3-D Thermo-Mechanical Analysis of the ITER Limiter Small Scale Specimen

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Fusion Technology Institute
University of Wisconsin-Madison
1500 Engineering Drive
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1. INTRODUCTION

This report describes in part, the R&D activity related to the small scale specimen of the ITER limiter. The limiter specimen is needed to experimentally examine the methods of construction and testing of prototype ITER limiters under near operating conditions. This 3-D thermo-mechanical modeling and analysis of the small scale specimen is intended to attempt to predict the temperatures and stresses which will result from the tests made on the specimen. The boundary conditions imposed are those expected from the test fixture in which the experiment will be performed. A steady state heat flux of 3 MW/m^2 will be used with an inlet cooling water temperature of 140°C. The test specimen is a layered composite of Be tiles bonded to Cu which in turn is bonded to stainless steel. Coolant channels run through the Cu and the stainless steel. The specimen is 50 cm long and 14 cm wide, with seven coolant channels in the Cu and three in the SS. A 3D finite element model has been created of one quarter of the specimen, taking advantage of the design symmetry. The interface between the various layers assumes no presence of intermetallic compositions and thus has a singularity due to the differing materials. Further, the analysis is purely elastic, assuming no plastic deformation. These two rather severe assumptions tend to give higher stresses at the interface between the materials than would normally be expected.

2. DESCRIPTION OF THE LIMITER SPECIMEN AND THE MODEL

The basic design of the specimen was provided by McDonnell Douglas Aerospace in July 1996 and is shown in Figure 1. The specimen consists of a Cu (GlidCop Al25) slab, 2 cm thick, 14 cm wide and 50 cm long bonded to a SS slab, 5 cm thick, 14 cm wide and also 50 cm long. The Cu slab has seven round channels equally spaced running the full length of the specimen and the channels are jacketed with SS tubes, 1.05 cm OD and 1.0 cm ID. Grooves 1 mm wide are cut into the Cu slab parallel to the channels and spaced between them, extending to within 1 mm from the Cu/SS interface. Effectively, the Cu now consists of blocks 2 cm square and each block has a SS jacketed round channel in it. The SS slab has three channels 2.4 cm in diameter running the full length at a distance of 2.5 cm from the Cu/SS interface. The five inner Cu blocks have protective Be material in the form of 2 cm × 2 cm tiles, 1 cm thick bonded to them, while the remaining two edge blocks are not protected with Be.

Figure 1 shows an end view of the small scale limiter specimen with all the dimensions. Figure 2 is a preliminary figure of the test setup in which the limiter will be tested. Here the test

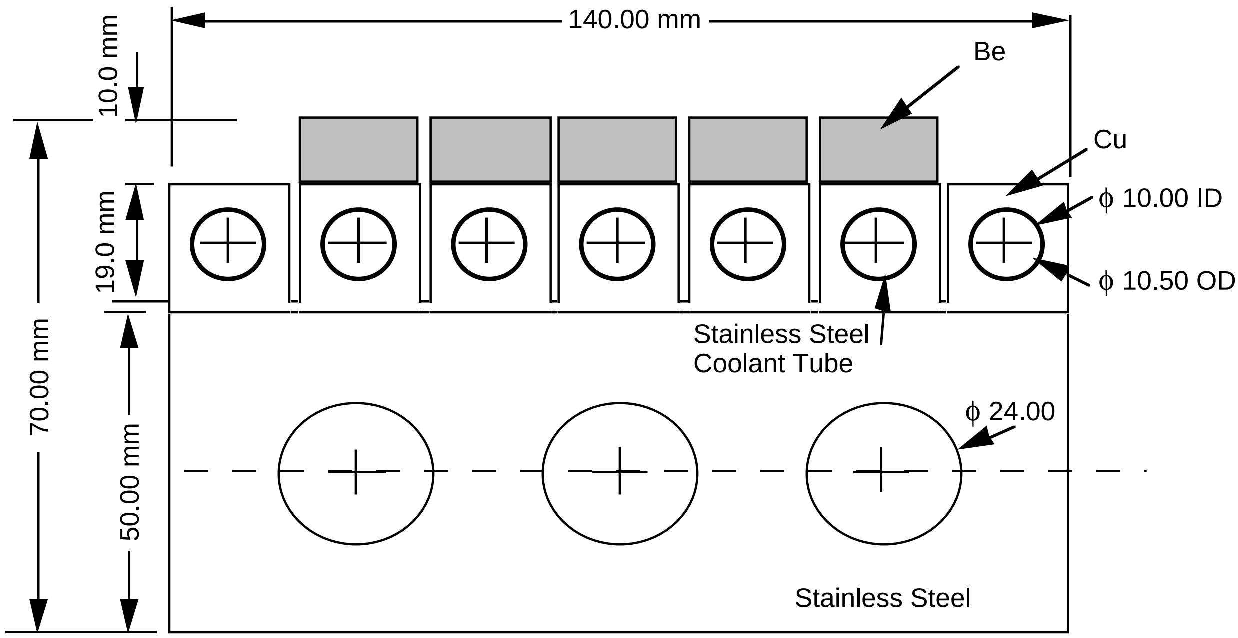

Figure 1. The geometry of the small scale specimen for the ITER limiter.

specimen is shown connected to the coolant lines but without the Be tiles. The limiter specimen will be mounted in the test fixture supported on both ends with the coolant lines attached. Lacking any different instructions with respect to cooling parameters, it has been assumed that the ITER limiter parameters will still hold for this test. These parameters are that the inlet water temperature is 140°C and the water heat-up rate at the 3 MW/m^2 heat flux is 29.2°C per meter of limiter. Since only one half of the limiter length is modeled, we have assumed an inlet temperature of 165°C and an outlet temperature of 172.5°C. This is consistent with a heat-up rate of 29.2°C per meter in a specimen which is only 24 cm long and is the same as that used in our earlier 3D thermo-mechanical analysis of the limiter [1,2] where only one quarter of a Be tile was analyzed down to the Cu/SS interface. The water velocity in the Cu blocks is 7 m/s giving a heat transfer coefficient of 4.69×10^3 W/m^{2}K. Similarly, the water velocity in the SS is 6.7 m/s and the heat transfer coefficient is 3.79×10^3 W/m^{2}K. A simplifying assumption is that those heat transfer coefficients remain constant throughout the length of the specimen. Temperature dependent material properties have been used in the analysis as taken from the ITER materials handbook [3]. As an example, Figure 3 shows the coefficients of expansion for Be, Cu and SS as functions of temperature.

