Assessing Braze Quality in the Actively Cooled Tore Supra Phase III Outboard Pump Limiter

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The quality of brazing of pyrolytic graphite armor brazed to copper tubes in Tore Supra's Phase III Outboard Pump Limiter was assessed through pre-service qualification testing of individual copper/tile assemblies. The evaluation used non-destructive, hot water transient heating tests performed in the high-temperature, high-pressure flow loop at Sandia's Plasma Materials Test Facility. Surface temperatures of tiles were monitored with an infrared camera as water at 120°C at about 2.07 MPa (300 psi) passed through a tube assembly initially at 30°C. For tiles with braze voids or cracks, the surface temperatures lagged behind those of adjacent well-bonded tiles. Temperature lags were correlated with flaw sizes observed during repairs based upon a detailed 2-D heat transfer analyses. "Bad" tiles, i.e., temperature lags of 10-20°C depending upon tile's size, were easy to detect and, when removed, revealed braze voids of roughly 50% of the joint area. Eleven of the 14 tubes were rebrazed after bad tiles were detected and removed. Three tubes were rebrazed twice.

Introduction

The Phase III Ouboard Pump Limiter (OPL) is a water-cooled modular limiter that has removed about 1 MW of power under essentially steady state thermal conditions during its operation in Tore Supra in 1993.[1,2] In collaboration with the Commissariat a l'Energie de Cadarache (CE), the lab which operates Tore Supra, researchers at Sandia's Fusion Technology Department have designed and fabricated a series of outboard moveable limiters for Tore Supra and participated in experiments with these limiters in Tore Supra. The design of this limiter and its fabrication have been reported elsewhere.[3-6] This paper focuses on the process used during fabrication of the limiter to evaluate braze quality.

As noted elsewhere in these proceedings, obtaining reliable quality in the joining of plasma-facing armor to water-cooled heat sinks has posed a continuing and significant problem for the few applications where water-cooled plasma-facing components are being used in the fusion program.[7][1] Indeed, in the development of the Phase III OPL, the problem of reliable joining forced a change from the initial design, in which pyrolytic graphite (PG) was brazed to dispersion-strengthened copper.[8] In the design adopted, strain and residual stresses from the brazing cycle, due to the gross mismatch in thermal expansion

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[1]This paper is a companion to a more general paper, Ref. 7, in these proceedings which discusses actively-cooled plasma facing components.

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coefficients between copper and PG, were accommodated by creep and plastic strain of the soft copper tubes.

The head of the Phase III OPL is a bank of 14 water-cooled copper tubes with several hundred brazed pyrolytic graphite (PG) tiles (Figs.1 and 2). The contour spreads the heat load across the face of the limiter. The burnout limit is roughly equal for all the tubes. Particles passing behind the limiter's leading edges are deflected toward the pumping duct.

The eight center tubes (Tubes 1e-4e and 1i-4i[2]) have tiles on both the plasma side and the deflector side. Tubes 5e-7e and 5i-7i have tiles on only one side. The leading edge tubes (7e and 7i) receive the highest heat loads and have twisted tape inserts to enhance heat removal; on these tubes, the tiles face in the toroidal direction, rather than radially inward (outward for the deflector tiles) as with the other tubes. Tiles on all tubes are parallel to the horizontal plane, except the tiles along the outer curved sections of the leading edge tubes which lie perpendicular to the tubes' axis.

In building the OPL, the brazing operation was completed on one tube at a time using a similar sequence for all the tubes. Machining of the plasma side and deflector side contours (i.e., the "shape outlines" in Fig. 2) was done on each tube assembly after brazing and before the tube assemblies were installed on the limiter. The brazed and contoured tube assemblies were then fitted into position and joined to mating pipe stubs that protruded from the headers on the partially assembled OPL.

