

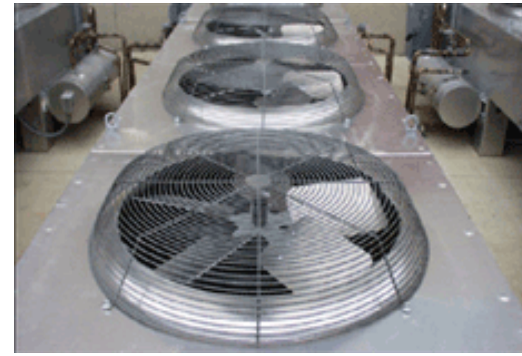

Electronics Cooling: Chip to Power Plant

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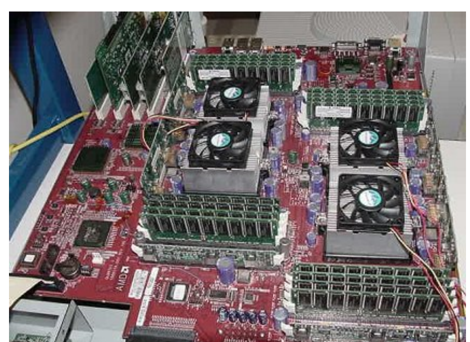
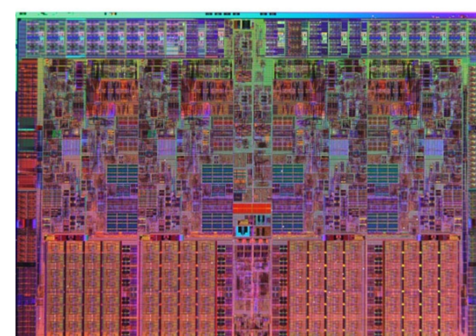
ARPA-E, March 2012

Why is this interesting?

- Electronic systems have some of the highest power densities ordinarily encountered in industry
  - Values range from ~30W/cm^2 for garden variety microprocessors to 2.5 kW/cm^2 for power electron tubes
  - The local heat flux in power laser diode stripes, and the channels of deep submicron CMOS transistors, can be much higher
    - At these dimensions Quantum mechanical effects dominate heat transfer
    - Diamond is used for heat spreaders
- Electronics is a very cost sensitive industry
- Electronic devices want to be as compact as possible

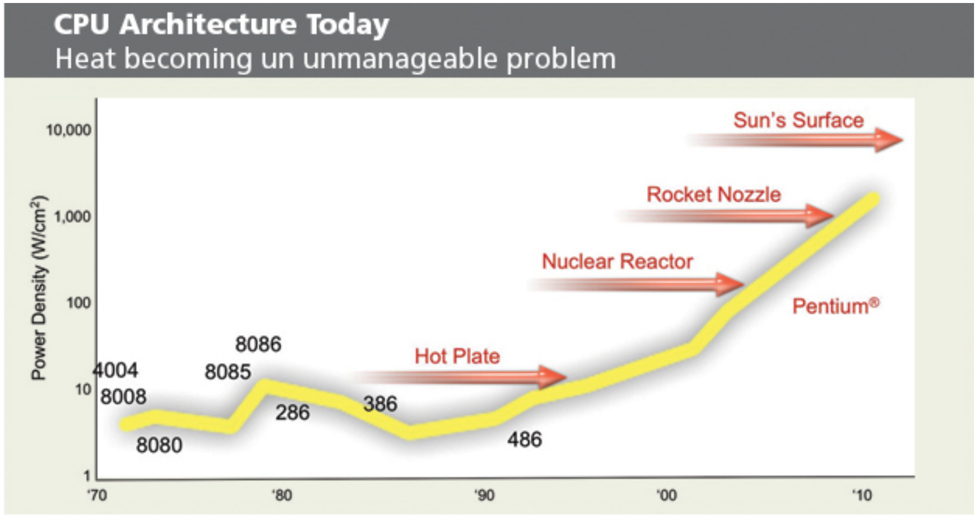
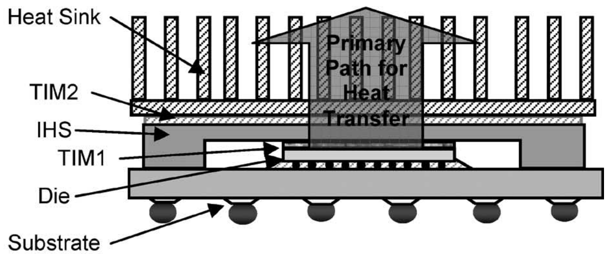
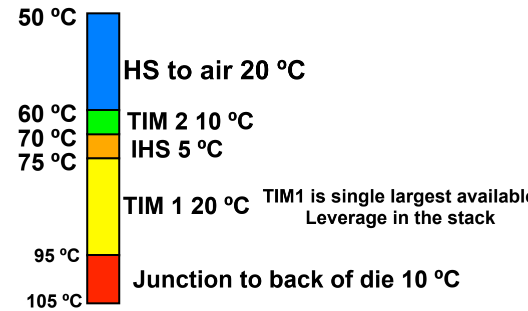


Figure 1. In CPU architecture today, heat is becoming an unmanageable problem. (Courtesy of Pat Gelsinger, Intel Developer Forum, Spring 2004)

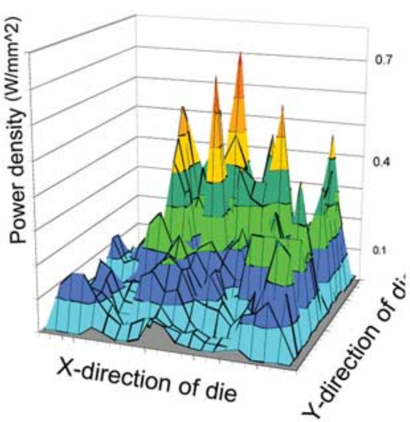
Electronics Cooling

Why is a processor so hot?

