A Practical Guide for Using Liquid Two-Phase Heat Sinks

Presenter

George Meyer
CEO, Celsia Inc.

We'll Answer these Questions

Do I Need 2-Phase?

- Benefits and consequences of solid materials
- Some basic rules of thumb

Are Vapor Chambers Just Flat Heat Pipes?

- Similarities: design, wicks & performance limits
- Differences: for moving or spreading heat

What Size Do I Need?

- Heat pipes: diameter, quantity, and shape
- Vapor chambers: thickness, area, and shape

How Do I Integrate Them?

- Attaching it to the condenser
- Mounting it to the heat source/ PCB

What Should the Heat Exchanger Look Like?

- Types of condensers
- Pros and cons

How Do I Model Thermal Performance?

- Heat sink ballpark
- Excel Model
- CFD analysis
- Proto testing

When to Use 2-Phase Devices

The Short Answer

- Only when the **design is conduction limited or**
- **Non-thermal goals** such as weight or size **can't be achieved** with other materials such as solid aluminum and/or copper.

Aluminum

(baselined at 1X)

Base thk: 1X
Weight: 1X
Cost: 1X

Even with increased base thickness, may not meet thermal requirements

Copper

Base thk: 0.5X
Weight: 3X
Cost: 1.6X

Copper significantly increases performance, weight & cost. May not meet shock/ vibration needs or thermal requirements

Two Phase

Base thk: 0.5X
Weight: 2X
Cost: 1.8X

Performance can be 5-15% better than solid copper sink with less weight penalty

2-Phase Rules of Thumb

1

2-phase devices are **incredible heat conductors**.

- 5 to 50 times better conductivity than aluminum or copper using copper/water 2-phase
- 1,000 to >50,000 w/mk. Exact figure is primarily dependent on the distance the heat is transported

2

Ideal when heat needs to be **moved** more than 30-50mm

- Remote fin stacks (heat exchangers) are a perfect example

3

If you're interested in **spreading** heat to reduce hot spot and/or attach to a local heat exchanger

- The ratio of heat spreader to heat source should be on the order of 30:1 greater area

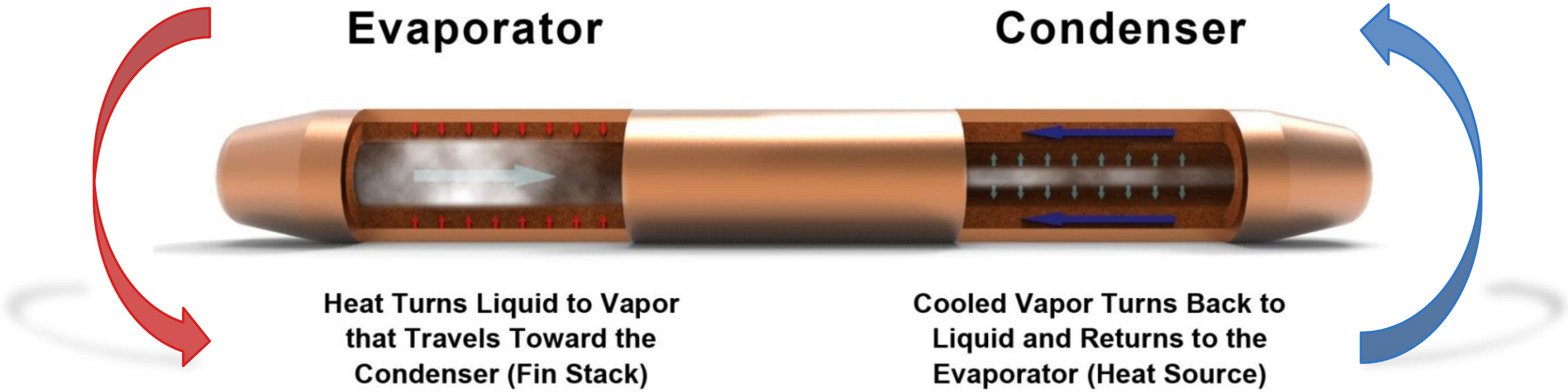
4

As with any heat sink, design in an **extra 30%-40% thermal headroom**

2-Phase Similarity: Inner Workings

Heat pipes & vapor chambers transfer heat through the **phase change of liquid to vapor and back to liquid**

Liquid is passively **pumped** from condenser to evaporator **by capillary action**

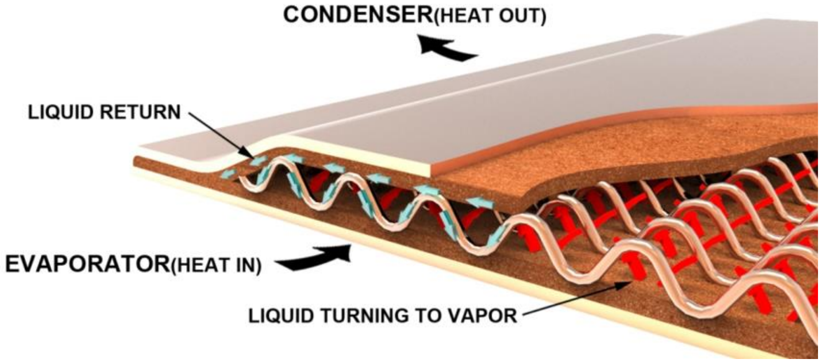


Heat Turns Liquid to Vapor that Travels Toward the Condenser (Fin Stack)

Cooled Vapor Turns Back to Liquid and Returns to the Evaporator (Heat Source)

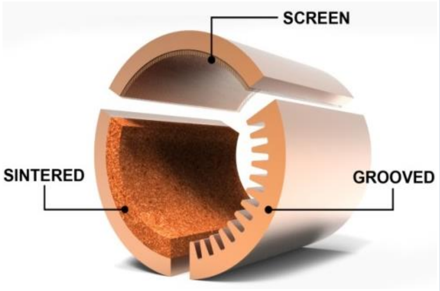
Used for very efficient heat transport & spreading

No noise or moving parts with very high reliability

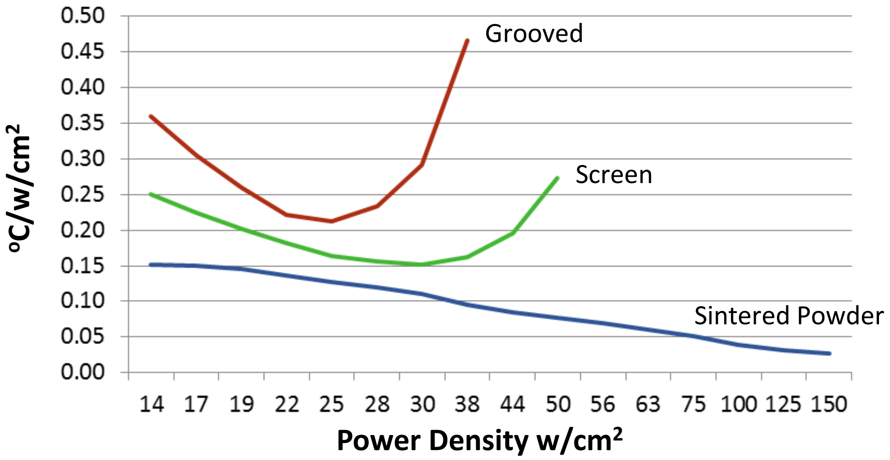


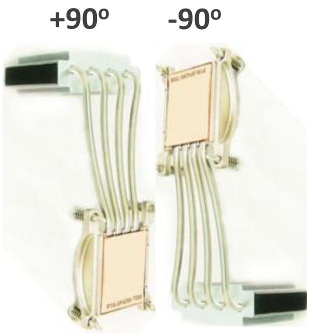
2-Phase Similarity: Wick Structures

	Power Density	Resistance	Orientation
Sintered Powder	<500w/cm^2 Good for freeze/thaw and bent shapes Small heat sources up to 1,000 w/cm^2	0.15-0.03 °c/w/cm^2	+90° to -90°
Screen	<30 w/cm^2 Main use is for very thin heat sinks due to high evaporator resistance. Limited bending.	0.25-0.15 °c/w/cm^2	+90° to -5°
Grooved	<20w/cm^2 Entry level price / performance must be gravity aided/neutral.	0.35-0.22 °c/w/cm^2	+90° to 0°