In building the Phase III OPL, 16 tubes were made and 11 were rebrazed. Two rebrazed tubes were rejected and the replacements were accepted. Of the 14 tubes installed on the OPL, nine were rebrazed and three of these had received a second rebraze.[3]

Non-Destructive Testing of Braze Quality

A "hot water test" was used after brazing and again after machining of the surface contours to determine the quality of the braze joints. The principle is quite simple. Hot water is passed through a tube assembly initially at room temperature. Where braze flaws or cracks (near the braze) exist, there is greater resistance to heat flow into thermal mass of the tile from the copper tube, being heated by the hot water and, as the assembly heats up, the temperatures of any flawed tiles lags behind those of adjacent well bonded tiles.

The sensitivity of this test depends upon the heat transfer coefficient between the water and the tube and upon the temperature difference between ambient conditions and the temperature of the hot water. Ideally, the tube would receive a change from ambient to hot water instantaneously. In practice, the water gives up heat to any upstream auxiliary piping and a detailed thermal analysis for a given tile would take

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[2]The "e" and "i" refer to the electron side and the ion side of the OPL. The tube number start at the center and fo out to the leading edges (Tubes 7e and 7i).
[3]Ref. 7 discusses these statistics.

into account this degradation of the source term. For the testing reported here, the "cold" upstream auxiliary piping consisted of a stainless steel elbow, the inlet side of a differential thermocouple block and a short length of stainless pipe. The rest of the upstream piping was kept hot continuously using a by-pass loop.

In our tests, hot water was supplied by the high temperature, high pressure flow loop of the Plasma Materials Test Facility at Sandia National Laboratories. An Inframetrix 600 infared (IR) camera and video digitizer recorded images of the tiles' faces as 120° C water at about 2.1 MPa (300 psi) passed through a tube assembly that had initially been at 30° C. 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.

On any one tube, the tiles are nearly identical in size (except near the ends of the tubes). Therefore, no correction for variations in thermal mass or conductance are needed for comparisons of neighboring tiles in the IR results, and direct viewing of the IR results can provide a straightforward and discriminating evaluation of braze quality.

"Bad" tiles, i.e., temperature lags of 10-20° C depending upon a tile's size, were easy to detect. Braze voids of roughly 50% of the joint area were revealed when such tiles were broken off the tube assemblies. The judgment to remove tiles was based upon 2-D thermal analyses of tiles with flaws (discussed in the next section) plus the confirmation of flaws in those tiles removed. The typical braze void on the bad tiles occured under the "top of the saddle" of a tile and was roughly symmetric with respect to the tile. A probable cause is interference from a slightly oversized tube that forced the tile away from the tube centerline as the tube expanded during heating. Another likely type of flaw would be a crack beginning at the end of the braze joint and running in the PG roughly parallel to the braze. Since the tiles were forcibly removed, we could not determine after the tiles were removed whether there were cracks in addition to any flaws observed. For example, we believe several adjacent tiles with similar asymmetric distributions of surface temperature on Tube 3i (unrepaired) were probably due to cracks formed during handling of the tube, rather than due to braze flaws.

Figure 3 shows the video data (processed IR images) of a view of the central portion of Tube 3i. Here, to the left of "-8", for several tiles (Tiles 3-8), the lower portion is darker than the upper portion indicating a asymmetric temperature distributions. As noted above this, and the grouping of several adjacent tiles, suggests that cracking along the braze may have occured, perhaps during handling of the tubes.

Figure 4 shows the processed IR images for the plasma facing surface of Tube 2e. The vertical bands are the edges of individual tiles. Below and to the right of the marker "18" is a light area (Tile 19). The difference in shading (color[4]) from Tiles 18 and 20 indicates a lag in temperature; the

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[4]Typically these images are viewed with computer added color to increase visual discrimination.

uniformity of surface temperature across Tile 19 suggests the lag is due to a symmetric braze flaw rather than an asymetric flaw or crack.

Figure 5 shows the temperature rise for selected spots on Tube 2e. The temperature lag for Tile 19 is apparent.[5] In Figure 5, the temperature lags are also plotted directly. The course sampling of the IR data (every four seconds in Figure 5) was representative of the data used and was considered adequate to show the magnitude and the rise and fall of the temperature lags for the large tubes. A final point near the equilibration temperature was also used to confirm that the emissivity of the tiles being compared was nearly the same. More rapid sampling was used for the smaller tubes. Typically the individual data points were an average at the designated location of the IR readings over 20 frames. The apparent scatter of individual readings was about ±2° C over times short compared to the rising temperature.

