Thermal Management Roadmap

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Electronic Industry Business Trends

- Packaging driven by product category
  - Market-driven price point
  - Cost/Function primary challenge
- Rapid bifurcation in product categories
  - High functionality and “value added”
  - Low cost commodity
- Supply Chain drives productivity
  - SCM Enables cost reduction
  - EMS growing 50% per year

Electronic Industry Business Trends

- Market Convergence
  - Computing/Telecom fueled 1990's "gold rush"
  - Automotive/Consumer 2000's ???
- Volume Drivers
  - Cell phones
  - Optoelectronics
  - Bluetooth
  - OLED displays
- Shrinking Product Cycles
  - Product release to peak production = 6-9 mo
  - Production end = 24 mo

Electronic Industry Technology Trends

- Moore's Law "fatigue"
  - Silicon device growth slows
  - Feature size shrink returning to 3 year cycles
  - SOP needed after 2005
- Under-Exploitation of Silicon Potential
  - Design Productivity Gap
  - Packaging Limitations
- Thermal Management
  - CMOS provided only temporary relief
  - Key element in performance, reliability, cost
  - Develop metrics for thermal packaging

Drivers for Thermal Packaging

- Air as the Ultimate Heat Sink
- Market-Driven Thermal Solutions
- Environmentally-Friendly Design
  - Low power consumption
  - Low noise: acoustic and EMI
  - Recyclability
- Feature-Rich Design Tools
  - Integrated with product CAD system
  - Parametric optimization

Design for Sustainability

- "spreading" + natural convection/radiation
- Least-material optimization
- Entropy generation minimization
- Least-energy optimization

Work allocation factor, ξ_{pp}

= Pumping work / Total cooling work

$= W_{pp} / [W_M + W_{PP}]$

Heat Sink Design Metrics

- Thermal resistance

$$R_{hs} = \theta_b / q_T$$

[K/W]

- Array heat transfer coefficient

$$h_a = q_T / (LW\theta_b)$$ [W/m²-K]

- Mass-specific heat transfer coefficient

$$h_m = q_T / (\rho_{fin} V_{fin} \theta_b)$$

[W/kg-K]

- Space claim heat transfer coefficient

$$h_{sc} = q_T / (LWH\theta_b)$$

[W/m³-K]

Design for Sustainability Metrics

- Coefficient of Performance

$$COP = q_T / IP$$

$$IP = V_{air} \times \Delta P$$

- Total Work Coefficient of performance

$$COP_T = q_T t_1 / W_T$$

$$W_T = W_M + W_{PP}$$

$$W_M = 85{,}000\ M \quad \text{(estimated)}$$

q_T: Heat dissipation, kW
W_T: Energy investment for cooling, kWh
W_M: Formation/fabrication work, kWh
W_{PP}: Pumping work, kWh

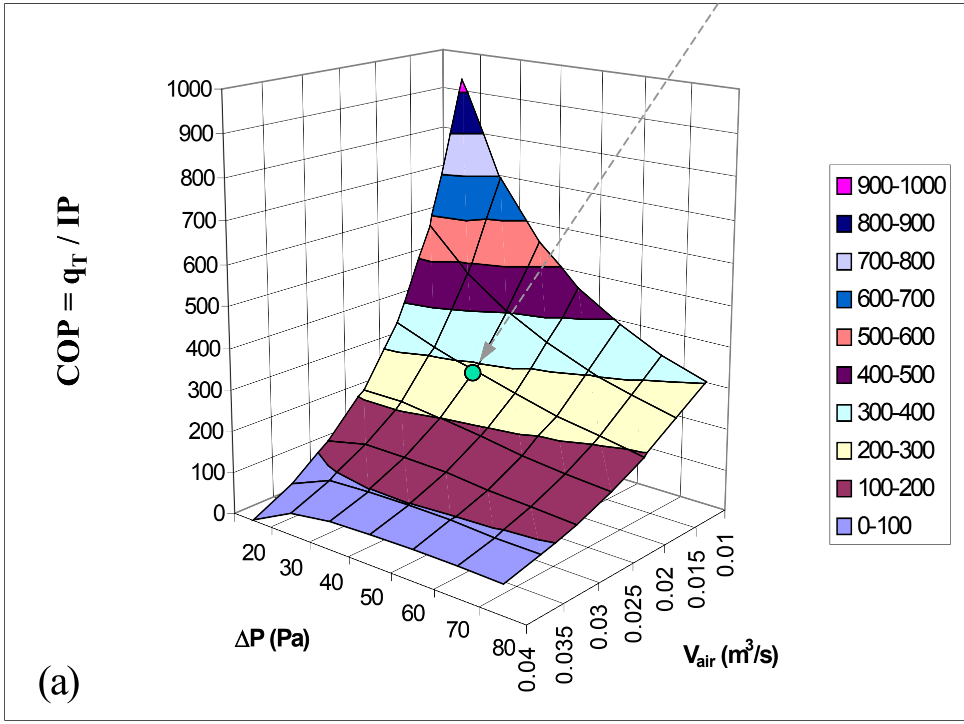
t_1: Duty cycle, h
M: Fin mass, kg
ΔP: Pressure drop, Pa
V_{air}: Volumetric flow rate, m^3/s