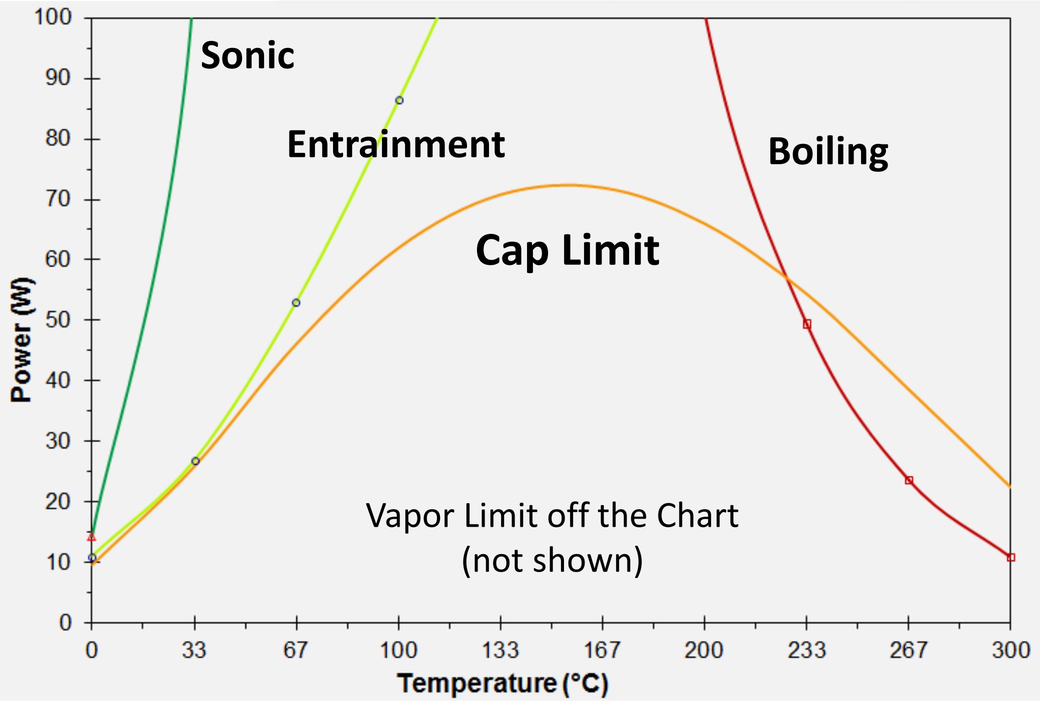
Evaporator Resistance (Typical Two Phase)





2-Phase Device Similarity: Performance Limits

Limit	Vapor Pressure	Sonic	Entrainment	Capillary 'the limiting factor'	Boiling
Cause	Operating well below design temp	Start-up power, low temp combo	Device above designed power input or at low temp	Input power exceeds design	Radial heat flux exceeds design
Problem	Vapor flow prevented	Large internal pressure drop	Condenser flooded with excess fluid	Capillary pump breaks down	Wick dries out
Solution	Change working fluid	Non-catastrophic. Device normalizes as it runs	Increase vapor space or operating temp	Modify wick structure	Increase wick heat flux capacity



Vapor Limit off the Chart
(not shown)

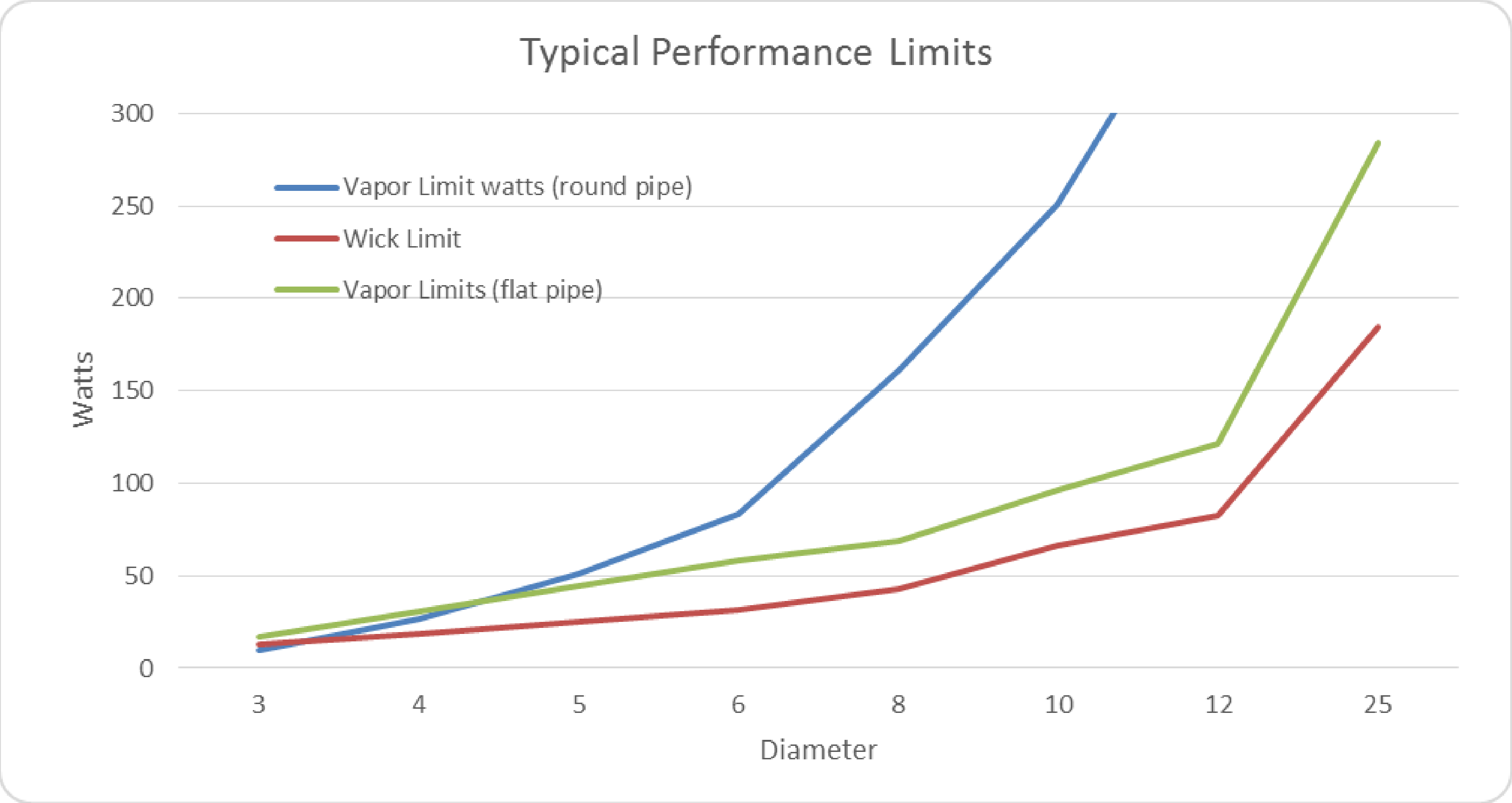
Capillary limit is the ability of a particular wick structure to provide adequate circulation for a given working fluid.

It is **usually the limiting factor for terrestrial applications.**

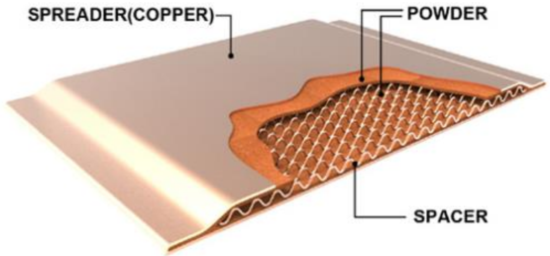
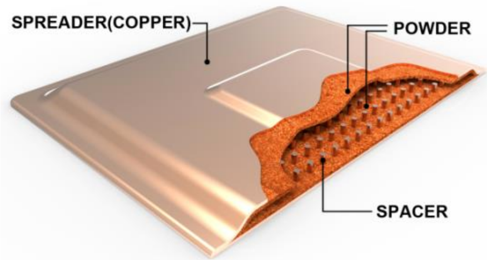
Performance Limits (continued)

Typical performance limits for various diameters

- The vapor limits are usually only a factor when using flattened heat pipes due to the size reduction in the vapor space

