Princeton Plasma Physics Laboratory

PPPL- 5091

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November 2014

PRINCETON PLASMA PHYSICS LABORATORY

Prepared for the U.S. Department of Energy under Contract DE-AC02-09CH11466.

Analysis of the Wendelstein 7-X Test Divertor Unit Scraper Element With Radiation Shields

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Early implementation of divertor components for the Wendelstein 7-X stellarator will include an inertially cooled system of divertor elements called the Test Divertor Unit (TDU) . One part of this system is a scraper element that is intended to explore methods of mitigating heat flux on the ends of the TDU elements. This system will be in place in 2017, after a run period that will involve no divertor, and will precede steady state operation with actively cooled divertors scheduled for 2019. The TDU scraper element is an experimental device with uncertain requirements and with loading conditions which will developed as a part of the experiment. The pattern of heat flux may vary from currently predicted distributions and intensities. The design of the scraper element must accommodate this uncertainty. Originally the mechanical design was to be based on extensive studies for the monoblock- based design of an actively cooled system. An obvious simplification is the elimination of the manifolding needed for the water cooling. Design evolution of the TDU scraper is addressed in another paper [1]. The wall panels on which the panels are mounted are to be maintained at 200C or less. Thermal ratcheting of the tiles, supporting structures, and backing structures is managed with adequate cooldown times, thermal anchors, where allowed, and radiative shields. Water cooling of the shields was proposed and rejected. Better radiation modeling is showing less need for multiple shields, but during initial run periods, the scraper element will have to be restricted to an acceptable operating envelope. Thermal instrumentation is recommended.

I. INTRODUCTION

WENDELSTEIN 7-X (W7-X), is currently under construction at the Greifswald branch of the Max-Planck-Institut für Plasmaphysik (IPP). It is the world's largest stellarator project. It will operate with extended pulses that will effectively require steady state divertor components. Actively (water) cooled divertor componenets will be required for W7X. Initial operation will not require the actively cooled components. The scraper is an inertially cooled component, currently at the pre-PDR level. Ultimately it and the TDU will be replaced with the water cooled components. Figure 1 shows the plasma surface, the Test Divertor Units (TDU) and the scraper elements.

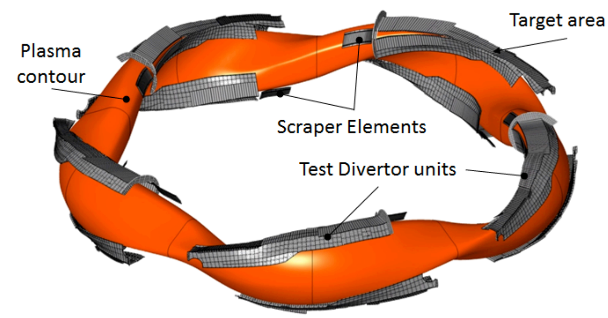


Fig. 1. W7X Plasma Divertor and Scraper Elements

II PF1c Mandrel Outer Shell and CHI Heat Loads

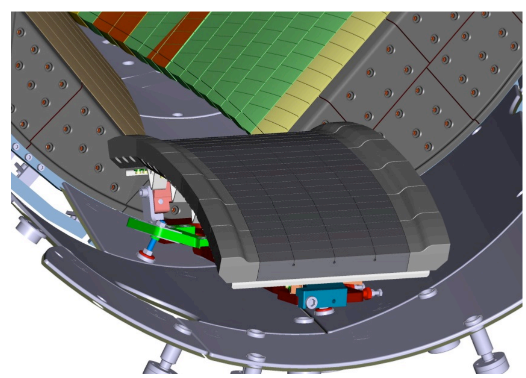


Fig. 2. W7X Test Divertor and Scraper Element

In figure 2 the scraper element is seen to be mounted on the wall panel with only three attachment points. These include features for dimensional adjustment. The mechanical design benefitted from extensive studies for the monoblock based actively cooled system[3][4][5].

II. REQUIREMENTS

Ref 1 includes a full list of requirements.

Heat Flux:

There are differences between the upper and lower heat flux but both will be qualified for the heat flux below:

The heat pattern was initially 8MW/m^2 and .1 m wide and rectangular in cross section.The design basis heat flux for the scraper now is 8MW/m^2 for 6 seconds over a "stripe" of 0.05 meter. The position of the stripe is uncertain but will remain in the "trough" – away from the end tiles that will protect the manifold in the actively cooled version of the scraper element.