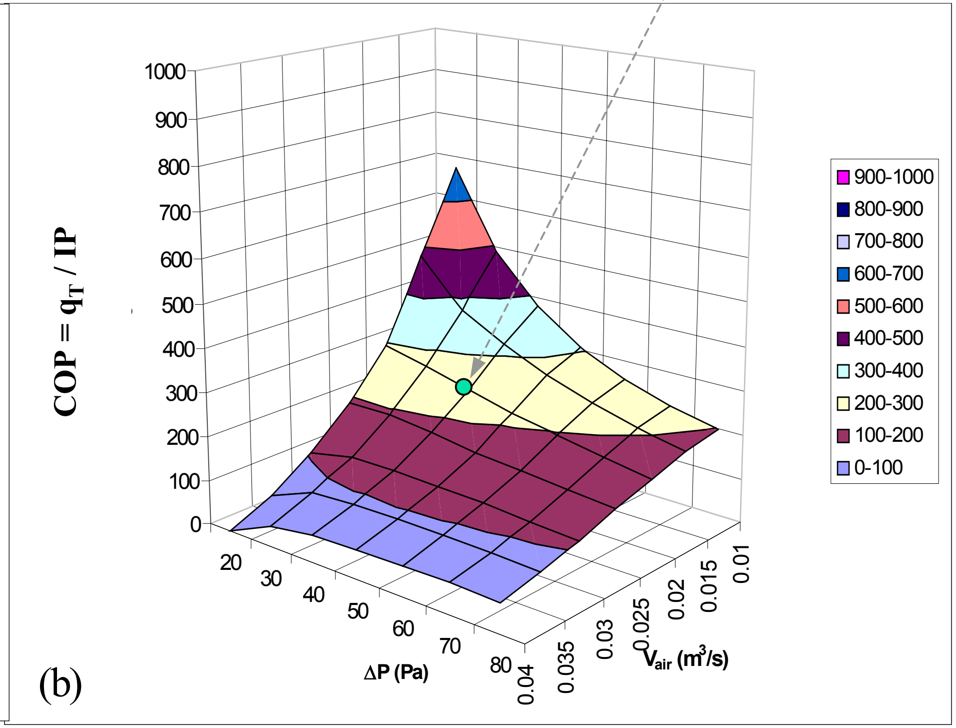
Coefficient of Performance

ΔP = 40Pa, V_{air} = 0.02 m^3/s
q_T = 284W, IP = 0.8W
COP = 355

Typical values

ΔP = 40Pa, V_{air} = 0.02 m^3/s
q_T = 194W, IP = 0.8W
COP = 243





Maximum heat transfer design

Least material design

$L = W = 0.1$ m, $H = 0.05$ m, $\theta_b = 25$ K, $k = 200$ W/m-K

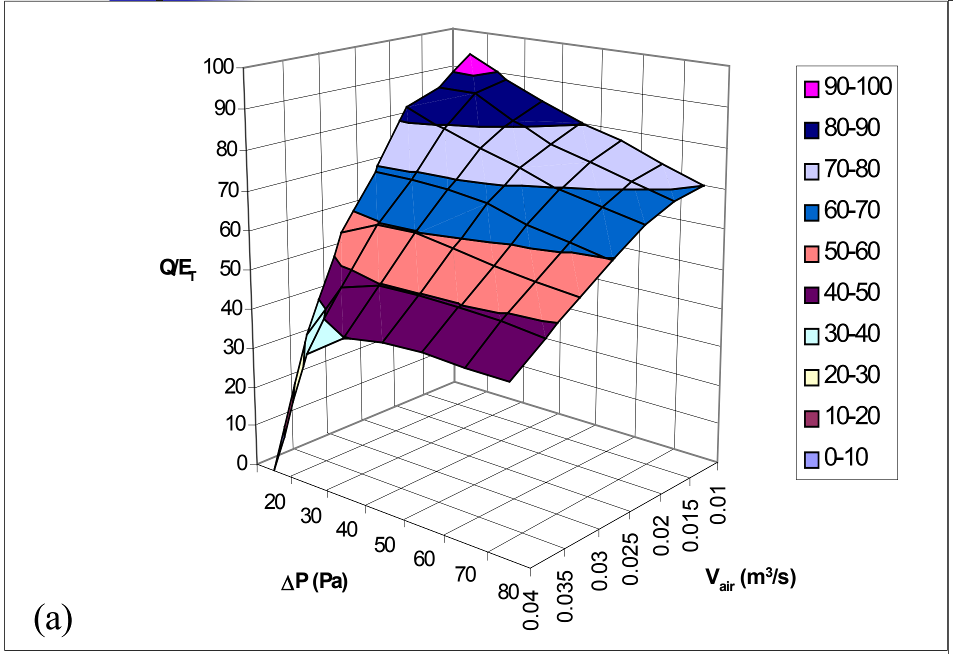
COP_T Comparison: Maximum Vs Least-material

Forced convection SISE plate-fins

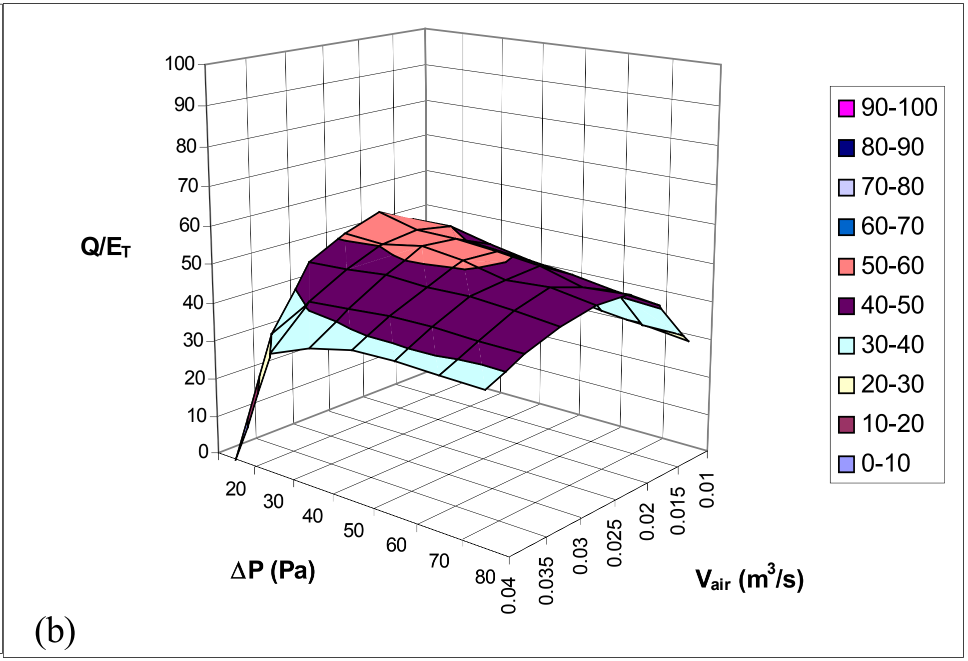
L= W = 0.1 m, H = 0.05 m, θ_b= 25 K, k = 200 W/m-K

Least material design

Maximum heat transfer design



(a)



(b)

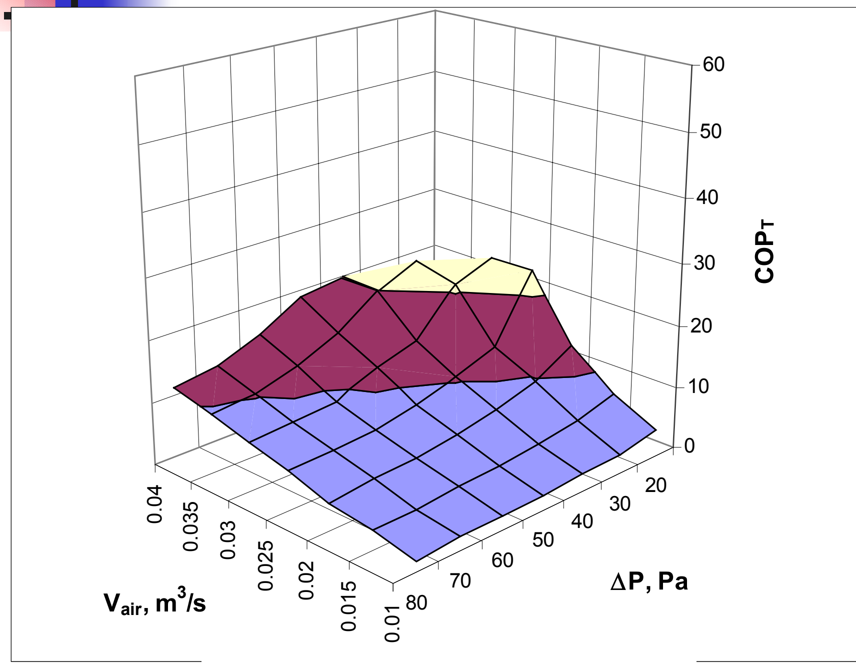
$$COP_T = q_T t_1 / W_T \qquad W_T = 85M + IP\, t_1$$

M - mass (kg), IP - pumping power (kW), t_1 - life cycle (6000 hours)