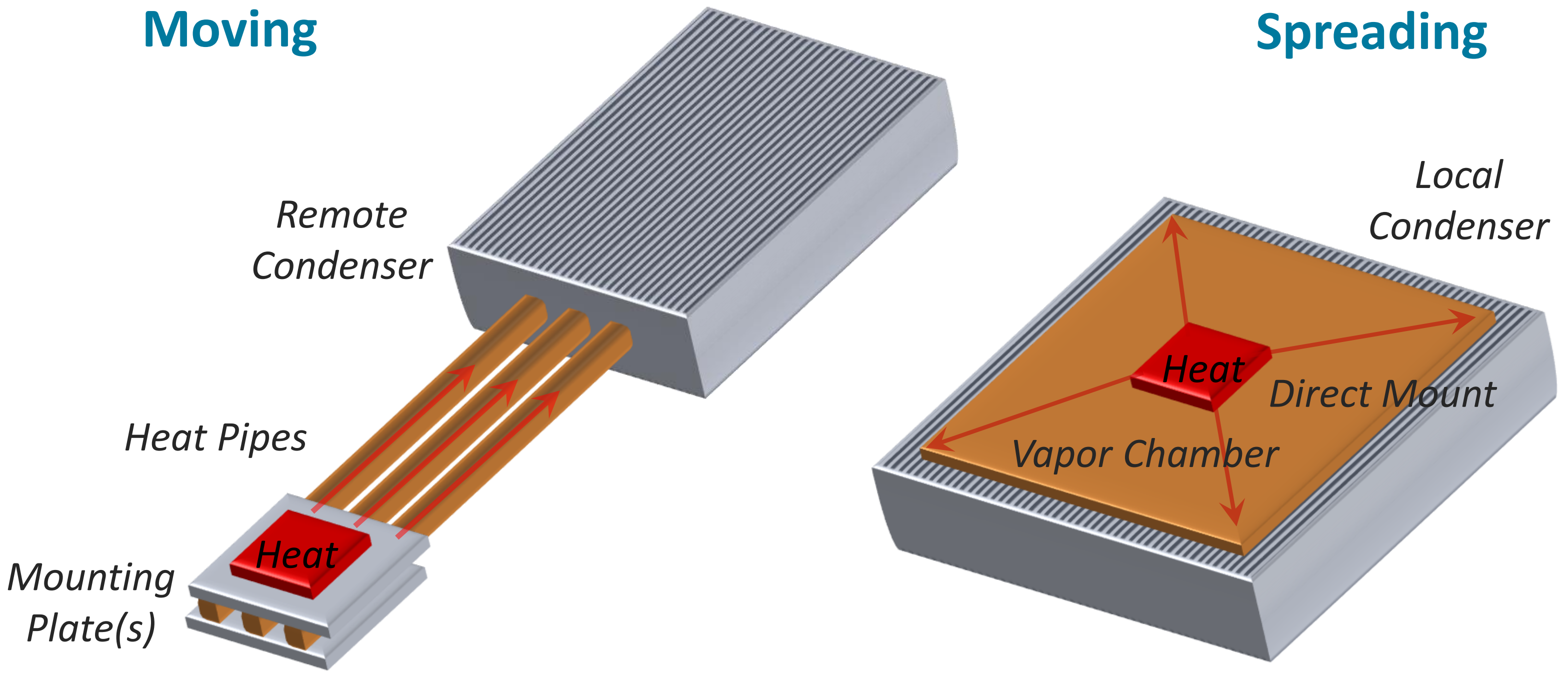


2-Phase Differences: Overview

	Heat Pipe	Hybrid 1-Piece Vapor Chamber	Traditional 2-Piece Vapor Chamber
			
Initial Form Factor	Small diameter tube 3-10mm	Very large diameter tube 20-75mm	Upper and lower stamped plates
Shapes	Round, flattened and/or bent in any direction	Flattened rectangle, surface embossing & z-direction bendable	Complex shapes in x and y direction, surface embossing
Typical Dimensions	3-8mm diameter or flattened to 1.5-2.5mm. Length 500mm+	1.5-4mm thick, up to 100mm W by 400mm L	2.5-4mm thick, up to 100mm W by 400mm L
Mounting to Heat Source	Indirect contact though base plate unless flat & machined	Direct contact. Mounting pressure up to 90 PSI	Direct contact. Mounting pressure up to 90 PSI
Relative Cost	Very cost effective, but increases quickly with large diameter, custom wick structure, secondary ops	Comparable to 2-4 heat pipes in higher power and/or high heat flux applications	More expensive than 1-piece design due to additional tooling cost and labor time, but large scale production closes the gap

2-Phase Differences: Moving or Spreading Heat?

While there's no hard line of distinction between the two,
think of the difference like this…



- Linear heat flow
- Remote condenser, usually

- Multidirectional heat flow
- Local condenser, almost always

When *Moving* Heat to a *Remote* Sink

99% of All Applications Use Heat Pipes

- Complex shapes often required
- Easily bendable in any direction
- Readily available in volume
- Will work against gravity ± 45°

Example #1 – Notebook computer

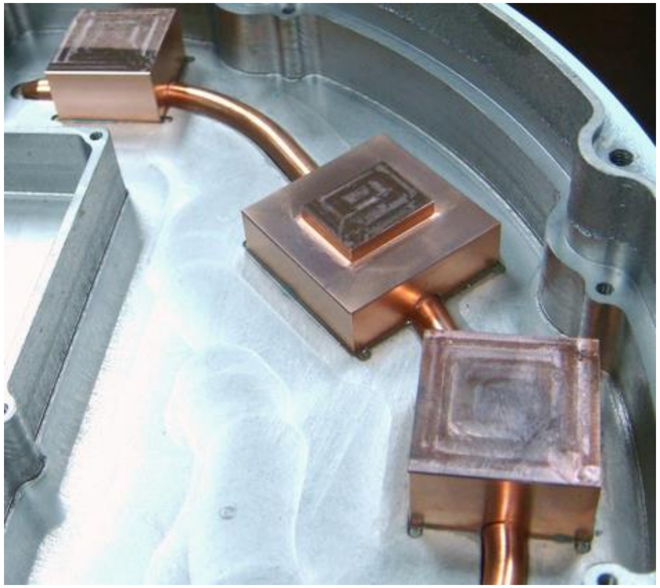
2 flattened heat pipes cool 3 heat sources

- With the right thermal modeling, heat sources can be daisy chained onto one device.
- Good example of heat pipe design flexibility.

When *Moving* Heat to a *Remote* Sink (continued)

Example #2 – Small Form Factor PC

Processor cooler that uses the system fan incorporates 4, 6mm heat pipes to move a nominal 100-135 watts to the air stream created by the system fan



Example #3 – Repeater Housing

Take the heat off of several components and move it to a finned section of a cast housing. It is common to have multiple heat sources on a heat pipe.

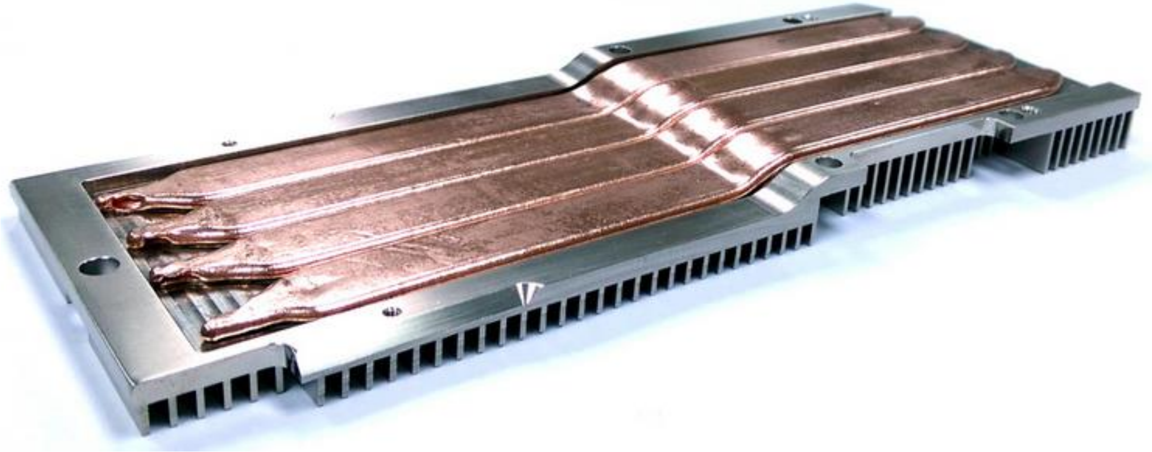
When *Spreading* Heat to a *Local* Sink

Heat Pipes are a Good Choice If

- Plenty of air flow
- Lots of room for fins
- Nominal power densities <25 w/cm^2
- Normal ambient
- <u>Every penny counts!</u>

Example #1 – Telecom Equipment Application

- For moderate performance applications where spreading needs to be augmented, the use of several heat pipes embedded into the base may be sufficient
- The use of heat pipes in the base does not eliminate the conductive losses but will help to reduce them.



