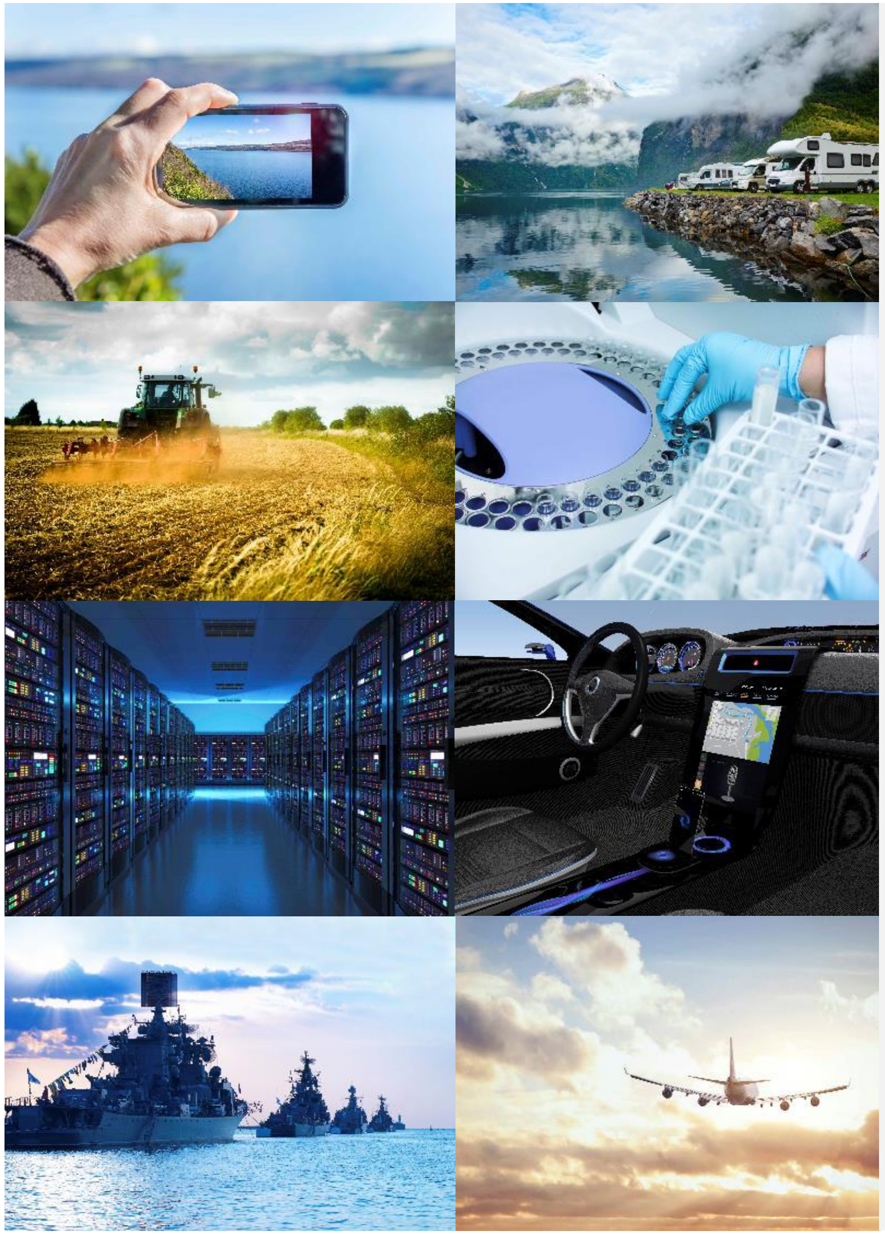

CTE Matching Heat Pipe Thermal Ground Plane (TGP)

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Date: April 26, 2019

BOYD CORPORATION

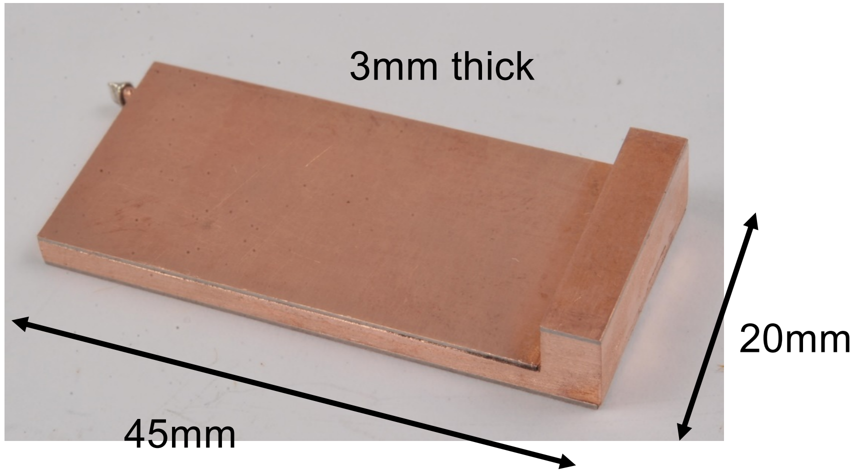
What is a Thermal Ground Plane (TGP)? Some history…

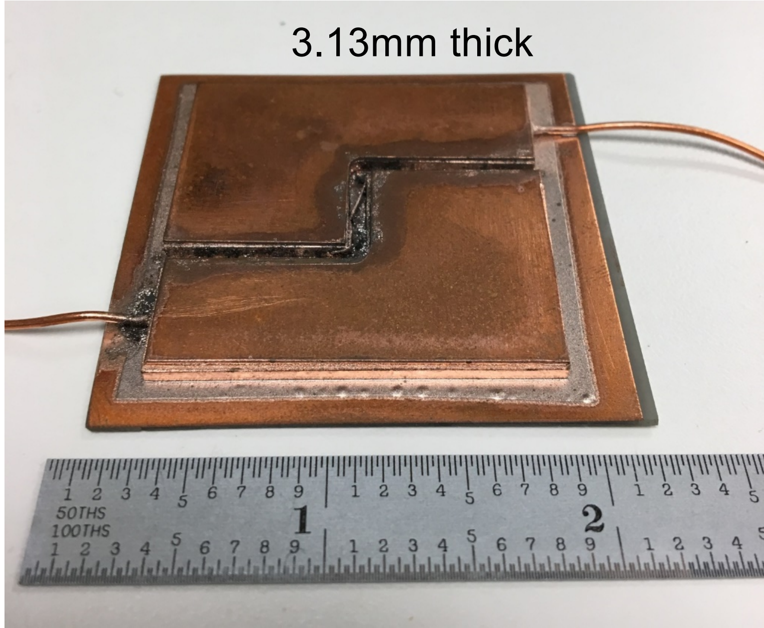
- 2007 DARPA BAA – Thermal Ground Plane
  - “thin, lightweight substrate for electronic systems that has thermal conductivity >100x common copper alloys used in these applications”
  - “in addition, matching thermal expansion coefficient to common electronic substrates (e.g. Si, GaAs, SiC)”

