ORNL High Conductivity Graphitic Foams

Dr. James Klett

Metals and Ceramics Division
P.O. Box 2009, Oak Ridge National Laboratory
Oak Ridge, Tennessee, 37831-6087
(865) 574-5220
klettjw@ornl.gov

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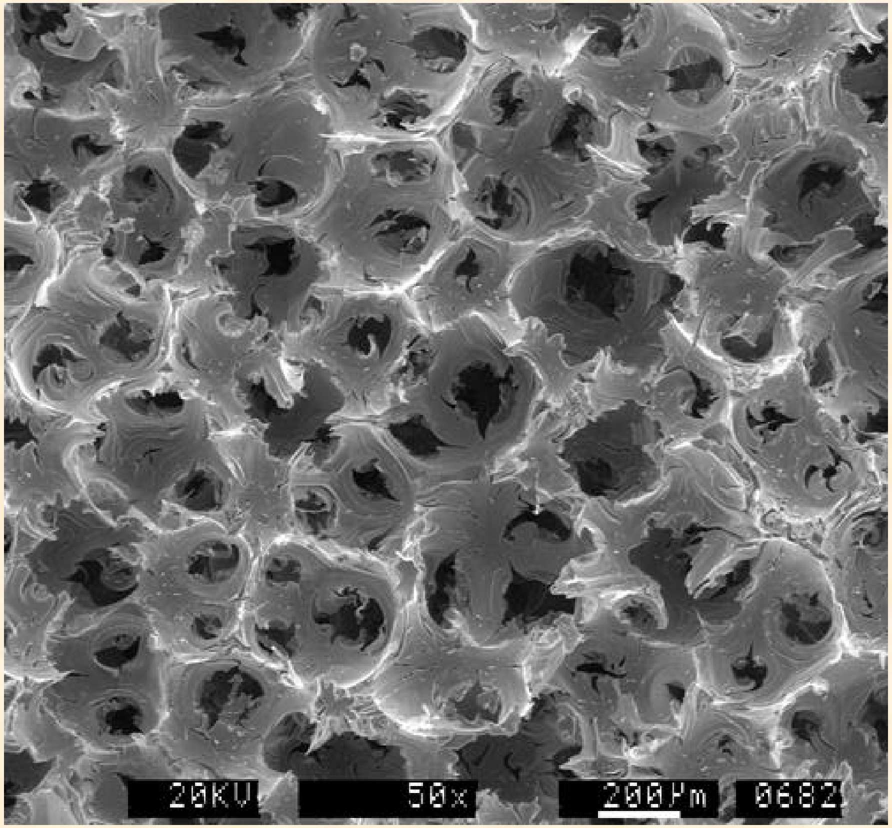
Outline

- **High thermal conductivity graphite foam**
  - **Material overview**
  - **Foam fabrication process**
  - **Why does this foam become so good**
- **Applications of Interest**
  - **Power electronics cooling**
  - **Transpiration/evaporative cooling**
  - **Electronics**
  - **Radiators**
  - **High temperature friction applications**
  - **Acoustics**

High Thermal Conductivity Graphite Foam

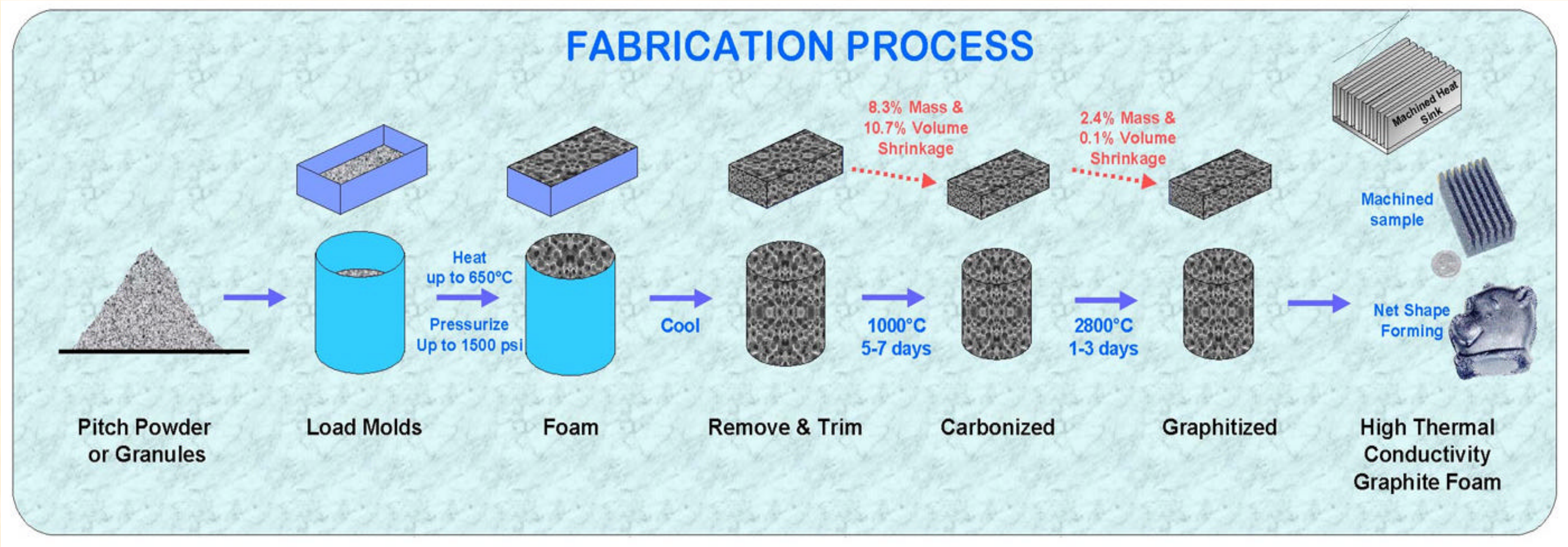
- **9 patents, 14 pending, 2000 R&D 100 Award Winner**



- ➢ Highly ordered graphitic ligaments
  - Graphite-like properties
- ➢ Dimensionally stable
  - low CTE - ~2 - 4 µin/in/°C
- ➢ Open porosity
  - Permeable to fluids
- ➢ Excellent thermal management material

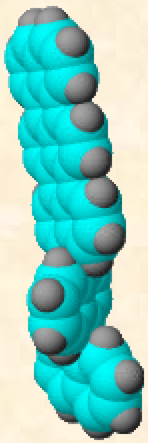
Production Method

- **Unlike traditional foaming techniques**
  - **No blowing (flashing) required**
    - **saves steps**
  - **No oxidative stabilization required**
    - **improved thermal properties**

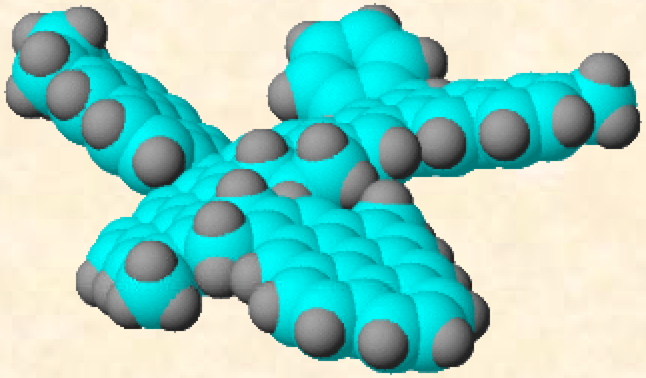


Mesophase Pitch

- **Typical molecular structures are different**
  - **may affect shear orientation during processing**
  - **may affect mechanical and thermal properties**



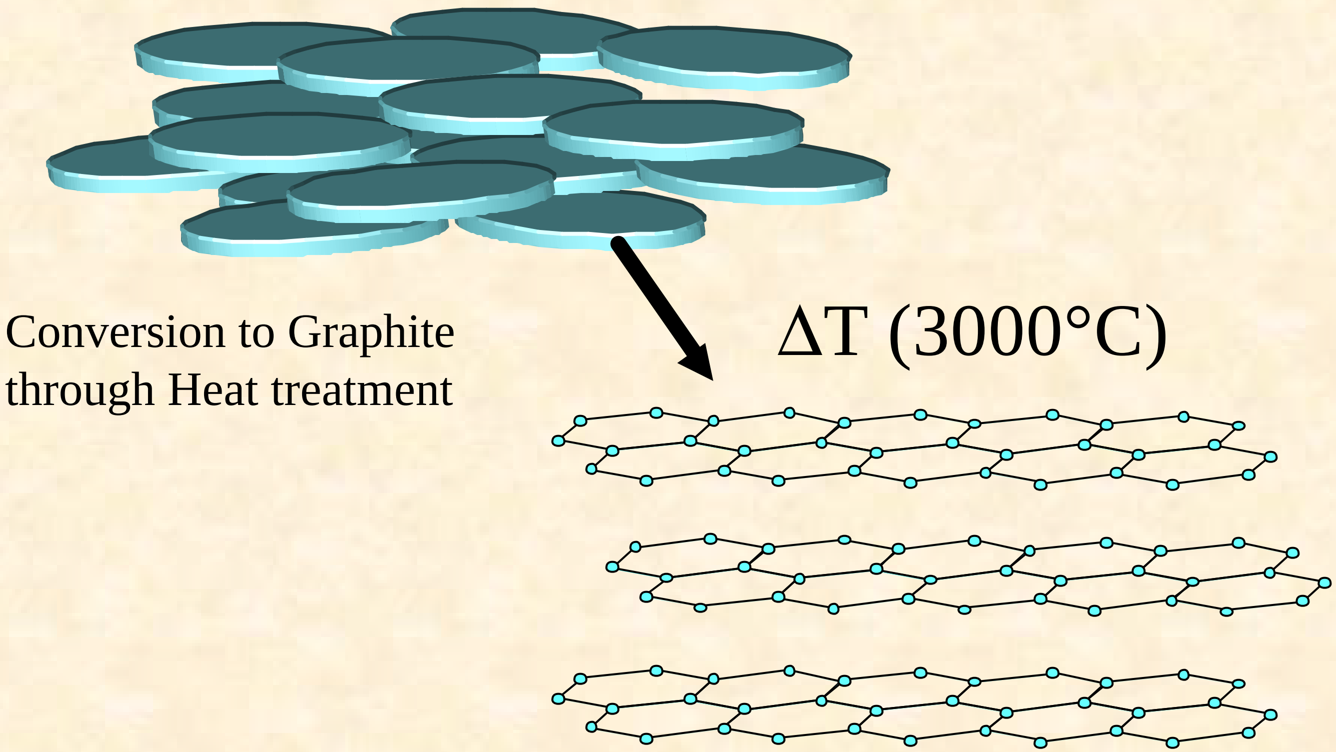
Mitsubishi AR Mesophase



Typical Petroleum Derived Mesophase

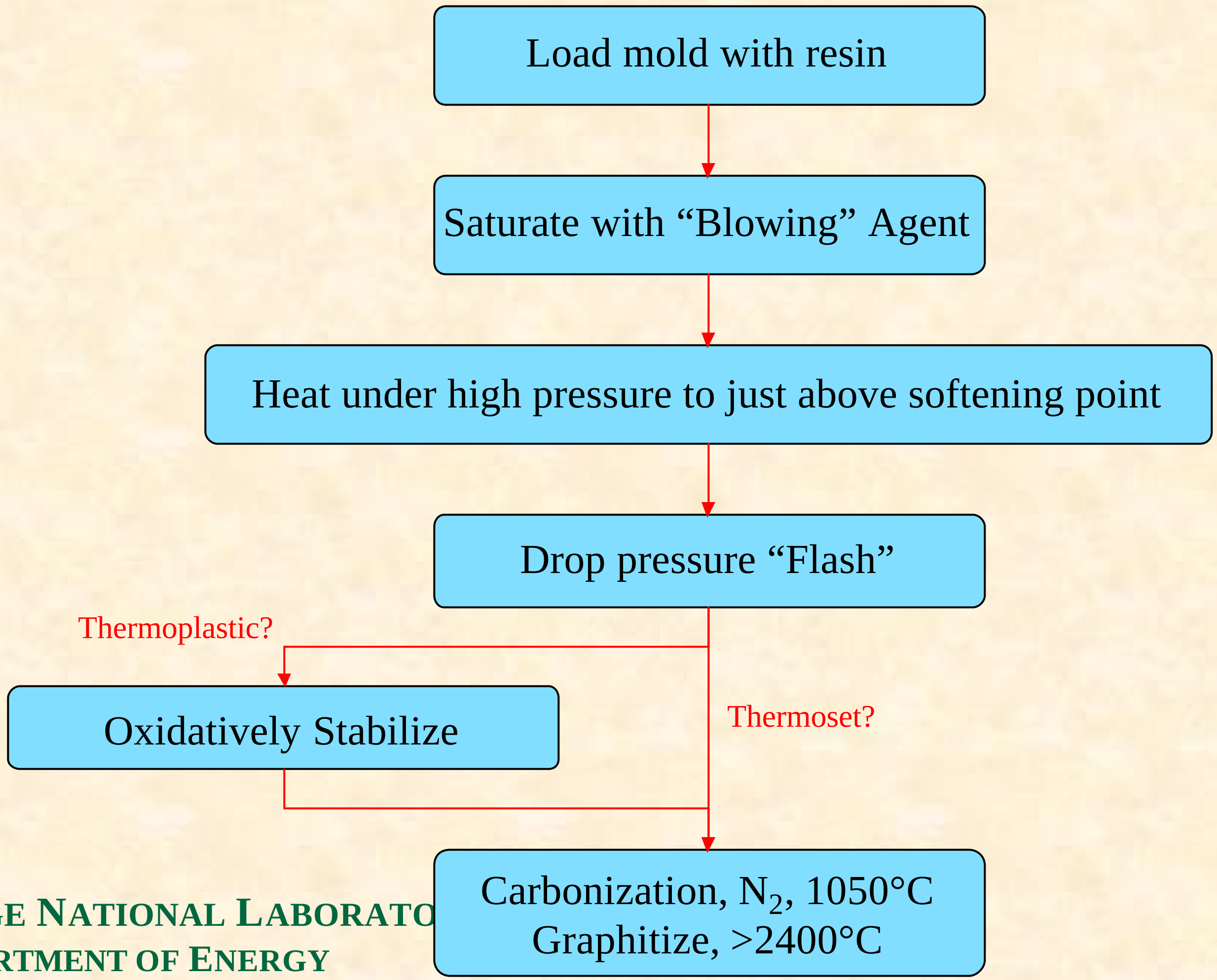
Mesophase Pitch

- **Under proper processing and heat treatments, the mesophase molecules become a Discotic Nematic Liquid Crystal**
  - **(400°C, 40 hours, Nitrogen Cover)**