Analysis of the Impact of Braze Flaws

The evaluation of the hot water tests was aided by 2-D finite element thermal-hydraulic analyses[6] of the thermal response of tiles with various flaws during the hot water tests. Figure 6 compares analytical results for the hot water tests with the surface temperature measured with the IR camera on samples which had intentionally machined flaws. As noted in the previous section, the sensitivity of the test depends in part on the rapid rise of the water temperature. The inlet water condition was modeled by approximating the measured curve temperature-versus-time. A single 2-D model was used for each tube and the degradation of the transient "hot wave front" as it passed down the tube itself was ignored.

Two corrections were made to these data. First, since the water temperature was well known, a value of the emissivity (tile surface) was used that reproduced the hot water temperature to which the tube and tiles eventually equilibrated. The assigned emissivity values ranged from 0.78 to 0.91 (a reasonable range for pyrolytic graphite). Second, as the heat from the hot water penetrates the tube and then the tile, the outer surface of the tile being observed with the IR camera is the last place that heat penetrates. This delay is accurately modeled in the analytical results. Since the start time (t=0) was not accurately indicated on the video tapes, the experimental data (in Figure 6) were adjusted so that the first point overlayed the appropriate analytical curve. Thus, the slopes and shapes of the curves based upon experimental data are really what is being compared with the analytical results.

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[5]It is also true that Tile 20 lags Tile 18 and Tile 21 is below all of them. The lag of Tile 21 is typical for all tubes. While most tiles can be idealized as blocks perpendicular to the tube, Tile 21 is far enough around the curve near the end of the tube to alter the geometry, i.e., increase the ratio of integrated heat capacity to thermal conductance.

[6]Meshes were created with PATRAN. ABAQUS 2-D calculations were done with 8-noded diffusion/continuum elements (DC2D8); values are computed by 3X3 Gaussian integration across the elements.

In Figure 6, the progression from no flaw to 50% to 80% (symmetrically centered) flaw in the analytical results shows the expected change in thermal response due to the presence of a flaw. The agreement of model and experiment is good for the unflawed tiles and less good for the flawed tiles. Even among the three no flaw samples, sample B4 had a significant temperature lag. The experimental results for 50% flaw (not shown) had the same trend in comparison as for the larger flaws in that the modeling predicted faster thermal responses than were observed in the experimental data. The reason for the disagreement is not yet understood but may be due to uncertainties in the actual versus specified area of the braze joints. Unfortunately, the intentionally machined and "well characterized" braze flaws in these samples were imperfectly rendered and their fragile nature made cracking a potential problem.

A similar but much more extensive analysis of tiles on the Phase III OPL under heat loads anticipated during Tore Supra operation was done to assess the impact of braze flaws and cracks on the performance of the OPL.[7] This analysis provided the basis for performance-related criteria for an acceptable levels of braze quality. The criteria vary with flaw type and tube size. For example, let us consider the effect on the performance of the OPL of a flaw (void) that is symmetric and extends (along the circumference of the tube) over 50% of the braze line. The effect of this very large flaw is not at all drastic in that the (local) peak heat flux at the tube-water interface does not increase significantly, although the surface temperature of the tiles might rise dramatically. This result is true for symmetric flaws in the thicker-walled tubes near the center of the limiter. The peak heat flux rises more quickly with applied heat flux for side flaws (flaws that begin where the braze joint starts at the side of the tube). Also, the performance of the leading edge tubes and other thinner-walled tubes is less forgiving of flaws. These results are explained more fully in the companion paper.[7]

Conclusions Regarding the Hot Water Test

The hot water tests provided a simple, effective method for identifying significant braze flaws or cracks. For our application, a relatively unsophisticated interpretation of the IR data was sufficient. In removing suspect tiles identified in the hot water tests, we invariably found significant braze flaws (voids of roughly 50% of the braze line).