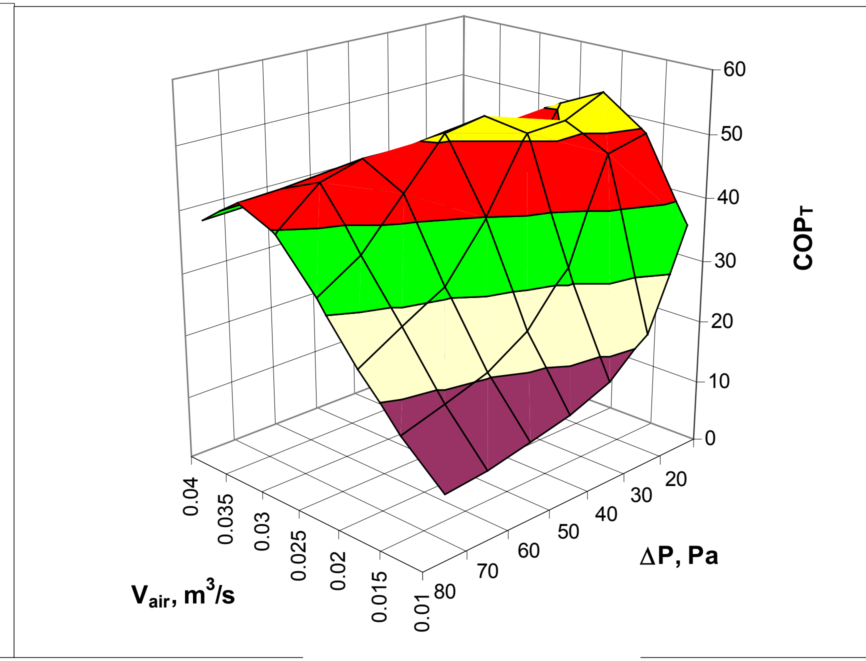
COP_T Comparison: Extrusion Vs Skiving

Forced convection SISE plate-fins

L= W = 0.1 m, H = 0.05 m, θ_b= 25 K, k = 200 W/m-K



(a) COP_T, **Extrusion**



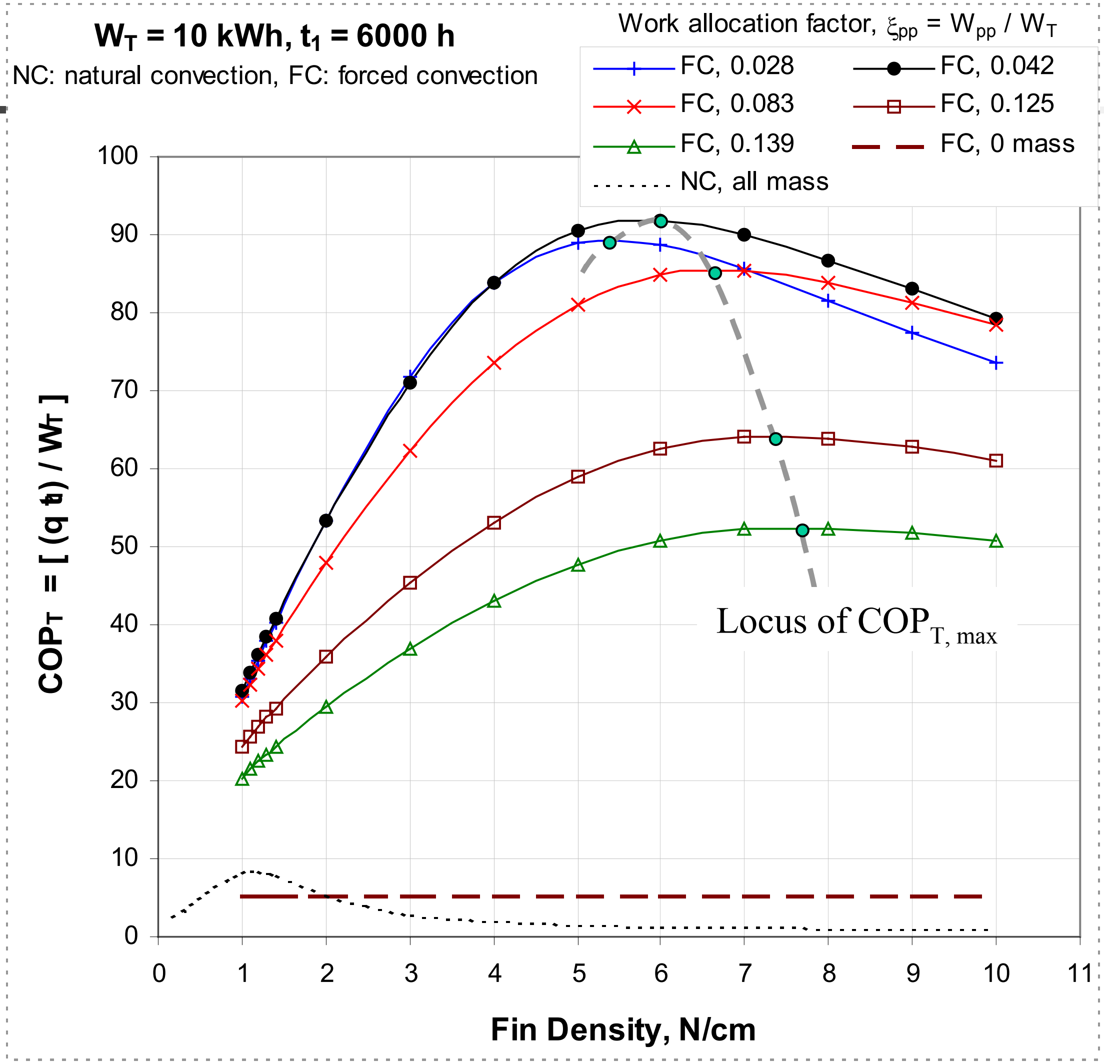
(b) COP_T, **Skiving**

$$COP_T = q_T t_1 / W_T \qquad W_T = 85\,M + IP\; t_1$$

M - mass (kg), IP - pumping power (kW), t_1 - life cycle (6000 hours)

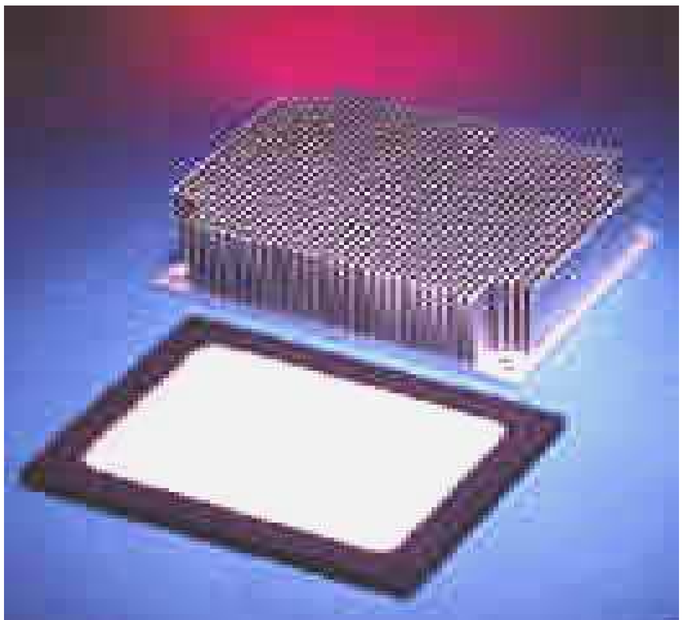
COP_T Optimization: Fixed Input Work

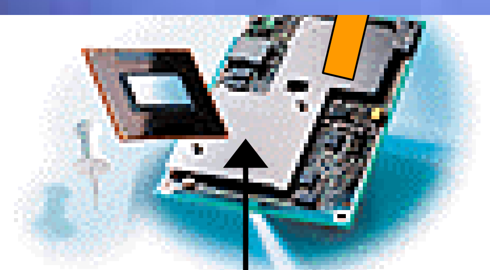
Forced convection SISE plate-fins, W_T = 10 kWh, t_1 = 6000h



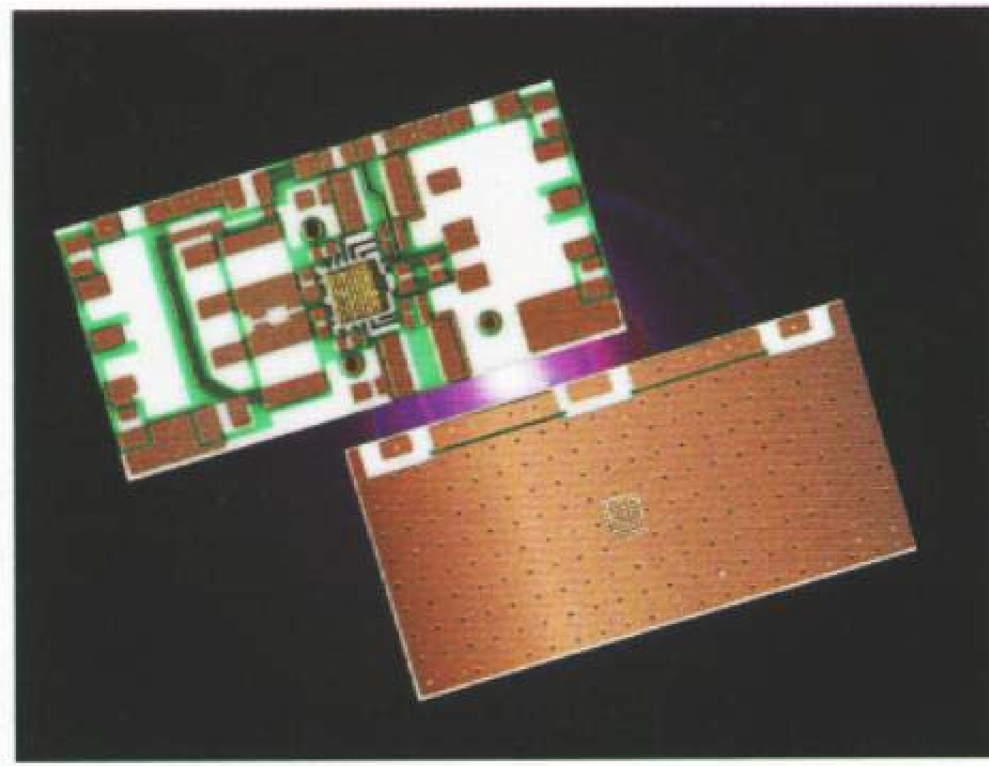
L = W = 0.1 m, H = 0.05 m, θ_0 = 25 K, k = 200 W/m-K

