HIGH FLUX VALUE MICRO HEAT PIPE ARRAYS

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Why Liquid Metal Micro Heat Pipes (MHPs)

- Phase Change Heat Transfer
- High Heat Flux Ability Using Liquid Metals
- Embedded Directly Under Electronics Heat Source
- Good Si or Ceramic CTE Matching Abilities

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Introduction

III. Micro Heat Pipes (MHPs):

- Concept was first introduced by Cotter in 1984
- Cotter defined micro heat pipe as being " the one in which the mean curvature of the vapor-liquid interface is comparable in magnitude to the reciprocal of the hydraulic radius of the total flow channel"
- The basic working mechanism is same as the heat pipes, the distinguishing factor being the omission of the "wick" structure
- Characteristic small sizes, makes MHPs suitable for the semi-conductor industry applications

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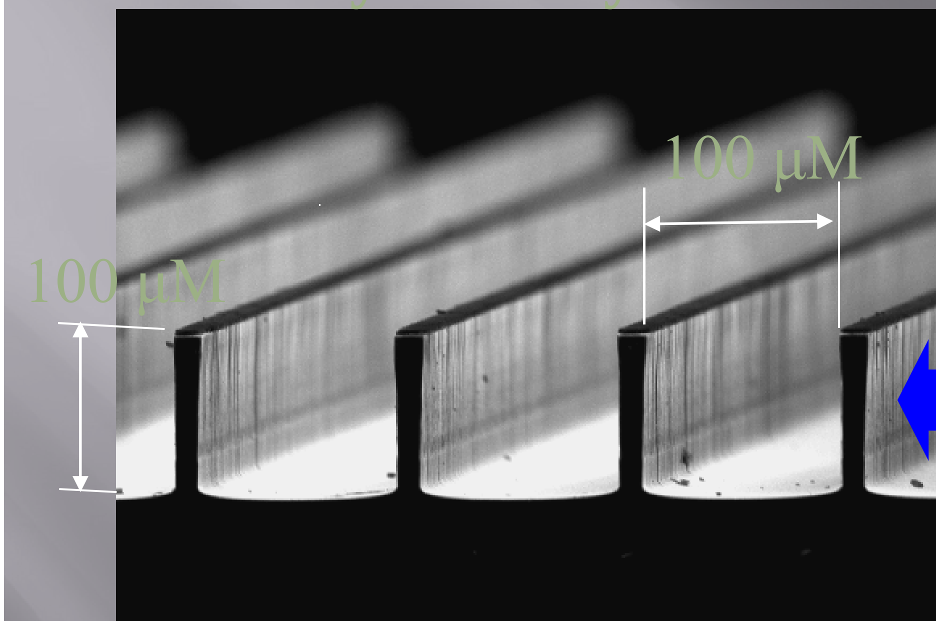
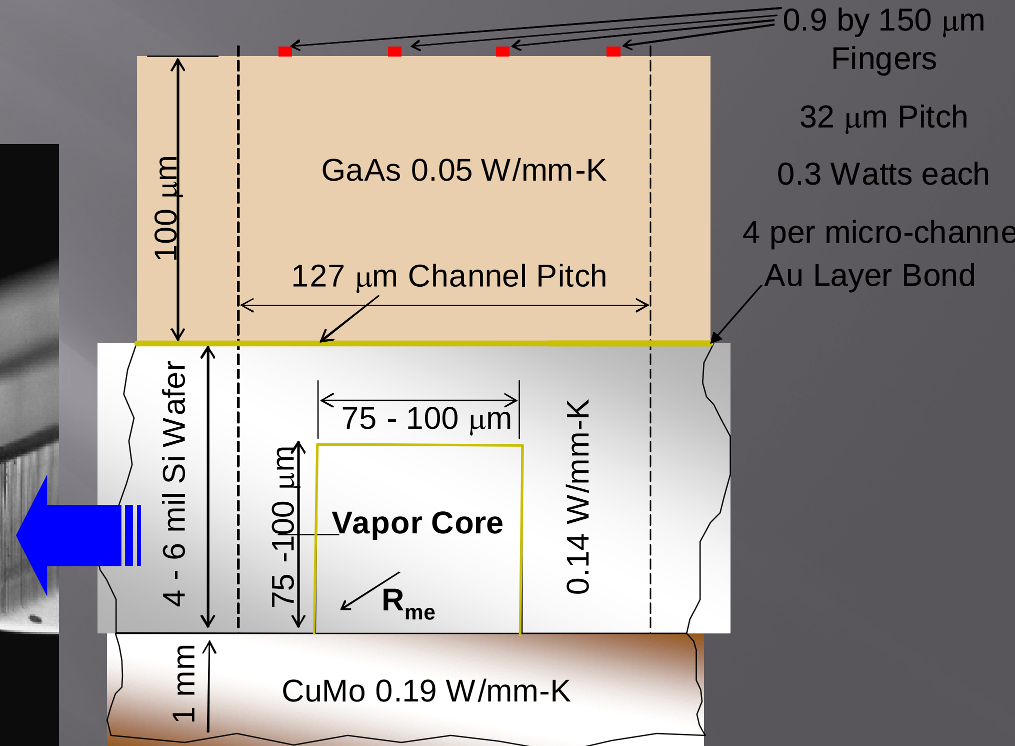
Micro-heat Pipes in Si Heat Spreaders

22 micro-channels in an array 5 mm by 10 mm





- DREI etch process performed in Auburn University micro-machining laboratory
- Process is well characterized and very repeatable in a manufacturing environment 4

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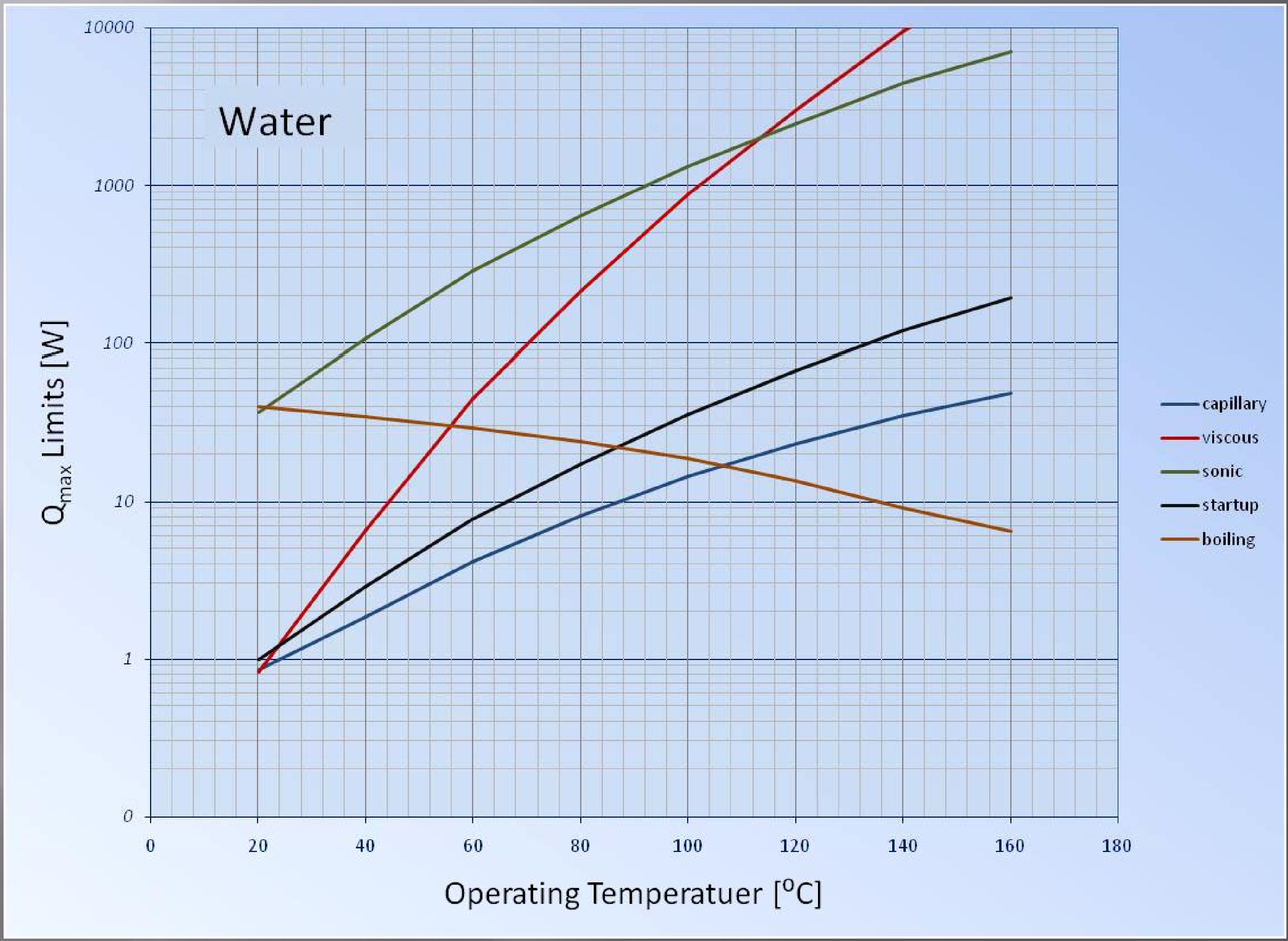
Operational Limits for Water μHPs



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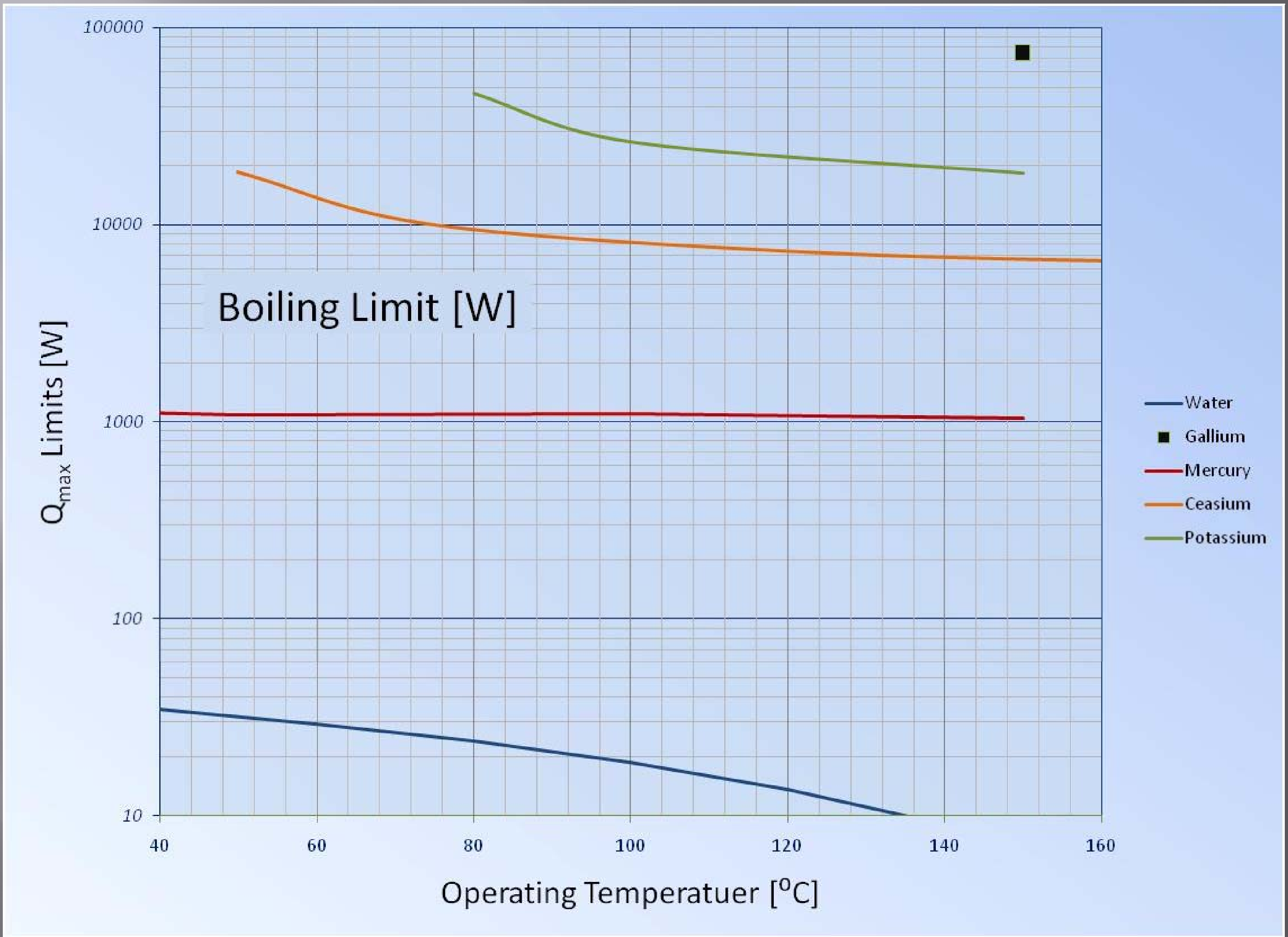
Boiling Limit Comparison