These heat specs are for DESIGN. Actual heating may vary in time, magnitude and position.

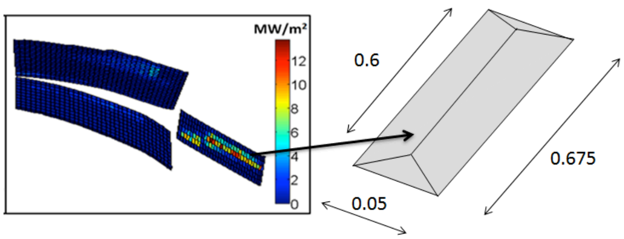


Fig. 3 Scraper Element Heat Flux Profile

Temperature Limit:

A limit of 1800 degrees C is chosen for the design basis of the scraper element. This is at the onset of sublimation in graphite.

In NSTX an administrative limit of 1200 C is set based on an extrapolation of thermocouple results to a surface temperature that is intended to be limited by carbon sputtering due to bombardment of energetic ions.

Tile Thermal and Mechanical Criteria:

The allowable stress for the graphite tiles is not well established. The tiles are not ductile. The NSTX criteria requires ½ the ultimate for brittle tiles. The allowable tile stress would then 20 MPa tension and 62.5 MPa compression for the Ringsdorf 6510 material. For NSTX's ATJ material, allowables are 13 MPa tension and 33 MPa compressive.

The surface temperature of the graphite tiles must be maintained below 1800C or 2072K. This temperature is derived from the onset of sublimation of the graphite[9]. In NSTX an administrative limit of 1200 C is set based on an extrapolation of thermocouple results to a surface temperature that is intended to be limited by carbon sputtering due to bombardment of energetic ions. Experience with **o**peration of W7X may require adjustments in the allowed surface temperature. The tiles are instrumented with thermocouples and IR cameras view the surface.

II. Analysis Model

The scraper element assembly consists of six modules supported on a spine which in turn is supported on a base plate that includes the necessary dimensional adjustments to properly align the tile surfaces. Each module can see the same range of heat flux magnitudes and positions. A single module is sufficient to study the effects of theheat flux on the tiles. For similar reasons, one module is planned for test in the GLADIS facility

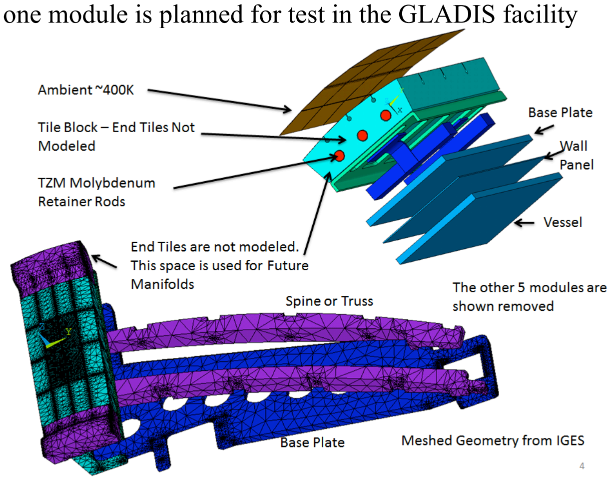


Fig. 4 Model Segment (1/6 of a scraper assembly)

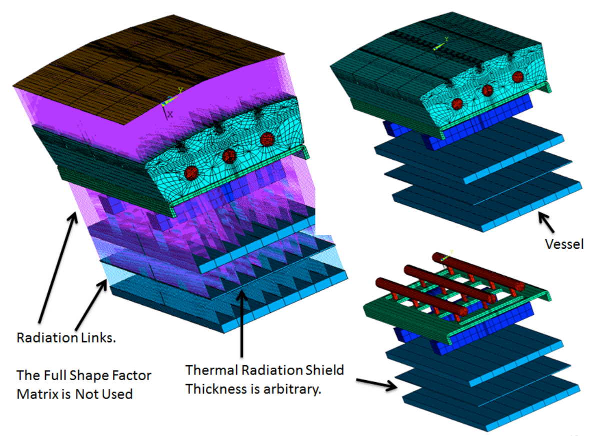
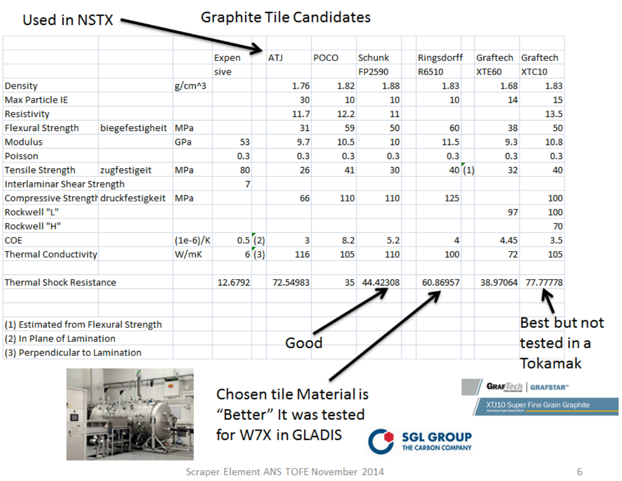


