Enhanced Surface Heat Removal Using a Porous Tungsten Heat Exchanger

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COLLABORATORS

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- Richard Nygren (Sandia National Labs.)

OBJECTIVE

- High Power Density Capability for Fusion Power Plants:
  - Peak Neutron Wall Load ~10 MW/m^2
  - Peak Surface Heat Load ~ 2 MW/m^2
- High Power Conversion Efficiency:
  - Greater than 40% (need high coolant exit temperature)
- High Availability:
  - MTBF is greater than 40 MTTR

Need to Improve Heat Load Capability of Plasma-Facing Components

MOTIVIATION

- The SOLID-WALL of the APEX Study is considering a W-alloy tube with W-foam inside to cool the First-Wall (FW) using Transpiration Cooling:
  - Lithium is boiled inside the FW tubes
  - Lithium pressure is low (<0.2 MPa).

- Do exploratory research using Helium coolant to measure the improved heat load capability of W-foam inside a W-tube.

APPROACH

Use Porous Structure inside the tube to Enhance Heat transfer from the Wall to the Coolant.

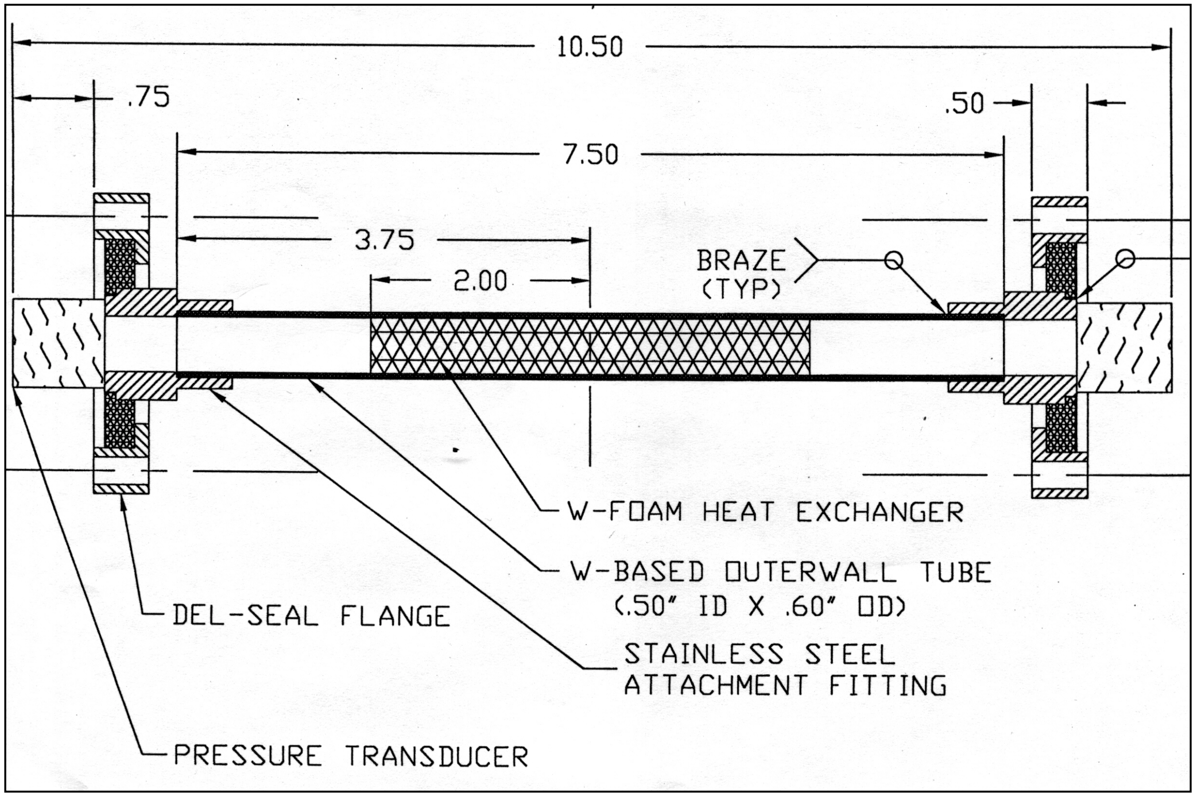
A Test Section using Chemical Vapor Deposited W-foam inside a W-alloy tube was constructed for testing in the Helium-Cooled E-Beam Facility at Sandia.