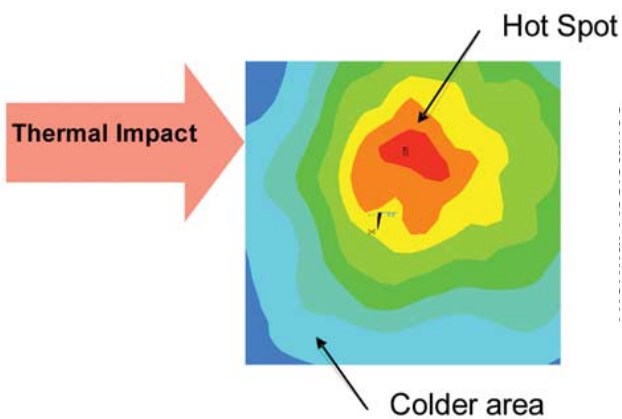




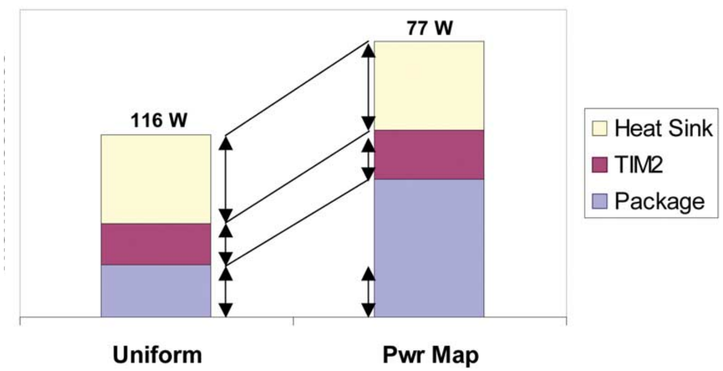
Typical junction to air temperature stack



On-Die Power Map



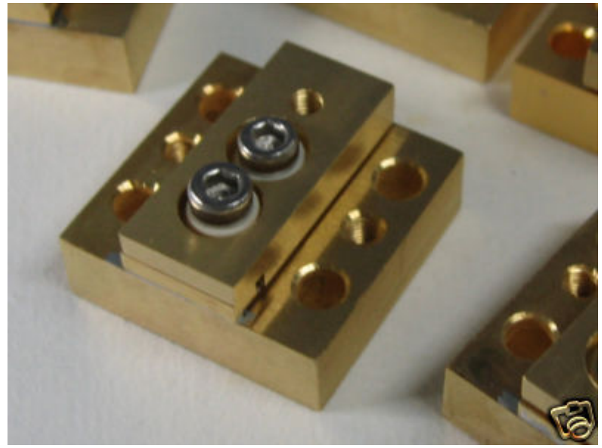
On-Die Temperature Map

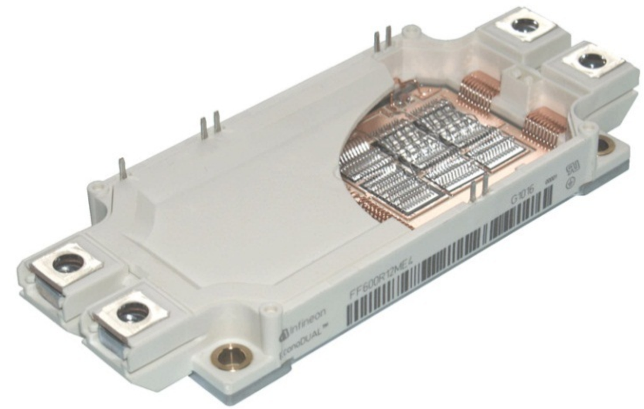


Effect of power nonuniformity on maximum dissipation for a particular configuration

Electronics Cooling

Some Other High Power Density Devices





Eimac 4CM2500KG
2.5 MW Power Tetrode

About 18” high

Uses mixed phase water cooling in the anode

2.5 kW/cm^2

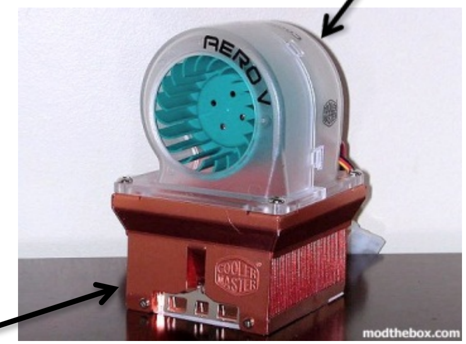
Power Laser Diode, up to 100W Output in this form factor. ~ 100W dissipated in 200 μm^2

