# Microelectronics Cooling
# "An Overview"

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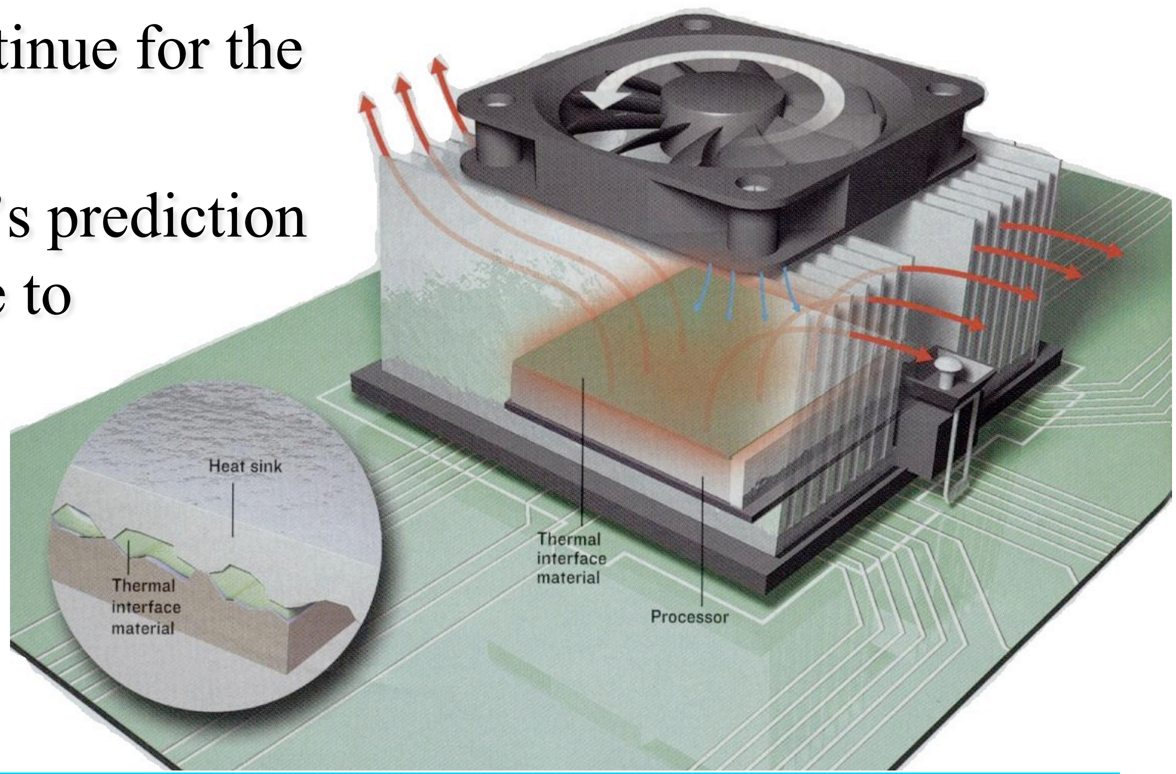
# Outline

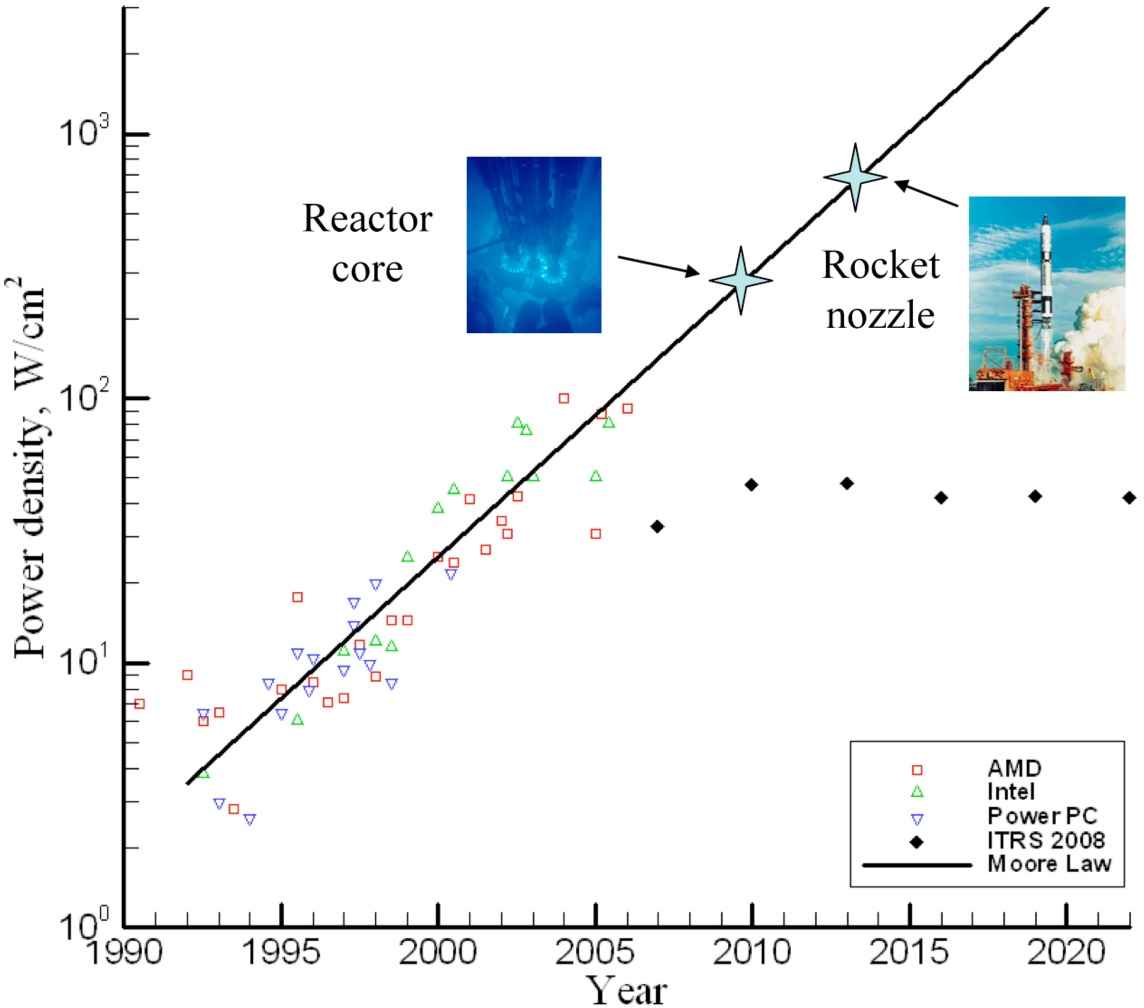
- Motivation
- Thermal Networks
  - Bulk properties
  - Spreading/constriction
  - Boundary heat transfer
  - Joint/interface heat transfer

# Motivation

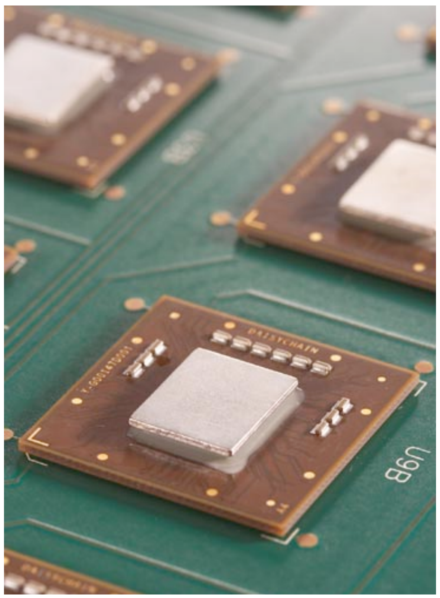
- Heat loads typically follow transistor density
- 1965: Gordon Moore observed that transistor density on ICs was doubling every 18 months and predicted it would continue for the foreseeable future
- After 45 years, Moore's prediction is beginning to fail due to thermal management issues

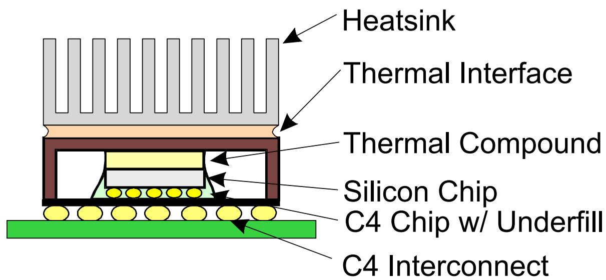


# Cooling Limits

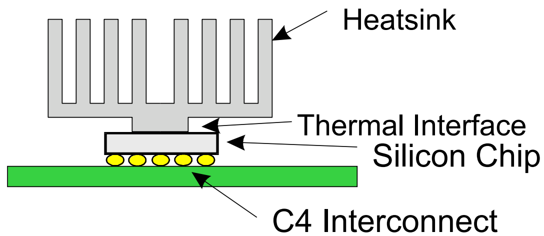


# Thermal Resistance Network

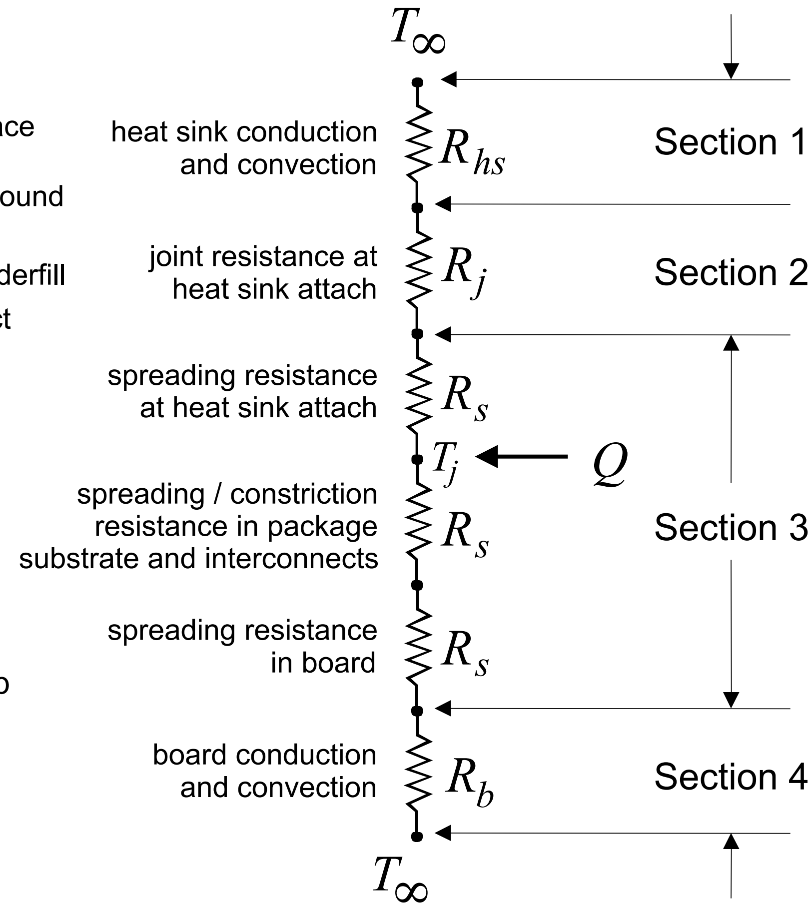





BGA with Heatsink



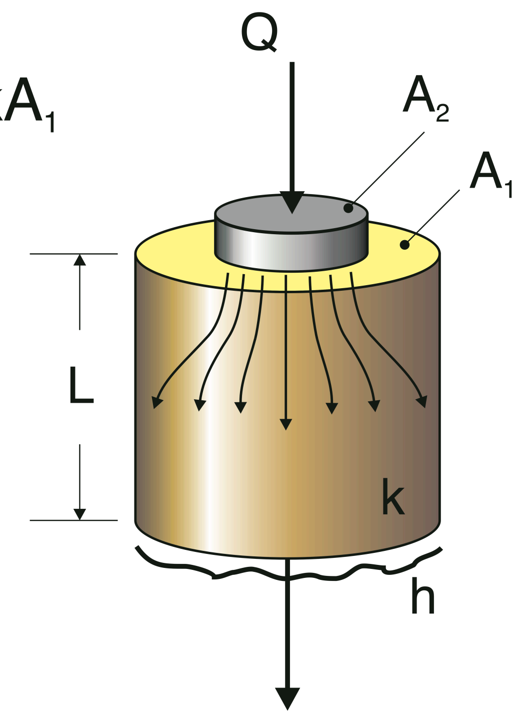

Flip Chip with Heatsink



# Component Resistances

## Material

$$R_{bulk} = L/kA_1$$




## Spreading

$$R_s = \frac{\psi}{\sqrt{\pi}\ kA_1}$$

where $\psi = f(A_1/A_2, L, h, k)$

## Joint

$R_j = 1/(h_j A_2)$, where

$$h_j = h_c + h_g$$

$$\left\{\frac{h_c\,\sigma}{m\,k}\right\} = 1.25\left\{\frac{P}{H}\right\}^{0.95}$$