Analyze the Test Section using FEM to model potential heat load capability improvements.

ULTRAMET Inc. successfully constructed a test piece with CVD W-Foam inside a W-tube.

FABRICATED TEST SECTION

- A Test Section (19 cm long W-tube) was fabricated:



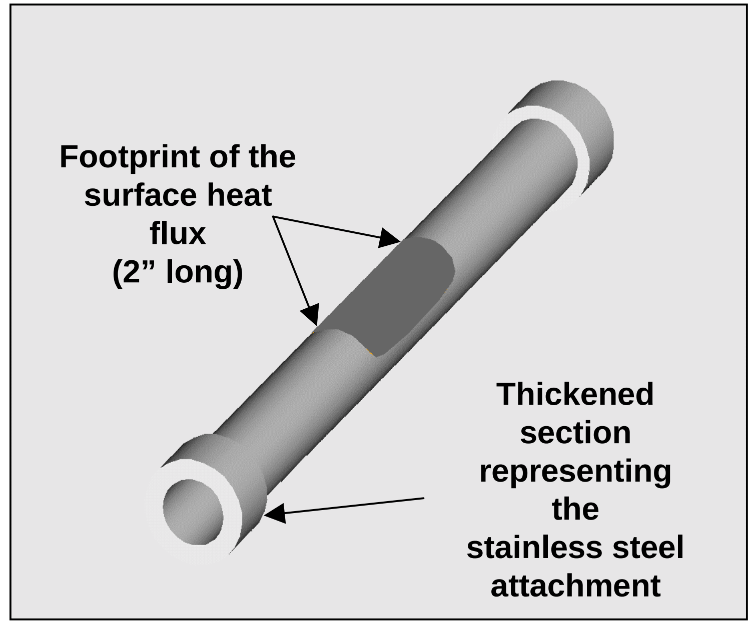
Dimensions: inches

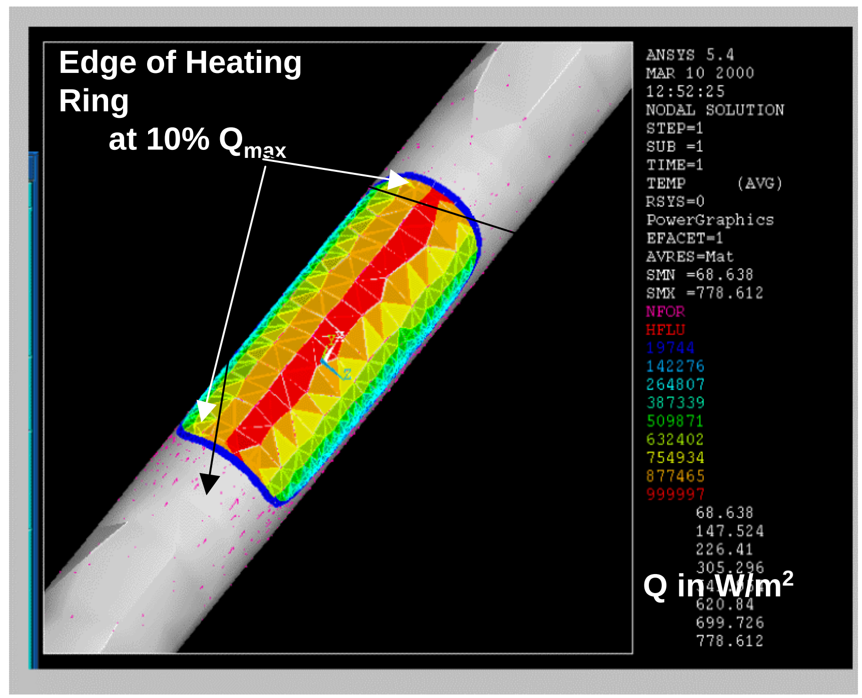
FEM MODEL

- A 3-D solid model was constructed based on the fabricated test section.
- The FEM model was built using the 3-D solid model to preserve as much detail as necessary.