When *Spreading* Heat to a *Local* Sink

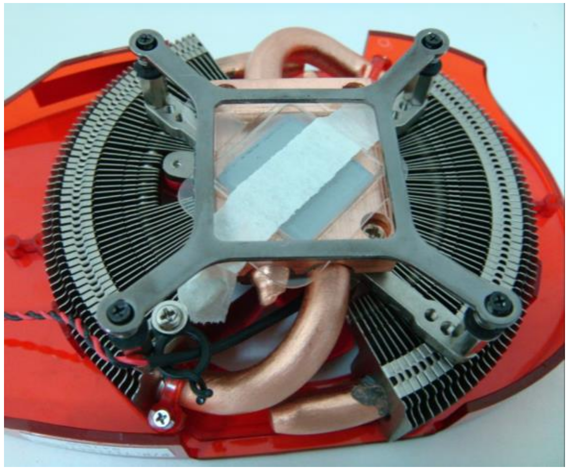
Vapor Chambers may be the Best choice if

- Z direction (height) is limited
- Power densities are high
- High ambient or low air flow
- <u>Every degree counts!</u>

Example #1 – Higher GPU power & density required design modification

One 3mm thick vapor chamber replaced two 8mm heat pipes. 6 degree C better performance and more even heat distribution across heat source surface

- Direct contact to the VC means one less interface and better spreading
- Flat design allows for additional fin area



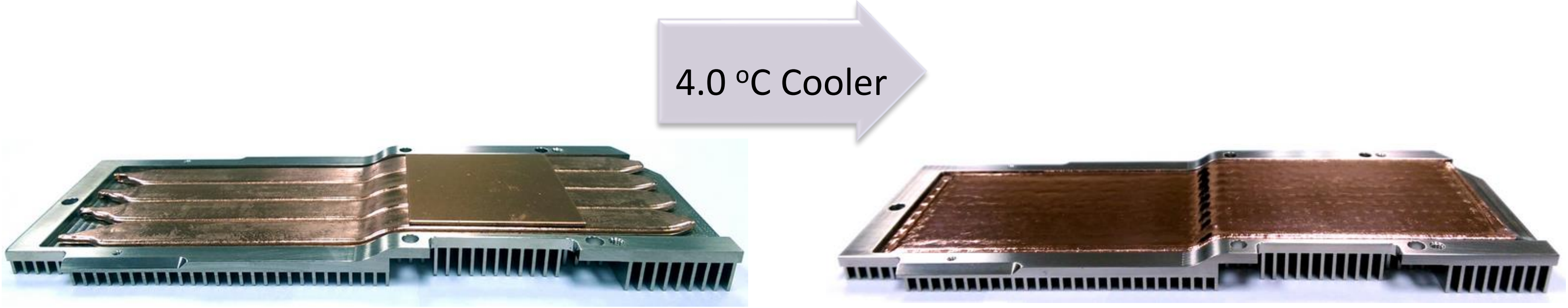
6 °C Cooler

When *Spreading* Heat to a *Local* Sink (continued)

Example #2 – Two versions of the same heat sink

Four flattened heat pipes versus a single vapor chamber

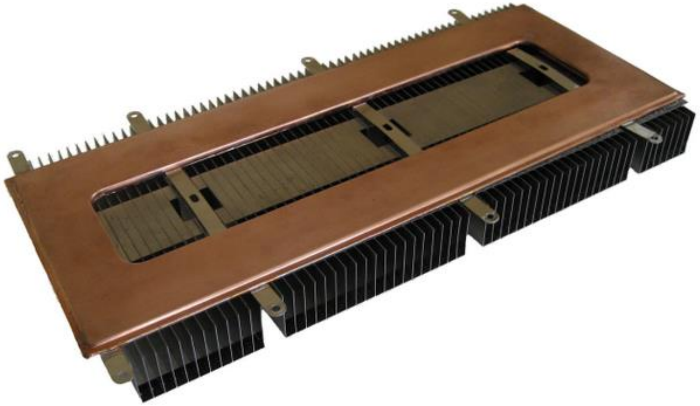
- Four degree C better performance from VC assembly due to direct contact with heat source. Heat source hot spots also reduced


4.0 °C Cooler

Example #3 – Weight was a critical design factor

Cools six 80 watt ASICs

- Two piece vapor chamber with center cut out for improved weight.
- Heat pipes were not an option due to requirement to thermally link all six ASICS



When *Moving* Heat to *Remote* Sink

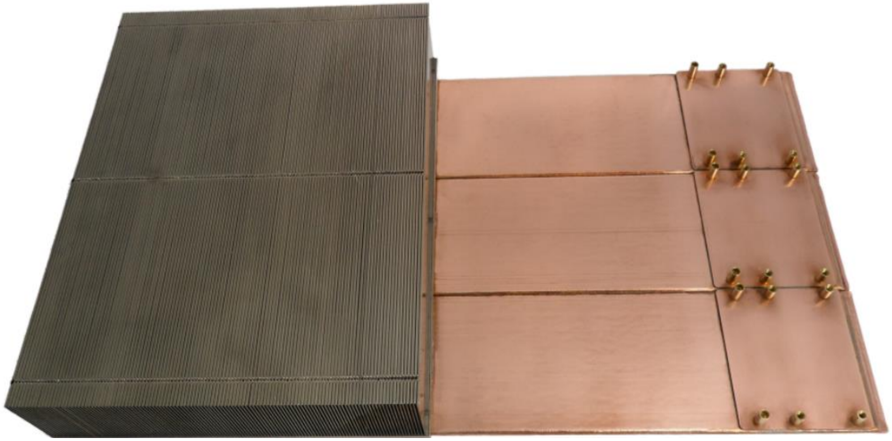
Vapor Chambers are a Good Choice If

- Thermal performance is critical
- Ultra-thin VC can allow for more fin area

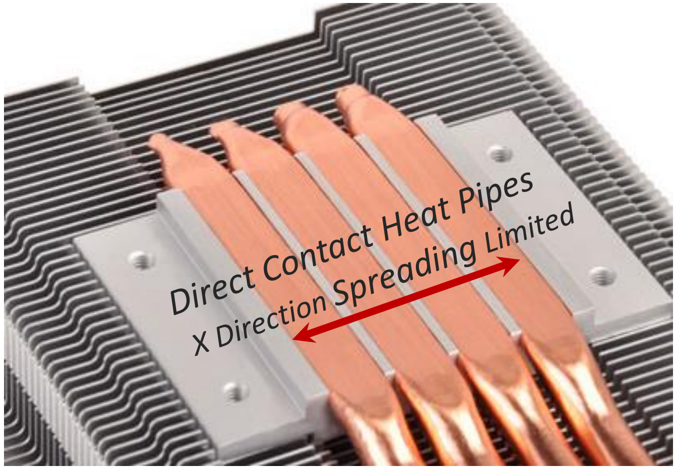
Example #1 – Three 450W RGB Laser Diodes for 3D Projector

Three vapor chambers each 70mm W x 300mm L move heat to a common fin stack

- Vapor chambers were used in place of heat pipes to reduce conduction loss



Spreading & Moving – Some Oddballs



Example #1 – Flattened / machined HPs are sometimes used to mimic a vapor chamber

Gaming desktop cooling overclocked processors

- Heat pipes make direct contact with the heat source, eliminating 2 interface layers
- If implemented correctly performance can be good, but cost rises quickly and heat spreading in X direction is still limited

Example #2 – Heat pipes and vapor chamber used in combination

Small form factor desktop PC cooling Core I7 chip

- VC replaced copper mounting plate
- 5 degree better performance than original design with reduced hot spots

Heat Pipe Sizing (copper, sintered wick, water)

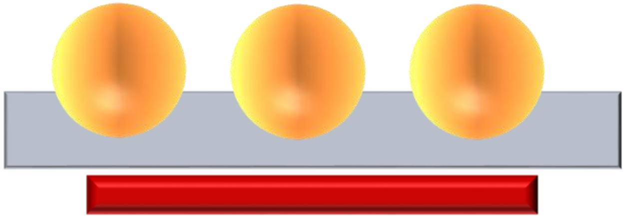
Diameter	3mm	4mm	5mm	6mm	8mm	10mm	12mm
Typical Power Range (W)*	5-20	8-35	11-50	13-65	20-90	24-100	33-135
Typical Flattening To (mm)	2.0~2.5	2.0~3.0	2.0~4.0	2.0~5.0	2.5~7.0	2.0~3.0	2.0~3.0
Resulting Width (mm)	3.7~3.3	5.31~4.8	7~5.7	8.6~6.72	11.4~8.8	15.5	18.6

* Power range: Low end = condenser directly below evaporator. High end = horizontal orientation

Challenge – Cool an 85W ASIC by moving heat to a remote fin stack in horizontal orientation

Possible Solutions

Three 5mm Round Heat Pipes vs. Two 6mm Flat Heat Pipes



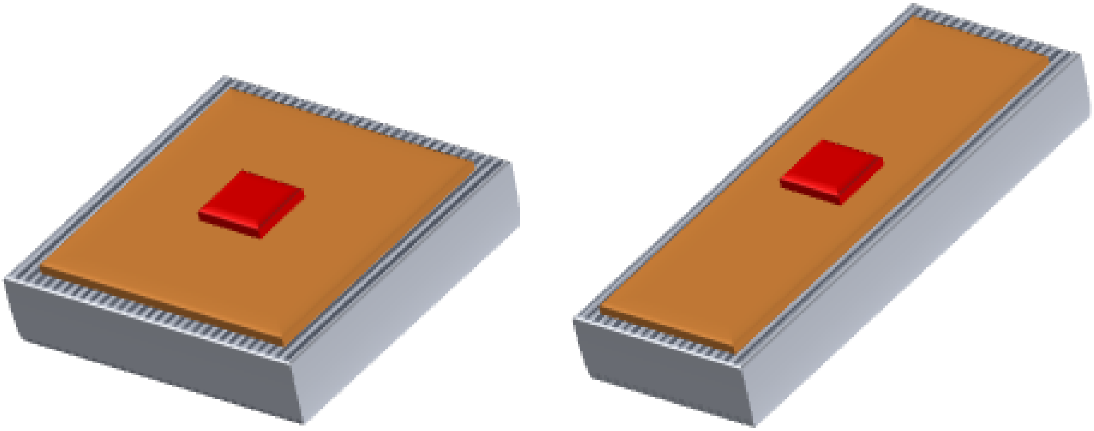
Comparison	Three 5mm Round Heat Pipes	Two 6mm Flat Heat Pipes
1. 30-40% Thermal Margin	121-142W	121-142W
2. HP Thermal Capacity (100%)	150W	130W
3. Calculated Therm. Margin	43%	35%
4. Evaporator Stack Height	7mm	4.5mm