IGBT Module. ~ 5 kW

"Off the Shelf" Cooling Solutions

Heat Pipes

High Pressure Blower



Fine Fin Heat Sink

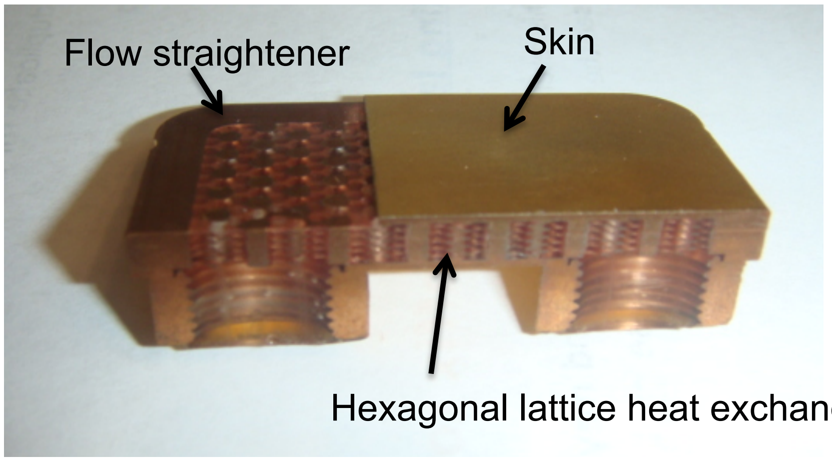
In electronics cooling the task is to extract the heat from a high flux region, and spread it over a large enough area that it can be rejected, while incurring the smallest possible temperature differential. In practice 10 ^{o}C heatsink to air is considered to be good performance

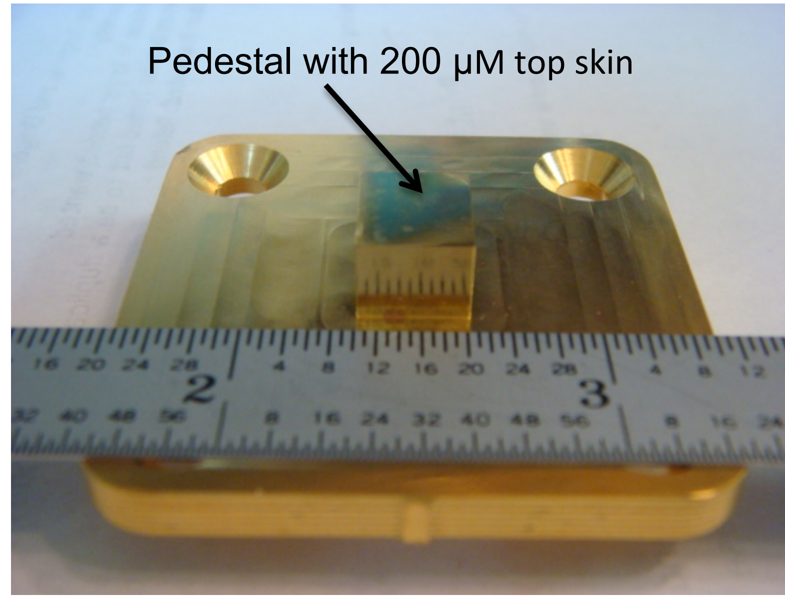
All modes of heat transport are used in electronic systems (including radiation in certain high power vacuum tubes).

Water cooled CPU cooler

3-1000Z Power Triode
operating normally
with anode glowing red

State of the Art Chip Cooling





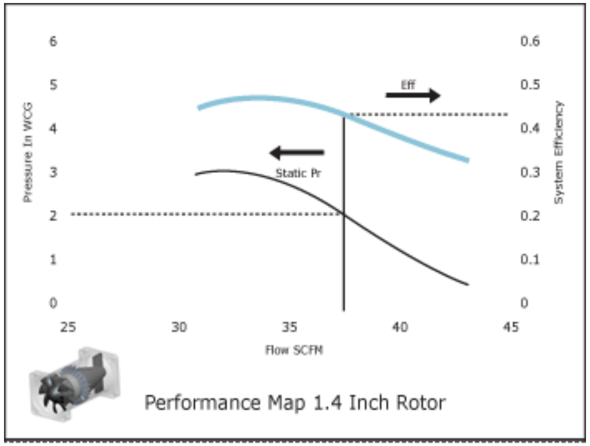
Water cooled heat exchanger that can cool 1 kW/cm^2 with a 10 ^oC ΔT from junction to water at 1 liter/min flow
Chip attached with a drop of mineral oil and enough pressure to coin it into the fully annealed copper skin
Direct bond copper process
Custom manufactured for a Sun Microsystems project by Curamik, www.curamik.de

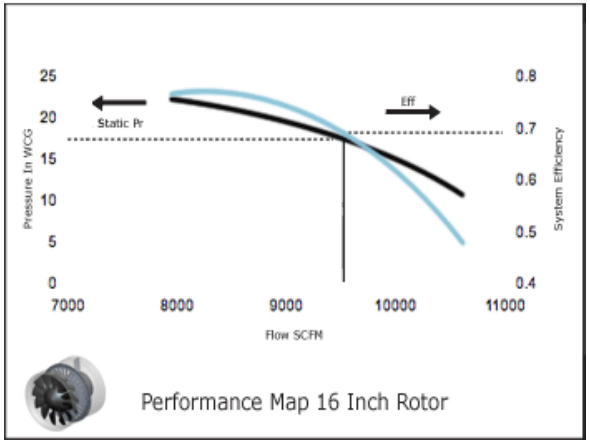
Moving Heat From Chip to Air

- Default, for moderate power density, is directly into a finned heatsink by conduction.
- When the power density is so high that the interface to the heatsink will have too much ΔT a 2-D heat pipe (vapor chamber) is inserted as a spreader.
- Forced convection with liquids in closely coupled microchannel heat exchangers is popular is overclocked PCs.
- If truly inert fluids are used, for example 3M Novec or FC-72, heat removal can be done directly from the exposed hot side of a chip by jet impingement, boiling, or spray cooling.
- When heat needs to be moved large distances phase change (pool boiling, spray cooling, microchannel boiling) is used, and the vapor is transported to a remote condenser.
- When the power density is above the burnout flux for boiling, forced convection in microchannels, or mixed phase boiling in microchannels, is used with a remote heat exchanger to air.
  - The remote condenser for phase change is the electronics version of a dry condenser for a power plant.
  - Electronic system condensers need to be compact. They typically have fine fin spacing on the air side, and extended surfaces on the vapor side. Fan power to drive air through the fins is noticeable in the total system power budget