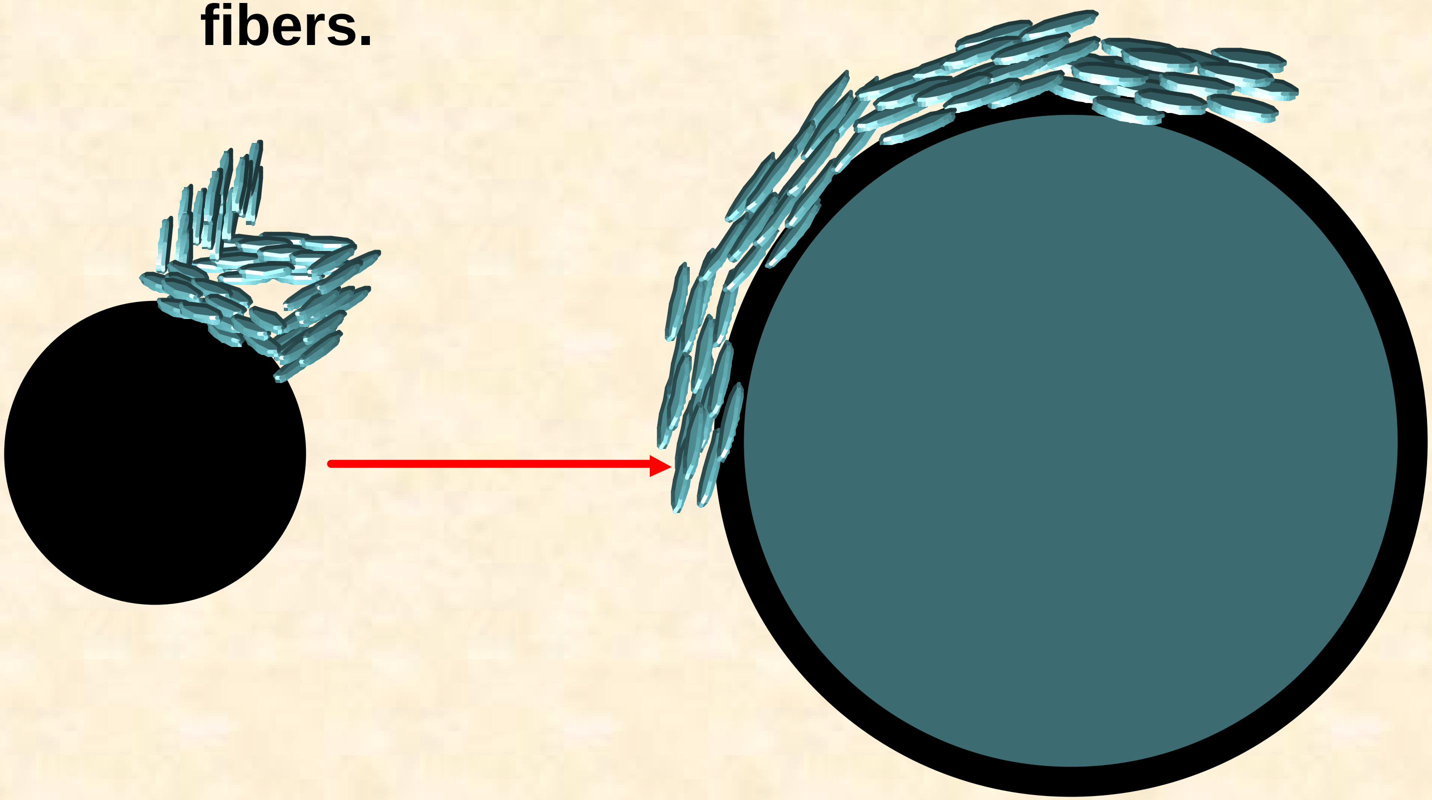
Traditional Carbon Foams - Manufacture

- **Traditional “Blowing” techniques**



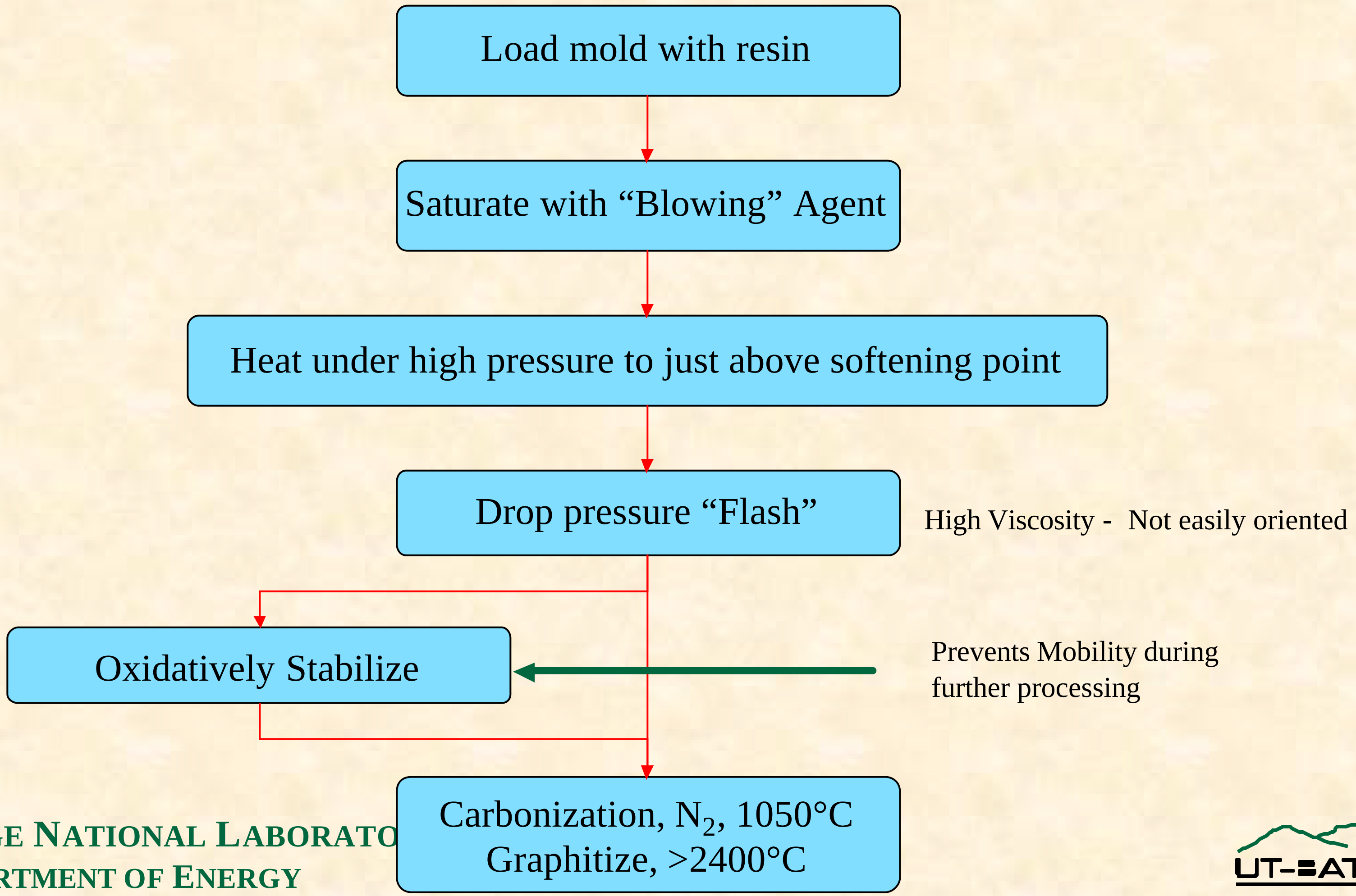
Bubble Growth

- **Bi-Axial Extension causes liquid crystal to orient parallel to surface of bubble**
  - **similar to extension caused during formation of fibers.**



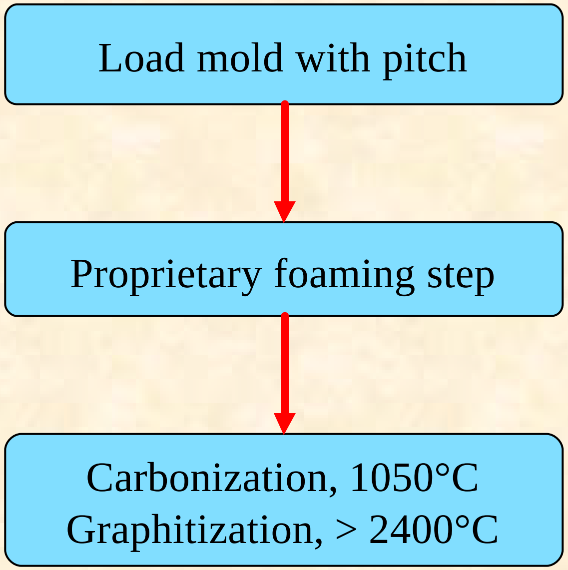
Traditional Foaming Problems

- **Traditional "Blowing" techniques**

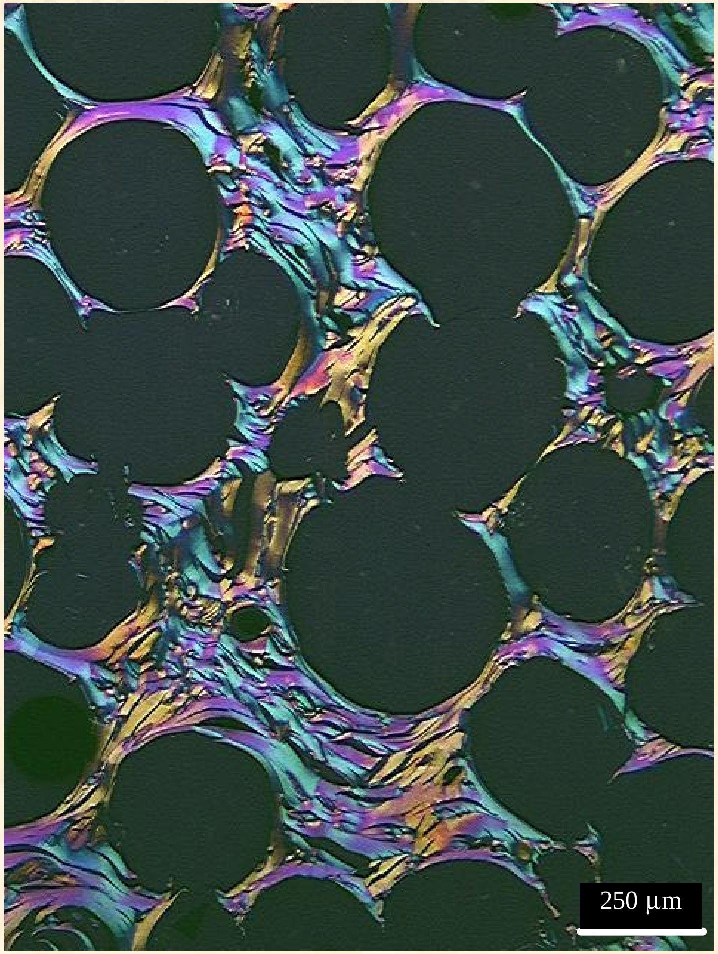


Novel Production Method

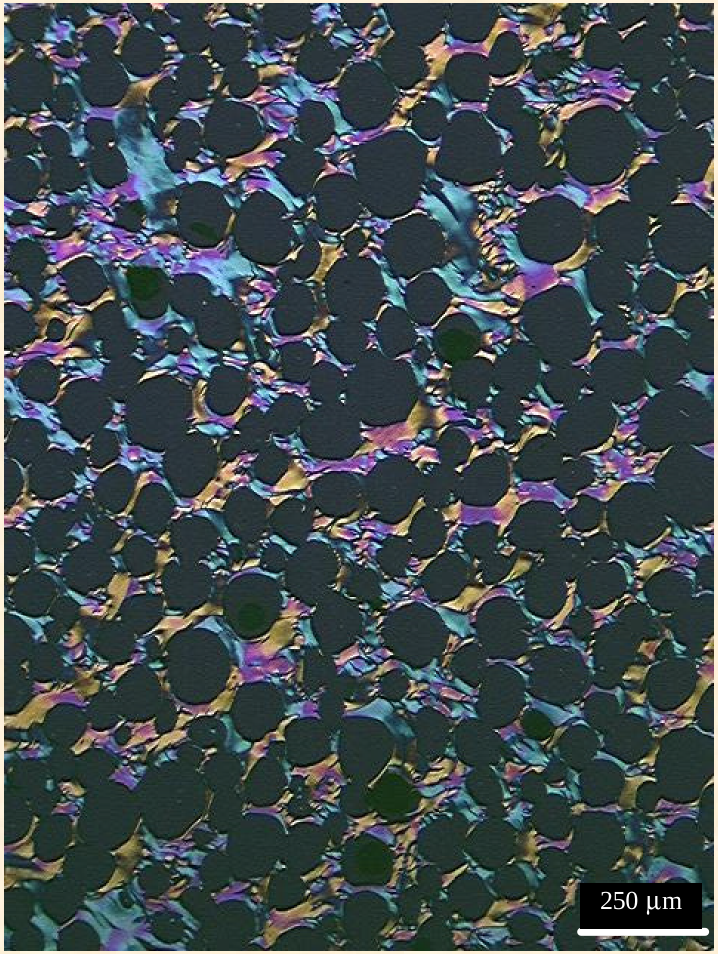
- **Proprietary method (many patents filed)**
- **Unlike traditional foaming techniques**
  - **No blowing (flashing) or pressure drop required**
    - **saves steps**
  - **No oxidative stabilization required**
    - **improved thermal properties**