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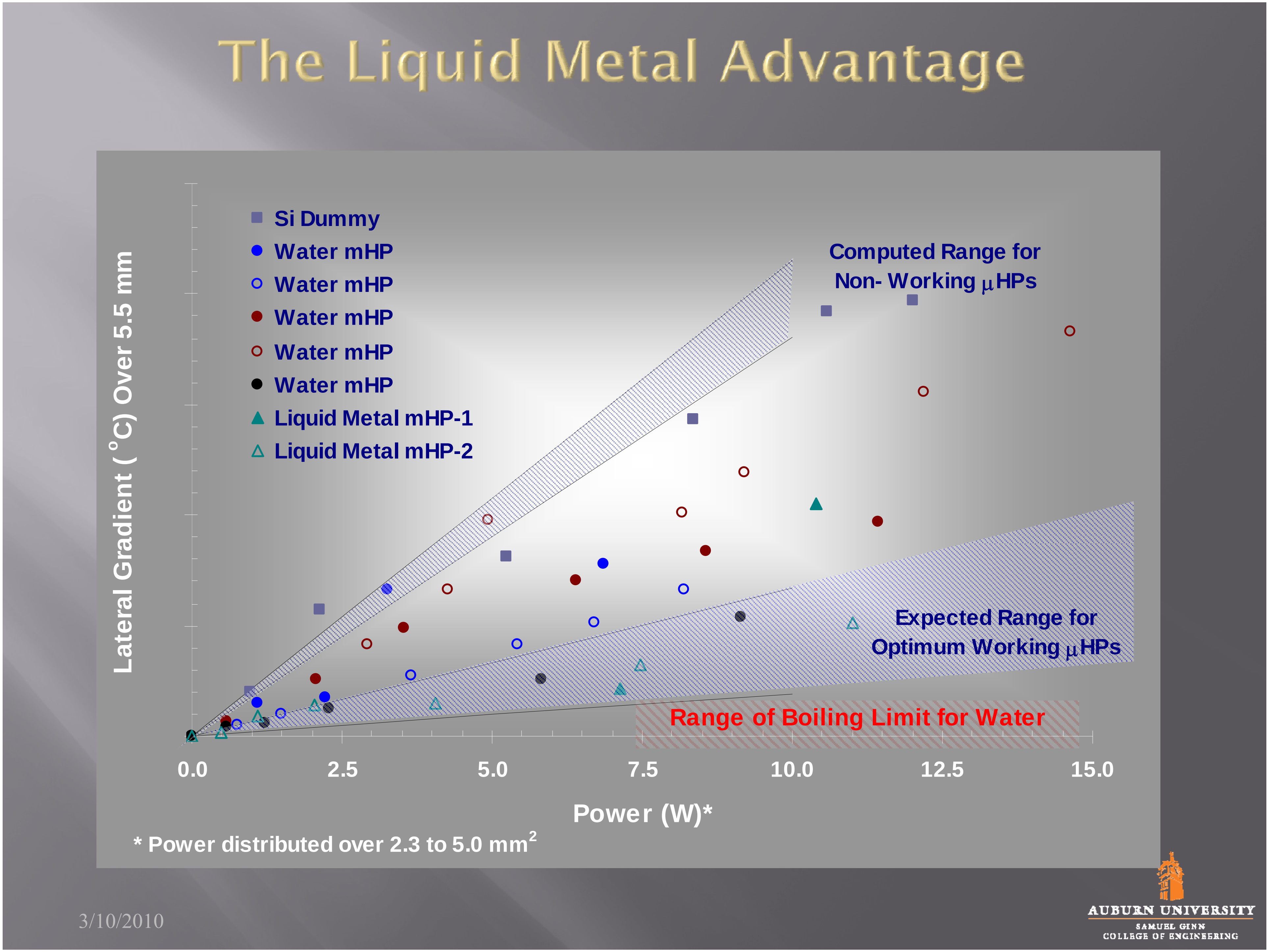
The Liquid Metal Advantage
Si Dummy
Water mHP
Water mHP
Water mHP
Water mHP
Water mHP
Liquid Metal mHP-1
Liquid Metal mHP-2
Computed Range for Non- Working μHPs
Expected Range for Optimum Working μHPs
Range of Boiling Limit for Water
Lateral Gradient (°C) Over 5.5 mm
0.0
2.5
5.0
7.5
10.0
12.5
15.0
Power (W)*
* Power distributed over 2.3 to 5.0 mm²
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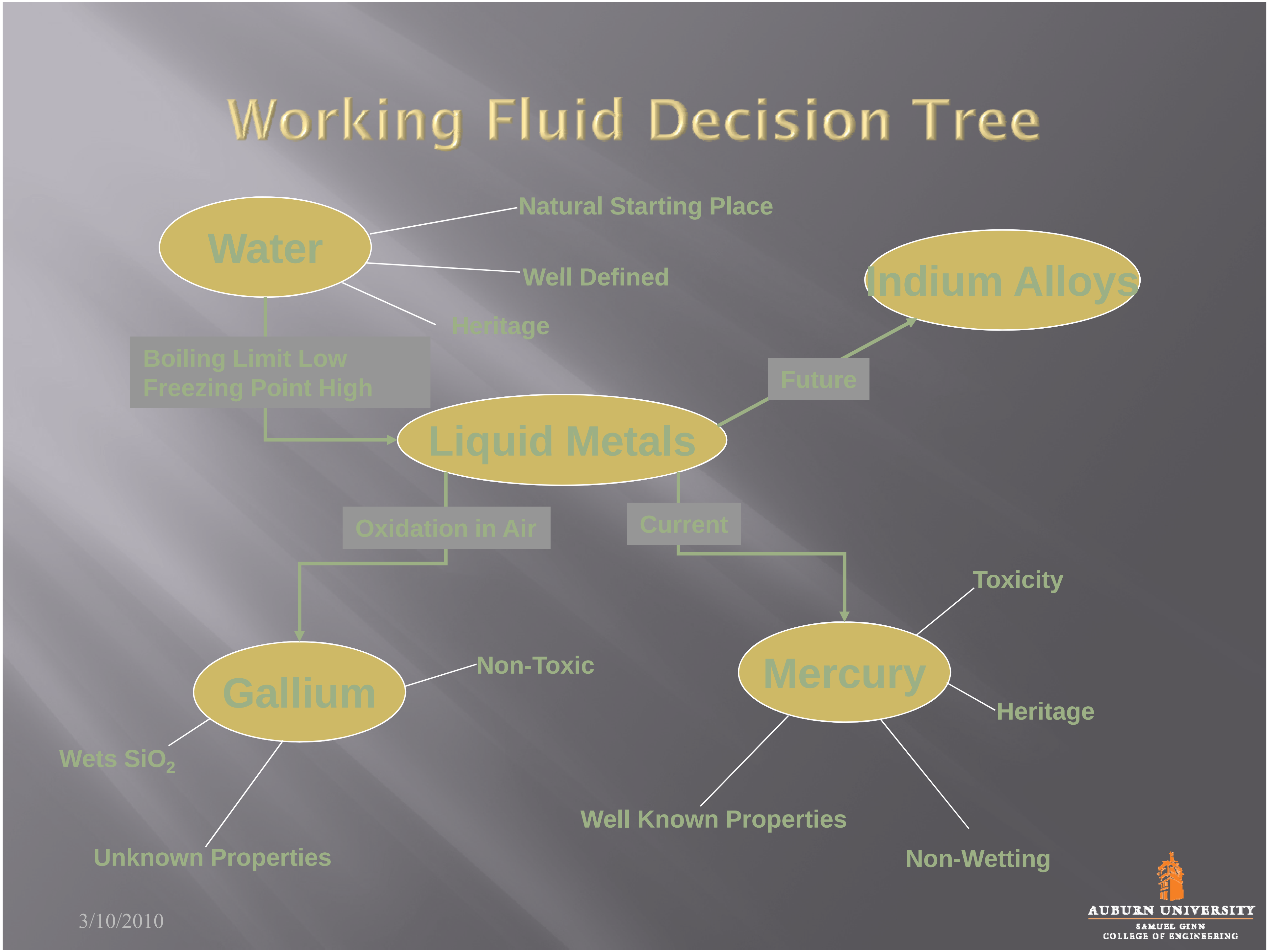
Working Fluid Decision Tree
Water
Natural Starting Place
Well Defined
Heritage
Boiling Limit Low
Freezing Point High
Indium Alloys
Future
Liquid Metals
Oxidation in Air
Current
Toxicity
Non-Toxic
Gallium
Mercury
Heritage
Wets SiO_2
Well Known Properties
Unknown Properties
Non-Wetting
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Driving Parameter – Critical Heat Flux

Incipient Site Radius	2.54×10^{-7}	50 Å
3M FCs	0.34 W/mm^2	
Water	1.2 W/mm^2	2.4 W/mm^2
Thermex$^{100°C}$		3.2 W/mm^2
Mercury$^{100°C}$	26 W/mm^2	46 W/mm^2
In-Ga Eutectic$^{100°C}$		34 W/mm^2

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Liquid Metal Working Fluids

- Liquid Metal MHPs Give Superior Performance.
  - B. Badran, et al., "Liquid-Metal Micro Heat Pipes," **Proceedings of the 29th National Heat Transfer Conference**, August 8-11, 1993, HTD Vol. 236, pp. 71-85 [4]
- Looked at Mercury, Sodium, Potassium
  - Hg (-38.4 C) Good Candidate
  - Na (97.8 C) T_{melt} Too High
  - K (63.7 C) T_{melt} Too High

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Benefits

- Higher Boiling Limit
- Higher Heat Transfer Performance – ref. [4]

	Melting Point	Specific Thermal Conductance*
Mercury	-38.4 °C	124
Sodium	97.8 °C	630
Potassium	63.7 °C	504

- Material Compatibility
- Commercially Available

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Other Options Include Indium Based Eutectics…

- Low Liquidus Temperature
- High Surface Tension
- Wets Si, SiO_2
- High Liquid Thermal Conductivity

Indalloy Number	Liquidus °C	Solidus °C	Elemental Composition (% by Mass)
60	15.7	15.7	75.5 Ga/24.5 In
77	25	15.7	95 Ga/5 In
14	29.8		100 Ga
18	61.5	61.5	61.72 In/30.78 Bi/7.5 Cd
162	72	72	66.3 In/33.7 Bi
25	77.5	77.5	48.5 Bi/41.5 In/10 Cd

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…And Gallium

- Ga
  - Unknown transport properties
  - Performance is not predictable
  - No heritage from heat pipe literature
  - Higher freezing point (~30 °C)
  - Low vapor density and pressure
  - No known safety concerns
  - Easier for sealing due to solid state during evacuation.

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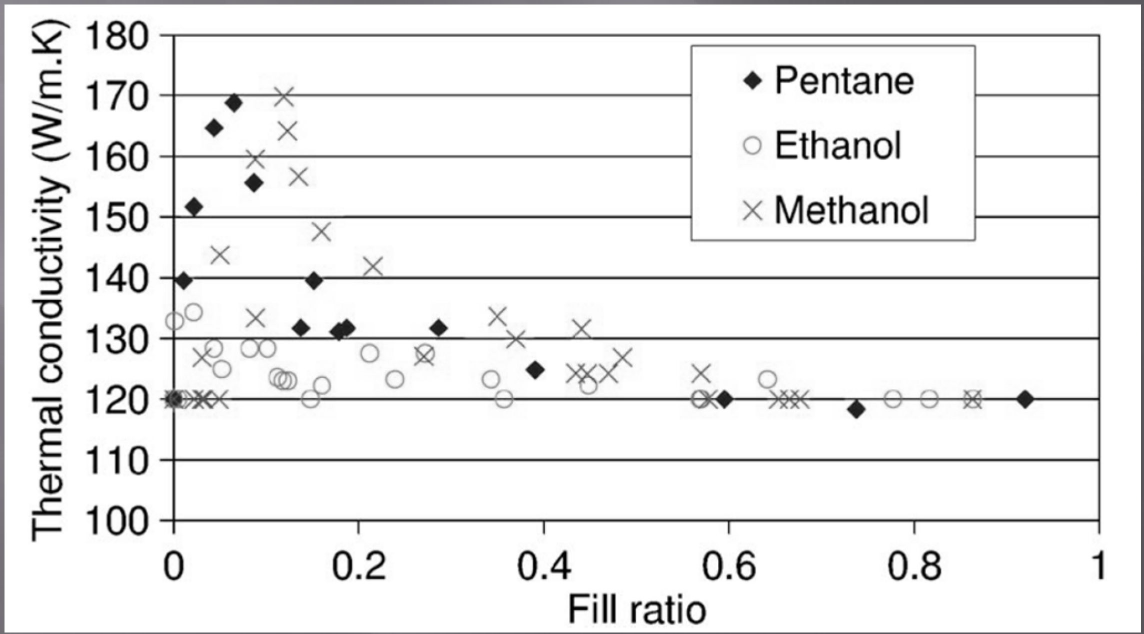
Factors Affecting the Working of MHPs

IV. Charge of the MHP:

- It is the amount of working fluid filled into the MHP
- Best performances of MHPs were recorded with lower fill ratios rather than with high fill ratios [5]



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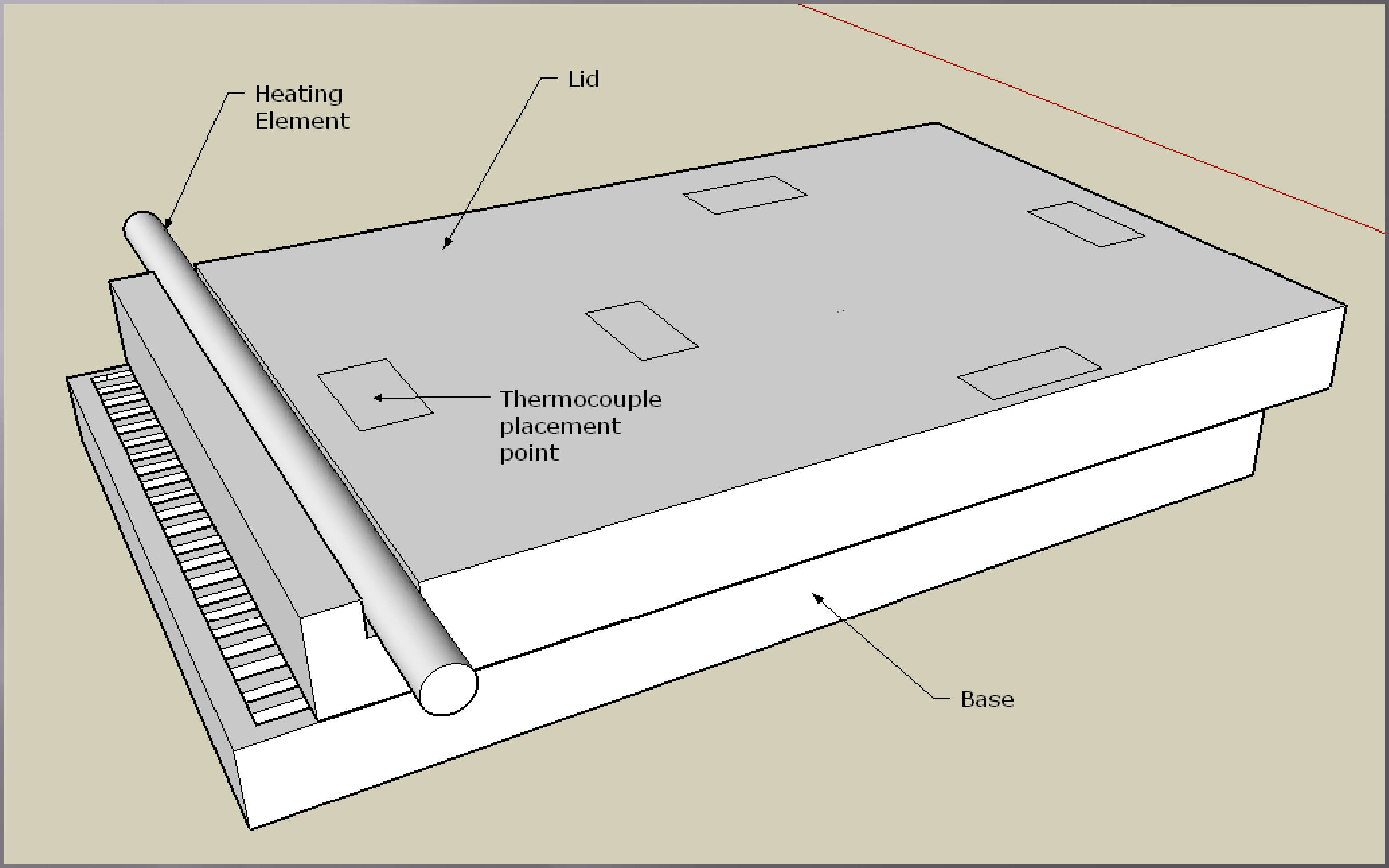
Testing of MHPs