FEM MODEL (cont.)

- A thin heated rim was included to model the edge of the heated section (<10% q''_{max})
- Tetragonal Solid Elements were used to mesh the 3-D Model into ~3000 elements.
- Heat transfer coefficients inside the tube are estimated in the case of the presence or absence of W-foam.





MATERIAL PROPERTIES AND FEM ANALYSIS PARAMETERS

W-Thermal Conductivity (RT/2000^{o}C)	130/95
Foam Thermal Conductivity (W/m-K)	4.5
Foam Porosity (%)	90
Foam pores/inches (ppi)	10
Foam Ligament diameter (cm)	0.0508
Helium Thermal Conductivity (W/m-K) @ RT/600˚C	0.149/0.229
Pr Number @ RT/600˚C;	0.70/0.72
μ (10^{6} kg/m-s) @ RT/600˚C	20.1/31.7

Helium flow rate	7 g/sec
Helium pressure	10 atm
Helium entrance temperature	30^{o}C
E-Beam produced heat flux	1 – 15 MW/m^2
Duration of Heating	10 – 30 sec
Duration of E-beam heating	10 – 30 sec
Length of W-tube	19.05 cm
Length of Foam	10.16 cm
Inner Tube Diameter	1.27 cm
Tube Wall Thickness	.254 cm
Length of Heated Section	5.08 cm

THERMAL MODEL FOR “NO-FOAM” TUBE

Hydrodynamically Fully Developed Turbulent Flow

$$\mathrm{Re}_{\mathrm{D}} = \frac{4\dot{m}}{\pi D \mu} = 34{,}000$$

Thermally Developing Turbulent Flow

$$\mathrm{Nu}_{\mathrm{D}} = \frac{hD}{k} = \left[0.023\mathrm{Re}_{\mathrm{D}}^{4/5}\mathrm{Pr}^{0.4}\right]\left[1 + \frac{1.4}{L_h/D}\right]$$

TRANSPORT MODEL FOR FOAM FILLED TUBE

1. Conservation of Mass: $\dot{m} = \rho V A = \frac{P}{RT} V A = const.$

2. Darcy's Law: $-\frac{dP}{dx} = -\frac{P_{in} - P_{out}}{L} = \mu \frac{U_\infty}{K}$

Permeability: $K = \frac{D_f^2 \; \Phi^3}{180(1-\Phi)^2}$

3. Steady-Flow Energy Equation: $\dot{m} c_p \frac{dT}{dx} = \int_0^{\pi/2} q'' \sin\theta D d\theta$

THERMAL MODEL FOR FOAM FILLED TUBE

Developing Porous Slug Flow Over a Plane Wall

$$\overline{\mathrm{Nu}}_{\mathrm{L}} = \frac{\bar{h} L_h}{k_m} = \frac{q''}{\overline{T}_w - \overline{T}_b} \frac{L}{k_m} = 1.329 \mathrm{Pe}_{\mathrm{L}}^{1/2}$$