Microstructures

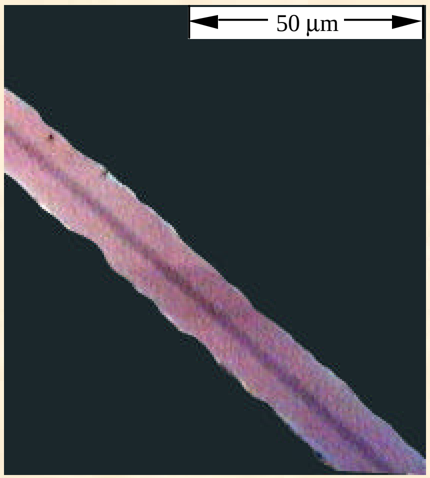


AR Pitch Derived Foam

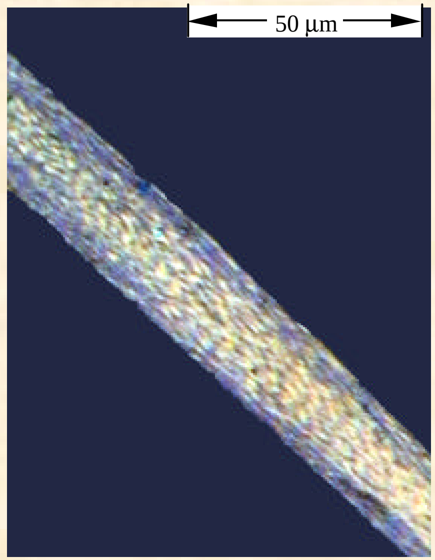


Conoco Pitch Derived Foam

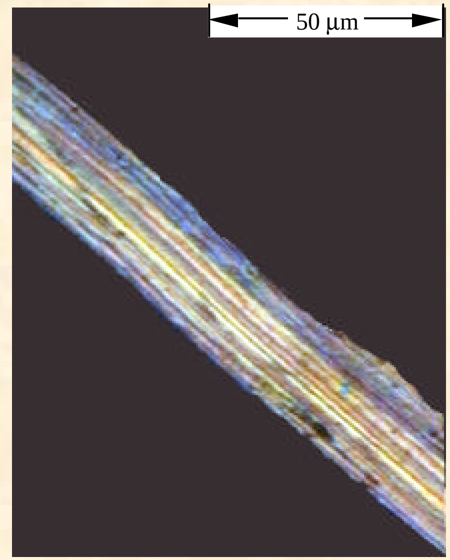
Ligaments vs Fibers



PAN Fiber
2800°C



P-55 Fiber
2800°C

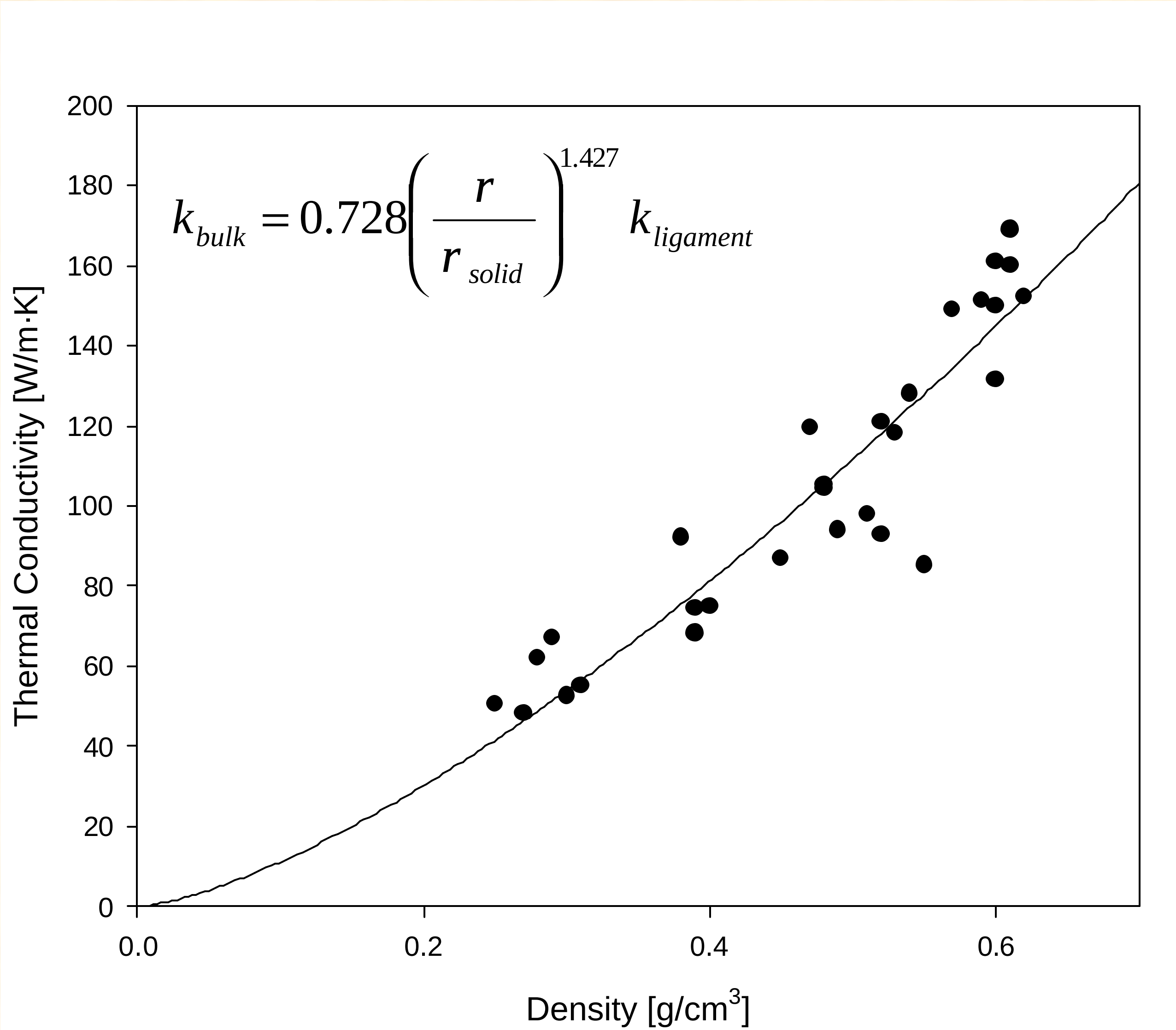


DKD-x® Fiber
2800°C

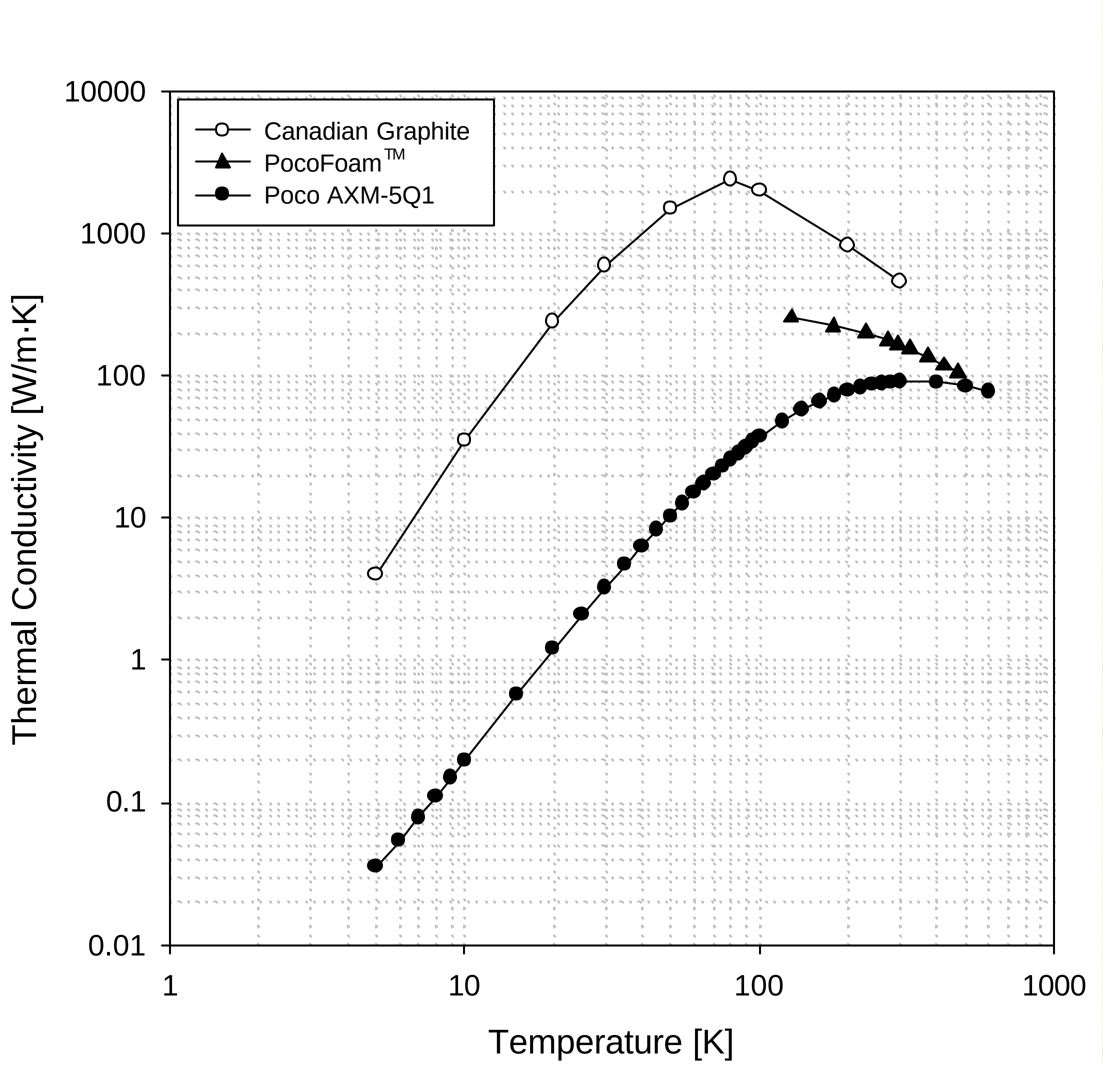
ORNL Graphite Foam
2800°C

Larger isochromatic regions (yellow and blue) indicate better crystal alignment and higher thermal conductivity