II. Structure and components of the MHP array die:



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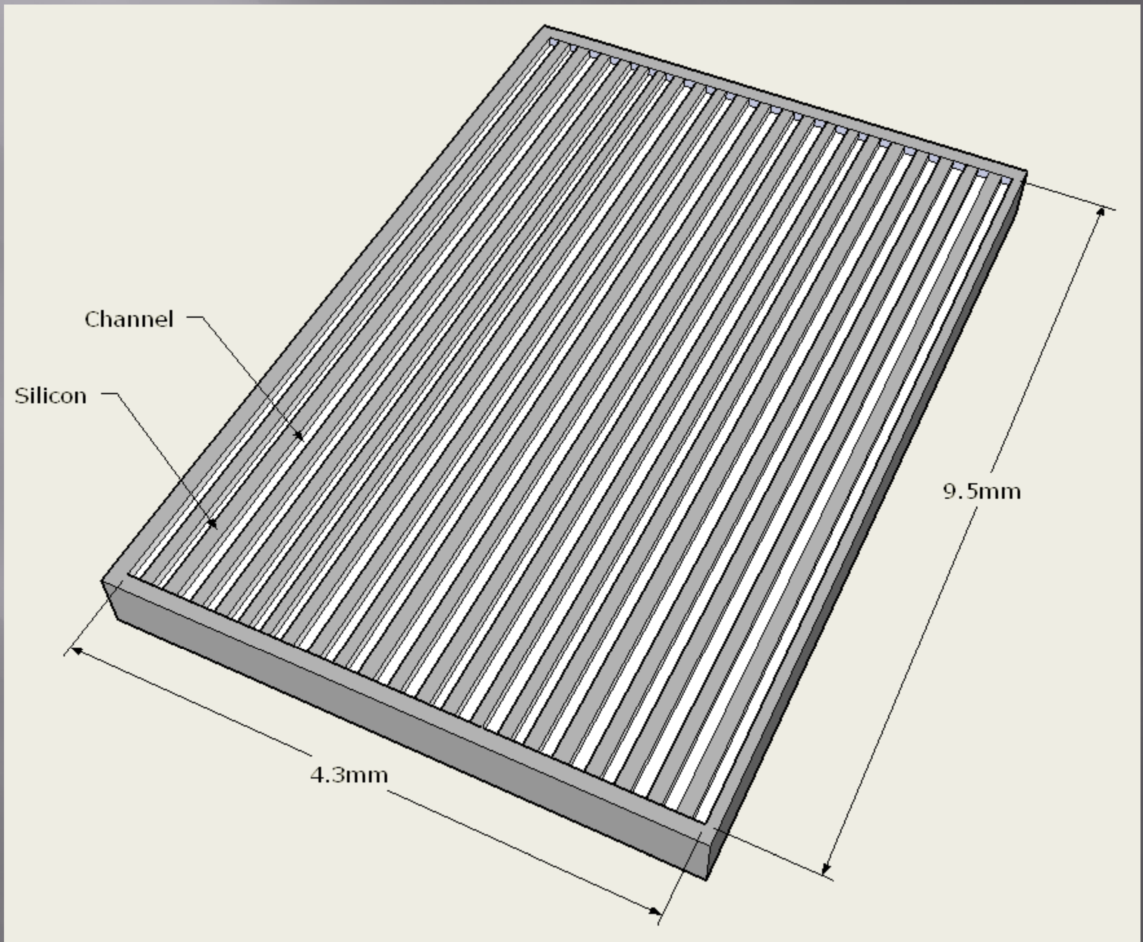
Testing of MHPs

- Base dimensions of the MHP array die



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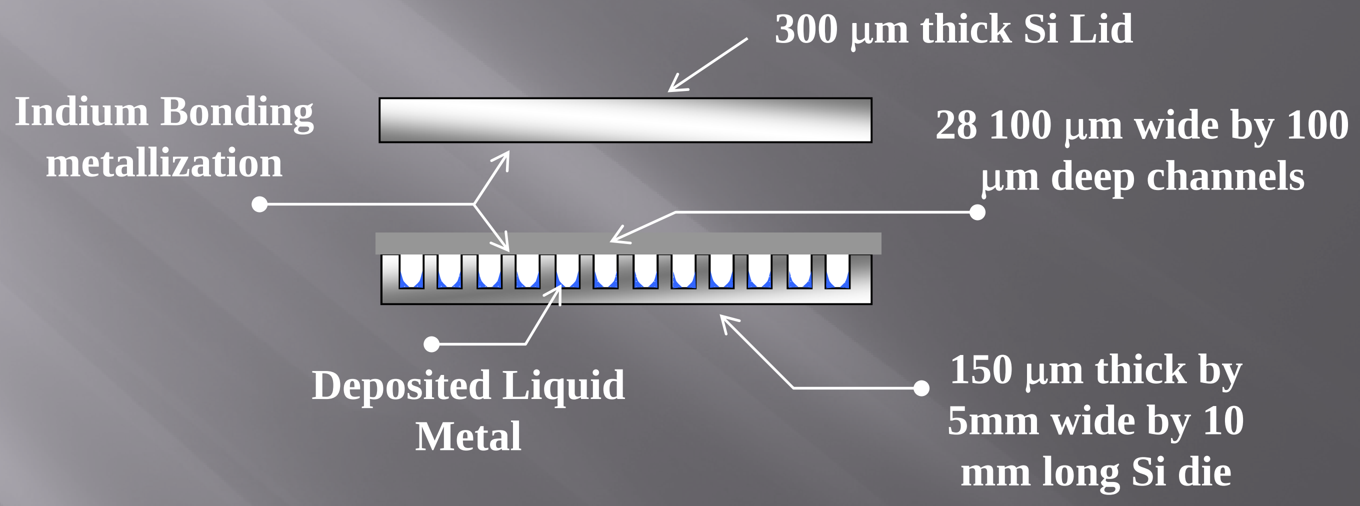
Assembly Cross-Section Dimensions



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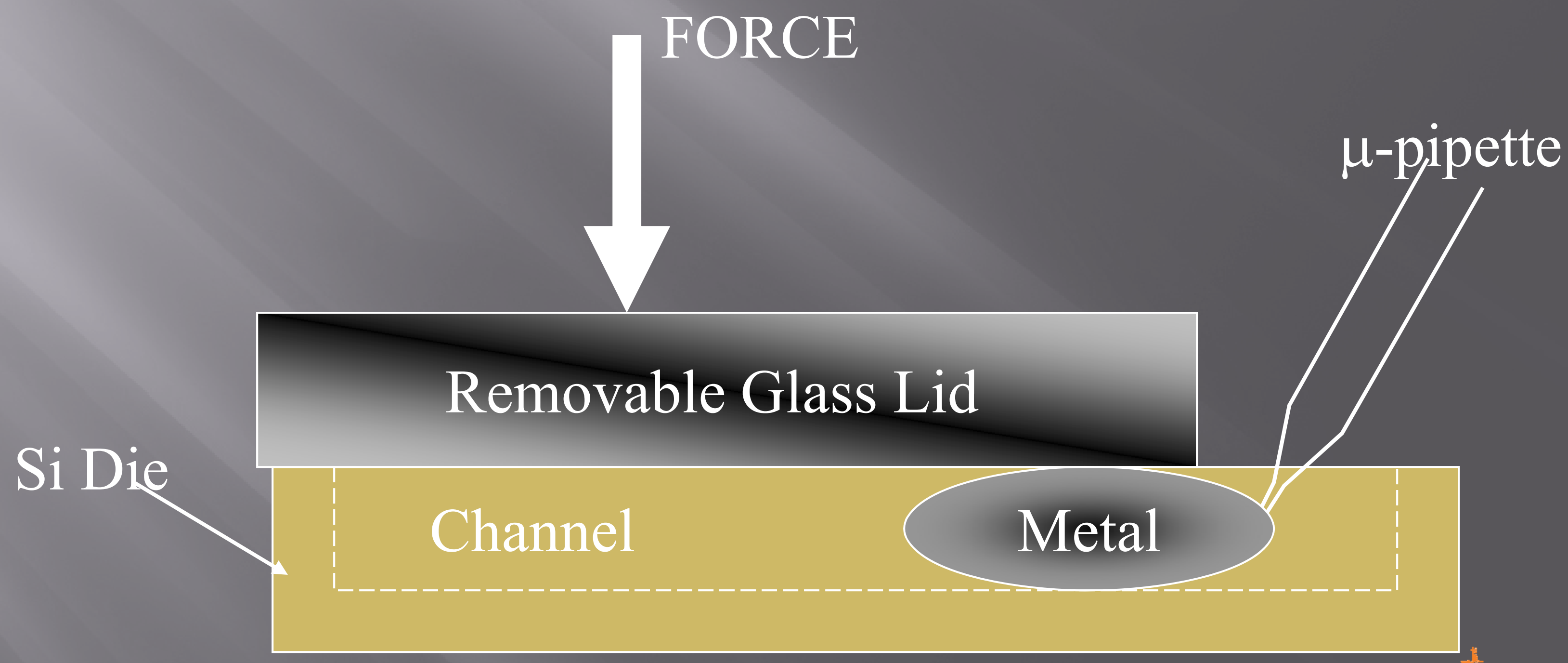
Liquid Metal Filling Technique



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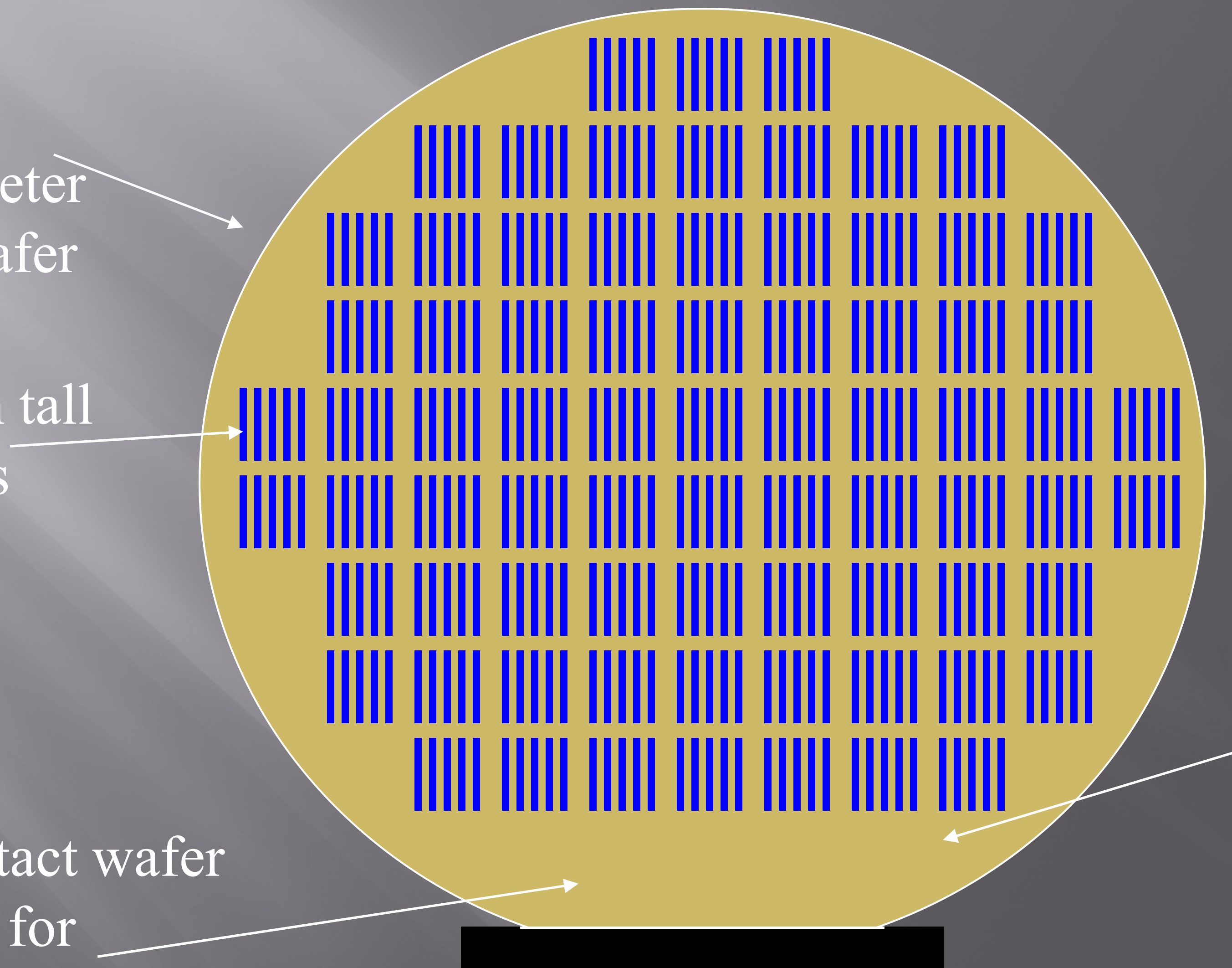
Drawing of Wafer Before Plating



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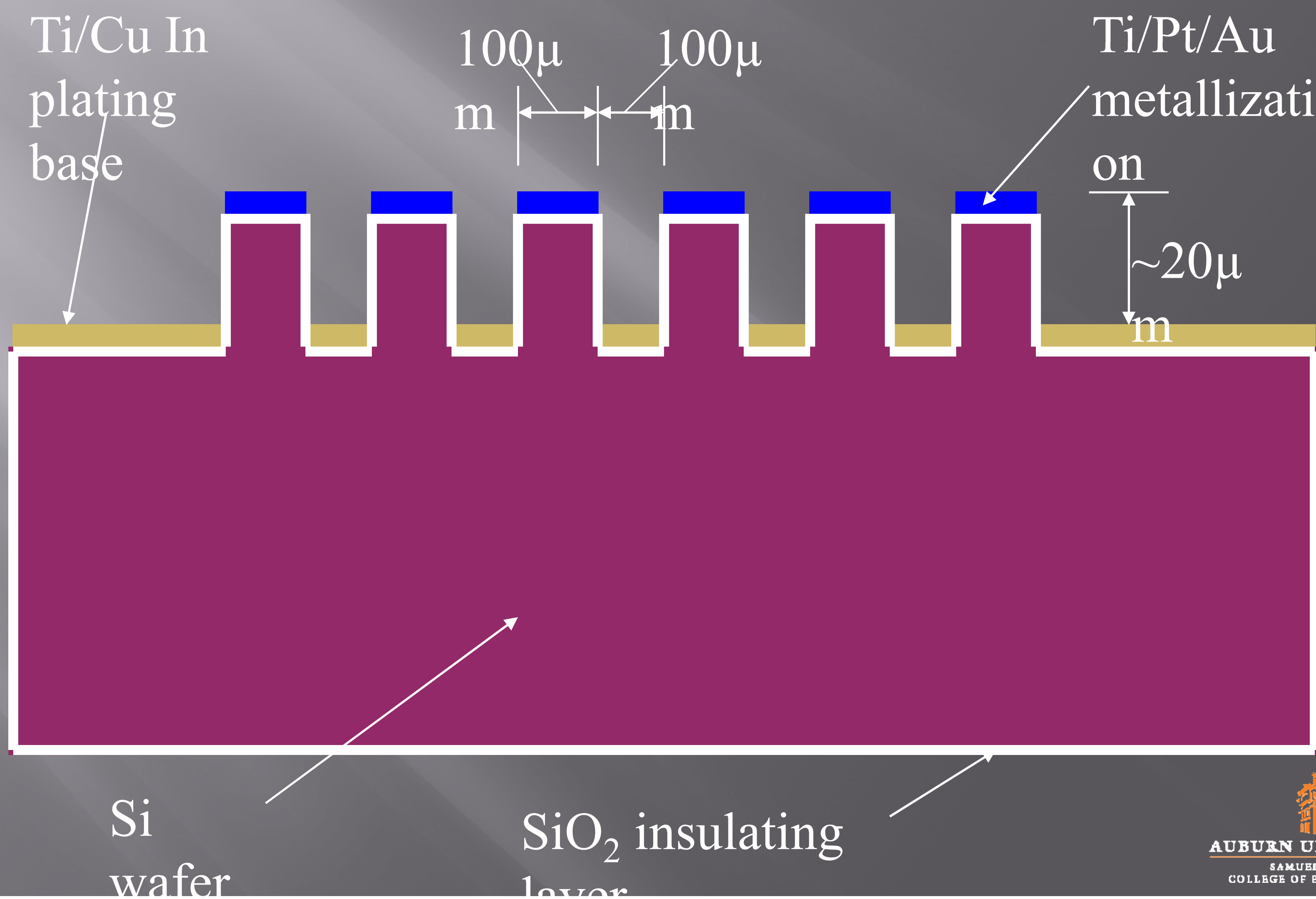
Cross-sectional View Before In Plating