$$h_g = \frac{k_g}{Y + M}$$

## Boundary

$$R_{bound} = \frac{1}{hA_1}$$

# Effects of Scale

Case 1: k=20 W/mK, t=2 mm, $r_1$=20 mm, $r_2$= 2 mm, h = 20 W/$m^2$K

scale by factor of 0.01

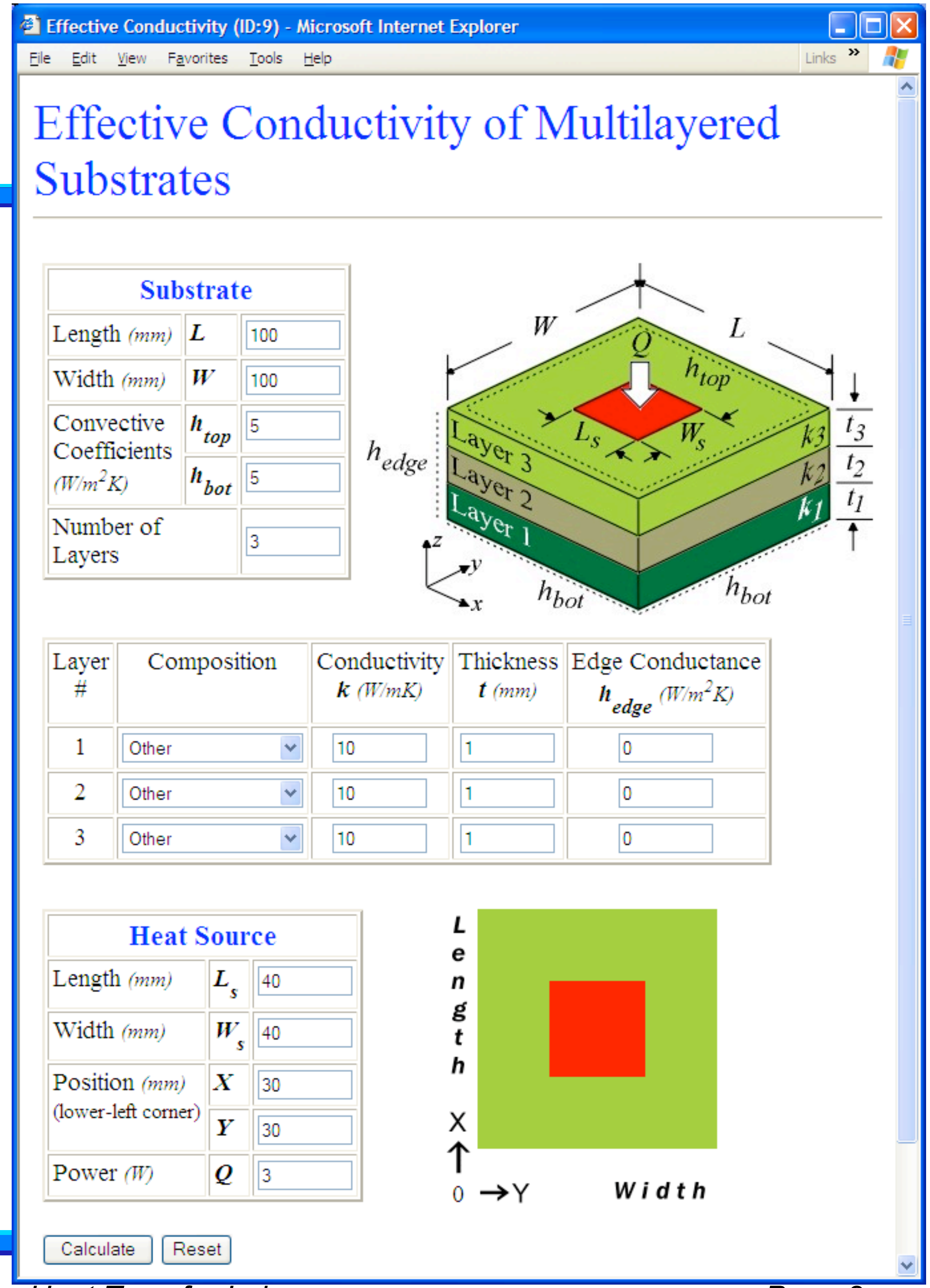
Case 2: k=20 W/mK, t=0.02 mm, $r_1$= 0.2 mm, $r_2$= 0.02 mm, h = 20 W/$m^2$K

| $^oC/W$ | Order | Case 1 | Case 2 |
|---|---|---|---|
| $R_{bulk}$ | $L^{-1}$ | 0.08 | 8 |
| $R_{contact}$ | $L^{-2}$ | 14 | $1.4 \times 10^5$ |
| $R_{spreading}$ | $L^{-1}(L^{-2})$ | 9.2 | 922 ($9 \times 10^4$) |
| $R_{boundary}$ | $L^{-2}$ | 40 | $4 \times 10^5$ |

# Bulk Properties

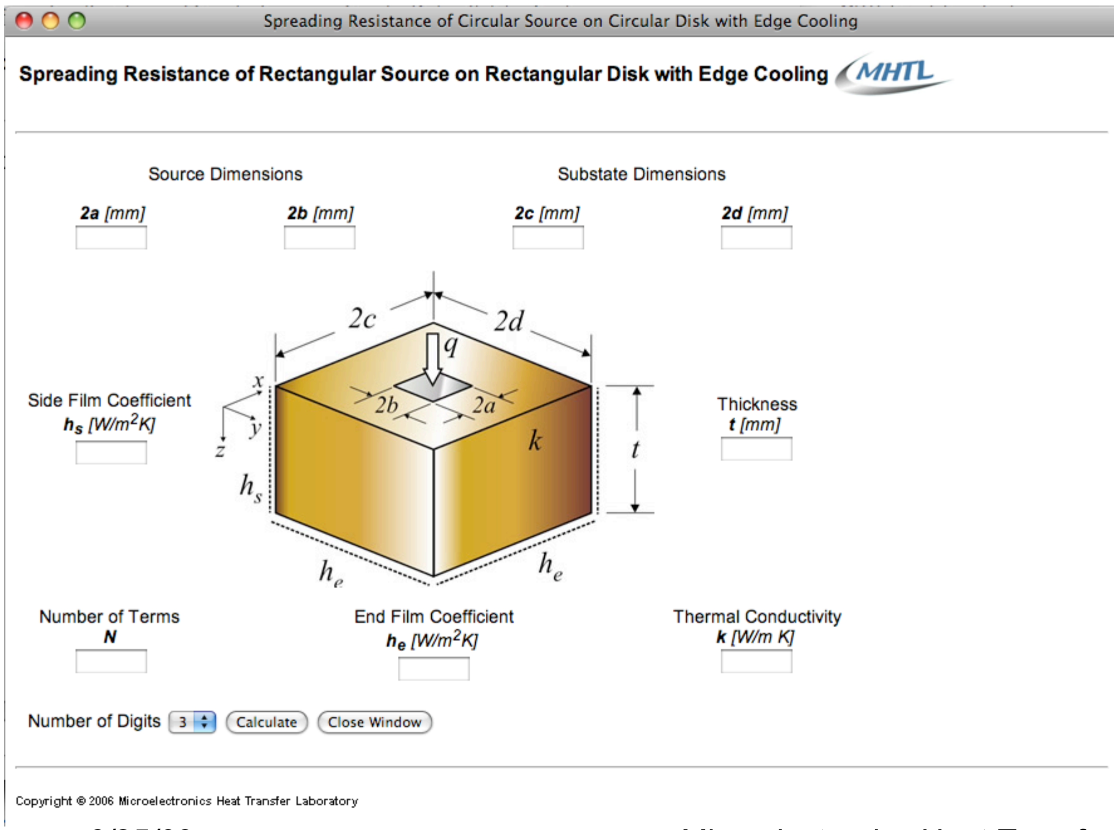
- Effective conductivity calculator based on Fourier series analysis
- Up to 20 layers, pre-programmed material properties available
- Calculated k effective based on relative source size, position and edge conditions

http://mhtlab.uwaterloo.ca/RScalculators.html



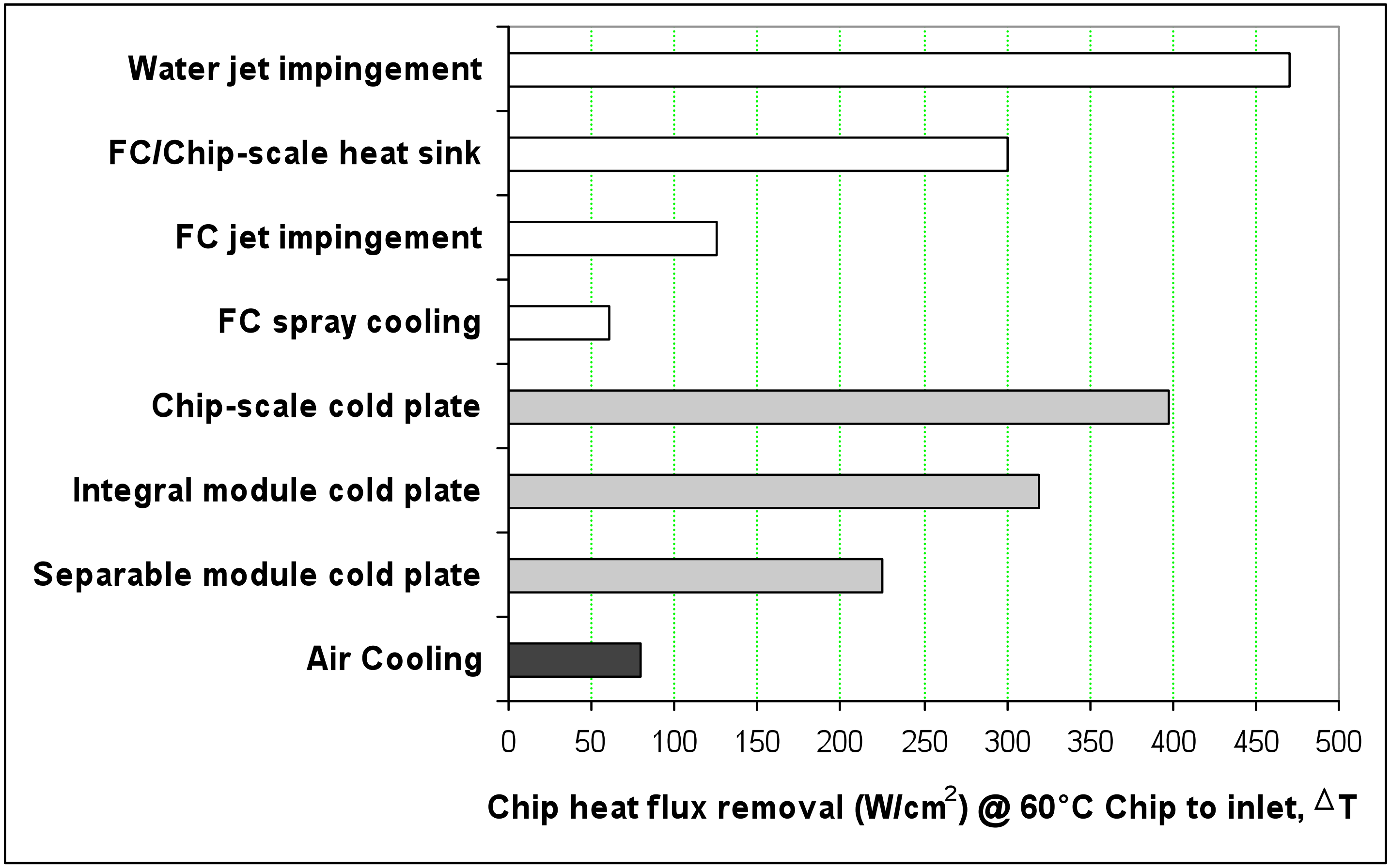
# Spreading Resistance

- General series solution for rectangular, multi-layered flux tubes: *"Influence of Geometry and Edge Cooling on Thermal Spreading Resistance," Muzychka, Y.S., Yovanovich, M.M. and Culham, J.R., AIAA Journal of Thermophysics and Heat Transfer, Vol. 20, No. 2, April-June, 2006, pp. 247-255.*



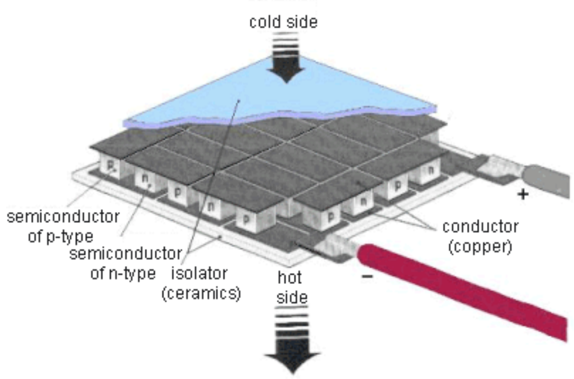

- Circular and rectangular substrates
- Single and multi-layers
- Finite, semi-infinite and infinite flux tubes
- Circular, strip and rectangular sources
- Isoflux, Parabolic, Equivalent Isothermal sources
- Edge cooling

