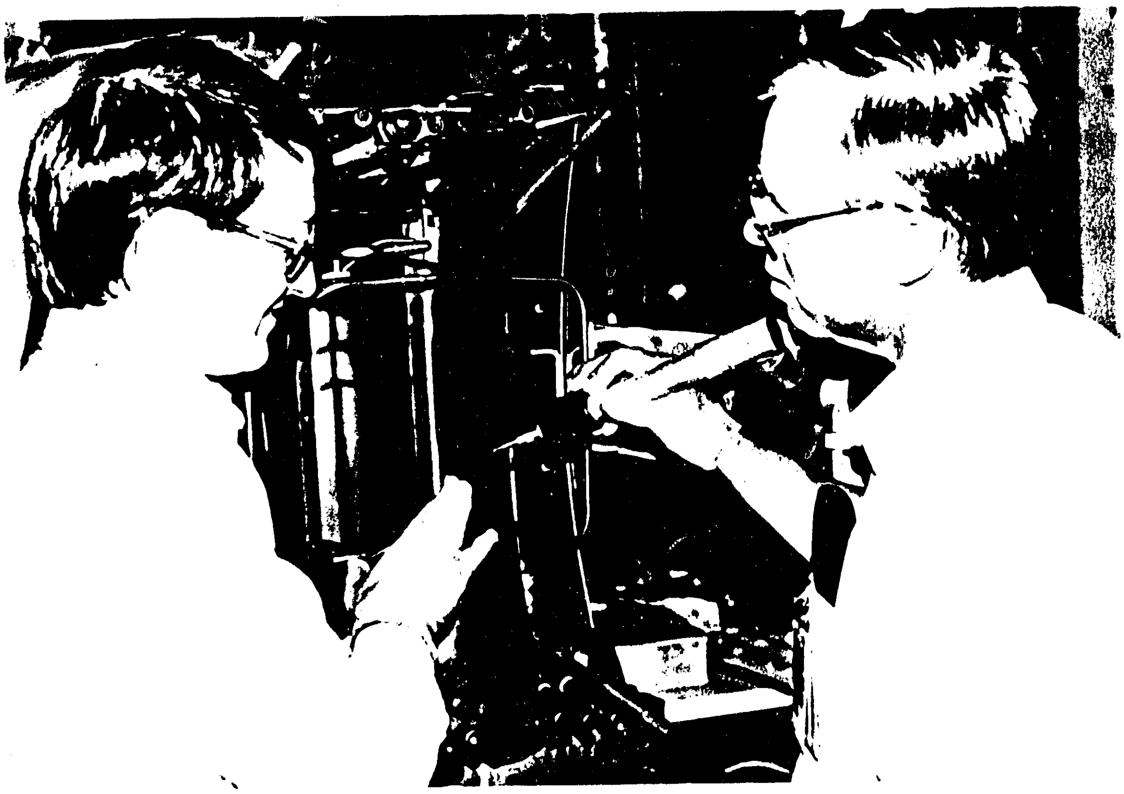
Figure 2. Horizontal cross section, half
the Tore Supra Phase III Outboard Limiter



(a)



(b)