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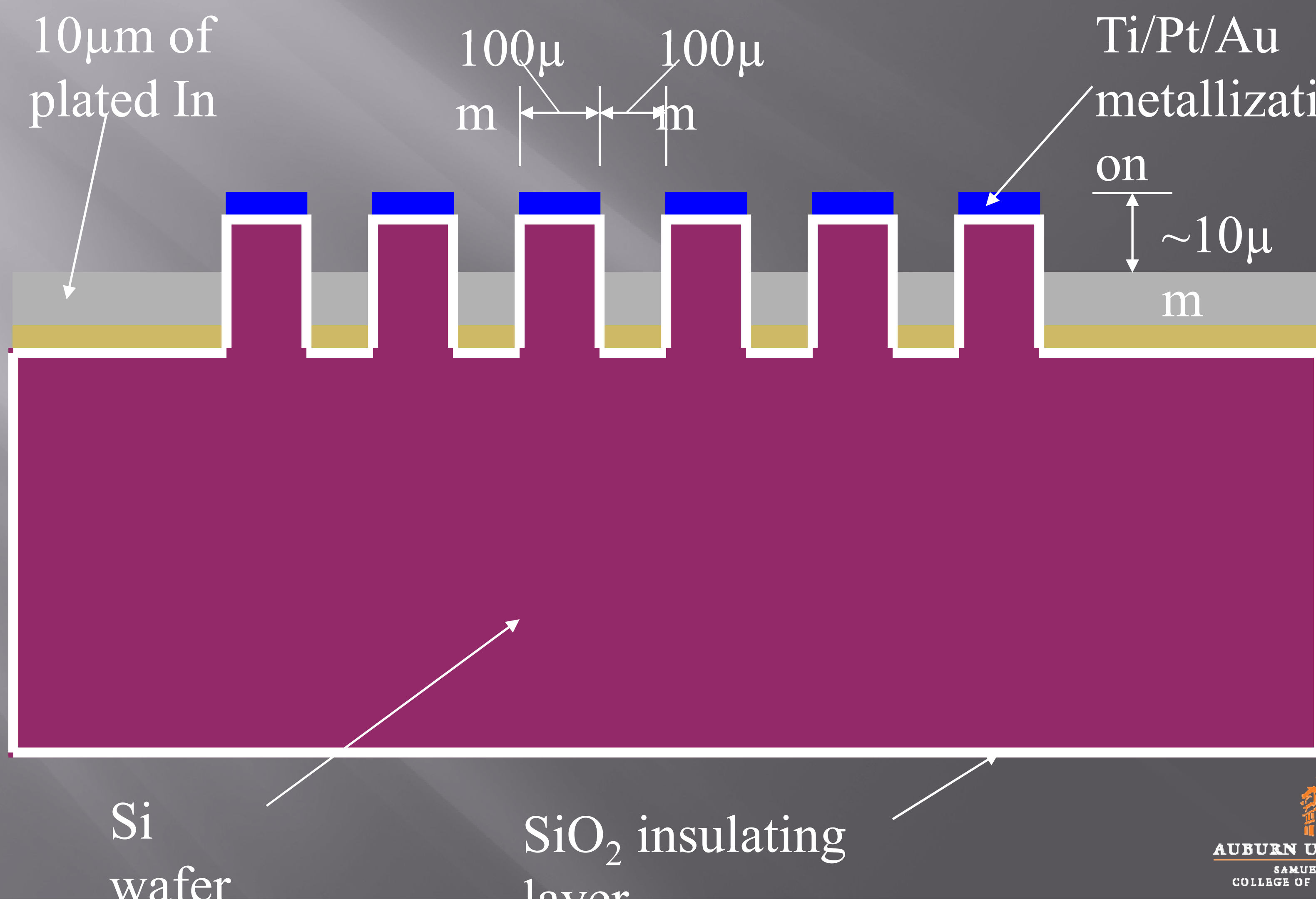
Cross-sectional View After 10µm In Plating



Step 1: Ti/Pt/Pd deposition

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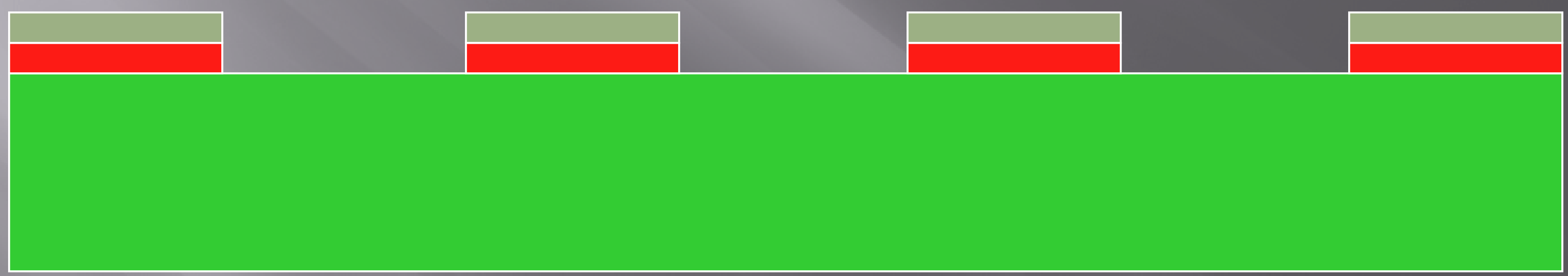
Step 2: coat Ti/Pt/Pd with PR and pattern Ti/Pt/Pd (wet etch)



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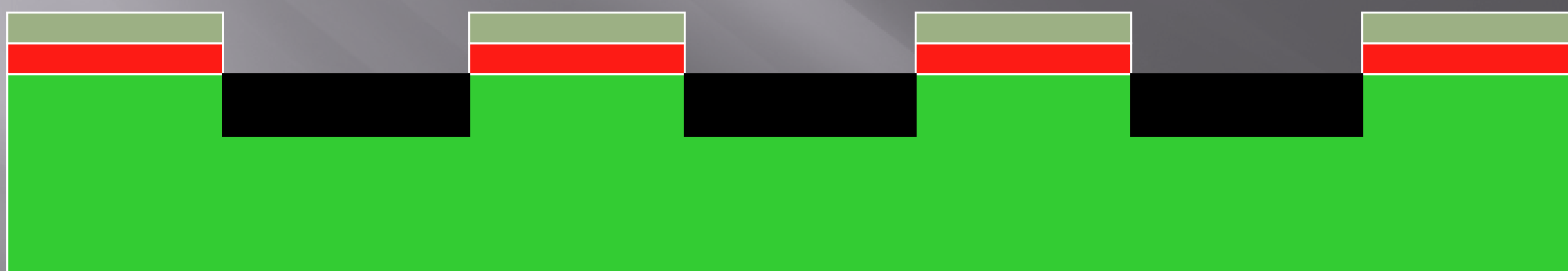
Step 3: 20μm DRIE



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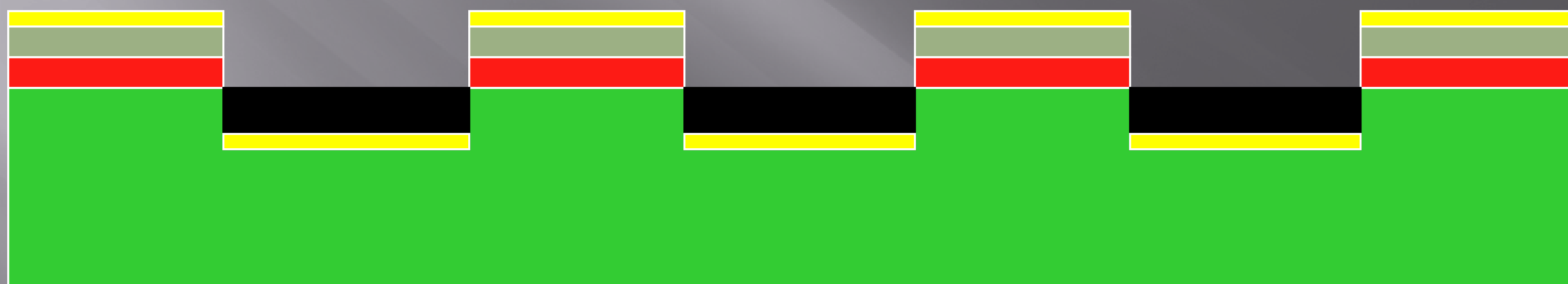
Step 4: Plating base metallization



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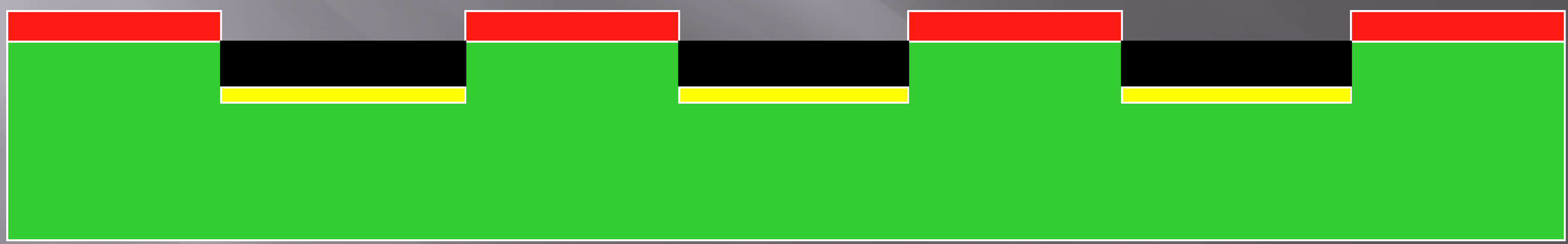
Step 5: Wash off PR / liftoff



Step 6: Send out for plating

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Die Assembly Procedure

- Etch wafer, saw and clean die
- Dip into melted metal bath
- Remove photomask
  - This step done before dipping for Hg channels
- Pattern lid
  - top – thermal sensors
  - bottom – channel metallization
- Evacuate and bond lid onto die

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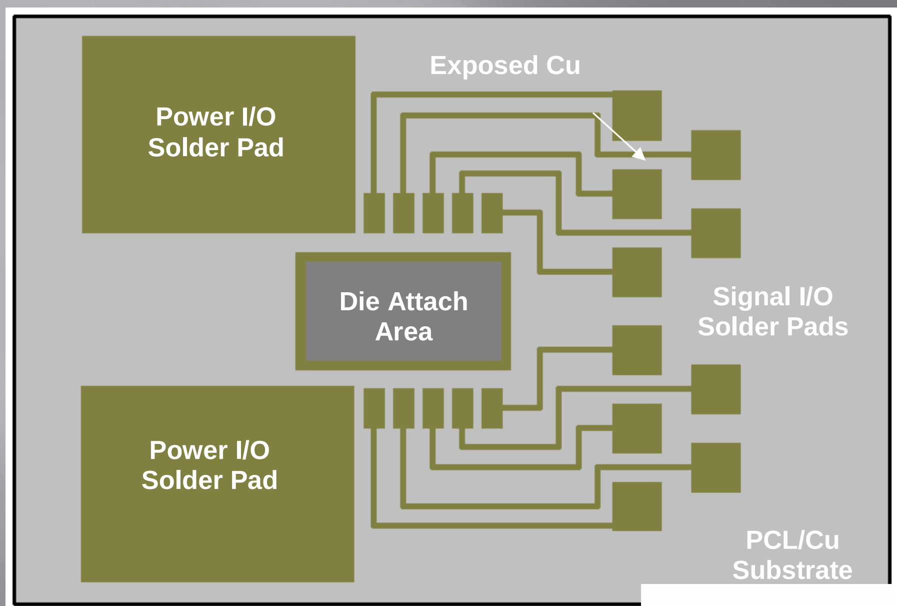
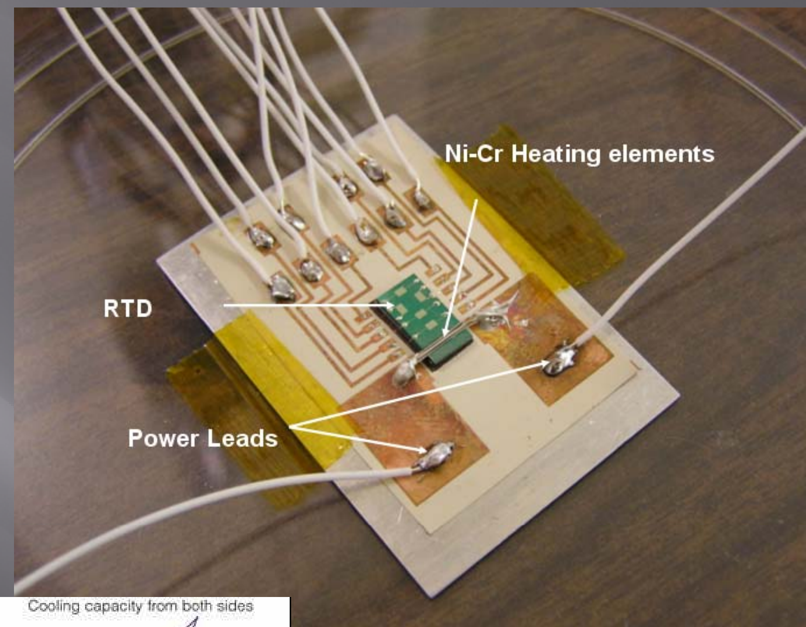
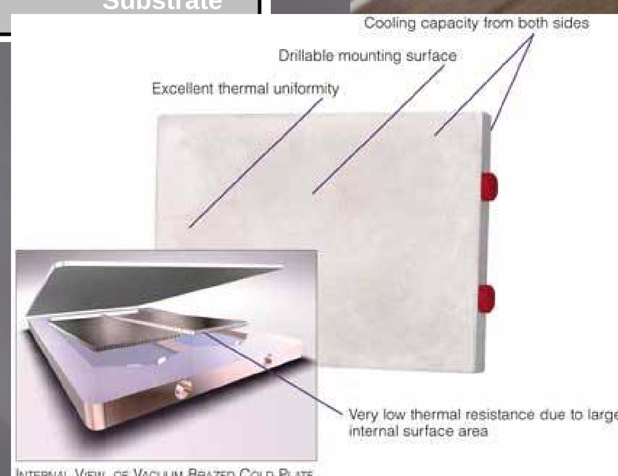
Test Board Design