Fig. 5 Model Segment Showing Radiation Links and Backing Structures.

III. Tile Material Selection

The basis of the conceptual design analyses used properties of the Graftech ATJ material. Thist is used in the highest heat flux divertor components of NSTX. ATJ is no longer commercially available. Candidate replacement materials are compared in the table below. Ringsdorf materials have been used for limiter components in W7X and have been tested in the high heat flux facility in Greifswald, GLADIS. The Ringsdorf material is currently the preferred choice. .



			Expen sive		ATJ	POCO	Schunk FP2590	Ringsdorff R6510		Graftech XTE60	Graftech XTC10
Density		g/cm^3			1.76	1.82	1.88	1.83		1.68	1.83
Max Particle IE					30	10	10	10		14	15
Resistivity					11.7	12.2	11				13.5
Flexural Strength	biegefestigheit	MPa			31	59	50	60		38	50
Modulus		GPa	53		9.7	10.5	10	11.5		9.3	10.8
Poisson			0.3		0.3	0.3	0.3	0.3		0.3	0.3
Tensile Strength	zugfestigeit	MPa	80		26	41	30	40	(1)	32	40
Interlaminar Shear Strength			7								
Compressive Strength	druckfestigkeit	MPa			66	110	110	125			100
Rockwell "L"										97	100
Rockwell "H"											70
COE		(1e-6)/K	0.5	(2)	3	8.2	5.2	4		4.45	3.5
Thermal Conductivity		W/mK	6	(3)	116	105	110	100		72	105
Thermal Shock Resistance			12.6792		72.54983	35	44.42308	60.86957		38.97064	77.77778

(1) Estimated from Flexural Strength
(2) In Plane of Lamination
(3) Perpendicular to Lamination

Fig. 6. Candidate Tiles

IV. Tile Surface Temperatures

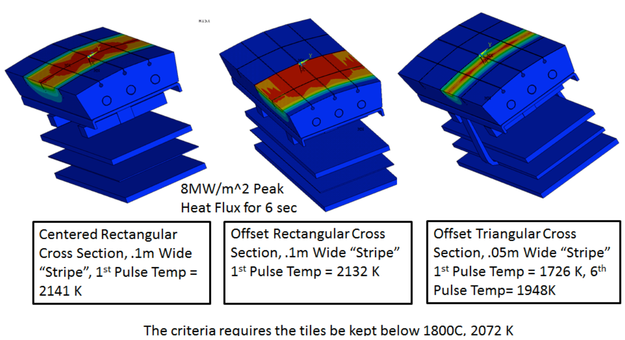


Fig. 7. Temperature Distributions for "Rectangular" and "Triangular Heat Profiles