Fig 3

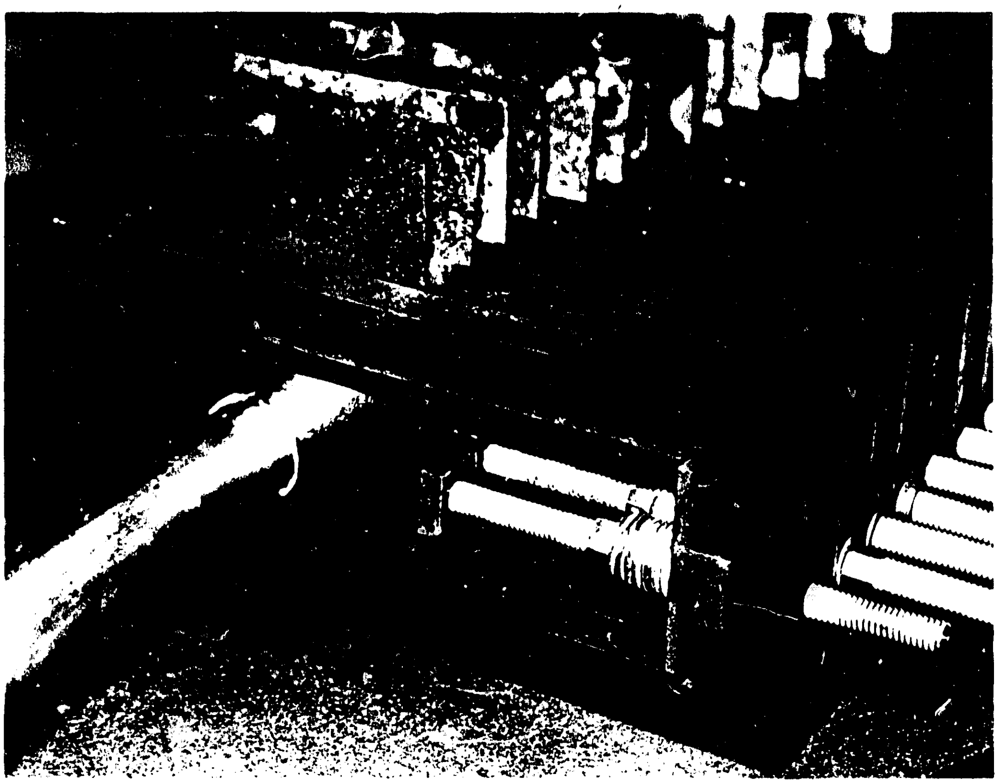


Fig 4

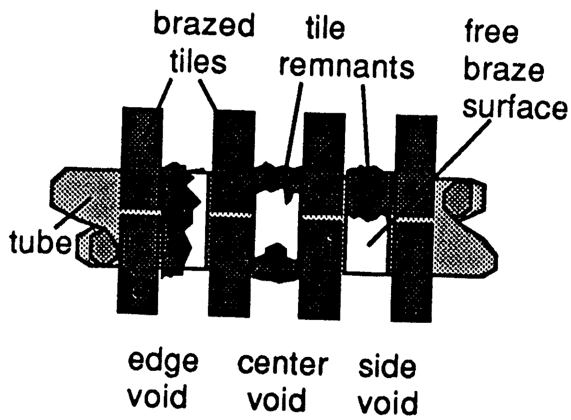


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Figure 5. Types of braze voids (light areas).

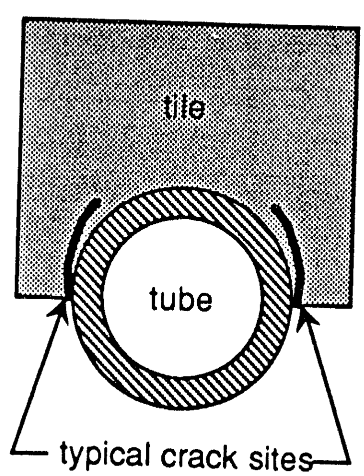

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Figure 6. Typical crack sites for brazed "saddle-type" PG tiles.