Fabricated Test Set Up



Lytron® Cold Plate



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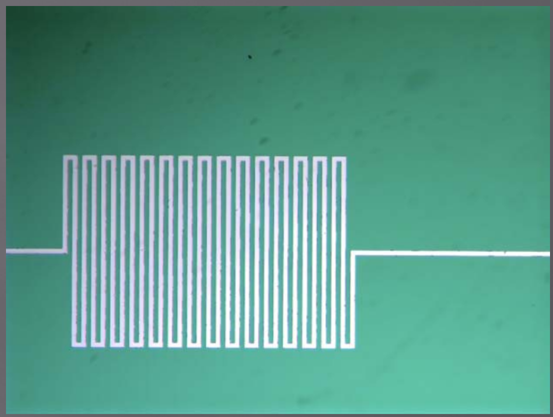
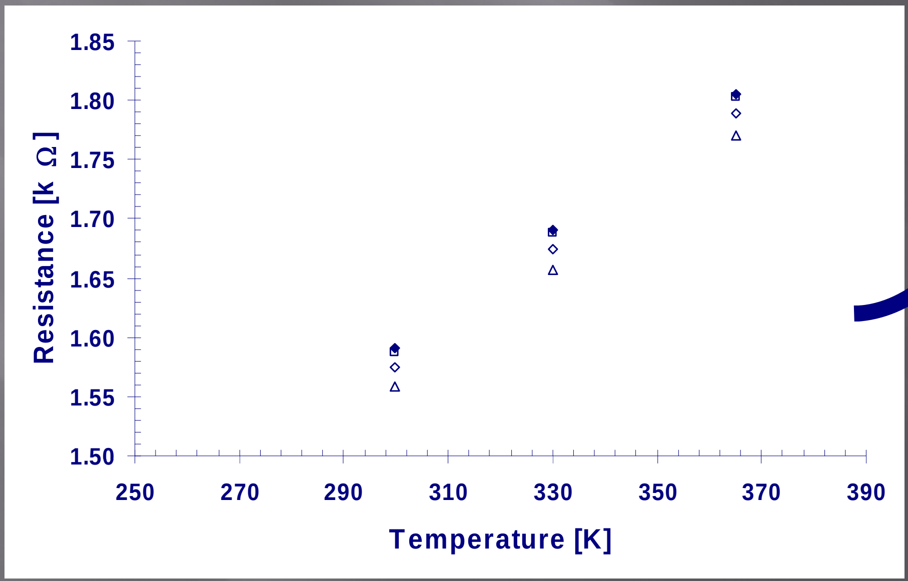
Platinum RTD Micro-Sensors

- Non-Production Feature
- 5 per MHP Die.
- Used in Tandem with IR Scope.
- Each Sensor Calibrated





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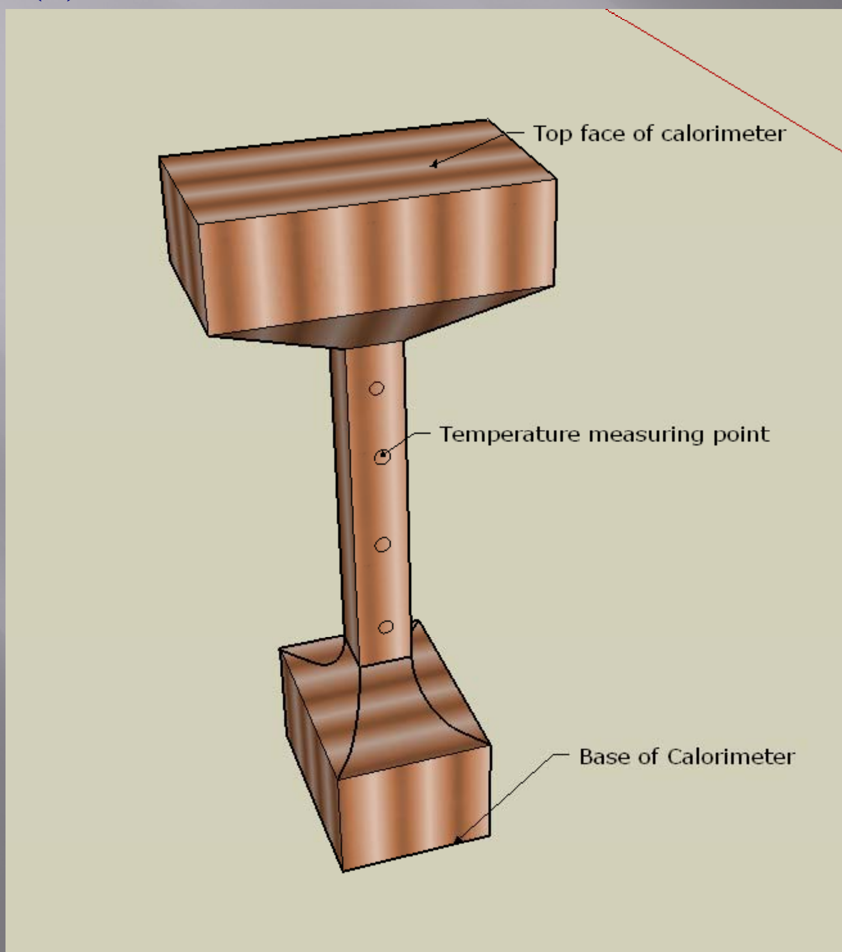
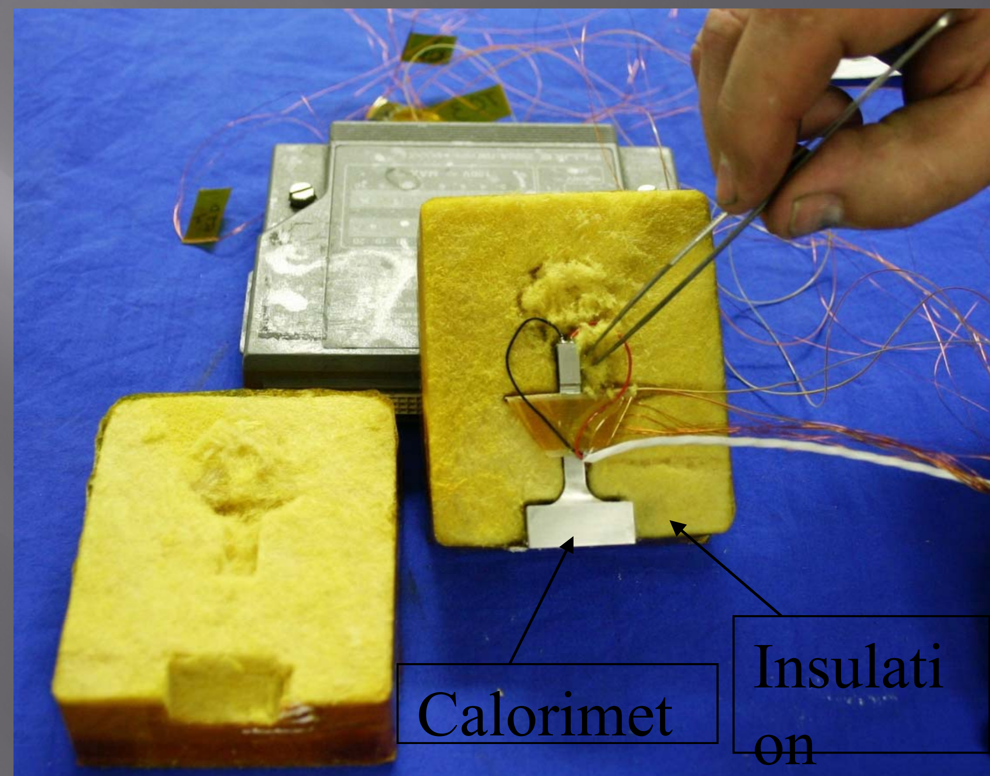
Testing of MHPs

Calorimeter

(a) Model



(b) Within the insulation cover



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Test Results

Thermal resistance

$$Thermal\ Resistance = \Delta T / Power$$

Where,

ΔT = Temperature difference between the evaporator and condenser regions of the MHP

Power = Input power to the MHP

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Test Results

A. First Method – Silicon Equivalence Method

Calculation of Equivalent Thermal Conductivity Using the Silicon Equivalance Approach

K silicon (W/m-K)	Name	Equation	Slope (ΔT/ΔQ)	R^2 Value	Silicon Equivalence	Equi.Thermal cond.(W/m-K)
148	Empty MHP	1.3968x+0.1111	1.3968	0.9882	1	148.0
	Water filled MHP-1	0.793x-0.2012	0.793	0.9987	1.76	260.7
	Water filled MHP-2	0.638x-0.0643	0.638	0.9987	2.19	324.0
	Silicon/Mercury-1	0.4689x+0.0895	0.4689	0.9836	2.98	440.9
	Silicon/Mercury-2	0.638x-0.0643	0.638	0.9987	2.19	324.0
	Silicon/Mercury-3	0.6525x-0.105	0.6525	0.993	2.14	316.8
	Silicon/Mercury-4	0.2329x+0.0678	0.2329	0.9956	6.00	887.6
	Silicon/Mercury-5	0.246x+0.1009	0.246	0.9954	5.68	840.4
	Silicon/Mercury-6	0.2618x+0.0882	0.2618	0.9898	5.34	789.6
	Silicon/Mercury-7	0.2824x+0.1128	0.2824	0.9963	4.95	732.0
	Silicon/Mercury-8	0.2797x+0.0614	0.2797	0.9978	4.99	739.1
	Silicon/Mercury-9	0.2742x+0.0413	0.2742	0.9978	5.09	753.9
	Silicon/Mercury-10	0.259x+0.2169	0.259	0.9861	5.39	798.2

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Test Results

Second Method – Effective thermal conductivity

$$Keff = [(Q / Amhp)]/[(T\max - T\min) / L]$$

Where,

Q = Input power

L = Length of the MHP

AMHP = Area of the MHP array

Tmax = Temperature at evaporator end for given Q

Tmin = Temperature at condenser end for given Q

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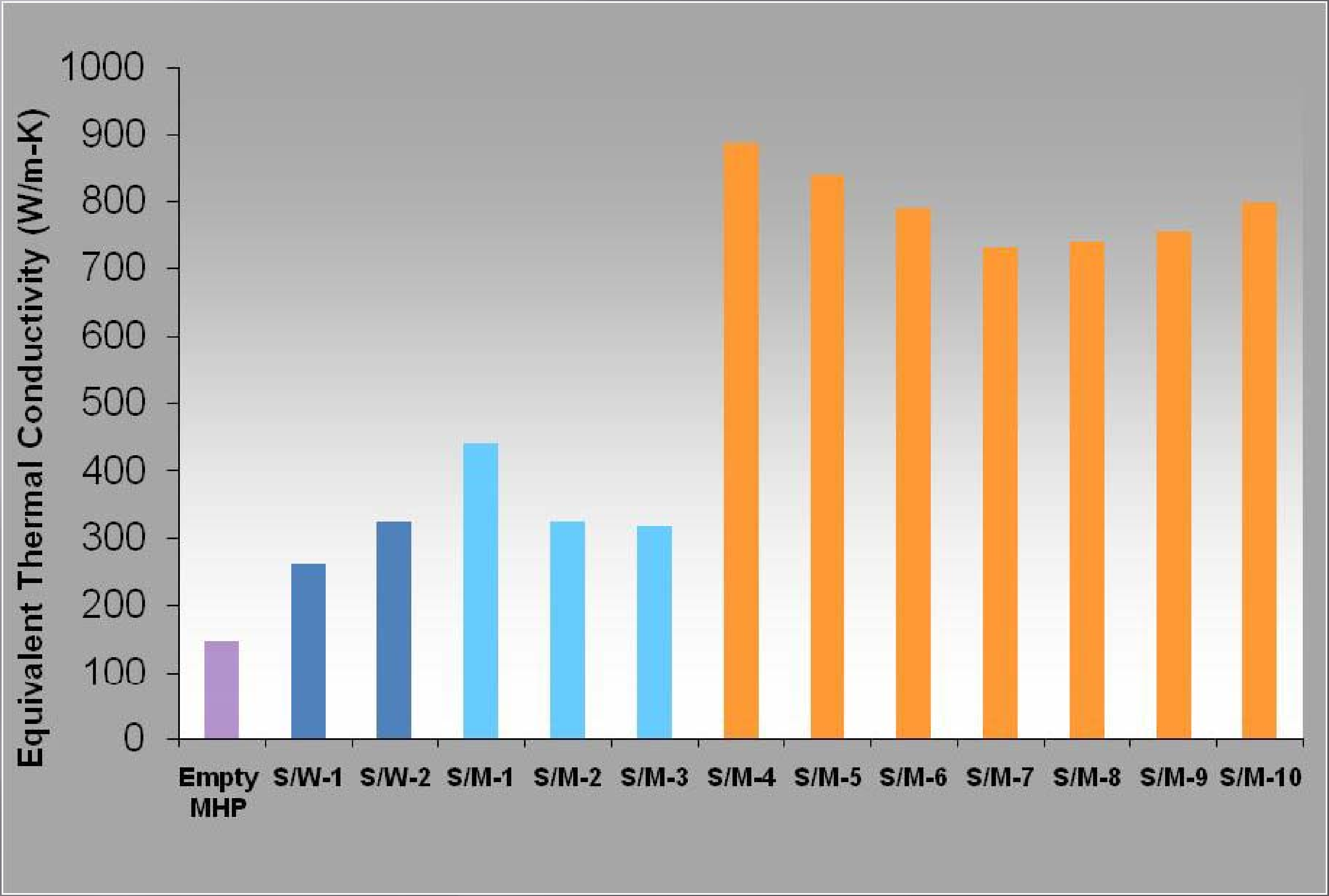
Equivalent Thermal Conductivity



