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

E.A. Mogahed and I.N. Sviatoslavsky

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E. A. Mogahed and I. N. Sviatoslavsky
Fusion Technology Institute
University of Wisconsin-Madison
1500 Engineering Dr., Madison, WI 53706

Abstract — This analysis describes in part, the design activity related to the small scale limiter specimen for ITER. Steady state heat fluxes of 3 MW/m^2 are expected. A 3D finite element model has been created to represent the beryllium-copper-steel layered construction of the limiter small scale specimen. The boundary conditions are chosen to simulate the actual conditions of the entire limiter. The Cu block has a 1 cm thick castellated layer of Be armor facing the plasma on one side and is attached to a 5 cm thick cooled SS backing on the other. The interface between the various layers assumes no inter-layer compositions and the analysis is elastic. These two rather severe assumptions tend to give higher stresses at the SS/Cu/Be interface. The maximum Be temperature is 586°C at the coolant exit. The maximum von-Mises stresses at the Cu/Be interface corners are 445 MPa. These stresses are superficially high due to the singularity at the interface and the assumption of no plastic deformation. It is proposed that any additional analysis should include the plastic deformation at the interfaces between different layers and also include an interface layer of materials to more closely simulate actual conditions.

I. INTRODUCTION

This paper 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 attempts 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 SS. 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 3-D 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 different material. 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.

II. 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 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 state 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 3-D thermo-mechanical analysis of the limiter [1,2] where only one quarter of a Be tile was analyzed down to the Cu/SS interface.

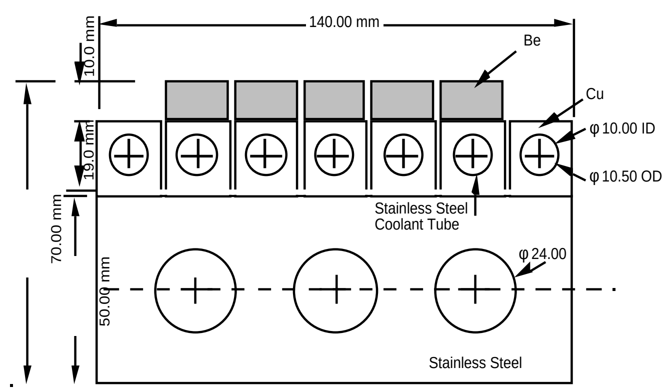

Figure 1. The small scale specimen for the ITER limiter.

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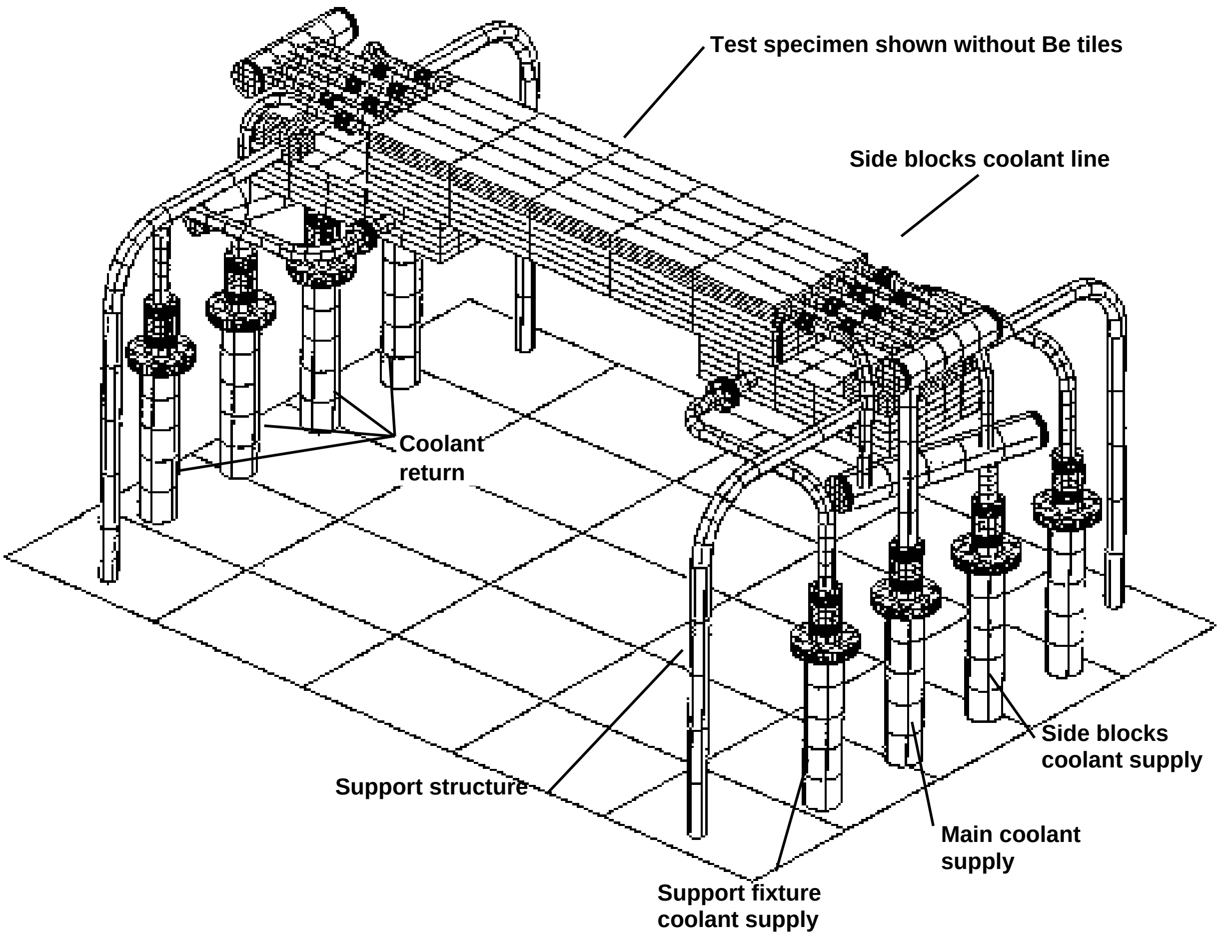