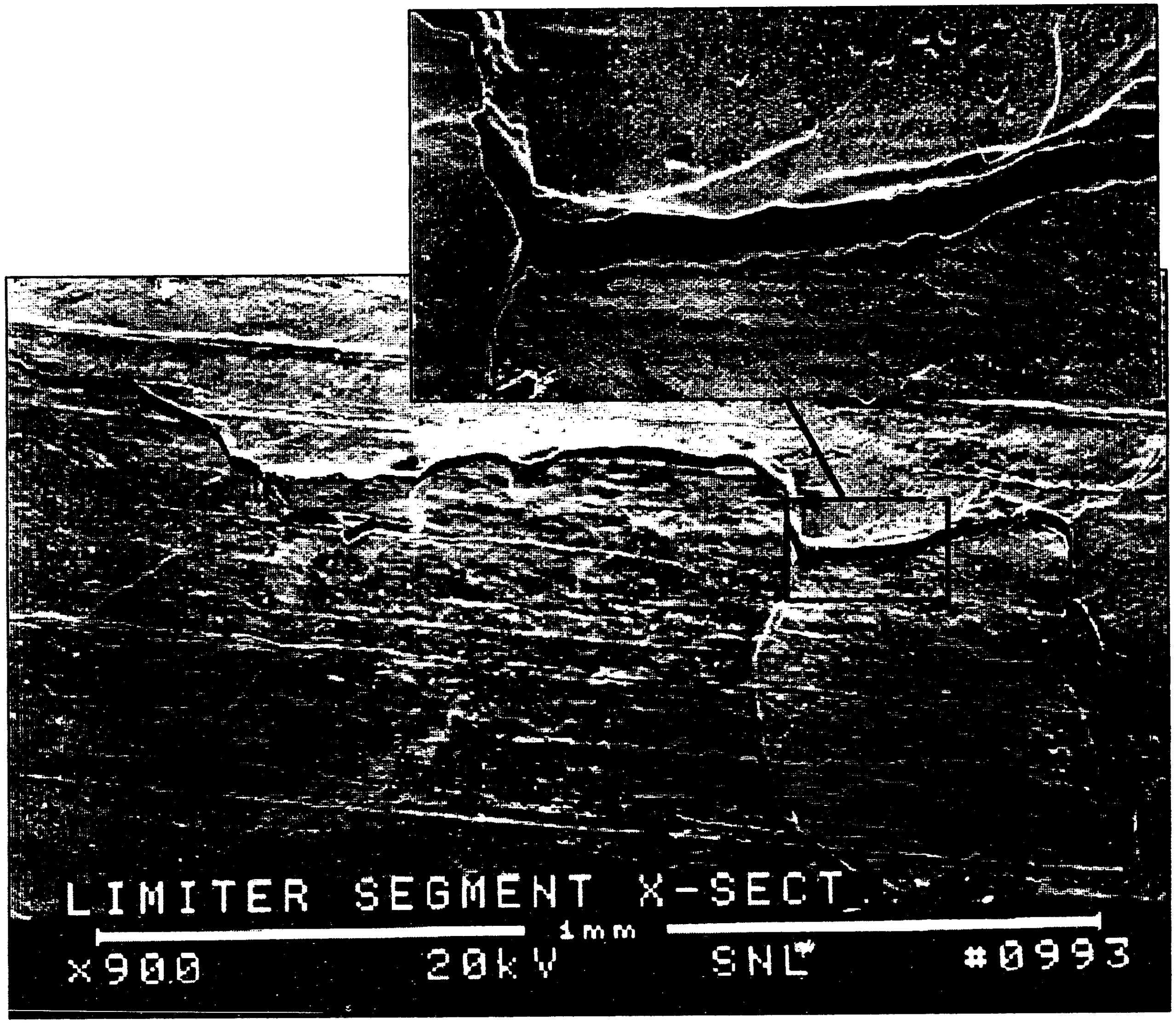

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fig7 single column

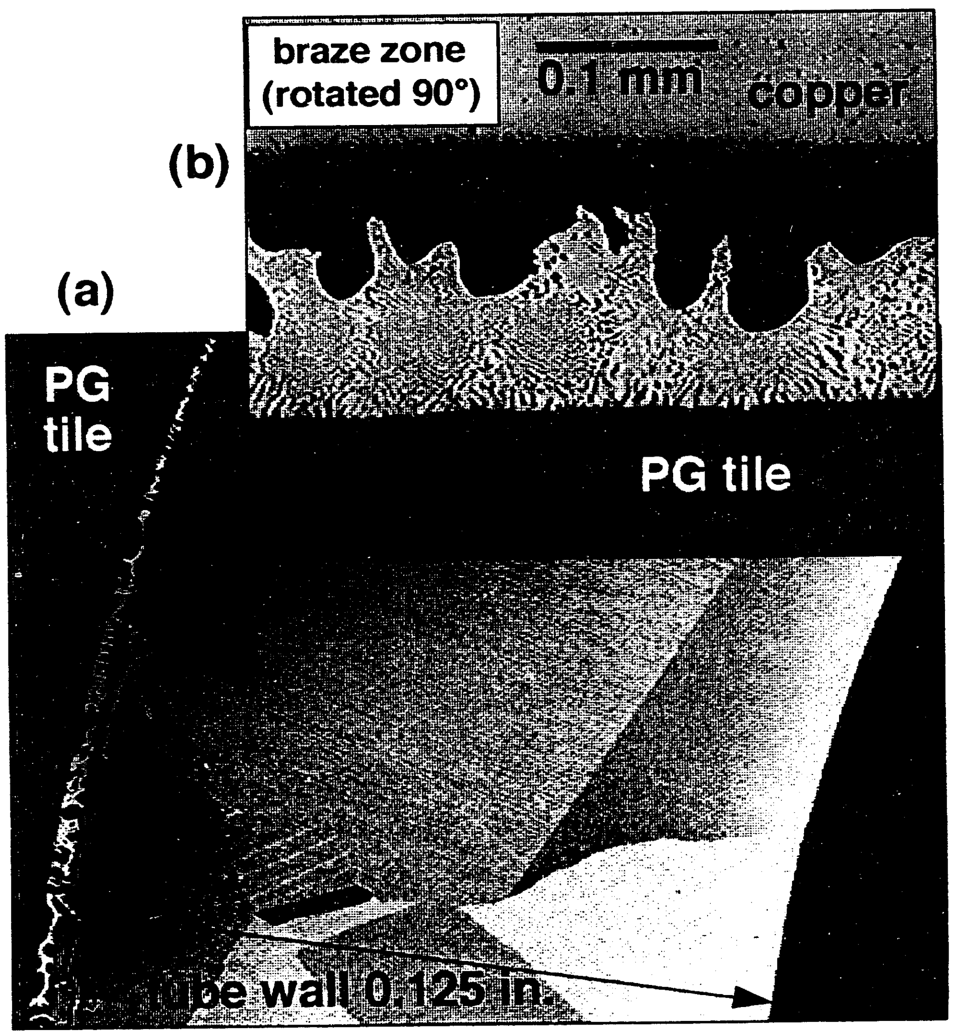

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fig8 single column

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