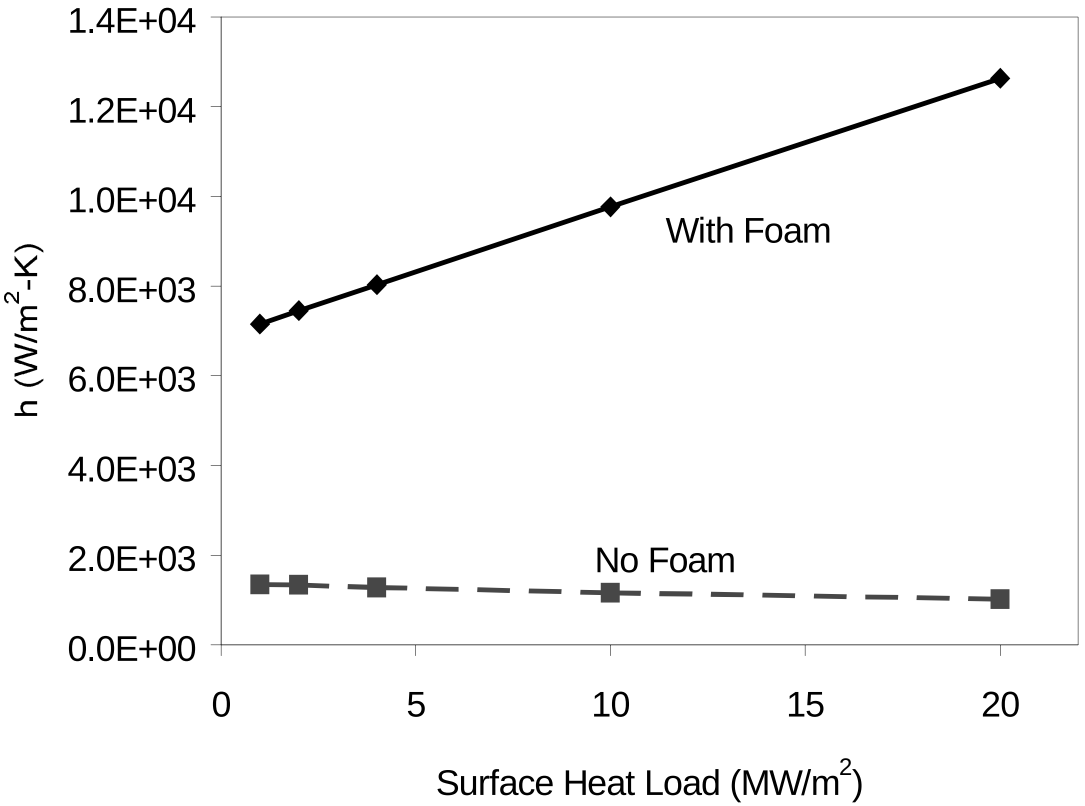
Peclet Number: $\mathrm{Pe}_{\mathrm{L}} = U_\infty L_h c_p / k_m$