Figure 2. Test bed for the ITER small scale limiter specimen.

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.

A 3-D 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 assuming 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 conditions 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.

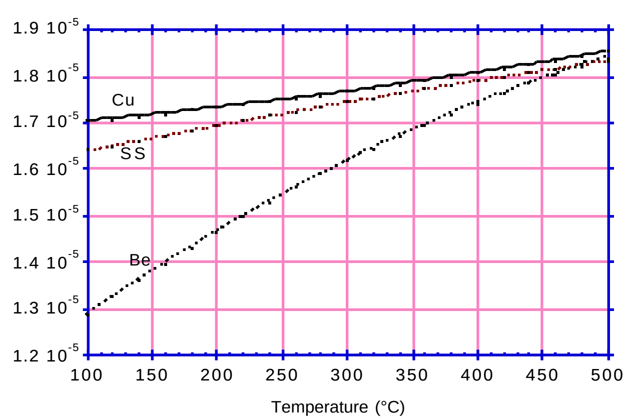

Figure 3. Comparison of the coefficient of thermal expansion for Cu, SS, and Be.

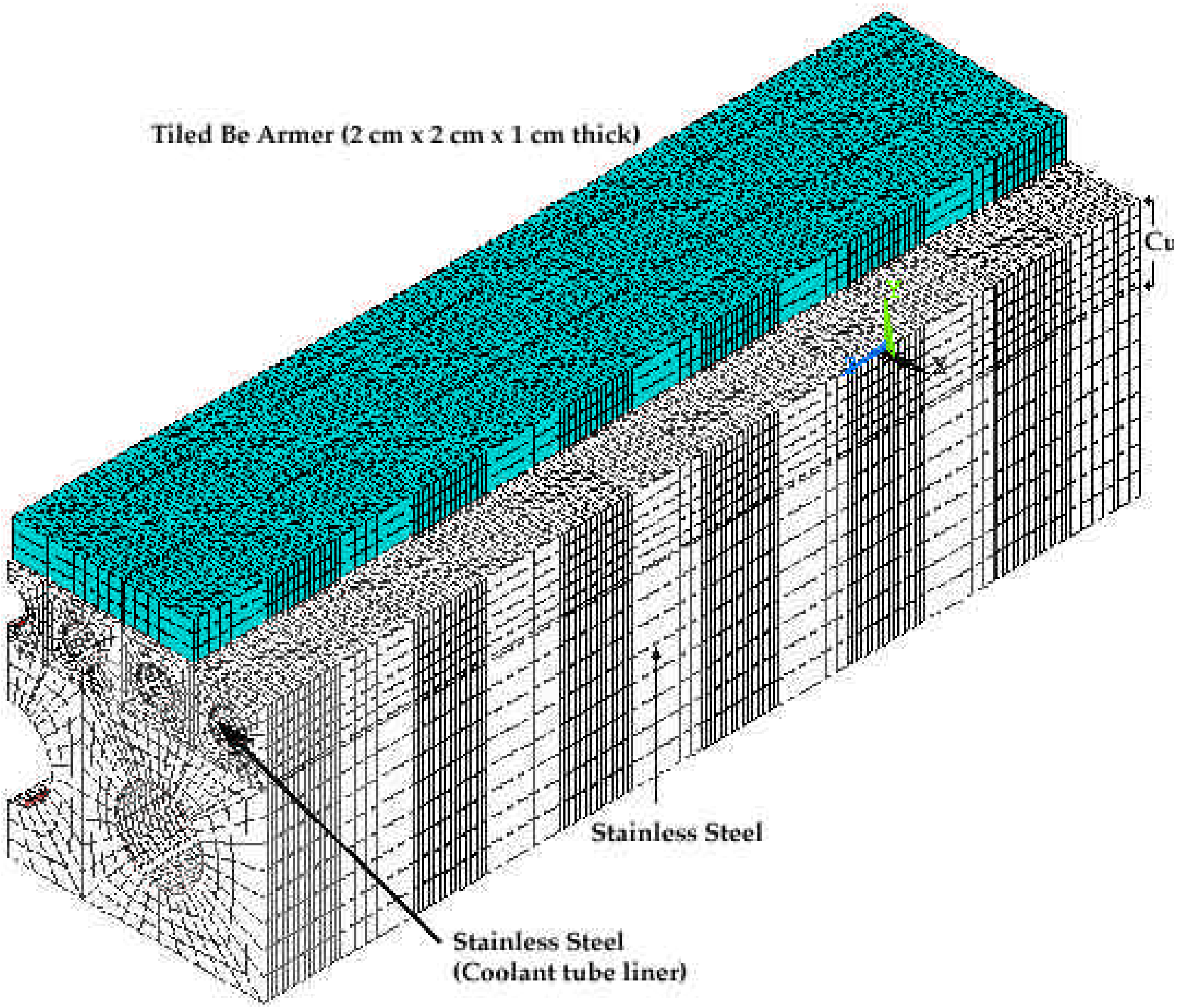

Figure 4. The 3-D finite element model.

Table I

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

Surface	Point (m)	Distribution
X-Y	Z = 0	Free everywhere
Y-Z	X = 0	Plane of symmetry, Δx = 0
	X = 0.07	Free
X-Y	Z = 0.24	Plane of symmetry, Dz = 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 tiles' 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.

III. RESULTS OF THE ANALYSIS

There are many figures generated in the 3-D thermo-mechanical analysis which cannot be included in this paper. The results will be paraphrased as best as possible in the text. Figure 4 shows the model representing 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, reducing the length from 50 cm to 25 cm.