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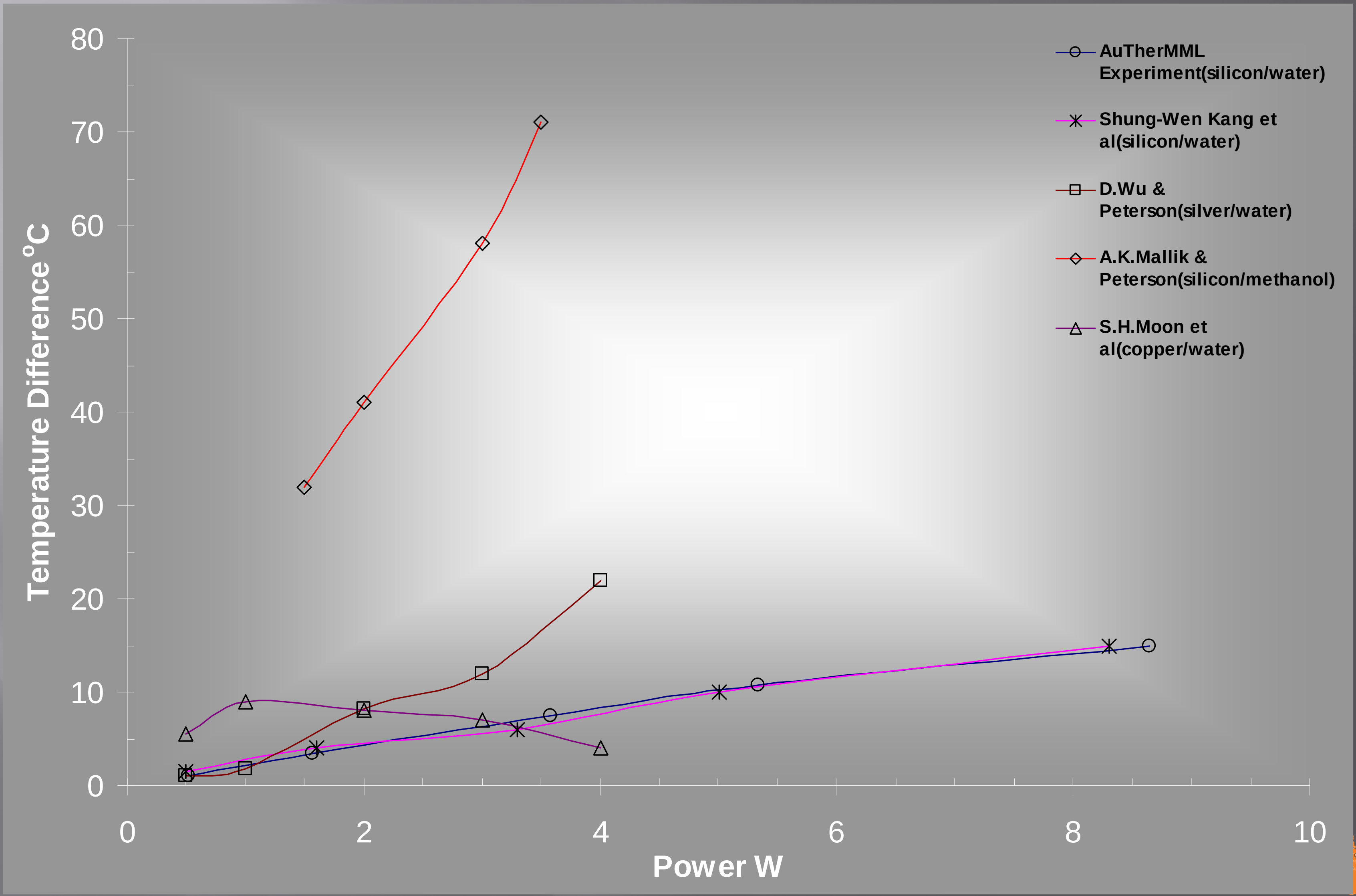
Comparison of Water μHP Performance



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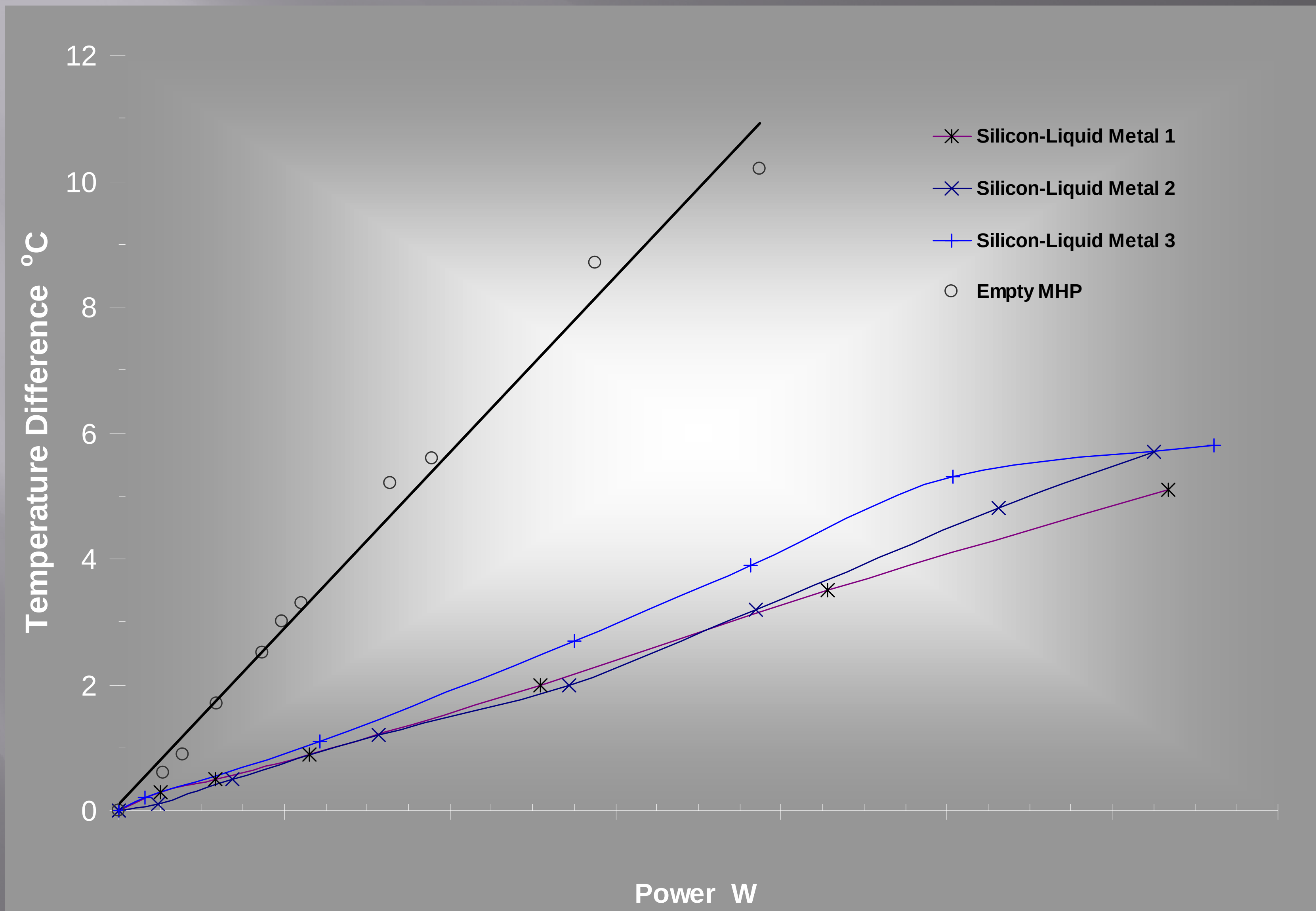
Liquid Metal Filled μHP Performance



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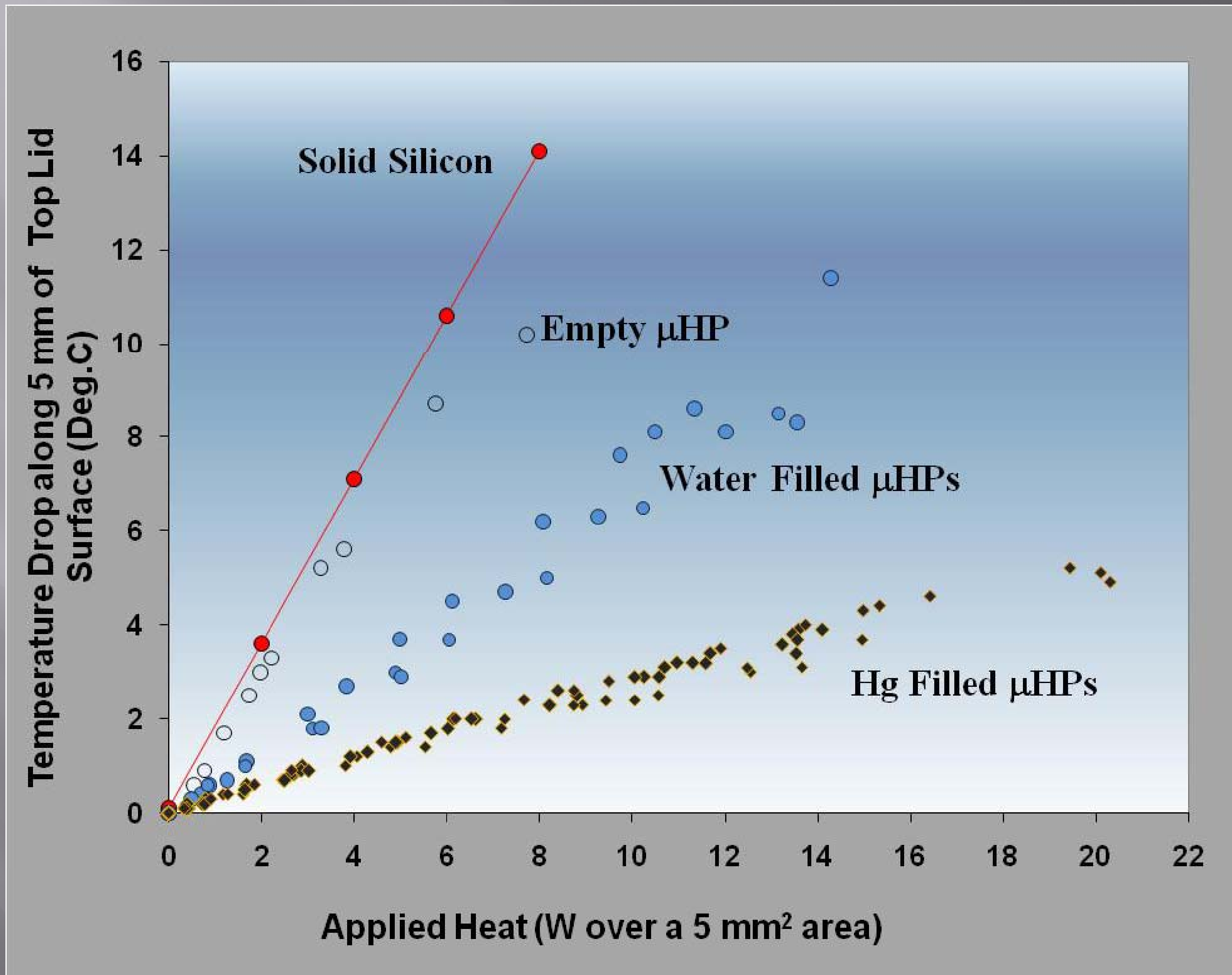
The Liquid Metal Advantage



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BACKUP SLIDES

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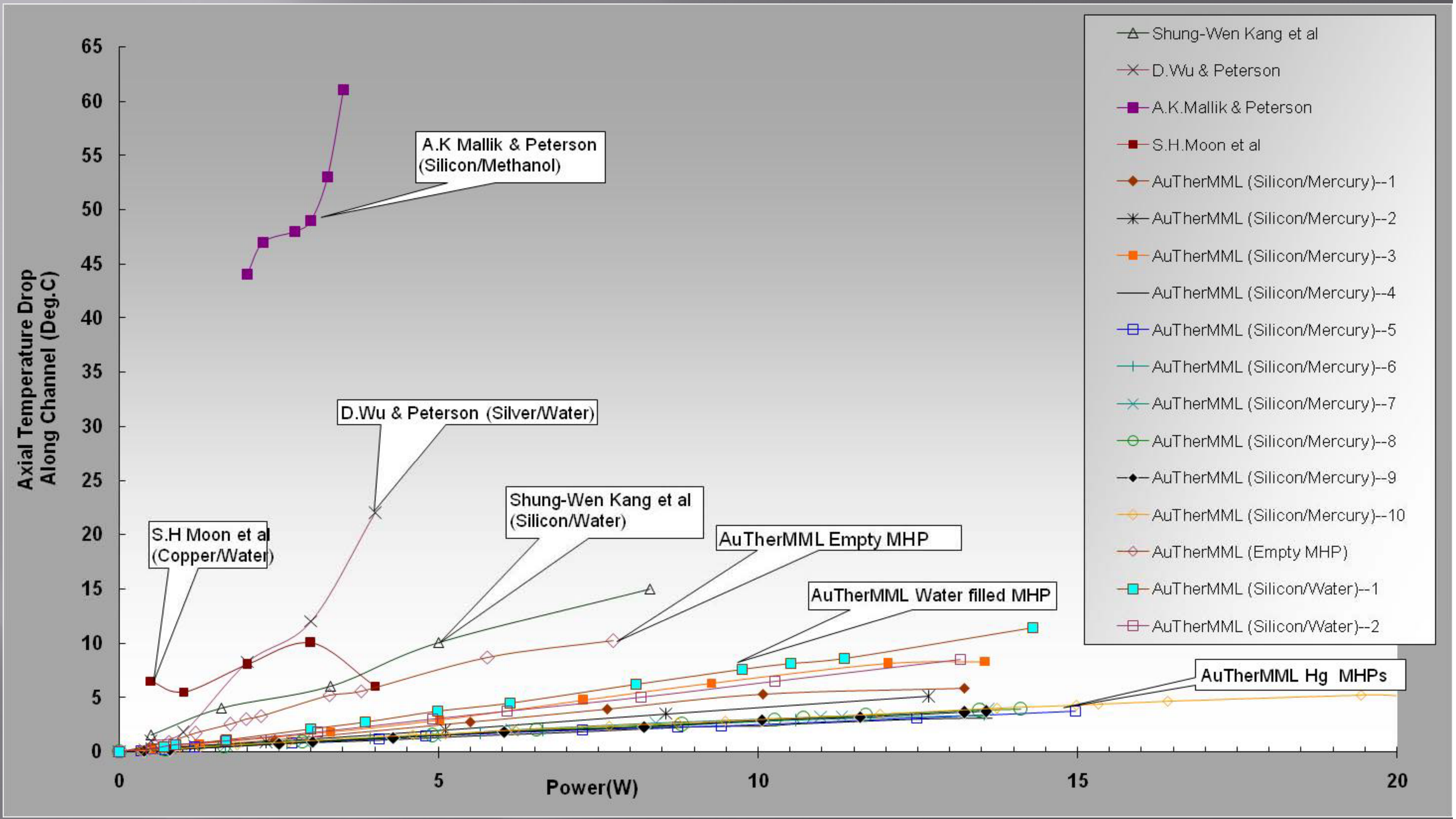
Equivalent Thermal Conductivity



