NRL Visit

SAND2013-4062P

Helium-cooled PFC Heatsinks Analysis and Testing

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Sandia National Laboratories

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Sandia National Laboratories is a multi-program laboratory managed and operated by Sandia Corporation, a wholly owned subsidiary of Lockheed Martin Corporation, for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Outline

- History of helium-cooled divertor development at SNL
  - Small business collaborations
  - IEA and Japan Phenix collaborations
- DoD applications
  - gyrotrons, cross-field amplifiers, rail guns, thrusters & nozzles
  - electronics cooling (air), hypersonic leading edges (H_2), heatpipes
- EB-60 and HeFL capabilities at Sandia's HHFF
- HHF testing results
- CFD analysis
- Summary

High Heat Flux at Sandia

2013: Sandia's PMTF is now the HHFF

- perform HHF testing as Work For Others (WFO)
- remain an NNSA Technology Deployment Center (User Facility)

NNSA has taken over custody from DOE SC.

Available for use by the fusion PFC community on a project basis.

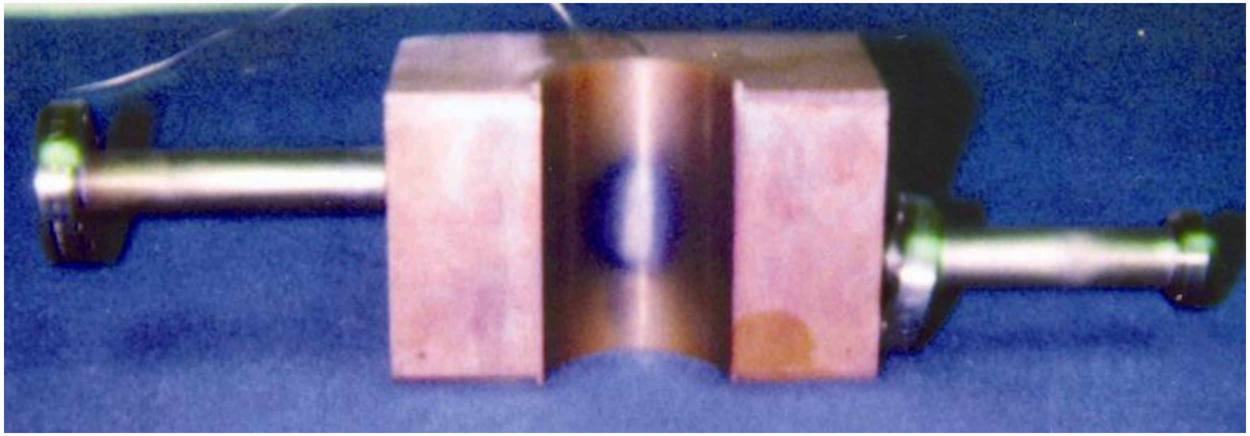
HHFF is now part of Dept. 1353 – Electrical Sciences

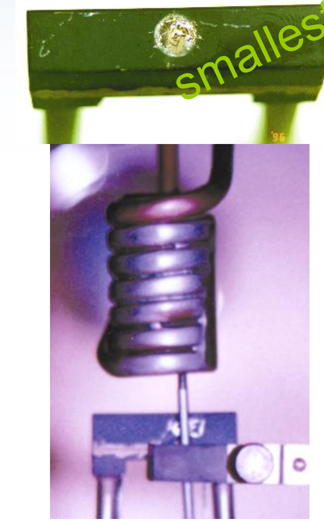
Several HX performance records achieved at the HHFF.

• Varian microchannel gyrotron (3800 cycles at 22 MW/m^2)	141 MW/m^2
• Thermacore porous metal gyrotron (10,000 cycles at 27 MW/m^2)	109 MW/m^2
• Thermacore He-cooled RF Faraday shield	10 .3 kW
• Thermacore porous metal HX	74 MW/m^2
• Vanadium He-cooled HX test	6 MW/m^2
• LBNL BNCT Al beam stops for cancer treatment (6.6 MW/m^2, 7.5 MW/m^2 max)	50,000 cycles
• Magnetron vane tips	78 MW/m^2
• Microwave Cross-Field Amplifiers	80 MW/m^2
• Helium Cooled Foam Divertor	22 MW/m^2

Magnetron Vanes

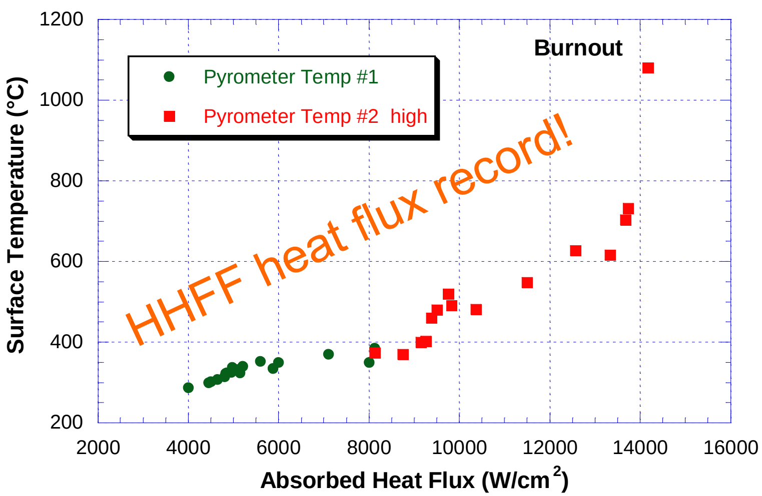
Gyrotrons: copper porous metal HX using water cooling

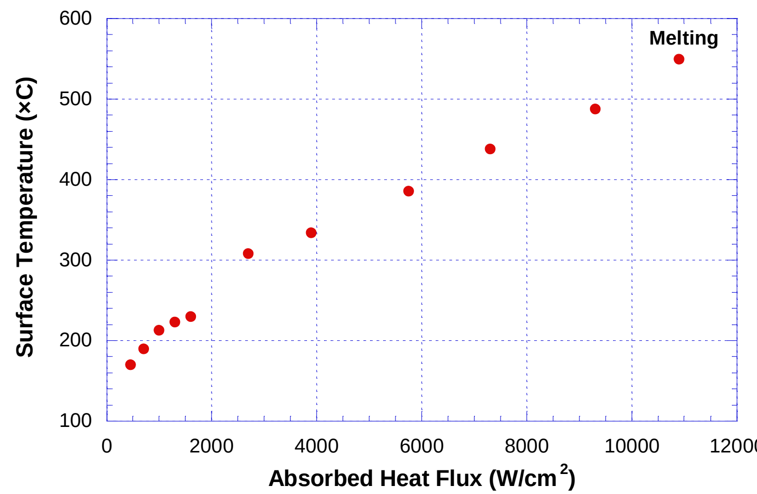




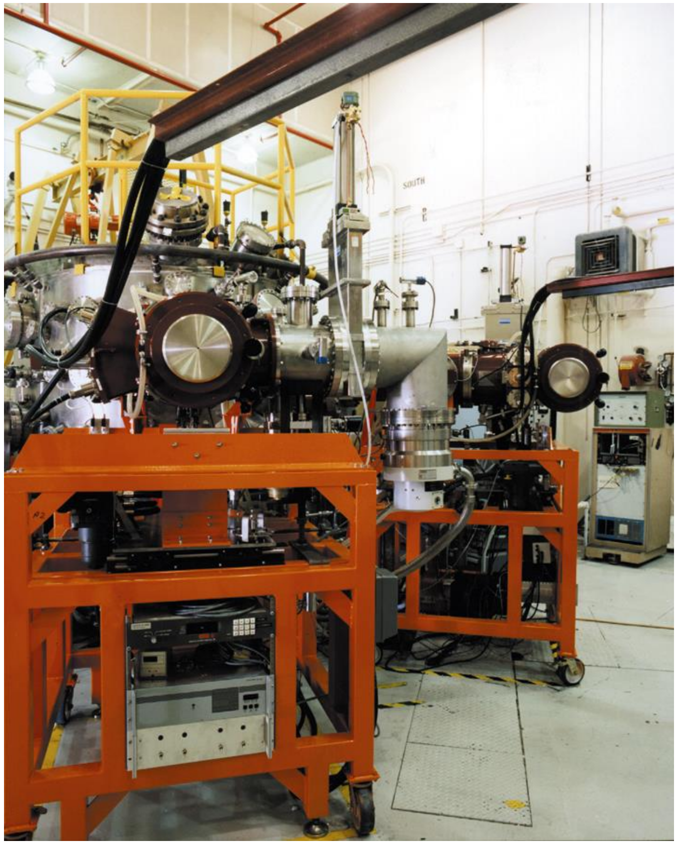
Varian Microchannel Gyrotron Cavity

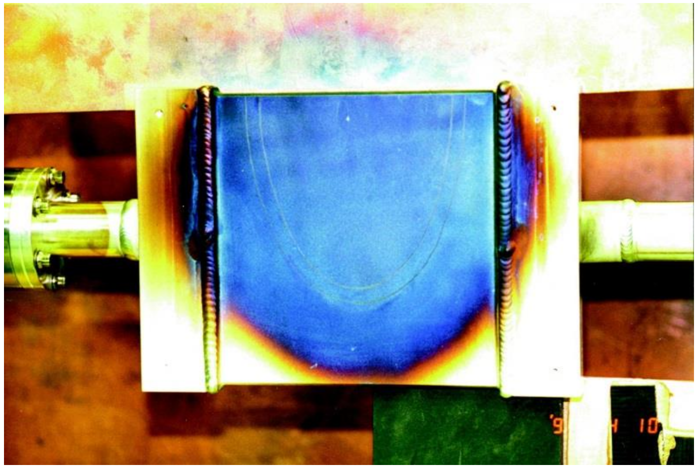
Thermacore Porous Metal Gyrotron Cavity



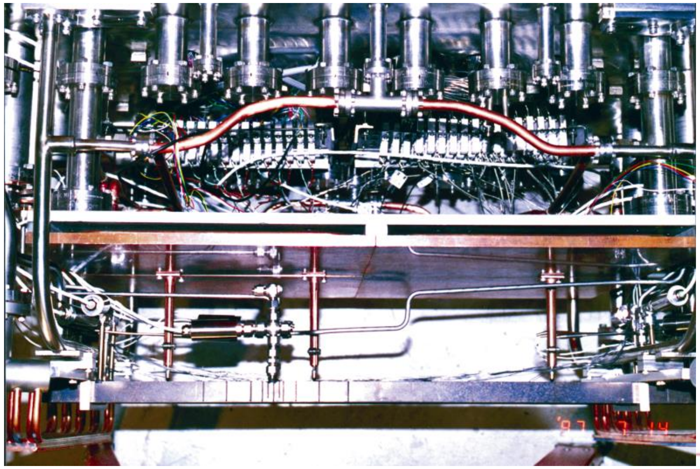


The EB-1200 can test full-scale components.

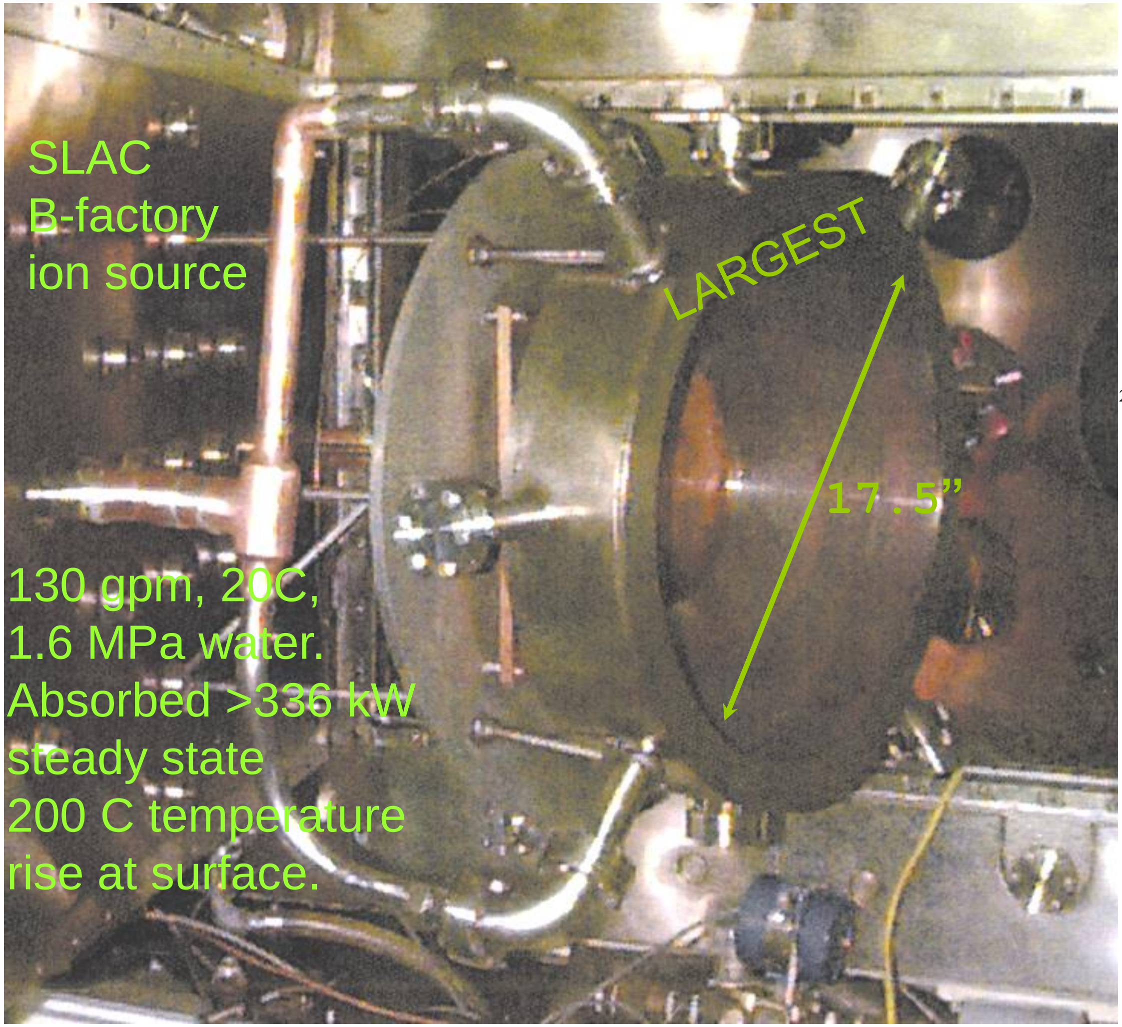


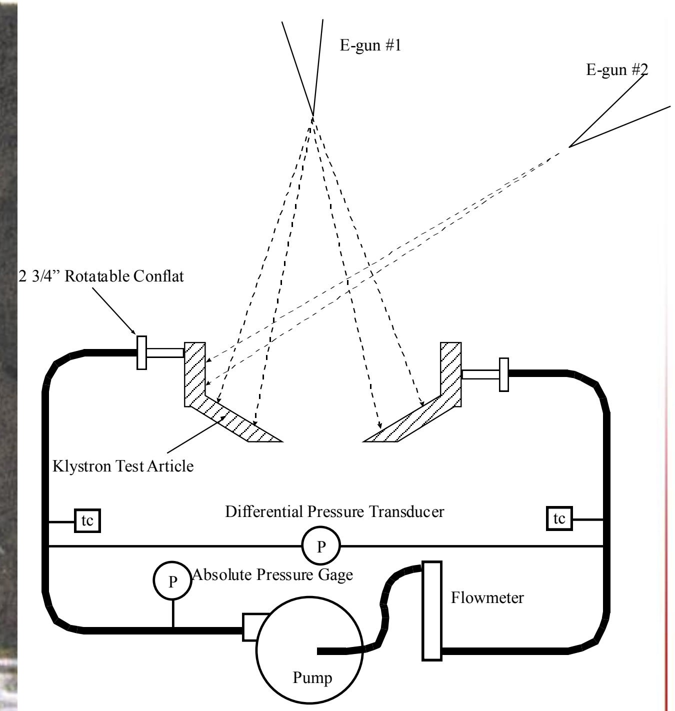


Aluminum BNCT target



Thermacore phase II SBIR project
Klystron collector: copper porous metal HX using water cooling

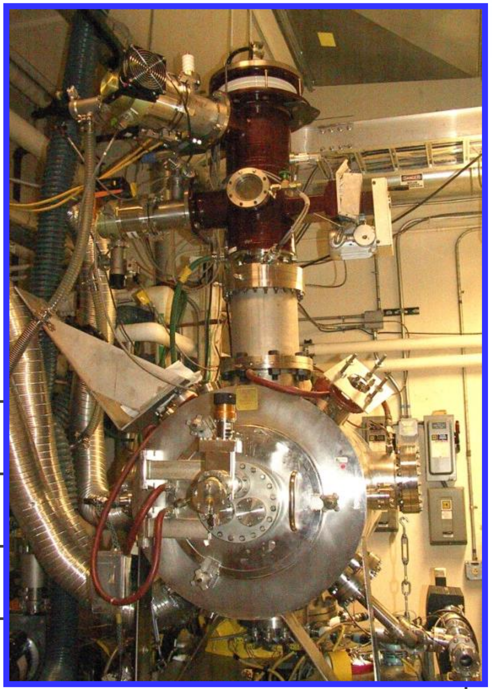




Max q”=31 MW/m^2
15 MW/m^2, 10,000 cycles
2s ON/2 s OFF

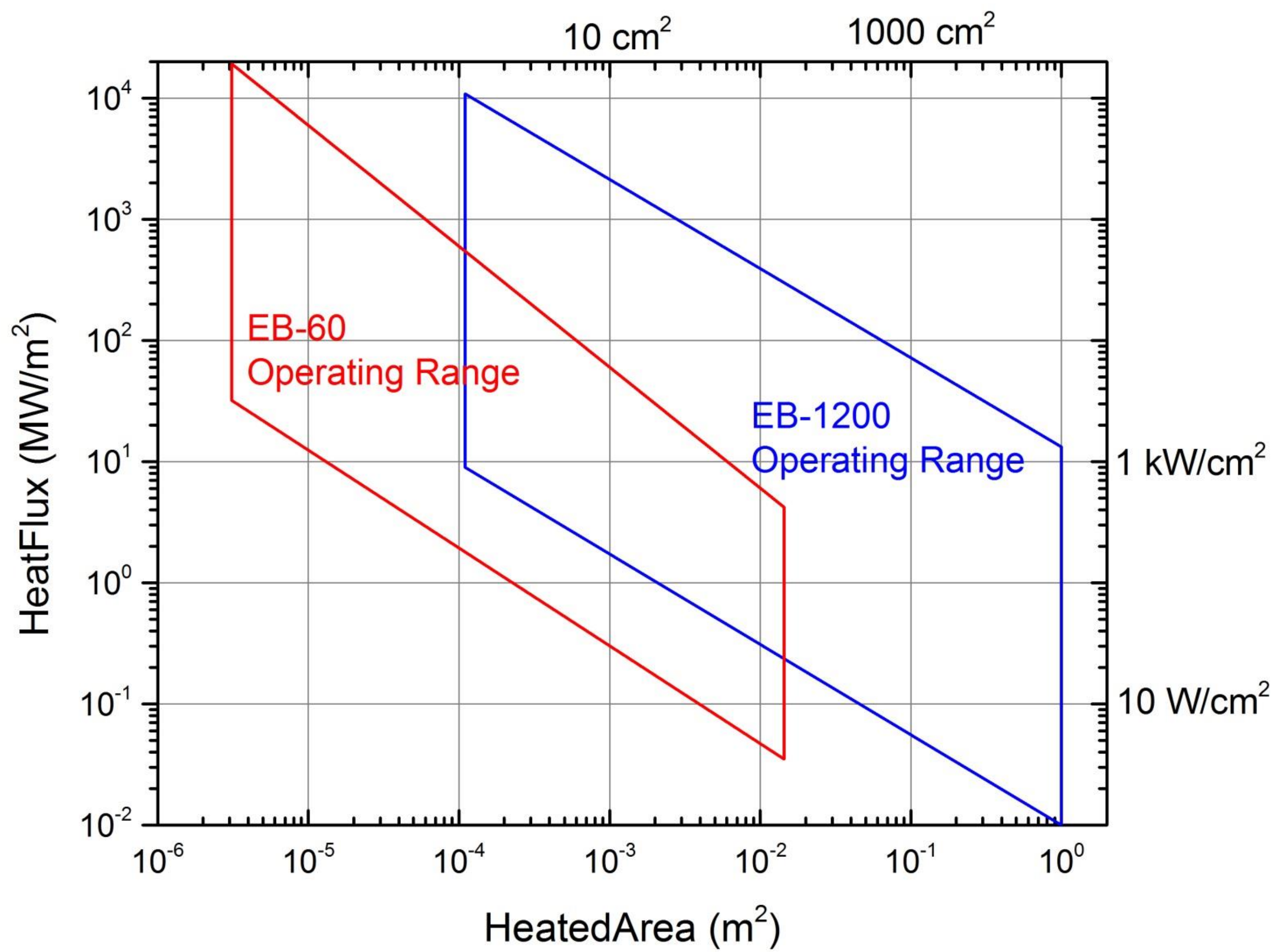
- e-beam testing gives <u>complete</u> access to the heated surface for optical, IR and pyrometry measurements
- low thermal conduction losses
- requires 10 mTorr or better vacuum
- RGA, OES and LIF possible
- Fiberscopes, borescopes

EB-60



Beam power	60,000W (60kW)
Accelerating voltage	30,000V (30kV)
Beam current	2A
Beam spot	2mm FWHM at target plane
Target area	0.1-10,000mm^2
Pulse length	From 2ms to continuous
Chamber pressure	~6 x 10^{-4} Pa, cold-trapped diffusion pump
Gun pressure	~1 x 10^{-6} Pa, turbopump

Our e-beams cover an amazing range of areas and flux levels.



Exotic raster patterns and high-speed pattern switching make complex spatial and temporal heat loading possible.

- E-beams are equipped with digital rastering.

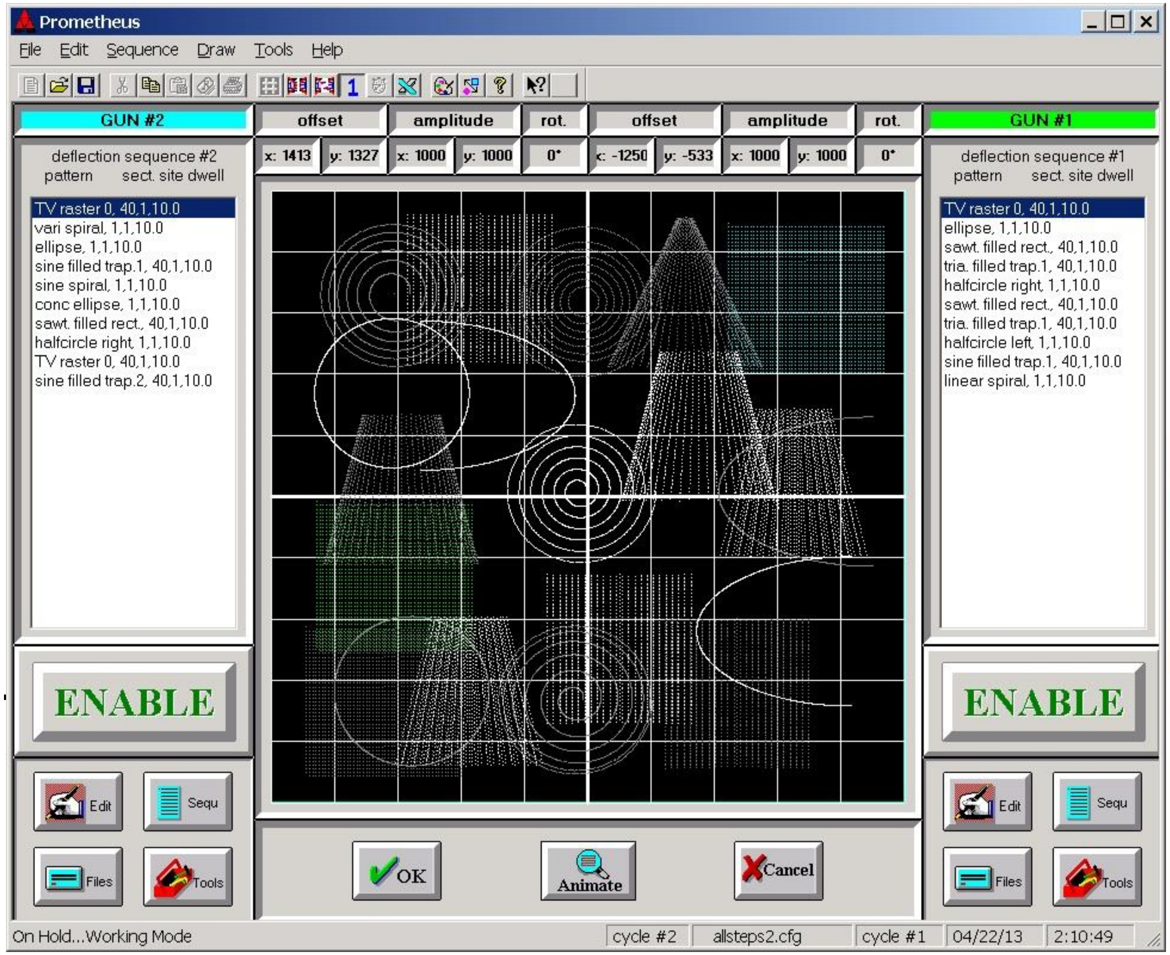
- The “Prometheus” program can raster at 10 kHz and pattern switch at 1kHz from one area to another.