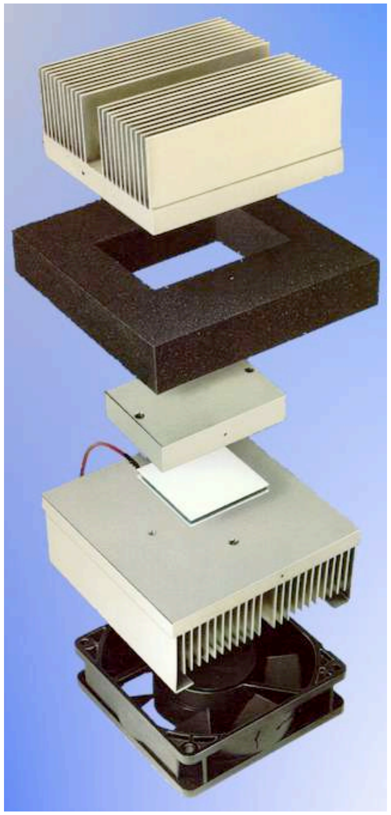
# Cooling Potential



# Boundary Heat Transfer

- Extended surfaces
  - Heat sinks: natural convection, forced convection
  - Cold plates: single phase liquid
- Two phase
  - Micro-refrigeration
  - Vapor chambers
  - Heat pipes
  - Hybrid systems
- Peltier devices



# Heat Sinks

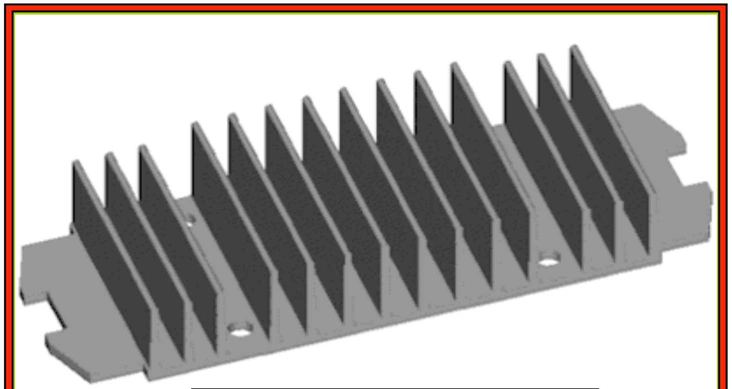
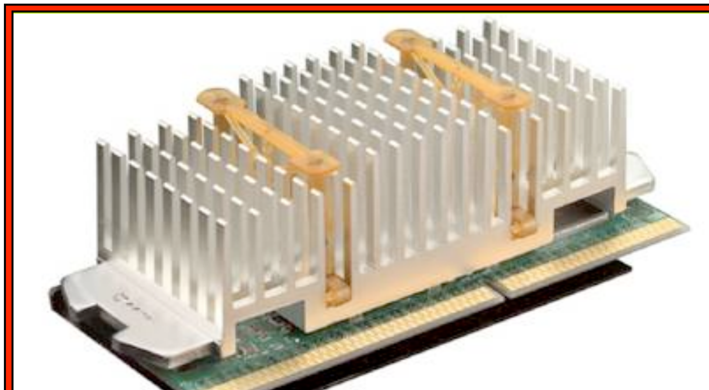


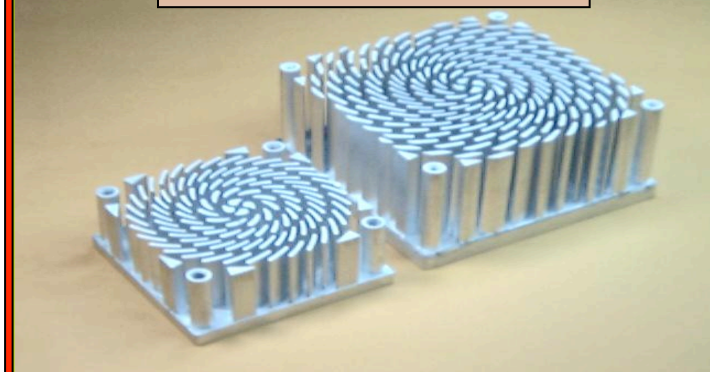
Plate Fin H.S.



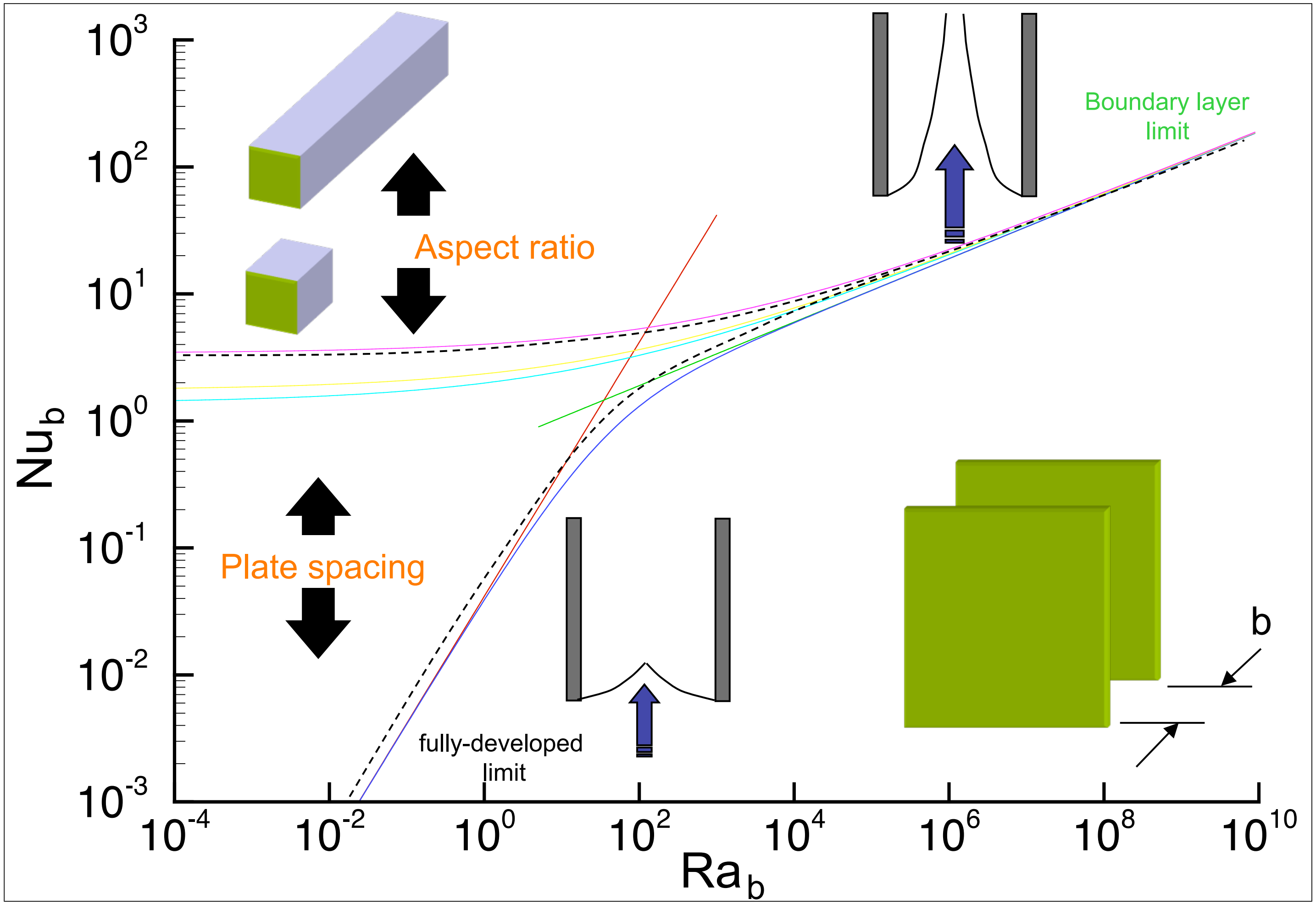
Pin Fin H.S.

Radial Fin H.S.

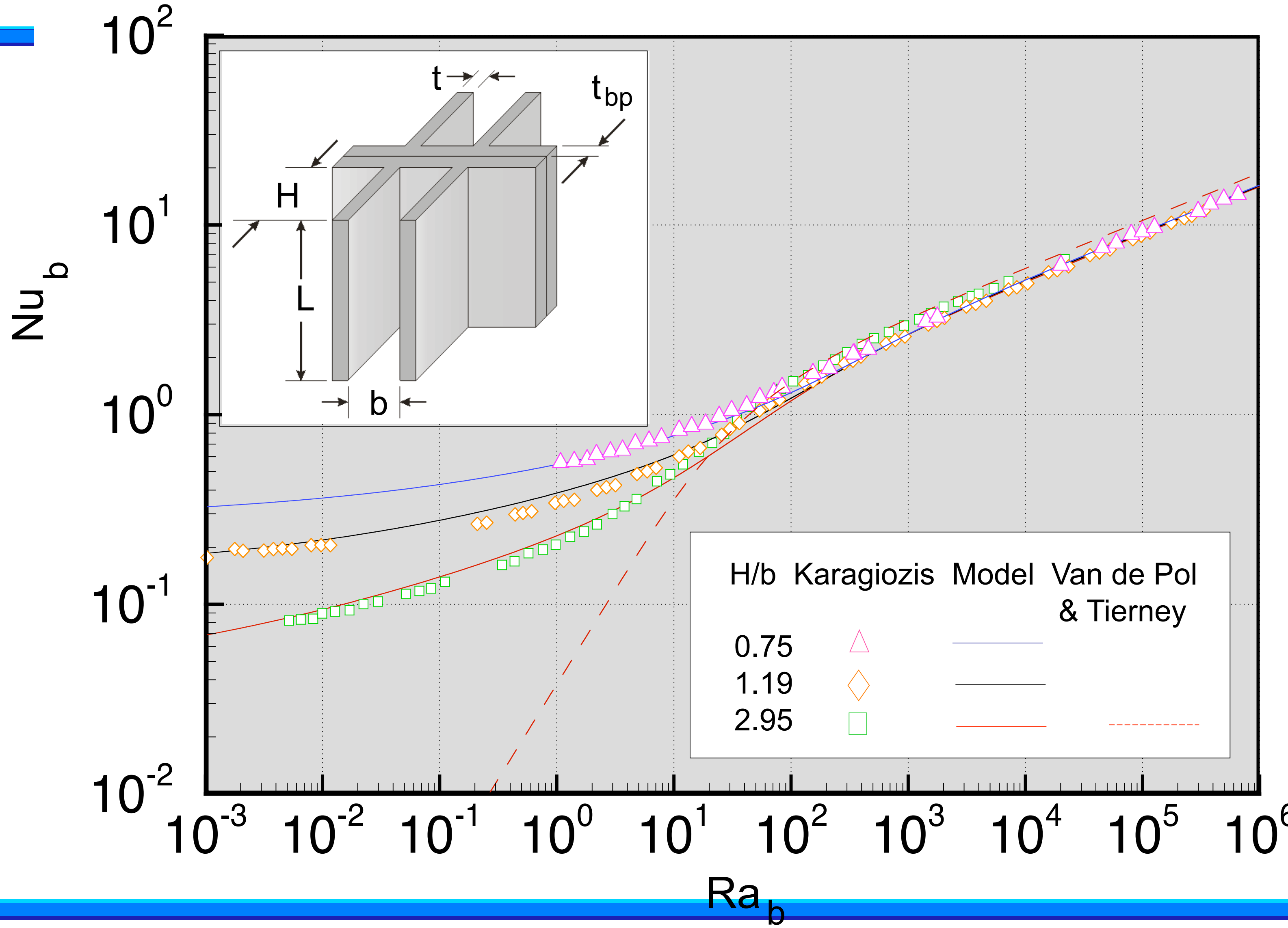
Specialty H.S.