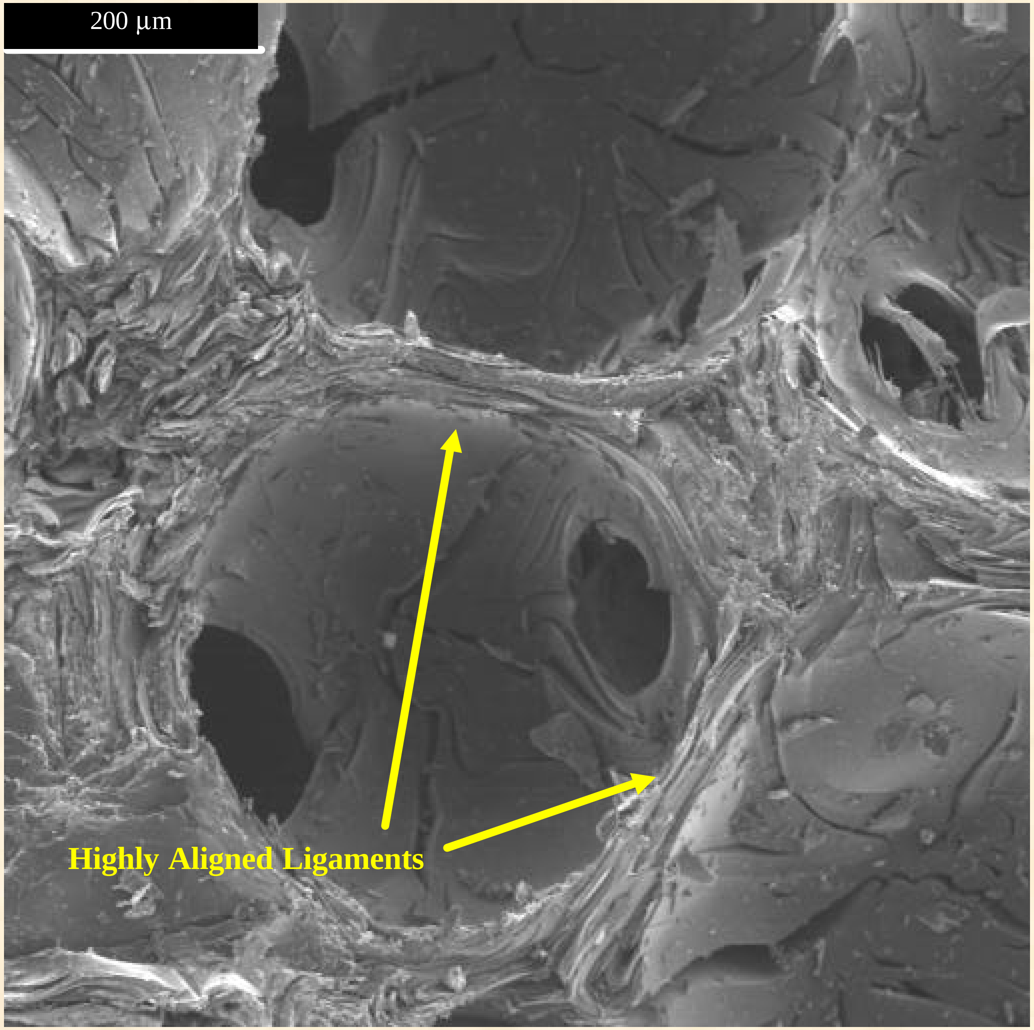
Thermal Conductivity vs. Density



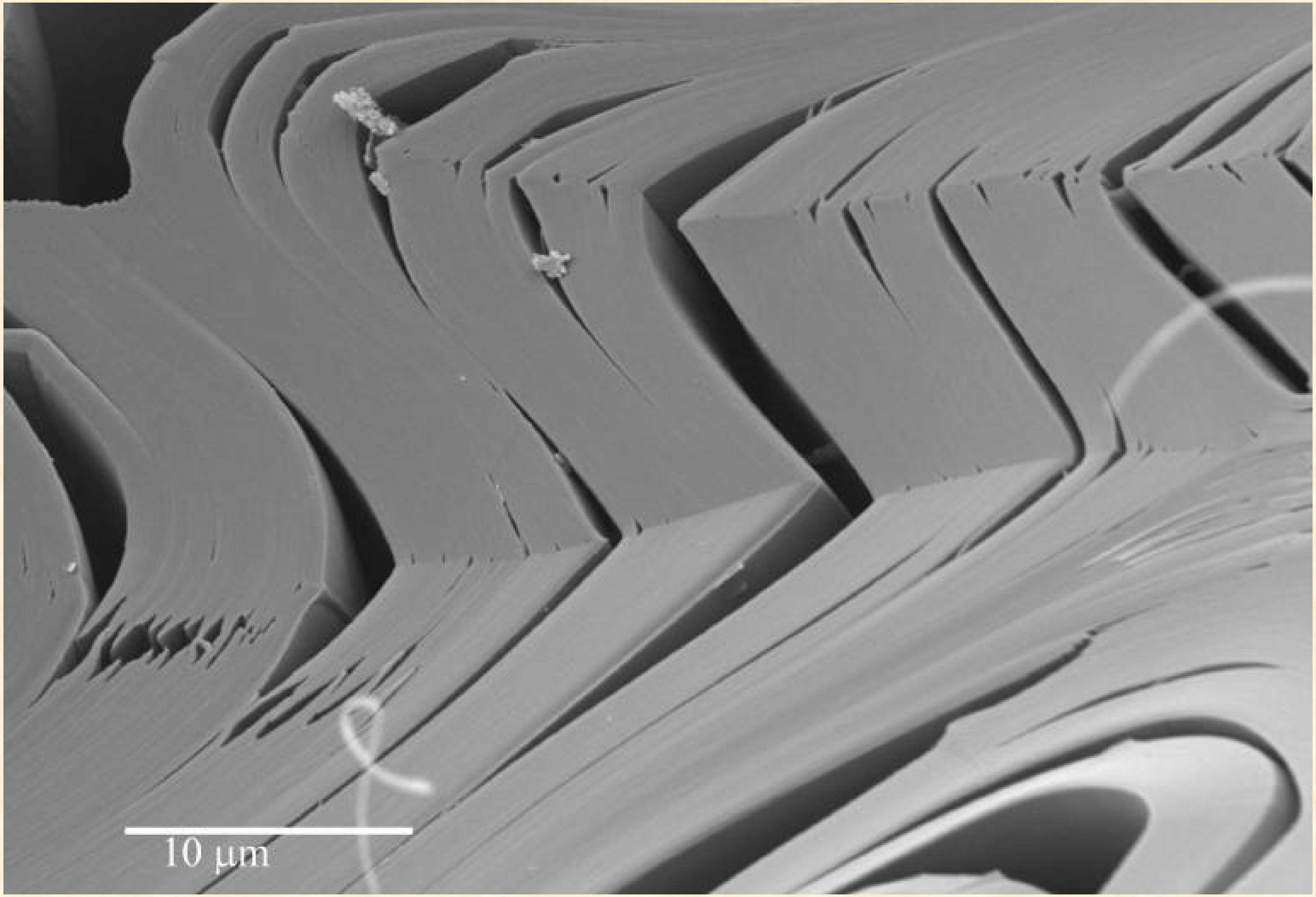
Thermal Conductivity vs. Temperature



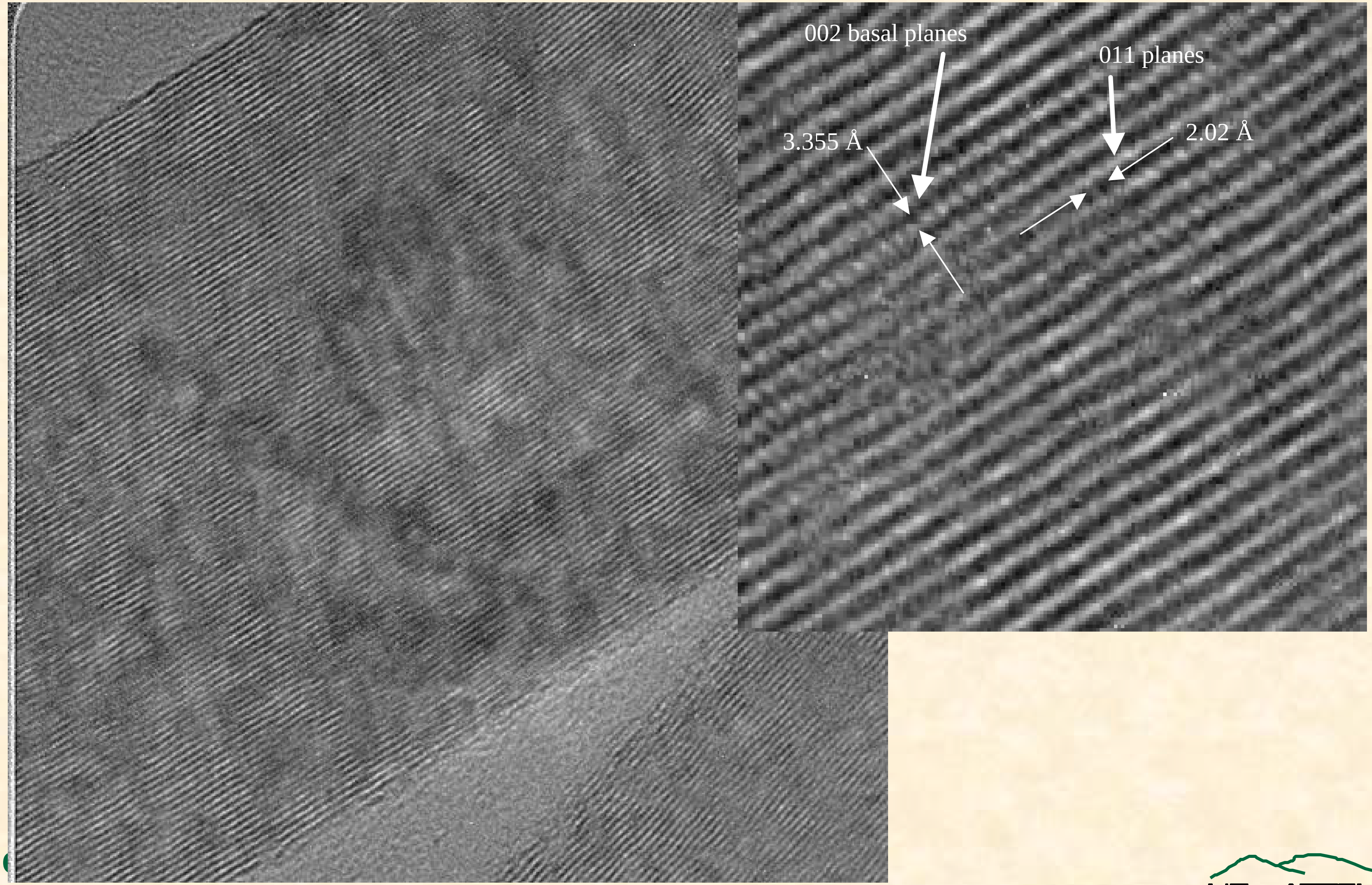
Graphitic Structure - AR Mesphase



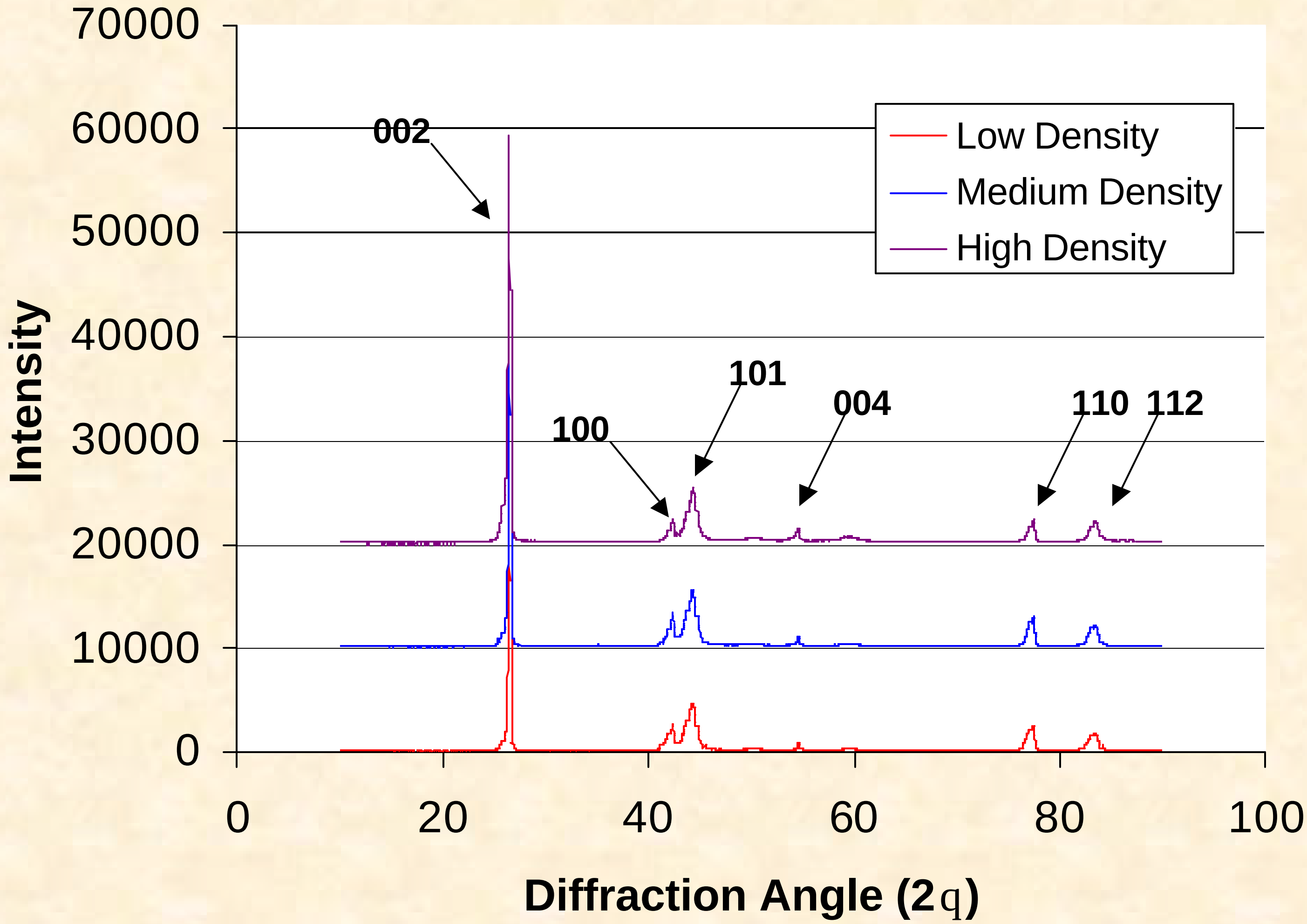
Thermal Conductivity vs. Density



Highly Aligned Graphite Structure



X-ray Analysis

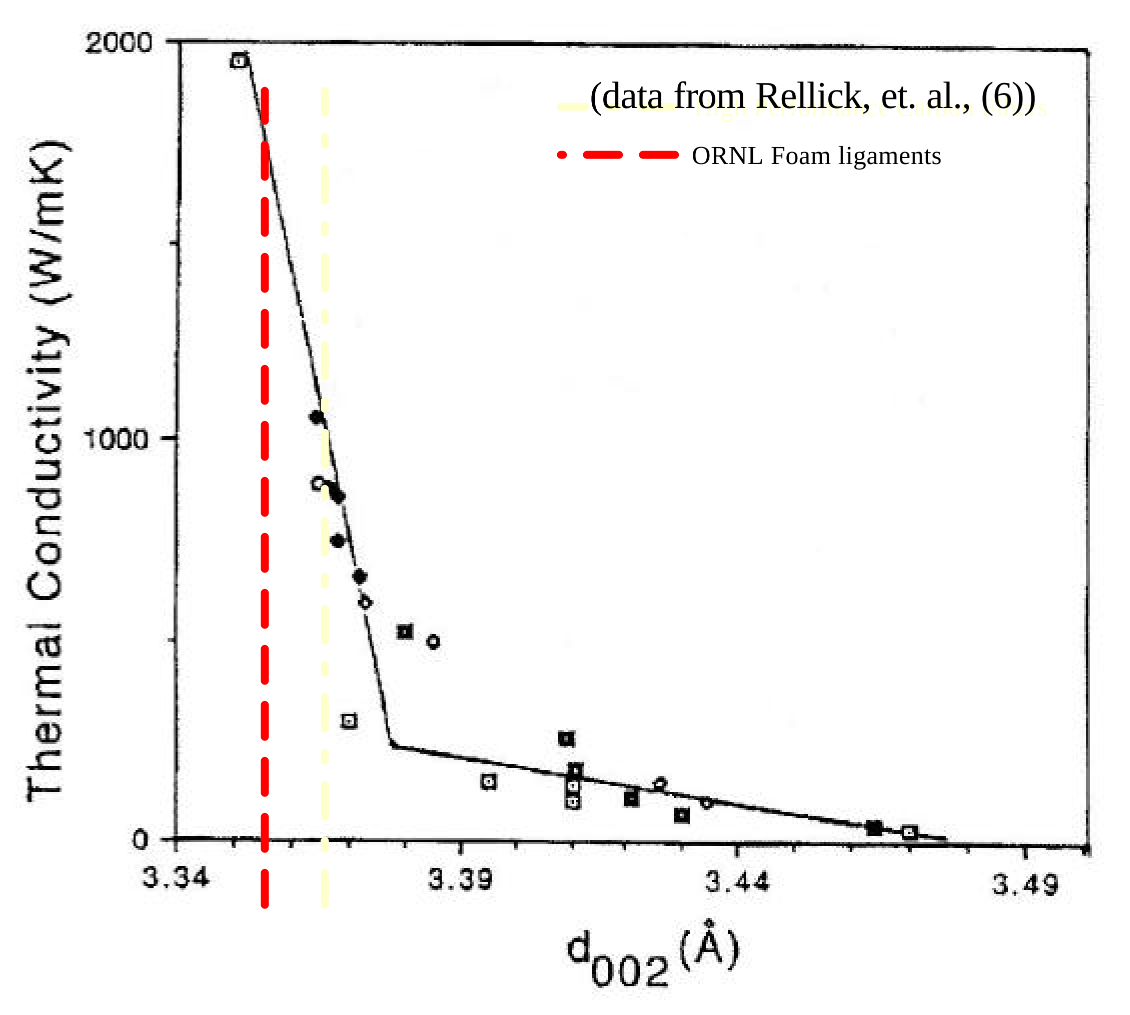


Comparison of Crystal Parameters to Fibers

	Density [g/cm^3]	d_{002} [nm]	$L_{c,002}$ [nm]	$L_{a,110}$ [nm]
Low Density Foam	0.29	0.3356	152	28
Med. Density Foam	0.51	0.3356	208	29
High Density Foam	0.64	0.3356	437	28
K1100 Fiber	2.20	0.3366	51	85