- Exotic patterns can be input
  Native, Excel, or Drawn

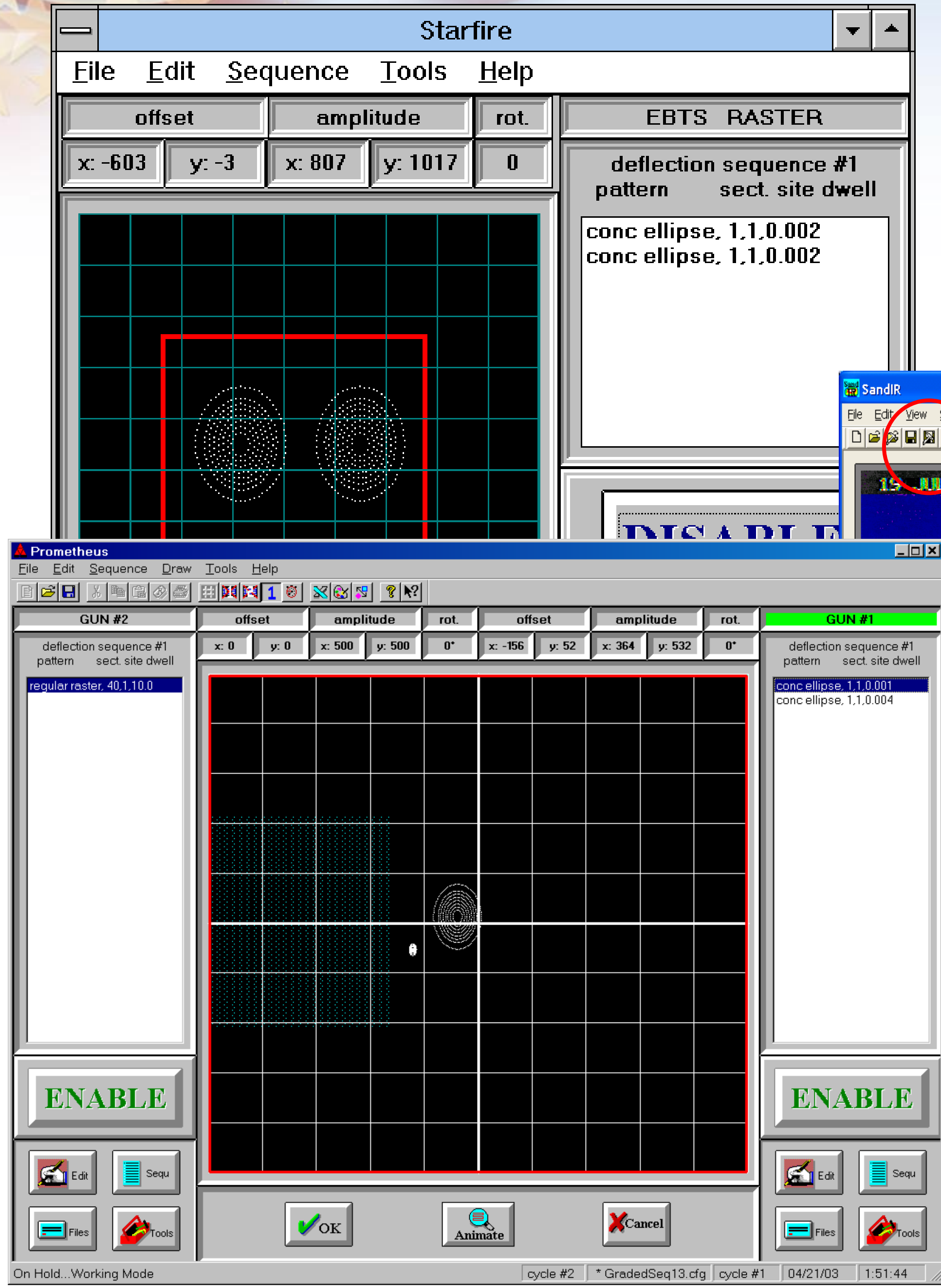
- Size, position rotation and aspect ratio can be controlled.

- 40 sections, 32 sequences, 10 steps.

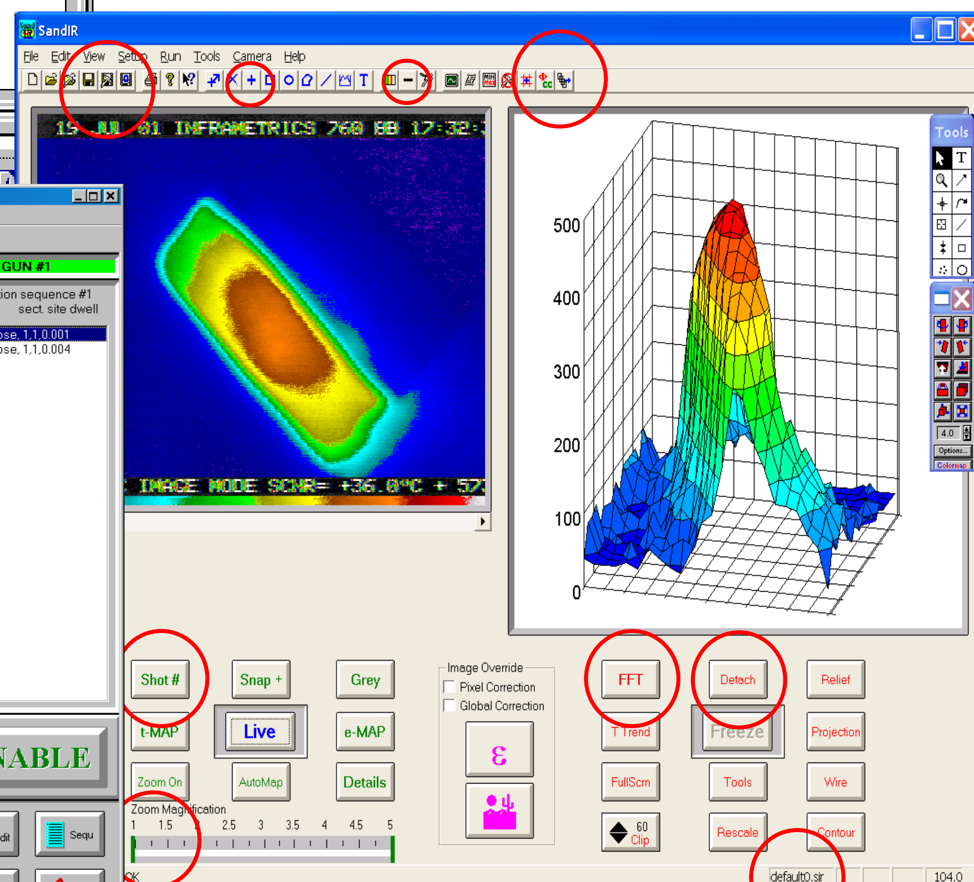
- Different dwelltimes can be set for each section.



EB-60 equipped with digital raster control, IR analysis, real-time calorimetry, flow diagnostics and TC array.



SandIR



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Many new HX technologies were tested at the HHFF.

• Gyrotrons	Thermacore and Varian (2)
• RF Mirrors	PPPL (1)
• Magnetrons/CFAs	Jaycor and CPI (2)
• Klystron Source	Thermacore (1)
• Porous metal HX	Thermacore (3)
• RF Faraday Shield (He)	Thermacore (3)
• Divertor Module (dual) (He)	Thermacore (2)
• Vanadium He-cooled HX	General Atomics (1)
• Tungsten Divertor (dual)	Thermacore (1)
• Tungsten Foam HX	Ultramet (1)
• Micro-channel He-cooled HX	General Atomics (2)
• Normal Flow He-cooled HX	Creare (2)
• BNCT photon beam stop	Lawrence Berkeley (1)
• BNCT target	Linac Systems (2)
• PEP-II photon beam stop	Stanford Linear Accelerator Center (1)
• Beryllium windows	General Electric (3)
• EUV Plasma source electrodes	Thermacore (3)
• C-C Heatpipe Space Radiator	AllComp (1)
• Hypervapotron Divertors	ITER (3) and Boeing (3)
• Single-channel He-cooled Mo HX	Ultramet (3)
• Multichannel He-cooled W HXs	Ultramet (3)

Continuation of non-DOE HHF Testing

DIII-D Graphite Tiles	GA (5)
W Lamellae Tiles	MIT (2)
TPX & Kstar CFC Tiles	PPPL (2)
NSTX CFC Tiles	PPPL (1)
FRIB Accelerator Targets	MSU (2)
Nanowire Enhanced HXs	Technova (2)
He/He Refractory Regenerator	Ultramet (1)
Li/He Refractory HX	Ultramet (1)
Be Armored Heatsinks	NGK (1)
PS Be Armored Heatsinks	LANL (2)
Be ITER FWQ Mock-ups	ITER (6)
W-coated Graphite Mock-ups	NIFS (2)
Swirl Tube or Finned Heatsinks	JAEA (8)
Swirl Tube Divertor Heatsinks	CEA (2)
W and CFC Armored Divertors	IPR (2)
Lithium jets	ALPS/APEX (4)
Lithium Emissivity	ALPS/APEX (2)
Molten Salt (FLiBe and FLiNaBe)	ALPS/APEX (2)

Why helium-cooling?

Advantages:

- **fluid of choice for a highly efficient, high temperature Brayton cycle exhibiting minimal wear and corrosion of gas turbines**
- inherently safe, inert chemical properties
- lack of corrosion
- single-phase heat transfer - no CHF as with water, but possibility of parallel flow instabilities
- lack of neutron activation
- easy separation from tritium

Disadvantages:

- low thermal mass (density x C_p <1% of water)
  → high pressure systems & high stored energy
- compressible gas → higher pumping/blower power and larger supply & return piping (compared to liquids)
- higher cost and sophistication of turbomachinery
  (e.g., compressors, high temperature turbines, and recuperators)

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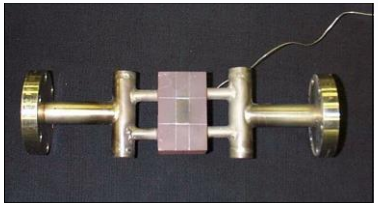
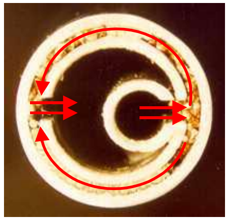
Background: Helium-cooled modules developed for PFCs

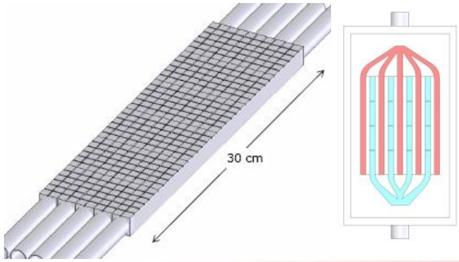
TR3

year	*Type of Test Article*	*fabricator*
1993	Cu Micro-channel HX (~100μ channel size)	Creare, Inc.
	Cu Divertor mockup A (0.46mm channels)	General Atomics
	Cu Porous (40%) metal HX (0.43mm dia.)	Thermacore, Inc.
1994	Cu Dual channel porous metal HX	Thermacore, Inc.
	Cu Div. mockup A retest, higher heat loads	General Atomics
1996	Cu Phase-II porous metal HX	Creare, Inc.
	Vanadium spiral-tube HX	General Atomic
1997	Cu Faraday shield A	Thermacore, Inc.
	Cu Divertor mockup B	Thermacore, Inc.
1998	Cu Faraday 2nd shield B	Thermacore, Inc.
	Cu Divertor 2nd mockup C	Thermacore, Inc.
1999	Div. mockup B retest, added diagnostics	Thermacore, Inc.
2000	W tubes with W foam	Ultramet, Inc.
2000	W FW module with W porous medium	Thermacore, Inc.
2001	VPS W tube with VPS porous medium	Plasma Processes
2006	W tube with W foam in axial flow	Ultramet, Inc.
2008	Sq. Mo w/ Mo foam, circumferential flow	Ultramet, Inc.
2010	4-Channel, Larger Area Mo panel	Ultramet, Inc
2011	Li/He Heat Exchanger	Ultramet, Inc
?	W Tee-tube Jet impingement	Plasma Processes
?	FZK 9-finger HEMJ	FZK, IEA
?	Phenix	JA/US

TR4







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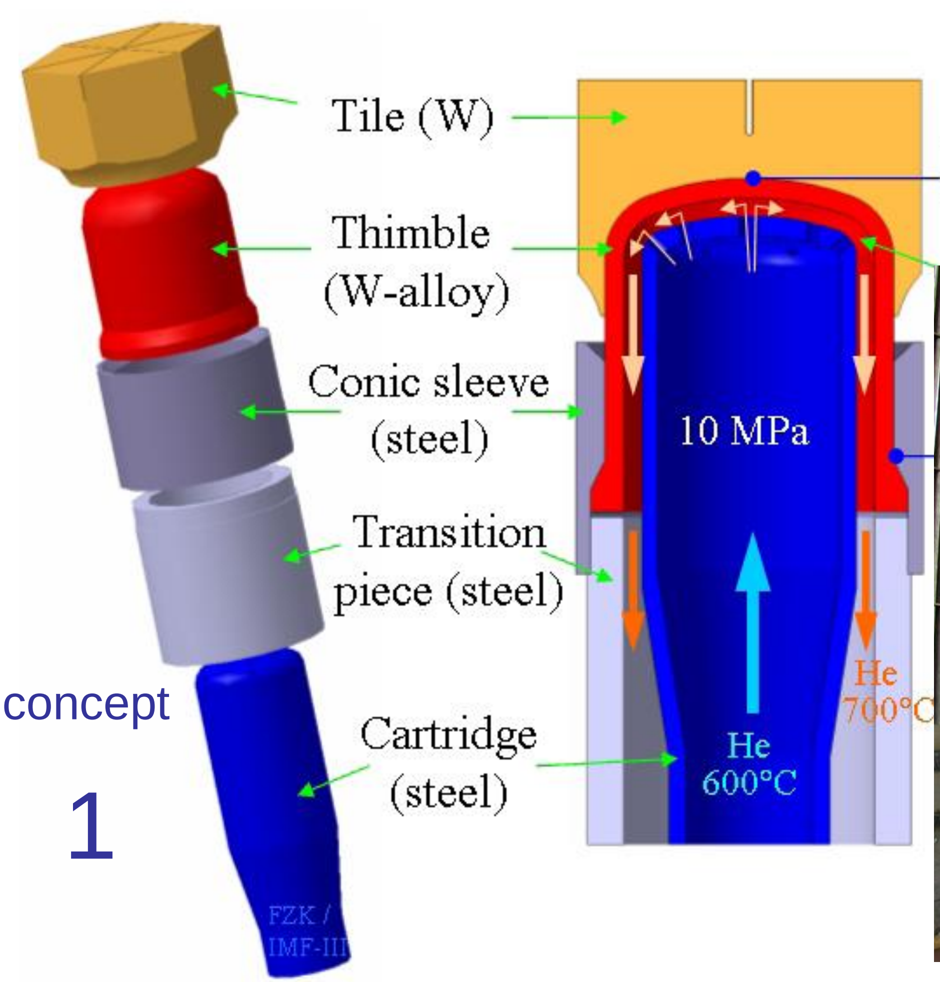
Gaps in helium-cooling

1. Ductile W-alloy development, and other refractories: Mo, V
2. Low-cost fabrication techniques w/ integrated manifolding
3. Joining development, armor and RAFS
4. Innovative, low-pressure-drop thermal designs
   CFD/HX modeling of porous media, helium jets, manifolding
5. Fabricate & test large area, multi-channel prototypes
6. Flow instabilities in multi-channel devices
7. High temperature, high pressure testing capabilities
8. Tritium permeation into the coolant
9. Purity control and high temperature diagnostics

HEMJ from FZK/Efremov (Norajitra)

2007

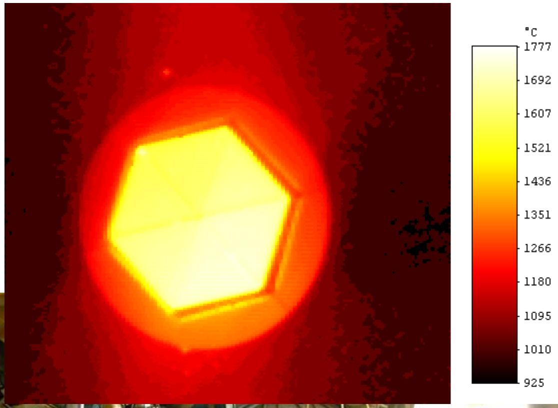
w/ FS: 600 C -700 C helium operating window!

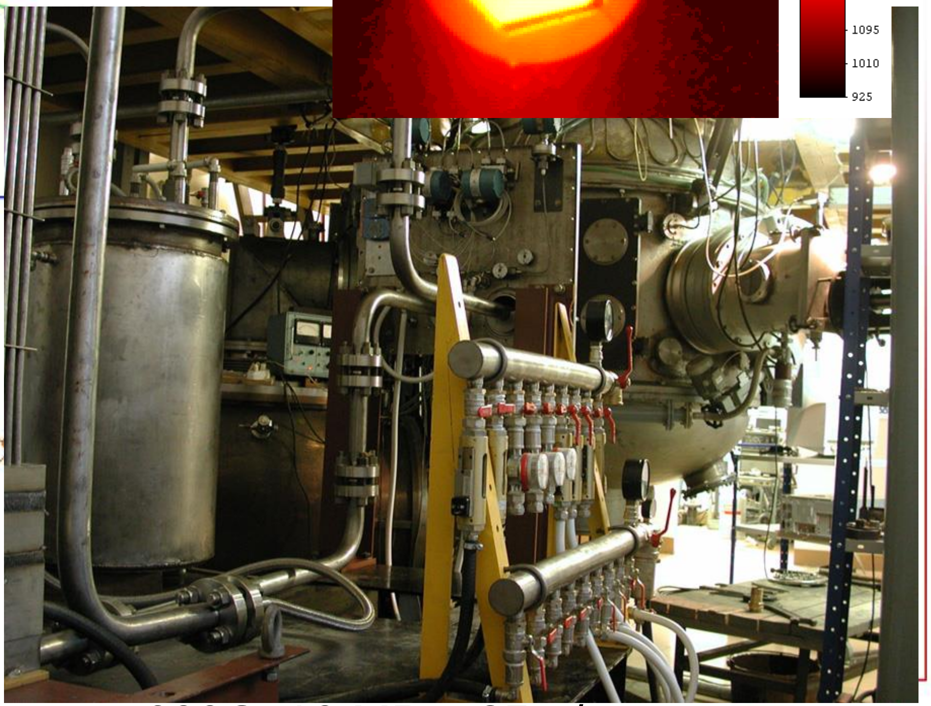


concept

1

Tsefey





600C, 10 MPa, 25 g/s

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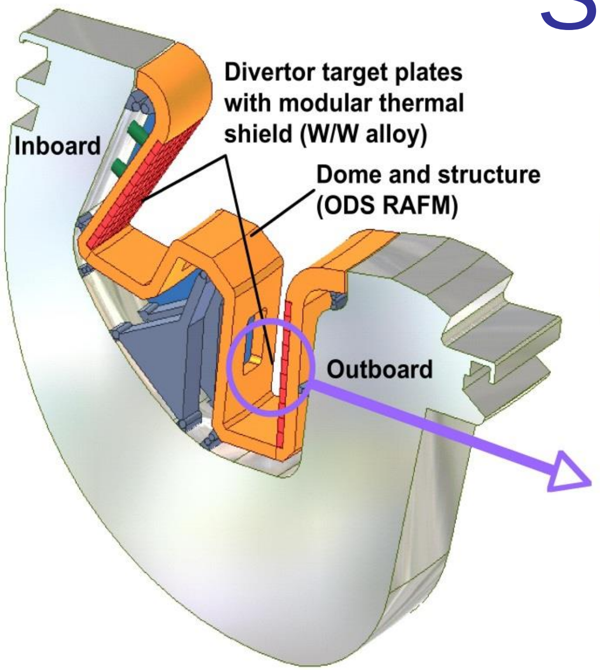
He-cooled modular divertor with jet cooling (HEMJ)

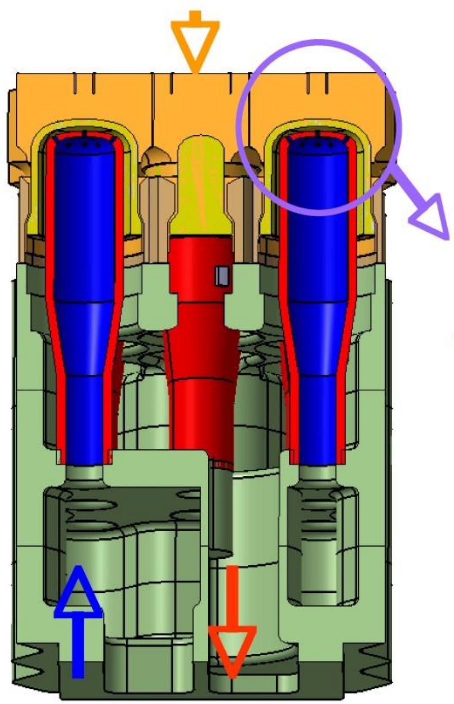
(from P. Norajitra's presentation)

Scale-up

$\dot{Q}=\dot{m}Cp\Delta T$



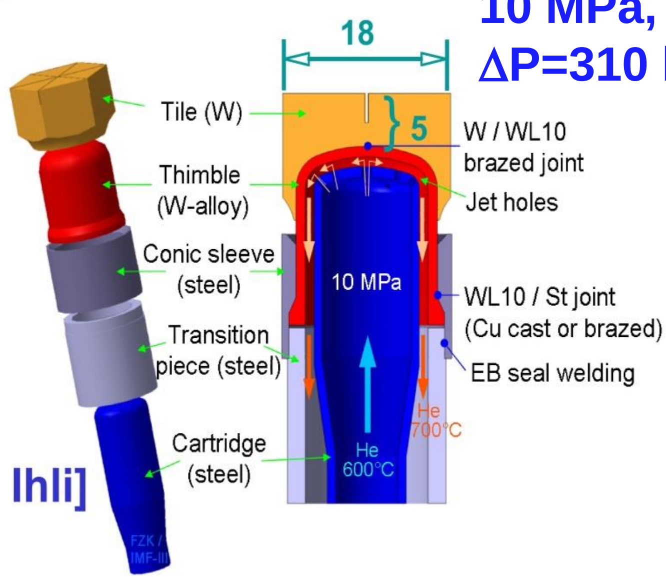
Divertor cassette



9-Finger module

[T. Ihli]

10 MPa, 13 g/s
ΔP=310 kPa



1-Finger module

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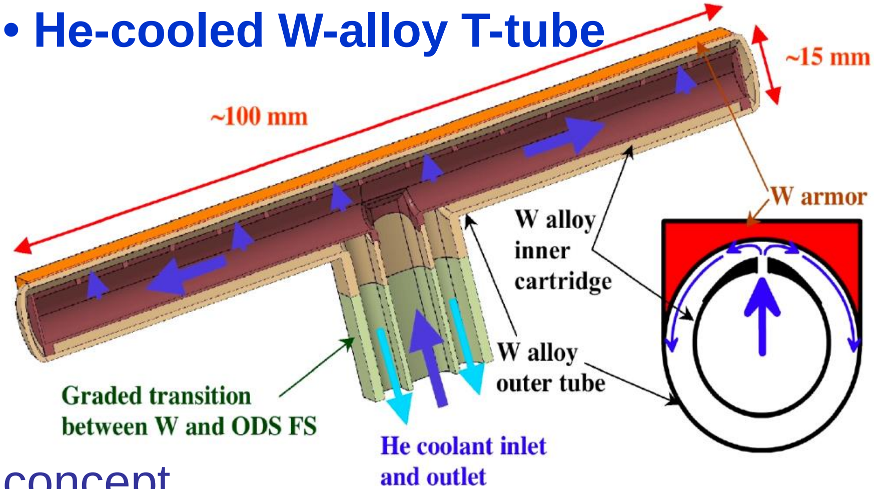
ARIES T-Tube Divertor Design
(from A. R. Raffray)