Effective Thermal Conductivity: $k_m = \Phi k_{He} + k_{foam}$

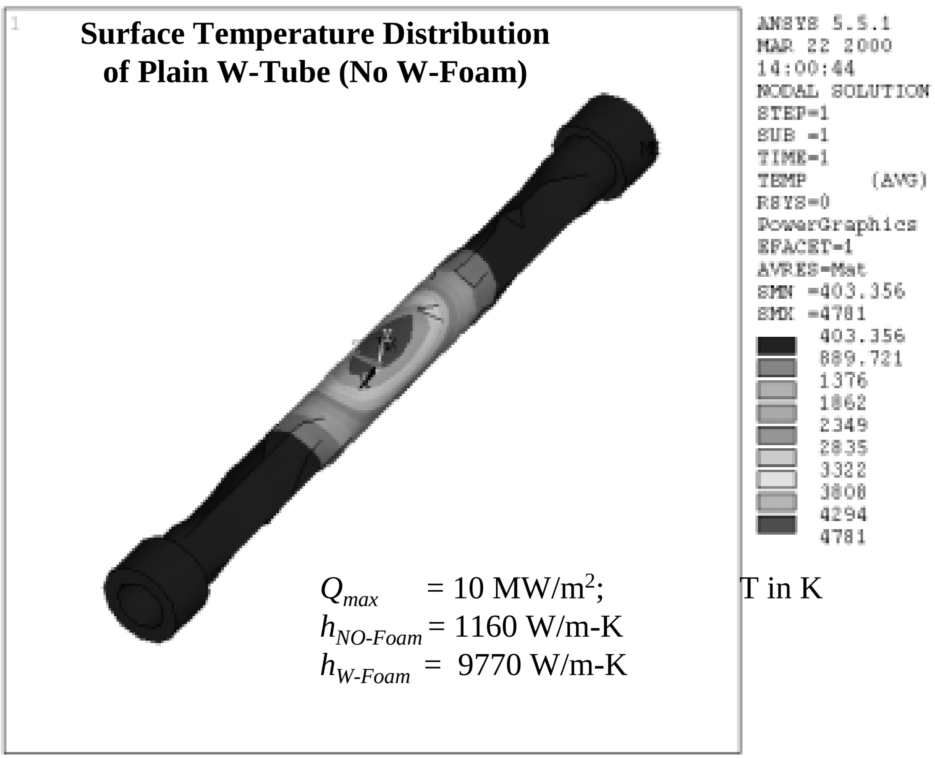
ANALYSIS RESULTS

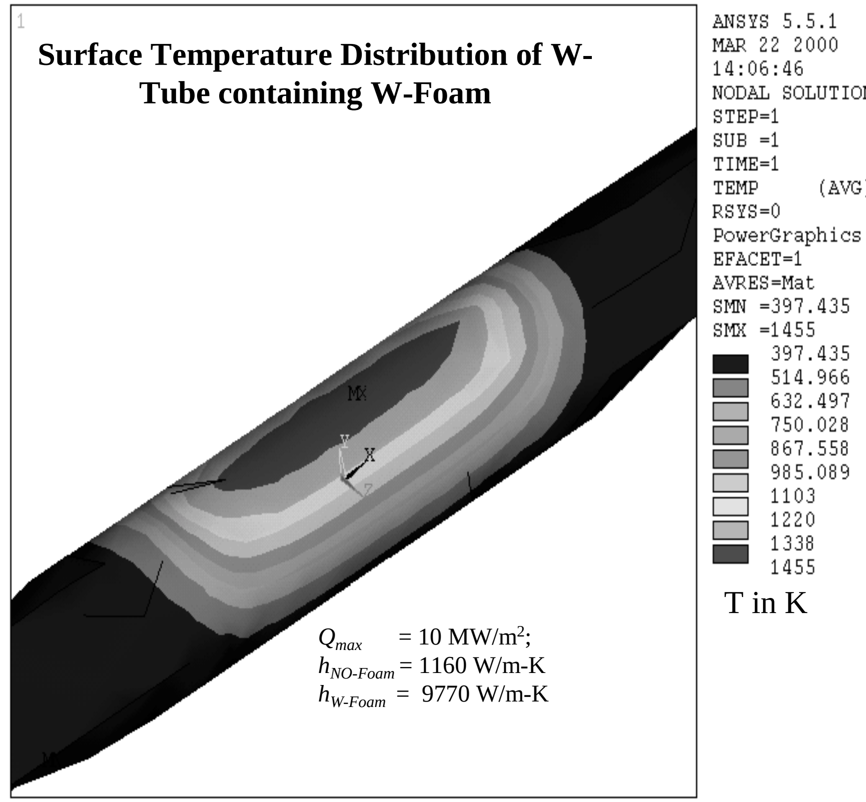
Effect of W-foam on the overall effective heat transfer coefficient.

- The foam covered region shows an order of magnitude improved *h* at high heat loads.