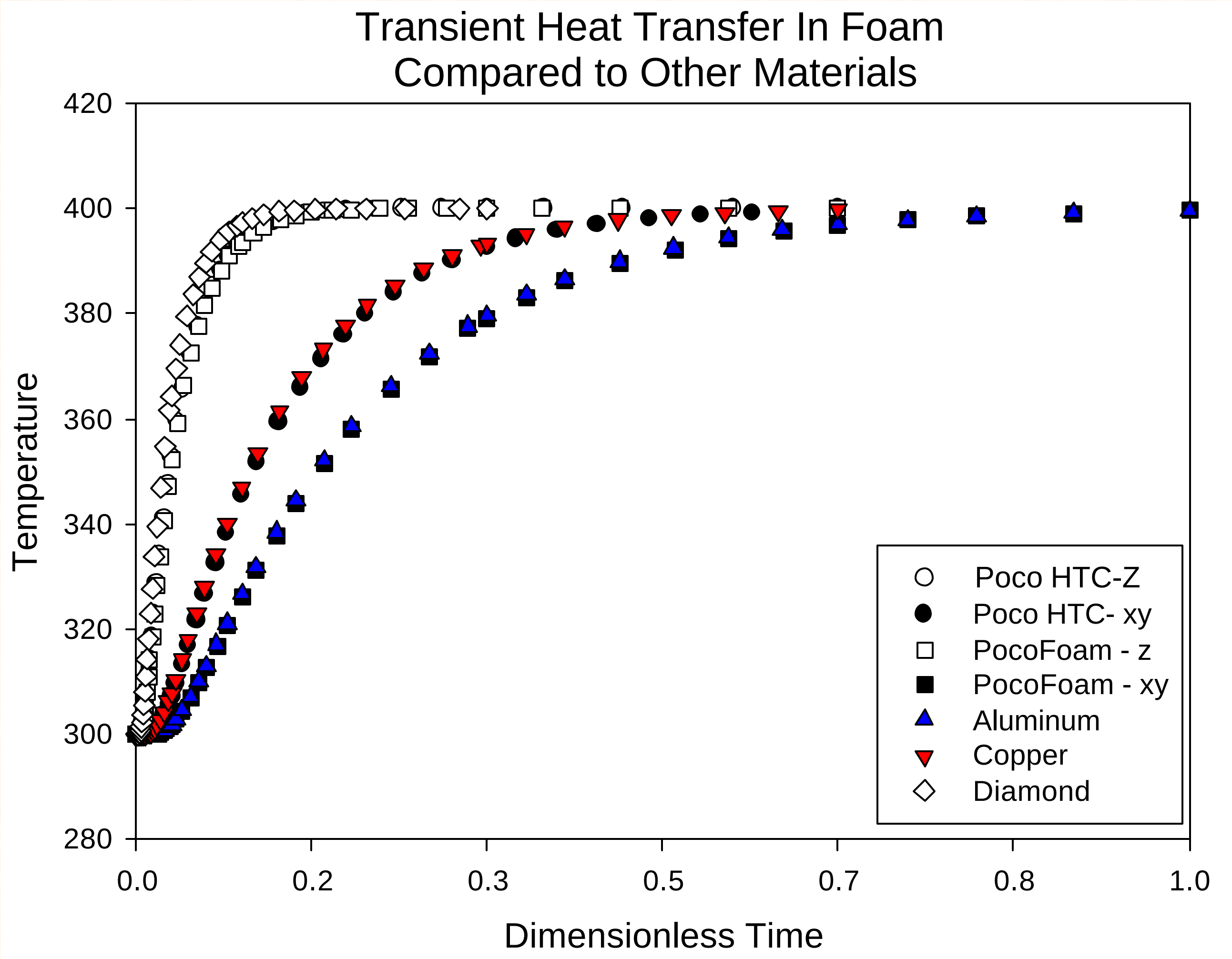
* Turbostratic graphite = >0.3440 nm
Single crystal graphite = 0.3354 nm

Crystal Effects on Thermal Conductivity



Thermal Response Time

- **Thermal response time of ORNL Graphite foam is similar to that of Diamond (less than 3% difference)**
- **Yet exhibits a surface area thousands of time greater than diamond**



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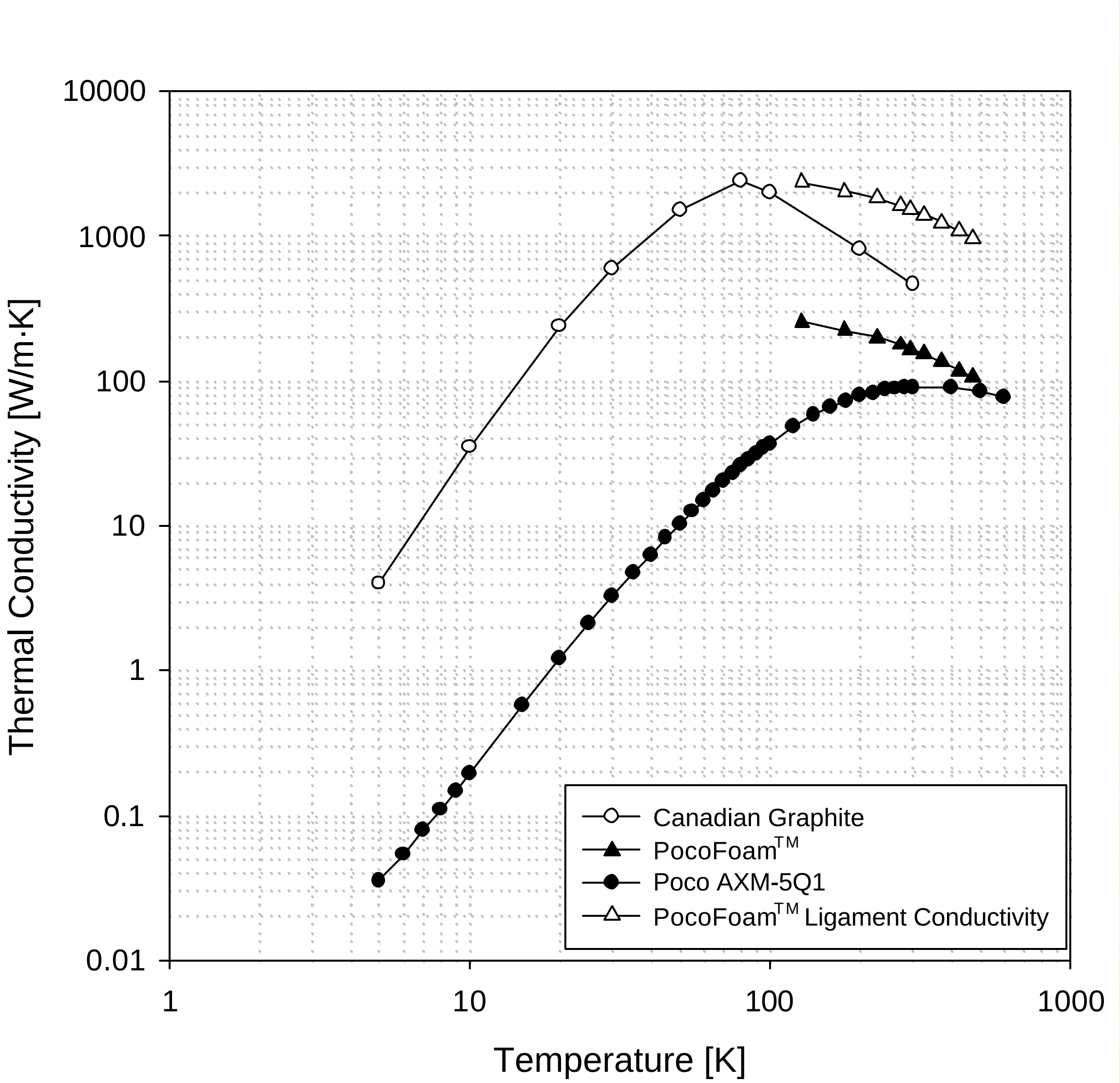
Thermally Conductive Foams

	Relative Density [%]	Ligament Conductivity [W/m·K]	Bulk Conductivity [W/m·K]
Aluminum Foam	25	180	~15
Copper Foam	25	400	~35
Foam with DKD-x type ligament	25	640	~56
ORNL Graphite Foam	25	1700	>170

Thermal Conductivity vs. Temperature



Mechanical Properties

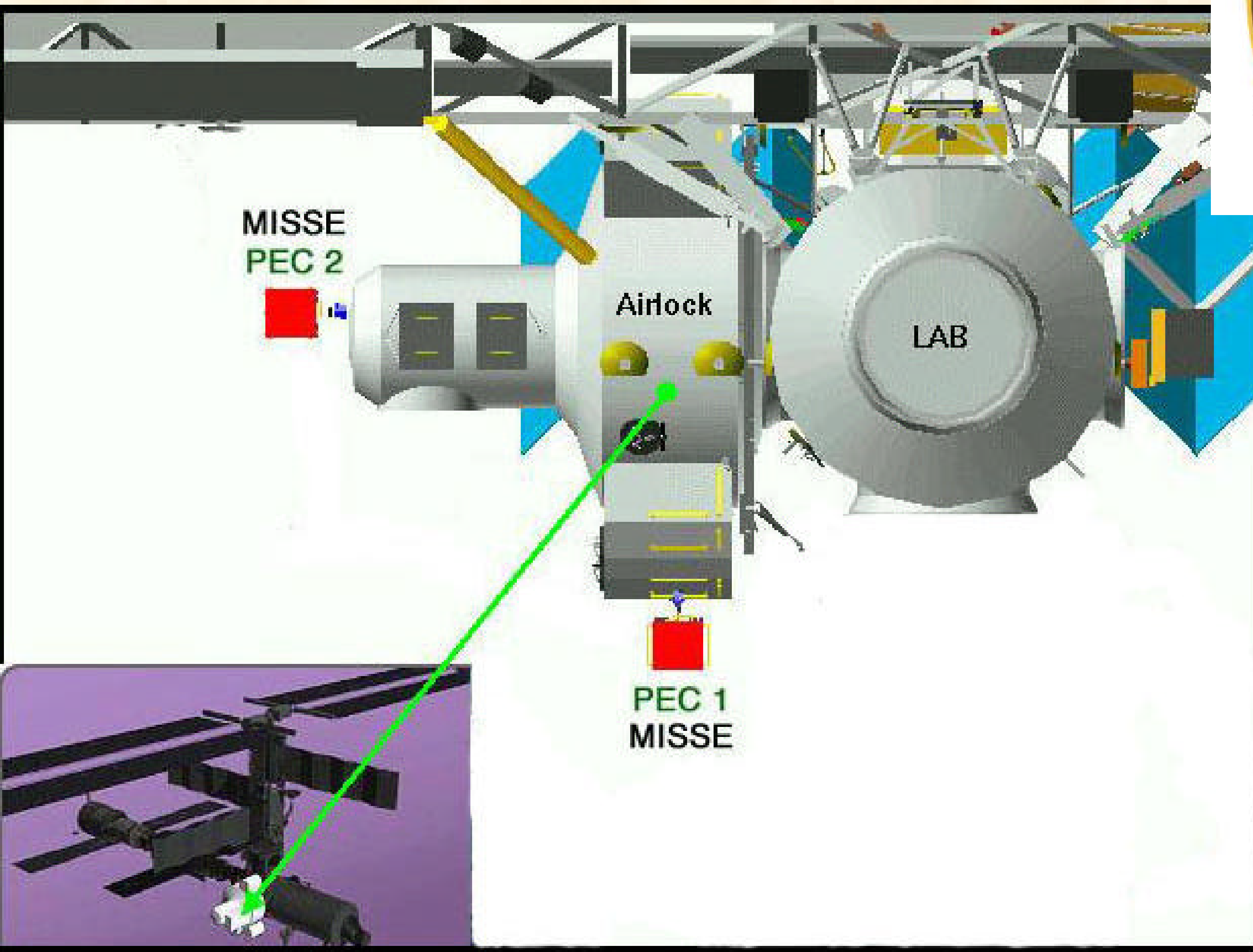
	Bulk Density	Strength - s				Modulus - E			
		Tensile	Flexural	Comp.	Shear	Tensile	Flexural	Comp.	Shear
	g/cc	psi	psi	psi	psi	ksi	ksi	ksi	ksi
As Formed	0.29	66	--	150	--	--	--	--	--
As Formed	0.51	170	--	430	272	58	--	--	49

Potential Applications of Graphite Foam

- Power electronics cooling
  - demonstrated 10x cooling potential compared to traditional heat sinks
- Fuel cell inlet air humidification
- Transpiration/evaporative cooling
  - electronics and leading edges
- Radiators
  - heavy vehicles, racing vehicles, aircraft, fuel celled vehicles
- Nuclear reactor core
- Composite materials
- Brake and clutch cooling
- High temperature friction applications
- Acoustics

Space Qualification?