Figure 5 is a view of the temperature distribution looking end on from the coolant exit side showing that the maximum temperature is 586°C occurring in the top Be layer. It also shows that the Be/Cu interface lies in the temperature range of 288 - 338°C and the Cu/SS interface in the temperature range of 189 - 239°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%. The bulk of the SS lies in the temperature range of 140 - 189°C and remains essentially constant across the length of the model.

A perspective view looking down from the cut side of the model showing the maximum von-Mises stress to be 445 MPa, occurring at the upper edge of the Be tiles and the inner surface of the SS tube on the constrained end of the model. The highest von-Mises stress of 549 MPa occurs at the bottom corner of each of 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.

A view of the von-Mises stress with Cu removed, seen from the constrained end, shows a different stress pattern on the extreme left side tube which has no Be protection tiles. Finally, a view of Cu alone with the Be and SS removed shown that the maximum von-Mises stress is at the right hand 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.

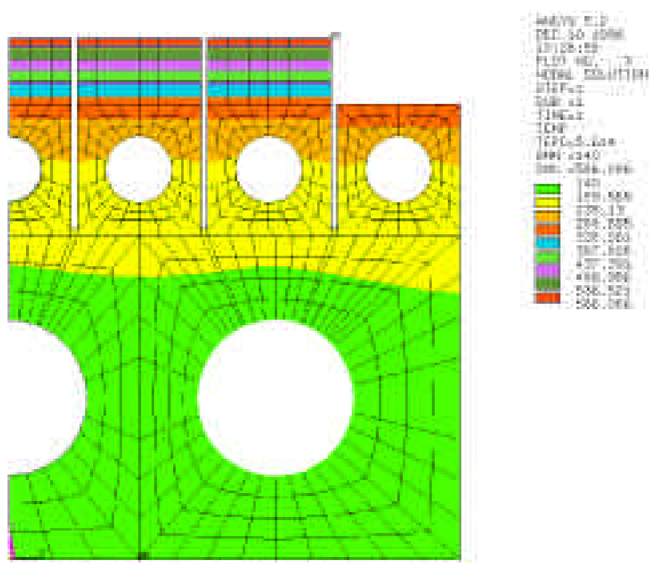

Figure 5. Temperature distribution in the plane of symmetry.

IV. 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 deformations. 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 3-D 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.

ACKNOWLEDGMENT

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