High efficiency fans

- Jet engine manufacturers have much better CFD than fan manufacturers
- Applying this to electronics cooling fans doubles the conversion efficiency from electric power in to air work out
  - This may be important for air cooled condensers
- Careful motor design helps the efficiency
- These fans develop more differential pressure than conventional designs
  - You can push air through more tightly packed fins, which reduces the thermal resistance of heatsinks
  - Delays adoption of liquid loops for about one generation

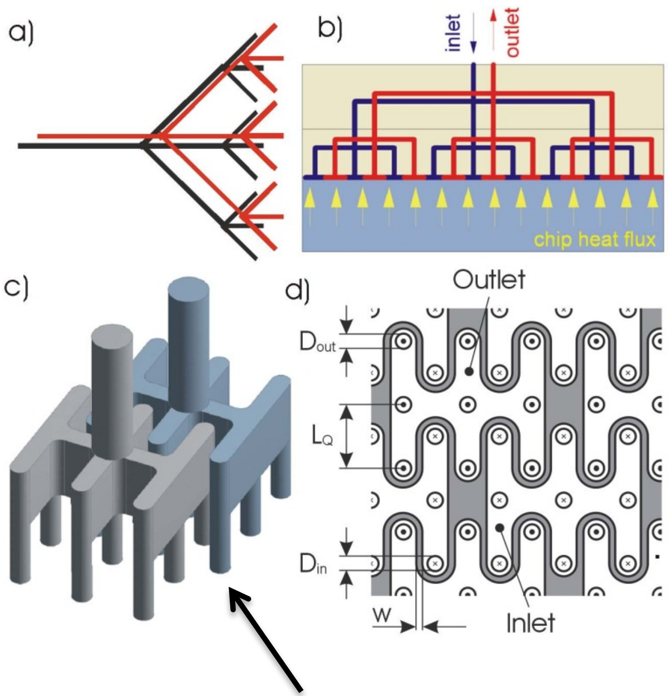


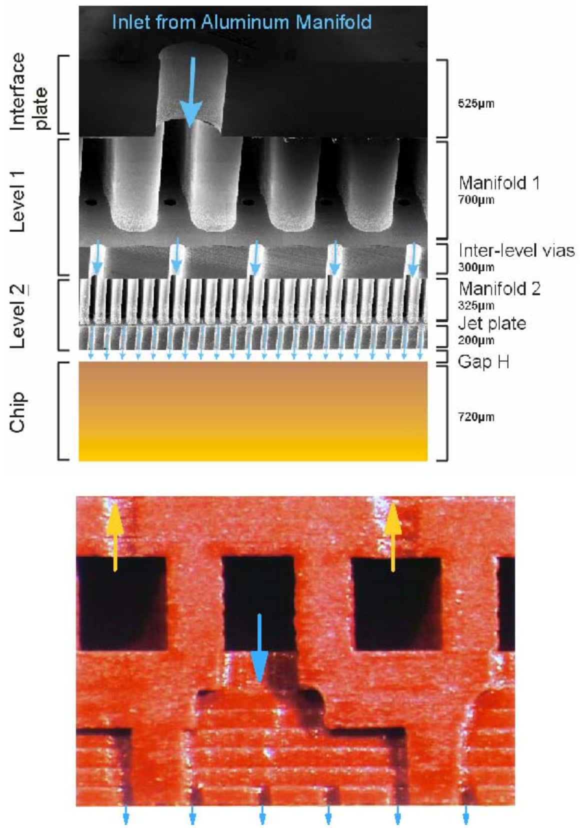


www.xcelaero.com

Pushing liquid at the chip

- **DIRECT LIQUID JET-IMPINGEMENT COOLING WITH MICRON-SIZED NOZZLE ARRAY AND DISTRIBUTED RETURN ARCHITECTURE** Thomas Brunschwiler, Hugo Rothuizen, Matteo Fabbri, Urs Kloter, and Bruno Michel IBM Research GmbH, Zurich Research Laboratory, 8803 Rüschlikon, Switzerland, tbr@zurich.ibm.com, +41 44 724 86 81. R.J. Bezama, and Govindarajan Natarajan IBM East Fishkill, 2070 Route 52, Hopewell Junction, NY12533, USA





Possible high performance condenser structure

0-7803-9524-7/06 IEEE

Electronics Cooling

Phase change with liquids

- Many possible boiling modes
  - Pool
  - Channel
  - Spray
- Technology dates back to “water boiler” power tubes circa WWII
  - They are still in production
  - Major factories in San Carlos and Palo Alto California
- Field is highly empirical
  - Simulation tools require many adjustable parameters to match experiments