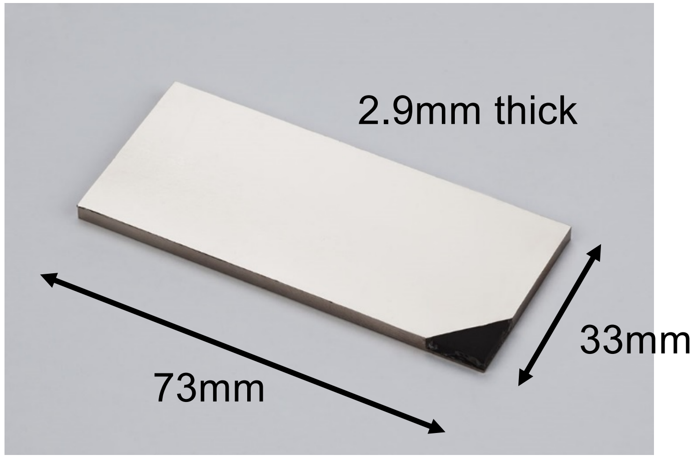
- Prior to the DARPA TGP program (2007), the term TGP was in limited use without the added connotation of low CTE. Also, the ground plane wasn’t necessarily flat.

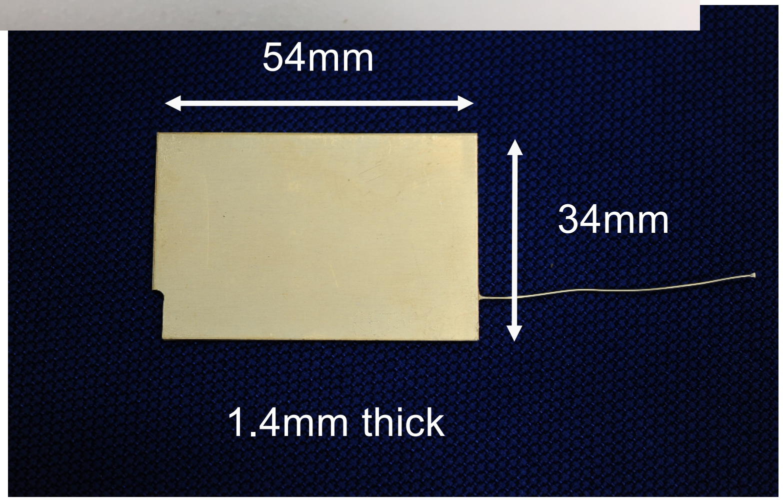
- CTE matching is application dependent concept that depends on the application (e.g. die size) and the method for attaching the die to the sink (i.e. the compliance of the TIM). For our purposes here, we won’t quantitatively impose CTE matching but will acknowledge that smaller difference in CTE between die and TGP is desirable.
- For this discussion TGP = thin, small form factor vapor chamber with CTE ≤ Cu