SOA Heat Spreaders



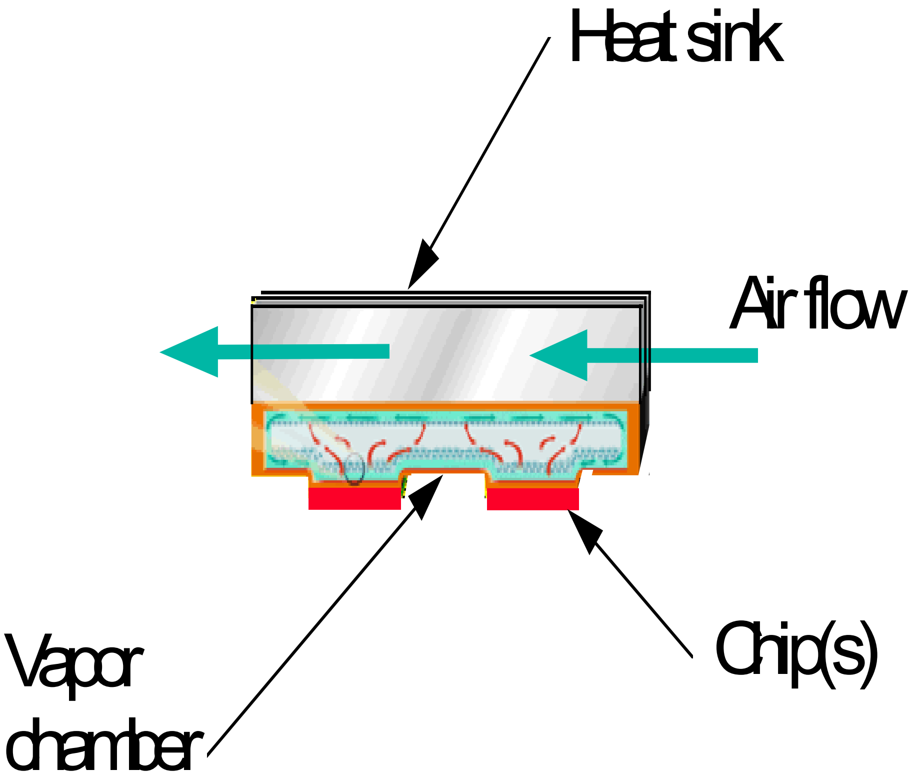


Ceramic-Coated Cu plate



Heat Spreaders
Technology Needs

- High k Coatings
- High k composites
- Vapor Chambers
- Micro Heat pipes
- 2ϕ Thermosyphons
- Micro-fluidics

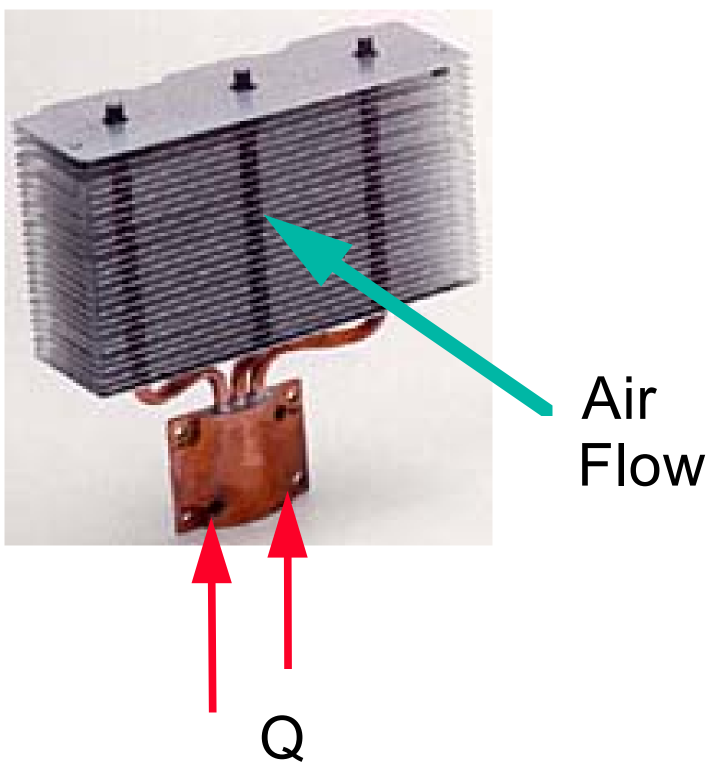


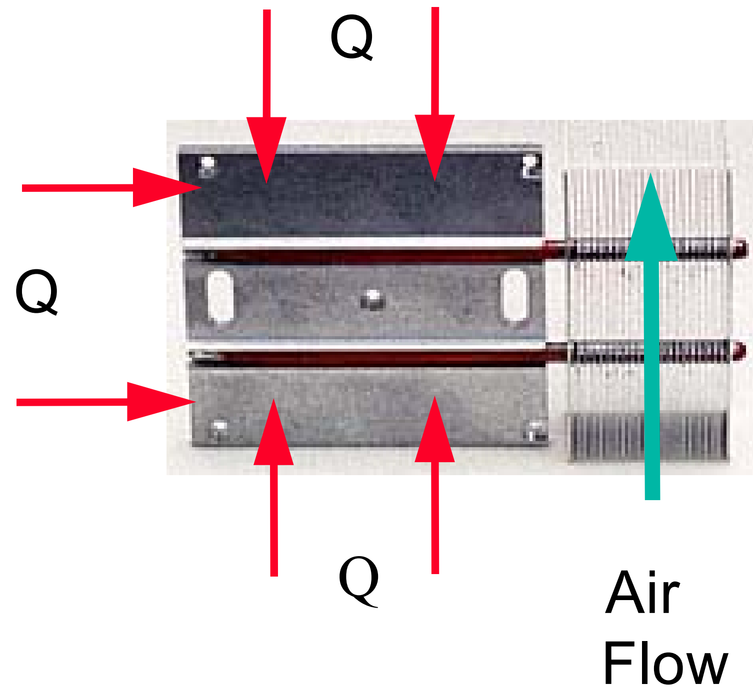
Heat Spreaders
Research Needs

- Low-cost, high-k, TCE-matched materials
- Algorithms for optimal design
- Improved on-chip spreading techniques
- Correlations/analytical models:
  - Dryout/rewetting of micro-channels
  - Dryout/rewetting of micro-porous structures
  - Local spreading resistance

Heat Pipes

Technology Needs





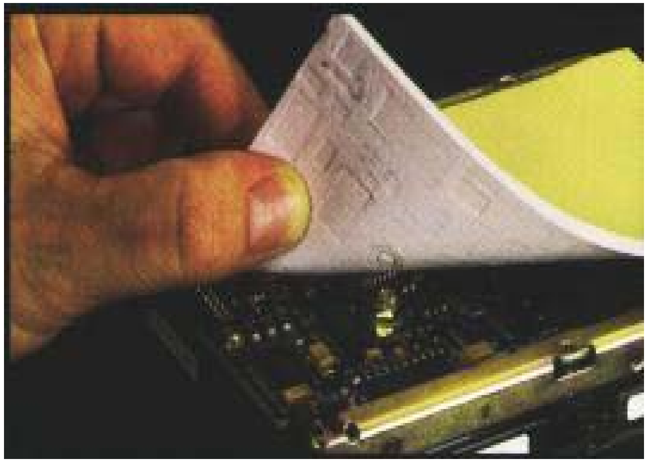
Heat Pipes
Research Needs

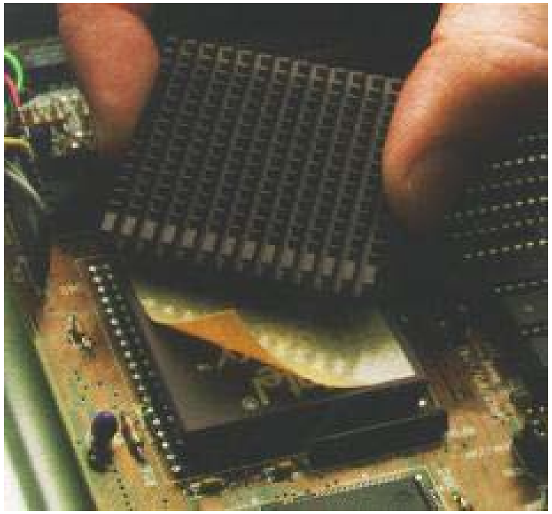
- Deformable & flexible “thermal-hinge”
- High radial & axial heat fluxes
- Long, Low cost, high performance
- Technology capable of withstanding harsh environments (automotive and aerospace)
  - High – g
  - High, cyclic temperatures
- Correlations/algorithm for thermosyphon design