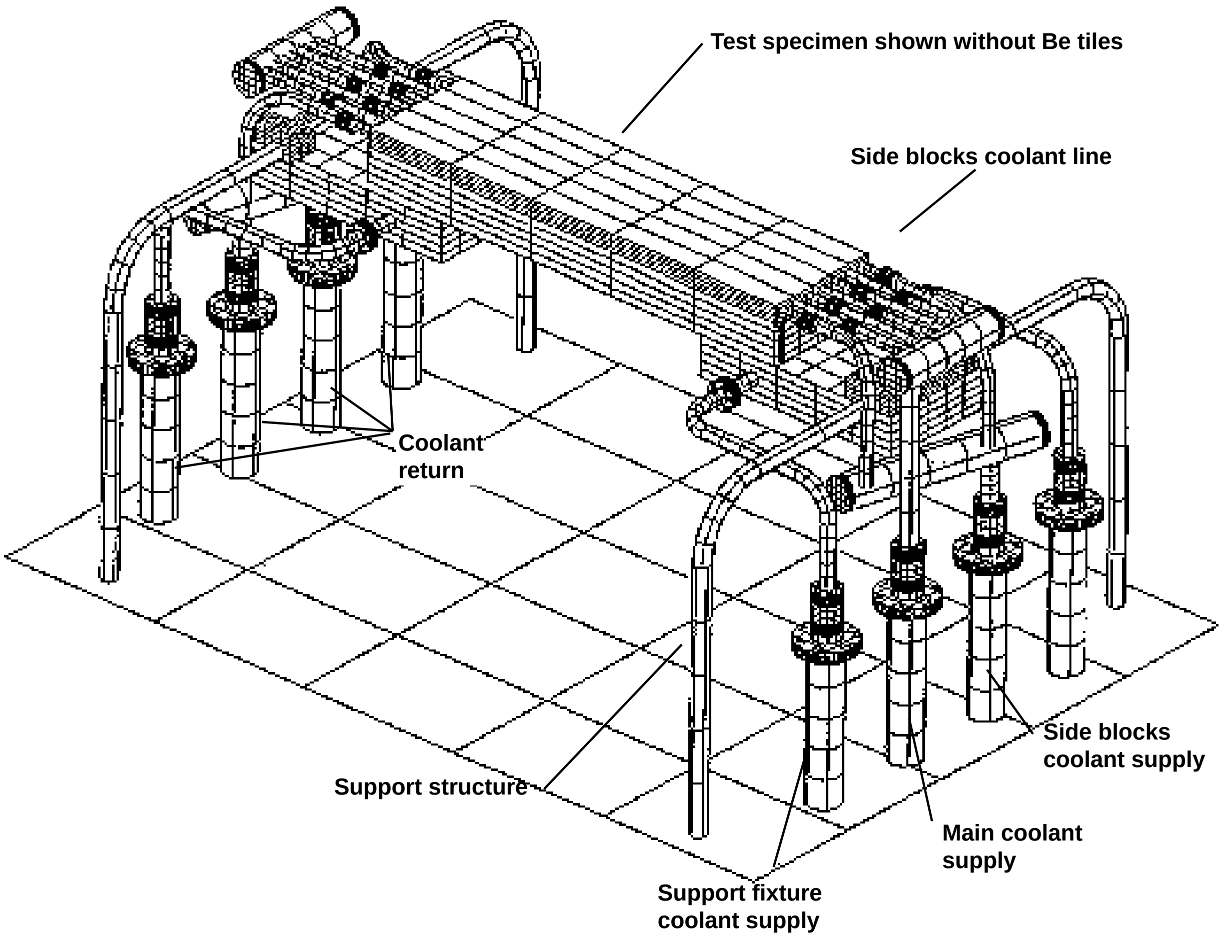

Figure 2. Test bed for the ITER small scale limiter specimen.

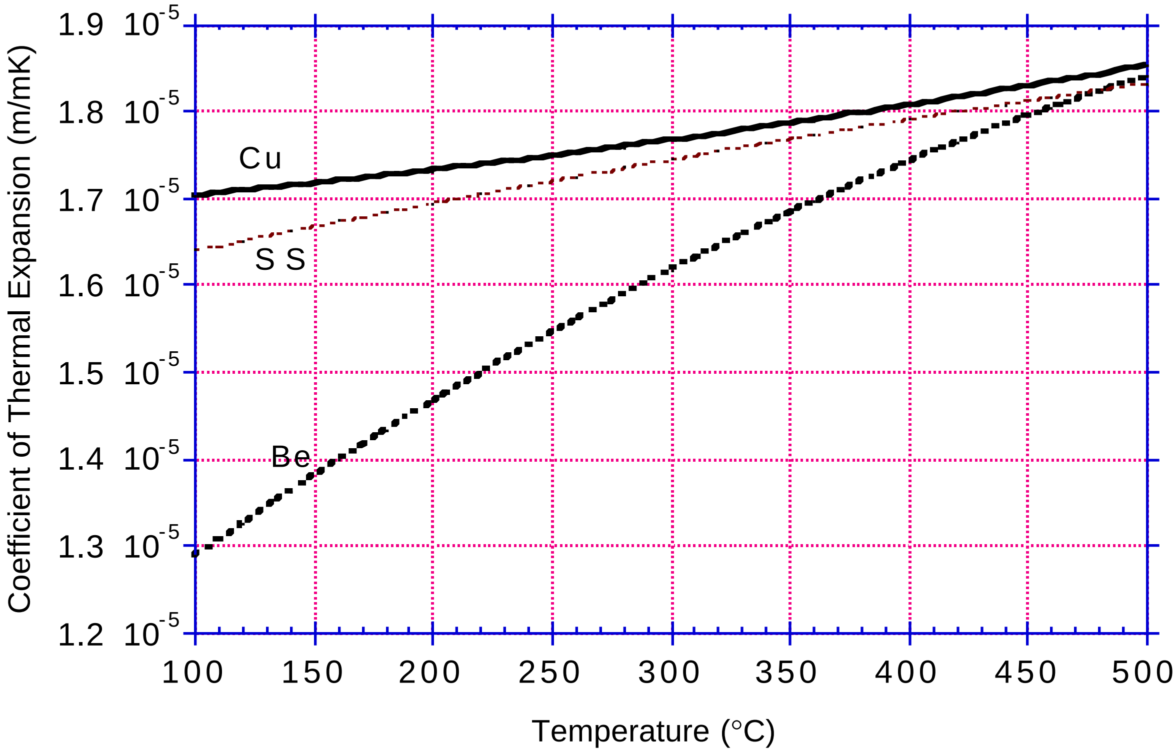

Figure 3. Comparison of the coefficient of thermal expansion for Cu, SS, and Be.