• **He-cooled W-alloy T-tube concept**



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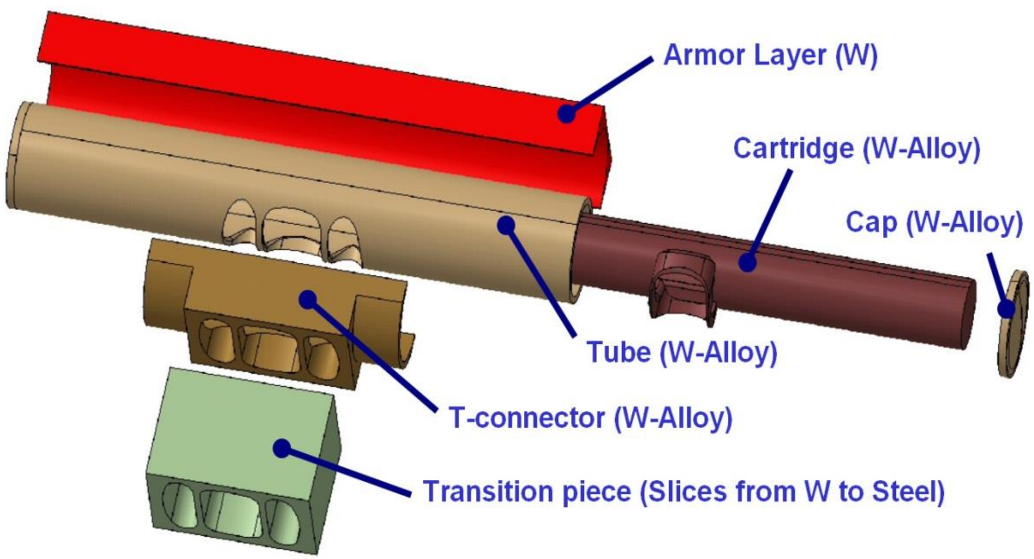

- **Design for a max. q" of at least 10 MW/m^2**
- **Mid-size configuration with credible manufacturing and assembly procedures (for CS or Tokamak application).**
- **Cooling with discrete or continuous jets through thin slots (~0.4 mm)**
- **10 MPa, ~600-700°C He coolant**
- **~600/700°C to 1300°C W-alloy**
- **A number of such T-tubes can be connected to a common manifold to form desired divertor target plate area.**

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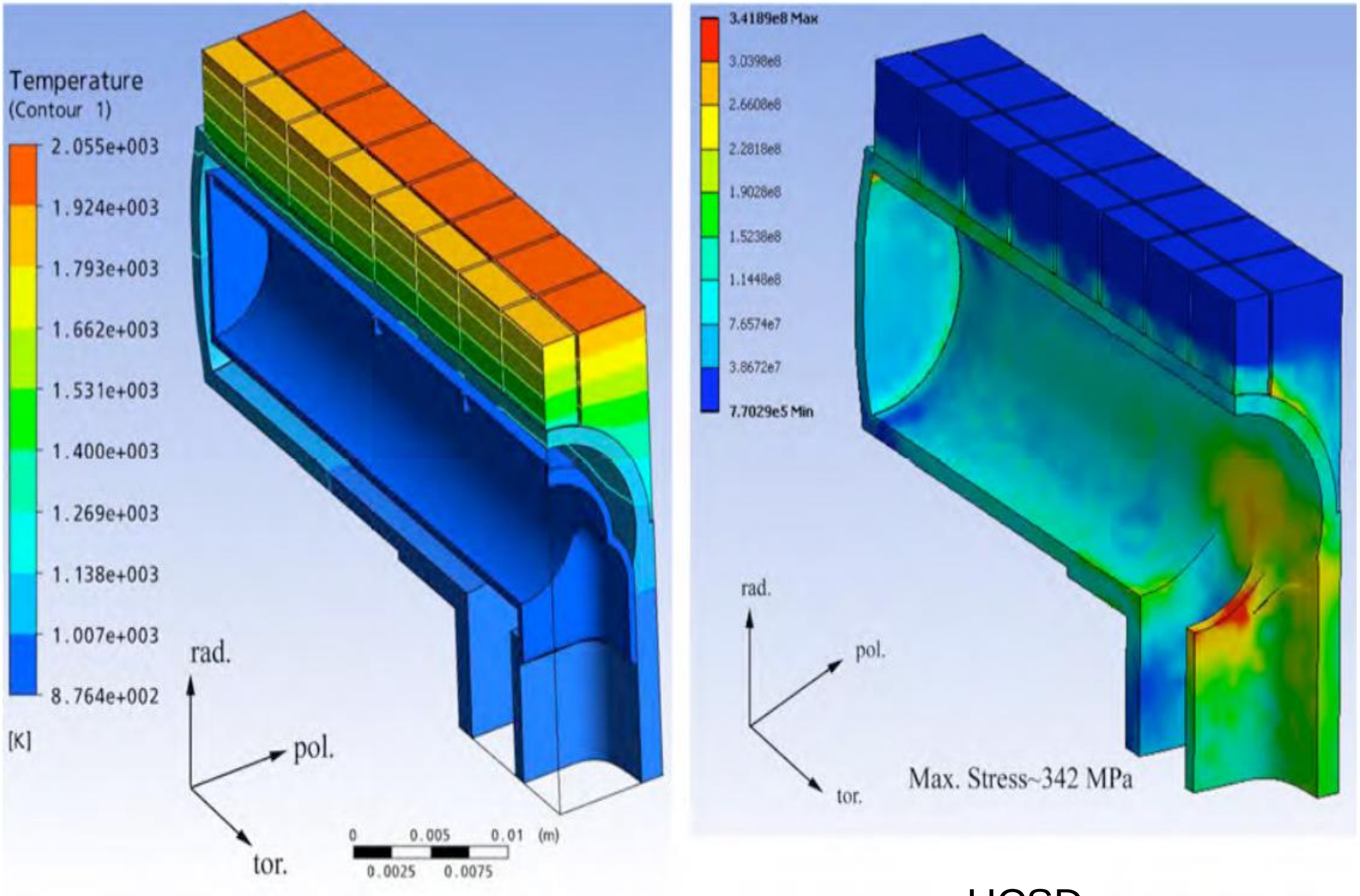
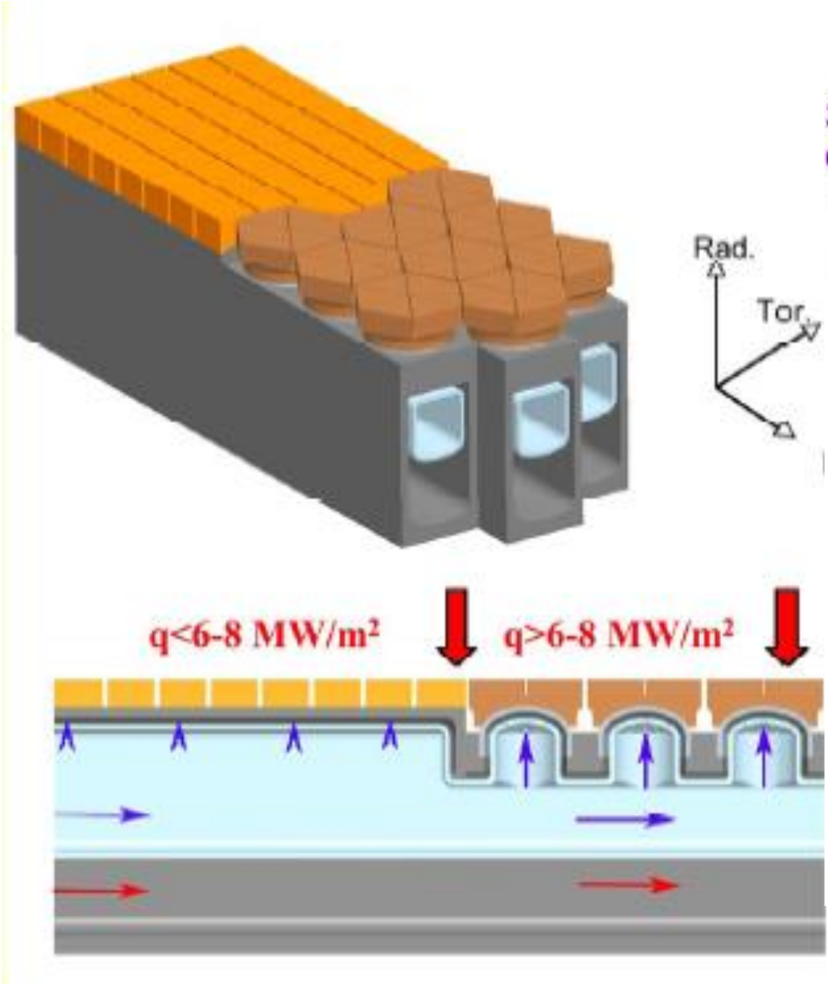
Armor has large temperature gradients, but acceptable stresses in the heatsink.

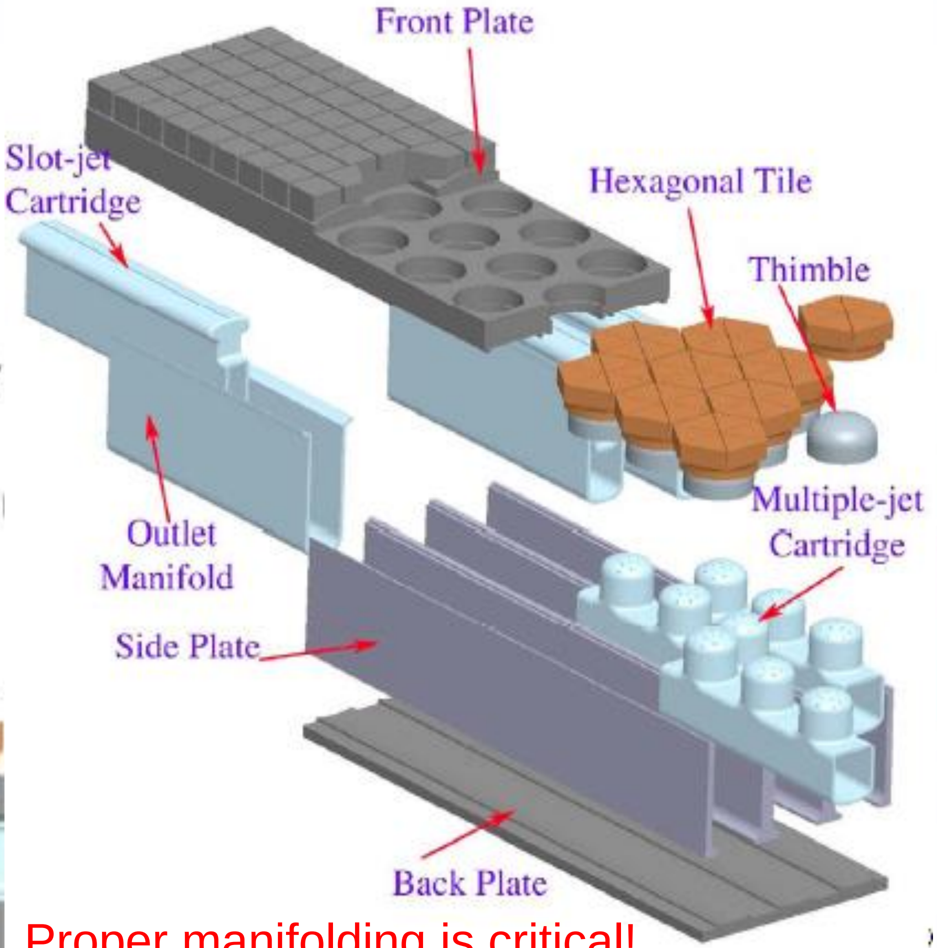


UCSD

DL Youchison 5931/30.05

ARIES work at UCSD and GIT

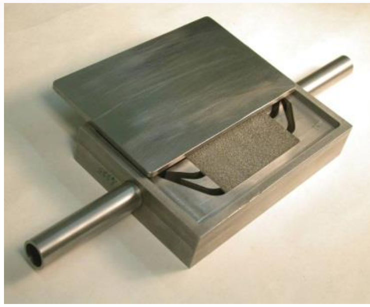


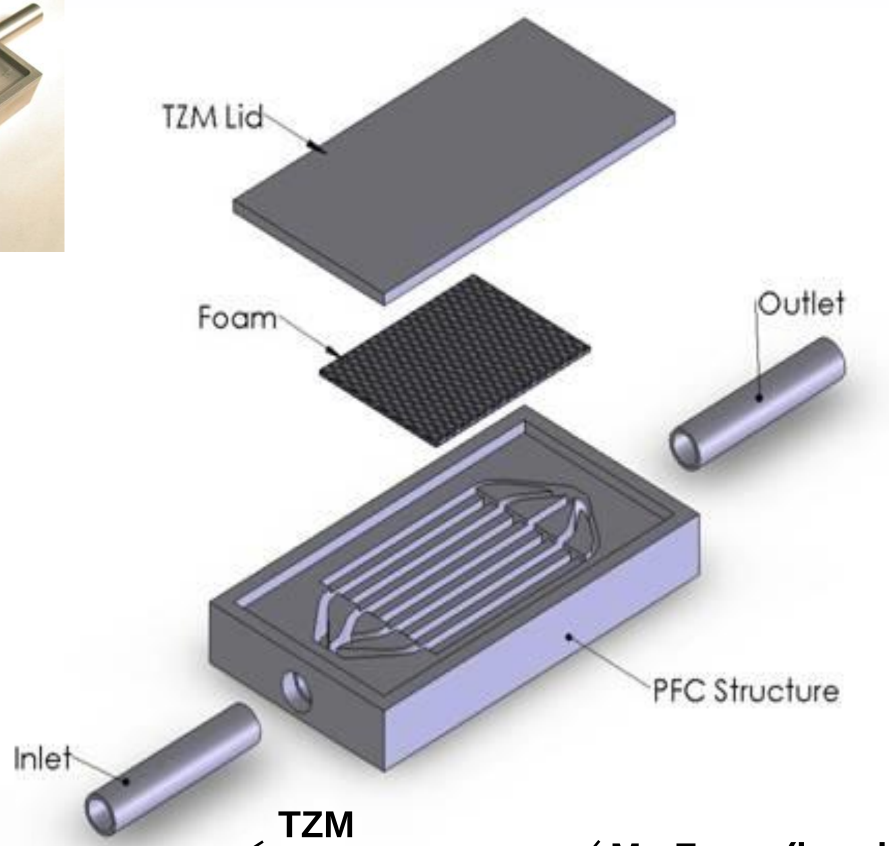


Proper manifolding is critical!
Control ΔP, tapering of slots and ducts

Ultramet fabricated Mo panels for HHF testing.

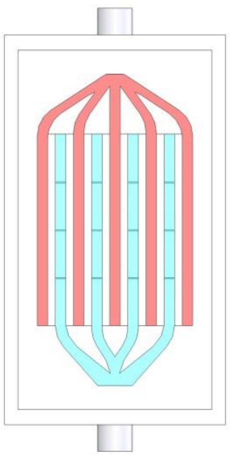
Tested in 2010





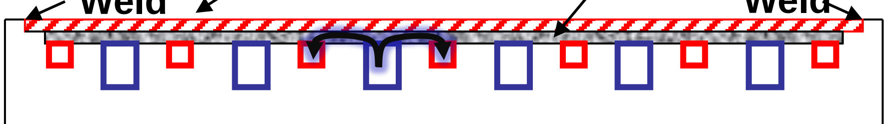
concept

3



- Multiple channel (4)
- Flat surface
- All refractory
- Short flow paths
- 600 C inlet temps
- 4 MPa
- $\Delta P \sim 22$ kPa @ 25 g/s

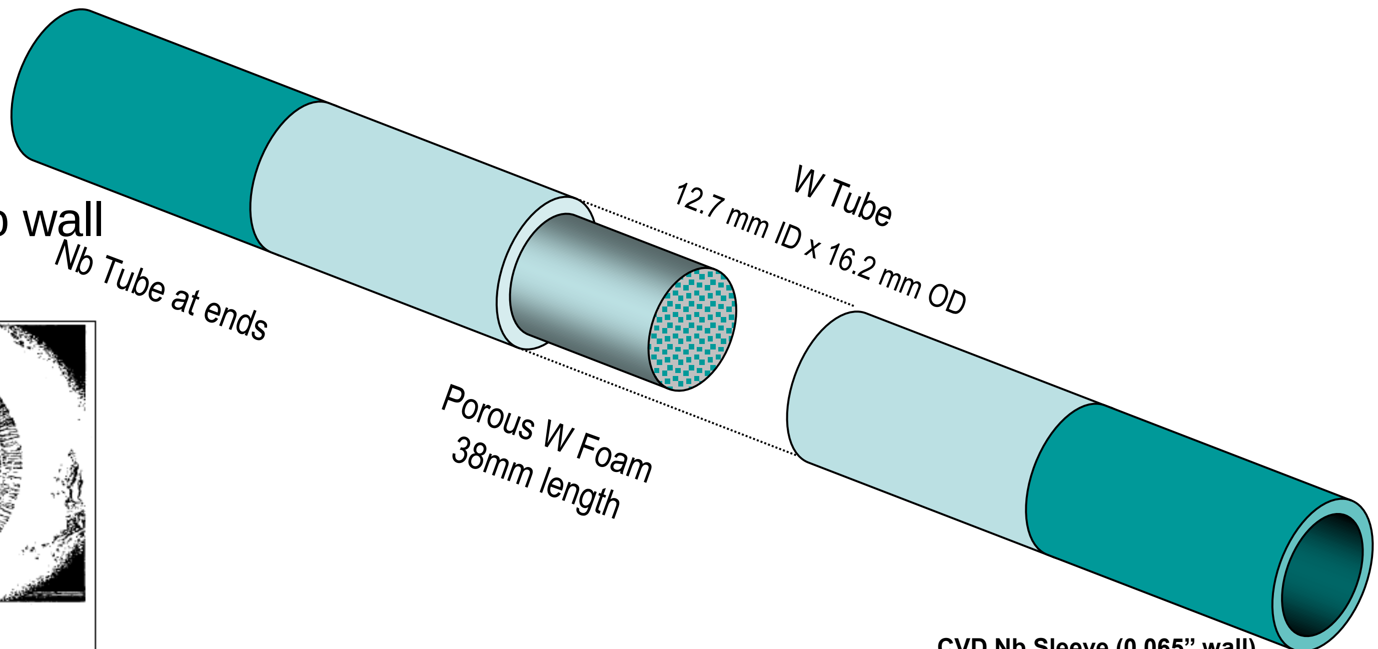
  Investigate:
  - Larger heated areas
  - Flow instabilities



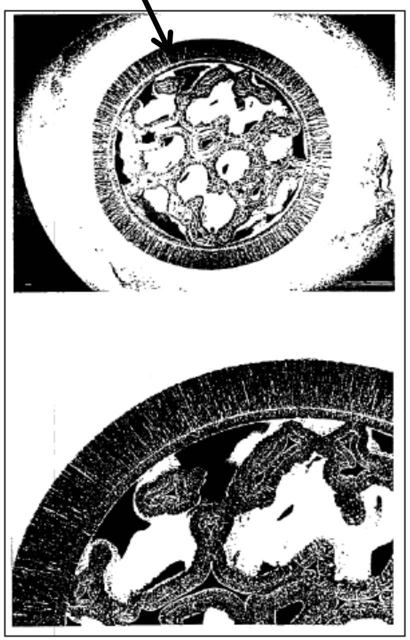
$\Delta P \;\alpha\; \rho v^2/2$

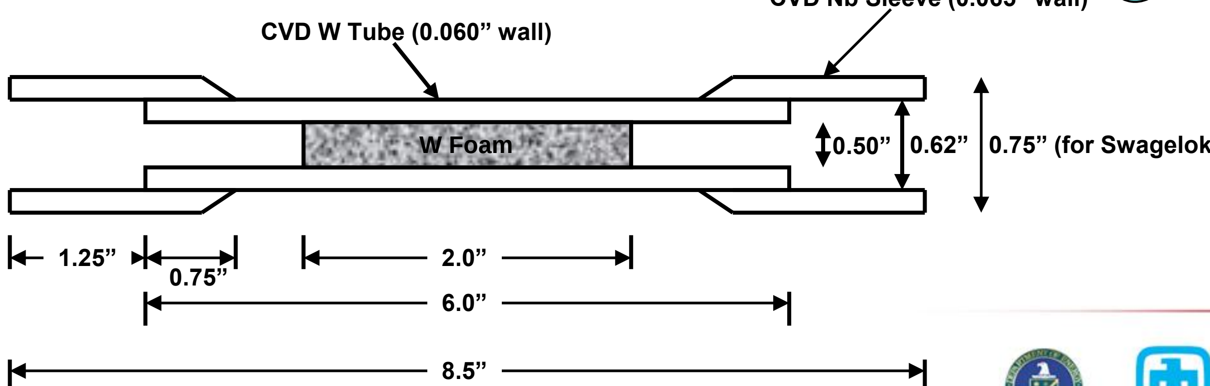
Edge-view: Blue - He inlet channels; Red – He outlet channels

2006 Ultramet Phase-I geometry – single channel, round tubes



Foam brazed to wall





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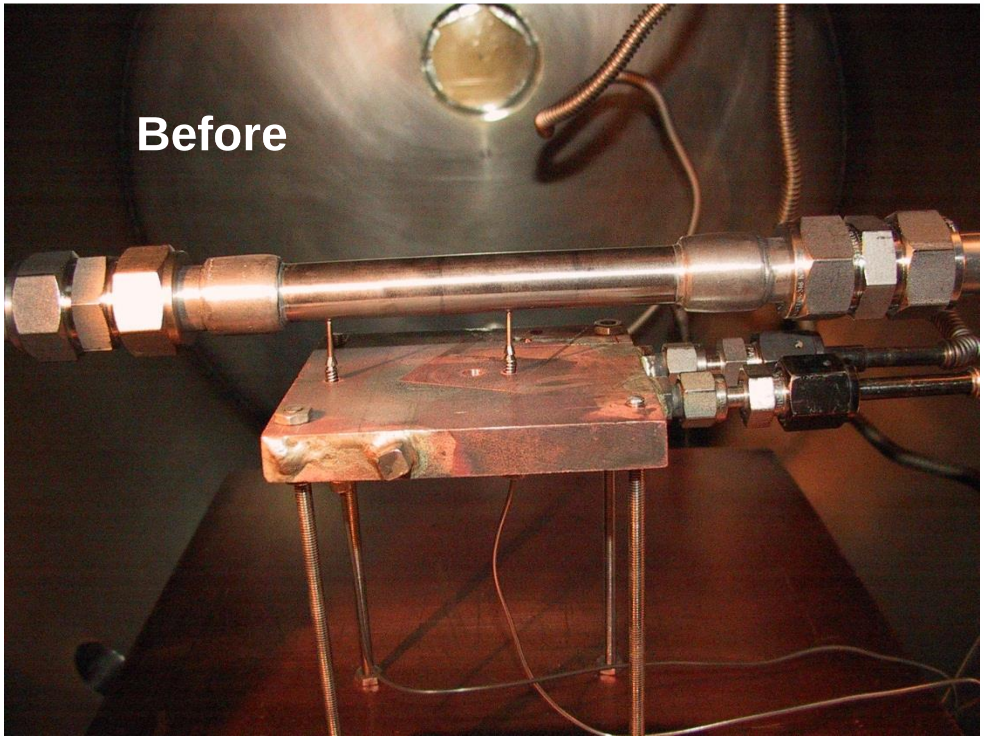
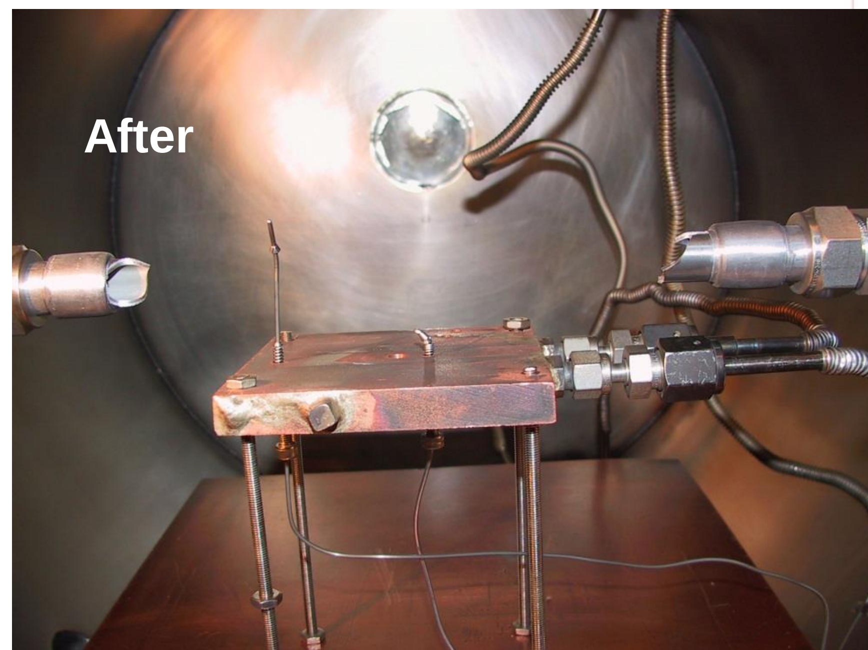
PN1 failed due to thermal cycling above 2000 C at 4 MPa