There are several important qualifications that would restrict the application of the hot water test or require more detailed treatment of the data. In our case, the analysis of the impacts of various types of flaws on the performance of the brazed tiles during service gave us comforting knowledge that, at least for the larger tubes, relatively large flaws (e.g., 50% symmetric flaw) could be tolerated. The combination of the good heat transfer using the high temperature flow loop and the relatively large flaw tolerance inherent in the design made a coarse evaluation of the IR

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[7]Examples of the latter analysis are included elsewhere in these proceedings.[7] This work will be reported in more detail in the future.

data adequate. As may be evident from Figure 6, if, for some armor configuration of interest, there is a need to discriminate smaller lags in temperature (e.g., smaller thinner tubes and smaller tiles), then a more accurate construction of the IR data may be necessary. This may imply either an accurate timing of when the heating truly starts (when the hot water first reaches that location) or else some type of reconstruction tied to an analytical curve, as was done for Figure 6.

Continuing Assessment of Braze Quality During Service

During its initial operation in 1993, this limiter successfully removed about 1 MW of power during ohmically heated shots. The limiter reached (steady state) thermal equilibrium, and preliminary data on its thermal performance were gathered with extensive calorimetry and IR thermography. [9,11]

The operation of the limiter in 1994 will begin with an intensive program to monitor the thermal performance of the limiter using the available water calorimetry and sufficiently detailed views of the limiter with IR thermography to resolve the temperatures on and temperature gradients across individual tiles. The objective is a data base from which safe power handling limits for the Phase III OPL can be developed.

These limits depend on the operating regime and also on the presence of cracks or braze flaws in various tiles. Flaws can increase the local peak heat flux at the coolant interface and thus reduce the margin for burnout as compared with an adjacent flaw free tile.

The safe power handling limits also depend upon idiosynchracies, such as misalignment from tube-to-tube within the limiter, that must be included in a map of the true heat load on each tile. With the true heat load on each tile defined for given plasma conditions, the effect of hot spots can be coupled with the effect of tile flaws and the maximum safe heat load of the more vulnerable tiles on the limiter can be assessed.

An example of this type of assessment has already occurred. During the brief operation of the limiter in 1993, the entire limiter was cooled with 50° C water.[8] In 1994, the face of the limiter will be cooled with 120° C water and only the leading edge tubes will have 50° C water. For the observed heat load on the limiter, the leading edge tubes are the most vulnerable and the margin of safety against burnout of the tubes on the face of the limiter is less than for the leading edges even when the face is cooled with 120° C water and there are significant existing flaws in some of these tubes.

The continued use of the Tore Supra Phase III Outboard Pump Limiter will provide important operating experience with a water-cooled plasma facing component capable of steady state heat removal. Its operating history as well as the experience gained in fabricating and testing contain relevant lessons for actively-cooled plasma facing components in the next generation of fusion devices.

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[8]The cold water provides the