# Modeling of Natural Convection



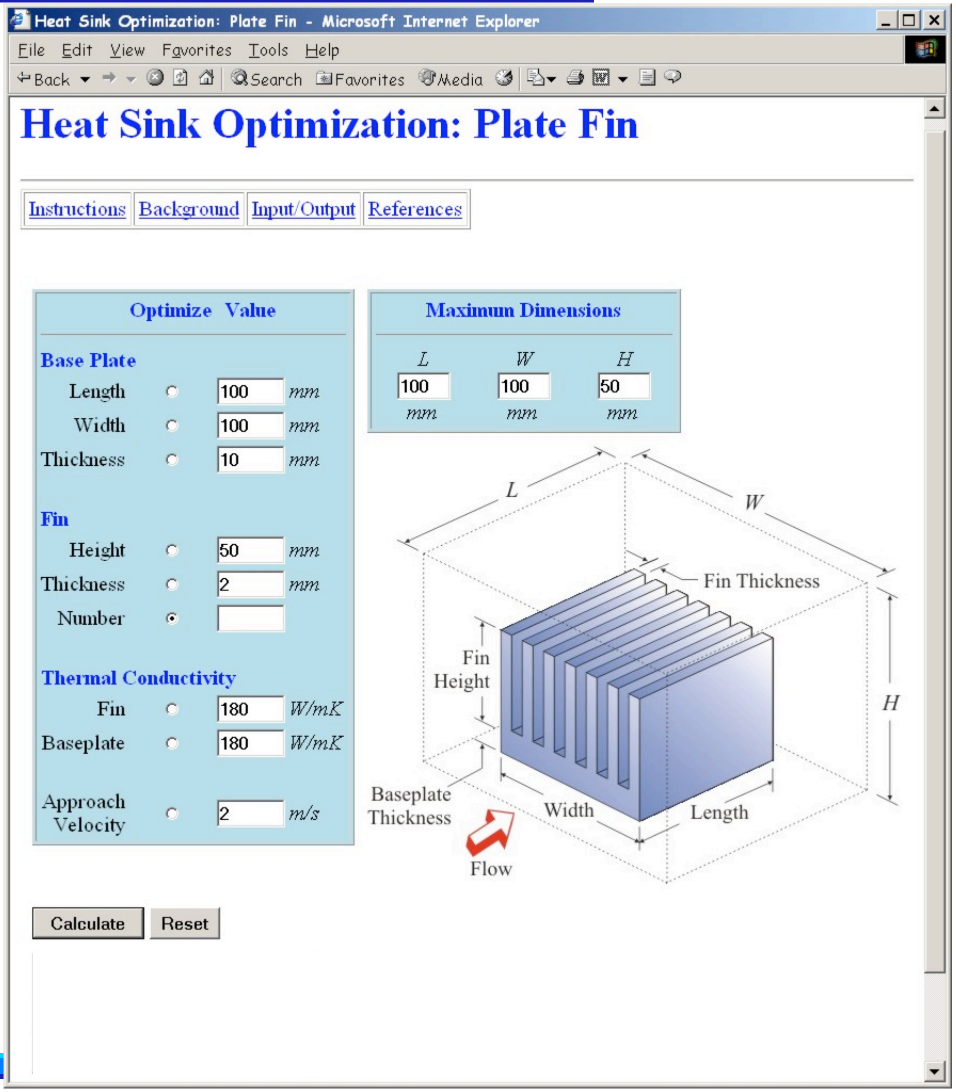
# Model Validation



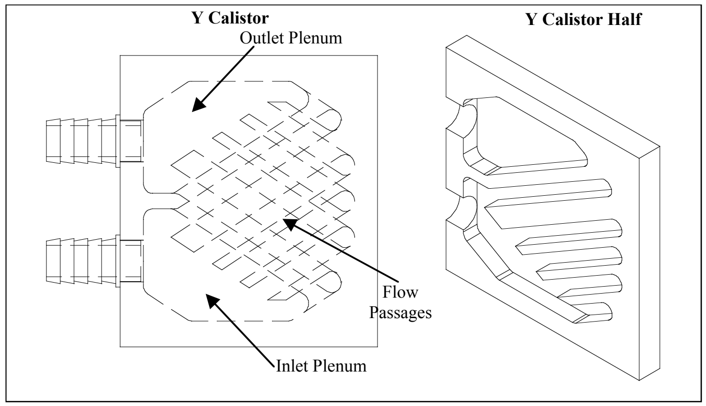
# Heat Sink Models

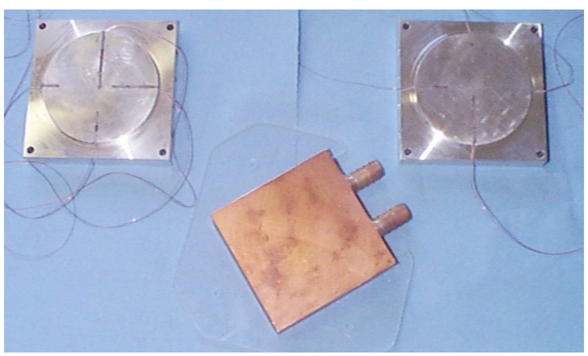
Entropy generation minimization model

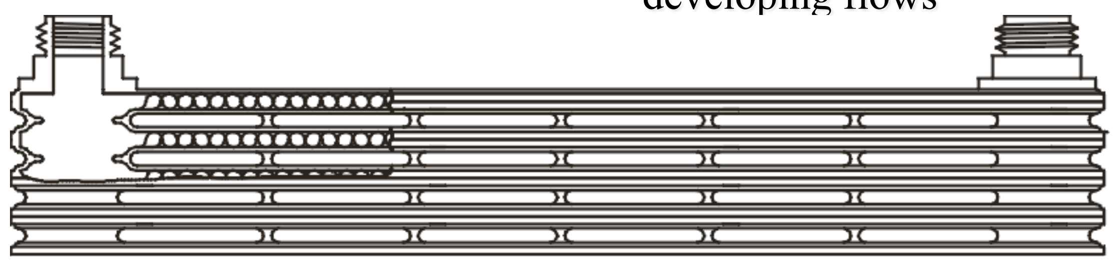
- select maximum working volume
- assign values to fixed parameters
- click calculate to determine optimum value for free parameters
- can be up to 9 free parameters
- determines true, simultaneous optimum value for all free parameters
- solution procedure is applicable for any thermodynamic system



# Single Phase, Liquid Cooling





- Compact cold plates for high heat flux applications
- Modeling and testing of:
  - Fully developed flow
  - Thermally developing flow
  - Simultaneously developing flows

# Micro-refrigeration

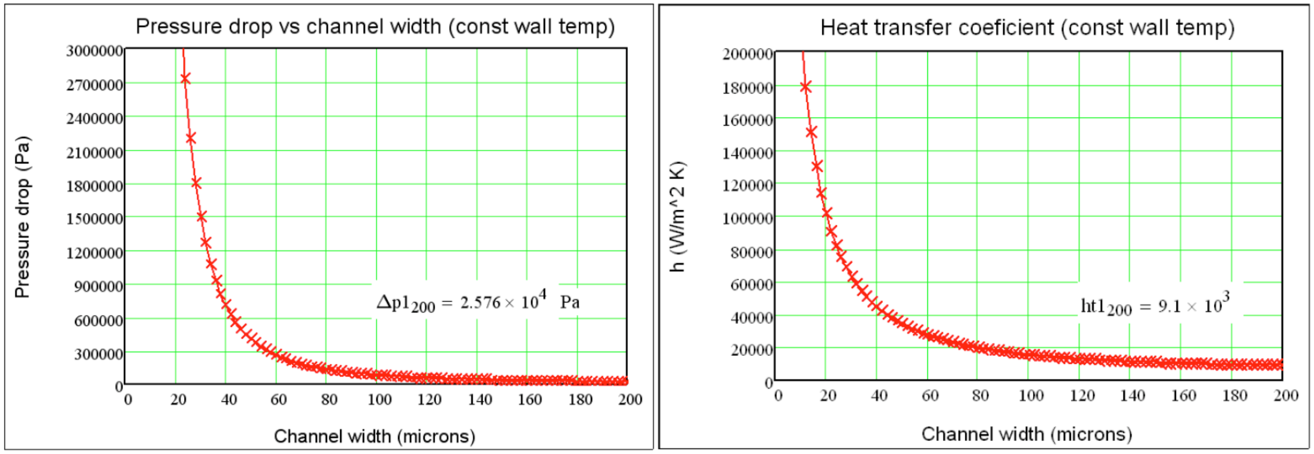
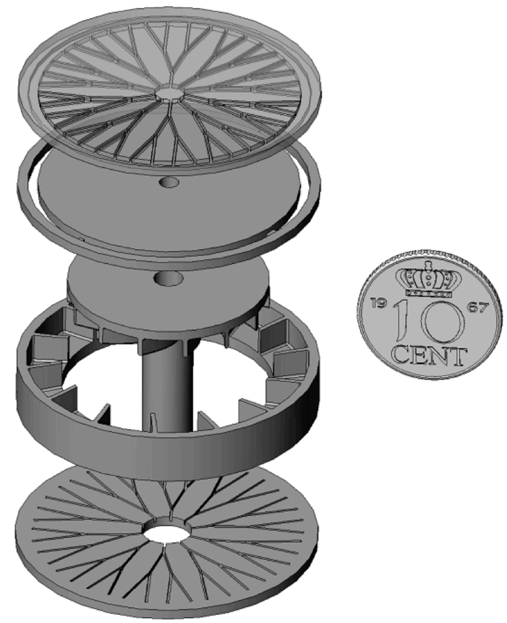
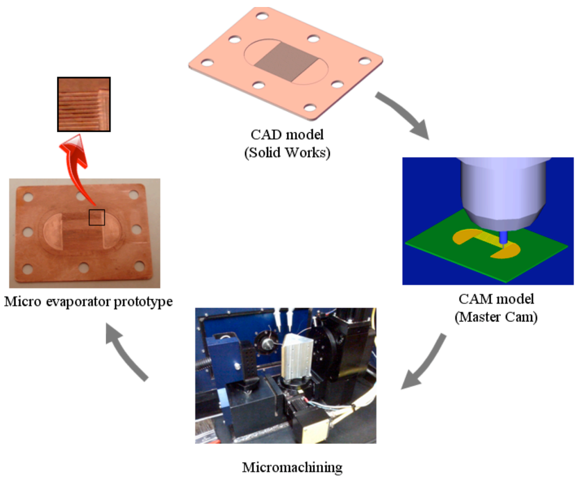
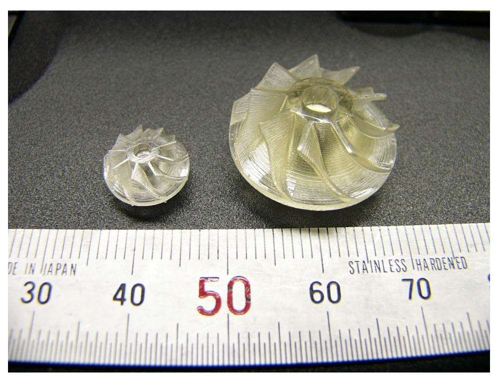
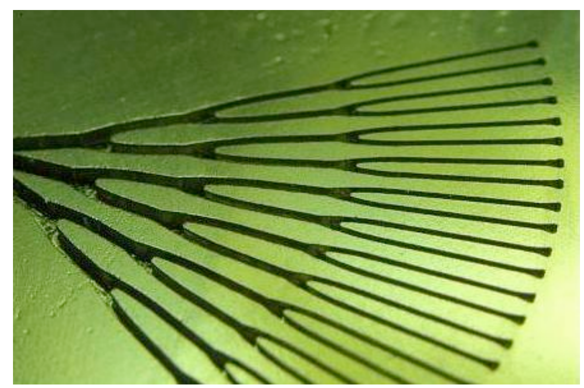



**Figure 4-5: MHE Pressure Drop and Heat Transfer Coefficient vs. Channel Width (Channel length 15 mm, depth 200 mm, flow 3.39x10$^{-3}$ kg/s, $T_{wall}$=59 °C)**



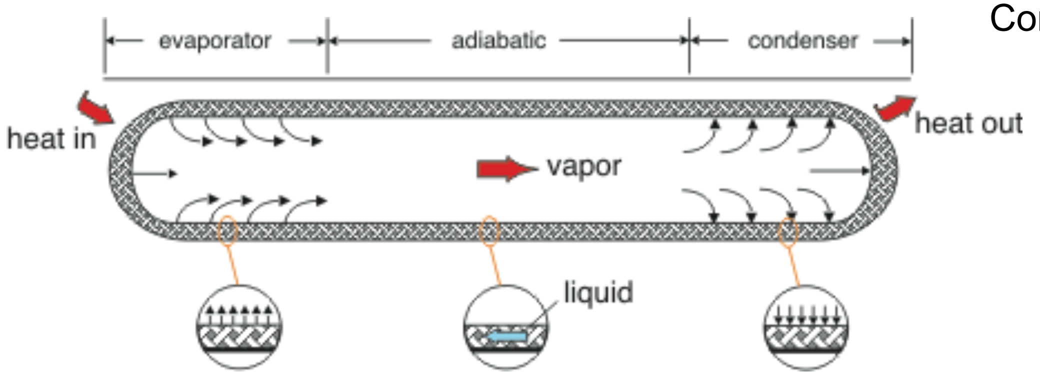



# Heat Pipes

Conventional Heat Pipe



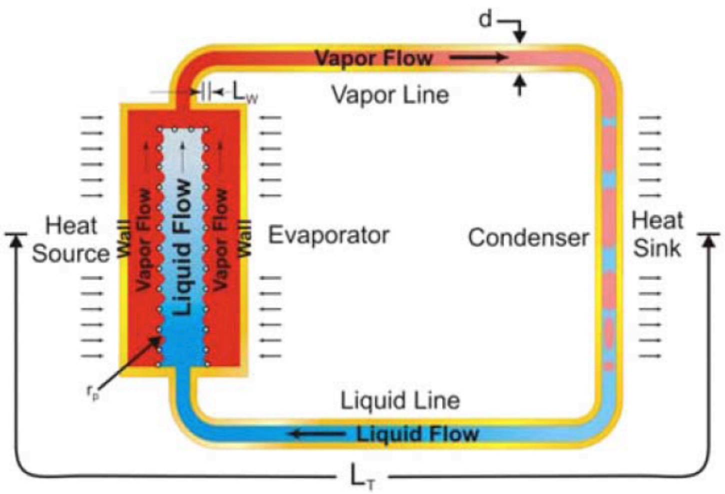
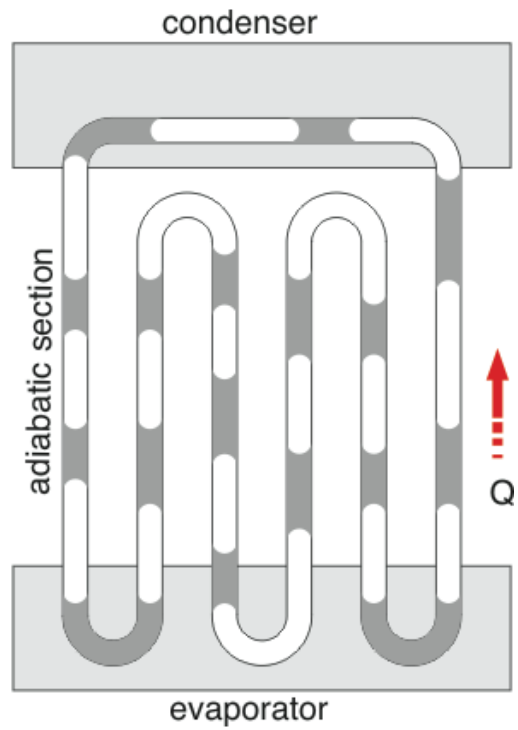