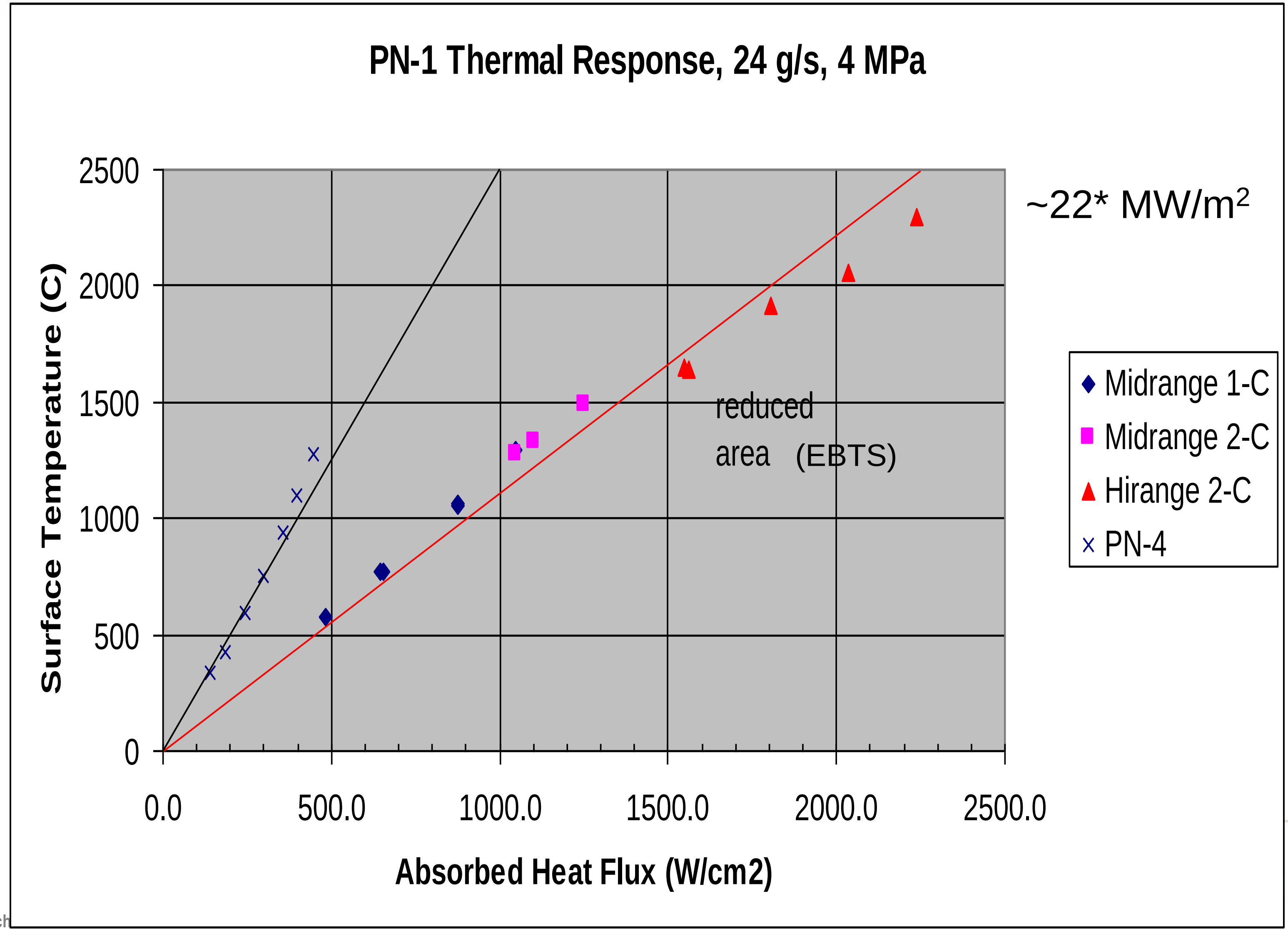


- Hi-Temp Brayton cycle application.
- More ductile refractory alloy at pressure boundary required.
- Foam HX performed well.



Achieved a maximum of 22.4 MW/m^2 along the axial centerline of the top surface and an average absorbed heat flux of 14 MW/m^2. The 4-MPa helium flowing at 27 g/s produced a pressure drop of 92 kPa and removed 7.2 kW at steady state.

2-3x performance enhancement with foam



~22* MW/m^2

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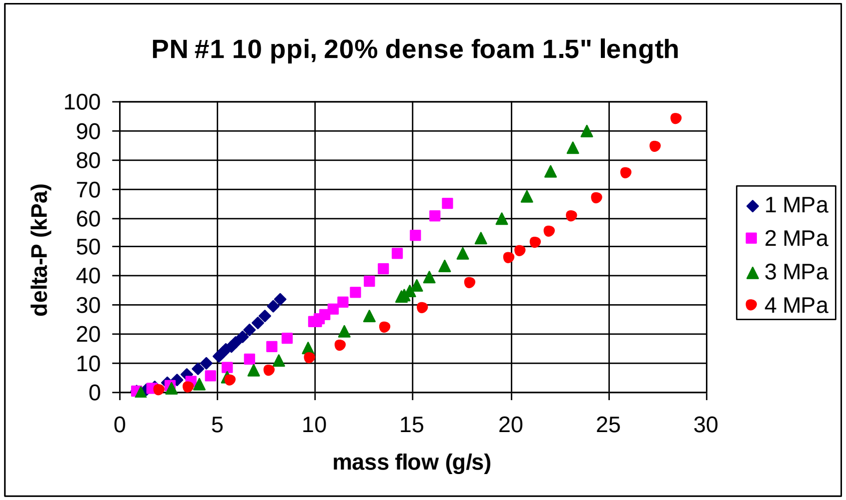
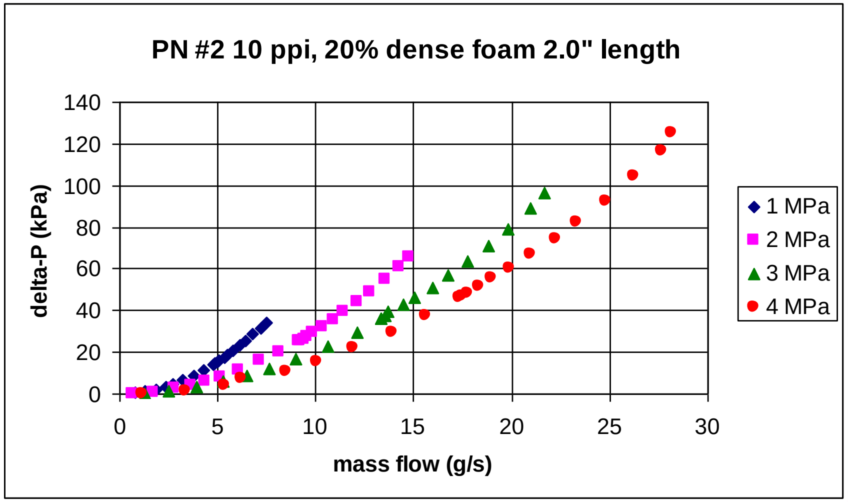
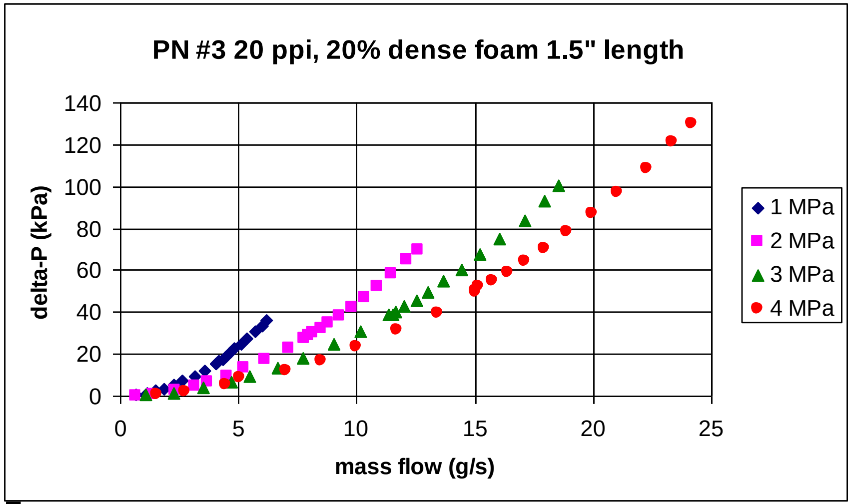
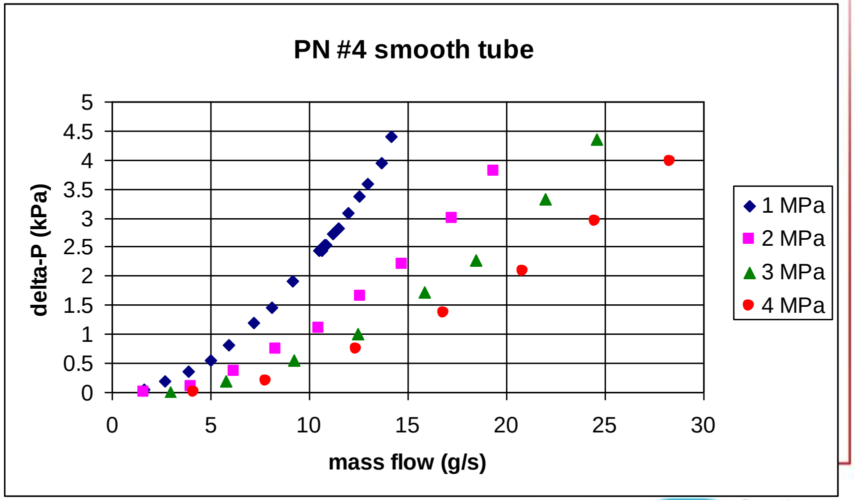
Measured flow characteristics of 4 Ultramet mock-ups









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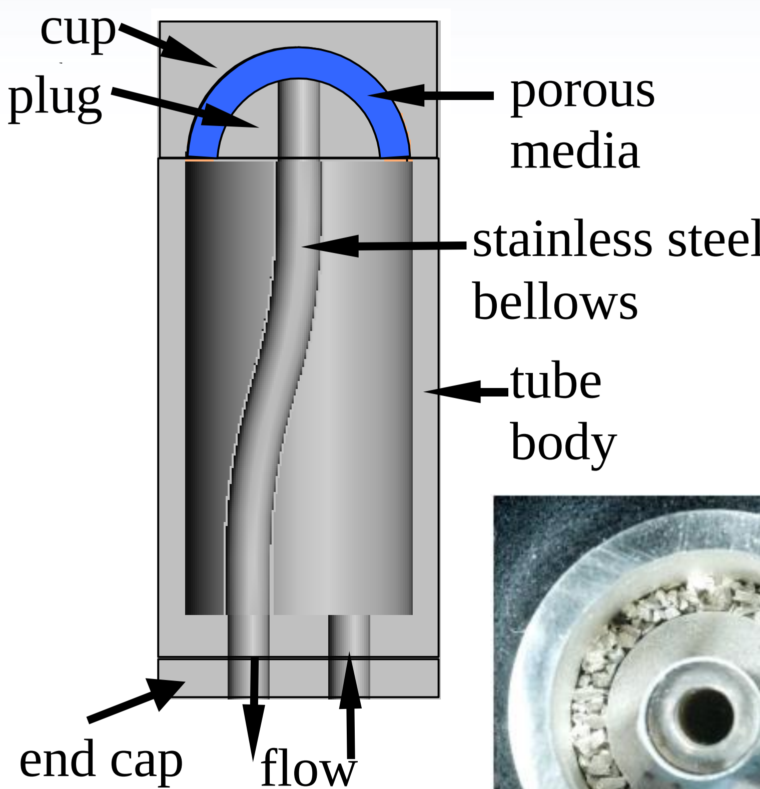
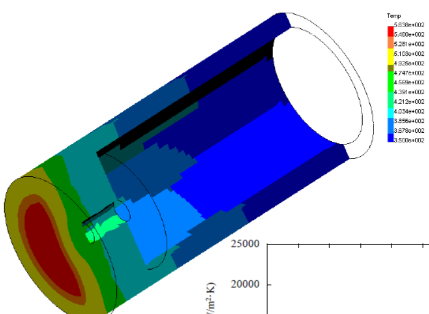
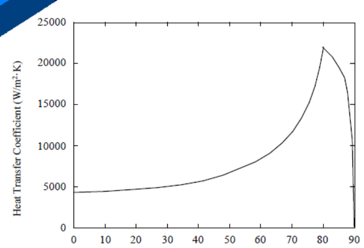
Two parallel W modules mounted in EB-60 chamber

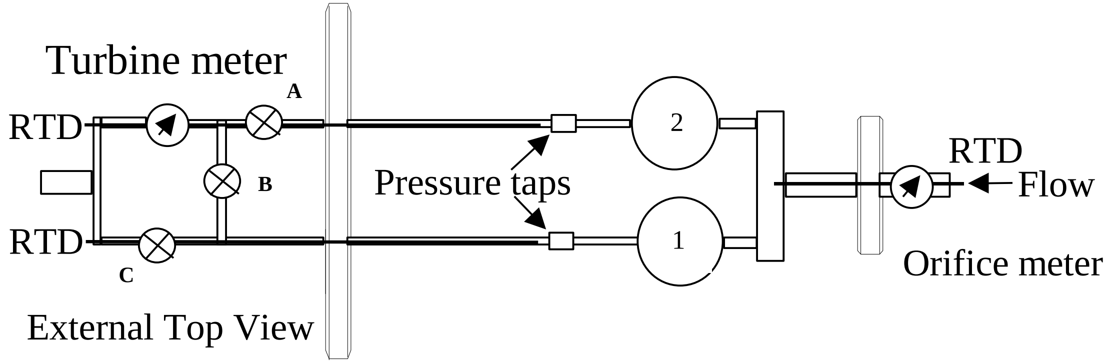






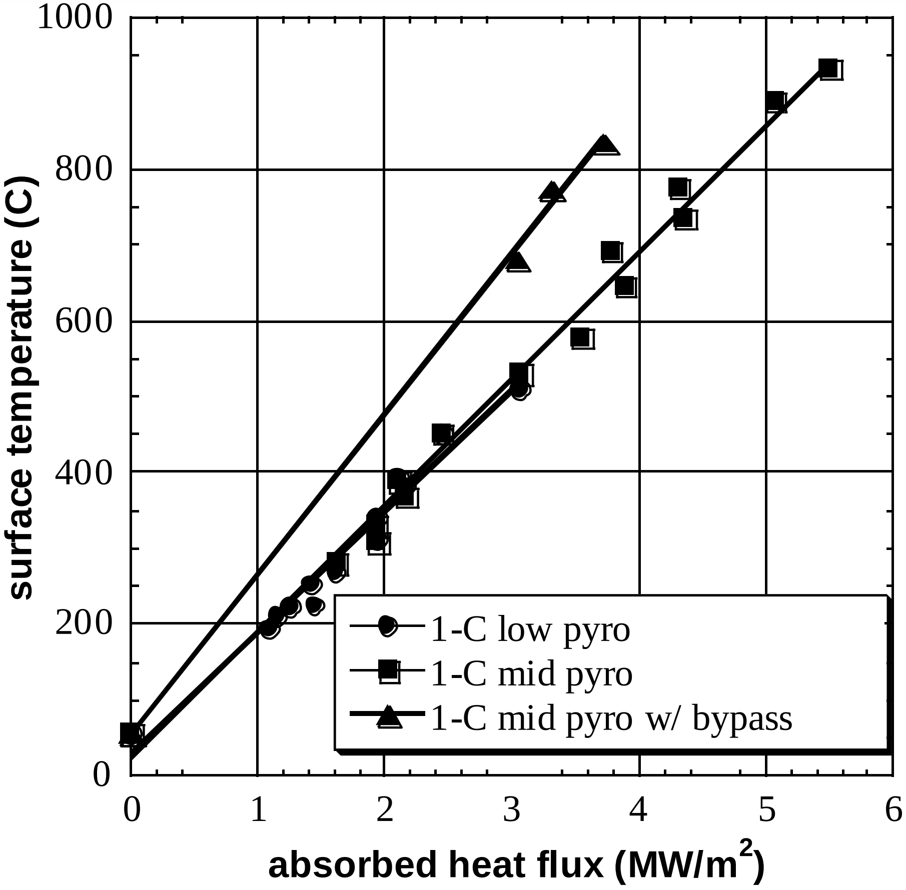
Refractory heat exchanger satisfied two major objectives. First, dual modules were designed to handle first wall heat loads and fabricated exclusively of high temperature materials. Secondly, test data were obtained that indicate good thermal performance, good fatigue resistance and characterized parallel flow instabilities.

Test configuration to investigate flow instabilities



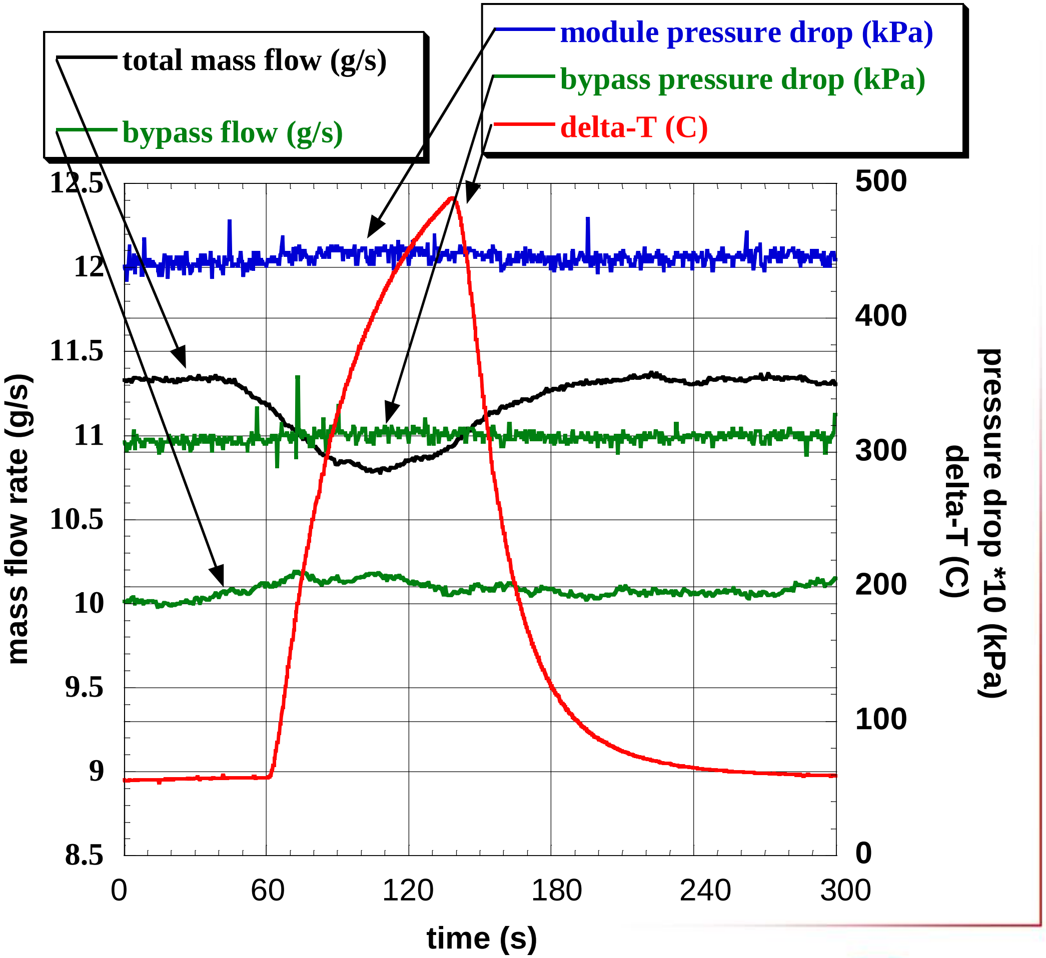
The EB-60 is equipped with a closed helium coolant loop (HeFL) which can operate at a maximum pressure of 4.1 MPa and loop temperatures as high as 300 °C. Helium mass flow rates as high as 100 g/s have been achieved for sample pressure drops near 186 kPa and total pressures of 4 MPa. By adjusting the loop blower speed one can produce a constant differential pressure, but cannot provide an independent mass flow rate.

Surface temperature response in parallel and bypass



PFC He-cooled modules - examples

Experiment had balanced parallel flow through heated target and bypass flow channel. Parallel flow instability, i.e., decrease in mass flow in heated section possible if bypass is available.



Test enabled by grant to Thermacore, Inc. from the US Dept. of Energy's Small Business Innovation Research program

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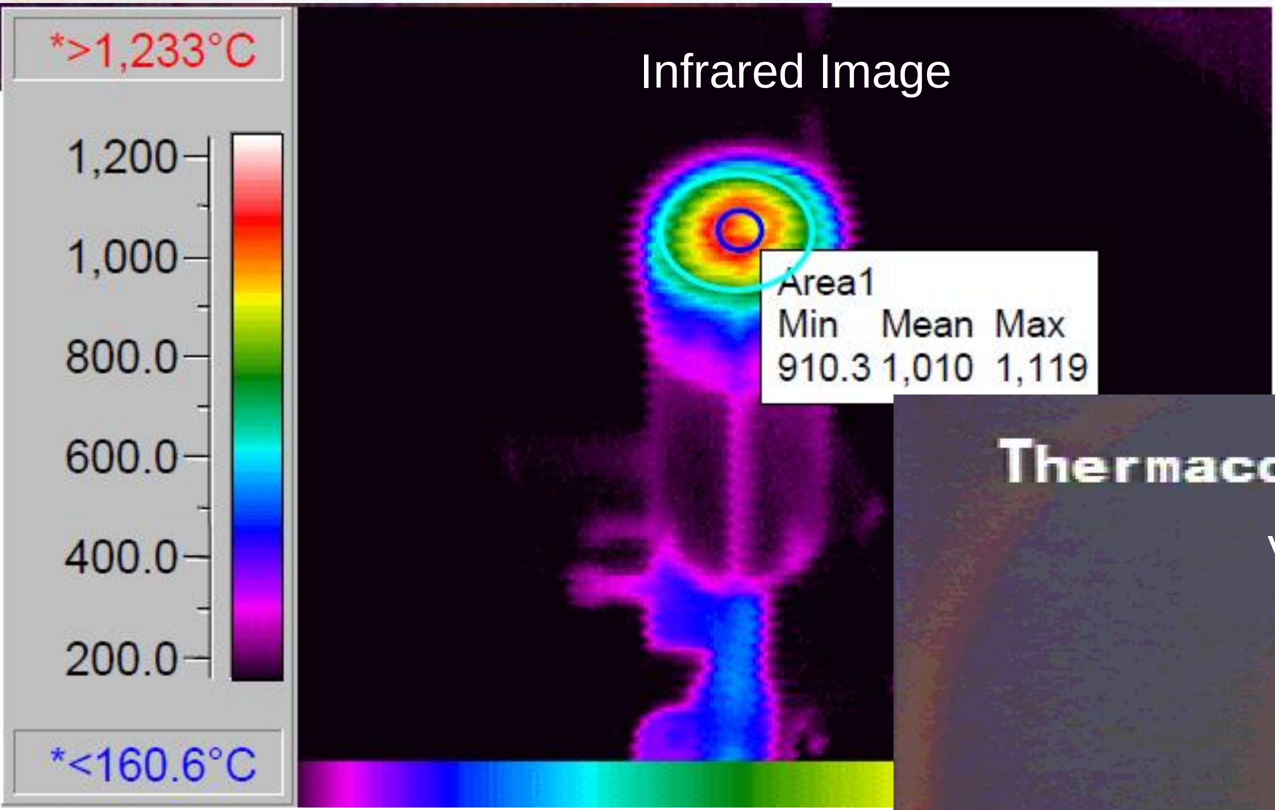
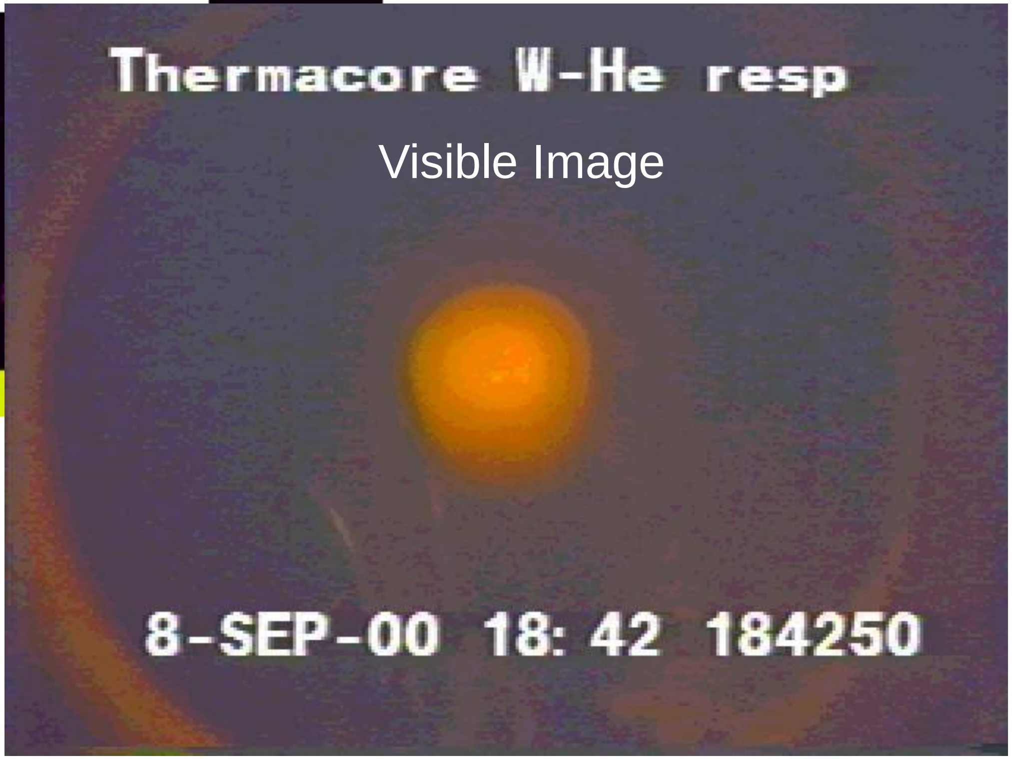
e-beam testing permits real-time diagnosis of heated surface