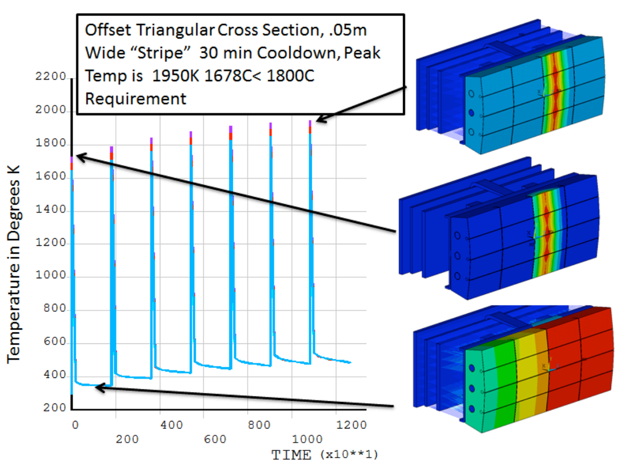


Fig. 8. Temperature Distributions for "Triangular" Heat Profile

V. Thermal Behavior of Supporting Structures

Accumulations of heat in the scraper element are radiated away from the tile to the surrounding inner vessel components. Additionally, heat is conducted through the tiles to the tile backing structures which radiate and conduct heat to the support brackets and wall panel and ultimately to the vessel wall. The average heat flux from all vessel internals , over all the vessel interior surface must be limited to 2 kW . Prediction of the amount of heat leaving the back side of the tile assemblies and radiating to the wall panels is an important design driver. For inertially cooled components in a vacuum, conduction through support structures and radiation are the available mechanisms for heat removal. With simple conservative radiation modeling and relatively short (10 minute) cooldown times, additional radiation shields were needed to meet the temperature limits for the wall panels on which the scraper is mounted.

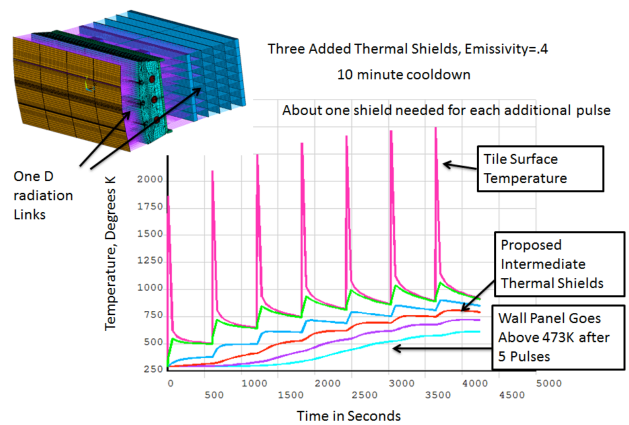


Fig. 9. Thermal Ratcheting with One D Radiation Modeled, and Multiple Thermal Shields

Longer cooldown times, a less restrictive heat flux profile, and better radiation modeling offered improved performance. And less need for multiple radiation shields.

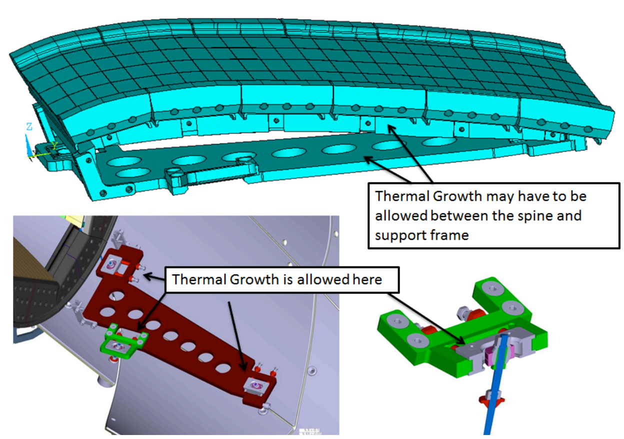


Figure 10 Scraper Element Showing Backing and Mounting Hardware

The uncertainties in the heat loading, and the relative ease of adding at least one thermal shield have argued for retention of at least one additional thermal shield to protest the wall panels.

VI Shearing Stress Mitigation

If the heat flux “stripe” falls exactly to one side of a cut in the tile, the tile expansion imposes a shearing load on the root of the cut. This produced a tresca stress marginally acceptqable for the Graftech material but somewhat below the allowable for the Ringsdorf material. Increasing the depth of the cut was accomplished by changinng the manufacturing approach to adding the relief at the root of the tile. Drilling from both sides of the tile block will allow a deeper cut.

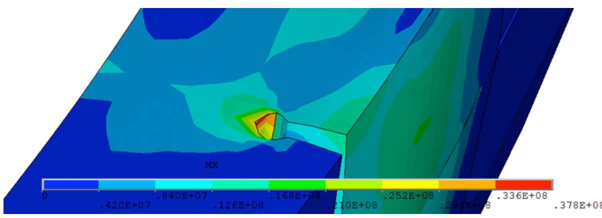


Fig. 11 Shearing Stress at Root of Tile Cut

The shearing Tresca stress is shown for the Graftech material, with the triangular heat flux, at the full first pulse temperature. It is below the tensile strength of 40 MPa, but not at the allowable of half this. Contouring of the radius at the cut will be needed.