A 3D finite element model has been created to represent the Be/Cu/SS layered construction. This model takes advantage of design symmetry and thus only one quarter of the limiter specimen is represented making it 24 cm long, 7 cm wide and 7 cm thick. There are 3.5 Cu blocks with only 2.5 blocks protected with Be, and there are 3.5 coolant channels in the Cu and 1.5 coolant channels in the SS. Figure 4 shows the geometry of the model with only 1/12 of the full length of the finite element model shown. The boundary conditions used in the analysis are given in Table I. These boundary conditions are chosen consistent with the available design symmetry and assume that the external support structure made up of the attached coolant tubes is insufficient to impose any appreciable restraint on the specimen. Thus, the planes of symmetry YZ at X = 0 and XY at Z = 0 are assumed fixed, while all the remaining surfaces can expand freely. Another imposed condition is that the zero stress temperature for the limiter is 140°C. The finite element software used for this analysis is ANSYS 5.2 [4] and the computing performed on a CRAY supercomputer.

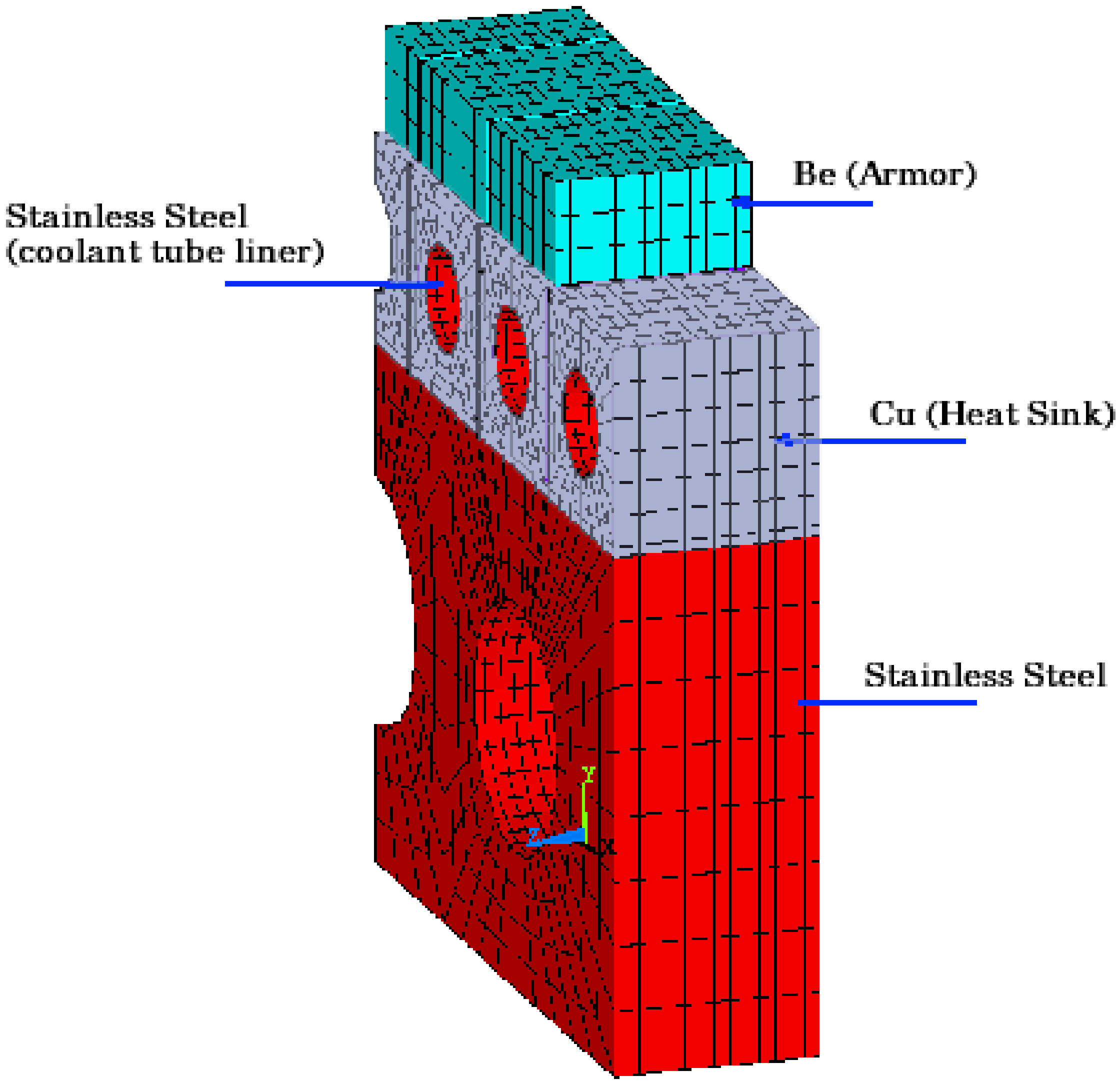

Figure 4. The 3-D finite element model for only one row of Be tiles.

Table I

The analysis is elastic and is performed with the following boundary conditions:

Surface	Point (m)	Distribution
X-Y	Z = 0 everywhere	Free
Y-Z	X = 0	Plane of symmetry, Δx = 0
	X = 0.07	Free
X-Y	Z = 0.24	Plane of symmetry, Δz = 0
	X = Y = 0	Δx = Δx = Δy = 0, (0,0,0.24) is fixed point in space
X-Z	Y = 0	Free
X-Z	Y = 0.07	Free (top surface of Be)

Note: The five surfaces of the Be tiles are free, and the Be tile's bottom surfaces are bonded to the Cu with no inter-metallic layer in between, as in the Cu bottom surface bonded to the SS with no inter-metallic layer in between. The pressure inside all the coolant tubes is 4 MPa.