MISSE
Materials International Space Station Experiment



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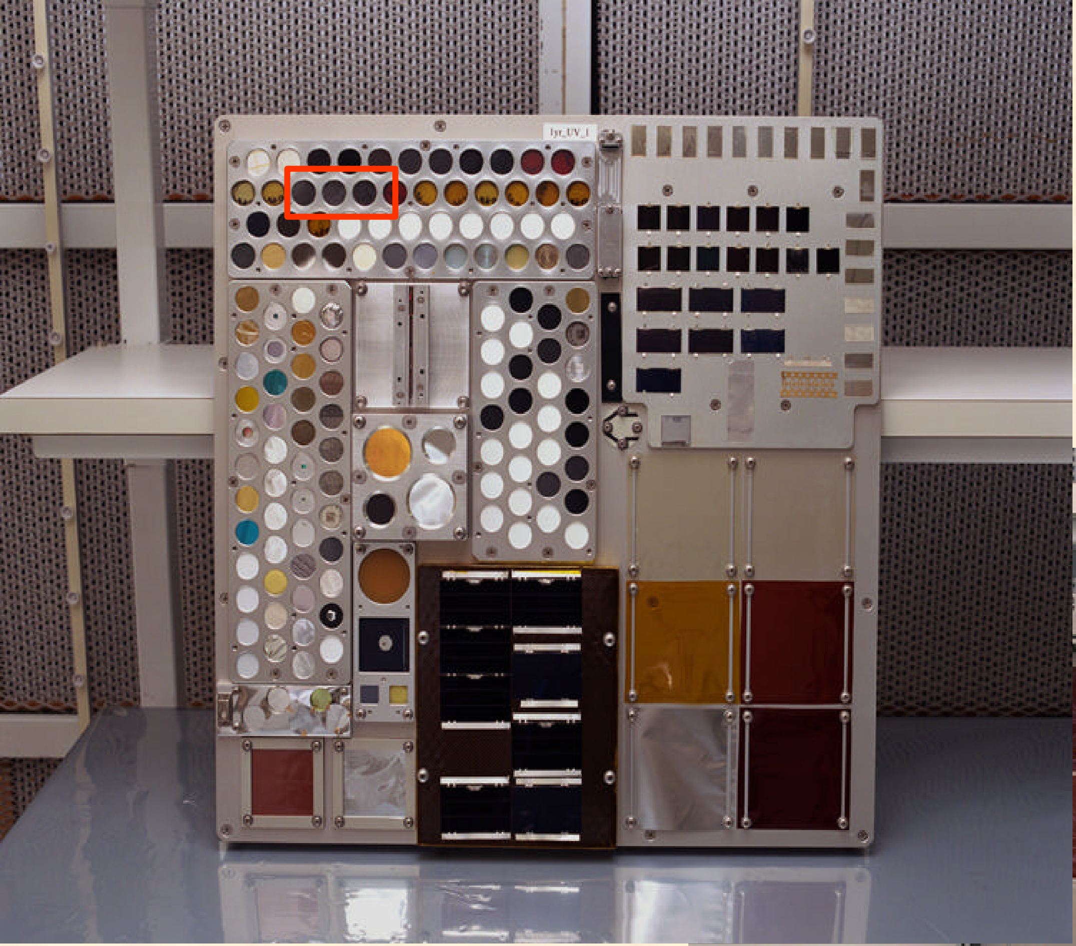
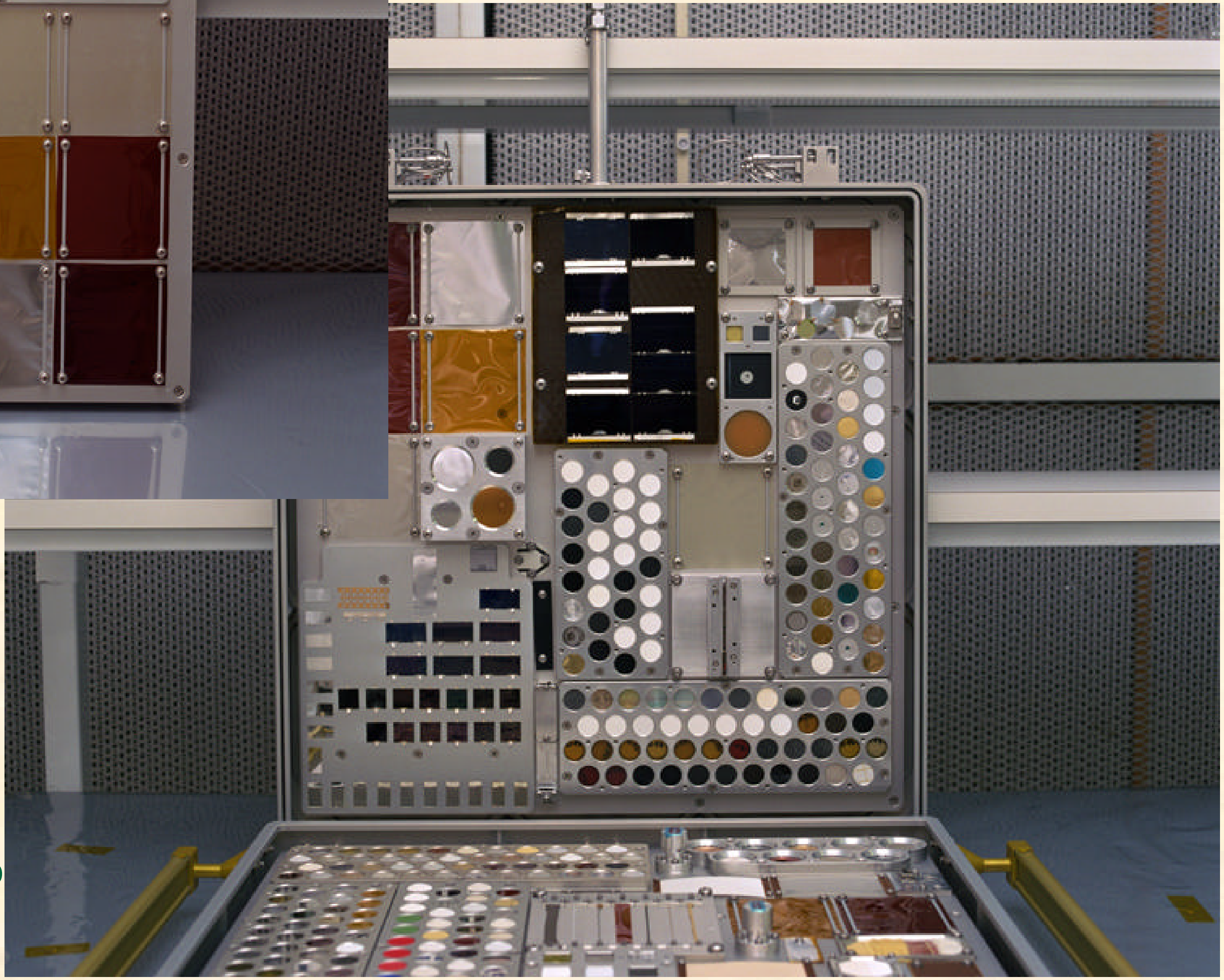


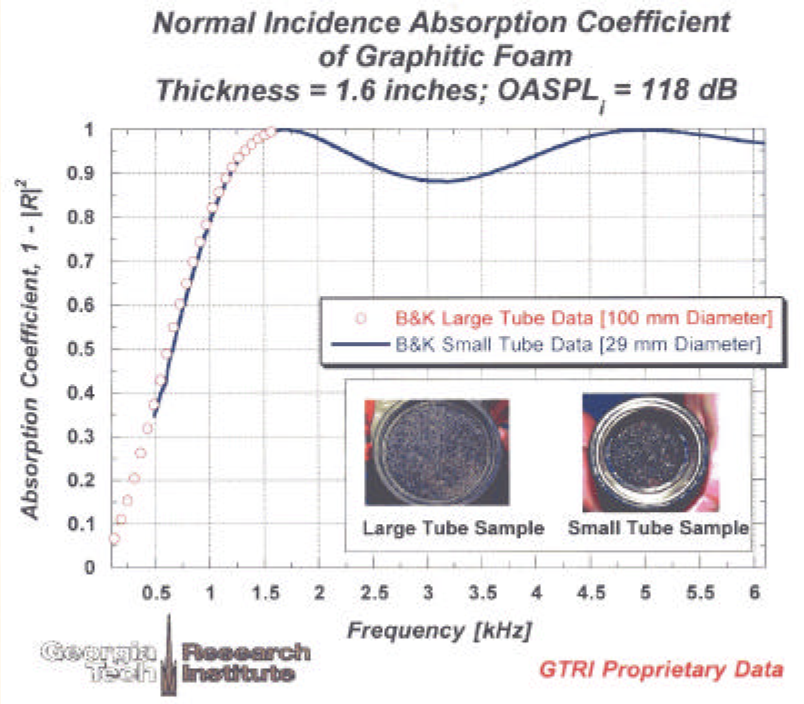


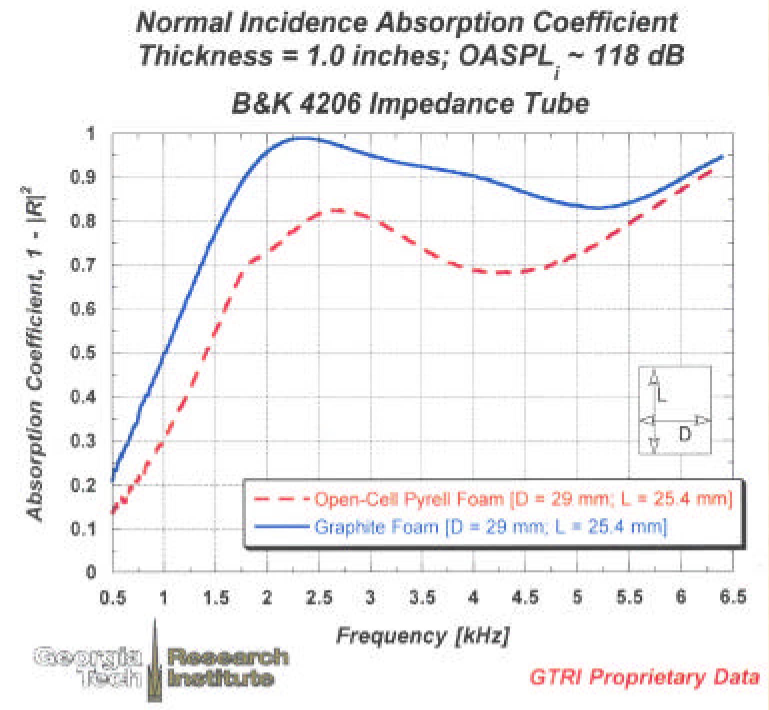
WPAFB, ORNL, and WVU carbon and graphite foams

Acoustic Absorption

Acoustic Absorption

- **ORNL graphite foams exhibit excellent acoustic absorption coefficients**
- **These foams performed up to 20% better than open cell Pyrell Foam (typically used in anechoic chambers) at all frequencies tested**





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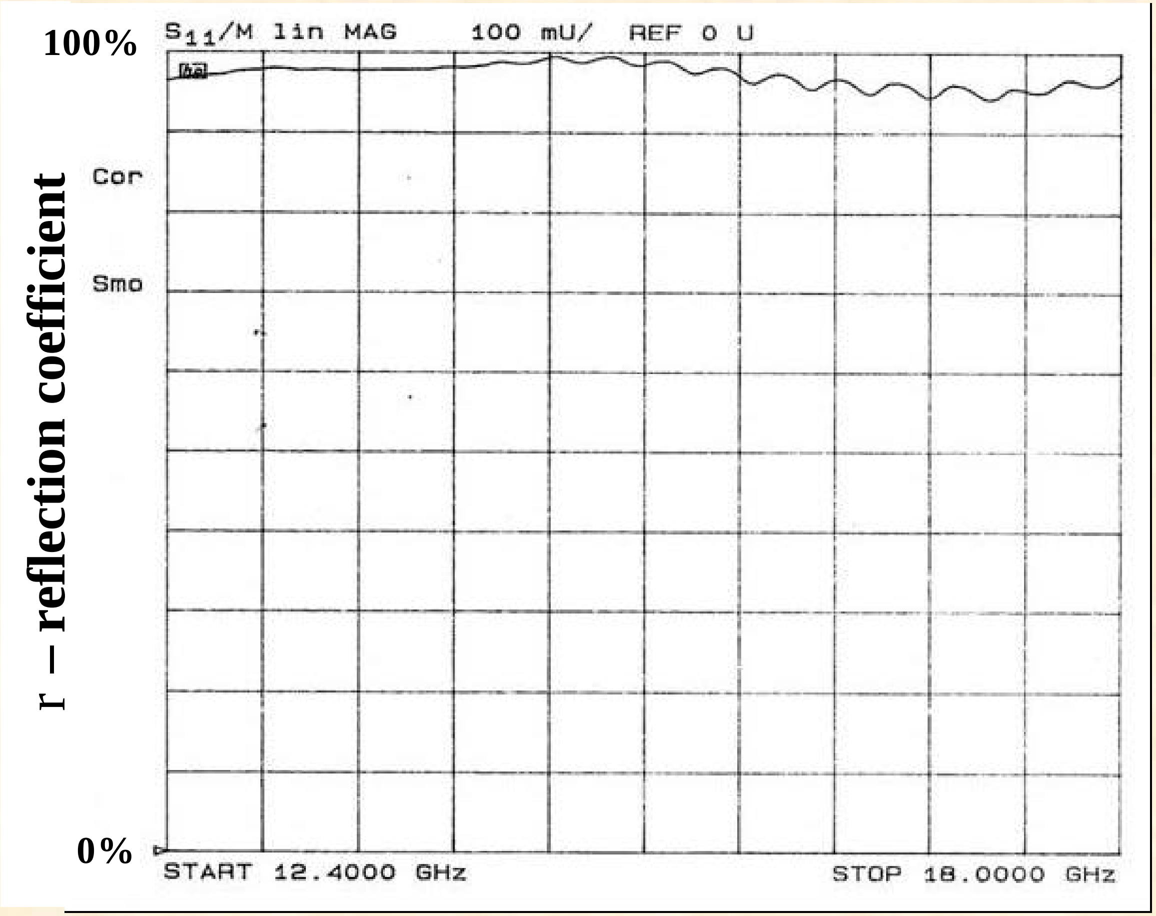
EMI Reflection

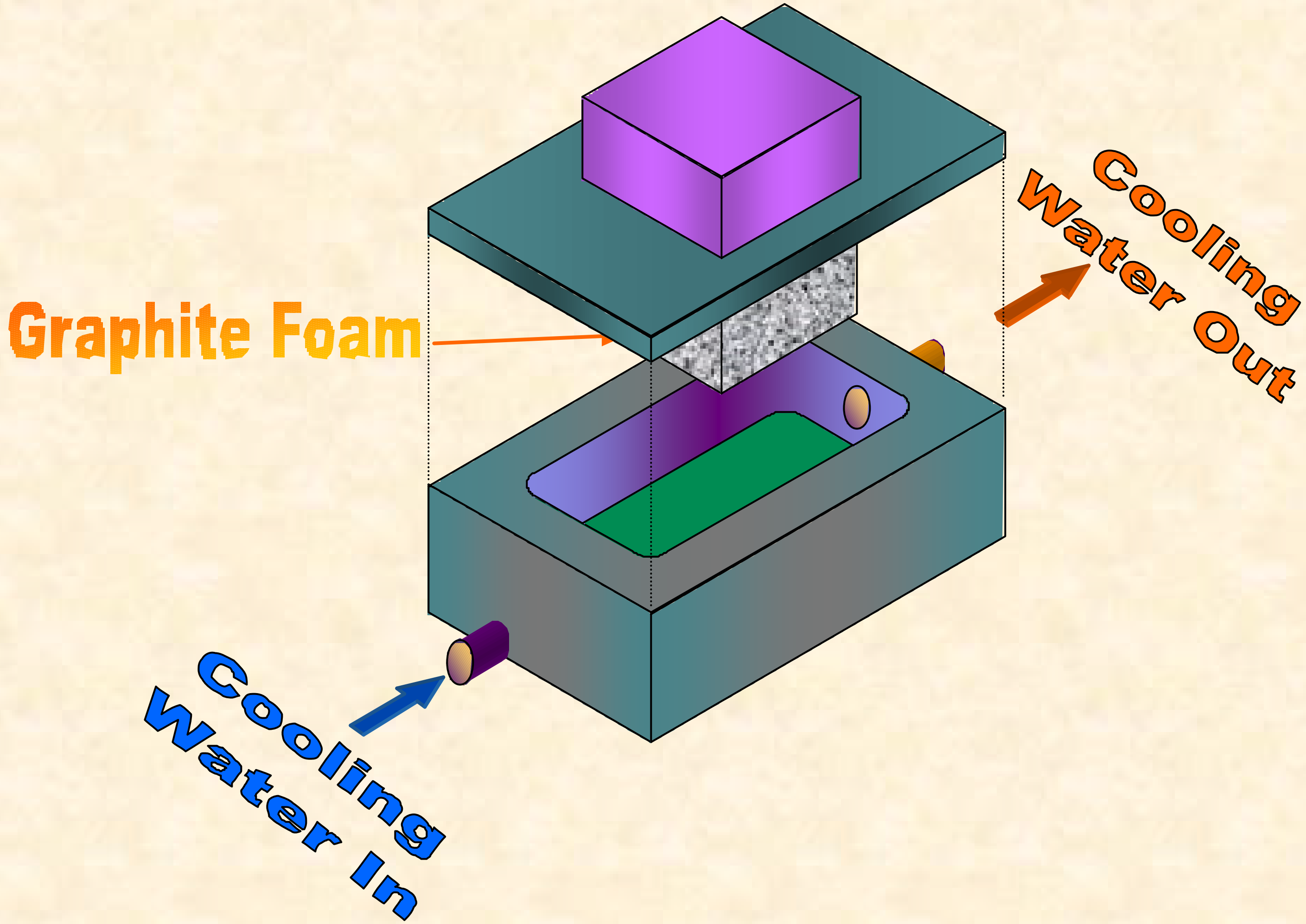
EMI Sheilding

- **ORNL graphite foams exhibit excellent reflection of incident electromagnetic energy**
- **Reflection coefficient rivals that of copper (however at 1/9th the mass)**