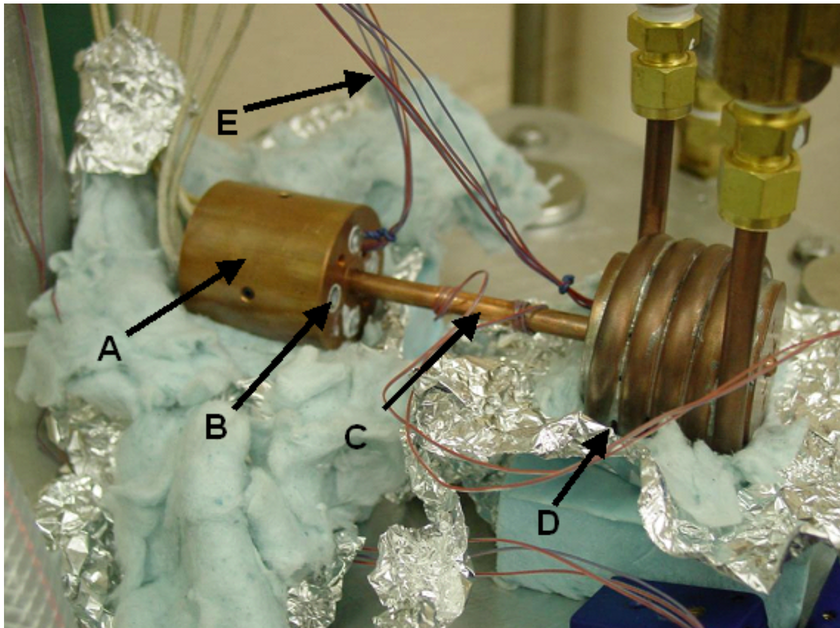

**Figure 8: Typical Loop Heat Pipe**

(Source: http://www.swales.com)

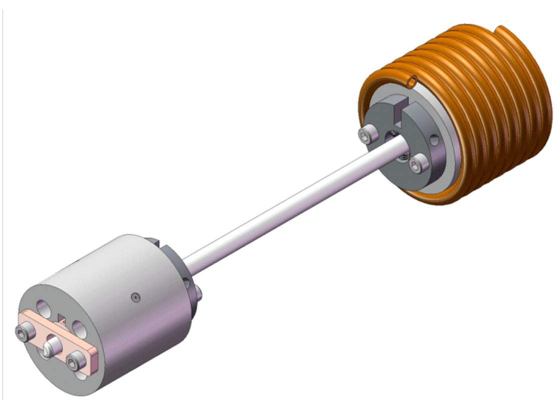


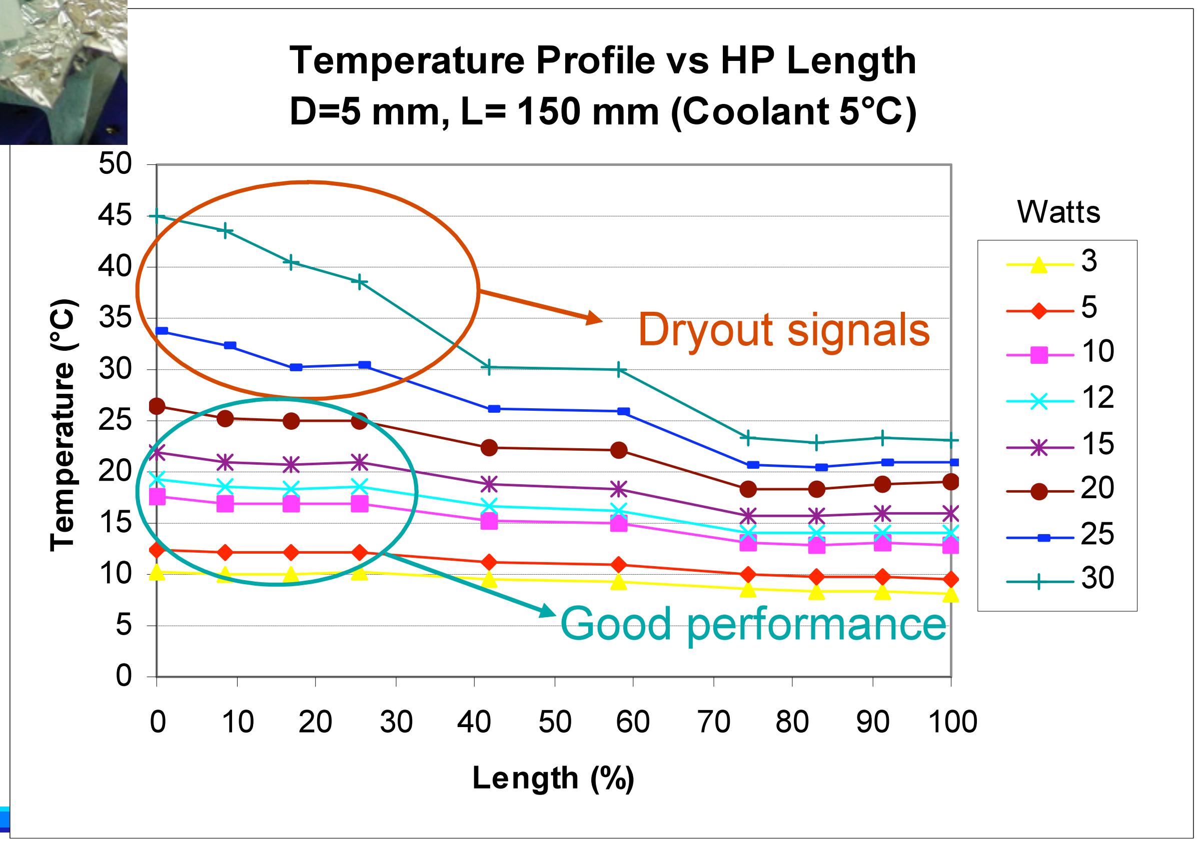

Pulsating Heat Pipe

# Heat Pipes



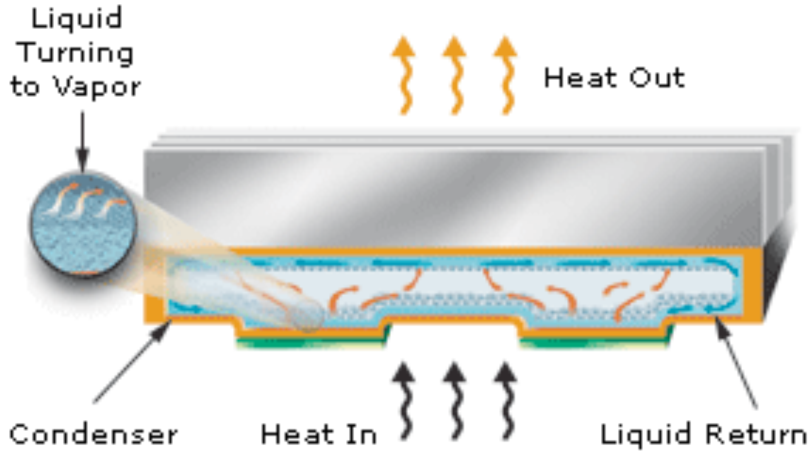
E
A
B
C
D



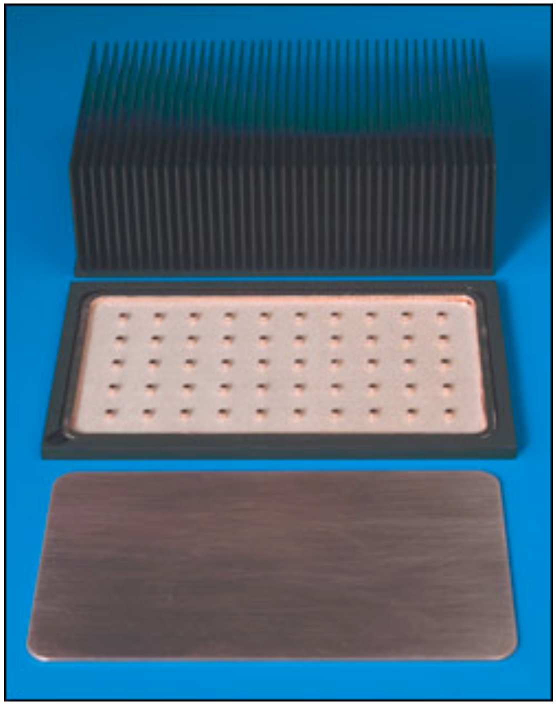
Temperature Profile vs HP Length
D=5 mm, L= 150 mm (Coolant 5°C)
Temperature (°C)
Length (%)
Watts
3
5
10
12
15
20
25
30
Dryout signals
Good performance
0
5
10
15
20
25
30
35
40
45
50
0
10
20
30
40
50
60
70
80
90
100