TGP Examples





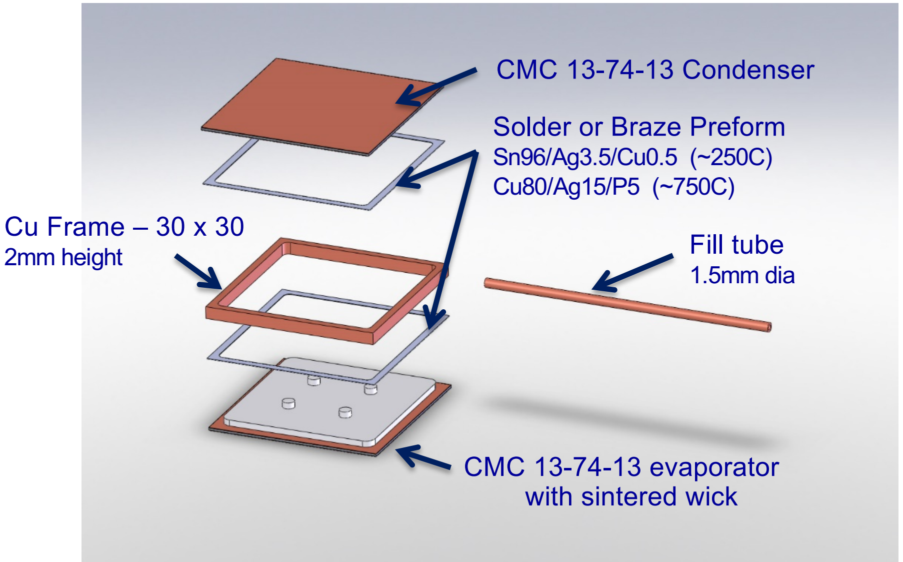


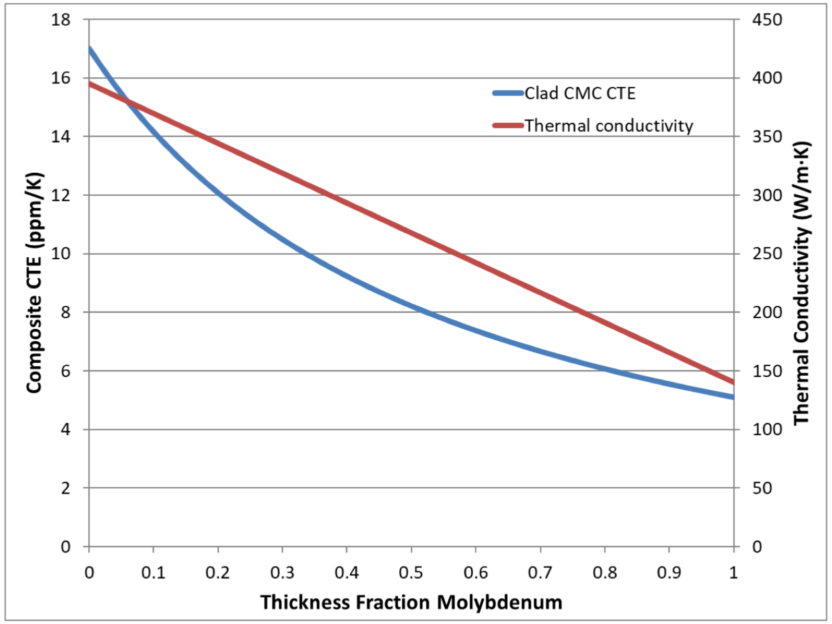


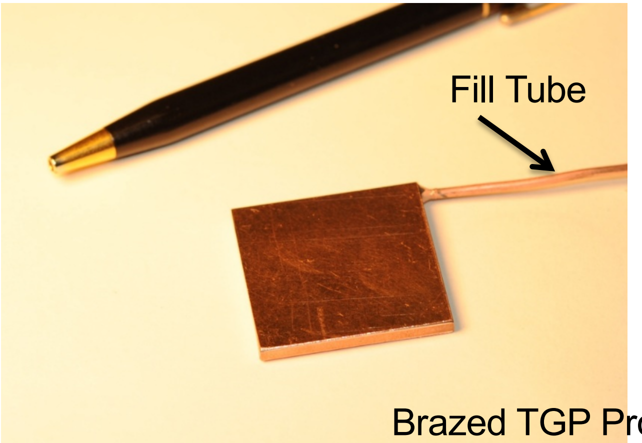
Typical TGP Parameters

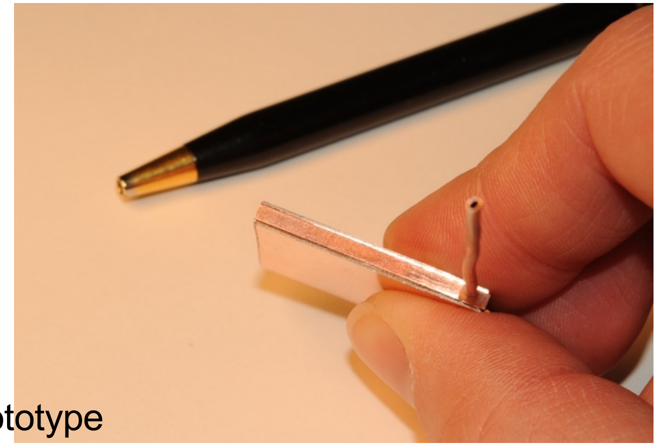
Parameter	Magnitude
Heat Load	Tens to Hundreds of Watts
Heat Flux	10s to 100s W/cm^2
Coefficient of Thermal Expansion	≤ Cu (17 ppm/K), <10ppm/K typical
Thickness	≤ ~3mm
Size	Range: 20mm to 70mm
Working Fluid	Water

EXAMPLE #1: TGP PROTOTYPE DESIGN





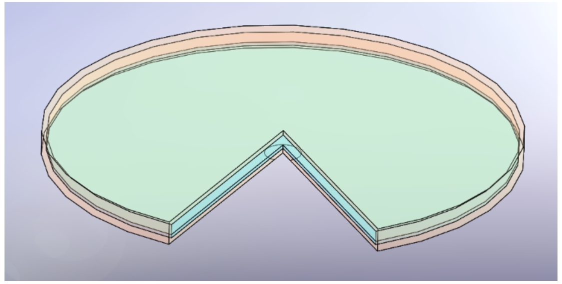




Brazed TGP Prototype

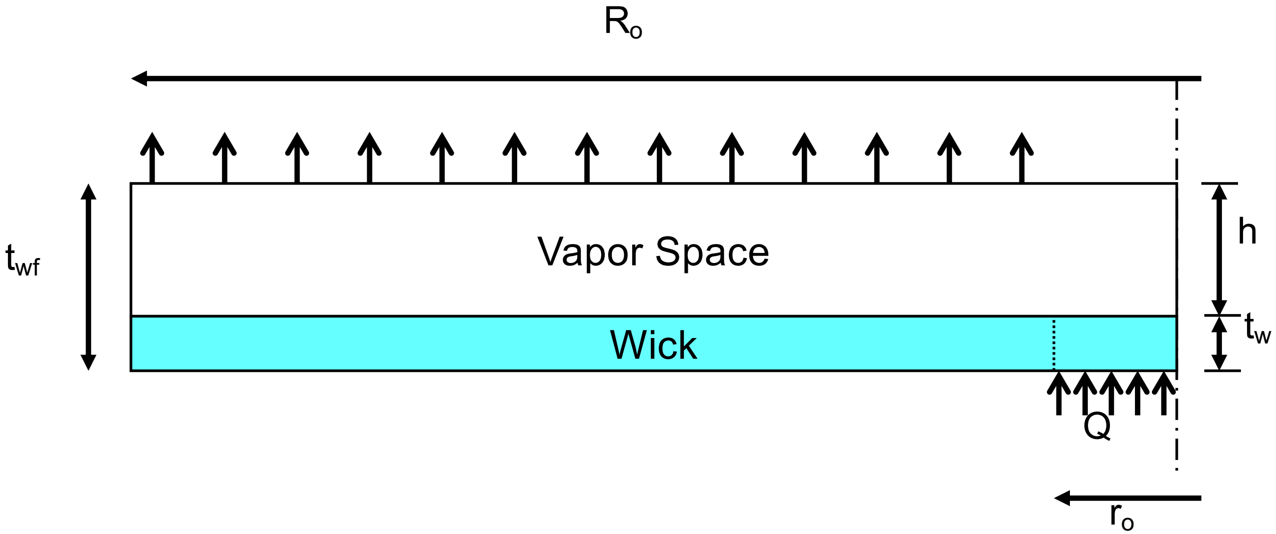
VAPOR CHAMBER – CYLINDRICAL GEOMETRY

Geometry of 1D cylindrical vapor chamber



For liquid flow

$$\frac{dP_l}{dr} = \begin{cases} \dfrac{\mu_l}{\rho_l K}\dfrac{\dot{Q}}{h_{fg}}\left(1-\dfrac{r_o^2}{R_o^2}\right)\left(\dfrac{r}{R_o}\right)^2\dfrac{1}{2\pi r t}, & 0 \le r < r_o \\ \dfrac{\mu_l}{\rho_l K}\dfrac{\dot{Q}}{h_{fg}}\left(1-\dfrac{r^2}{R_o^2}\right)\dfrac{1}{2\pi r t}, & r_o \le r \le R_o \end{cases}$$



For vapor flow

$$\dddot{V} = \frac{-h^3}{12\mu_v}\frac{dP_v}{dr}2\pi r$$

- Integrating liquid and vapor pressure gradients and neglecting body forces gives:

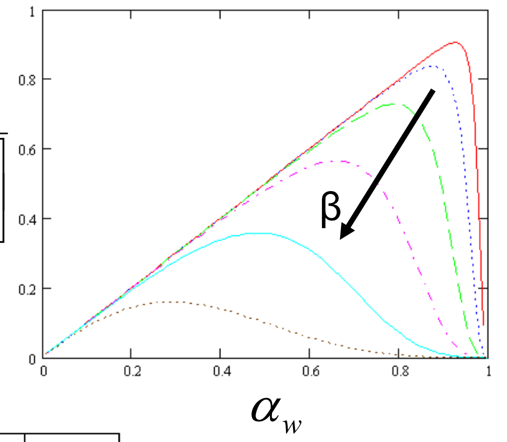
$$\dot{Q}_{\max} = \left[\frac{4\pi\left(1-\frac{r_o^2}{R_o^2}\right)}{\ln\left(\frac{R_o}{r_o}\right)}\right] \frac{\left(\frac{\rho_l h_{fg}\sigma}{\mu_l}\right)\left(\frac{K}{r_c}\right) t_{wf}\alpha_w}{\left[1+12\left(\frac{K}{t_{wf}^2}\right)\left(\frac{\nu_v}{\nu_l}\right)\left(\frac{\alpha_w}{(1-\alpha_w)^3}\right)\right]}$$

where

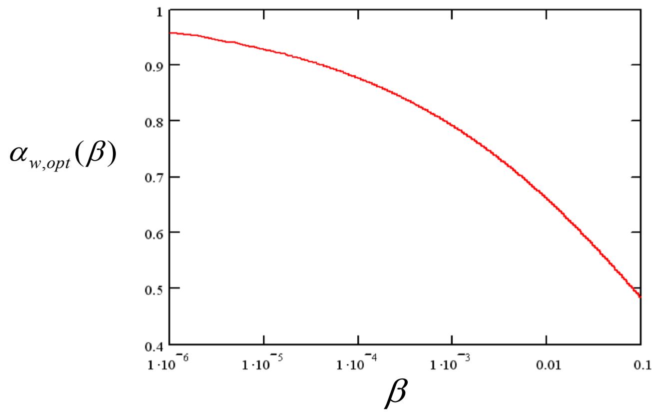
$$\alpha_w = \frac{t_w}{t_{wf}}$$

$$\beta = 12\left(\frac{K}{t_{wf}^2}\right)\left(\frac{\nu_v}{\nu_l}\right)$$

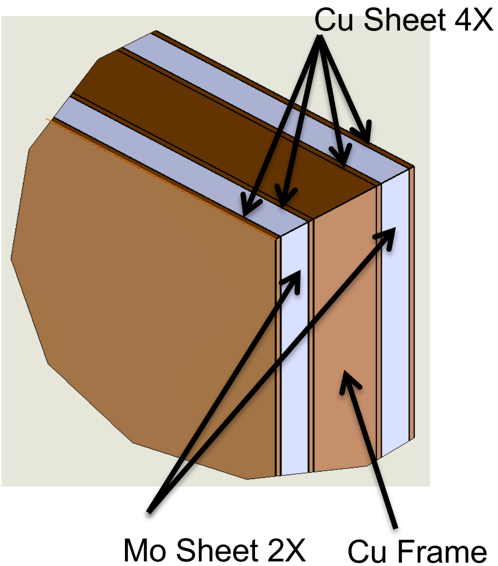
$$\frac{\alpha_w}{\left[1+\beta\frac{\alpha_w}{(1-\alpha_w)^3}\right]}$$



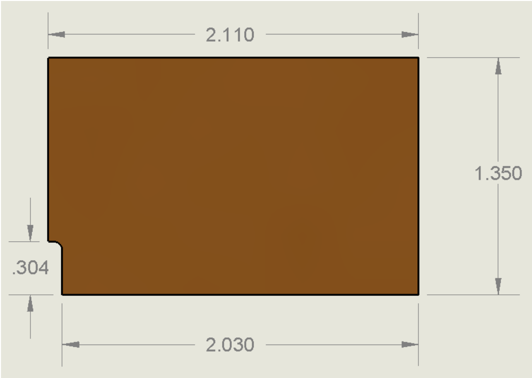
$$\alpha_{w,opt} = 1+\frac{1}{2}\sqrt{3\beta}-\frac{1}{2}\sqrt{3\beta+4\sqrt{3\beta}}$$