SOA Interface Materials

Grease

Elastomer



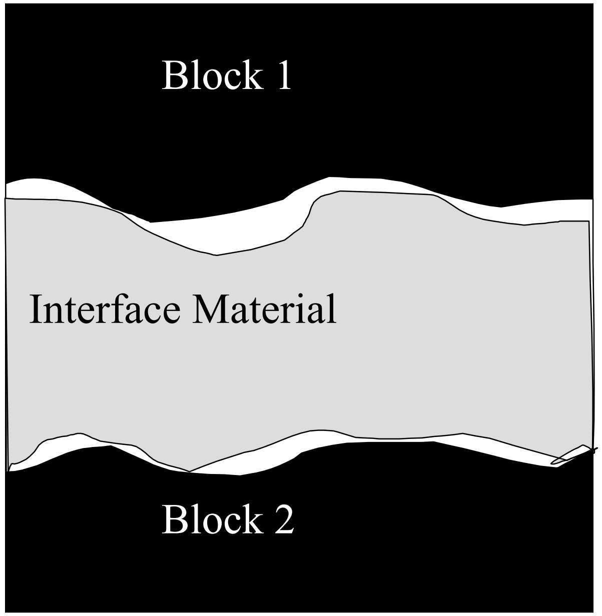


Phase Change Material

Classs	Grease	Phase Change	Elastomer	Epoxy	Eutectic
Performance [K/W/cm^2]	0.3 - 0.7	0.35 - 1.0	1+	0.25-0.5	~0.1

Thermal Interfaces
Technology Needs

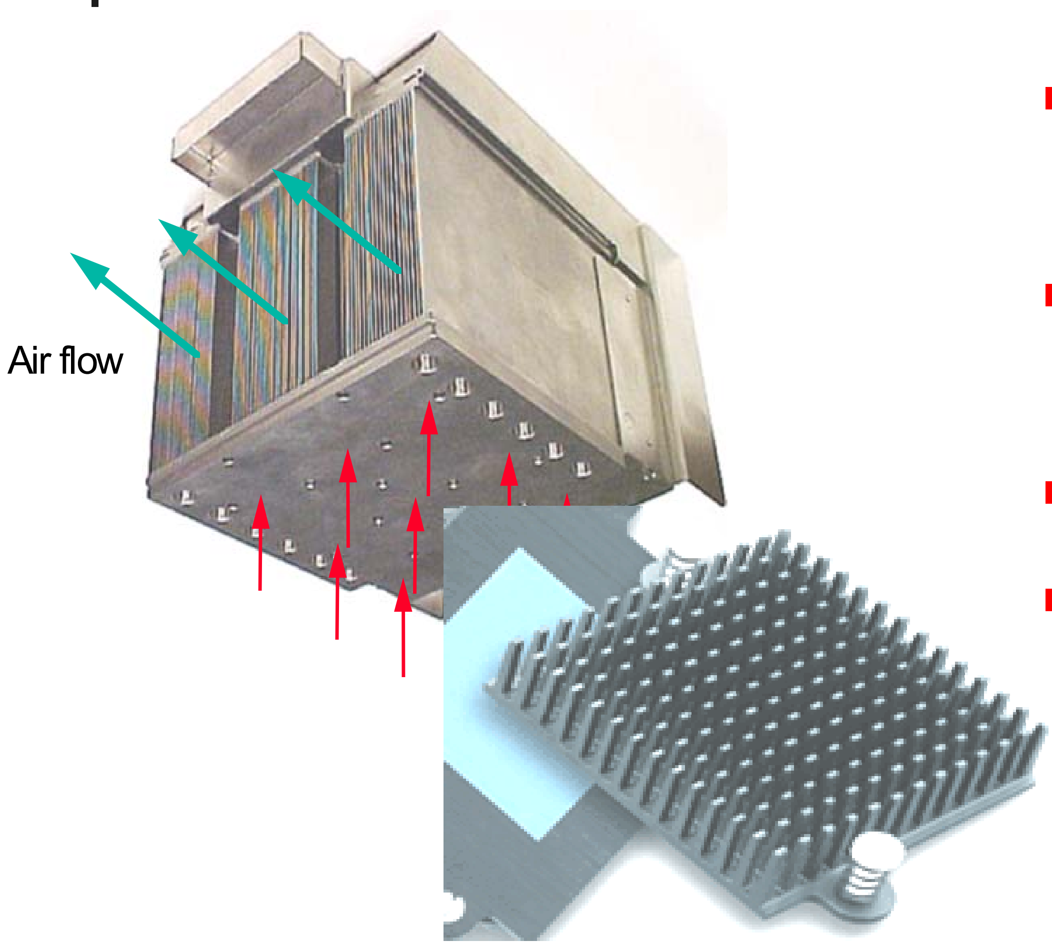
- Develop standardized measurements
- Characterize normal process variations
- Optimize filled polymers
- Study time variant thermal properties
- Create new thermal elastomers
  - k = 20-100 W/mK,
  - Thin bondlines (~10-25μm)
  - Low elastic moduli



Thermal Interfaces
Research Needs

- Nanoparticle-filled high-k pastes, epoxies, elastomers
- Techniques/materials to minimize interfacial stresses
- Correlations/theories for fatigue of bonded interfaces
- Microencapsulated PCM packaging materials

Air Cooling
Technology Needs



- High aspect-ratio, closely-spaced fins
- Design/Optimize for manufacturability
- High head fans
- Low acoustic/EMI noise

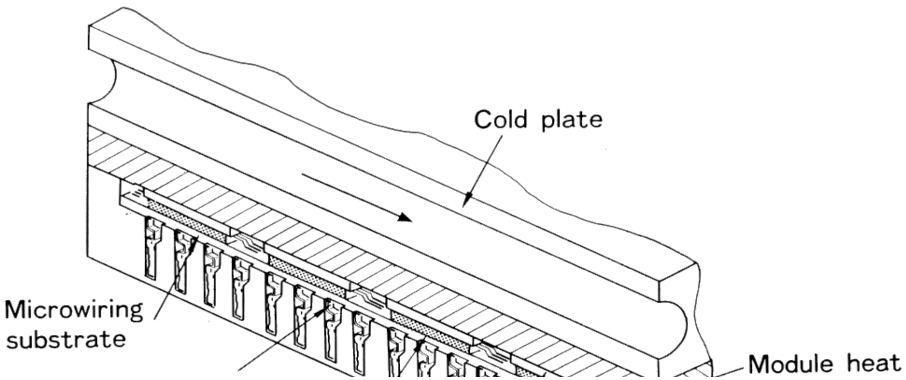
Air Cooling
Industrial Research Needs

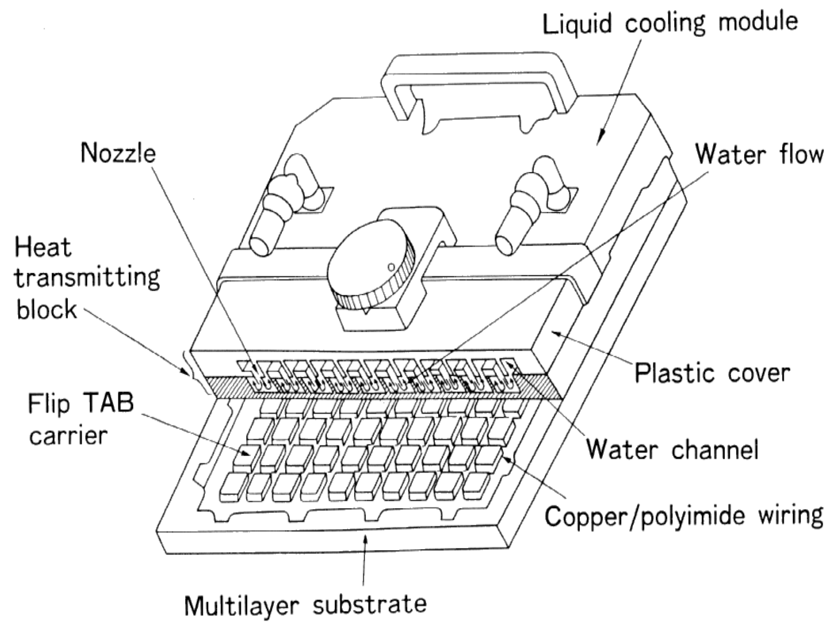
- Advanced manufacturing techniques for metal and composite material heat sinks
- Compact high head/moderate flow/low noise fans
- Low power consumption micro-fans for notebook computers and handheld electronics
- High pressure/high flow blowers with low acoustical and EMI noise