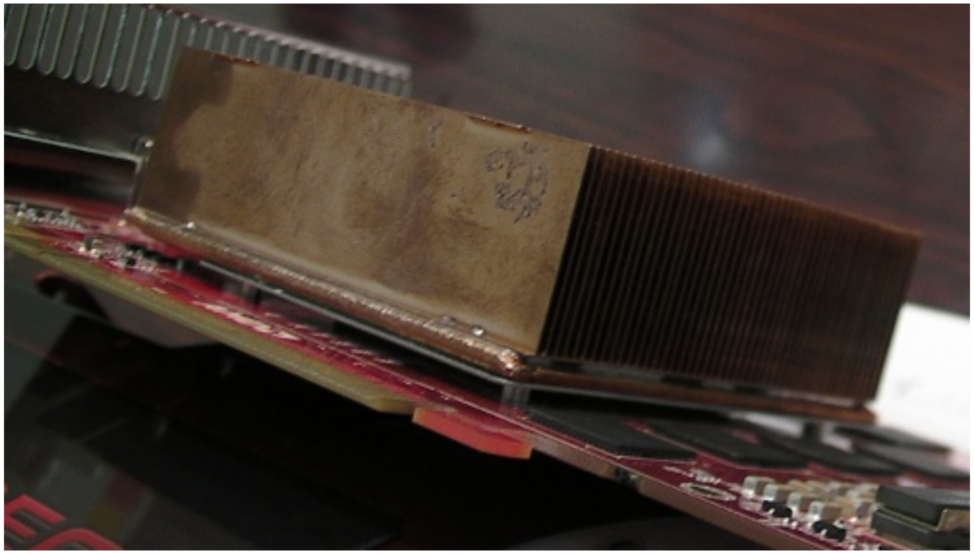
# Vapor Chambers



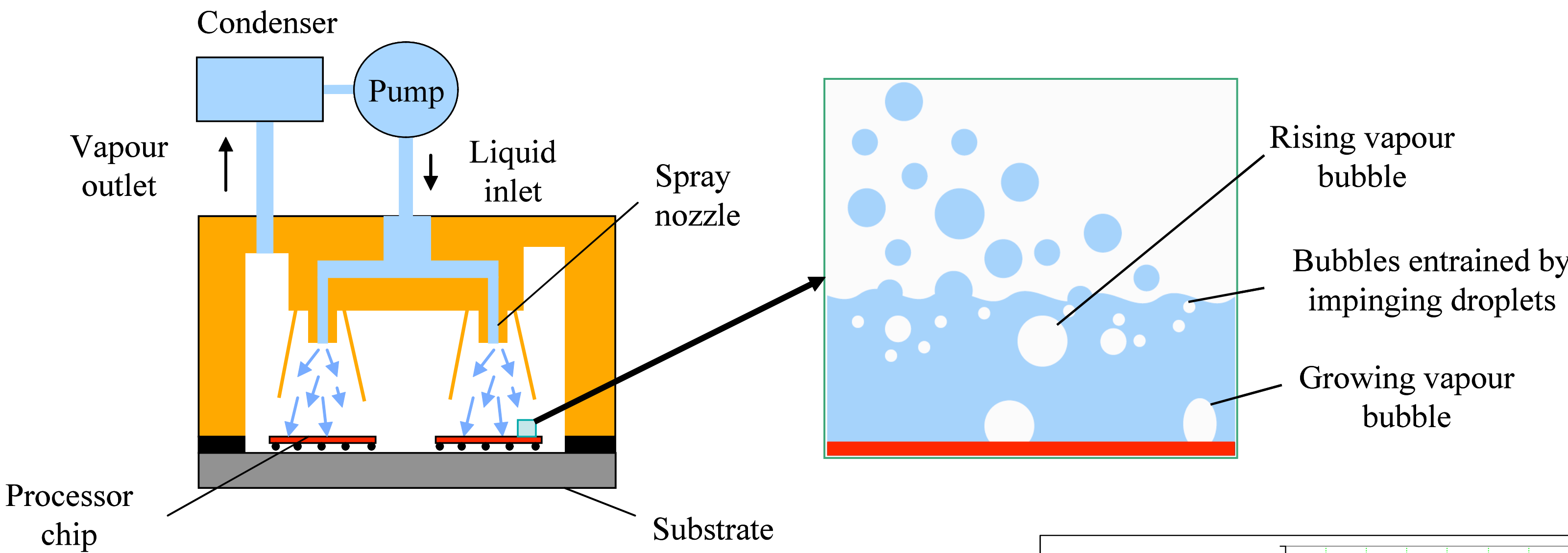

Illustrations courtesy of Thermacore and Advance Cooling Technologies

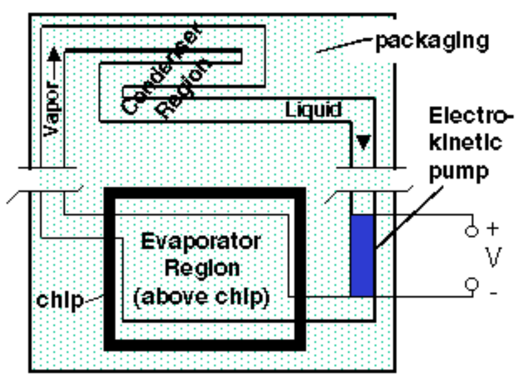
- http://www.1-act.com/
- http://www.thermacore.com/

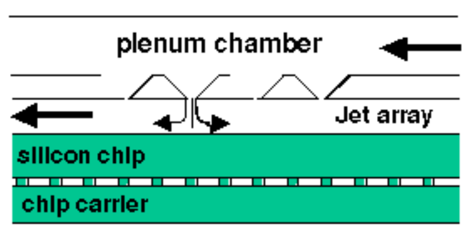


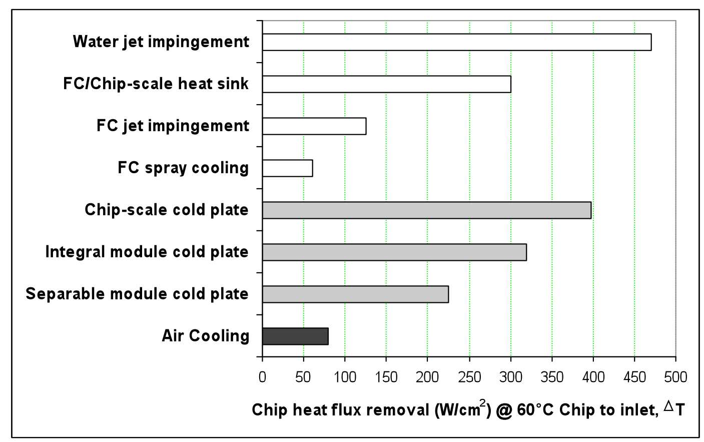


# Jet Impingement

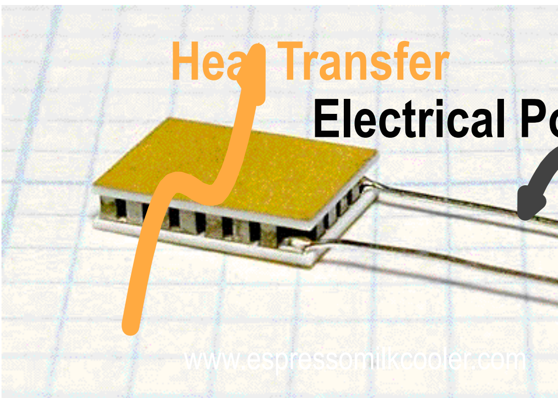


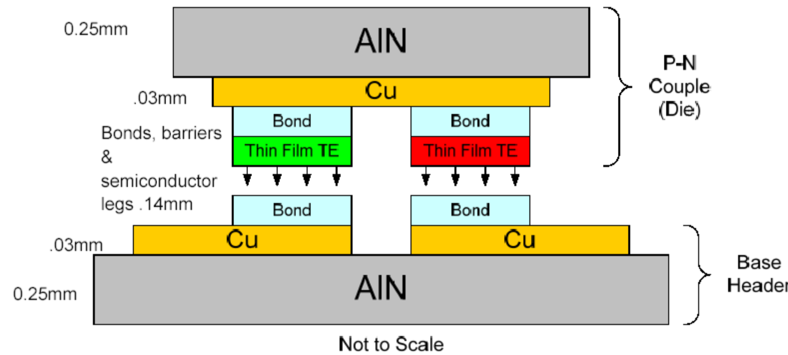



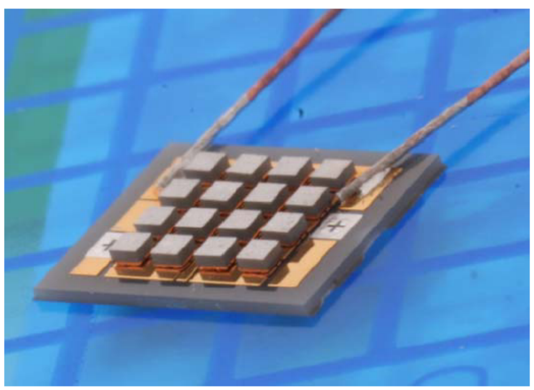



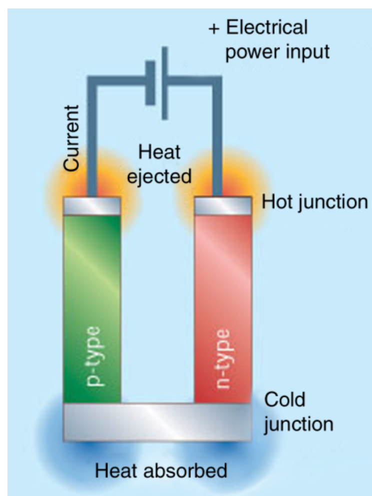
# Peltier Devices

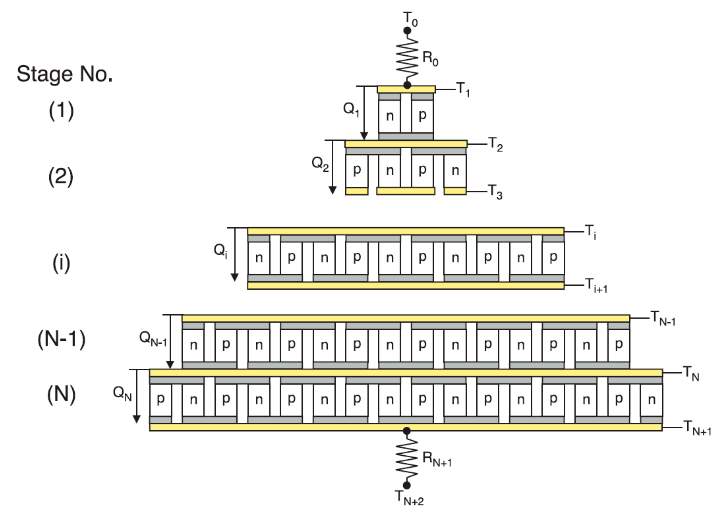


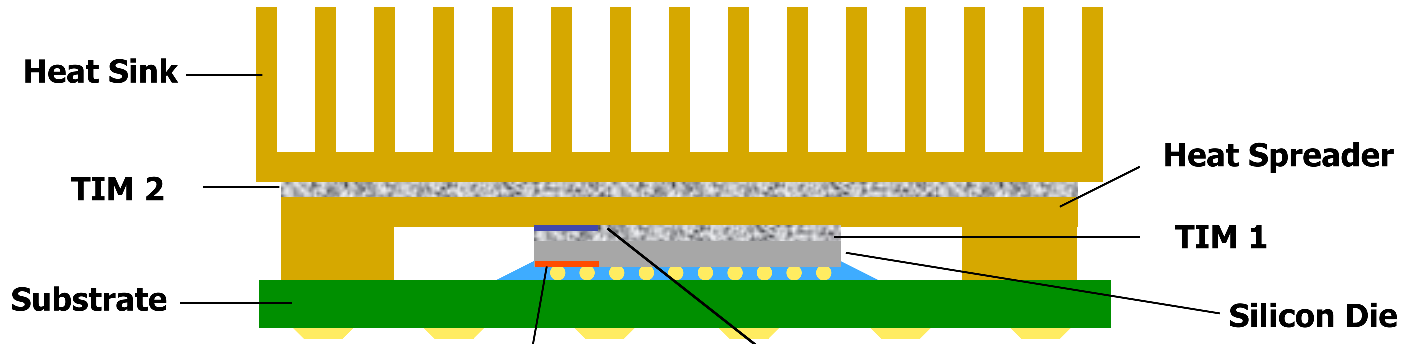

- electric current driven through a Bismuth-Telluride junction
- heat absorbed at the cold junction and released at the hot junction