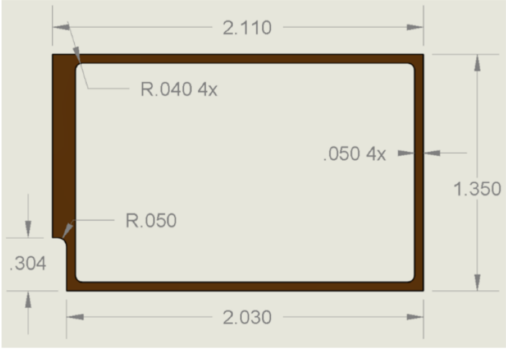


EXAMPLE: ASSEMBLY CTE THERMAL STRESS ANALYSIS

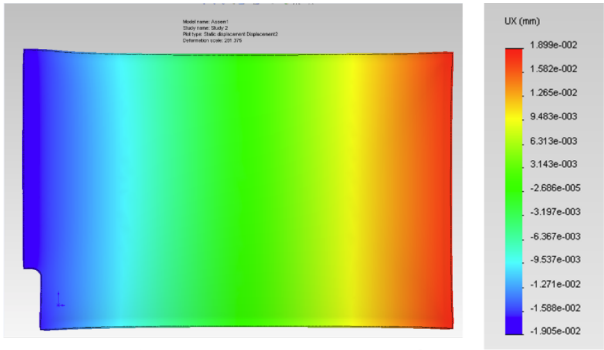


CMC 13-74-13 sheets 0.38mm thick
Cu frame 0.64mm thick

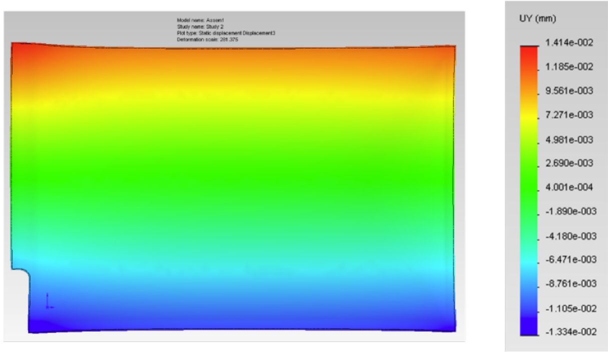




Displacement with imposed 100C ΔT

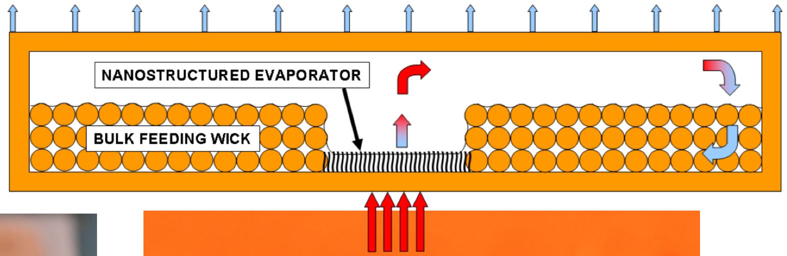


CTEx = 7.1ppm/K

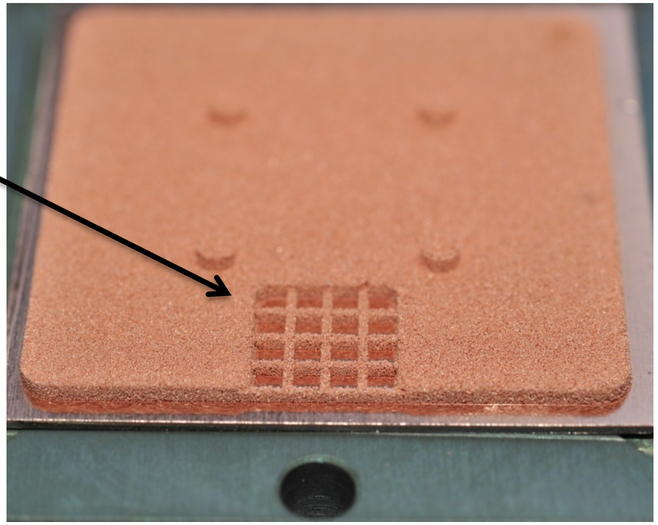


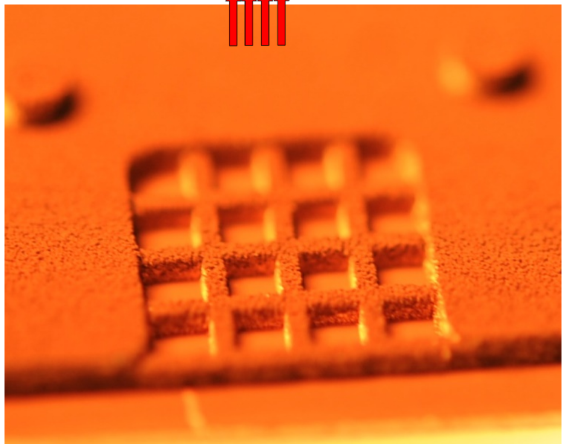
CTEy = 8.0ppm/K

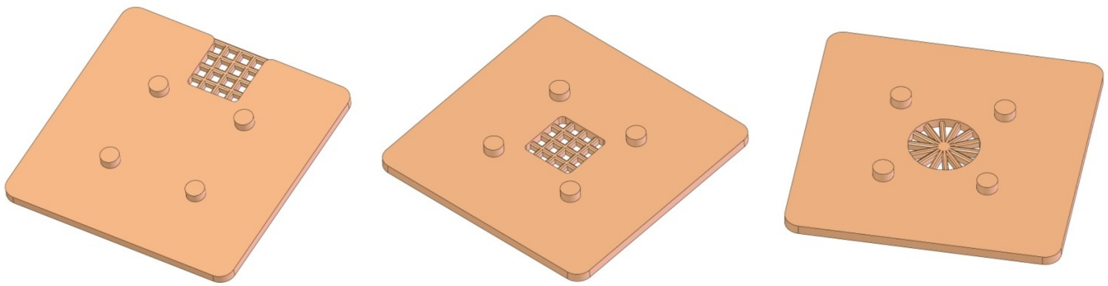
HIGH HEAT FLUX AREAS - FEEDING WICK STRUCTURES



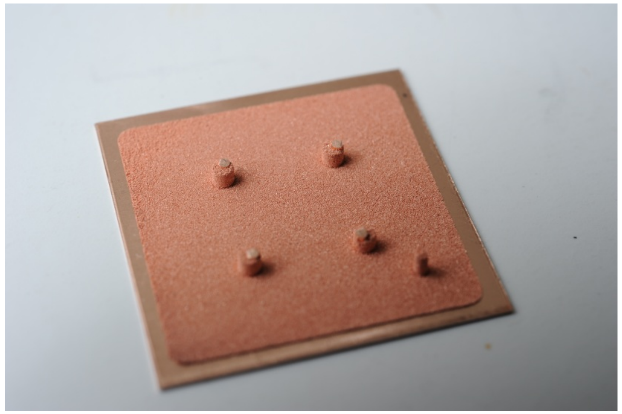
Fabricated Patterned Feeder Wick



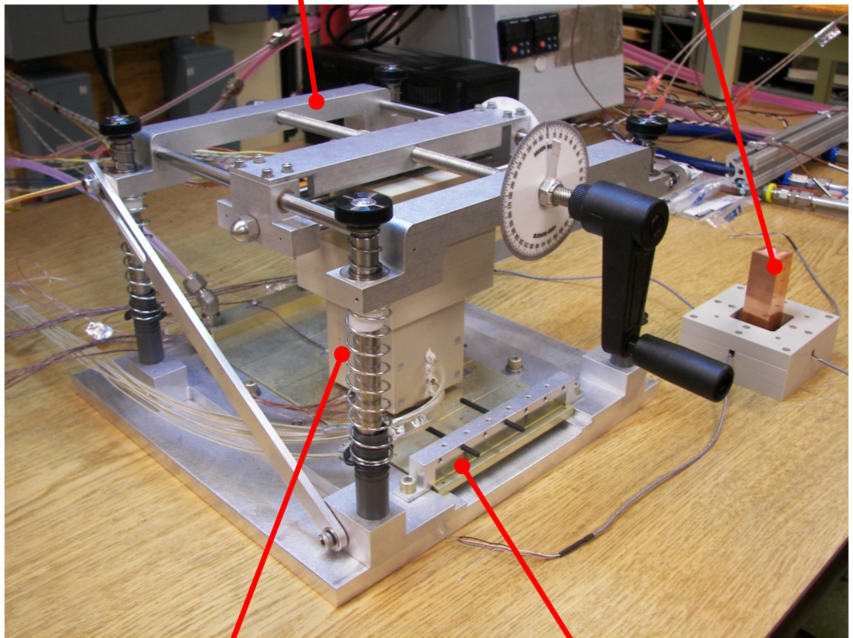


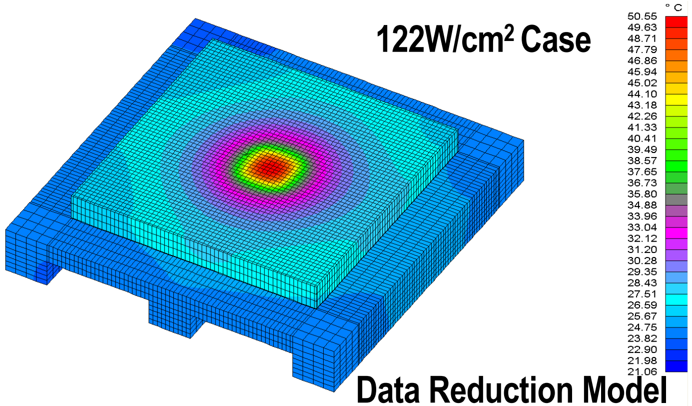


Alt Patterned Feeder Wick Structures