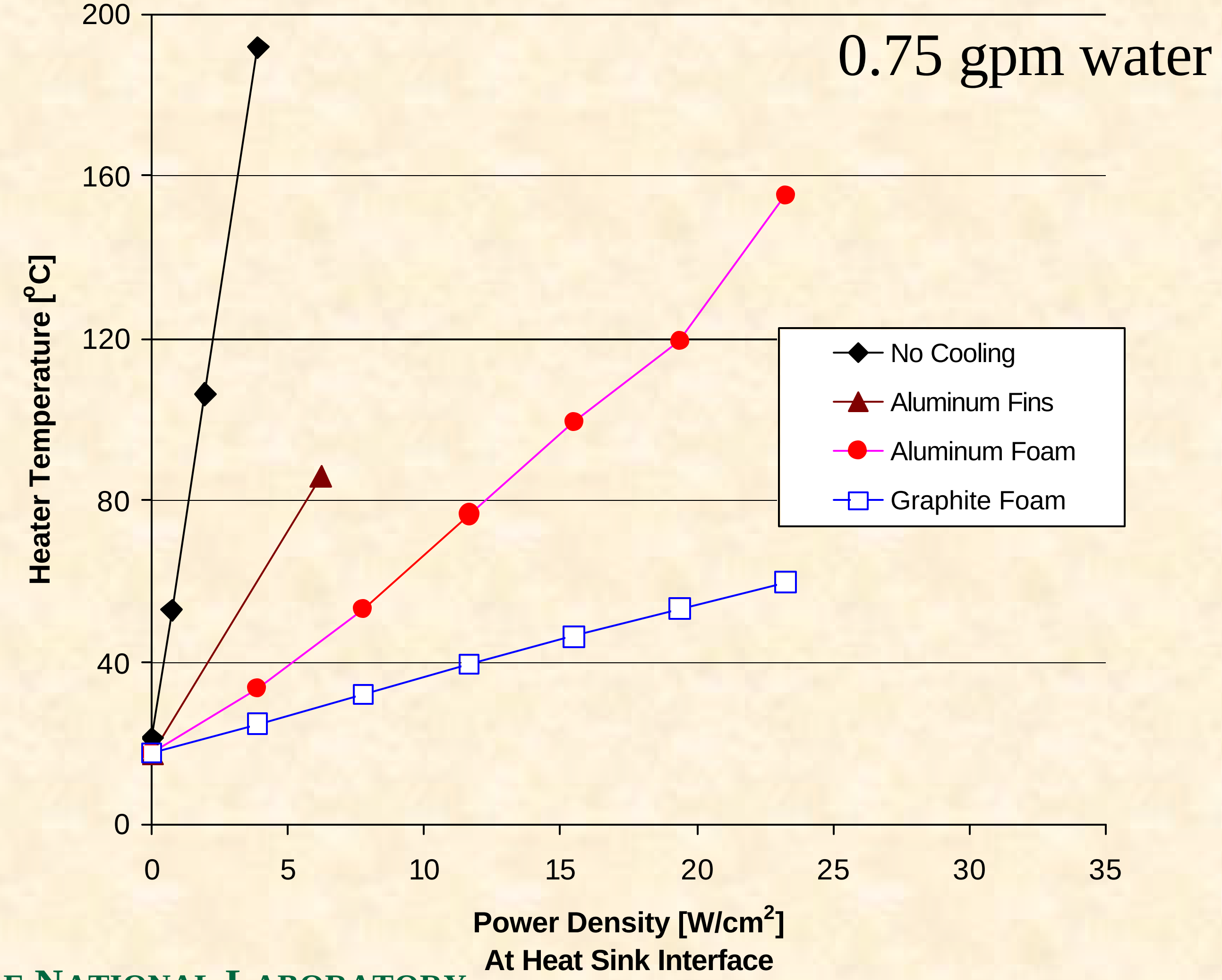


Power Electronics Cooling

Model Heat Sink

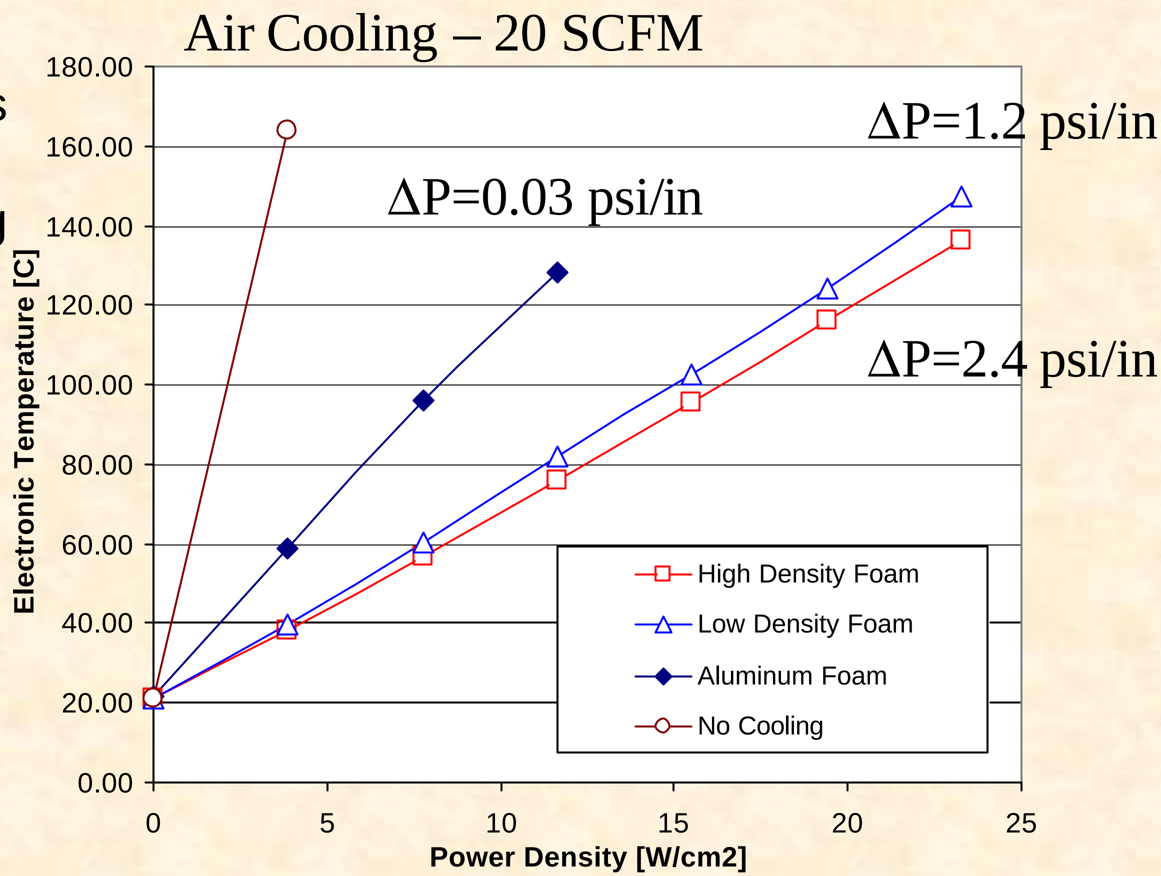


Electronic Temperatures vs. Power Density



Excellent performance of foams with air

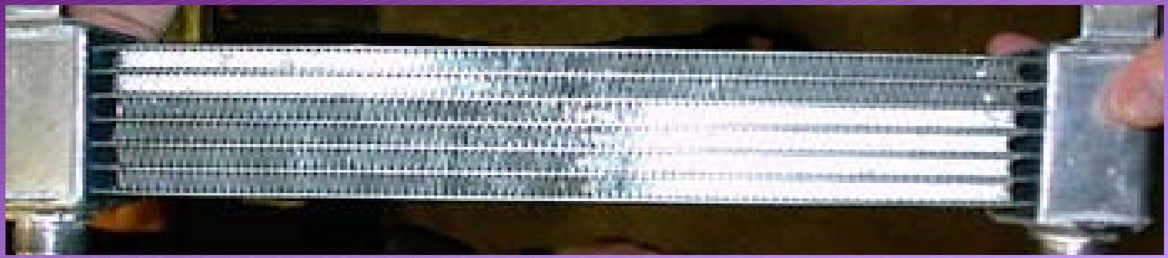
- Foams have been demonstrated to reduce temperatures significantly compared to existing systems
- However, pressure drops were exceedingly large (with both air and water)
- Corrugations have been shown to reduce pressure drop by 10x



Radiators

Graphite Core rejects 34% more heat

C&R Aluminum Core



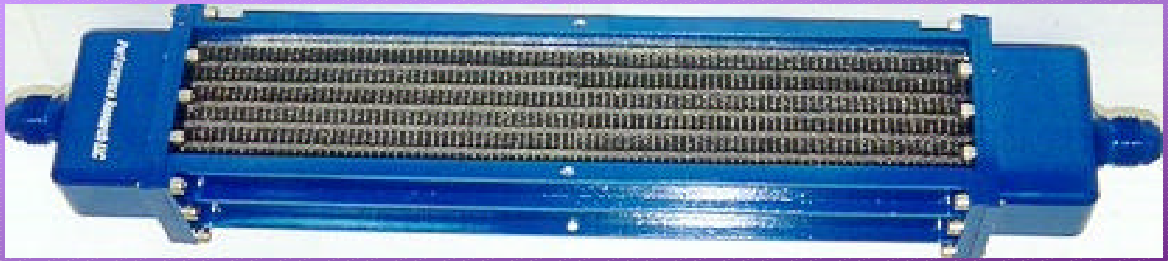
Louvered Aluminum Fins

Core size = 12 in. x 3 in. x 1.5 in.

Overall Surface Area = 0.71 m^2

Heat Dissipation = 6 kW

Graphite Foam Core



Machined Carbon Foam Fins

Core size = 12 in. x 3 in. x 1.5 in.

Overall Surface Area = 0.42 m^2

Heat Dissipation = 8 kW

Graphite Core has only 60% of the fin surface area

Foam surface affects heat transfer

- It has been shown that the graphite foam structure at the surface can result in disruption of boundary layer
  - Thompson et al., 2003, Univ. West. Ontario
- This increases mixing and improves local heat transfer coefficient
- In addition, it has been shown that there can be sufficient transpiration of air into the foam at the surface, thereby increasing surface area for heat transfer.

Evaporative Cooling Developed With National Security Agency (NSA)

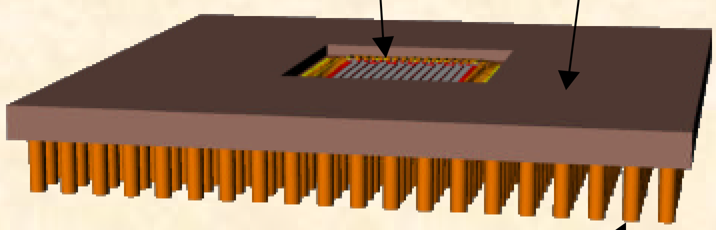
Currently being funded by MDA for Phased Array Radar LRU Modules (T/R Devices)

Standard Chip Packaging

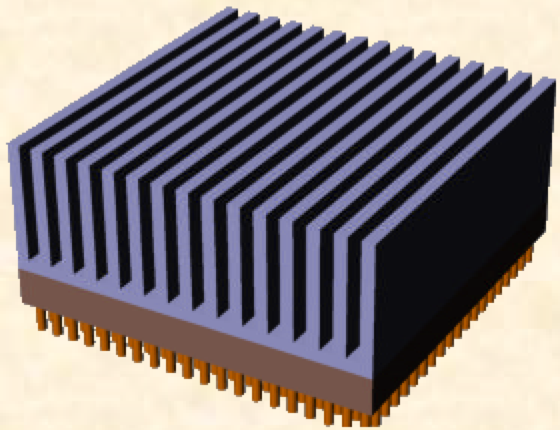
Current designs of IC chips are inefficient and not designed for heat transfer

Integrated circuit placed in a recess

Low conductivity ceramic package yields large thermal resistance

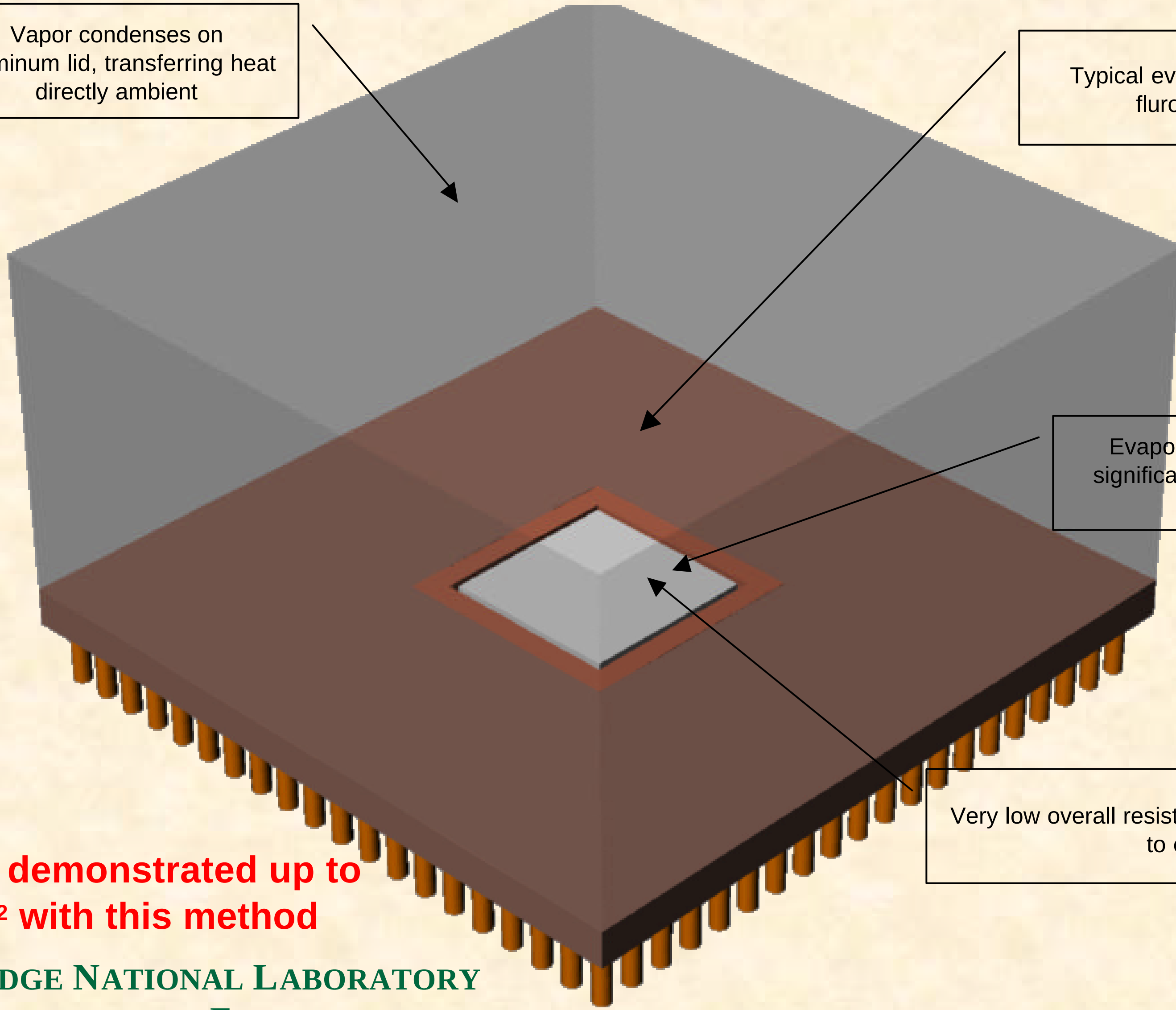


Large overall resistance between chip and heat sink results in most heat going through wire bonds to connecting pins