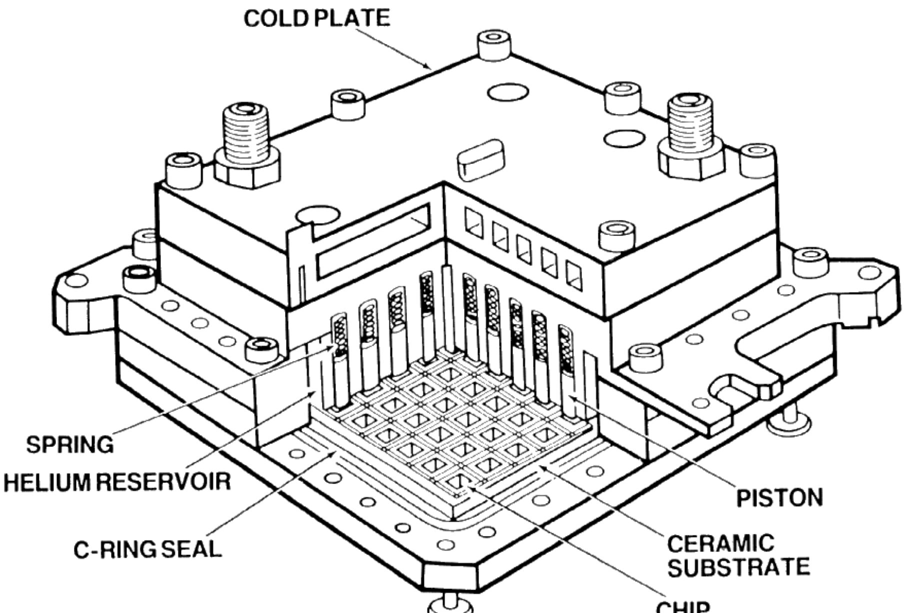
Air Cooling
Research Needs

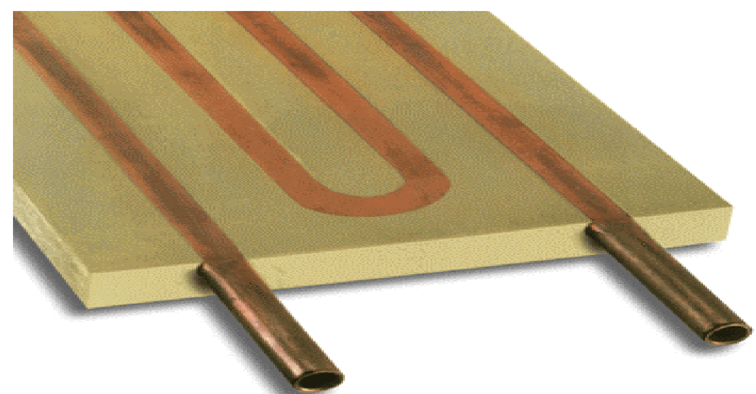
- Models/correlations for heat transfer in transition and low Reynolds number flow
- Low Reynolds number turbulence models for use in CFD codes
- Heat sink design/optimization procedures
  - Mass constraints
  - Volume constraints
  - Energy requirements/constraints

SOA Liquid Cooling

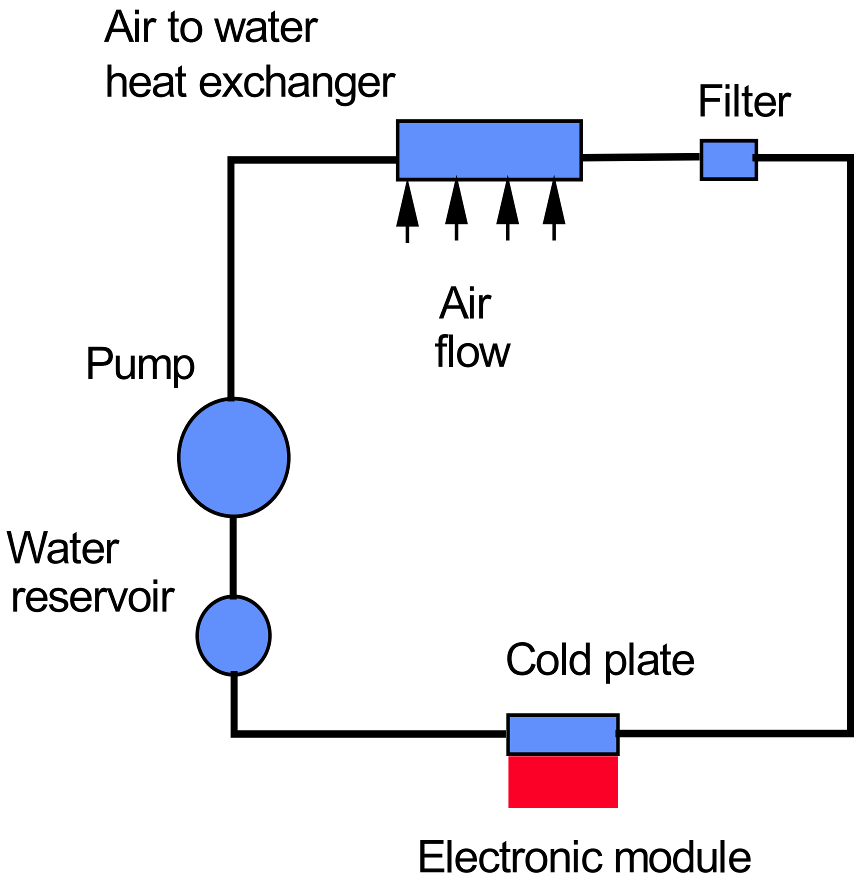






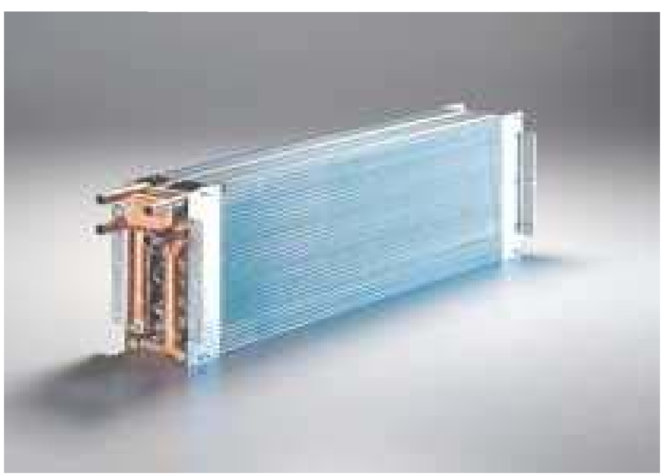


Liquid Cooling
Technology Needs



- Superior coolant
- Exploit known technology – cold plates, compact HX, pumps
- Wide range of enhancements