Power tubes

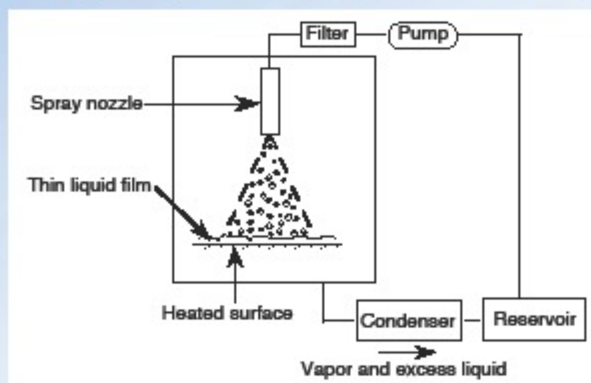
Spray Cooling

- **Liquid forced through a small orifice shatters into a dispersion of droplets that strike a heated surface**
- **Nozzle types:**

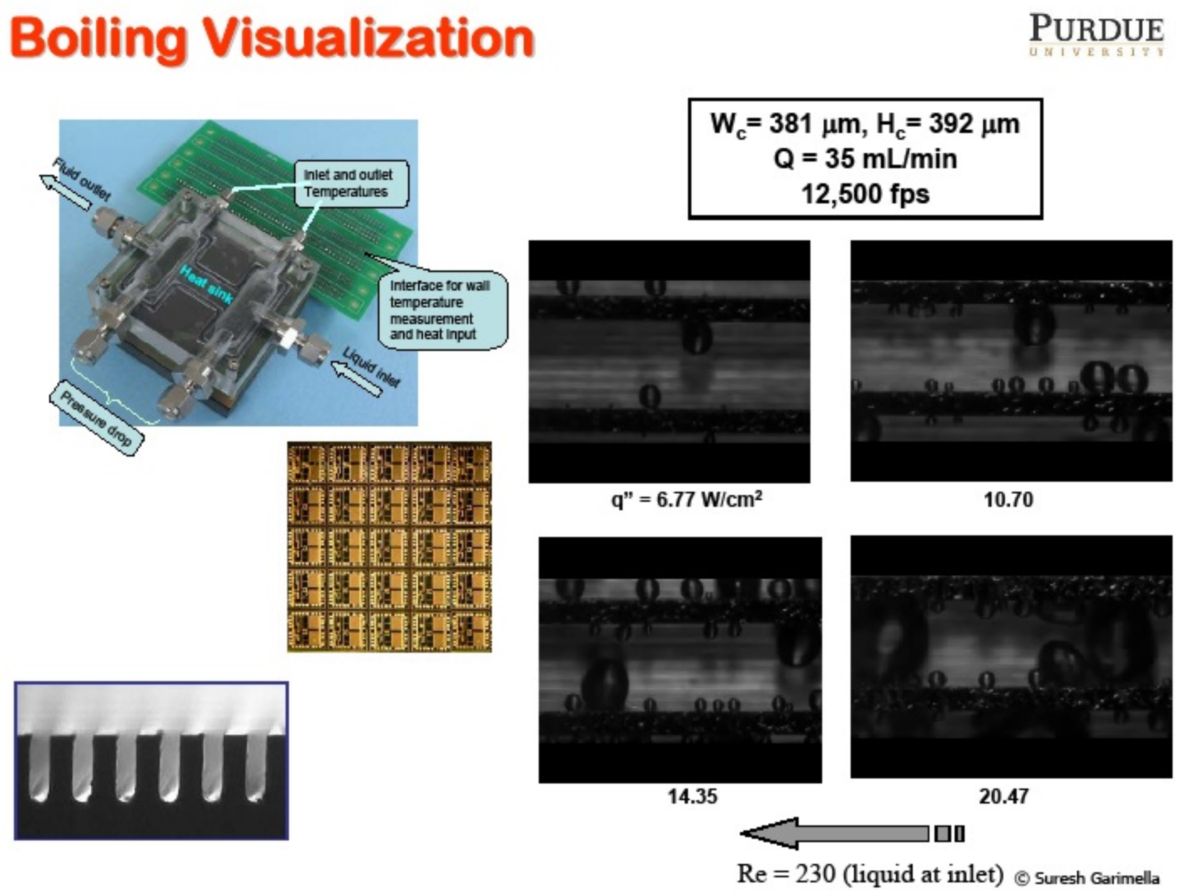
Images from Spraying Systems

- **Typical spray cooling loop for electronic cooling:**

Typical critical heat flux is ~240 W/cm^2 for FC-72



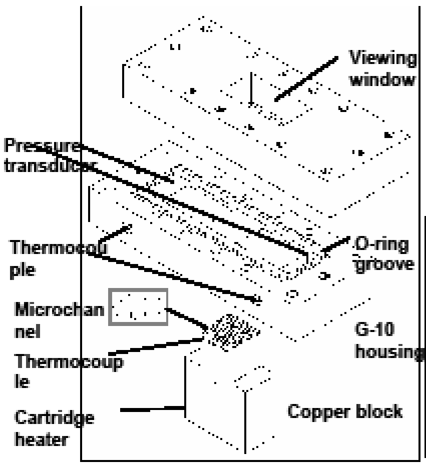
Boiling in channels



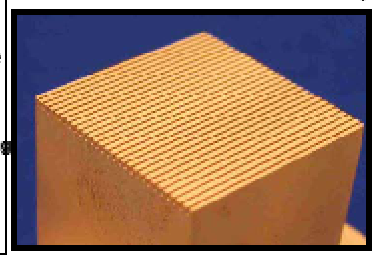
Garimella, H-P cooling Symposium, September 2006