Very inefficient heat transfer design (many thermal interface resistances) results in high chip temperatures and limits power density

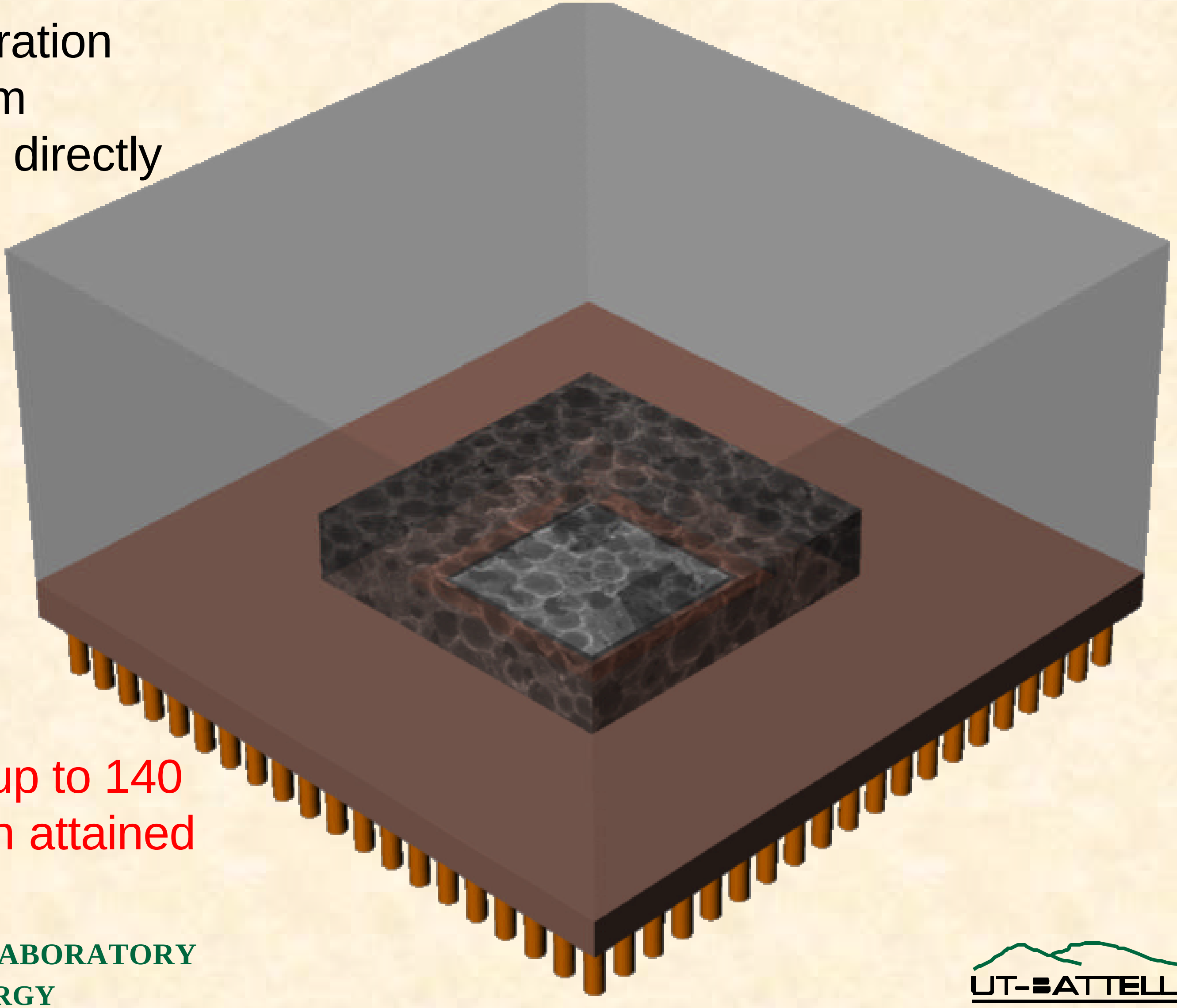
Evaporative Cooling Chamber



NSA has demonstrated up to 28 W/cm^2 with this method

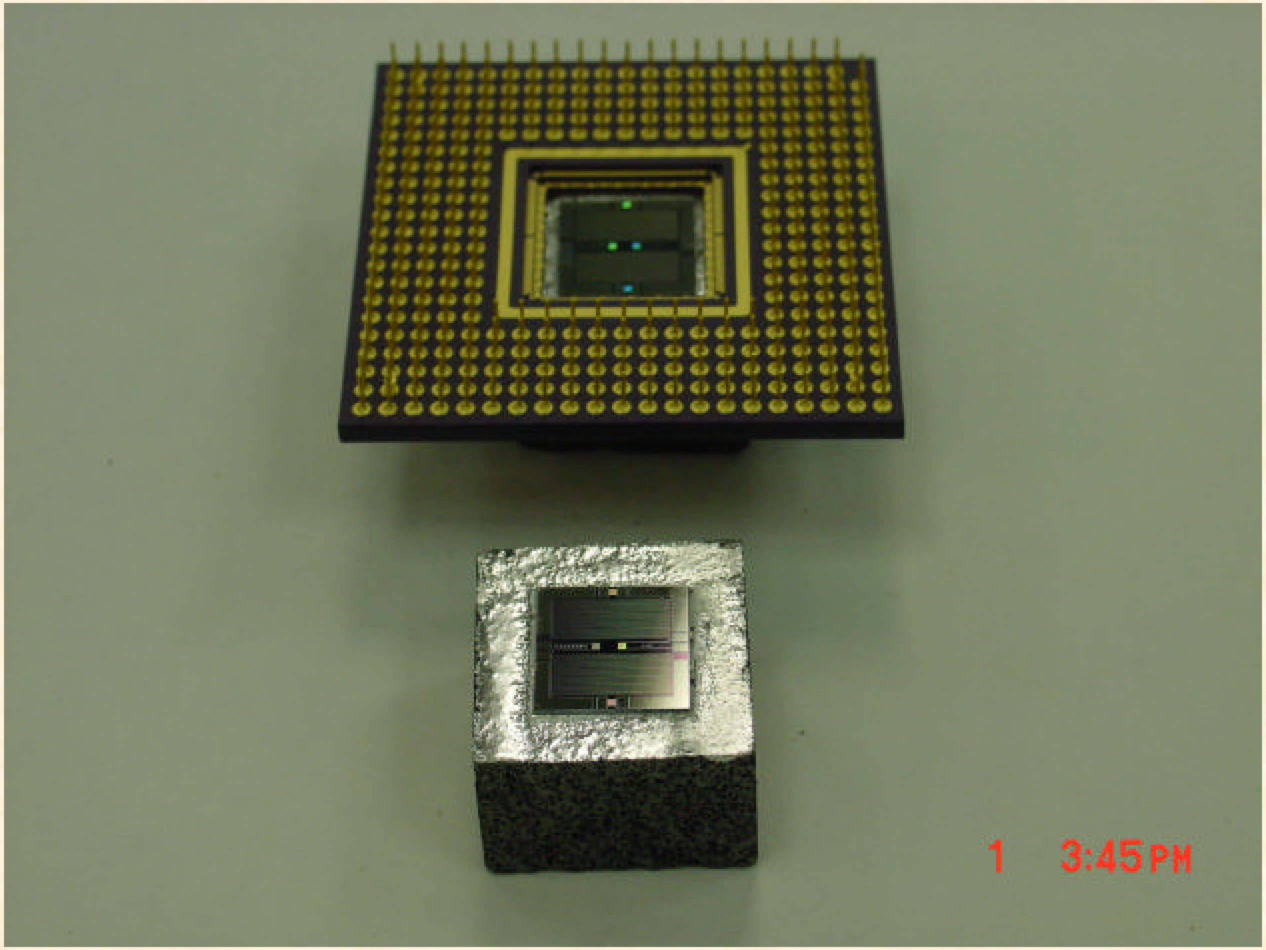
400% Improvement with Graphite Foam

Enhanced evaporation with graphite foam spreader bonded directly to silicon chip



Power densities up to 140 W/cm^2 have been attained

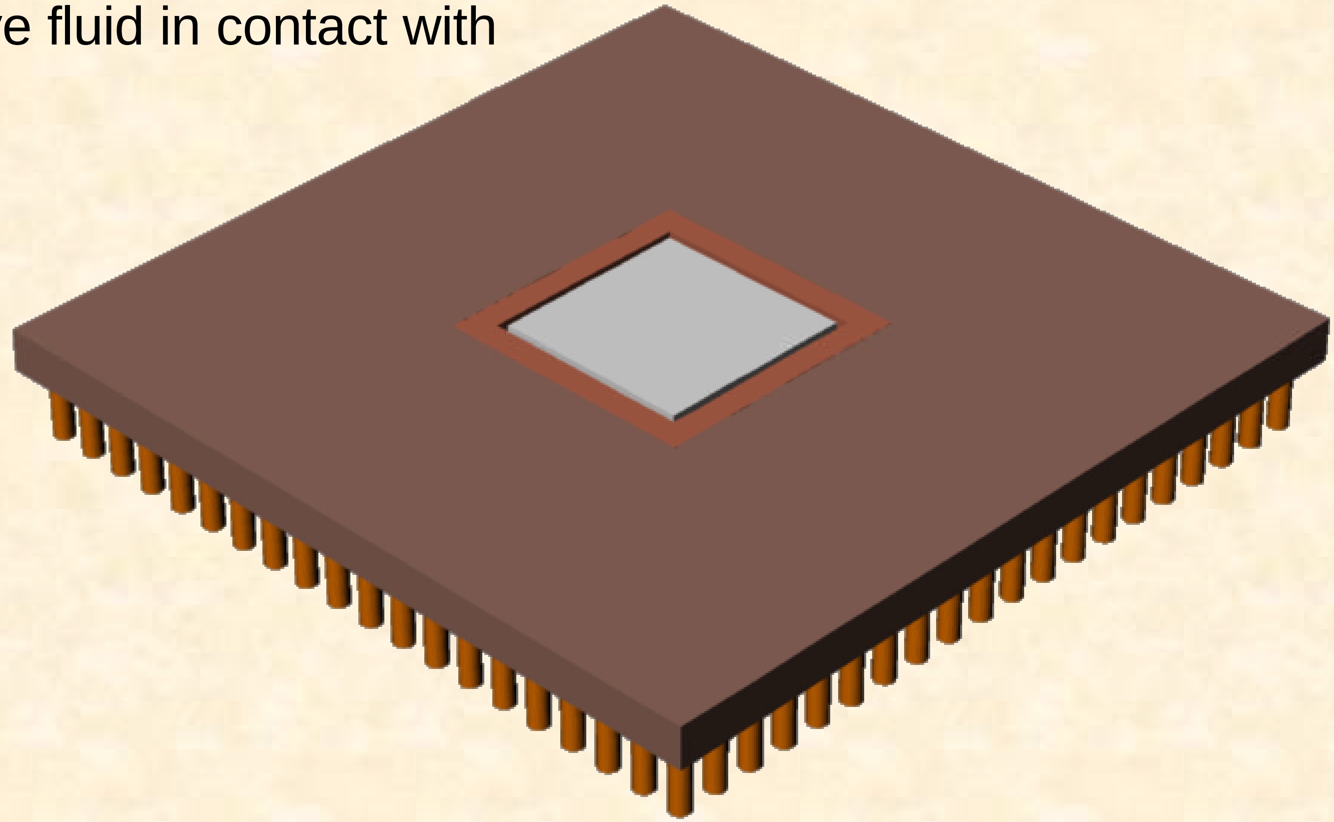
Silicon Chip Soldered to Graphite Foam



Evaporative Cooling

Bare silicon is exposed for directly joining heat sink or heat spreader

Place evaporative fluid in contact with heat sink



Passive Evaporative Cooling

- **Working system**
- **Very high power densities achievable**
- **No active cooling**
  - **No fans**
  - **No water cooling**

100 W/cm^2

Computer Chip Cooling

- **A prototype heat sink for major chip manufacturer has been made**
- **Limit of thermal resistance of 0.39 C/W at fan speeds of 3500 rpm was assumed**
- **Our design exhibited a 30% reduction in resistance with 50% reduction in weight**
  - **This design did not use evaporative cooling**
  - **Evaporative cooling designs are anticipated to be more efficient**

High Temperature Friction Components

High Temperature Frictional Studies

- **It was thought that a densified version of the foam would provide superior frictional performance than existing carbon-carbon due to the very high out of plane thermal conductivity**
- **Samples were densified with a naphthalene precursor and subsequently graphitized, thereby increasing density by factor of 2.**

Excellent wear rates

Test	Specimen		Friction Coefficient	Wear Rate (mm^3/Nm)
I	Pin	Densified carbon foam	0.27 ± 0.001	6.5×10^{-6}
	Disk	Densified carbon foam		1.2×10^{-5}
II	Pin	Densified carbon foam	0.22 ± 0.001	5.6×10^{-6}
	Disk	Ti-6Al-4V		N.M.
III	Pin	440 SS	0.35 ± 0.004	2.8×10^{-6}
	Disk	Ti-6Al-4V		1.4×10^{-4}
IV	Pin	Teflon	0.29 ± 0.001	6.1×10^{-4}
	Disk	Ti-6Al-4V		N.M.

Conclusions

- **Graphite foam represents an enabling technology for novel heat management designs**
- **Most applications will require a “blank sheet” approach to thermal design**
- **There are many applications were multi-functionality of the foams will allow new solutions**

Acknowledgements

- **Lynn Klett, Claudia Walls, April McMillan, Mike Trammell, Nidia Gallego, Tim Burchell**
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- **NSA – Laboratory for Physics Sciences**