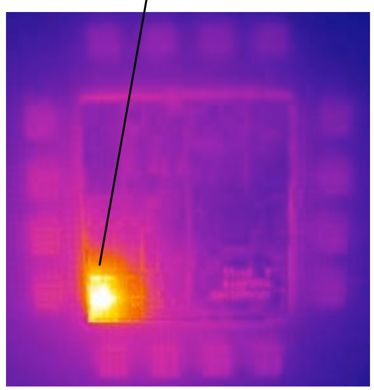


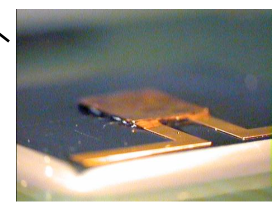


# Embedded Semiconductor Cooling



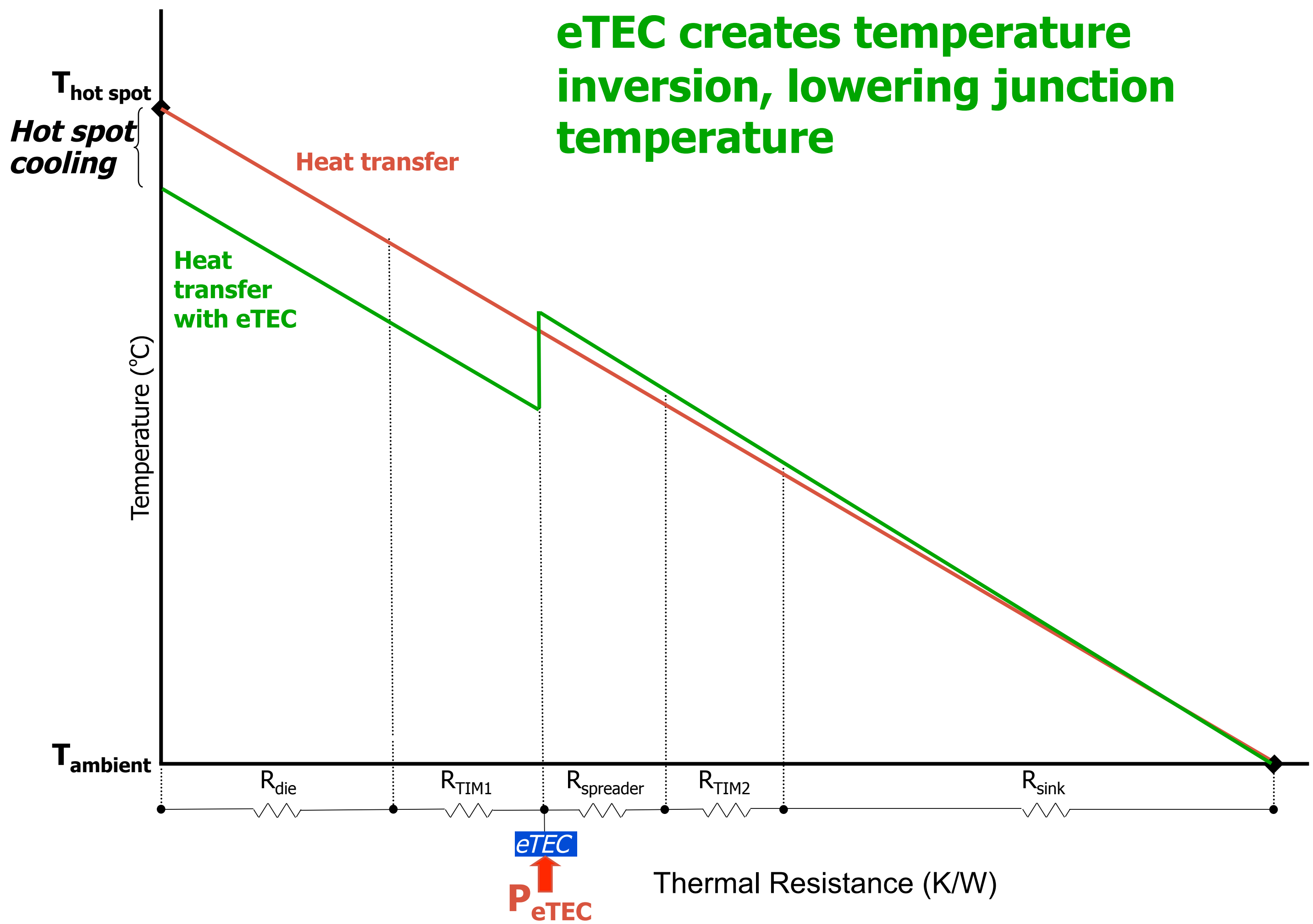


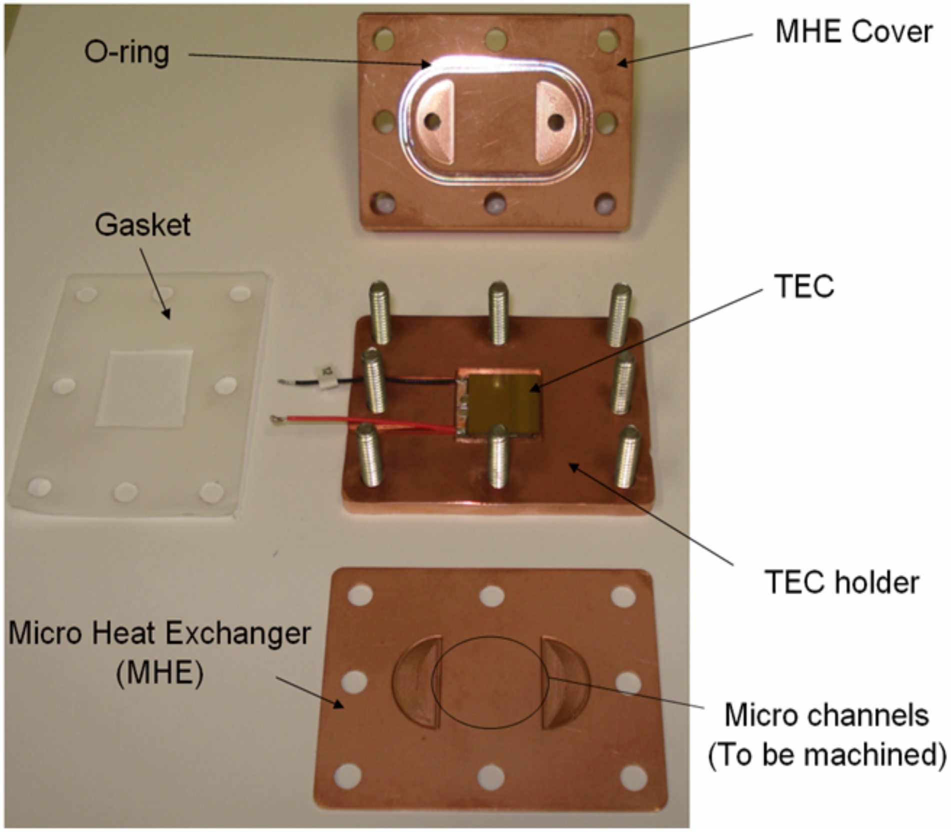
2.5 mm x 2.5 mm
100 μm thickness

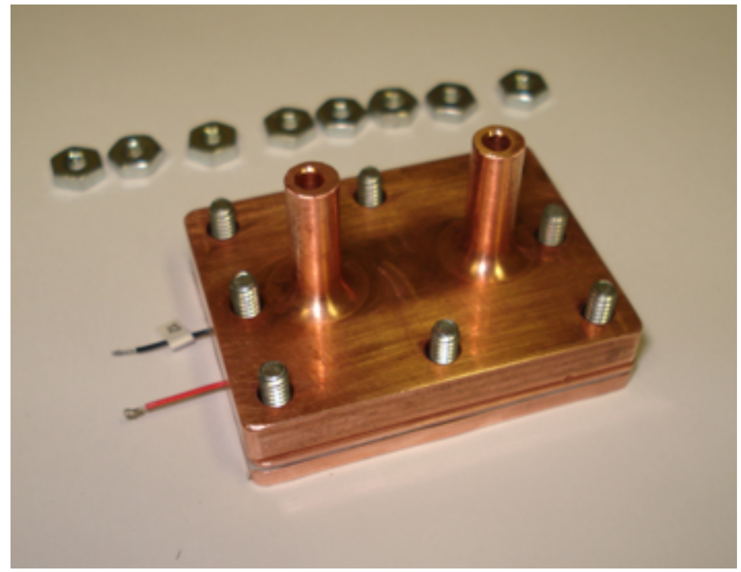
## Embedded TEC in Package

- Reduces effect of non-uniform heat transfer
- Cools hot spot by 5-15°C

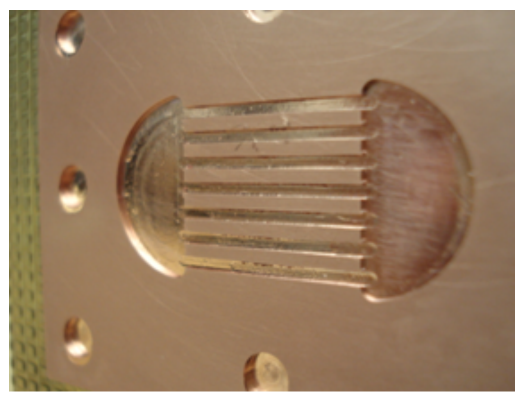
# 1D Thermal Model



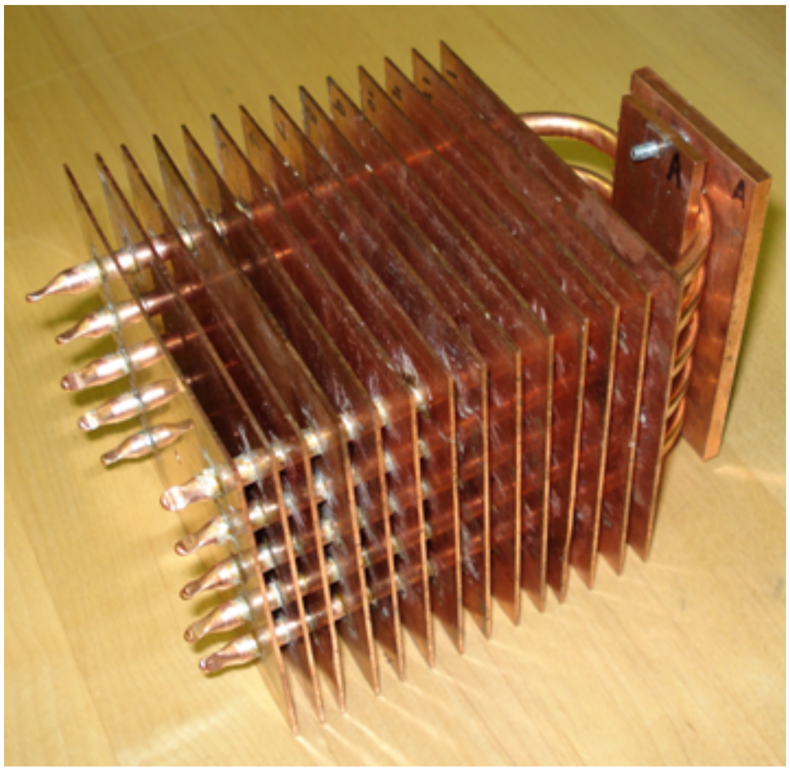


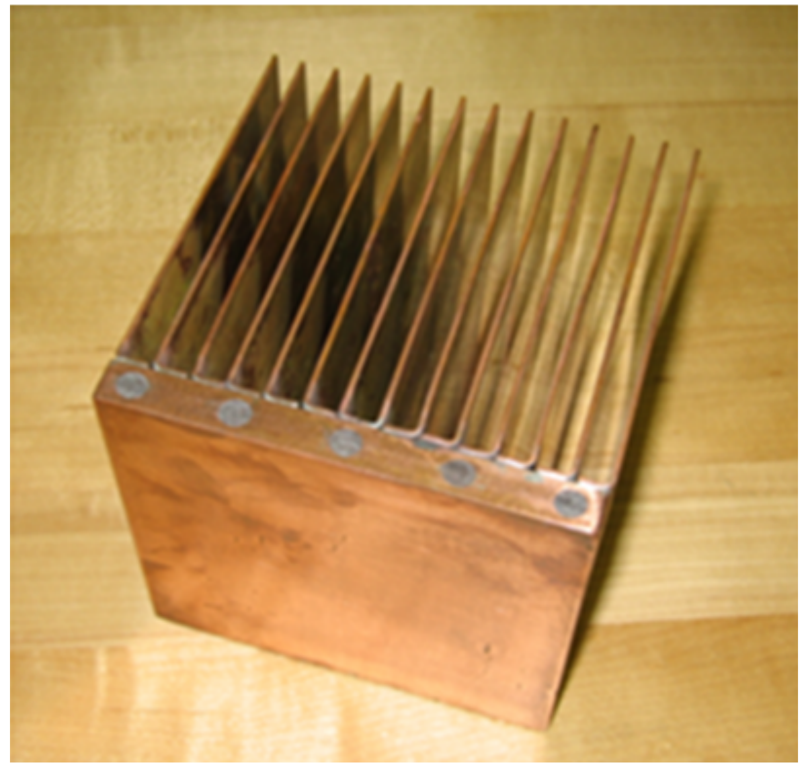



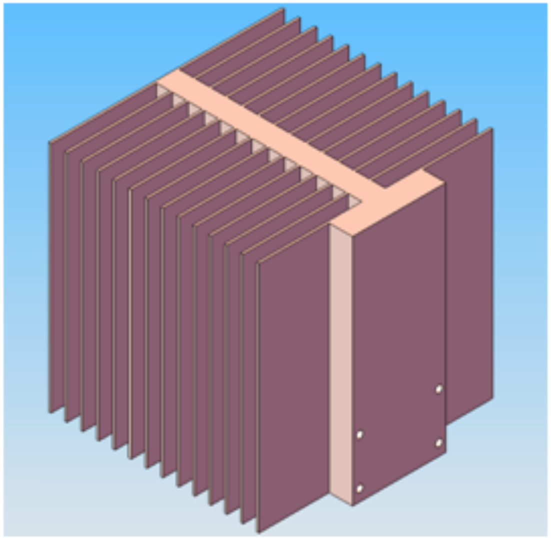
# Hybrid Systems



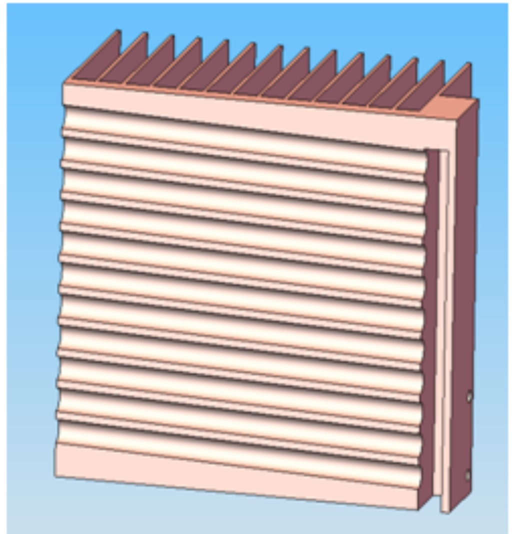
# Hybrid Systems



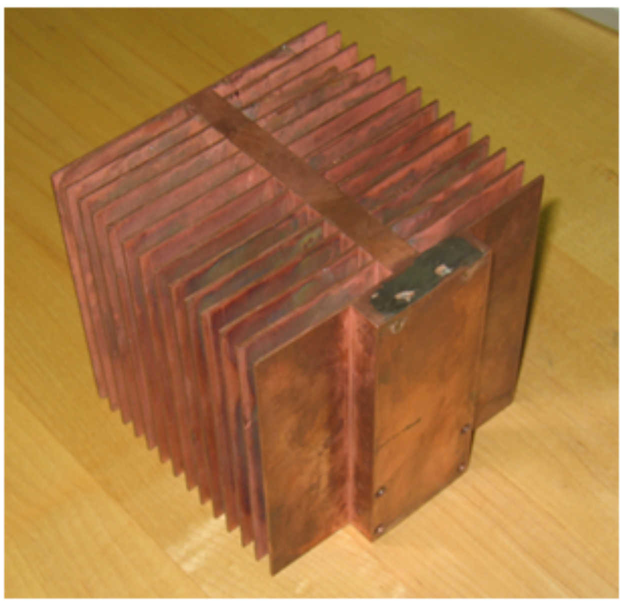




a



b



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# Hybrid Systems

# Thermal Contact Resistance: Non-Conforming, Rough Surfaces

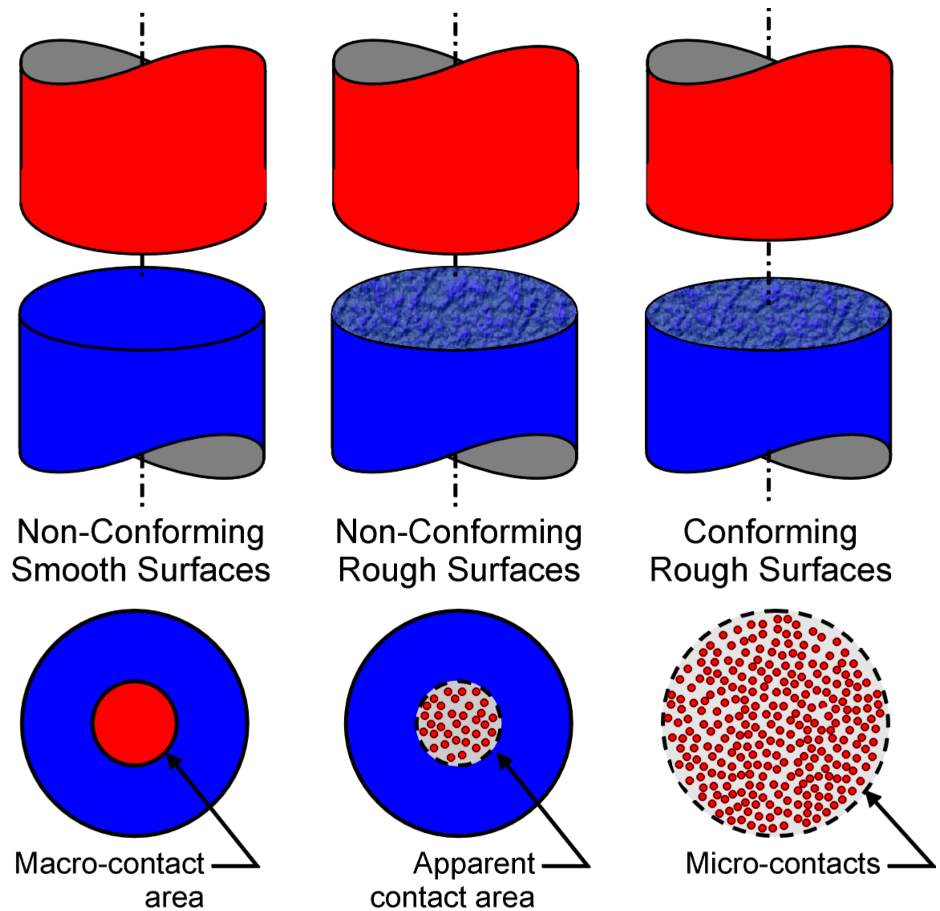
MHTL

## Objectives

- develop thermo-mechanical models for predicting contact resistance in real surfaces with microscopic roughness and waviness

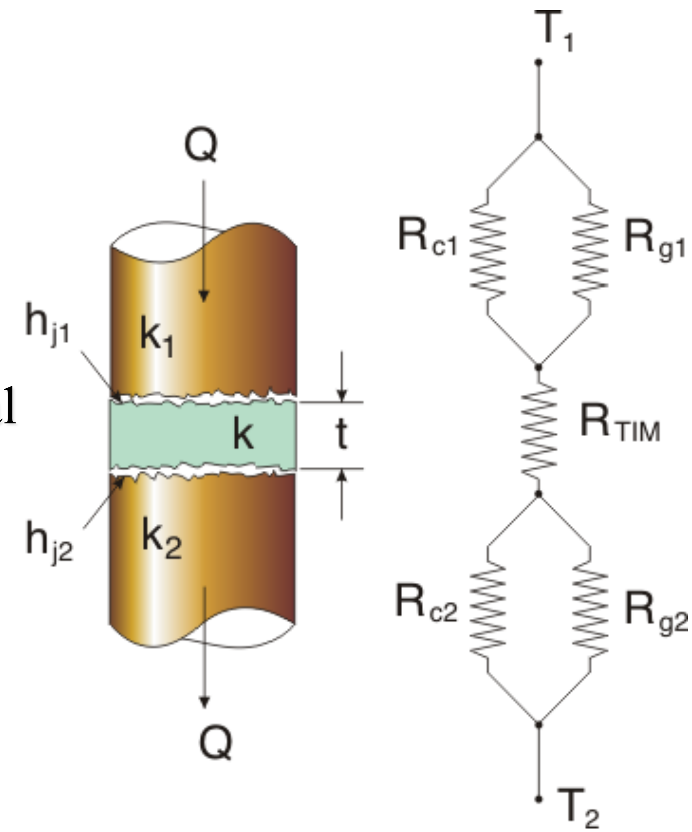