Vapor Chamber Sizing (copper, sintered wick, water)

Tube Size	**16.5mm**	**19.4mm**	**25.4mm**	**30mm**	**32mm**	**37mm**	**43mm**	**48.4mm**	**53.5mm**	**70mm**
Typical Power Range (W)	50~150	60~180	90~250	120~360	130~390	180~420	220~490	250~550	270~610	360~800
Typical Flattening To (mm)	2.0~3.0	2.0~3.0	2.0~3.0	2.5~3.5	2.5~3.5	3.0~4.0	3.0~4.0	3.0~4.0	3.0~4.0	3.0~4.0
Resulting Width (mm)	25.6	30.3	40	46.8	50	57.5	67.4	76	83.5	109.2

* Power range: Low end = condenser directly below evaporator. High end = horizontal orientation

Challenge – Cool a 85W ASIC by moving heat to a local fin stack in horizontal orientation

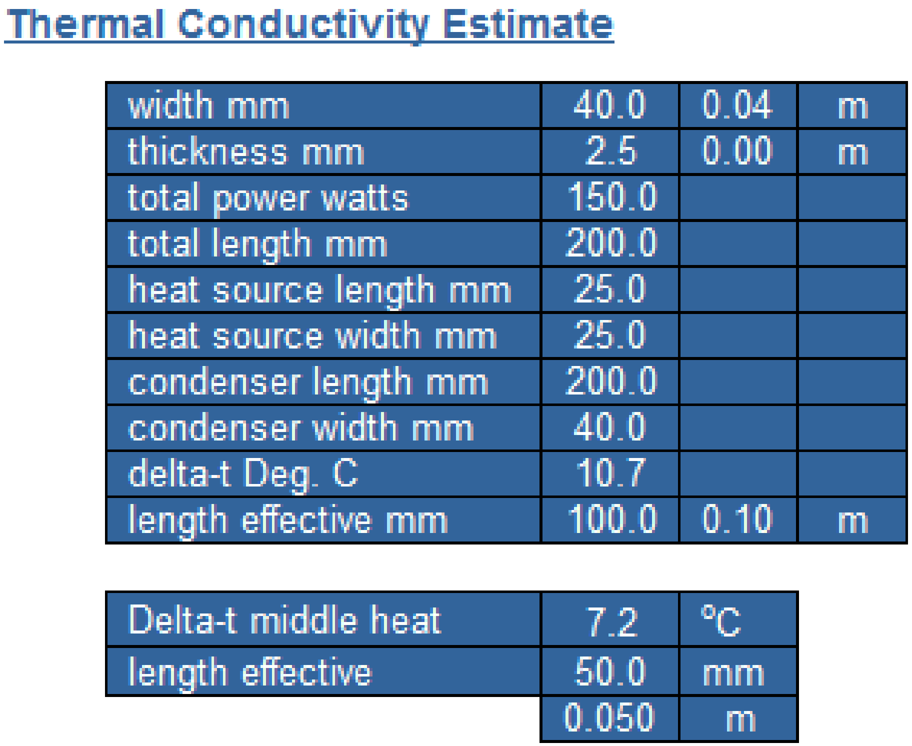


Comparison

1. 30-40% Headroom Req.	130-140W	130-140W
2. VC Heat Capacity (100%)	150W	130W
3. Calculated Headroom	50%	30%
4. Evaporator Stack Height	3.5mm	3.5mm

2-Phase: Effective Conductivity

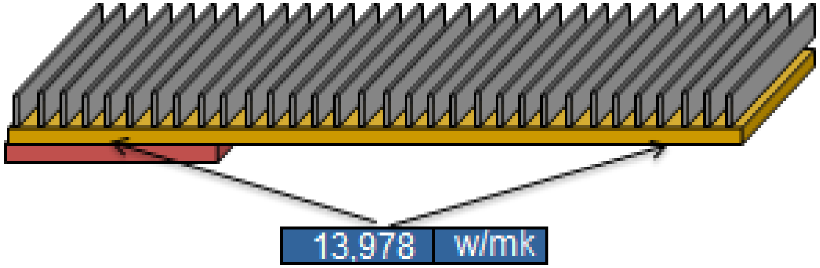
- Power & distance transported are modest for most electronics : 1000 to 10,000 w/mK being moved 150-300mm
- For industrial applications where powers are higher and the distances may longer the numbers are typically from 10,000 to as high as 50,000
- Each application for a two phase heat transfer device will have a different effective conductivity. Mainly a function of distance heat is moved

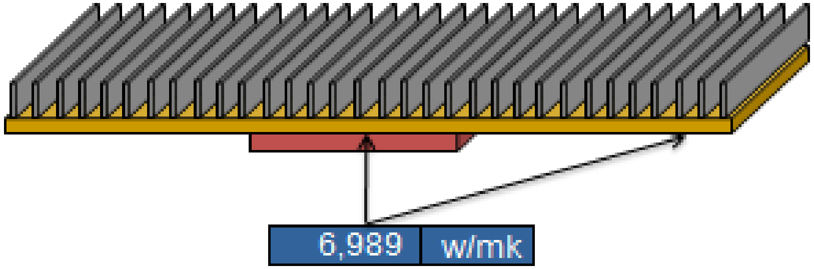


Thermal Conductivity Estimate

width mm	40.0	0.04	m
thickness mm	2.5	0.00	m
total power watts	150.0		
total length mm	200.0		
heat source length mm	25.0		
heat source width mm	25.0		
condenser length mm	200.0		
condenser width mm	40.0		
delta-t Deg. C	10.7		
length effective mm	100.0	0.10	m

Delta-t middle heat	7.2	°C
length effective	50.0	mm
	0.050	m

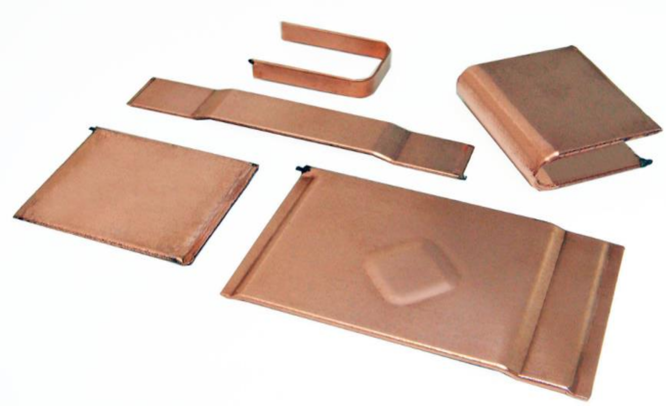




Bending & Shaping

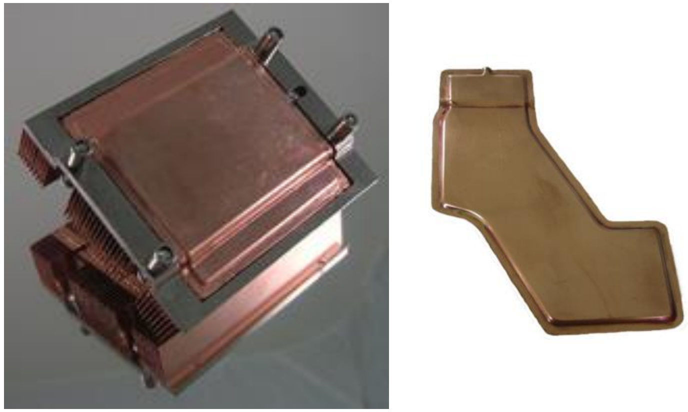
Heat Pipes

- Bend radius 3X diameter of heat pipe. Example
- Flatten to 1/3 diameter of original pipe (typical)
- Machining if pipe wall thickness permits. Allows direct contact with heat source



1-Piece Vapor Chamber

- 10mm bend radius along narrow plane
- Flattened to 1/10 – 1/20 diameter of original pipe (typical)
- Surface pedestals of 0.5-1.0mm high available for recessed heat sources



2-Piece Vapor Chamber

- Stamped bend to 1x thickness of the sheet metal, typically done as a ‘step’. Note – steep bends increase vapor pressure drop significantly
- Upper and lower plates are stamped flat.
- Stamped surface pedestals of 3-5mm high available for recessed heat sources