3. RESULTS OF THE ANALYSIS

Figure 5 shows the whole model in perspective. This figure shows very clearly how the model represents one quarter of the specimen, with a cut through the length parallel to the tubes dividing the specimen in half and a cut perpendicular to the tubes, cutting the specimen length from 50 cm to 24 cm.

Figure 6 shows the temperature distribution looking end on from the coolant exit side. The maximum temperature is 586°C and occurs in the top Be layer. The Be/Cu interface lies in the temperature range of 338°C and 288°C, and the Cu/SS interface is in the range 239°C and 189°C. Referring to Figure 3 we note that the difference in the coefficients of thermal expansion between Be and Cu at the interface temperature of ~320°C is 10% and thus, one would expect to see a high stress at this interface due to this singularity. On the other hand, the temperature at the Cu/SS interface is ~200°C and at this value the coefficients of thermal expansion for Cu and SS differ by only 2%. Thus, it is not expected that there will be a high stress at this interface. The bulk of the SS lies in a temperature range of 189°C -140°C. Figure 7 shows the temperature distribution from a perspective view of the whole model. This figure shows that the temperatures remain essentially constant across the length of the model.

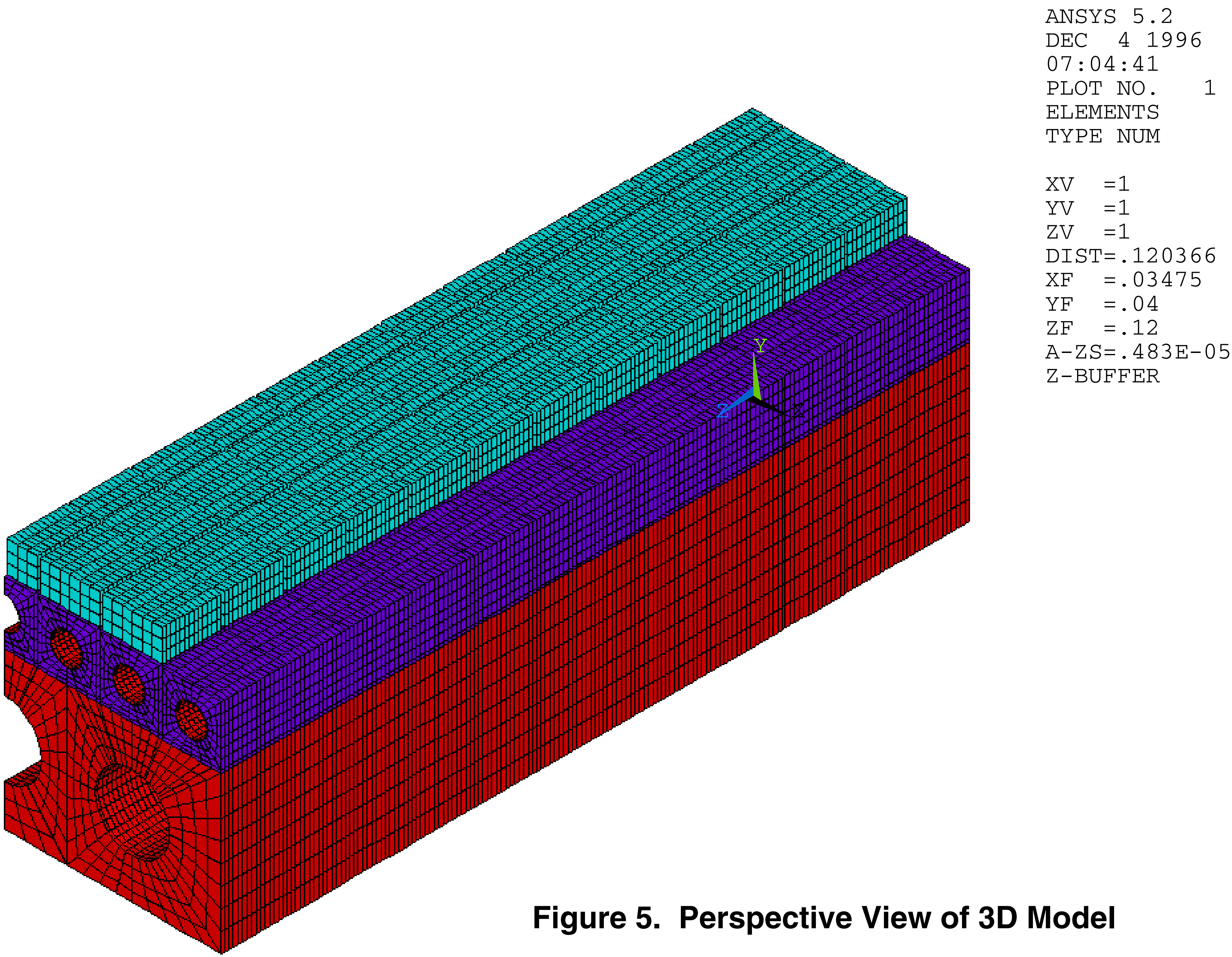

Figure 5. Perspective View of 3D Model

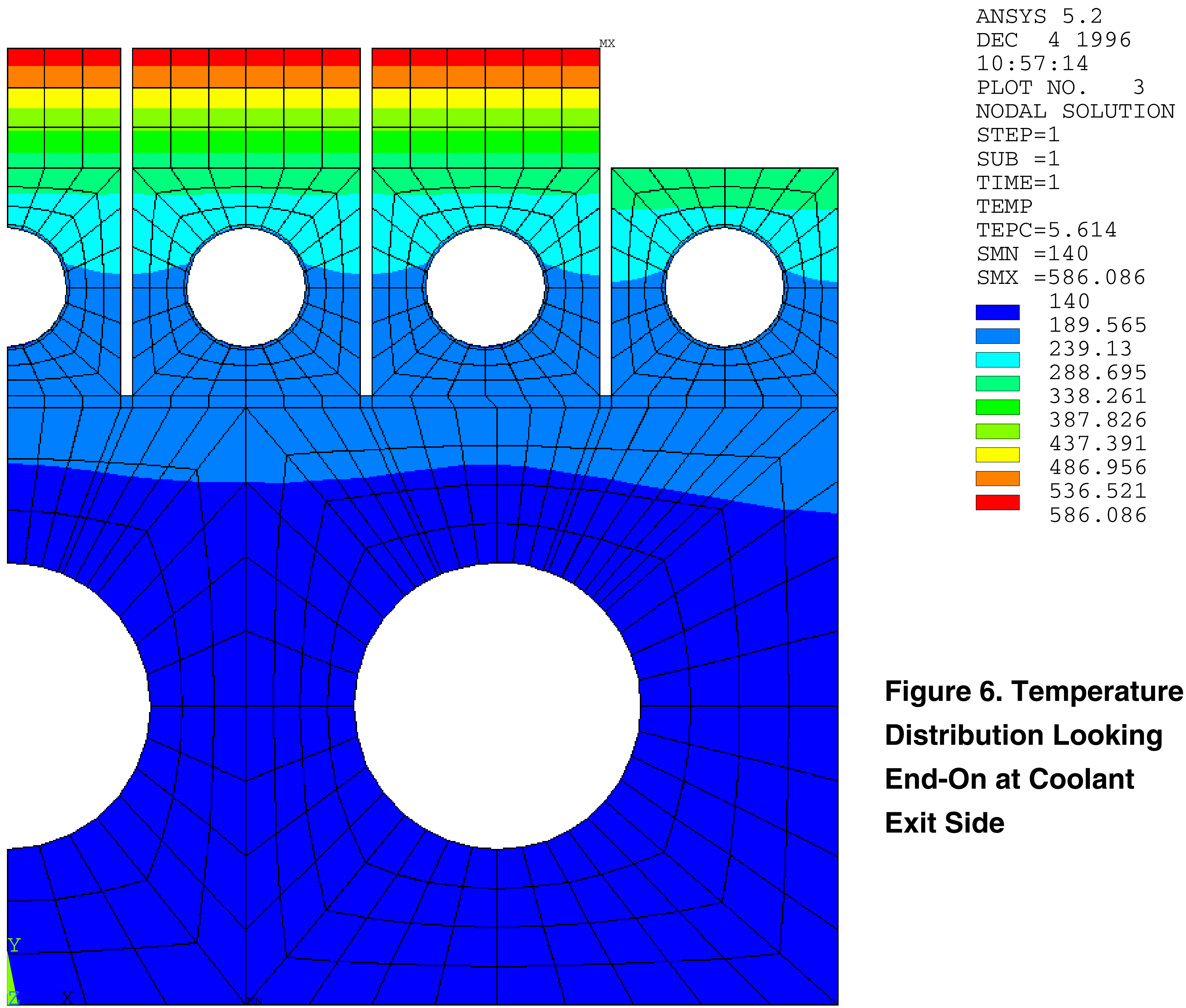

Figure 6. Temperature Distribution Looking End-On at Coolant Exit Side

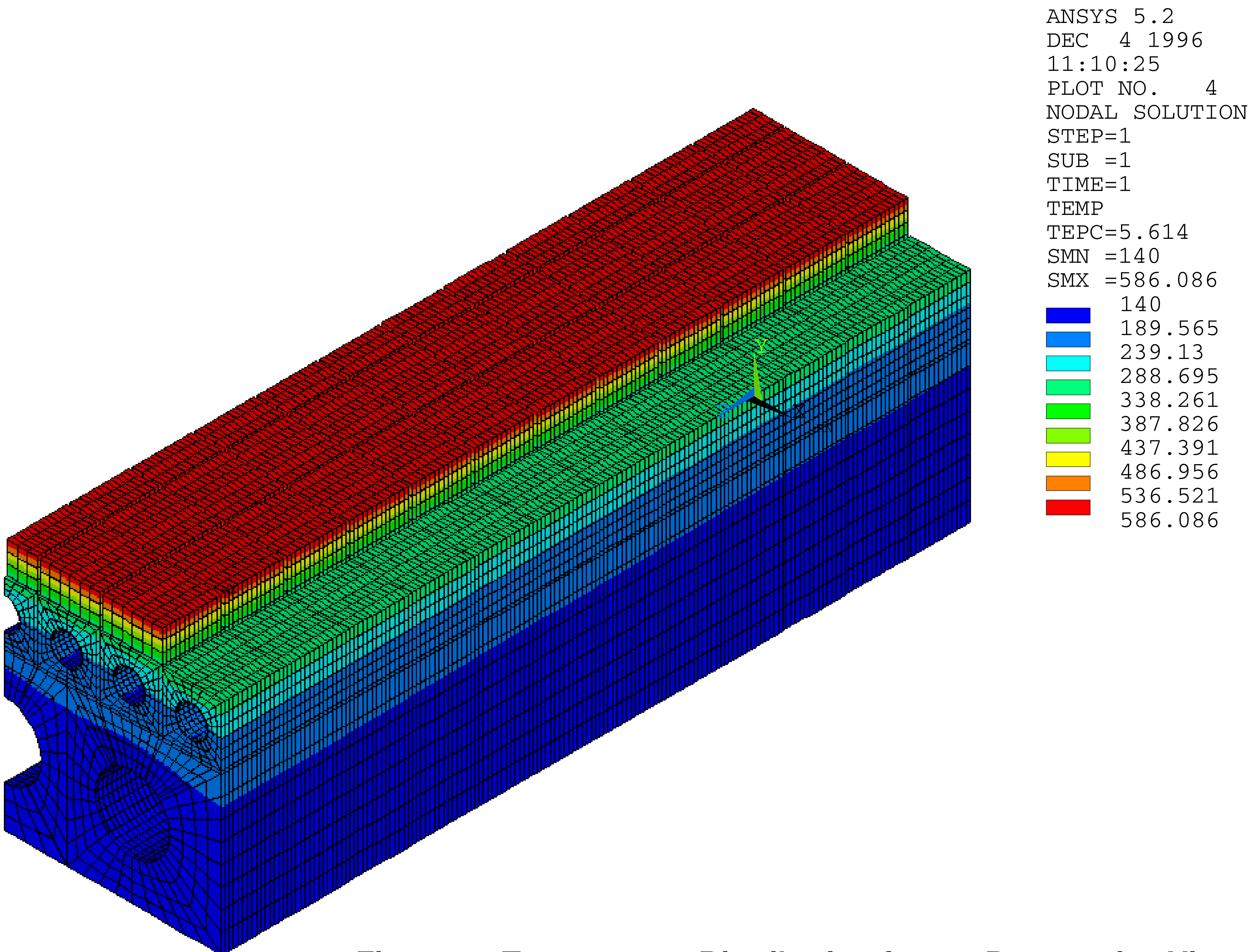

Figure 7. Temperature Distribution from a Perspective View

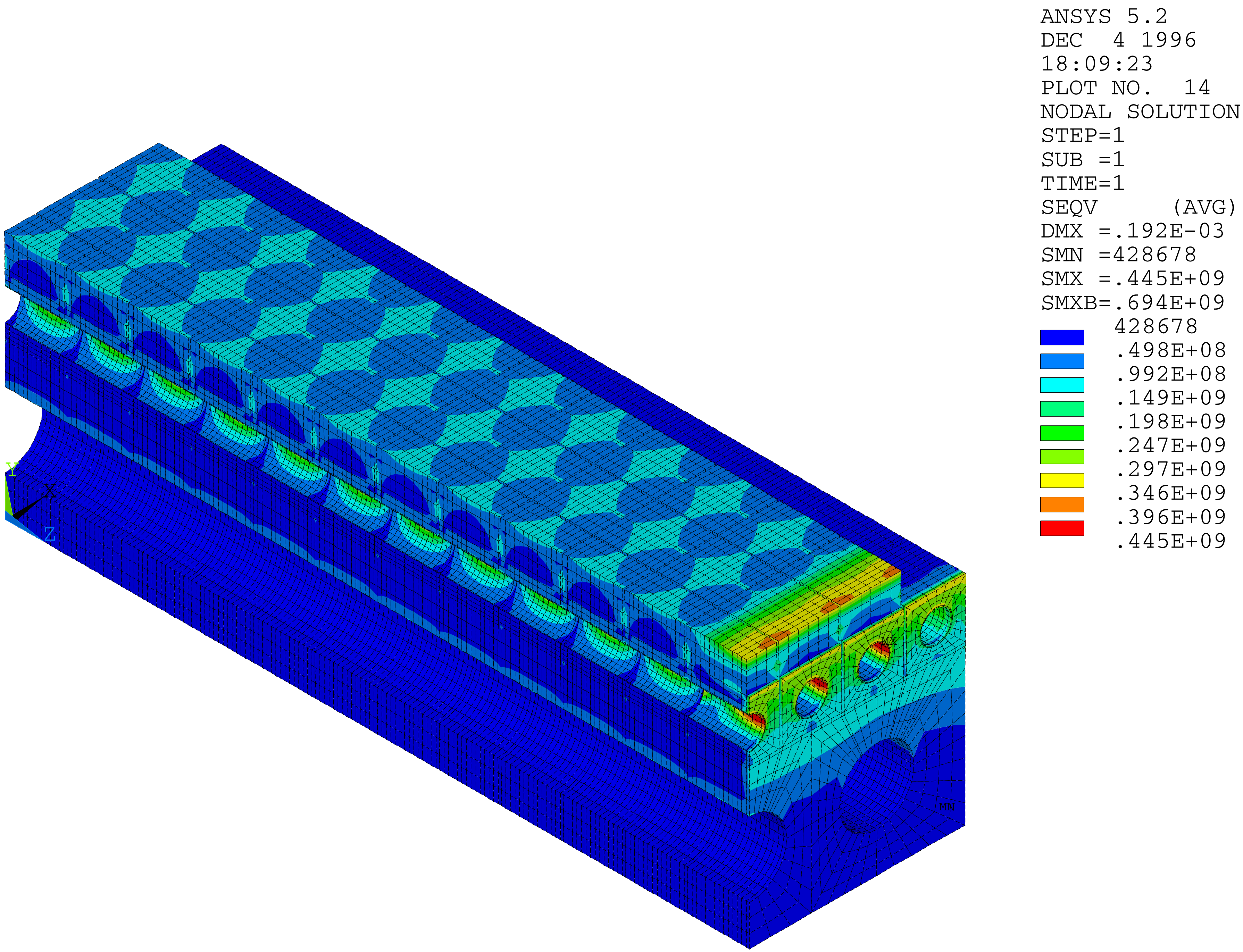

Figure 8. Von-Mises Stresses Looking on Perspective View

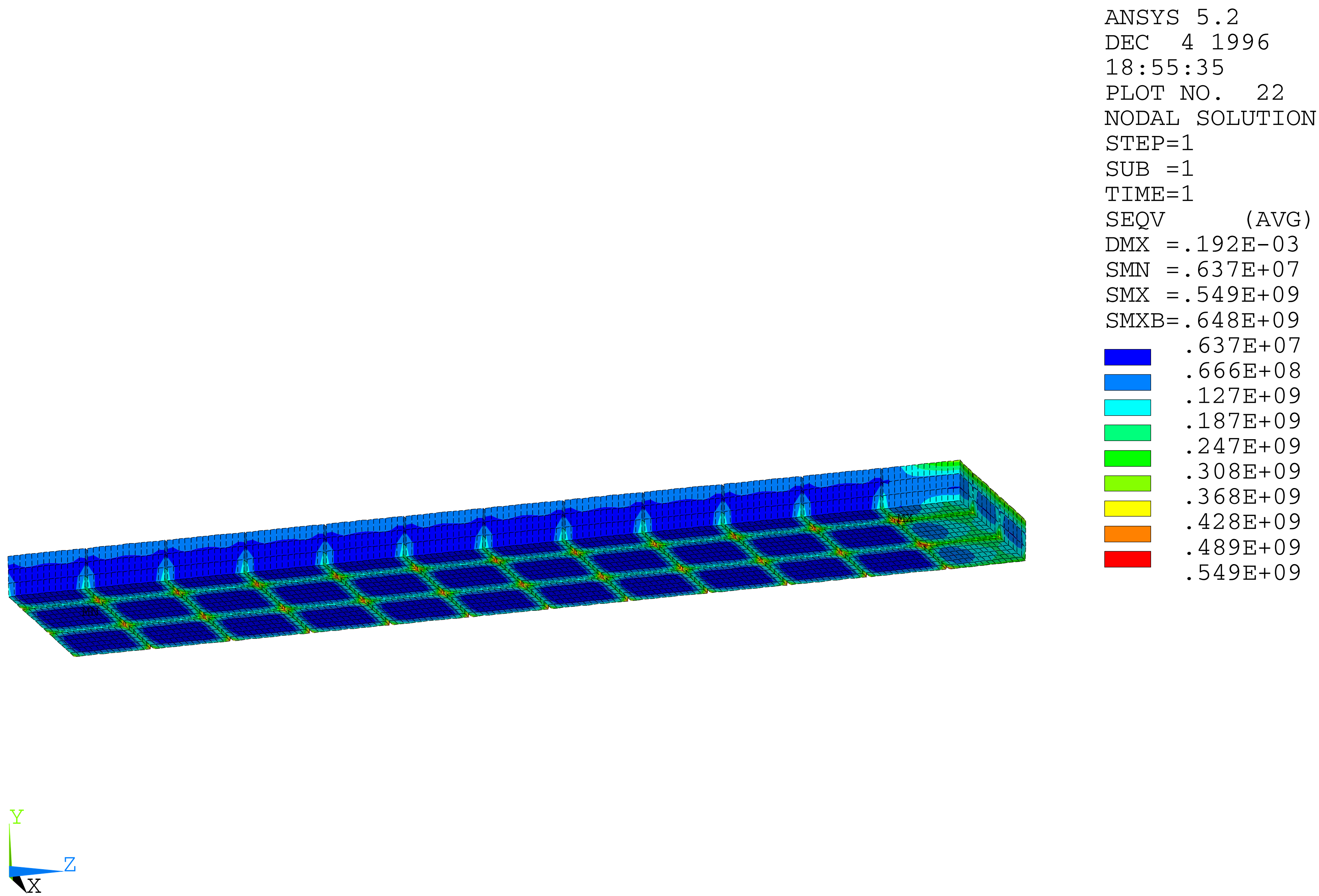

Figure 9. Von-Mises Stresses in Be Tiles from Below

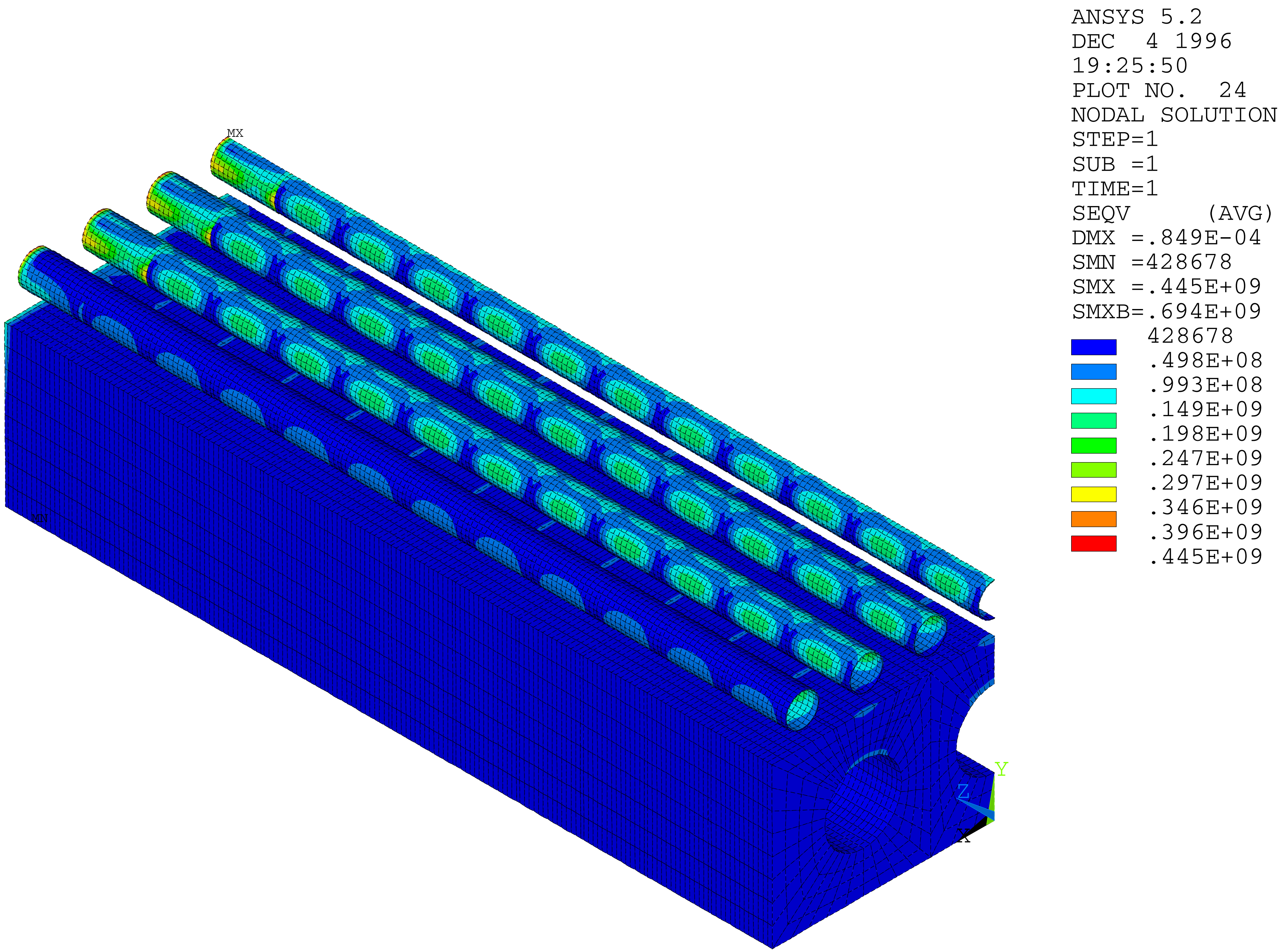

Figure 10. Von-Mises Stresses in Model with the Cu Removed

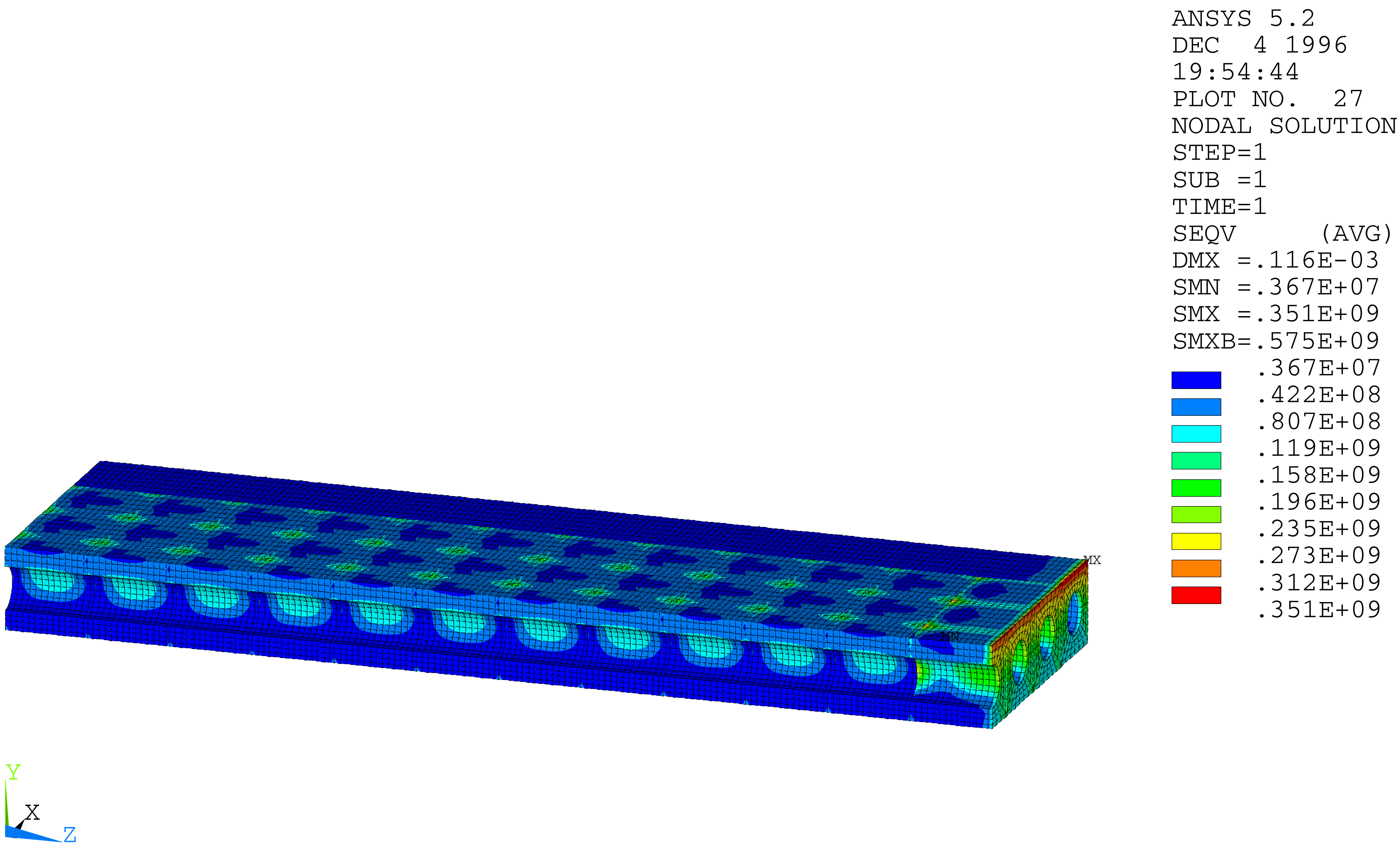

Figure 11. Von-Mises Stresses in the Cu with the Be Tiles, the SS Tubes and the SS Backplate Removed

Figure 8 shows the Von-Mises stresses from a perspective view looking down from the cut side of the model. The highest stress in this figure of 445 MPa occurs at the upper edge