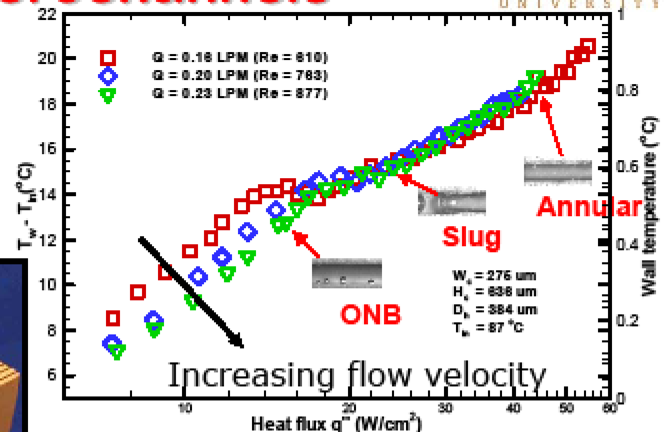
Two-Phase Transport in Microchannels

PURDUE UNIVERSITY



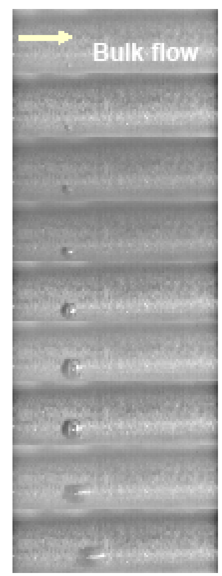
Liu, Lee, Garimella, *IJHMT*, 2005

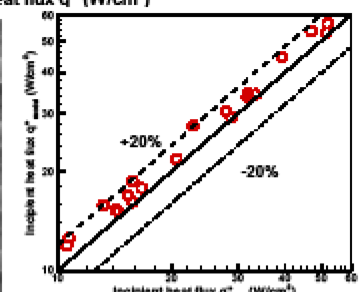


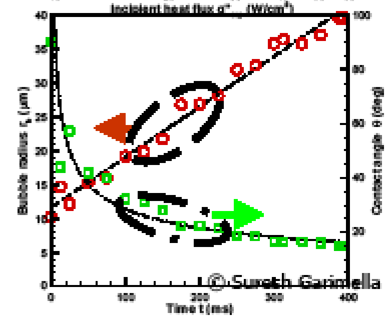


Unresolved issues

- Flow boiling mechanisms not fully identified
- Flow regime maps need to be constructed for the microscale
- Boiling instabilities and associated flow mal-distribution not well predicted
- Single-microchannel results not readily extrapolated to multiple microchannels
- Models for flow boiling



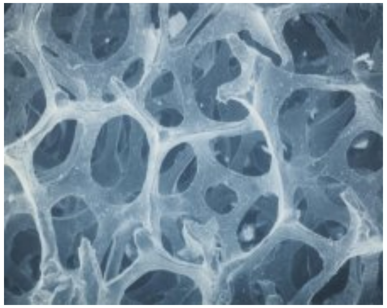




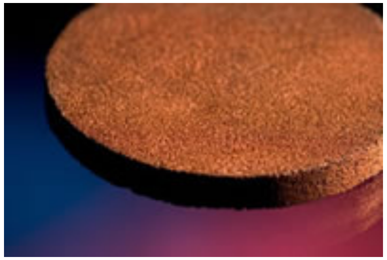
© Suresh Garimella

Garimella, H-P cooling Symposium, September 2006

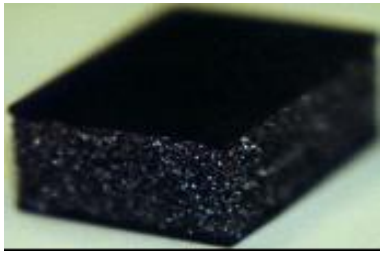
High area structures



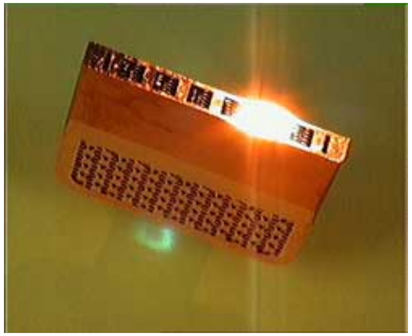
Aluminum foam
Cheap, light, wide range of pore sizes and densities
www.ergaerospace.com



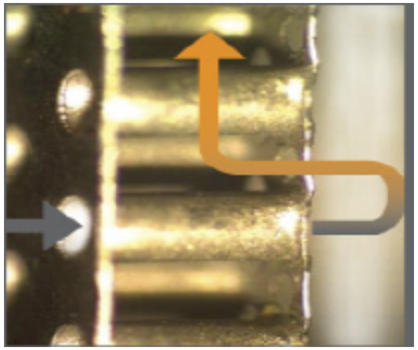
Copper foam
Developed as filter media, moderate range of pore size and density



Graphitic foam
Developed by ORNL
Small pore size, exceptional thermal conductivity