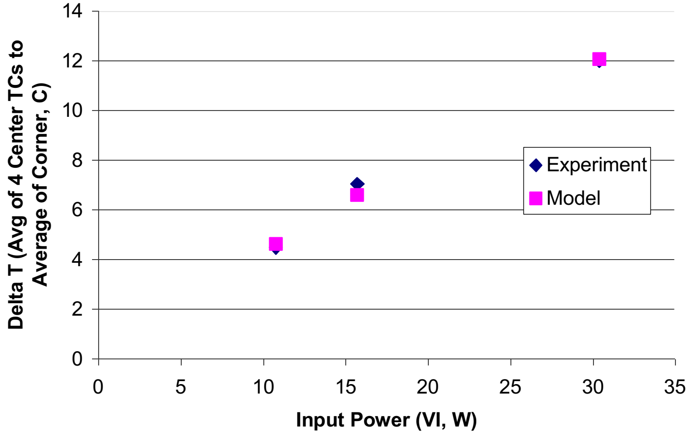


TGP CHARACTERIZATION TEST EQUIPMENT

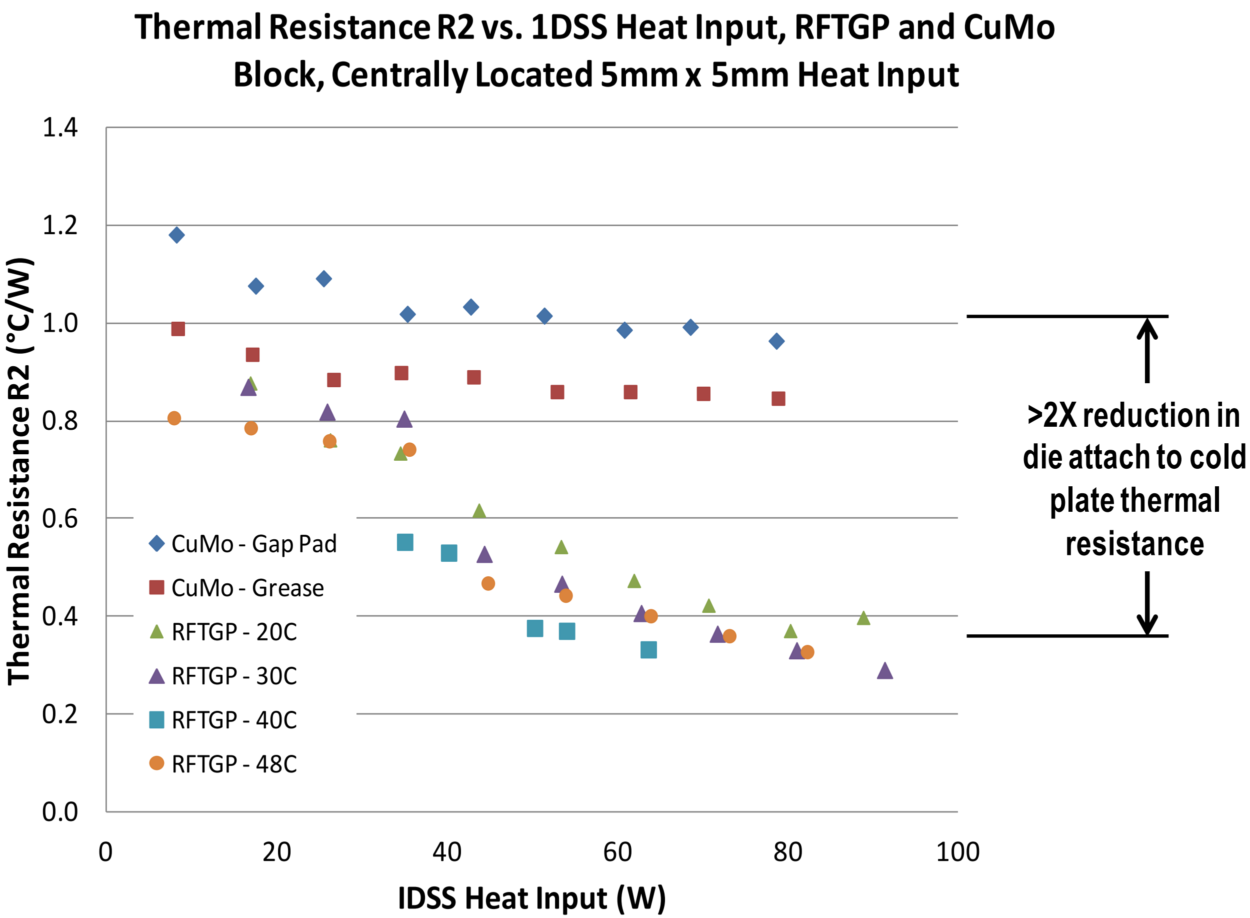




Baseline Data – 15/85 CuMo Block k = 145W/mK

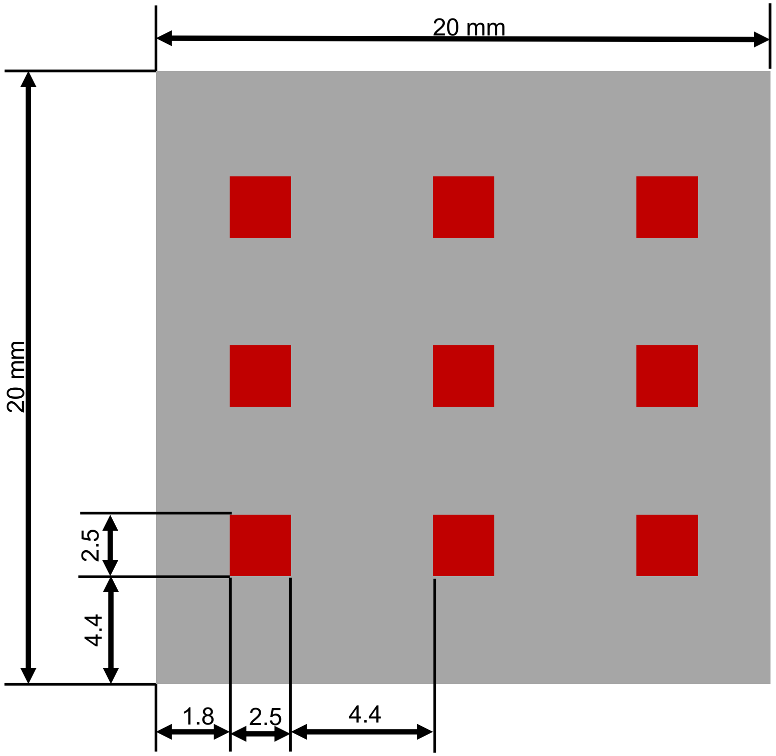


COMPARATIVE DATA – TGP VS CU-MO MMC



Example#2: Hot Spot Simulation Analysis

Example die and hot spot layout



Base heat flux = 45 W/cm^2

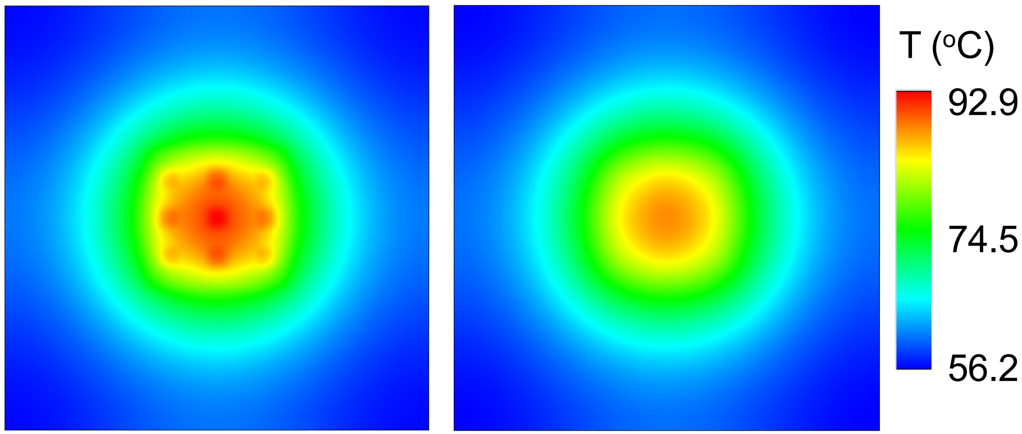
Hot Spot heat flux = 150 W/cm^2

- Total power dissipation = 240W.
- Conduction-based thermal model.
- Spreader size = 55x55 mm
- Air-cooled heat sink simulated on the condenser side including TIM2. h_{eff} = 2000 W/m^2K.
- Sintered powder wick structure.