of the Be tiles and the inner surface of the SS tube on the constrained end of the model. Figure 8 does not show the high stresses at the corners of the Be tiles at the interface with the Cu. This is shown in Figure 9, which is a view of the Von-Mises stresses on the bottom of the Be tiles. It shows that the stresses on the corners of the Be tiles at the Be/Cu interface are 549 MPa and they occur in all the Be tiles. As mentioned earlier, these high stresses are due to the singularity at the Be/Cu interface, and they are evident only in the Be.

Figure 10 is a view of the Von-Mises stresses with the Cu removed as viewed from the unconstrained end of the model. The tube on the extreme left side is the one which has no Be tiles on the Cu and this is evident from the different stress pattern on it. Here the maximum stress is 445 MPa and it occurs in the SS tube wall at the constrained end of the model. The last figure in this series is Figure 11, which shows the Von-Mises stresses in the Cu alone with the Be tiles, the SS tubes and the SS base removed. Here the maximum stress is at the right corner of the constrained end and is 351 MPa. The highest stress in the Cu at the interface with the corners of the Be tiles is ~273 MPa as compared to the complementary stresses at the corners of the Be tiles of 549 MPa. The repeating stress pattern in this figure is due to the constraint on the Cu by the bonded Be tiles.

4. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

The present study is a thermo-mechanical analysis of a small scale specimen of the ITER limiter. It consists of a layered structure of Be tiles bonded to cooled Cu blocks which in turn are bonded to a cooled SS base structure. The analysis assumes no intermetallic layers at the interface between the materials and assumes only elastic deformation. Temperature dependent material properties, as specified by the ITER materials handbook [3], have been used throughout. Thermal hydraulic parameters are the same as those used in the ITER design with an inlet water temperature of 140°C and a heat flux of 3 MW/m^2. The specimen has been modeled in 3D taking advantage of design symmetry. It is 24 cm long, 7 cm wide and 7 cm deep, representing one quarter of the specimen. The model is constrained at the planes of symmetry and a zero stress condition is taken at 140°C. The software used is ANSYS 5.2. The results show that the highest stresses of 549 MPa occur in the Be, at the corners of the Be/Cu interface. The complementary stresses in the Cu at the same location are 273 MPa. The next highest stress occurs in the SS tubes embedded in the Cu blocks. These stresses are 445 MPa and are partly due to the constraint imposed on the end of the model at the plane of symmetry. There does not appear to be a problem at the Cu/SS interface where the dominant stresses are in the range of 100 - 150 MPa.

The recommendations which accrue from this analysis are:

1. Consideration must be given to some intermetallic layer at the Be/Cu interface to mitigate the singularity at that point.

2. An elastic/plastic analysis should be performed to determine if these stresses can be alleviated by plastic deformation.

3. Rounding off the corners of the Be tiles at the Be/Cu interface can substantially reduce these high stresses.

ACKNOWLEDGEMENT

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