Laminated “Direct Bond Copper” heat exchanger
www.curamik.de

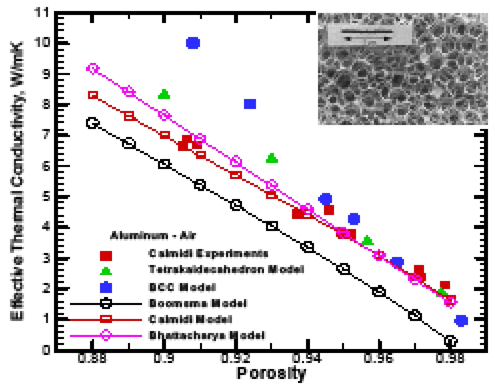


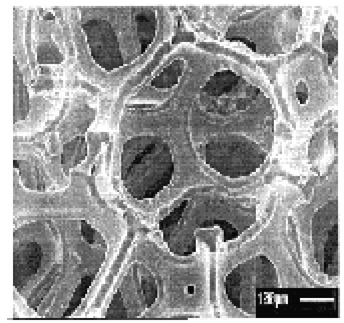
Mezzo Technologies electroformed microchannel heat exchanger
0.5 to 0.8 mm tubes

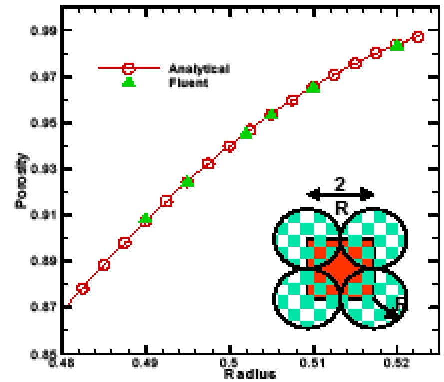
These structures make good filters
This limits application environments

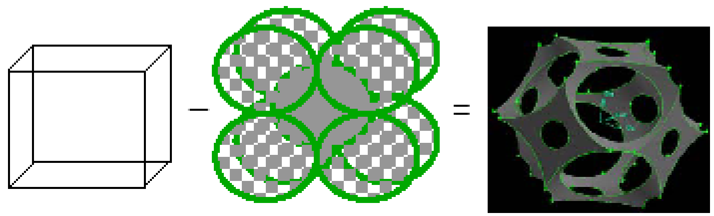
Enhanced Transport in Open-Cell Foams

PURDUE UNIVERSITY

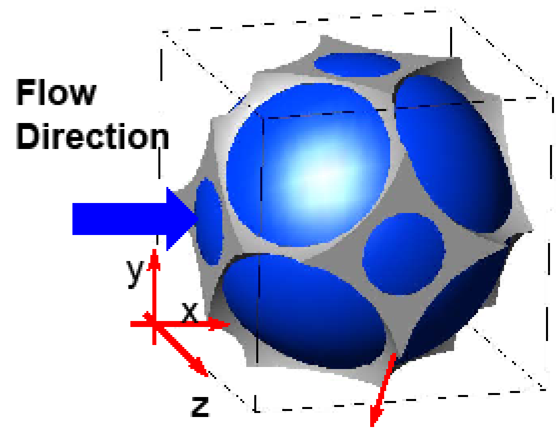




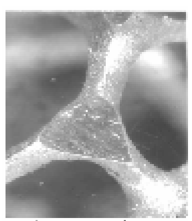




Cube BCC Final Geometry



Constant Heat Flux



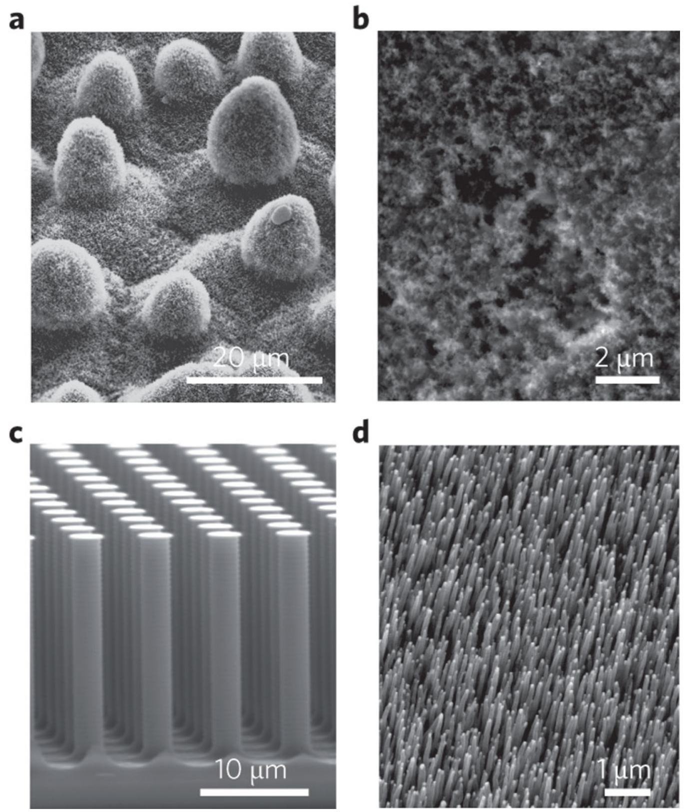
Krishnan, Murthy, Garimella, *ASME JHT*, 2005
Krishnan, Murthy, Garimella, *ASME JHT*, in press

Controlling Condensation

- Condensation is more efficient on a hydrophobic surface
  - Eliminates thermal resistance of liquid film
  - Clears the surface faster

Lotus leaf

Silica coated burned out candle soot
Exceptional performance,
Repels both water and oils,
rugged