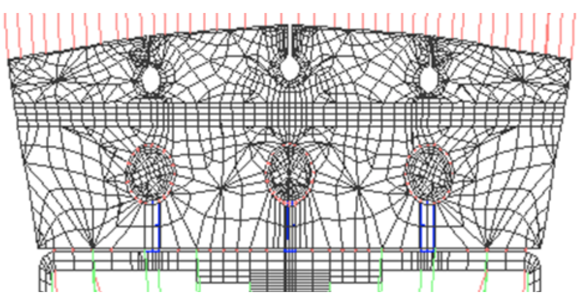


Fig. 12 Straight Cross Drilled Root Cut

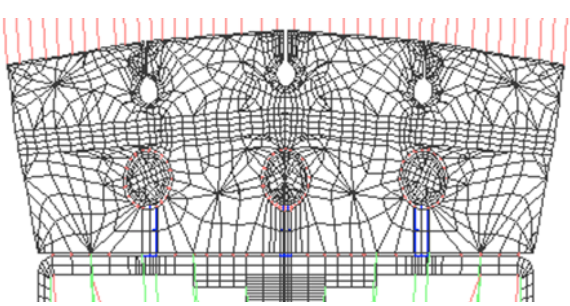


Fig. 13 Proposed Angled Cross Drilled Root Cut, Drilled from Both Sides

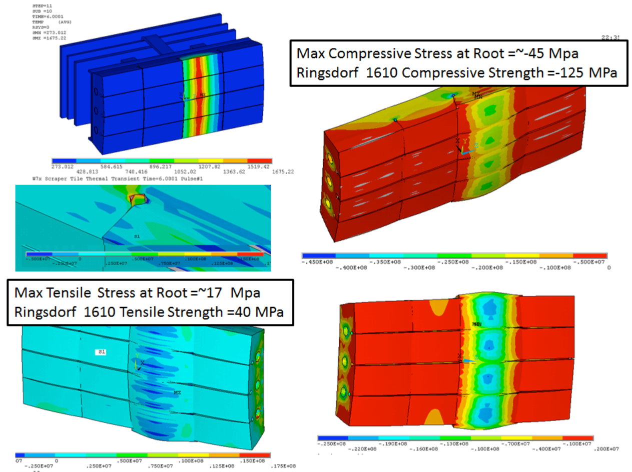


Fig. 14 Shearing Stress Evaluation for the Ringsdorf Material.

To qualify the Ringsdorf Material, the tensile allowable is compared with the max principal stress. A more appropriate failure criteria should be investigated for the brittle tile material.

VII. Addition of Langmuir Probes

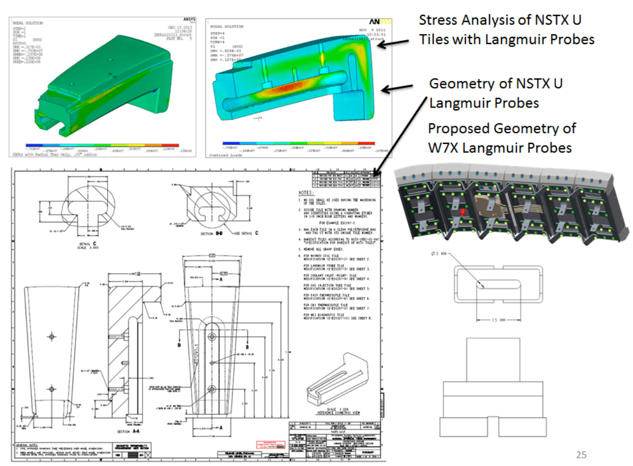


Fig. 15. NSTX U and W7X Scraper element Langmuir Probes

The Langmuir probes planned for use in the scraper element have not yet been analyzed for their impact on the tile stresses. The upper inserts in Fig 16 are from the stress analysis results for the NSTX-U Langmuir probe tiles. Solutions were found to obtain acceptable stresses in NSTX-U, and this points to the feasibility of including the Langmuire probes in the W7X tiles.