Bending Rules of Thumb

- **Spec a straight heat pipe or vapor chamber with 30% thermal margin.**
  - Example: A heat load of 70w should use a heat pipe designed with a Qmax of no less than 100w.
- **Add total bend radius of the heat pipe/VC. While not perfect this will get you very close to actual.**
  - Example: one 90 degree bend and another 45 degree bend = 135 degrees of bend
- **For each 10 degrees of bend Qmax will decline by ~0.56%.**
  - In our example from above: 135 degree total bend divided by 10 multiplied by 0.56% = 7.6% decrease in Qmax.
- **So for our 70 w heat source with two bends totaling 135 degrees we'll need a heat pipe with a Qmax of 100/(1-.076) = 108.2w.**

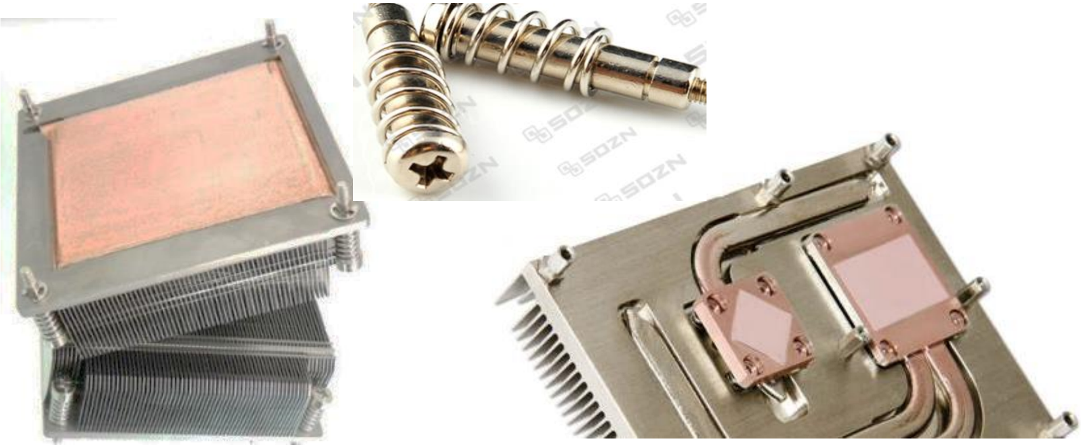
PCB / Heat Source Mounting Options

Clip Style Attachment

- Pros: $ low cost
- Cons: Low pressure- higher TIM resistance

Push Pin Attachment

- Pros: $ low cost, easy Install
- Cons: Low pressure, only good for small heat sink (light weight)



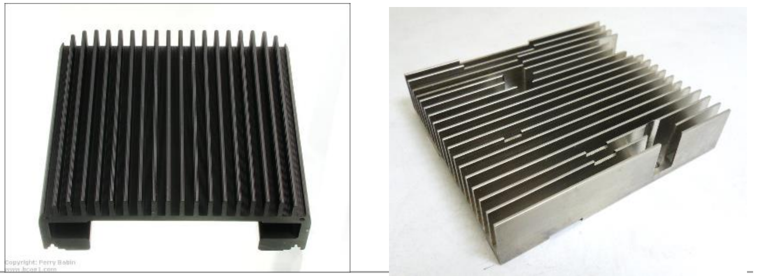
Spring Loaded Screws

- Pros: Higher pressure for better TIM performance
- Cons: hardware can get pricy

Heat Exchanger Design (Fins)

Extruded

- Pros: 100’s of suppliers, Low Cost
- Cons: Somewhat limited in fin ratio

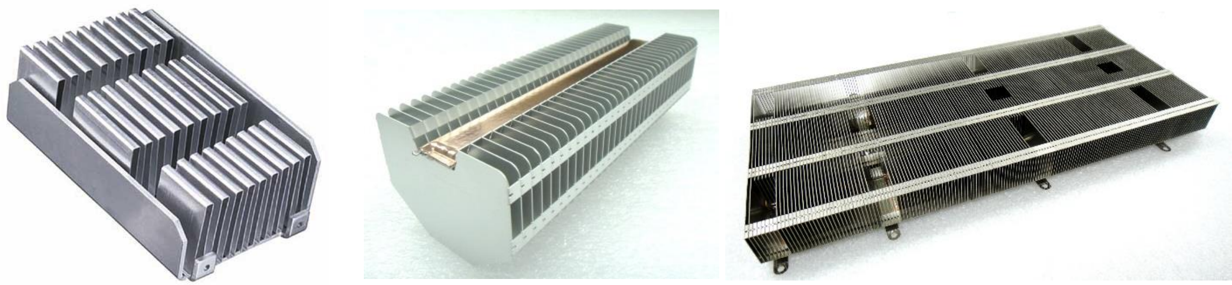


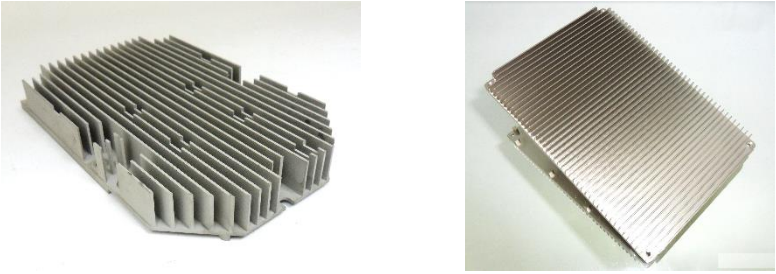
Formed – Skived, Forged

- Pros: more flexible in fin design
- Cons: tooling cost can be expensive, $$ ($$$) cost

Stamped-folded

- Pros: great design flexibility
- Cons: $$ tooling cost





Machined - Printed

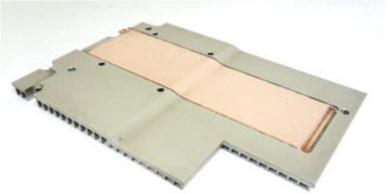
- Pros: widest design flexibility
- Cons: slower process add expense

Assembly Attachment

Soldering

90% of the time

Direct copper to copper bonds or nickel plating over aluminum



VC soldered to a machined forced convection heat sink

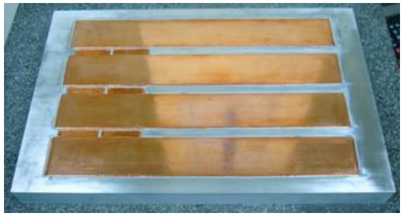
Steel mounting plate soldered to a vapor chamber

Heat pipes soldered to nickel plated copper blocks

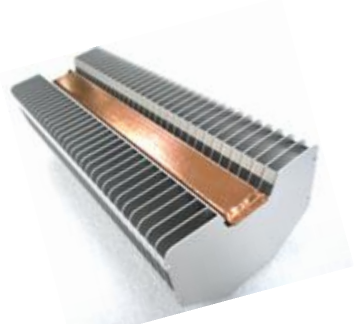
Thermal Epoxy

10% of the time

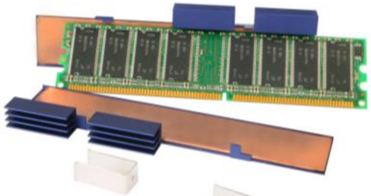
Only for very large parts. Test to ensure minimal thermal impact