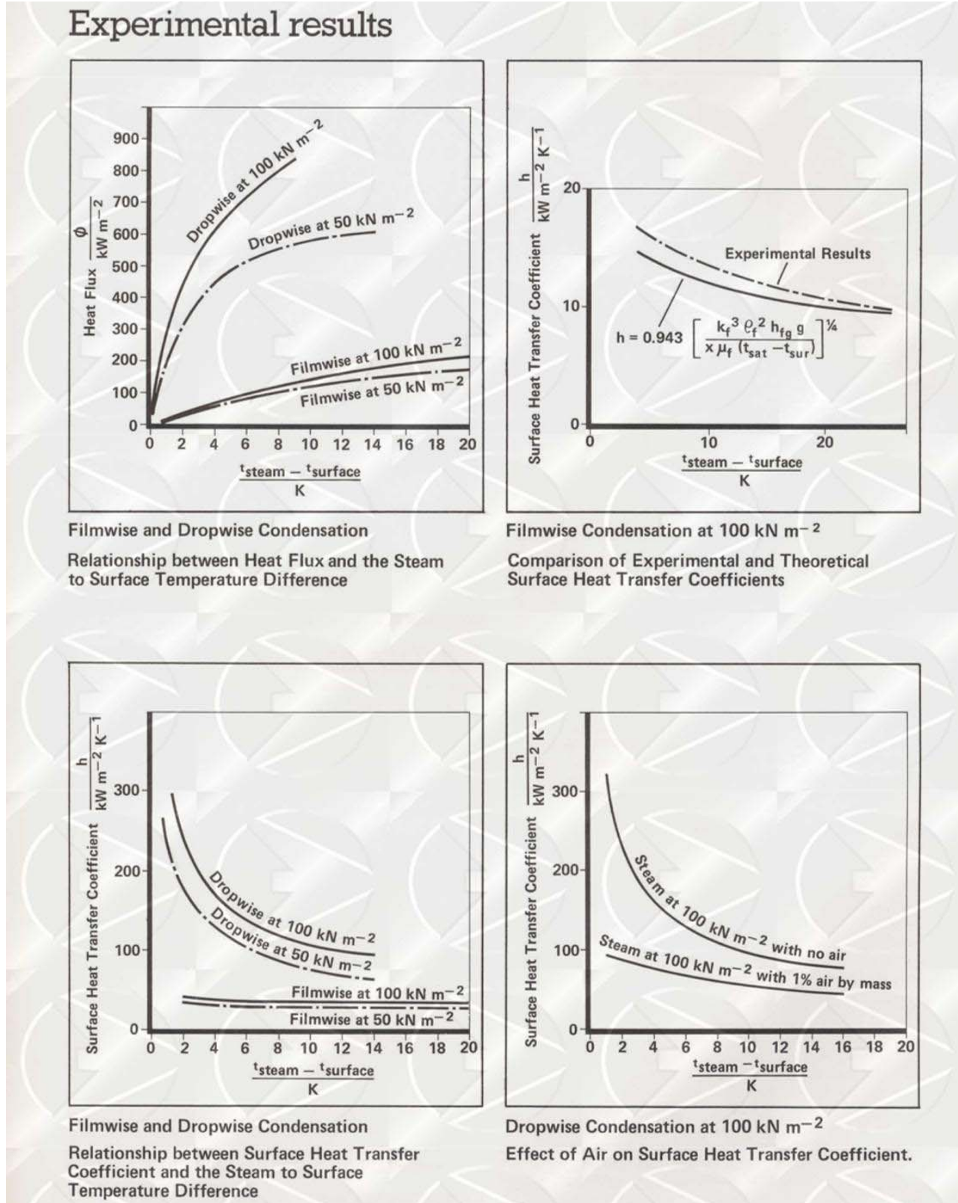
Etched Nano-pillars

Nanotube forest

Electronics Cooling

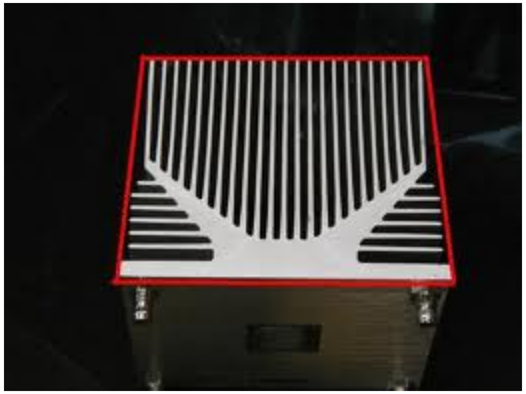
Condensation Regimes

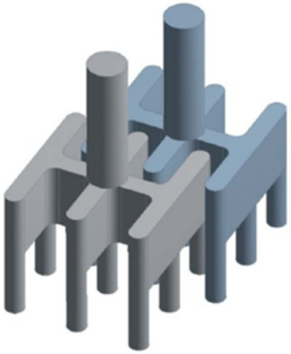
Note improved performance for dropwise condensation



Optimizing Condensers

- Nanostructured surfaces can improve condensation efficiency, and reduce temperature drop
- For total system optimization the condensation heat flux must be matched to the capability of the fin to air structure on the outside of the condenser
- This optimization may result in a very non-traditional structure, with small condensation patches coupled to large branching fins or fractal fubing geometries with very fine condensation regions





- It may be necessary to have additional second level structure internal to the condenser to limit steam flow, or to make only part of the available area active
- The air fin structure must be globally matched to the available air flow