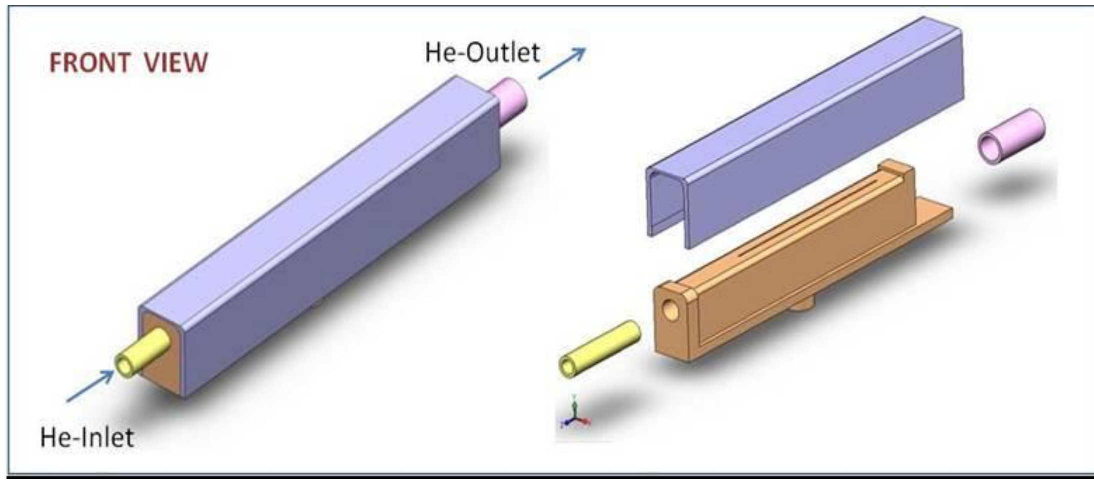


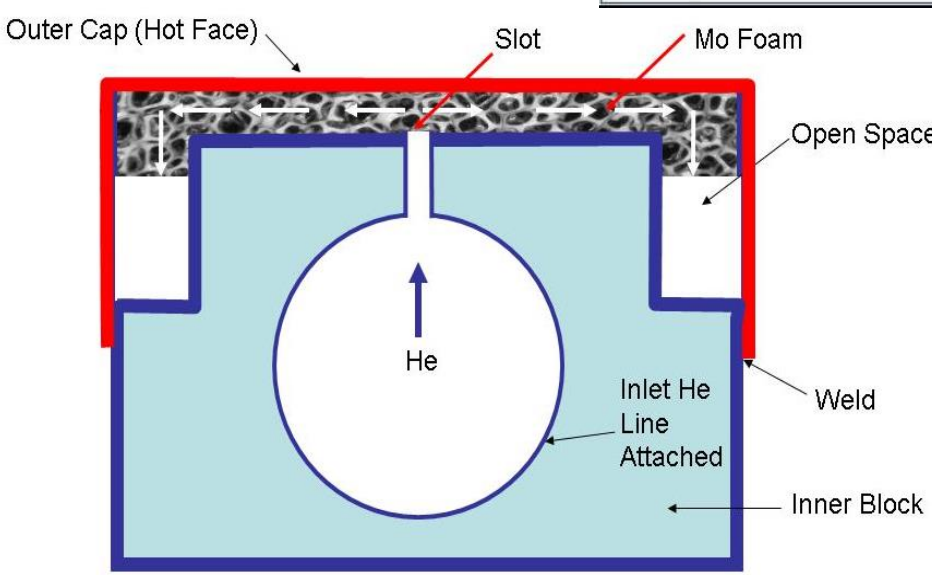
Visible requires neutral density filter
When testing W or Mo (welders mask)

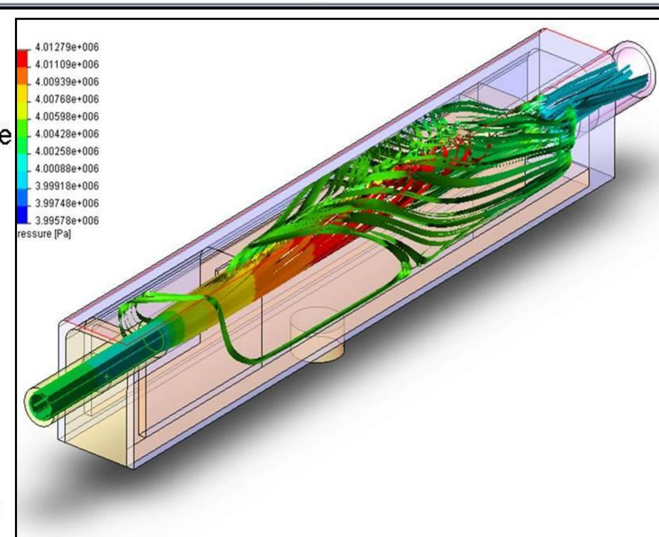
4 Single-Channel Heat Exchangers tested in EB-60
- All Molybdenum, e-beam welded -

2008

1. No foam
2. 45 ppi 77% porosity
3. 65 ppi 77% porosity
4. 100 ppi 77% porosity







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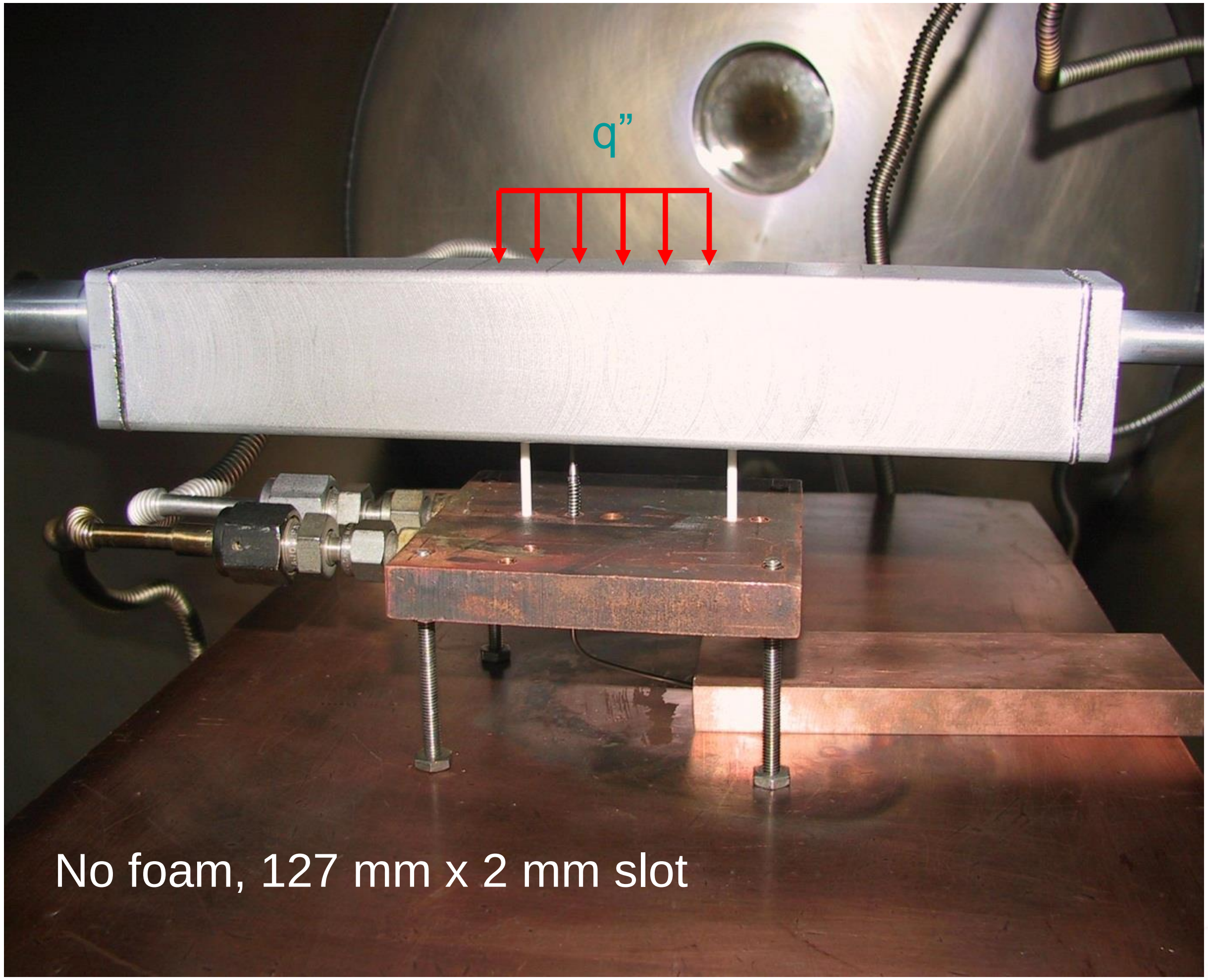
Ultramet single channel test set-up in EB-60



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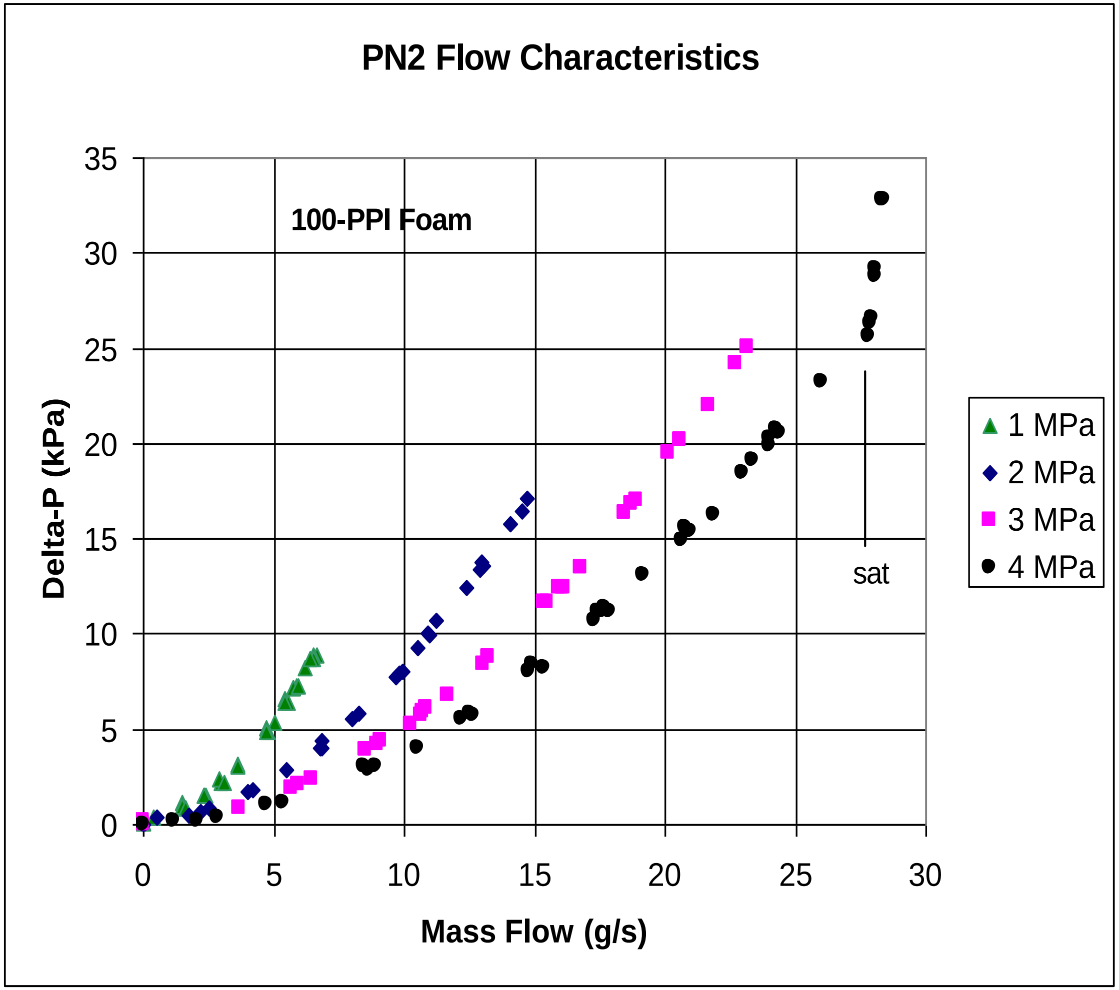
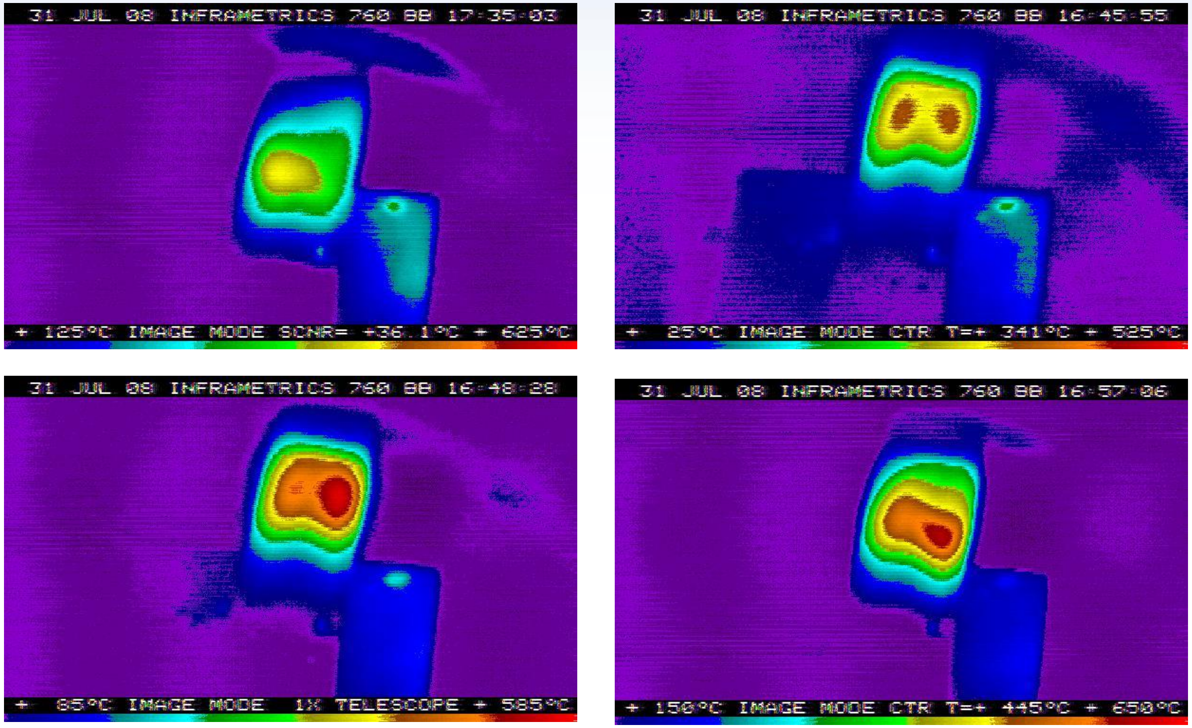
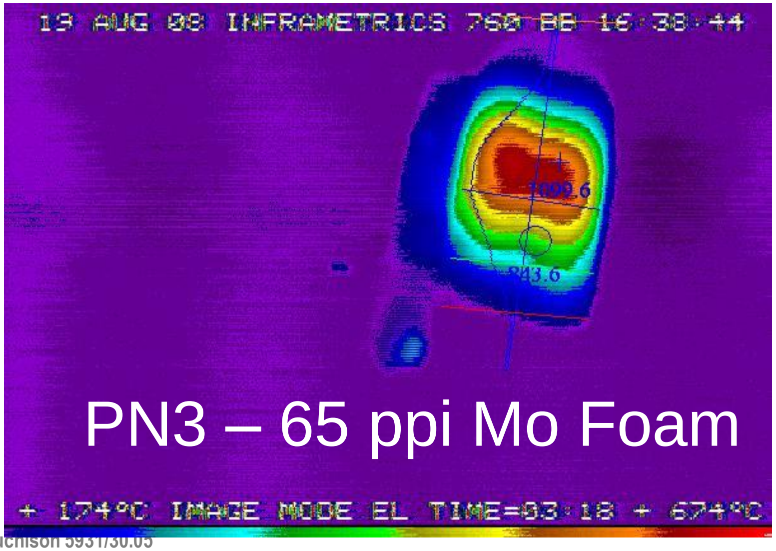
Ultramet pressure drop 100 ppi foam



PN1 – No Foam



Slotted jet concepts are susceptible to flow instabilities! Slot tailoring and variable manifolding required.

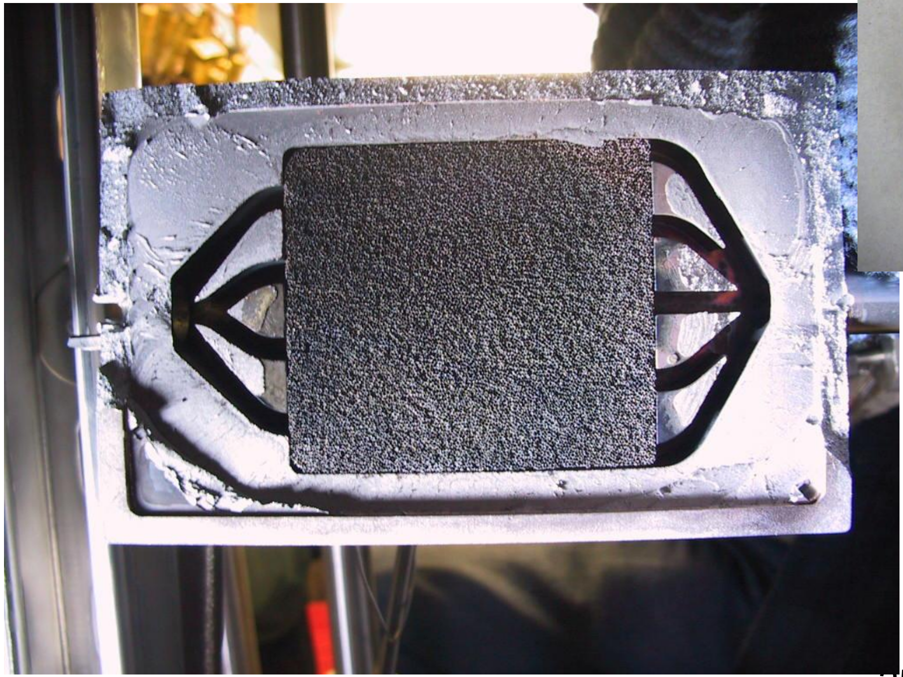


PN3 – 65 ppi Mo Foam

Foams or engineered pressure drops, if tolerable, can mitigate the effect.

Materials testing required

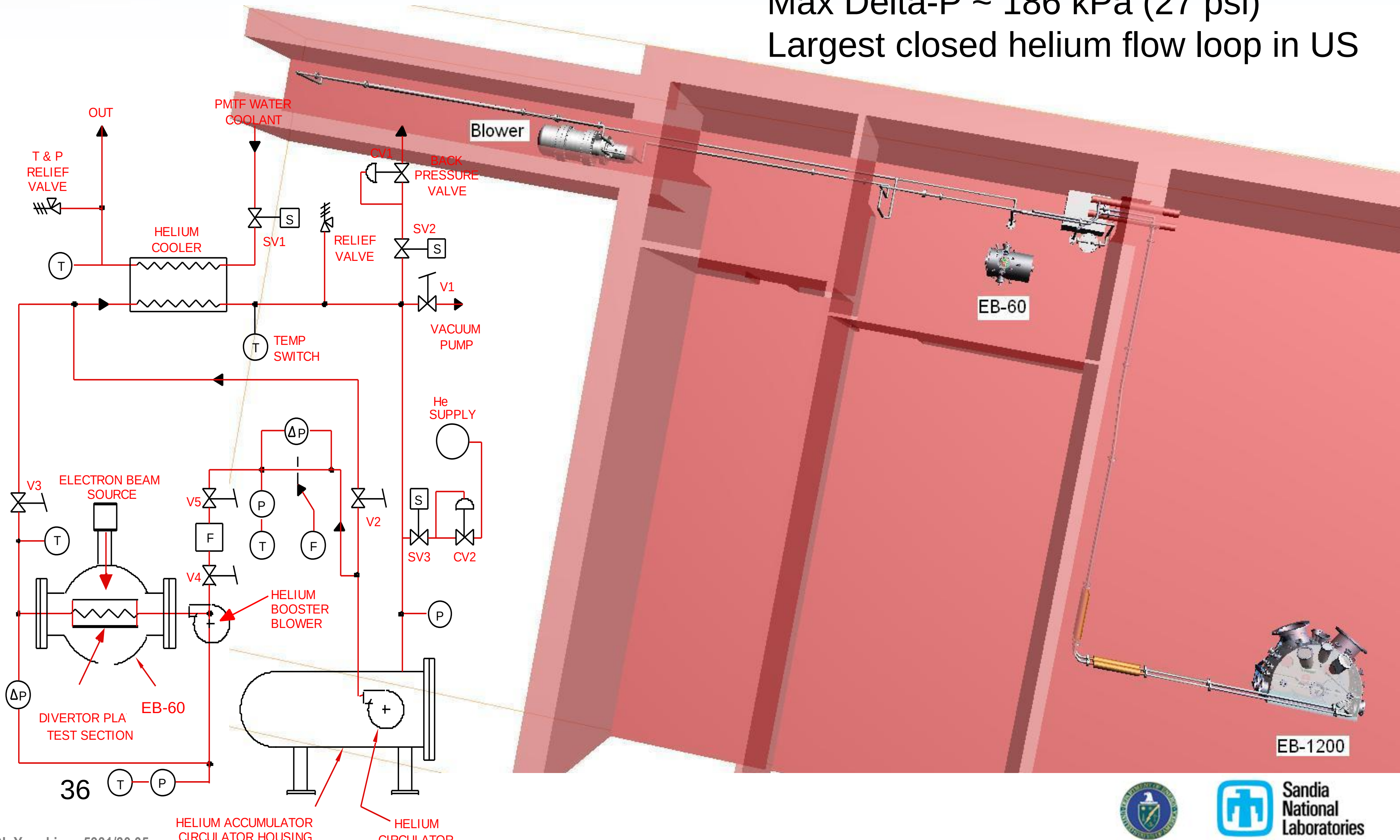
Lamellar failure mode in plates!
Seen in both TZM and W faceplates



Ultramet 4-channel mock-ups after pressurization.

HeFL was upgraded in 2010.