Direct contact VC epoxied to an aluminum heat sink



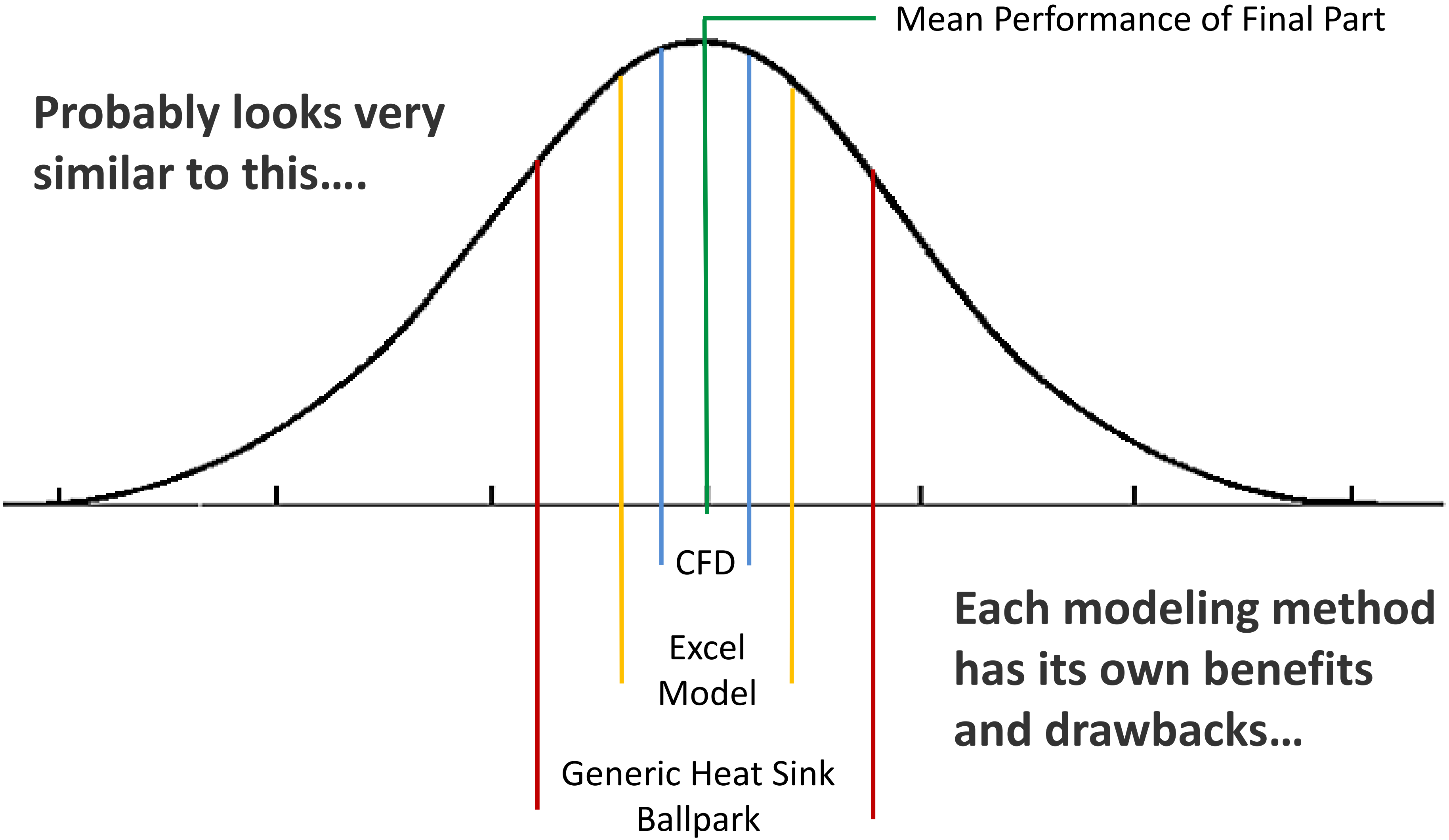
HBLED vapor chamber – natural convection



1.5mm VC memory module

Performance Modeling Accuracy Curve

Probably looks very similar to this….



Each modeling method has its own benefits and drawbacks…

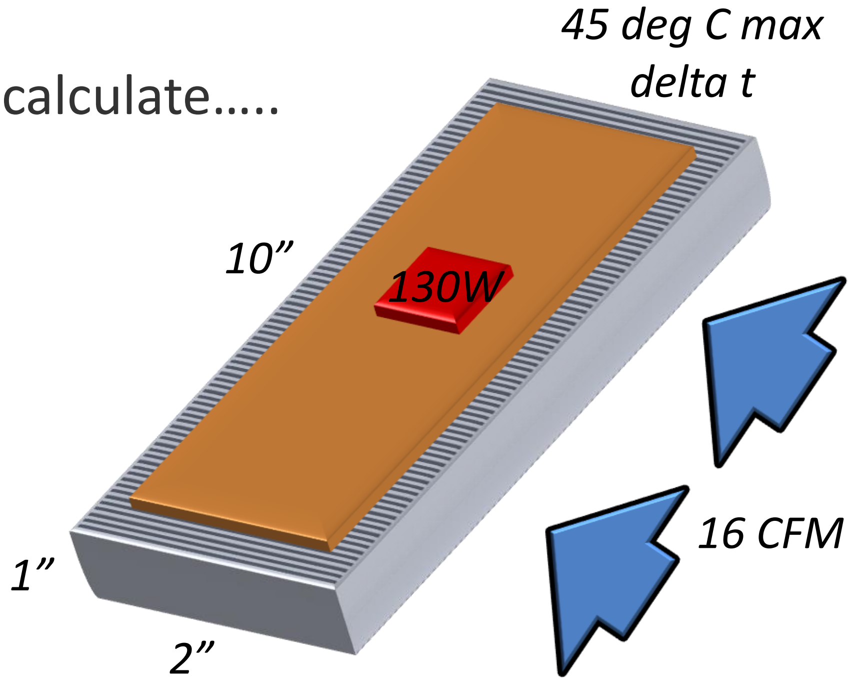
Heat Sink Ballpark Calculation

Benefits

- Very Fast (5 min)
- Can do while in a meeting
- Risk level, high or low
- Answers – Is it Remotely Possible?

Method Overview

- For a given heat source (W), max. delta-t, airflow (CFM), and heat sink size…
- Use some rules-of-thumb constants to calculate…..
  - Effective air temperature rise
  - Fin to air resistance
- Add these two together and add a fudge factor to see how much of the available delta-t you used up.



Heat Sink Ballpark Calculation - Example

Known

Power in Watts (Q)	130			
Max Delta-T (deg C)	45			
Forced Convection (CFM)	16	*or if unkown*	0.15*Q= 20	CFM
Natural Convection (CFM)	2.8	*Assume 40 LFM = 2.8 CFM*		
Heat Sink Dimensions (in)	10.0	2.0	1.0	
	Above = L	Above = W	Above = H	

Rough Calculations

1. Effective Air Temp Rise (deg C)		
Forced Convection	8.53	2.1*Q/CFM/2
Natural Convection	48.75	2.1*Q/CFM/2
2. Fin Area (sq.ft)		
Forced Convection (10 per inch)	2.78	sq. ft. fin area. Count both sides of each fin
Natural Convection (4 per inch)	1.11	sq. ft. fin area. Count both sides of each fin
3. Estimate fin-to-air delta-t		
Forced Convection (Deg C)	17.78	Q*0.38/Fin area in sq. ft.
Natural Convection (Deg C)	222.30	Q*1.9/Fin area in sq. ft.
4. Add #1 and #3 from above and tack on an extra 10 degrees for other resistances		
Forced Convection	36.32	*Deg C used of the available 45 deg delta-t*
Natural Convection	281.05	*Deg C used of the available 45 deg delta-t*
5. Ballpark conclusion - heat exchanger using forced convection should work.		

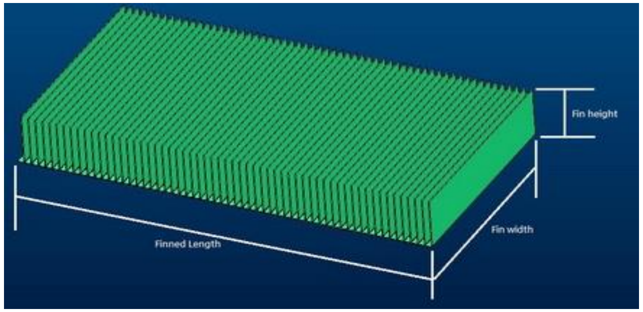
Excel Modeling: Delta-t = 39.2 °C

Benefits

- Low Cost
- Fast & Fairly Easy to Design
- Run Simple Scenarios
- Answers – Should we Move to CDF/Proto?

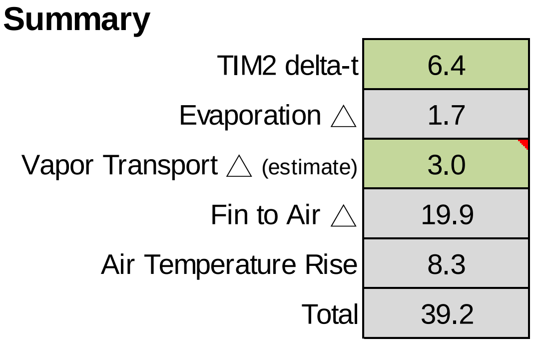
Inputs

- Heater: length, width, total power
- Ambient Temp
- Heat Exchanger: fin length, width, height, pitch
- Air Velocity
- TIM 2 Thermal Resistance



Calculations

- Heater: area & power density (w/cm2)
- Heat Exchanger: number of fins, fin area, face area
- Air Flow (cfm)
- Delta-Ts: TIM 2, evaporator, vapor transport, fin to air, air temp rise, total delta-t