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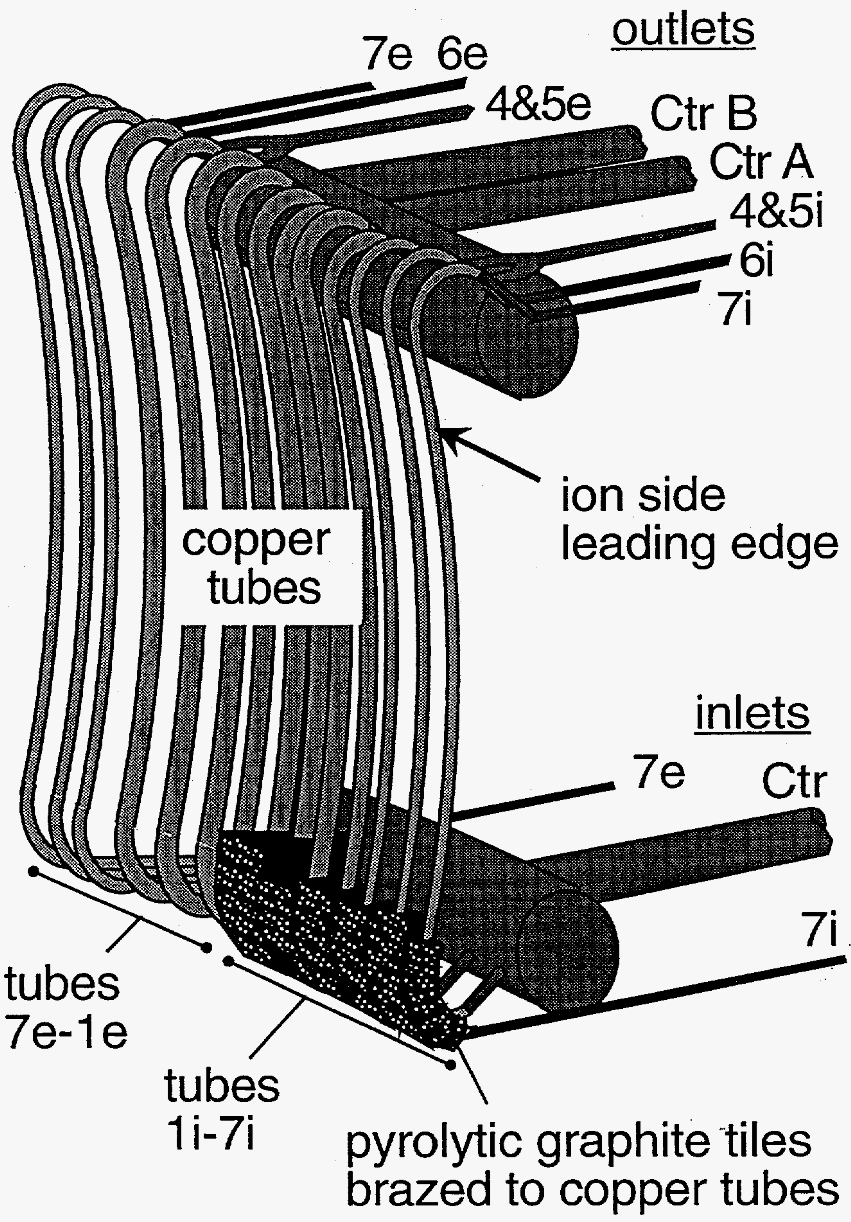
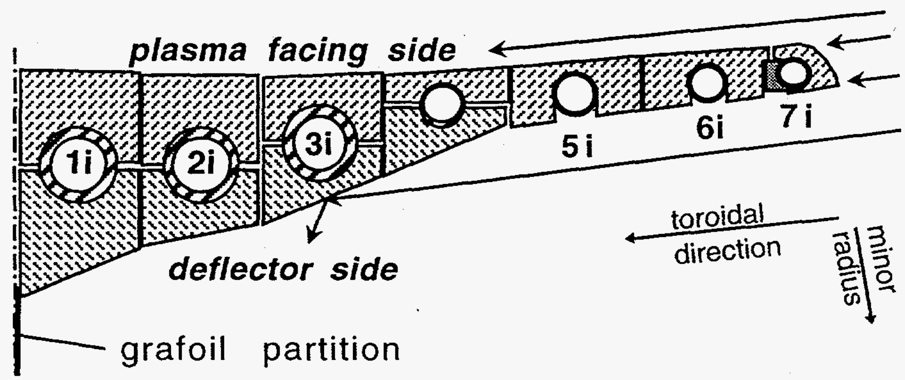
Figures



ISFNT DP2-18: Nygren Fig. 1. single column

Figure 1. Phase III Outboard Pump Limiter Piping
Copper tubes (light gray), stainless steel (dark gray),
and a few pyrolytic graphite tiles (black) are shown.