100 g/s, 4 MPa, 60C helium
Max Delta-P ~ 186 kPa (27 psi)
Largest closed helium flow loop in US



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HeFL upgrade to serve EB-60 & EB-1200 (Ultramet CRADA)

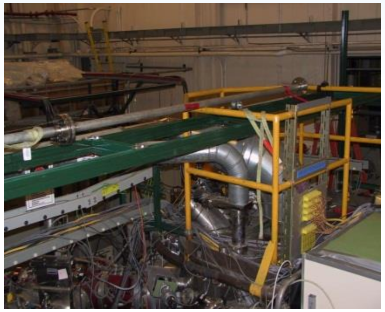
objectives

- more mass flow ~ 100 g/s, 4 MPa helium
- larger head 186 kPa (27 psi)
- high temperature testing (1100 C)
- large area heat flux capability (37x74 cm^2 in EB-1200) (10x10 cm^2 in EB-60)
- multiple channels (flow instabilities)
- 200+ kW heat rejection

equipment

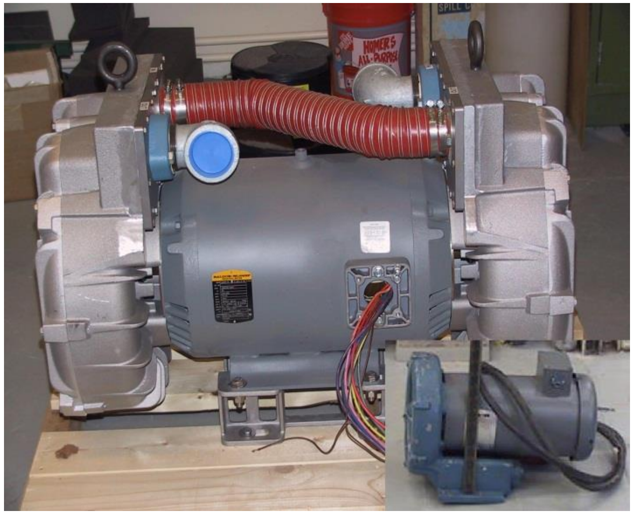
1. new dual stage blower (30 hp)
2. new blower pressure vessel
3. Ultramet refractory foam regenerator
4. helium/water spiral heat exchanger
5. additional piping with hi-temp valves and exp. joints
6. e-beam powered “helium heater” (EB-1200 ONLY)

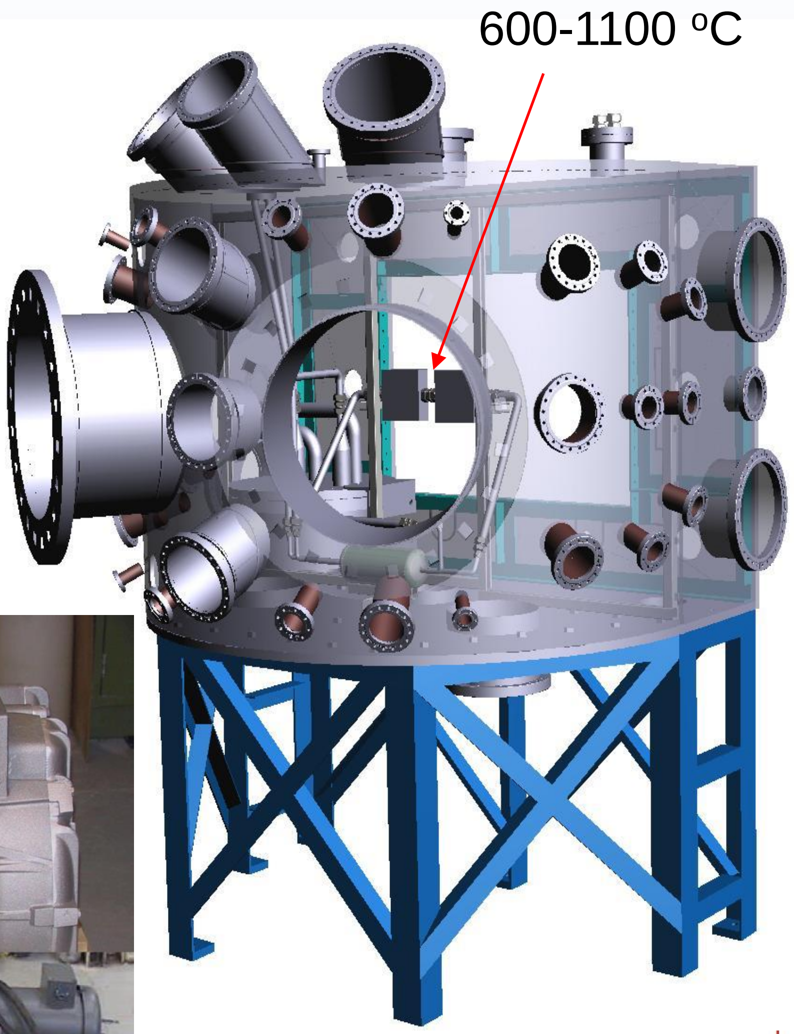
SNL HeFL upgraded to 100 g/s @ 4MPa to facilitate high-temperature experiments in EB-1200.



Pressure Safety!

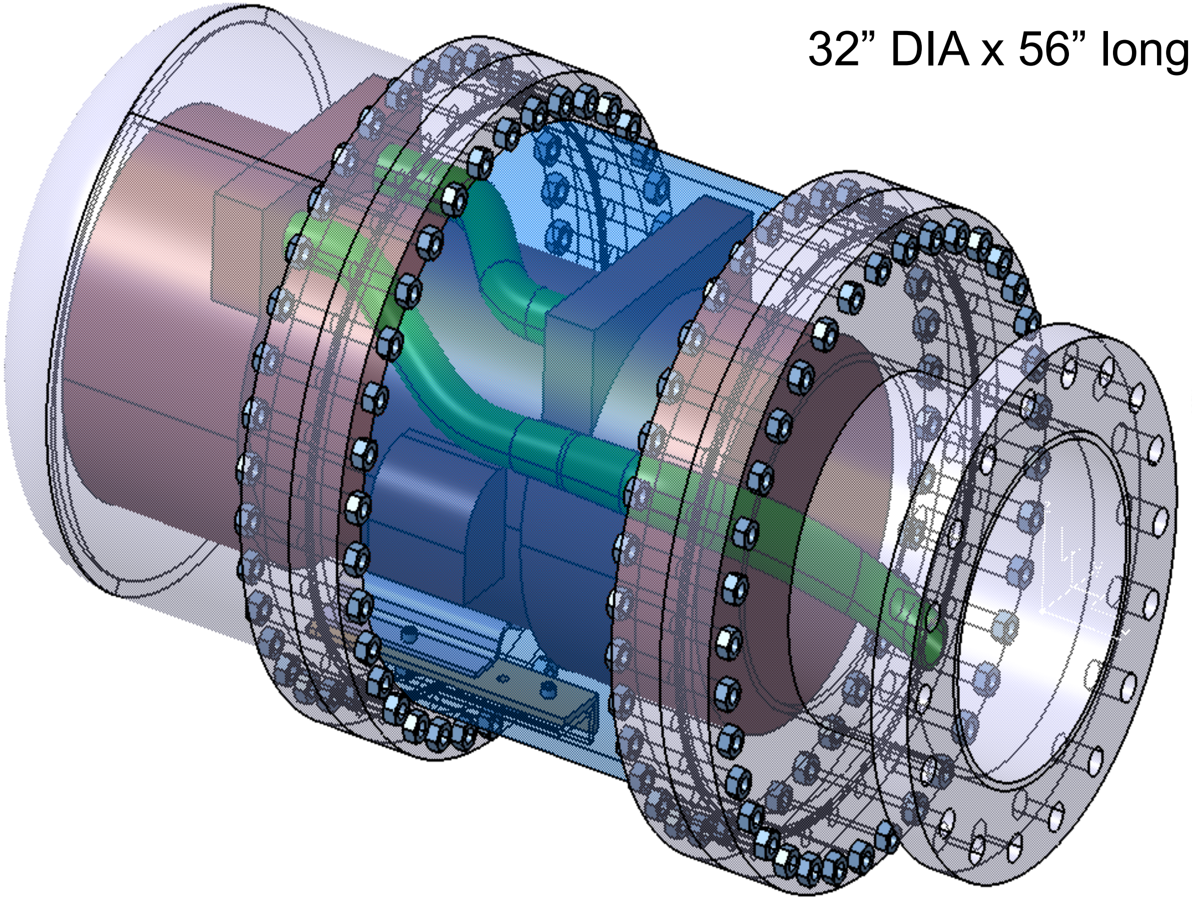
-High temperature pressure systems require enormous resources and attention
4 MPa much easier than 10+ MPa

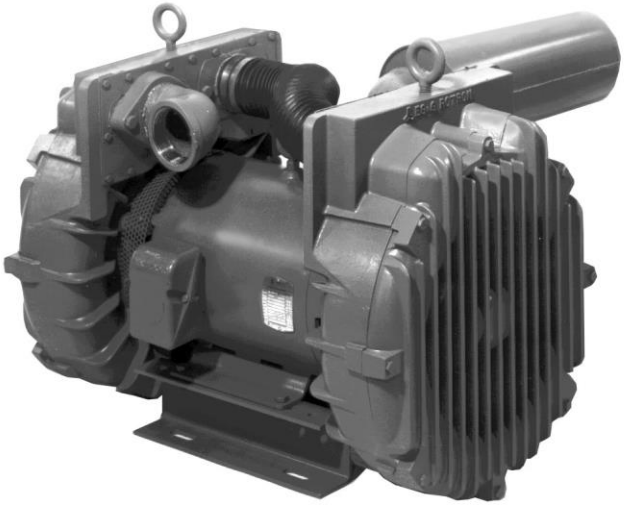




Pressure vessel and blower

32" DIA x 56" long





DL Youchison 5931/30.05

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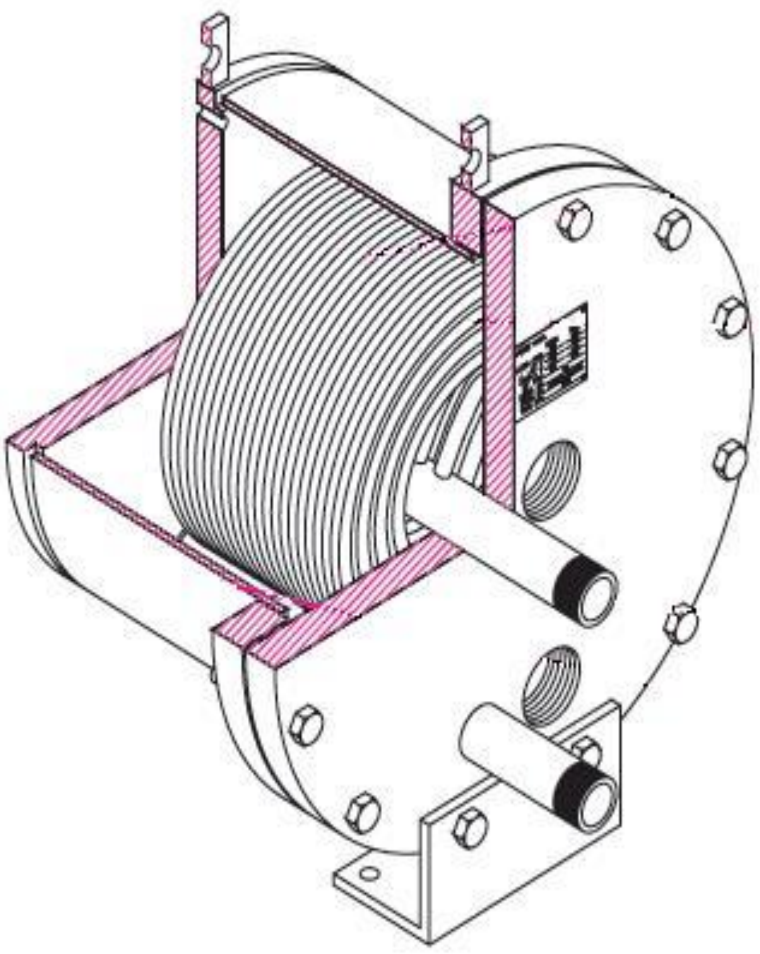
He/H2O HX provides connection to HeFL

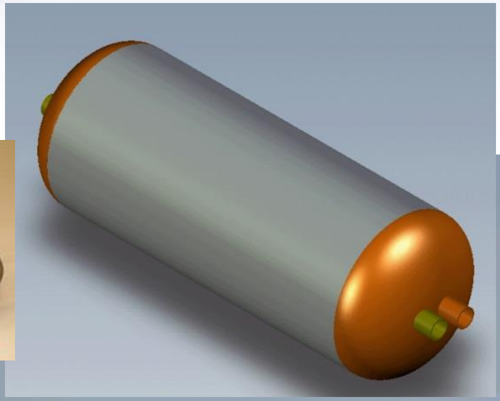


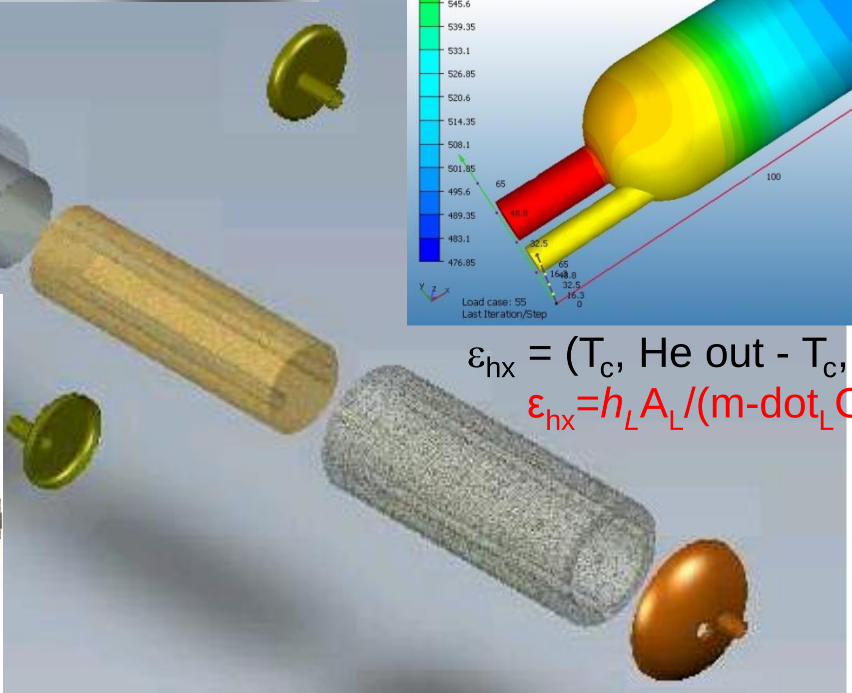
Tin=550C
Tout=100C

Power= 242 kW
828,000 Btu/hr

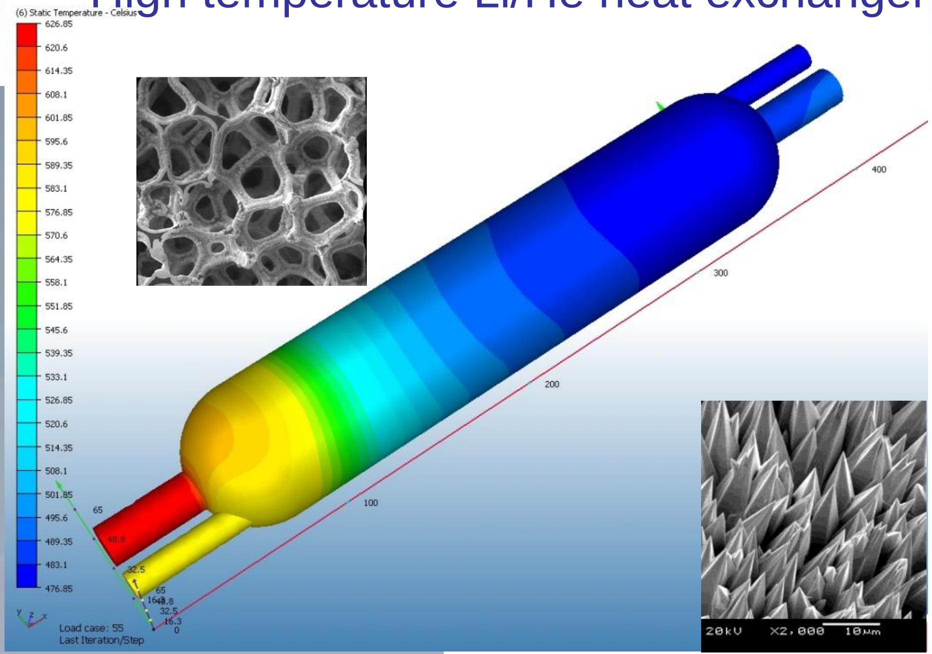
All Refractory Regenerator Available.
Sandia patented technology

All Mo





High temperature Li/He heat exchanger



$\varepsilon_{hx} = (T_{c}, \text{He out} - T_{c}, \text{He in}) / (T_{h}, \text{Li in} - T_{c}, \text{He in})$

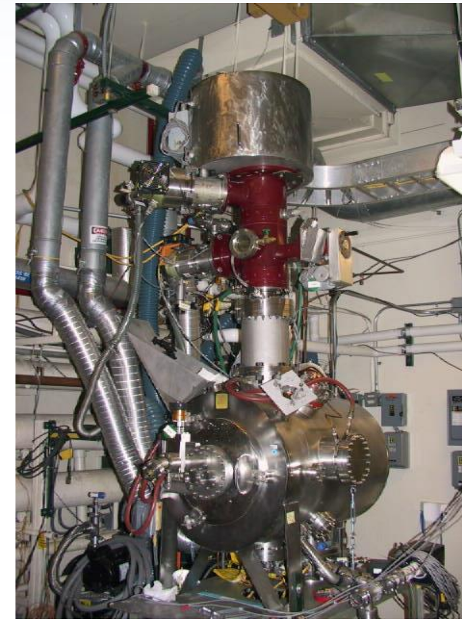
$\varepsilon_{hx} = h_L A_L / (\text{m-dot}_L C_{p(L)}) / [1 + h_H A_H / (\text{m-dot}_H C_{p(H)})]$

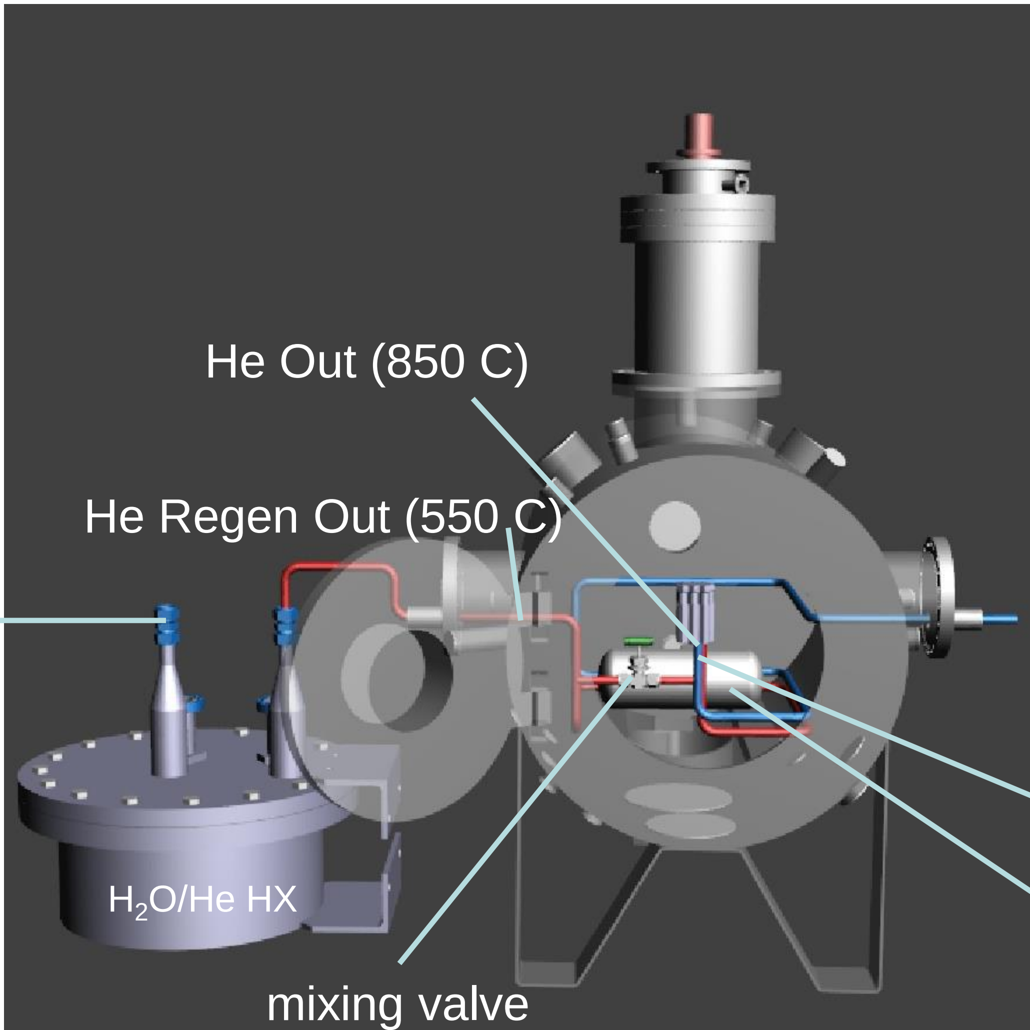
HX effectiveness

thin Mo wall

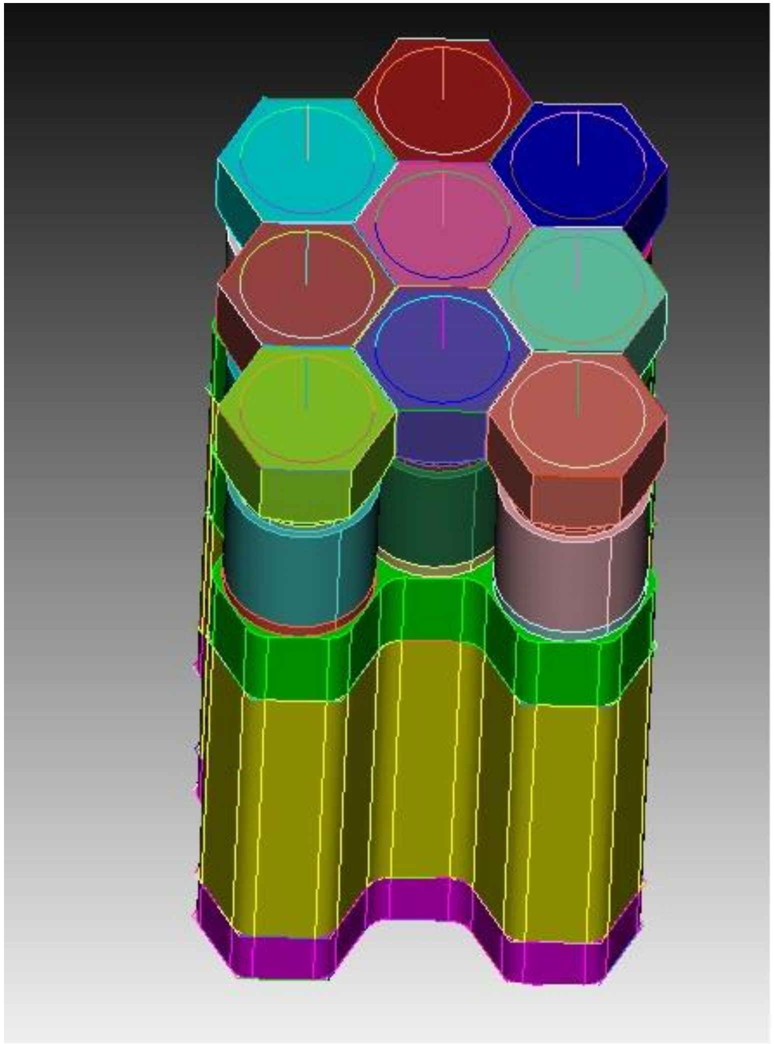
High temperature He/He regenerator

EB-60 Hi-Temp He Setup – 9 Finger HEMJ thermal management



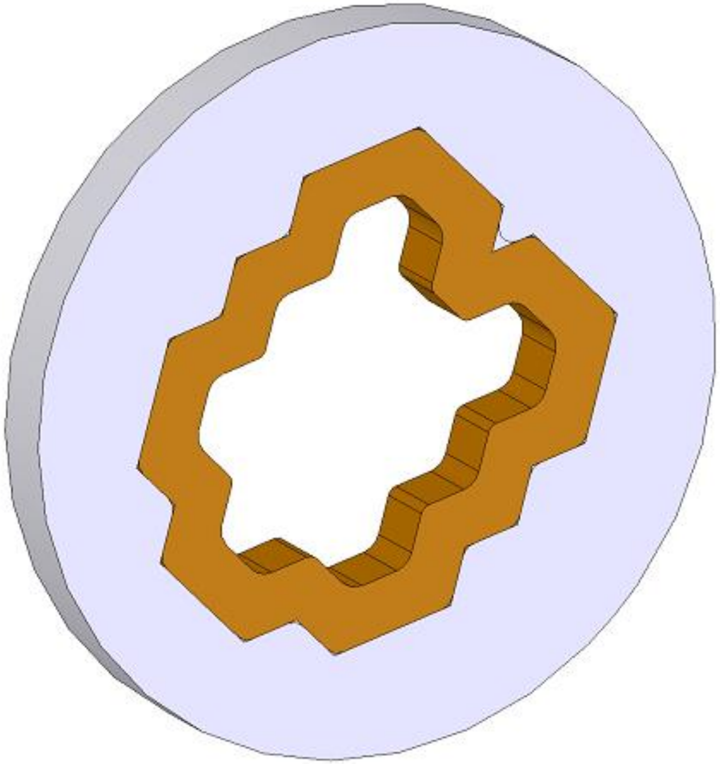


IEA NTFR Annex II Subtask 1



8 @ 10.4 MW/m^2
4 @ 20.8 MW/m^2
2 @ 41.7 MW/m^2
1 @ 83.3 MW/m^2

P_{TOT}=60 kW
f=50%



FZK 9-Finger module is available for testing

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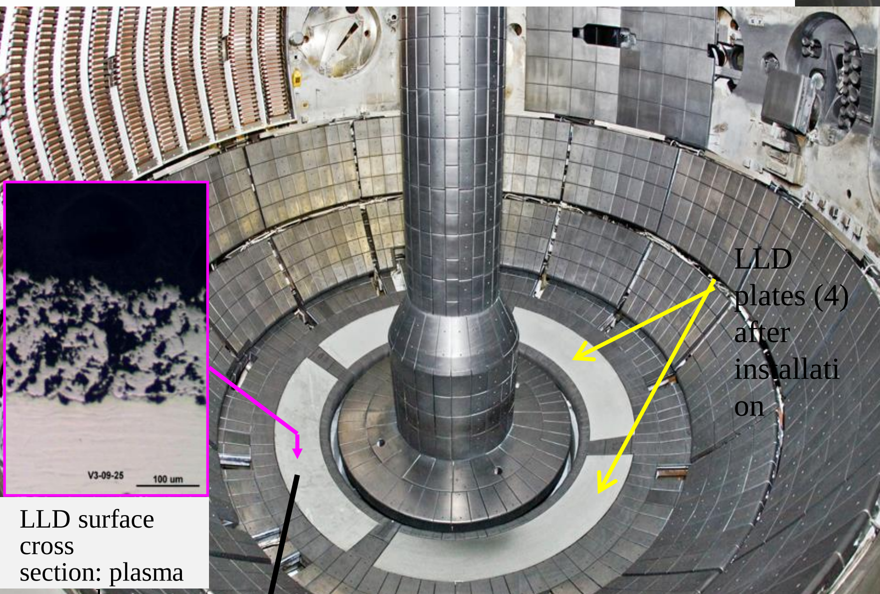
CFD Jet Analysis