- Effective heat transfer coefficients for evaporation and condensation are included in the TGP model based on experimental data.
- T_{amb} = 30°C.

Copper spreader vs TGP spreader

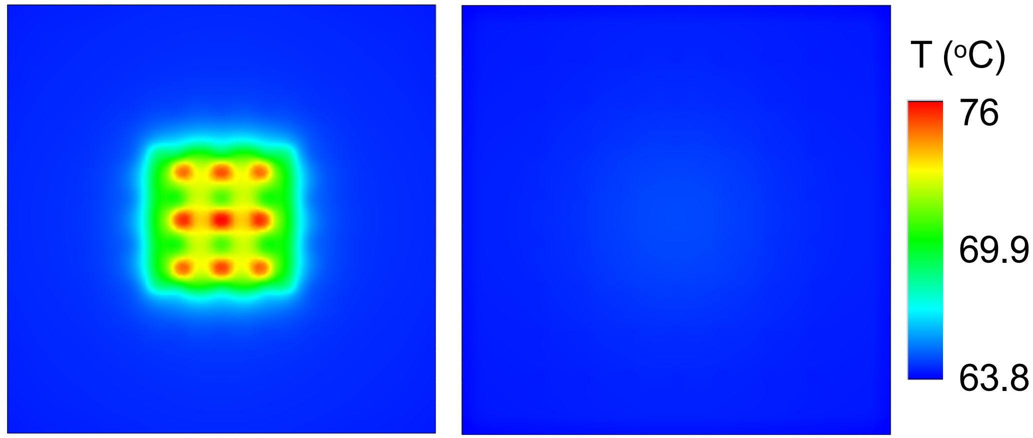
- The TGP spreader is able to decrease the heat source temperature by 17°C compared to a traditional copper spreader.
- To match the max temperature of the copper spreader case, power can be increased by 35% (324W).
- Sensitivity analysis showed that the contact area of the heat sink affects the temperature decrease.
  - To maximize the spreading benefit of the TGP, the heat sink must cover as much surface area of the TGP as possible.
  - TGP spreader generally outperformed Cu spreader if spreading ratio (sink area:die area) is greater than about 4:1.