ISFNT DP2-18 (NYGREN)
single column

Fig 2. Cross section: ion-side half of Phase III limiter head

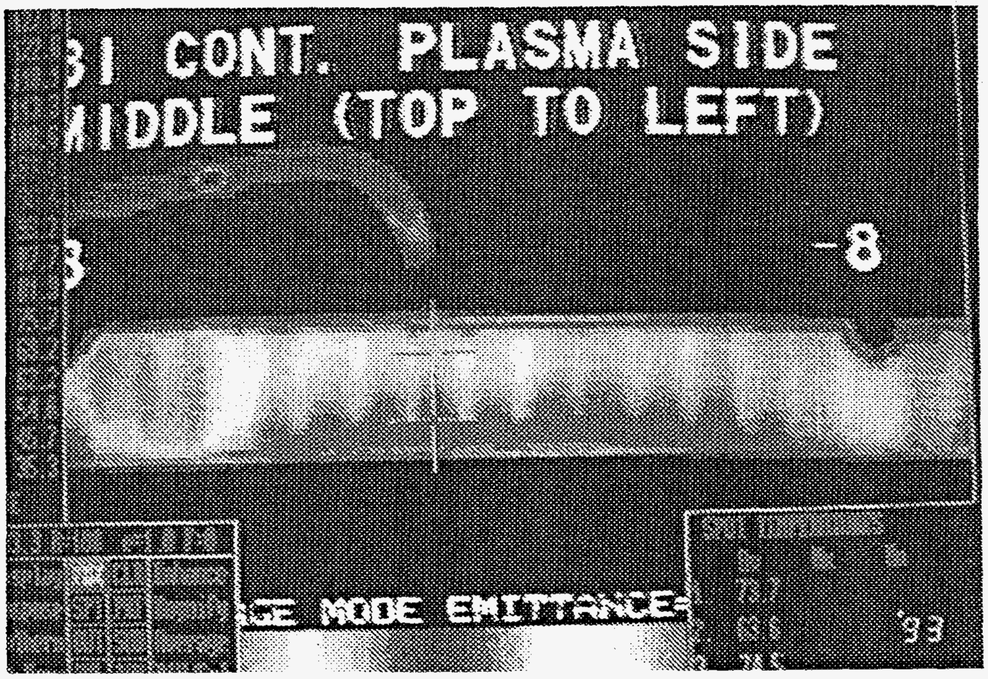


Figure 3. Still frame from (color) IR output for Tube 3i hot water test.

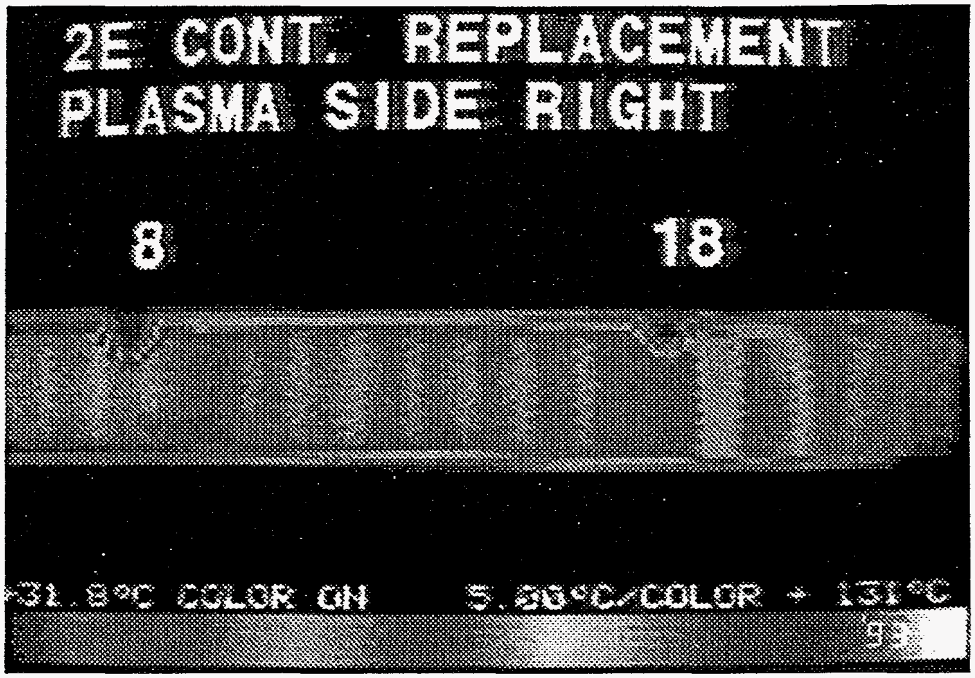


Figure 4. IR output for Tube 2e, plasma side, right end. Black depressions below 8 and 18 are markers.