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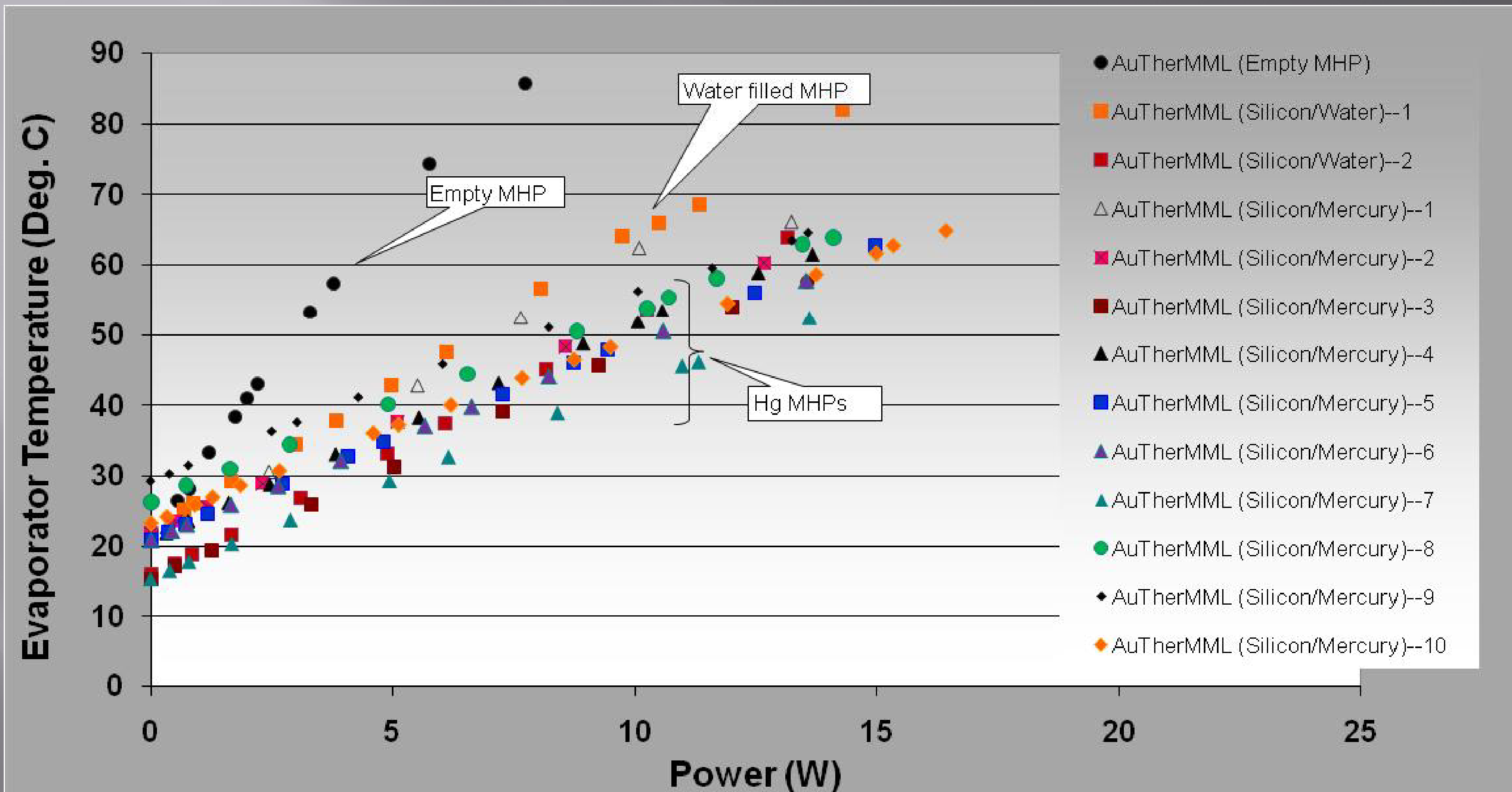
Evaporator Temperature



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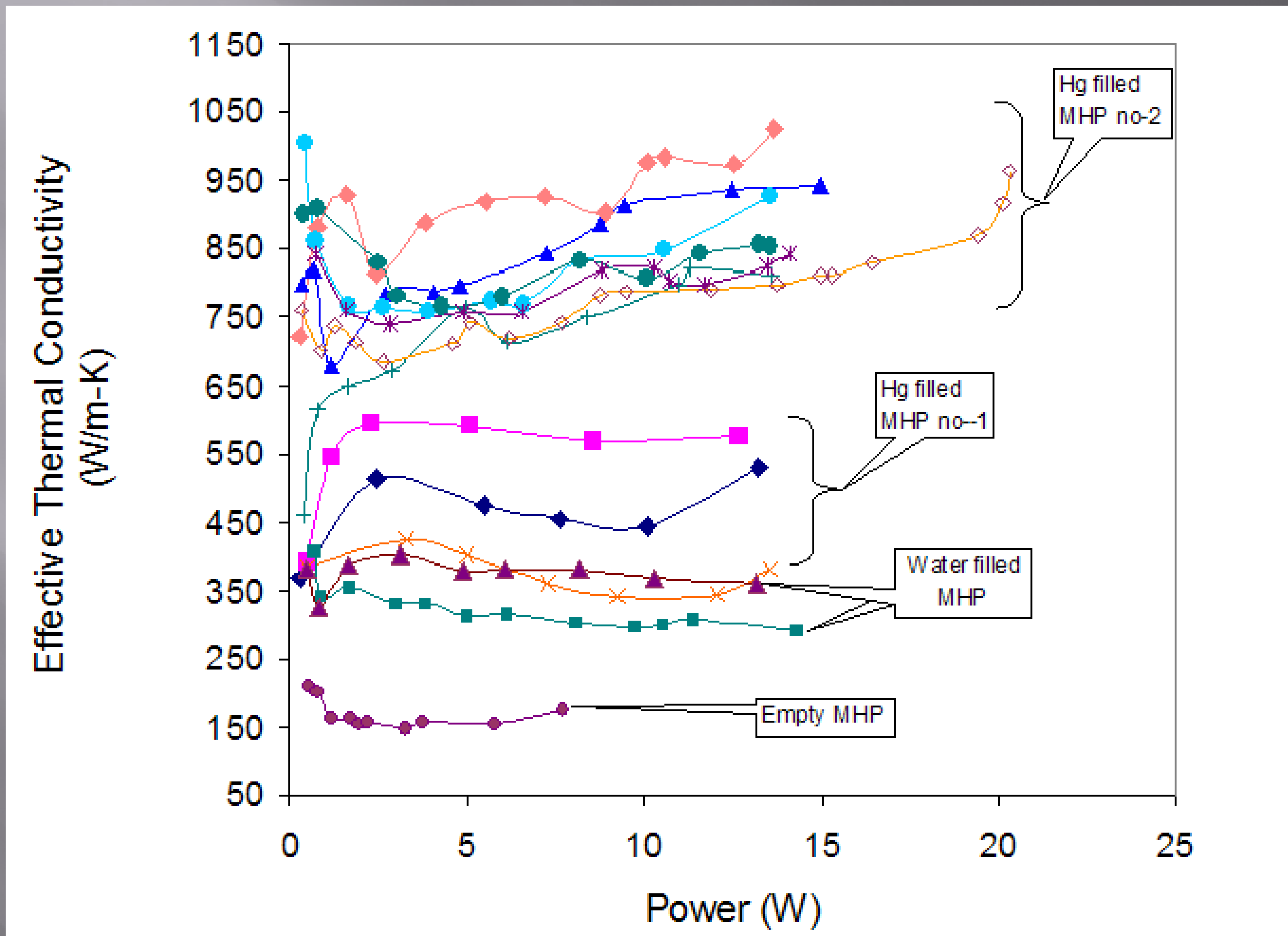
Test Results

- Effective thermal conductivity vs. Power for various MHPs



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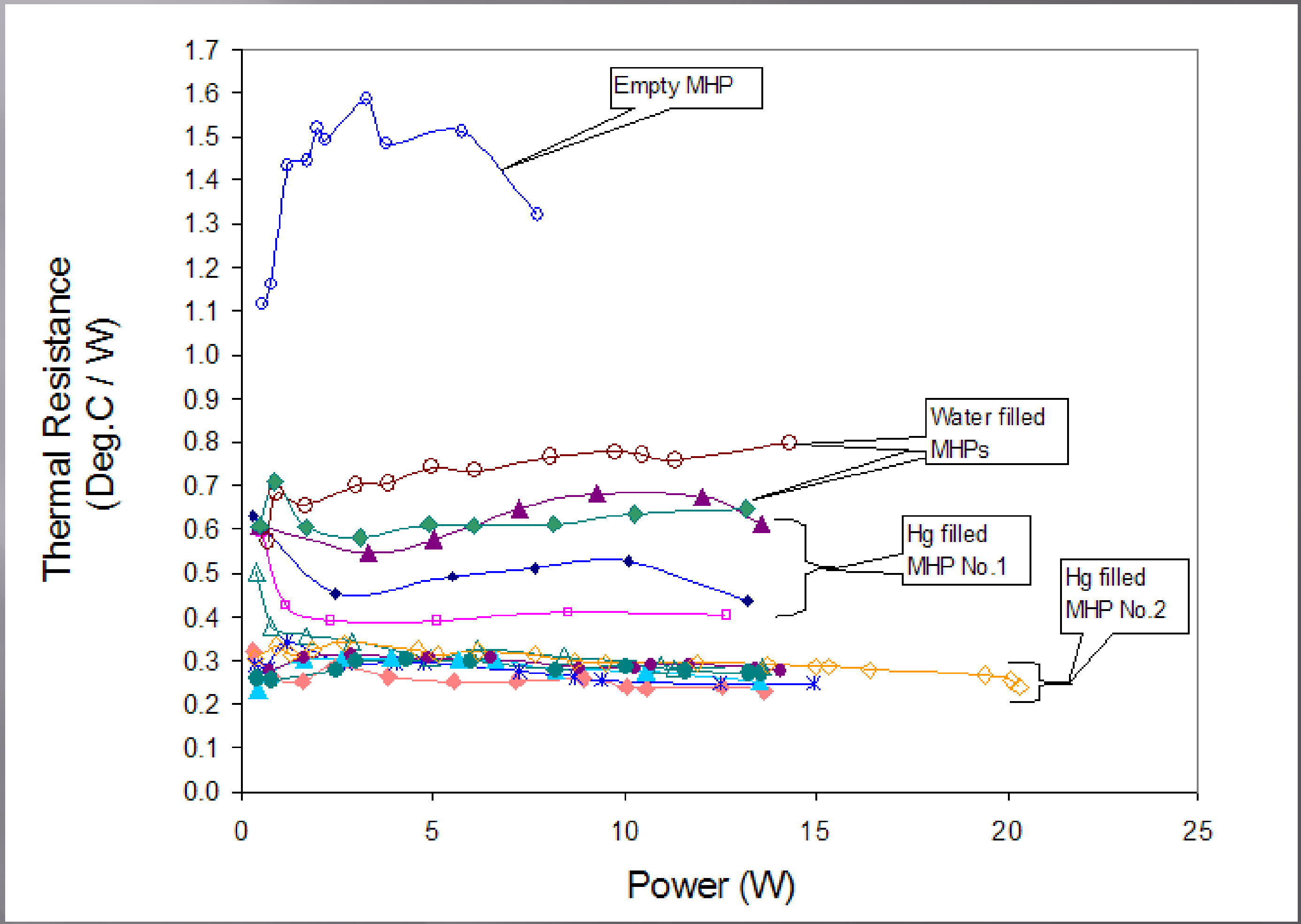
Test Results

Thermal resistance vs. Power



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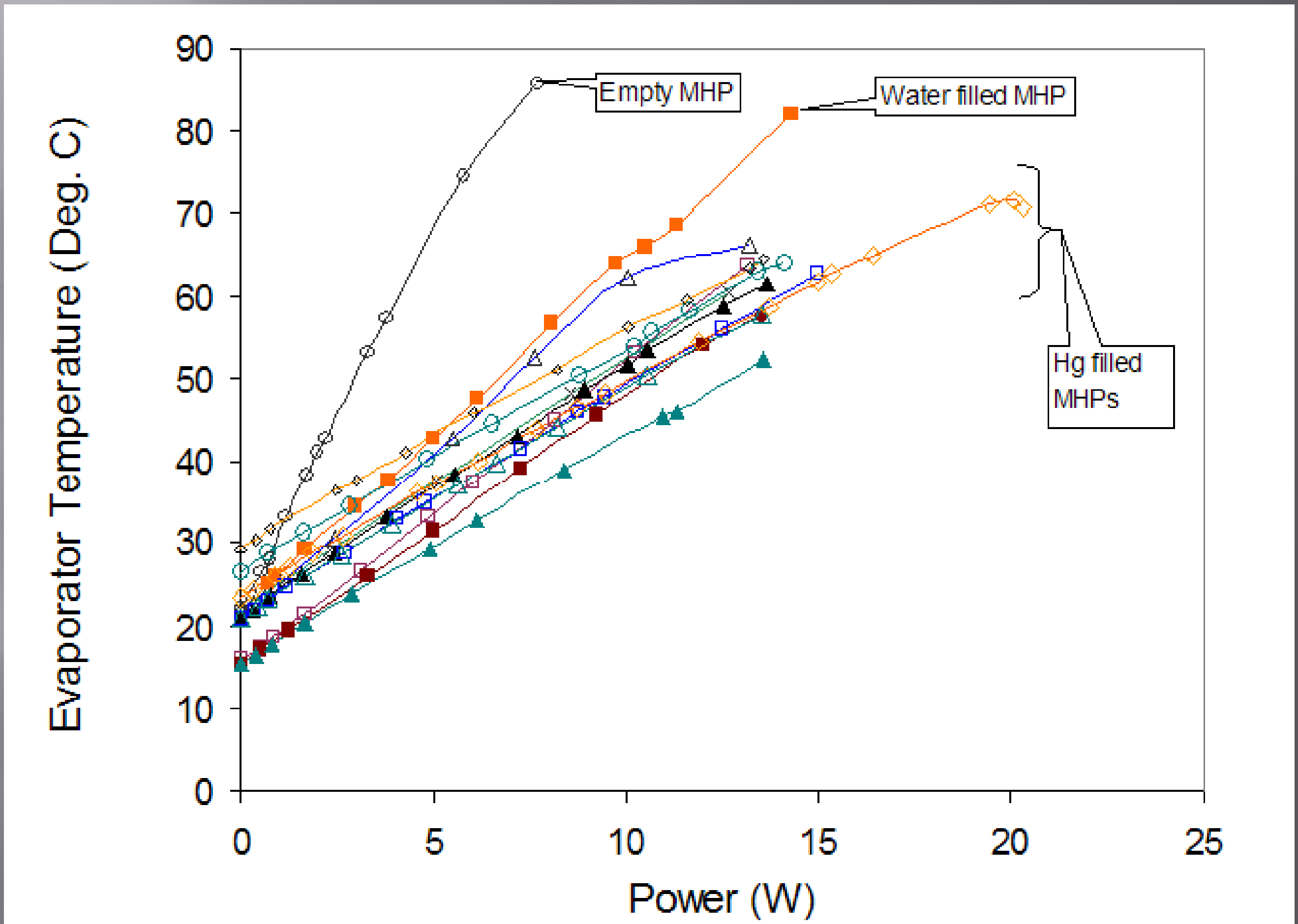
Test Results