## Overview

- mechanical models combine the effects of plastic deformation at the microscopic level with elastic deformation at the macroscopic level



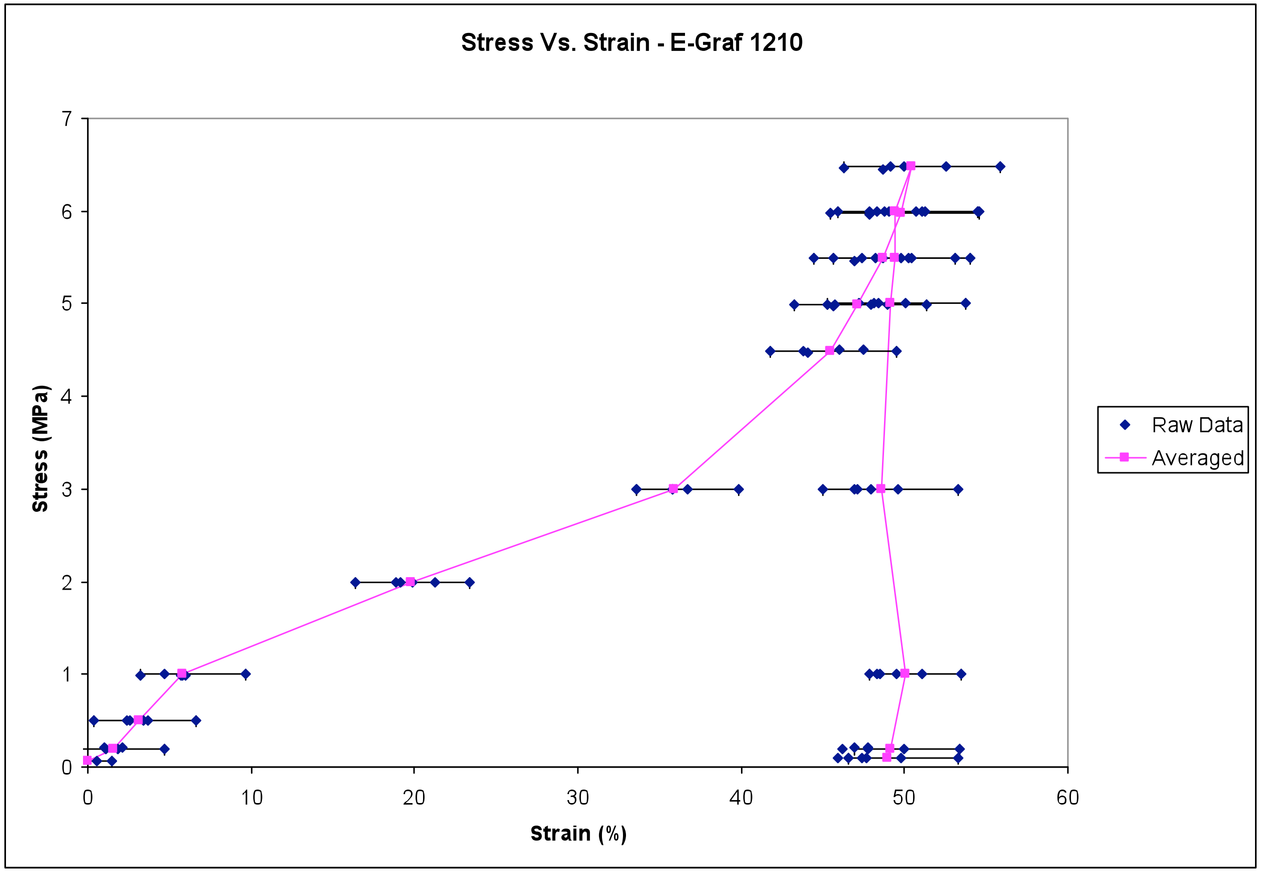
# Thermal Interface Materials

- Two major categories
  - Solid layer materials – polymers, graphite, metal foils
  - Fluidic materials – thermal grease, phase-change materials
- Current industry design practice
  - Select TIM based on manufacturer's specifications
  - Limited experimental verification or analytical modeling
- TIM manufacturer's specifications
  - Variety of measurement techniques
    - ASTM D5470 and variations
    - Laser flash diffusivity tests

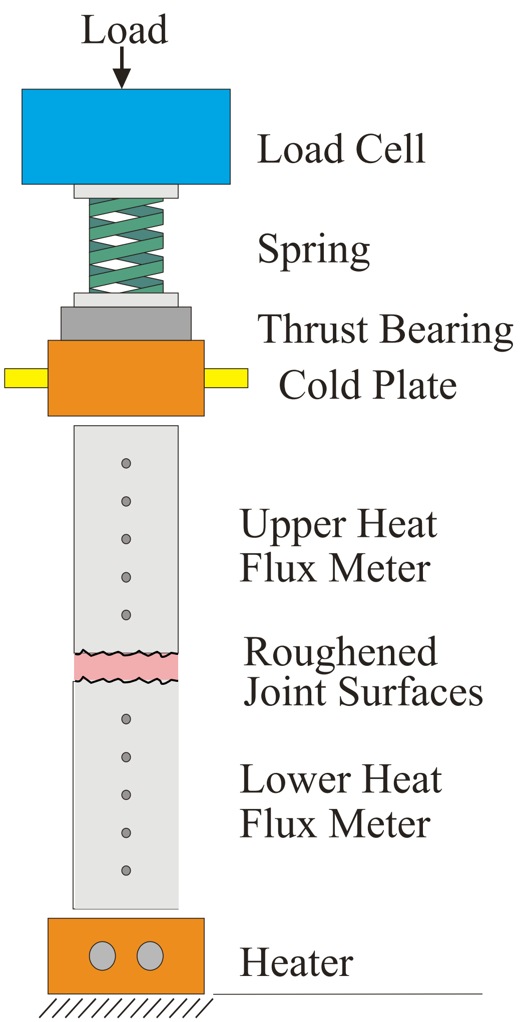


# Sample Thickness Measurements

- Thickness vs. load tests for E-Graf 1210

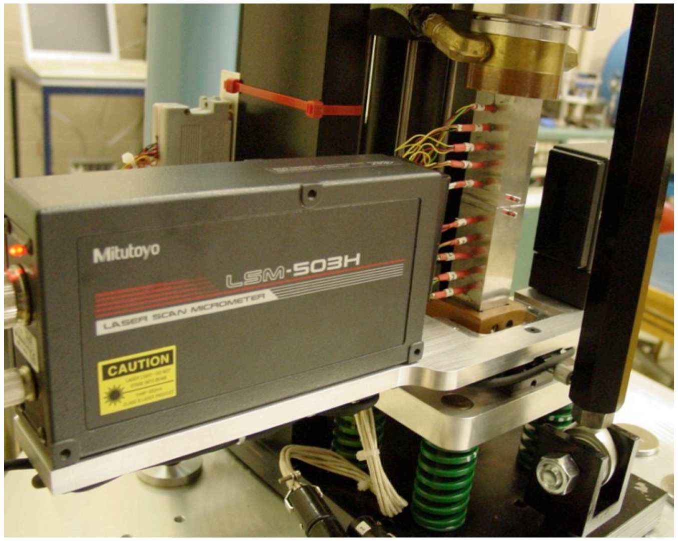


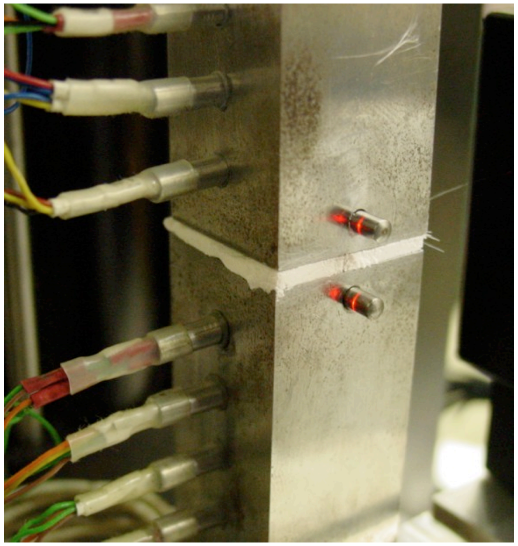
# Thermal Resistance Testing




## Thermal Interface Testing

- steady state test
- prescribed interface pressure
- prescribed heat load
- measure temperature drop across the interface
- measure heat load with flux meters
- measure interface thickness with laser extensometer
- k = (Q x t)/(A x  [T1 – T2])



Questions?