Liquid Cooled Cold Plates



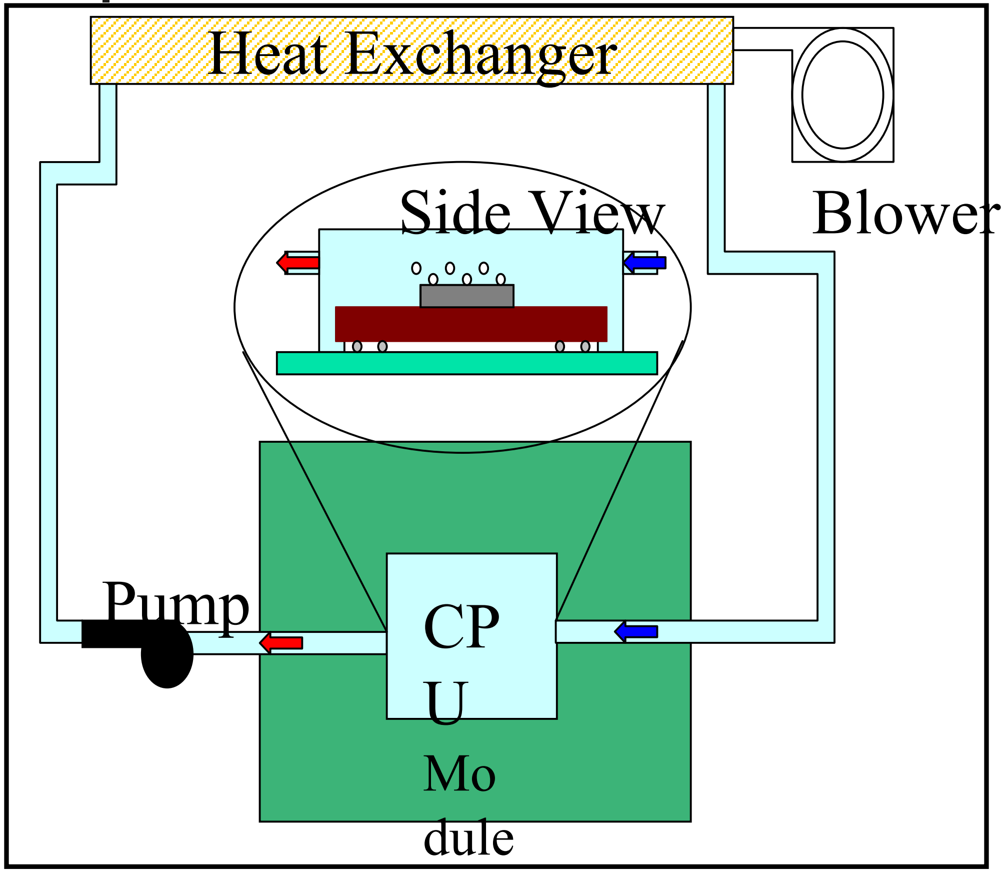
Piston Diaphragm

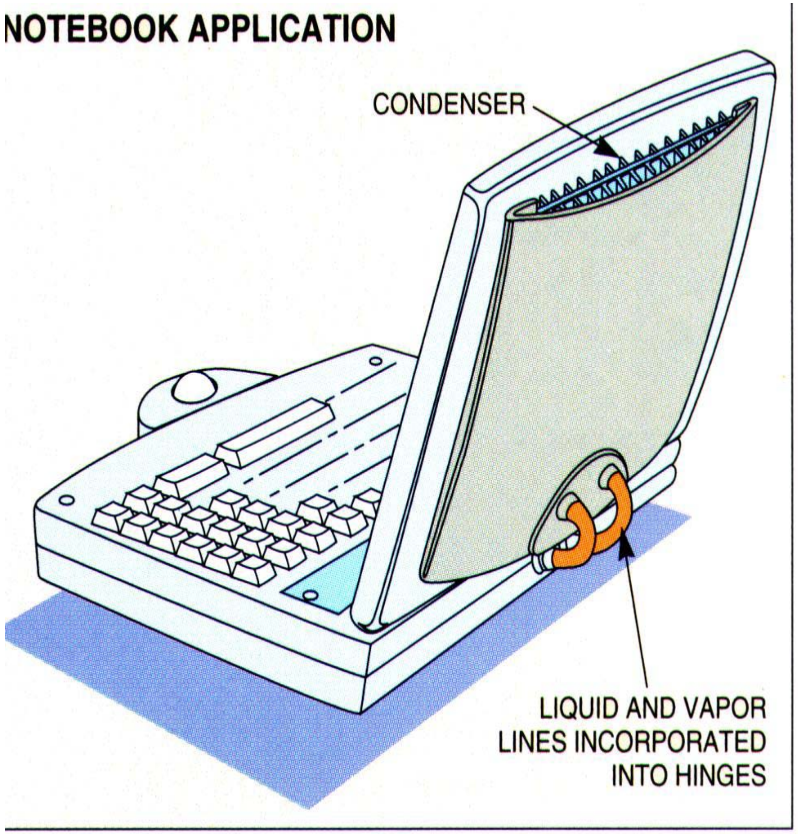
Magnetic Drive

Liquid Cooling
Research Needs

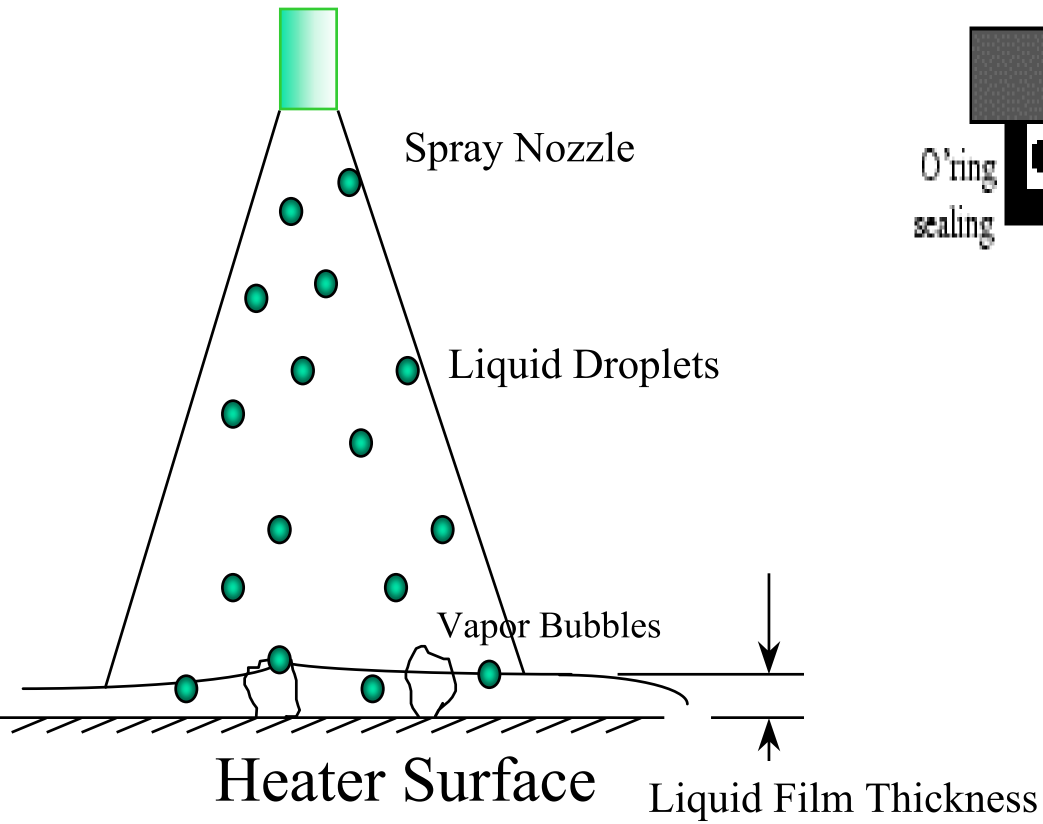
- Miniaturized components with high reliability and enhanced performance
- MEMS and meso-scale HX components
- MEMS and meso-scale cold-plates
- Direct “water” cooling of chips/packages

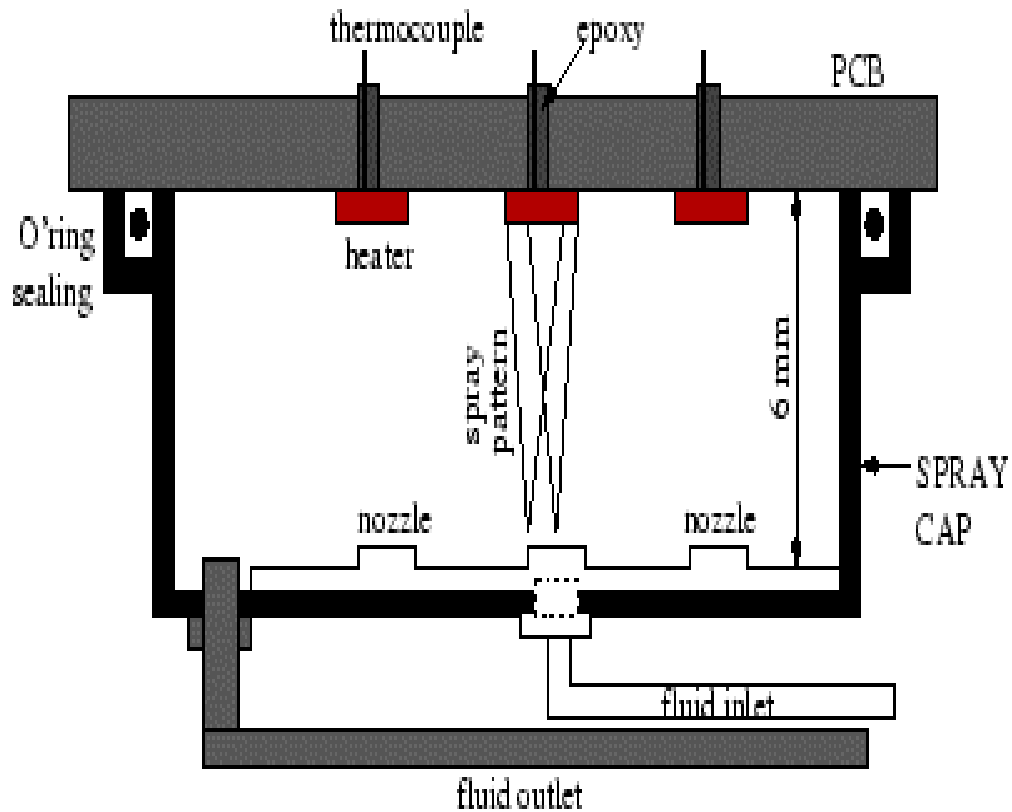
Direct Liquid "Immersion" Cooling





SOA Spray Evaporative Cooling
(Cray SV Module)