VII 3D Radiation Modeling

The conceptual design of the scraper element relied on one-D radiation link elements. The actual radiation heat transfer will be much more complicated. 3D effects with lateral view factors will increase heat removal from the back side of the scraper element with less heating of the wall panel. The appropriate way to model 3D radiation effects is to use the AUX 12 radiation utility in ANSYS. This was attempted with the full interior vessel surface, TDU surfaces and the scraper surfaces. This proved to be too large a radiation matrix to solve in a reasonable time or with available computer memory. A field period was attempted next and this was successfully solved.

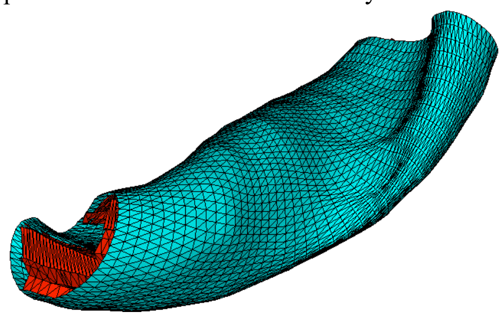


Fig. 16. Surface Element Model of One Field Period

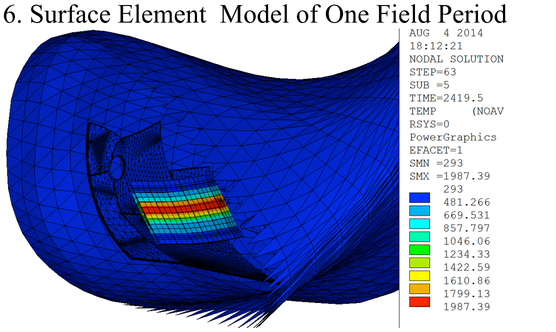


Fig. 17 Scraper Elemement Surface Temperature after Multiple Shots (8MW/m^2, Rectangular Profile

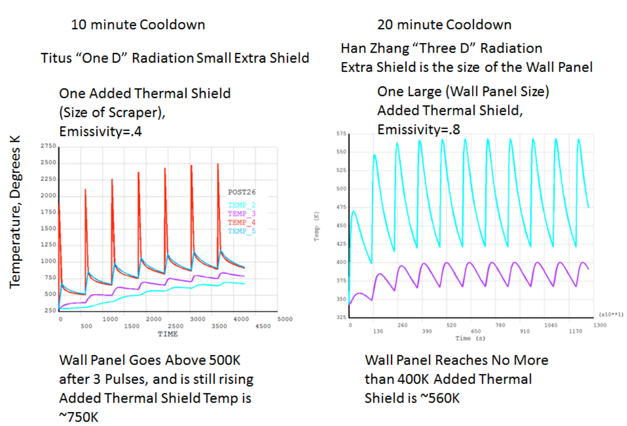


Fig. 19 Comparison of One D and 3D simulations

Unfortunately the comparison in figure 19 is for two different cooldown times which strongly effect the ratcheting behavior. However the 3D results look good. They look even better with the .05m wide triangular heat profile. With 30 minute cooldown it might be possible to eliminate the extra shield and still keep the wall panel temperature below 200C. However the ease of adding the shield and the uncertainty in the heat flux argue for retention of the shield.

VIII. CONCLUSIONS

The conceptual design of the inertially cooled scraper element is acceptable for the PDR design requirements of 8 MW/m^2 for 6 seconds over a .05 meter wide triangular "stripe"

ATJ-Like Material is needed for thermal and stress performance. Ringsdorf 6510 is acceptable.

8MW/m^2 .05m Triangular heat pattern with 30 minute cooldown is acceptable. Other pulse lengths, power levels and cooldown times can go above the tile allowable. Selective use of Shot power levels and instrumentation of tiles, backing structures and radiations shields is recommended.

Thermal response of the backing structures is much improved with a more rigorous treatment of radiation– Use of the 3D ANSYS AUX 12 radiation matrix. But there is still a potential for elevated temperatures of the spine, backplate, and wall panel that requires an additional thermal shield

Tile stresses are for the most part within the Ringsdorf 6510 Tile Material Allowable of 20 Mpa in Tension and 62.5 MPa in Compression.

Positioning the heat "stripe" boundary at a tile cut boundary causes a shearing stress, and higher than allowed Tresca stress – Use two sided angle drilled holes for the root radius,

ACKNOWLEDGMENTS

*This work is supported by US DOE Contract No. DE-AC02-09CH11466

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