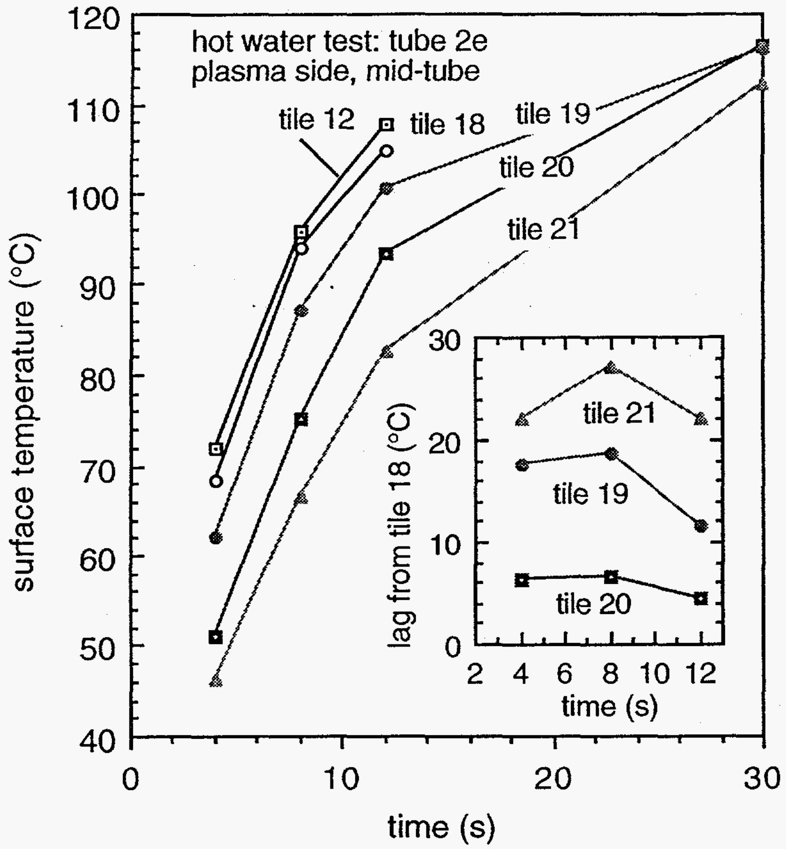


Figure 5. Surface temperature versus time for selected points on Tube 2e during hot water test. Temperature lag is shown in the insert.

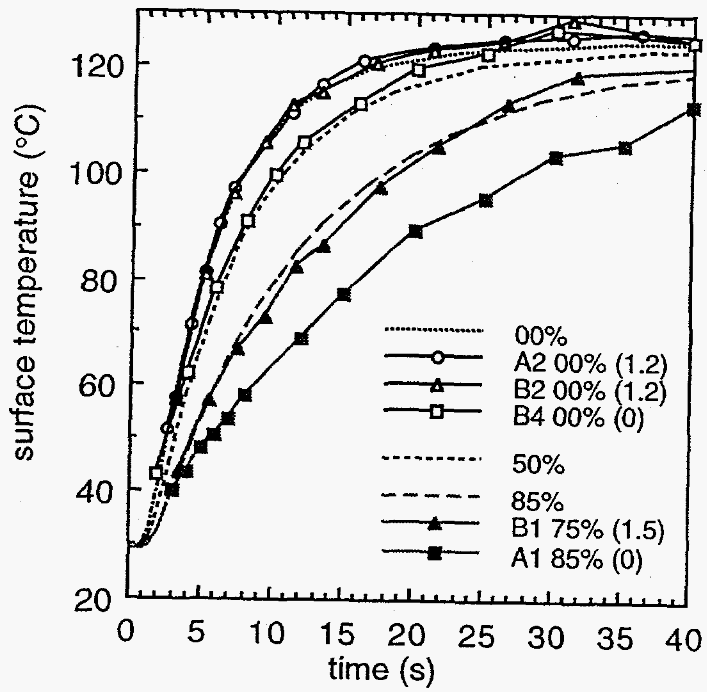


Figure 6. Finite element mesh for 53% symmetric flaw in Tube 3.