- GIT – HEMJ and Tee-tube (experienced)
  - Model validation with experiments
  - Jet performance & Heat Transfer
- SNL – Evidence of flow instabilities (new)

*(seen experimentally, but yet to be predicted by CFD)

  - Non-uniform heating
  - Effect of Manifolding

Potential applications to NSTX at Princeton



LLD surface cross section: plasma sprayed porous Mo

photo of the LLD

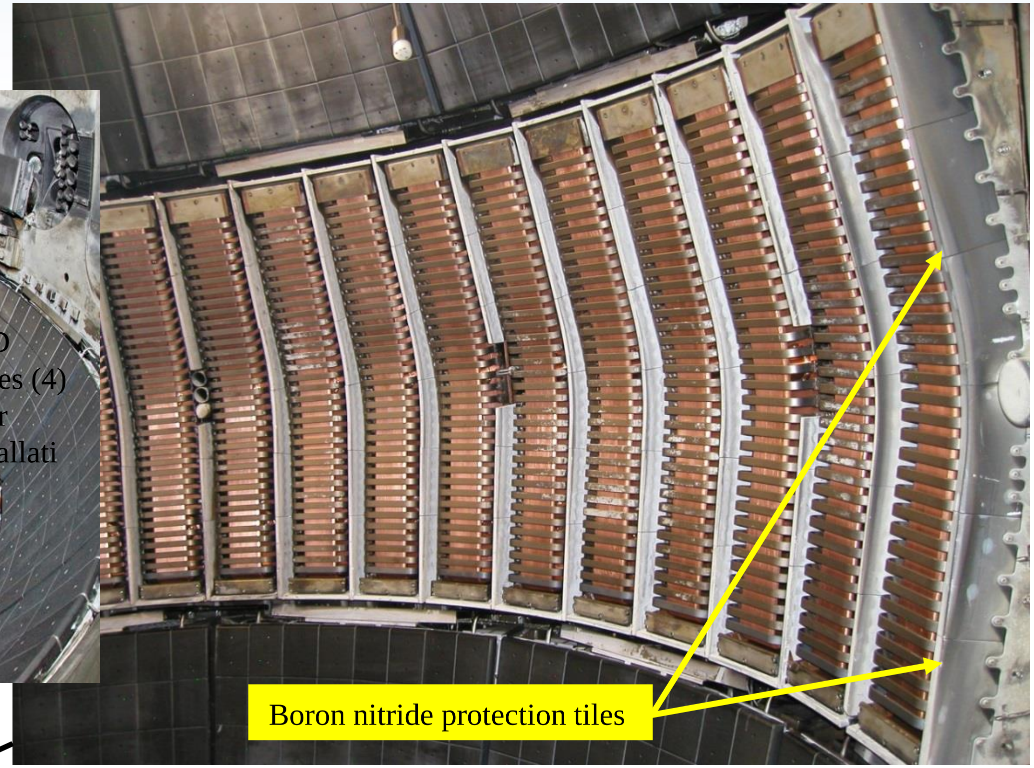


Photo of NSTX RF launcher with boron nitride guard limiter at right. (Photo courtesy of Bob Ellis, PPPL)

1. Gas cooling of guard limiters and faraday shields
2. Cooling of mid-plane or divertor materials probes – CEP
3. BN tipped fast TCs (PSU/ARL)
4. Gas cooling of lithium substrates for heat removal - LLD

Concluding remarks

- testing of helium-cooled heatsinks at DEMO-like temperatures
  - record heat fluxes on copper devices ~ 29.5 MW/m^2
  - heat fluxes on pure W with porous media to 6 MW/m^2
  - heat fluxes on Mo with foam enhancement to 8.5 MW/m^2
- micro-cracking and failure modes for refractory materials
- experimental database for CFD analysis – HX and flow instabilities
- designs/testing for NSTX-U faraday cage edge cooling or probes
- strong Phenix - IEA NTFR collaboration: HEMJ from KIT, tee tubes from ARIES
- HHFF now available for DoD projects.

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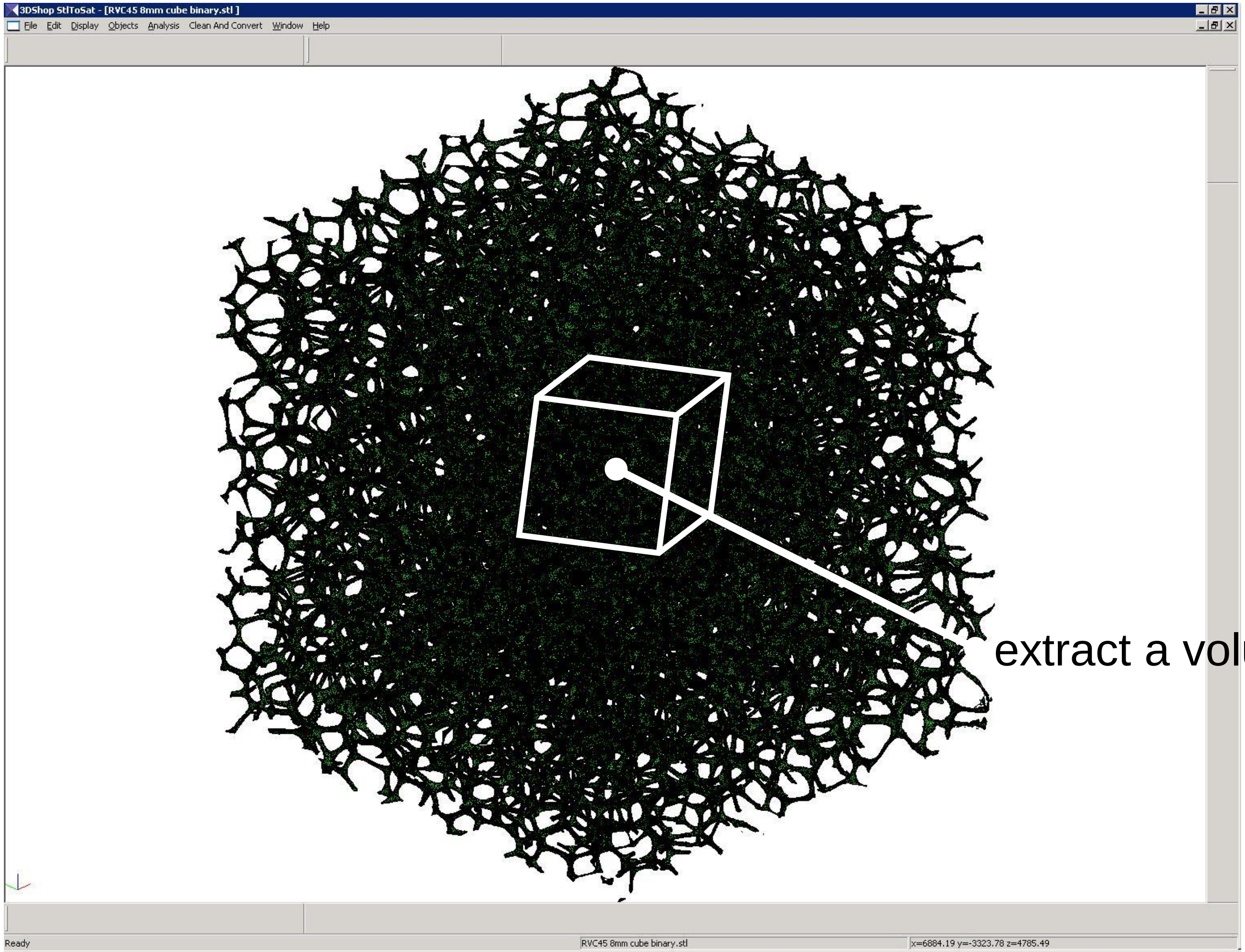
Porous Media Modeling Extras

SNL experienced in porous media – led to recuperators/regenerators

Processing geometry and meshing remain greatest challenge.

8 mm x 8 mm x 8 mm 45 ppi RVC skeleton



extract a volume

Tomography
•VGStudio MAX by Volume Graphics

File translation
•3dShop by C4W
•Rhino 3d
•Cubit
•Star CCM+

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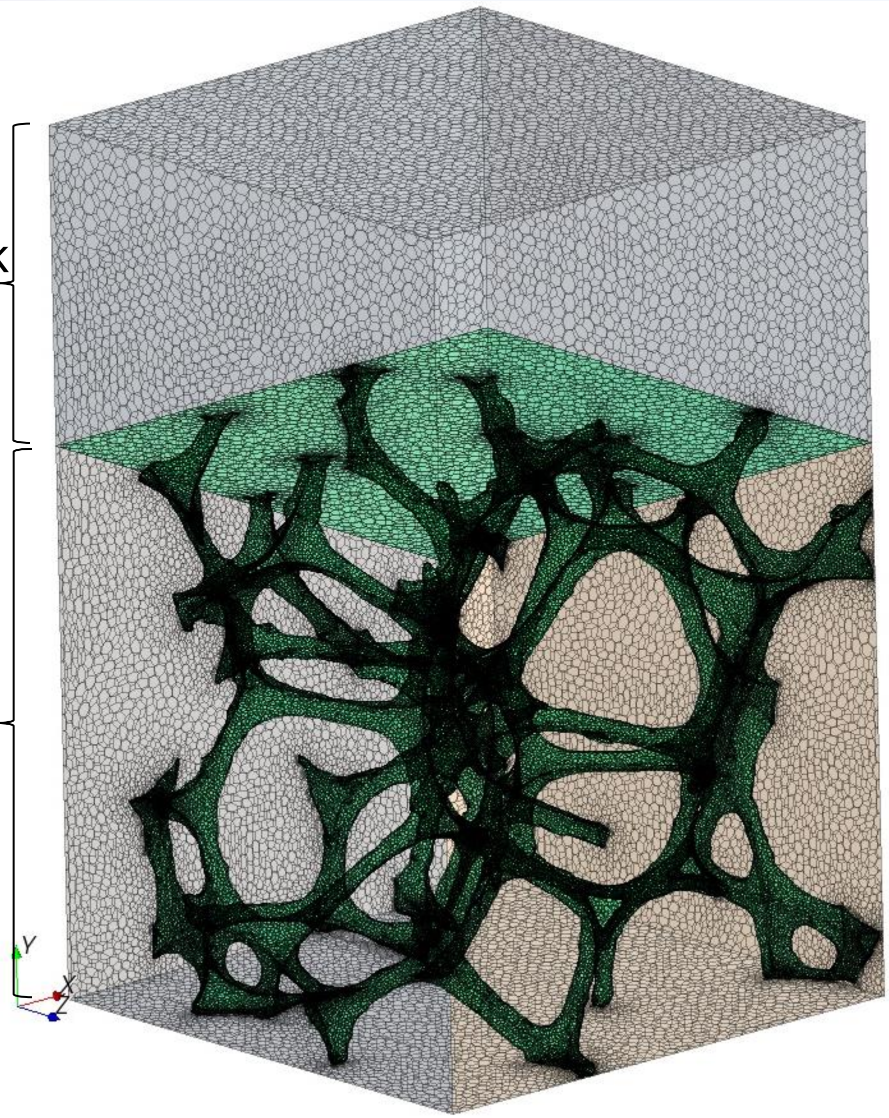
Modeling is computationally expensive.



Commercial CFD Codes

- Star-CCM+ v5.04
- Cfdesign v10

One-million element polyhedral mesh with three prism layers at all solid/gas interfaces.

1.7 mm x 1.7 mm x 2.7 mm high. Arbitrarily chosen volume extracted from 8x8x8 mm^3 volume shown earlier. Wall added in CCM+.

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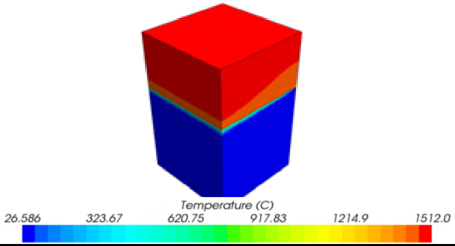
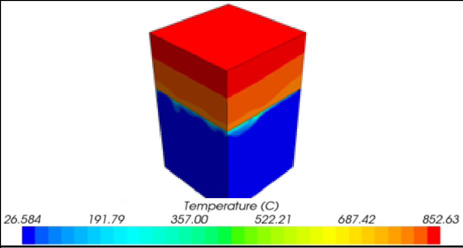
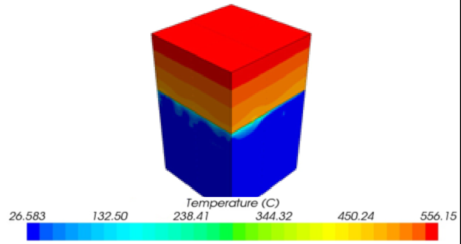
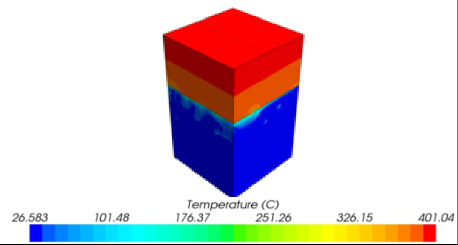
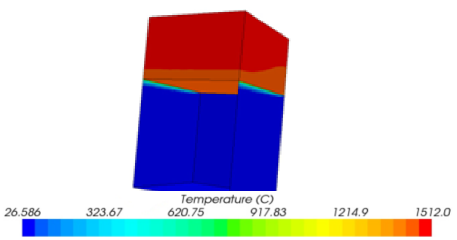
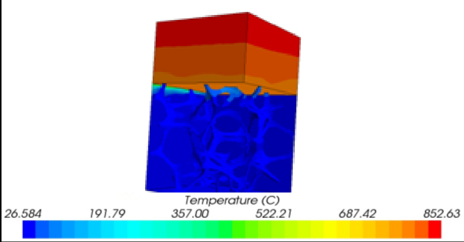
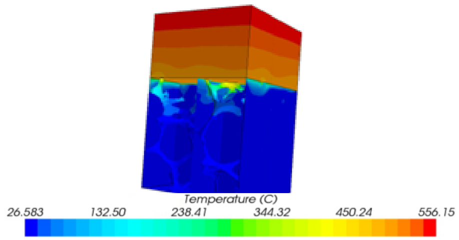
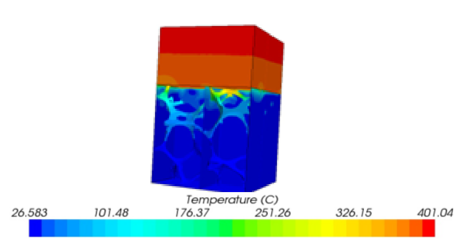
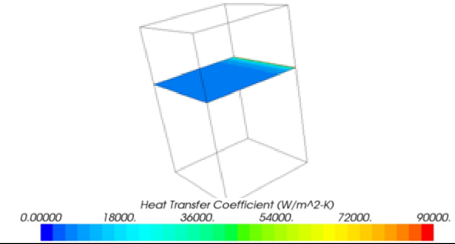
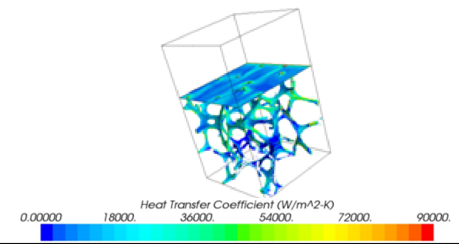
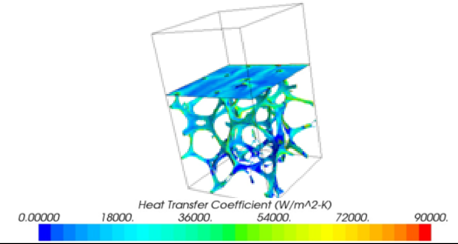
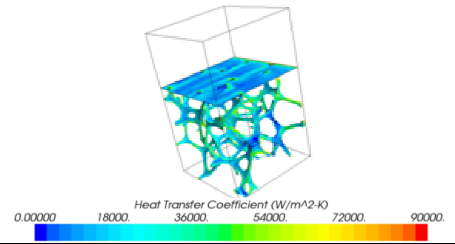
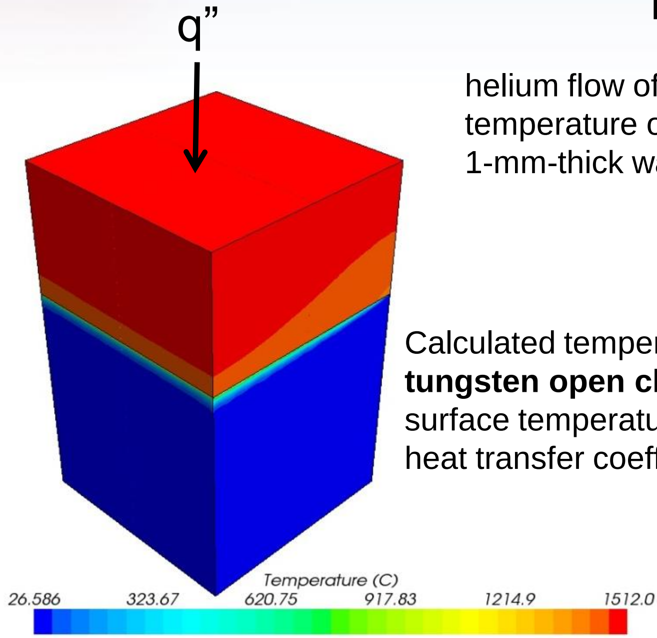
Porous media is effective in enhancing gas cooling.

Table 1. Comparison of Foam Effectiveness to Open Channels

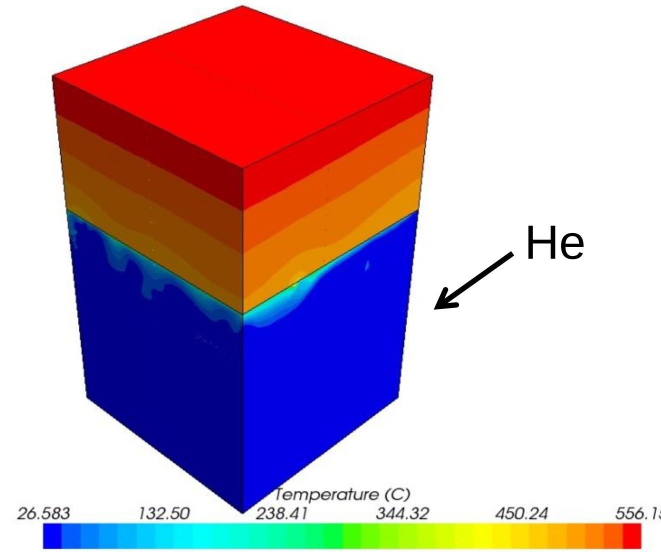
Open Channel	Unconnected 45-ppi W foam	Connected 45-ppi W foam	Connected 45-ppi Cu foam
			
			
			
h=7100 W/m^2K	h=13,200 W/m^2K	h=21,500 W/m^2K	h=28,350 W/m^2K

Conductivity of foam can affect performance.

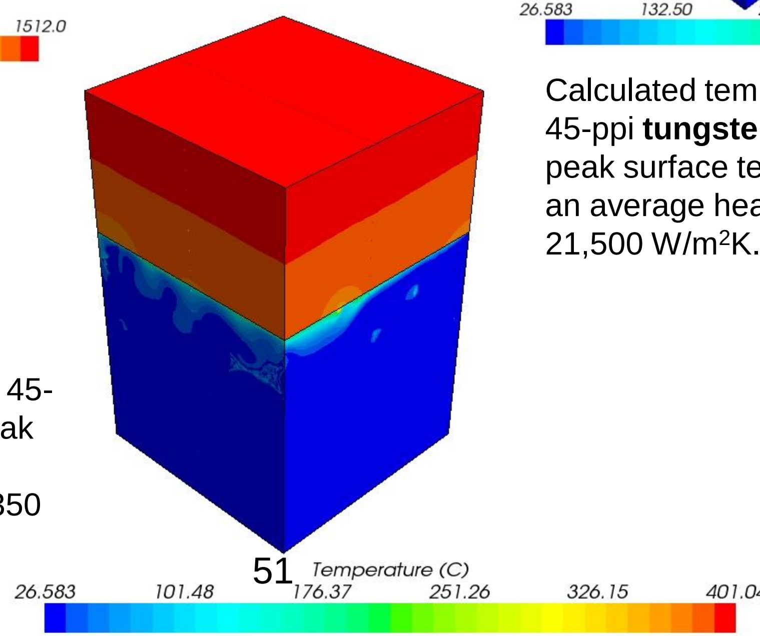
helium flow of 1 g/s at 4 MPa with an inlet temperature of 26.8 ^{o}C. q"=5 MW/m^2 on a 1-mm-thick wall.



Calculated temperature distribution in a **tungsten open channel** duct reveals a peak surface temperature of 1512 ^{o}C with an average heat transfer coefficient of 7100 W/m^{2}K.



Calculated temperature distribution in a 45-ppi **tungsten foam channel** reveals a peak surface temperature of 556 ^{o}C with an average heat transfer coefficient of 21,500 W/m^{2}K.



Calculated temperature distribution in a 45-ppi **copper foam channel** reveals a peak surface temperature of 401 ^{o}C with an average heat transfer coefficient of 28,350 W/m^{2}K.