Copper Spreader



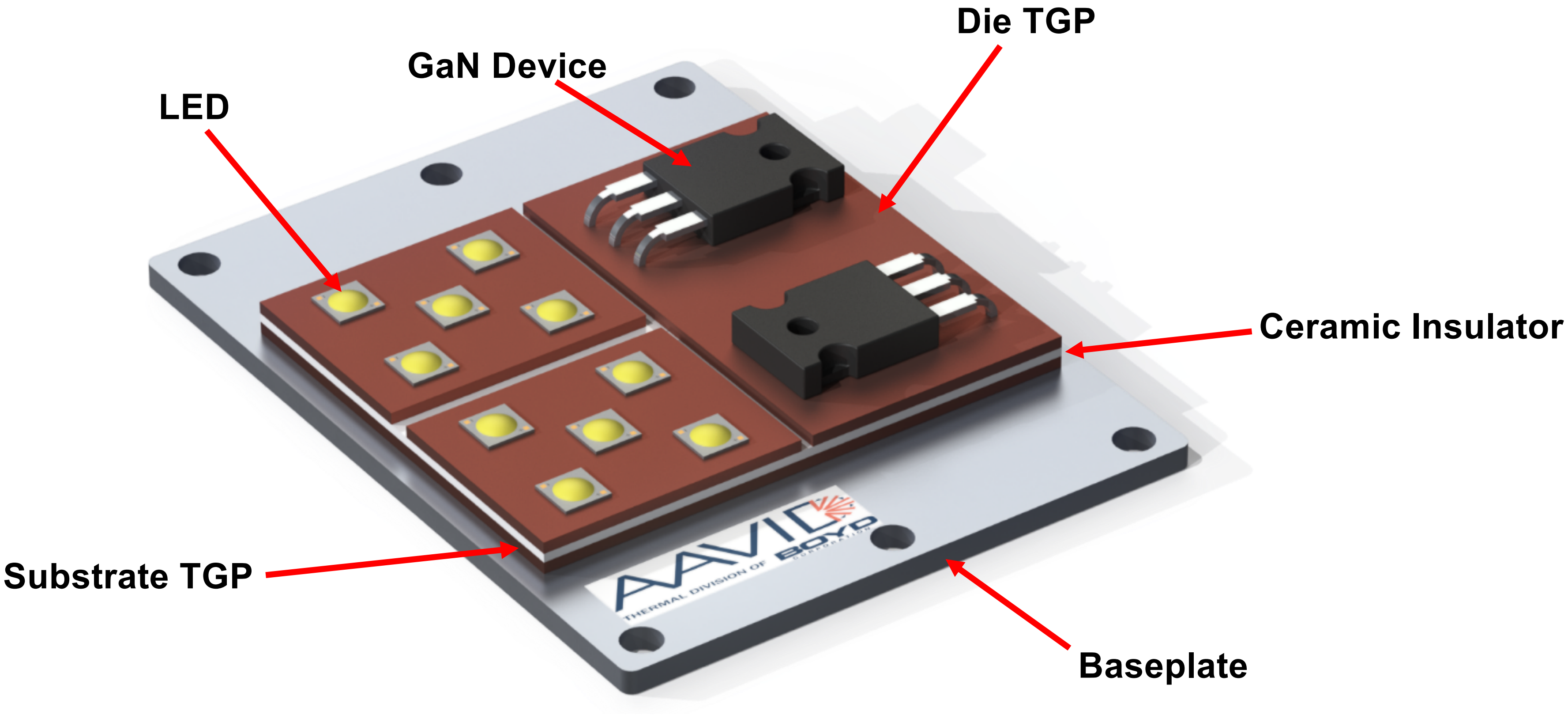
Input side | Output side

TGP Spreader

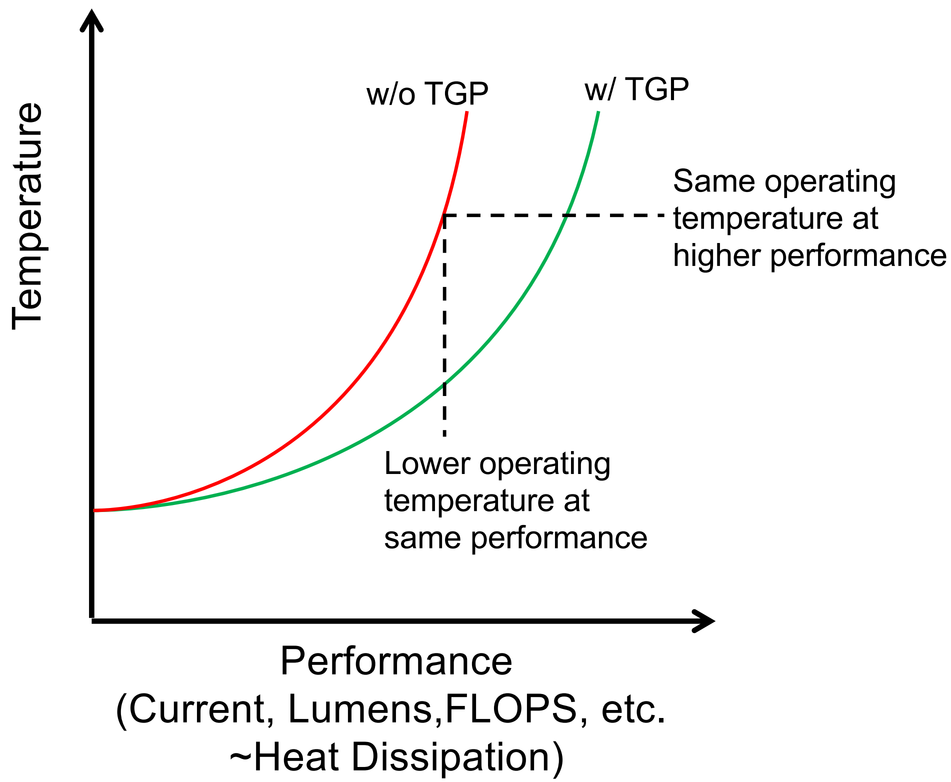


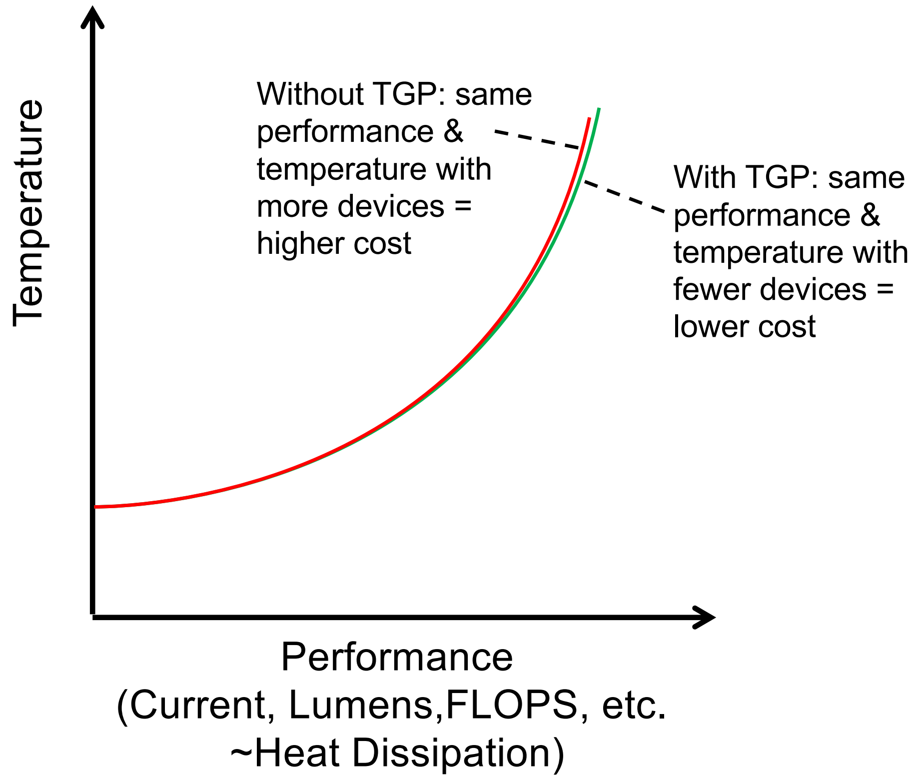
Evaporator Side | Condenser Side

OTHER TGP APPLICATIONS



EXAMPLE #3: COST VS. PERFORMANCE TRADE





SUMMARY

- Any vapor chamber can be thought of as a Thermal Ground Plane. Recent literature assumes TGPs to be thin, small form factor vapor chambers, usually with some attempt to use lower CTE materials.
- TGPs can be used to spread heat effectively in applications where lower CTE is required. An architecture based on clad Cu-Mo-Cu is shown here with CTE ~7.5ppm/K, less than half of similar copper structures.
- Analysis shows that this TGP will be capable of reducing hot spot temperatures even in applications where the overall spreading ratio is not especially high.
- Improved TGP thermal management may enable reducing the number of components, which may make possible reduced system cost, or increased throughput.