- Evaporator temperature vs. Power for various MHPs



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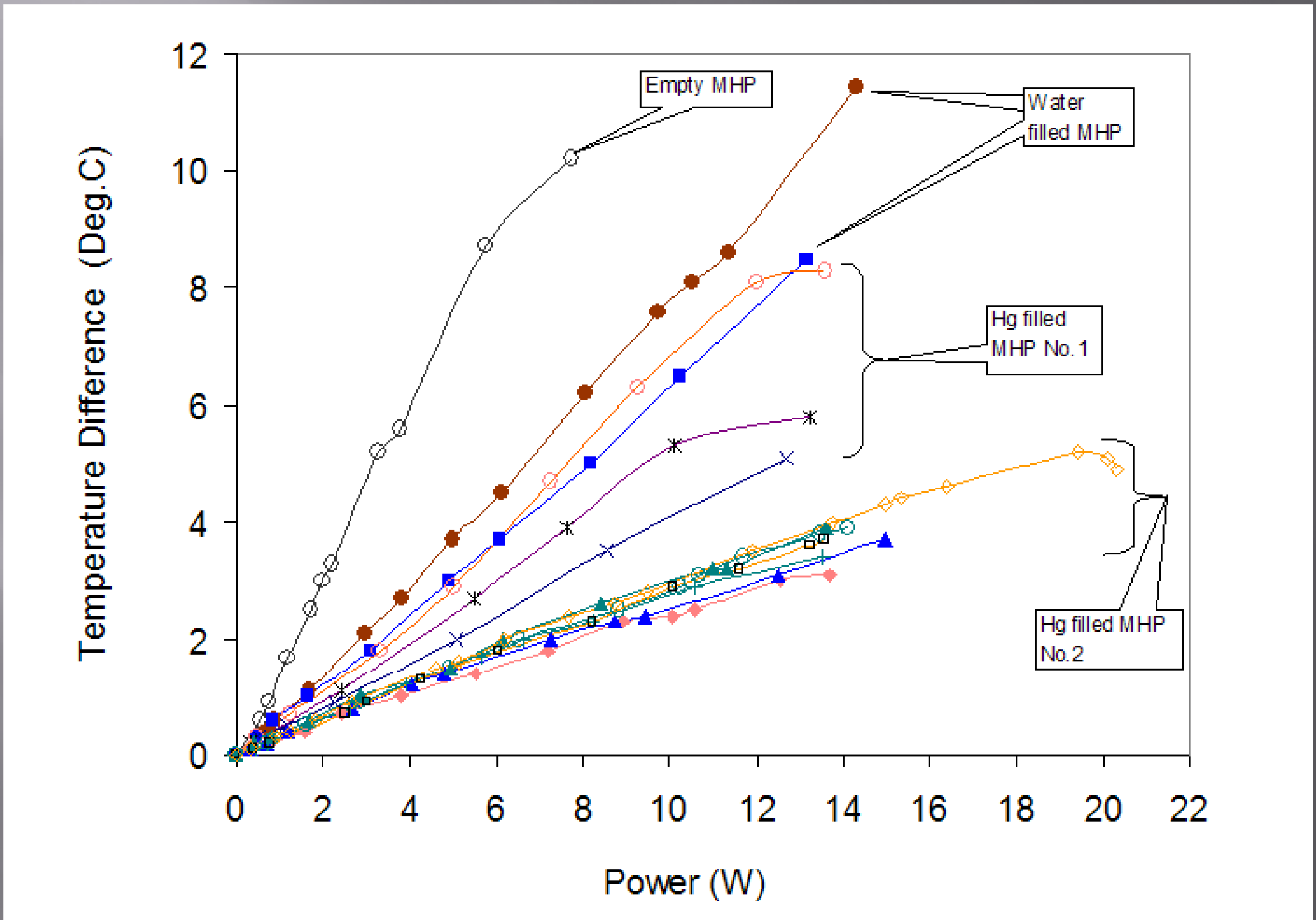
Test Results

- Temperature difference vs. Power for various MHPs



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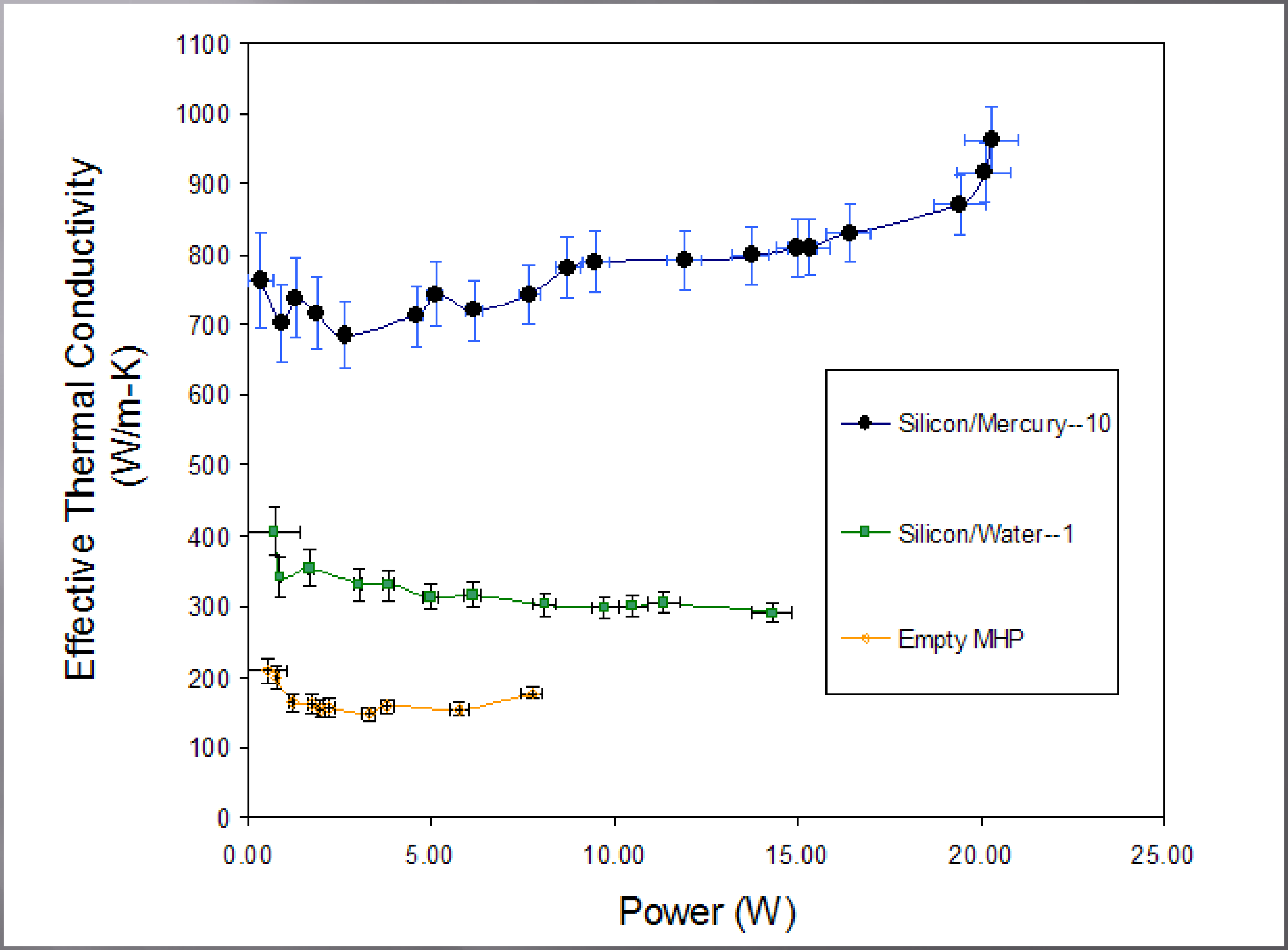
Test Results

- Uncertainty Analysis



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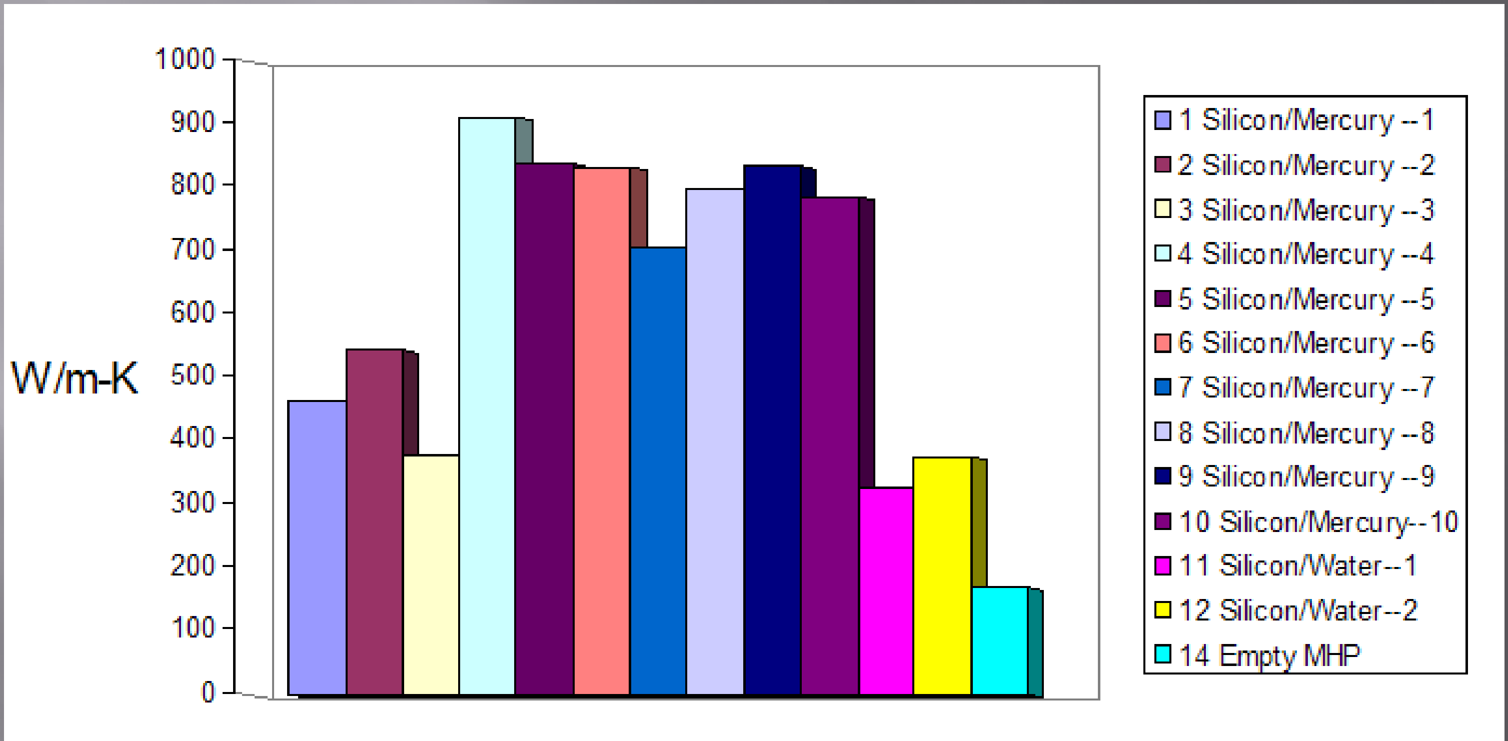
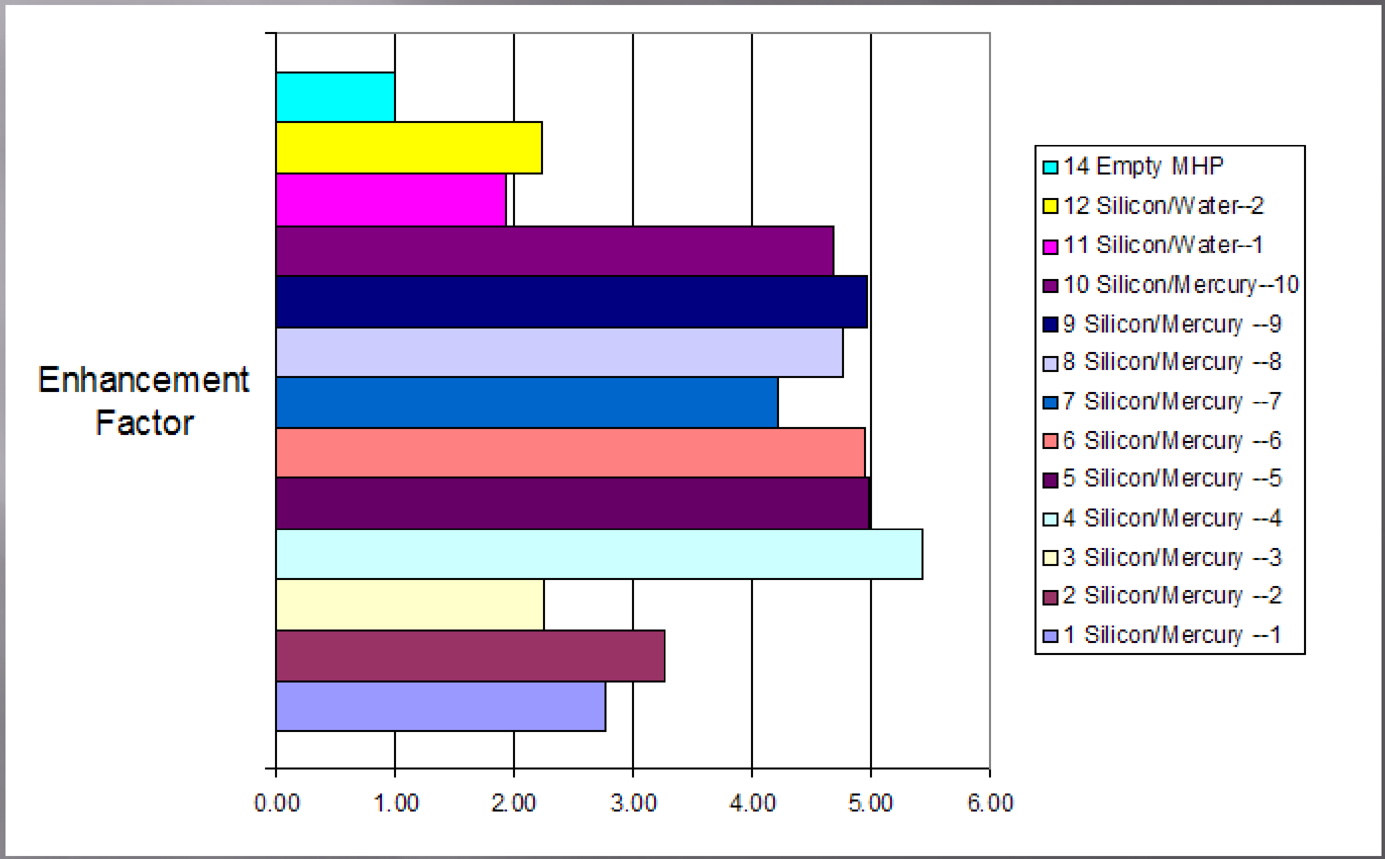
Test Results

- Comparison of average effective thermal conductivities for various MHPs



Test Results

- Enhancement factor : Improvement of the average effective thermal conductivity a charged MHP over that of an empty MHP



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