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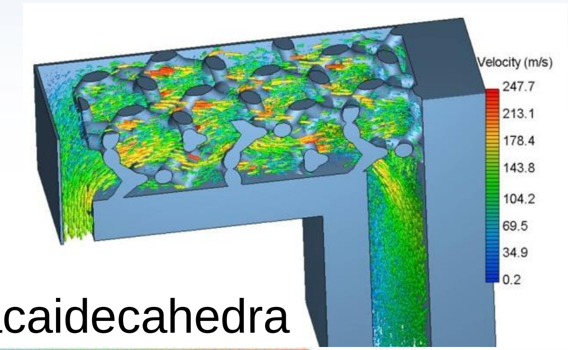
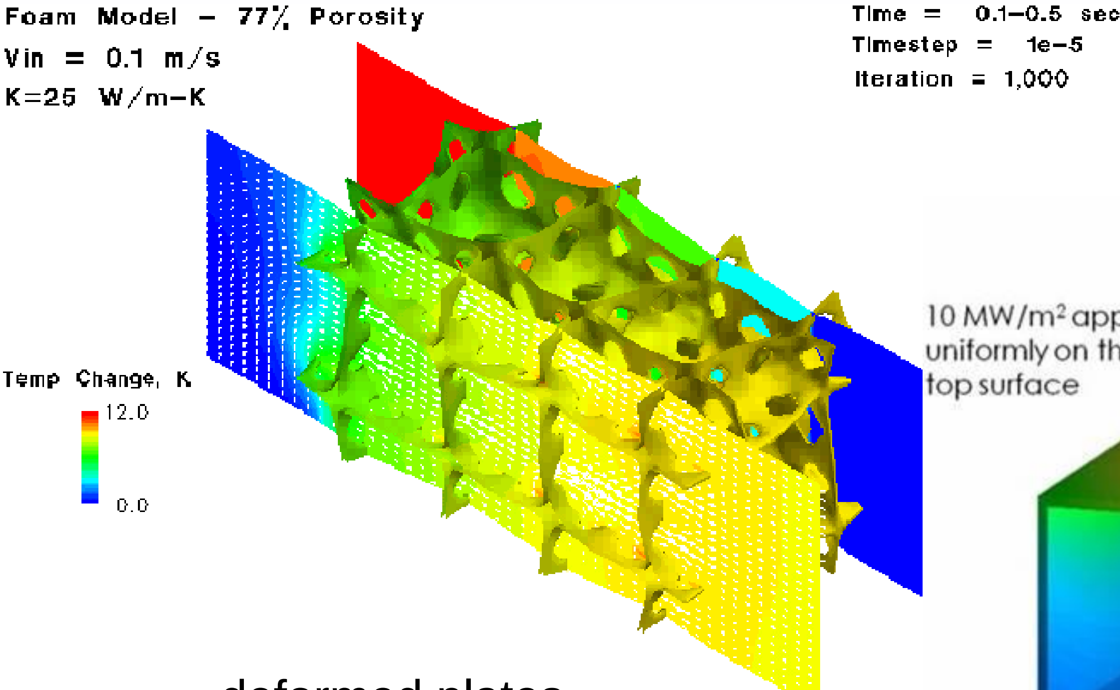
Back-up Extras

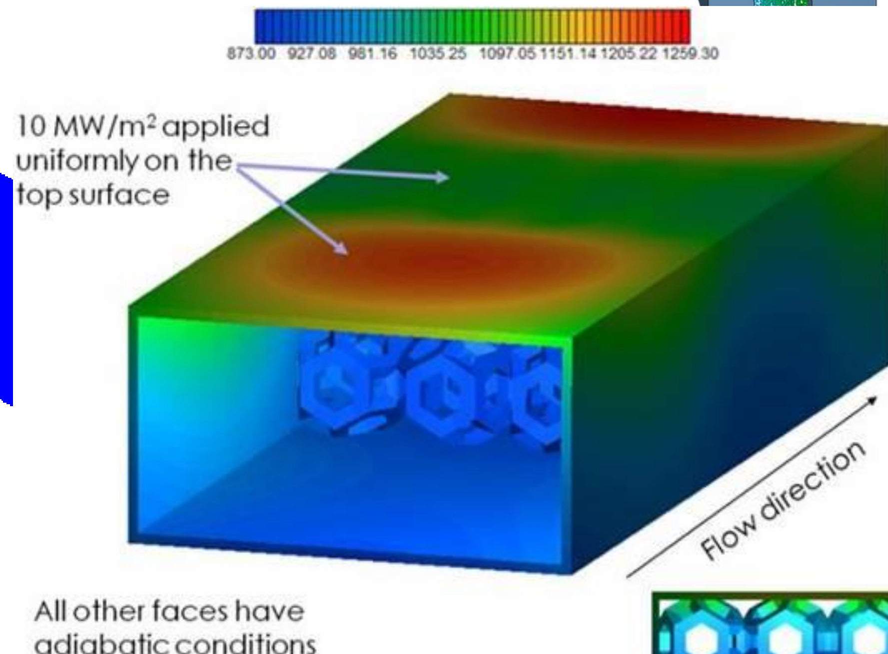
Previous modeling relied on periodic structures.



tetracaidecahedra



deformed plates



Failed to capture the randomness in cell size, window orientation, non-uniform ligaments and other unique characteristics of commercial foams.

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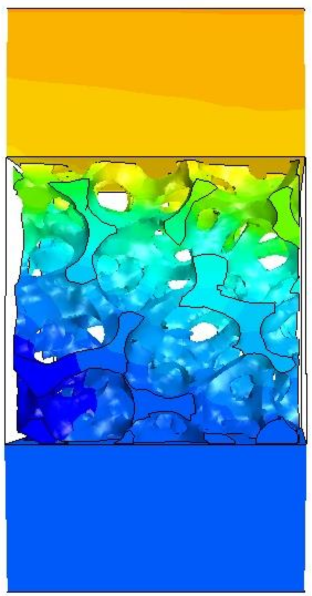
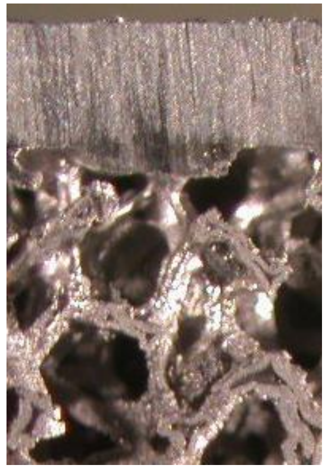
DL Youchison 5931/30.05

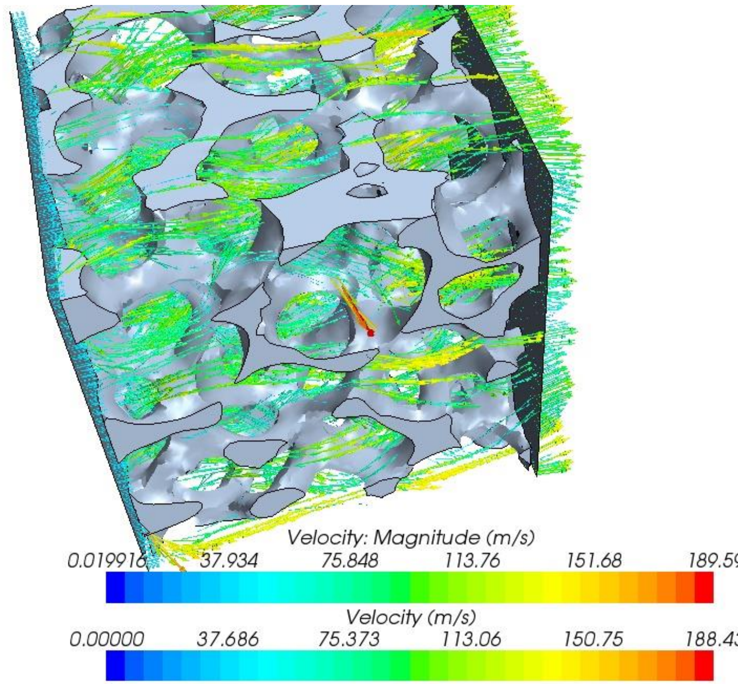
Analysis reveals turbulent mixing and fin effect created by foam.

627 C

27 C He





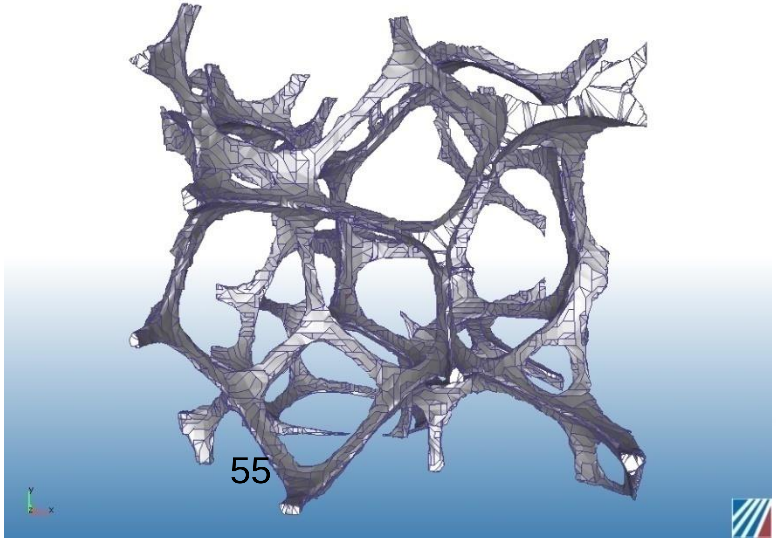


Convection models for 2 mm x 2 mm 65 ppi, 10% dense moly foam attached to 1 mm thick moly walls. Temperature distribution is shown on left with velocity vectors and streamlines through the foam on the right.

We perform CFD modeling of foam porous media heat transfer on the microscale.

- Computerized X-ray microtomography was completed at Sandia on Ultramet supplied foam samples. The smaller files were translated from stereolithography format to ACIS solid modeling format.
- The solid models of the detailed foam microstructure were meshed and analyzed by commercial computational fluid dynamics (CFD) codes (CFDesign and CCM+) to determine the effective permeability and ligamental heat conduction.
- Foam models derived from computerized x-ray tomography were closed with facesheets of SiC on one side and steel on the other inside CCM+.
- The CCM+ tet mesh was exported to Abaqus for stress analysis.
- Deflections, inelastic strains and stresses were computed in the ligaments and permeation barrier facesheets using Abaqus.

X-ray microtomography file of carbon foam after translation to ACIS solid modeling format.



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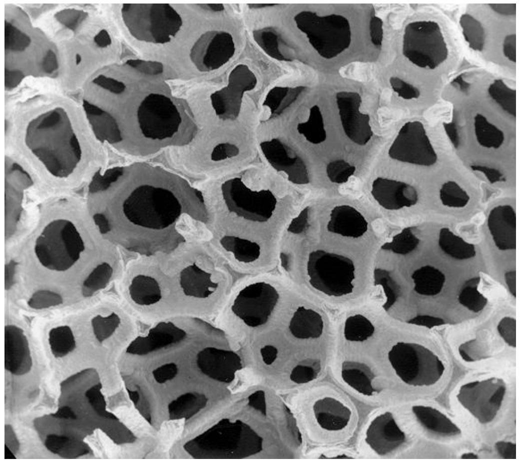
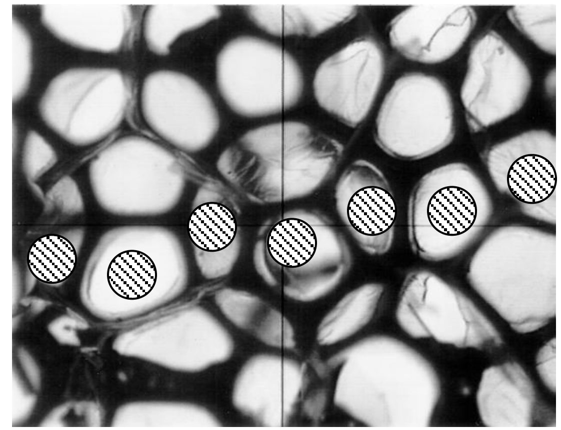
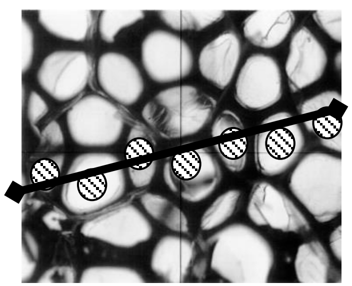
Foam Nomenclature

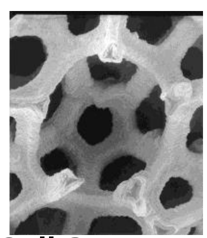




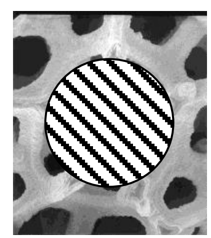
PPI = Pores Per Inch



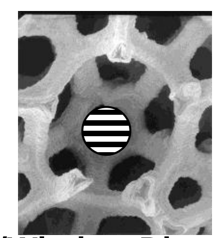
PPI = Pores Per Inch



Cell Structure



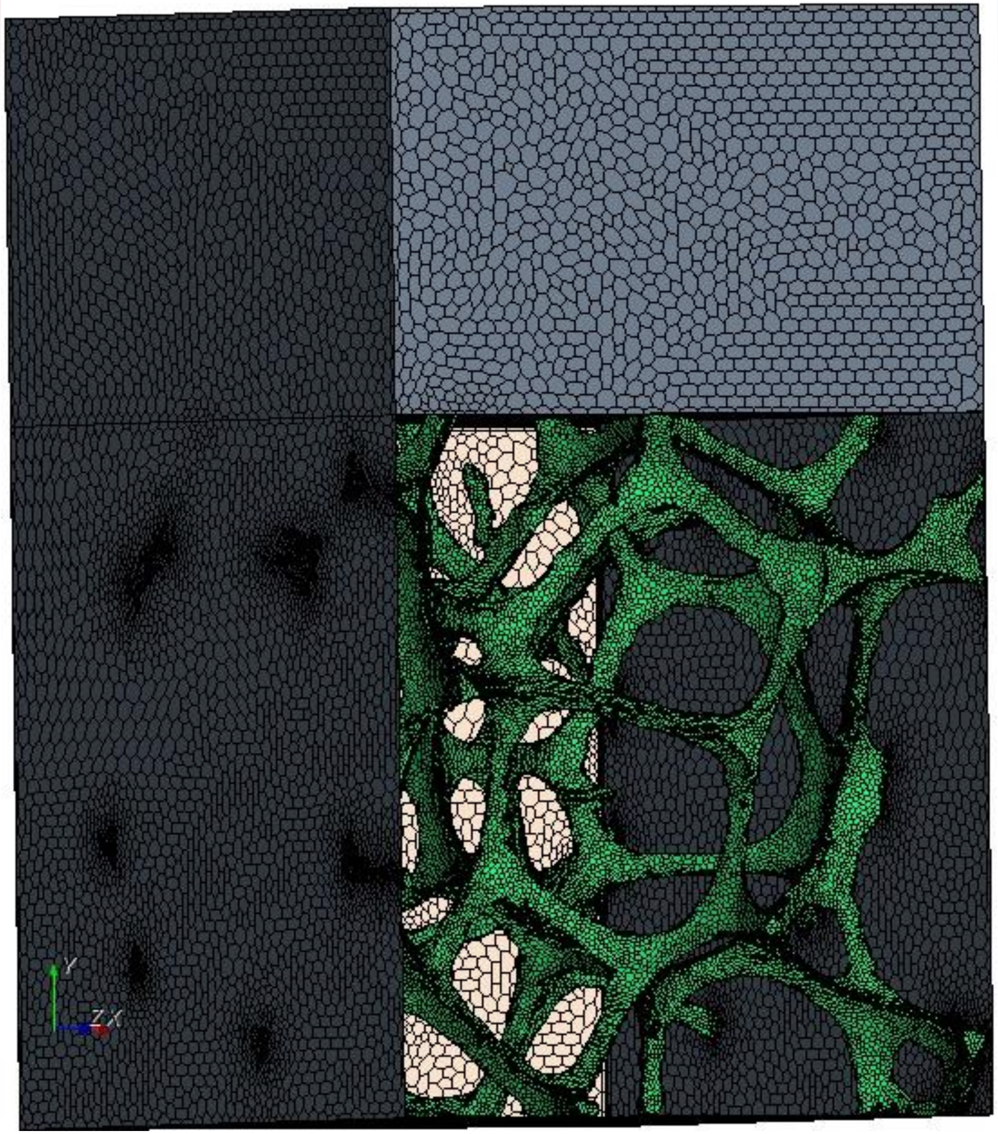
Cell Diameter

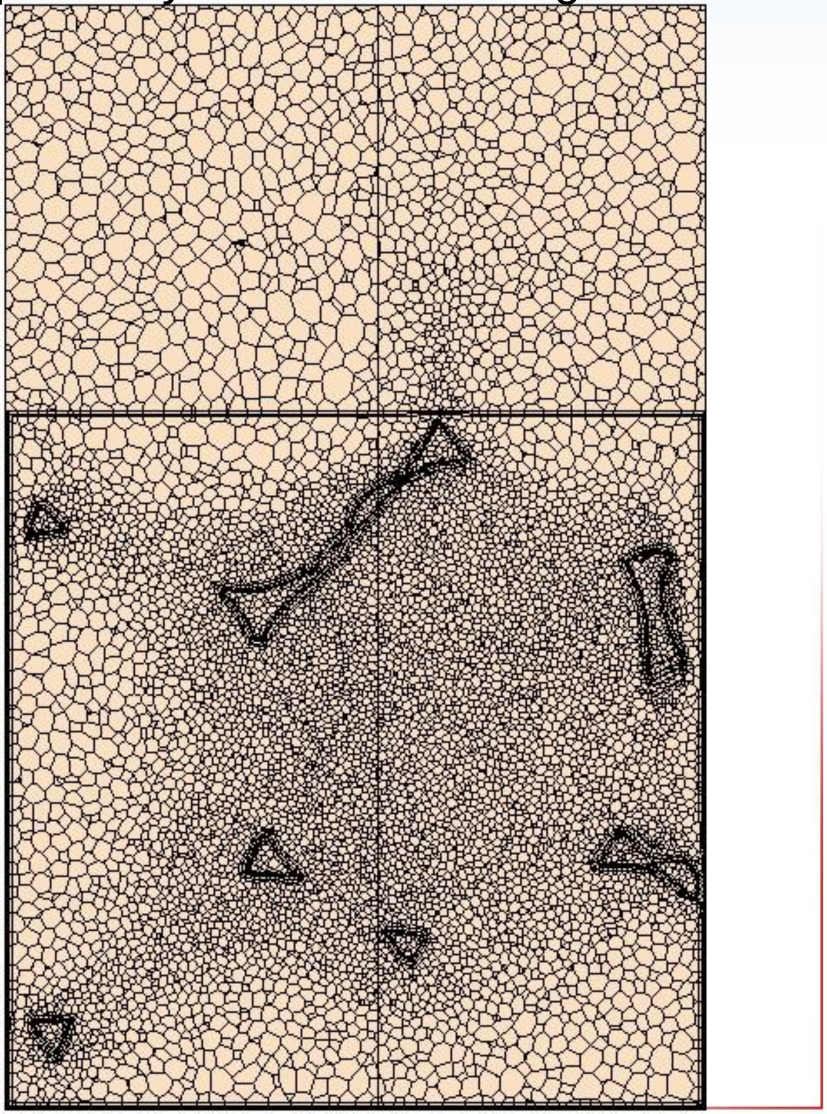


Pore/Window Diameter

Imprint and merge 3 solids and a fluid

3 prism layers at walls and ligaments





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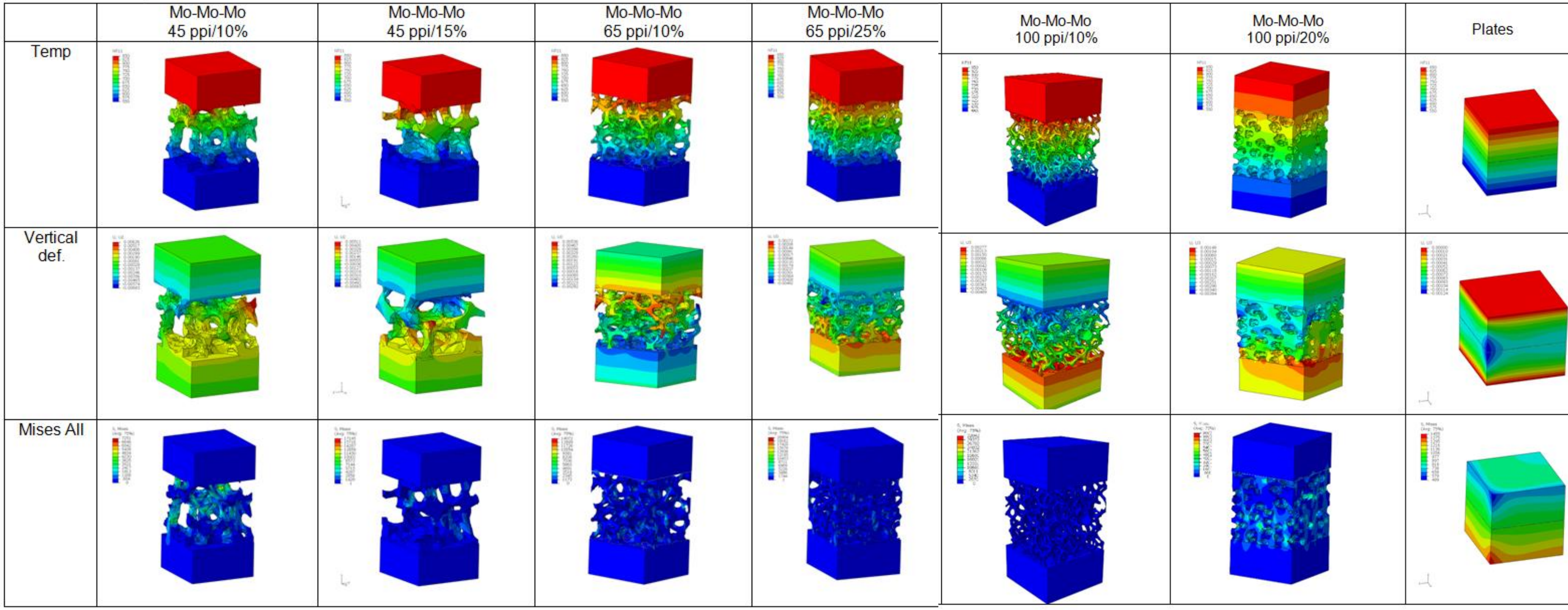
Modeling of Mo Foam



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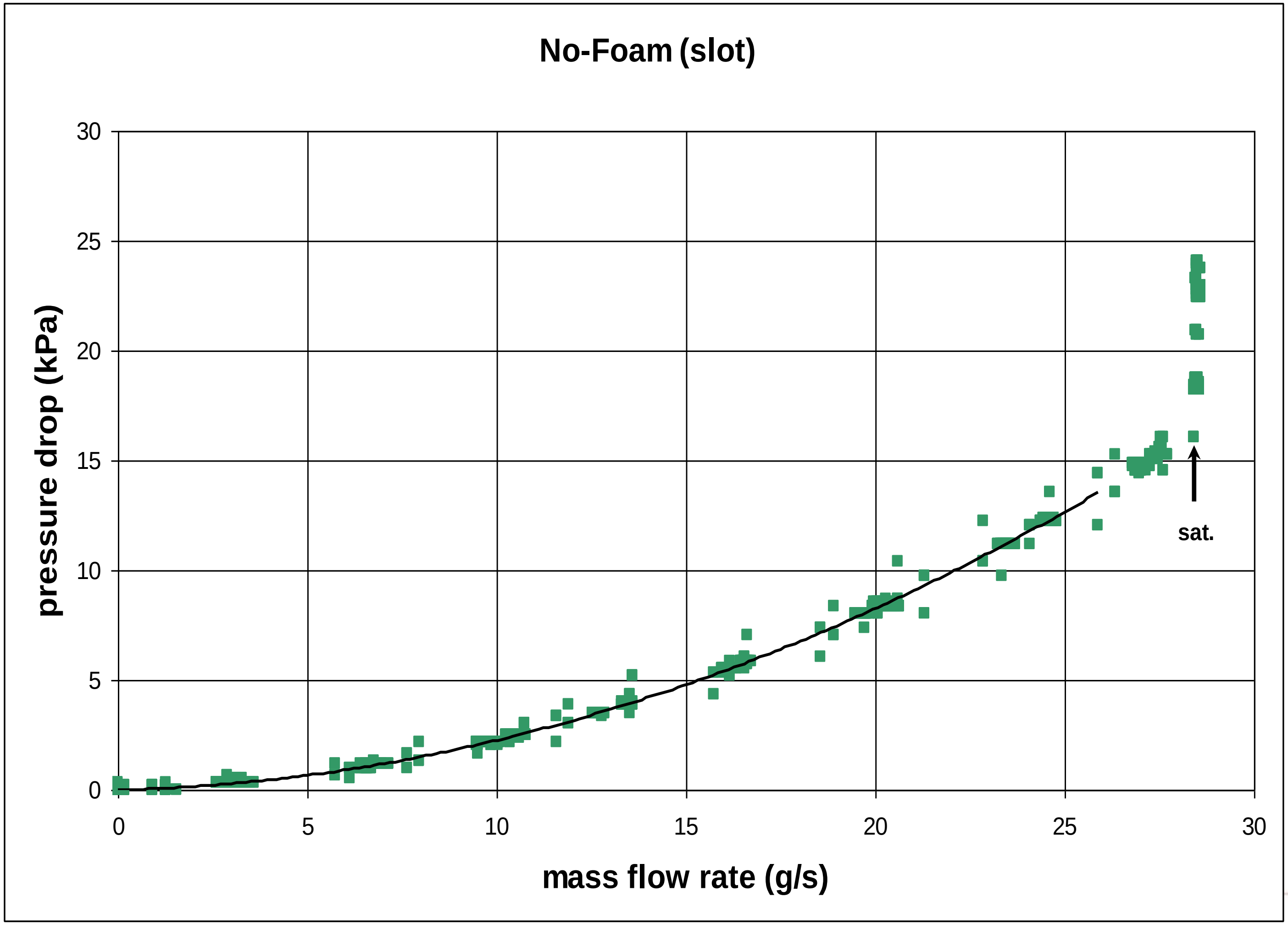
Flow test results (127 mm slot, no foam)



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