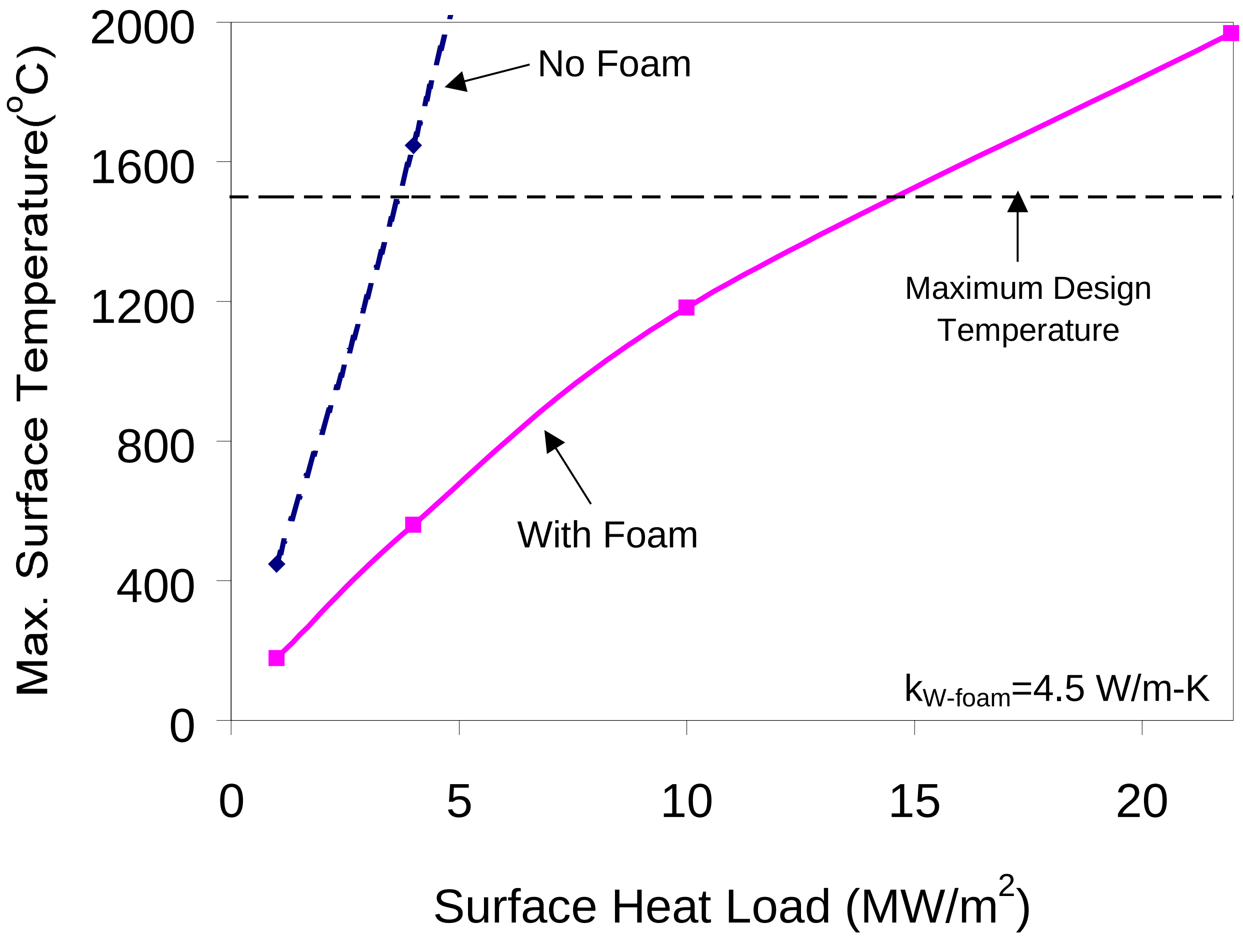
FEM RESULTS





- The foam containing W-tube shows a factor of three reduction in maximum surface temperature from 4788 K down to 1455 K.

EFFECT OF SURFACE HEAT LOAD



SUMMARY AND CONCLUSIONS

- Improvements in surface heat load capacity of plasma-facing components is essential for fusion power plant.
- The use of porous material to enhance the heat conduction from the wall to the coolant is being investigated.
- A W-tube with CVD W-Foam has been fabricated and a thermal FEM analysis has been performed.
- Enhanced heat transfer coefficient, based on fundamental fluid flow through porous material was developed and used in the FEM analysis.
- The W-foam has the potential to improve the heat load capabilities of W-alloys by a factor between 3 and 5 at operating temperatures above 1200^{o}C.