Summary

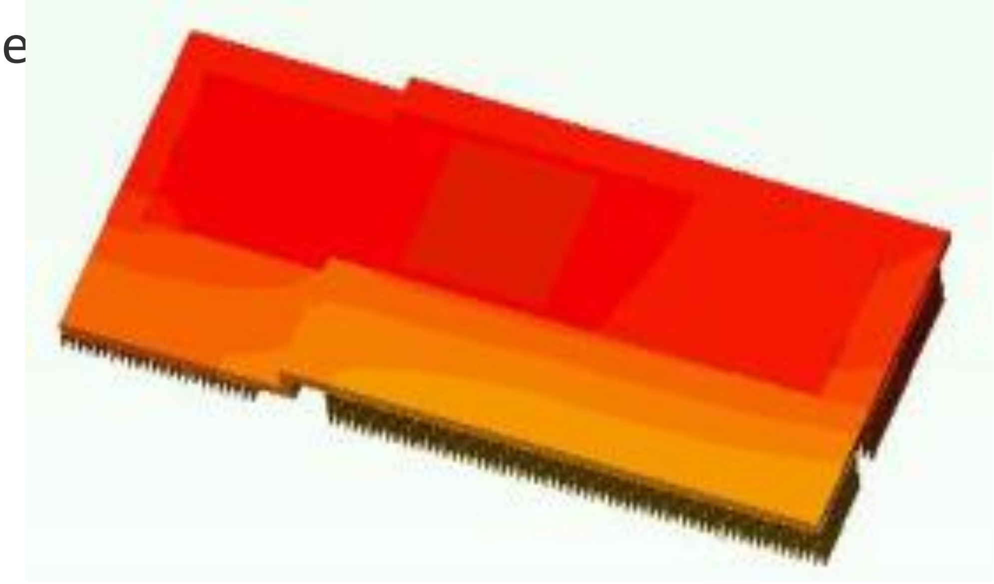
TIM2 delta-t	6.4
Evaporation △	1.7
Vapor Transport △ (estimate)	3.0
Fin to Air △	19.9
Air Temperature Rise	8.3
Total	39.2

CFD Analysis: Delta-t = 37 °C

Benefits

- Auto Optimization of multiple criteria
- Allows you to Focus on Key Design Goals. Weight vs Cost
- Get pretty pictures for presentations
- Answers - Have we Optimized to Meet Goals

- The real value in CFD is more for its optimization flexibility that it is for its improved accuracy vs other me
  - Fin Pitch & Thickness
  - Base Thickness
  - Type of Metal
  - Type of TIM
  - Air Flow



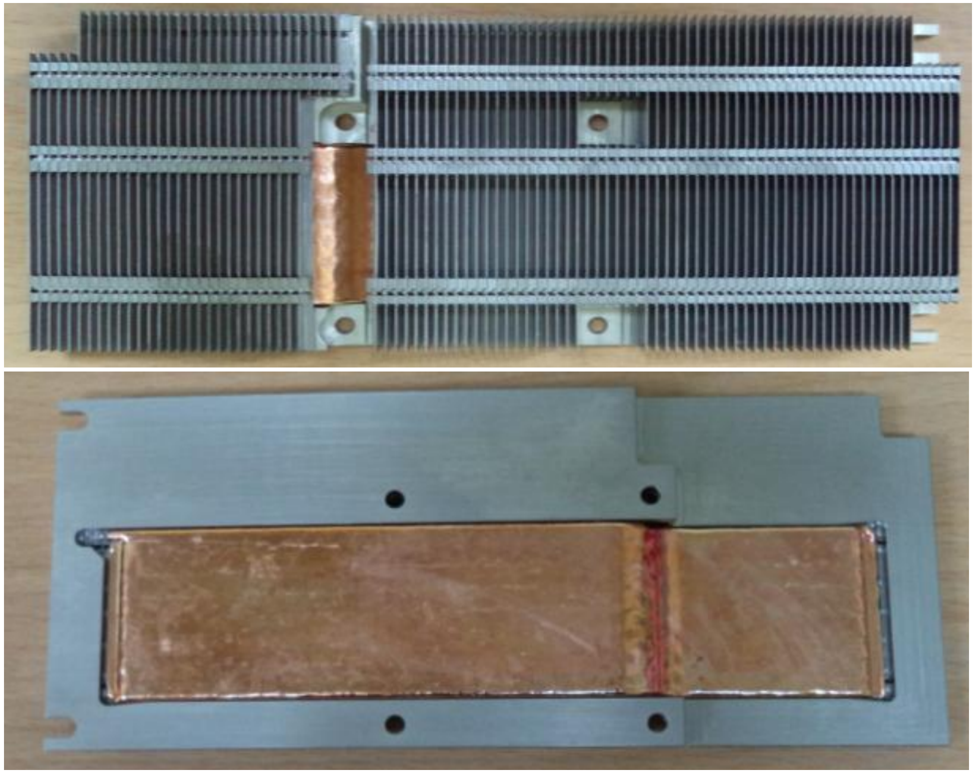
But, There’s no Substitute for Actual Test Data

Benefits

Delta-t = 41 °C

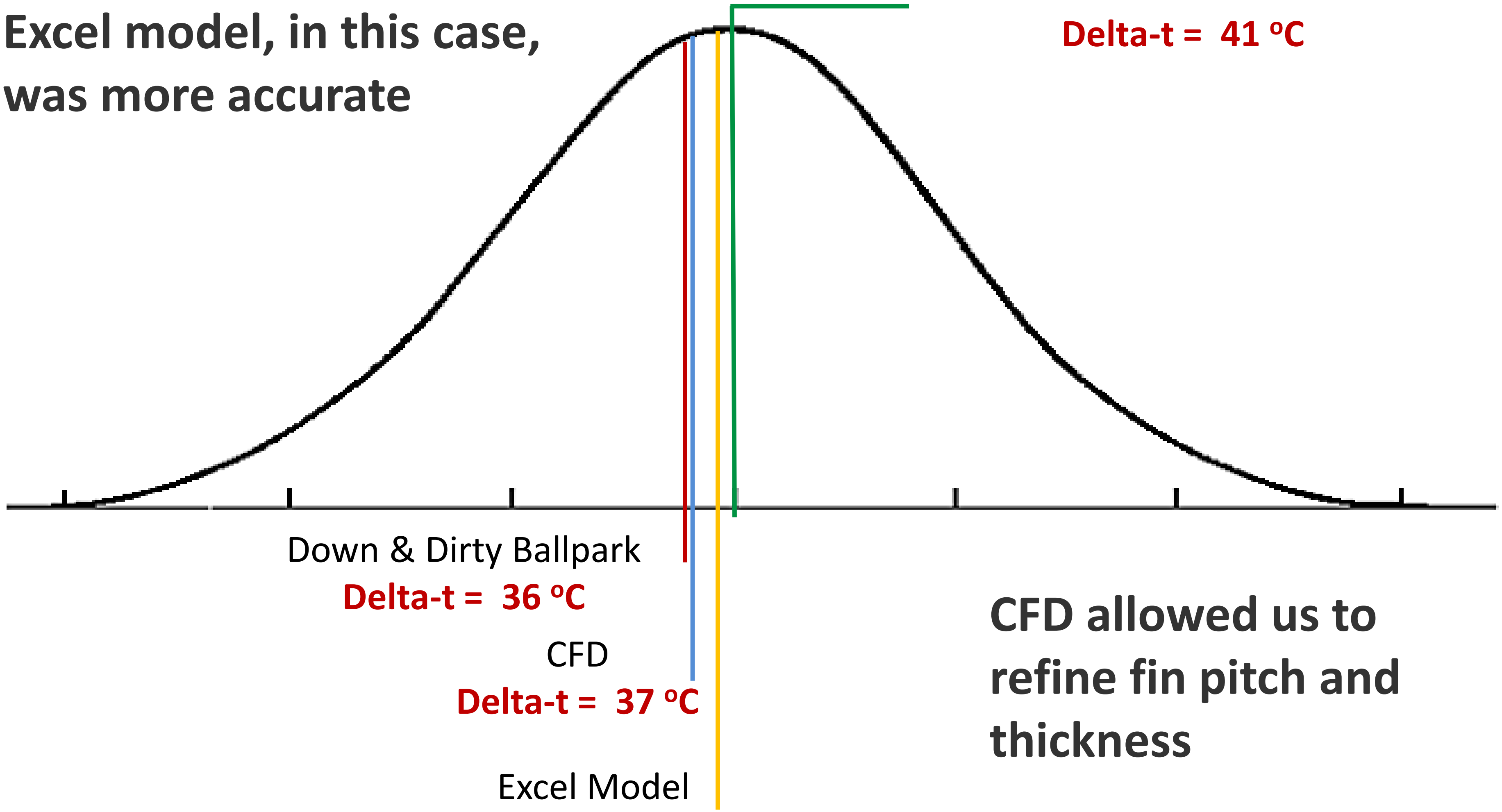
- Use data to optimize current and future thermal models
- Real data allows you to trouble shoot both product performance and prediction accuracy
- Helps identify variations between design and hardware

- Transitioning from a model to a real part is critical
  - Validate model as early as possible
  - Build and test at various conditions



Performance Modeling Accuracy Result

Excel model, in this case, was more accurate



Mean Performance of Final Part

Delta-t = 41 °C

Down & Dirty Ballpark

Delta-t = 36 °C

CFD

Delta-t = 37 °C

Excel Model

Delta-t = 39.2 °C

CFD allowed us to refine fin pitch and thickness

Q&A --- Thanks for Attending!

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na.sales@celsiainc.com

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