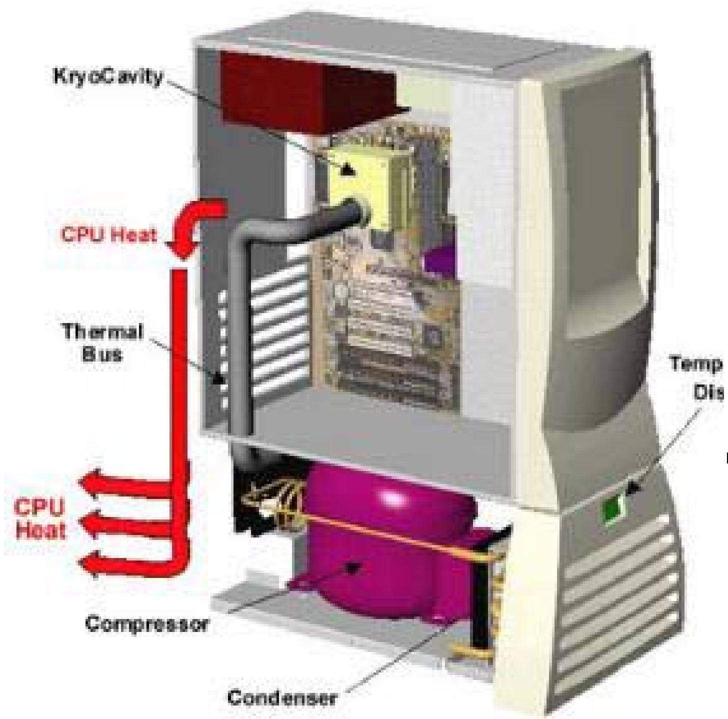




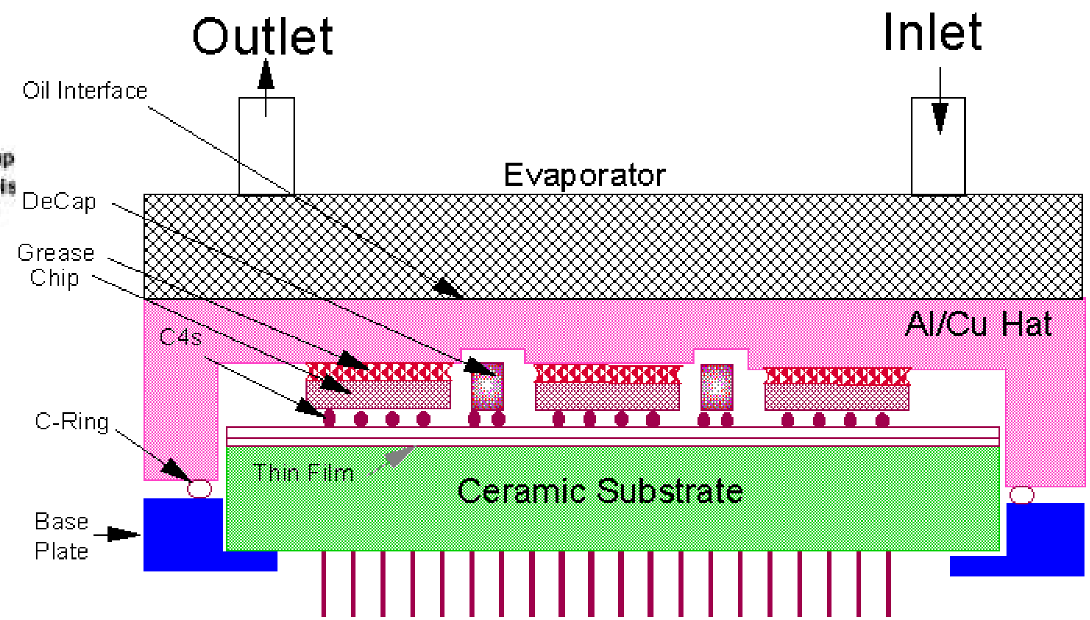
Direct Liquid Immersion
Research Needs

- Thermofluid single- and two-phase correlations
  - new dielectric coolants
  - Non-uniform fluxes
  - 3-D structures
  - Dryout and CHF
- Nanoparticles for enhancing dielectric coolants
- MEMS/meso-scale thermal enhancement
- Correlations/models - evaporative spray cooling

SOA Vapor Compression Refrigeration



IBM S/390 G4



Kryotech

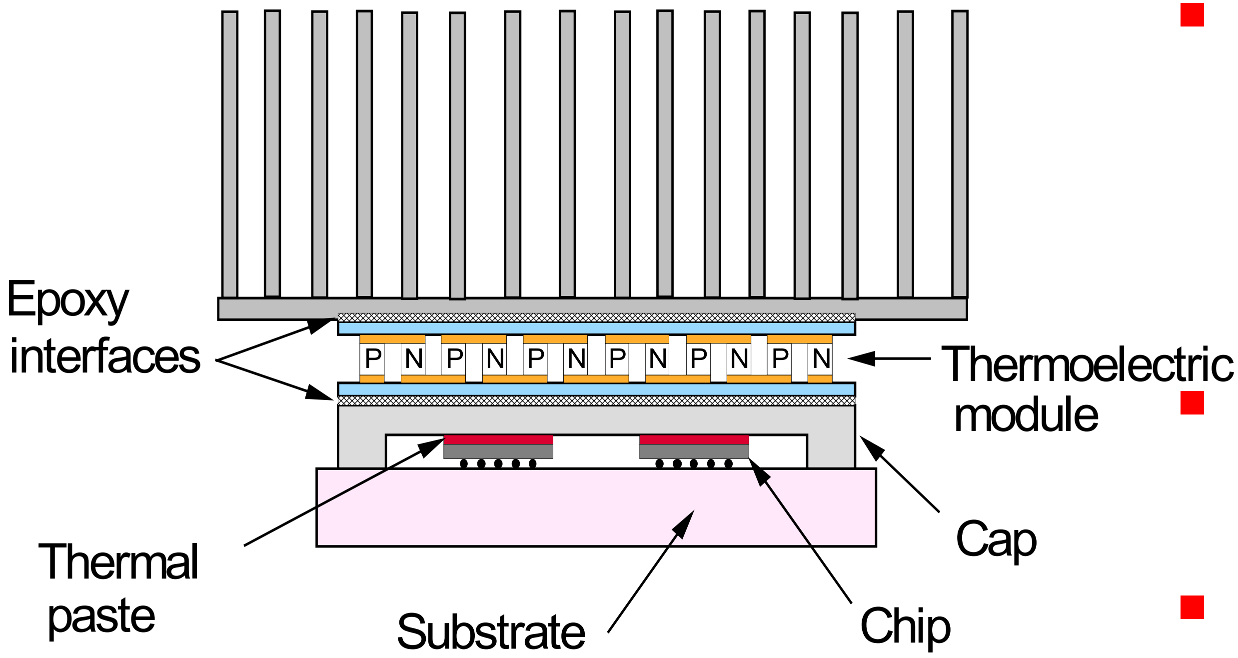
Issues in Refrigerated Packaging

- CMOS Chip/CPU Performance
- Multiple High Power Devices
- Cost of Refrigeration System
  - Life Cycle Cost
  - Volume, Mass
  - Power Consumption
- Reliability of Refrigeration/Packaging
  - Refrigeration Hardware
  - Condensation on PCBs + Refrigerant Lines
  - Vibration

Refrigeration Cooling *Research Needs*

- Highly reliable miniaturized components
- MEMS/meso-scale, low-cost, low noise refrigerators using solid-state, vapor compression, or absorption cycles
- MEMS/meso-scale, low-cost, package-size cold plates
- New thermoelectric materials and fabrication methods

TE Refrigeration
Technology Needs



- Low-cost semi-conductor Technology
- Higher Z factor
- Improved interfaces

Fundamental Thermal Packaging Research

- Low-cost, high-k packaging materials
- Low-Cost, reliable PCM's
- Enhancement of convection/boiling/spray
- Heat Sink/HX Manufacturing processes
- Compact liquid cooling /refrigeration systems
- Improved solid state refrigeration
- Low environmental impact systems
- Integrated modeling tools

Concluding Thoughts

- **Critical Need in Spreading/Interfaces**
  - On-chip
  - On-PCB
  - Heat Sink Base
- **Untapped Potential in Direct Air-Cooling**
  - Heat Sink Optimization
  - Heat Sink Manufacturing Advances

Concluding Thoughts

- **Liquids Provide Superior Spreading**
  - Pumped Cold Plates
  - Pumped/Sprayed Dielectric Liquids
  - Passive Immersion
- **Refrigeration Creates New Options**
  - Chilled Air-Cooling
  - Refrigerated Cold Plate
  - Low Temperature Operation