ADVANCED COOLING TECHNOLOGIES

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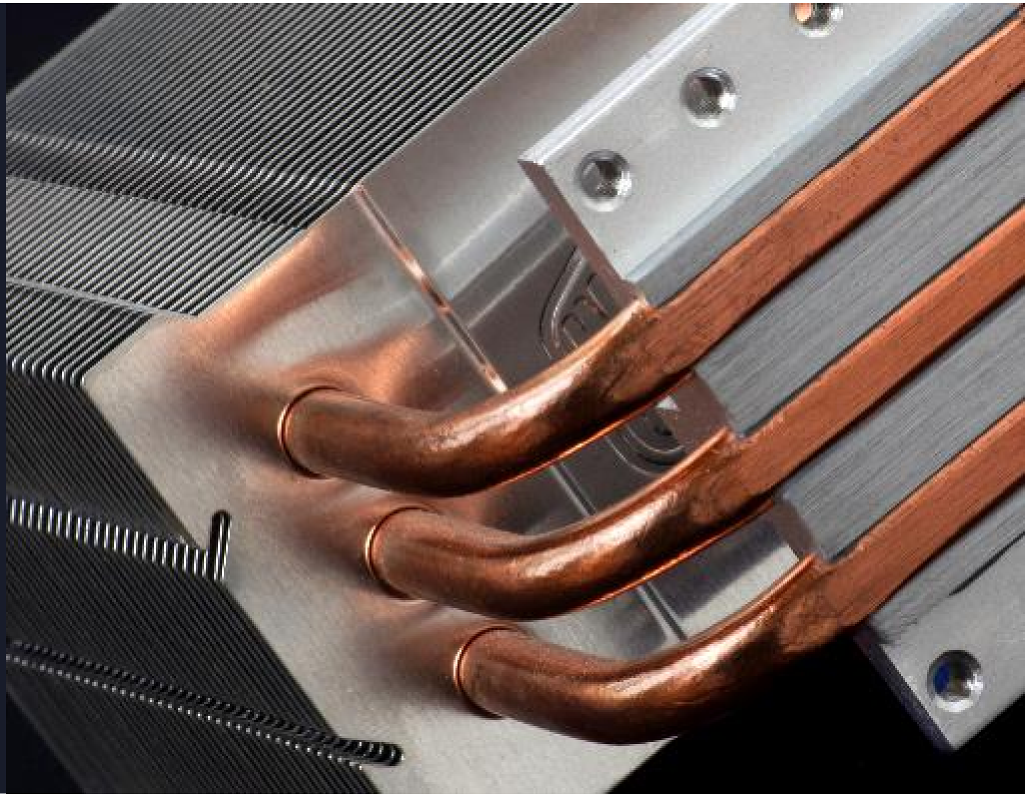
HEAT PIPE MODELING AND DESIGN



ADVANCED COOLING TECHNOLOGIES

The Thermal Management Experts | www.1-ACT.com

Founded in 2003

- Profitable and growing each year
- Over 200 Employees
- Over 150,000ft^2

Core Values

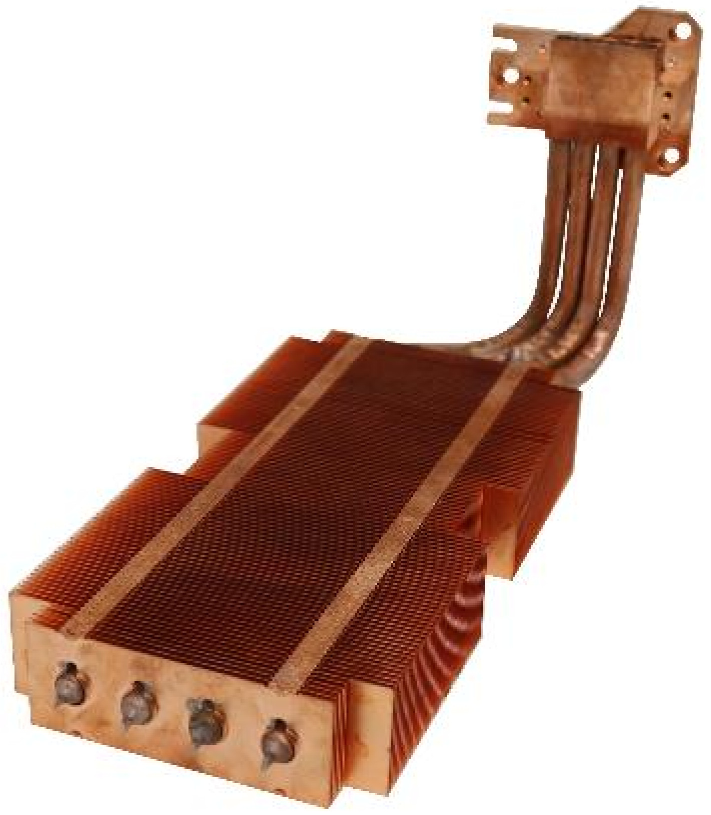
- Innovation
- Teamwork
- Customer Care

Awards

- Product Innovation Awards:
  - 2020 Military & Aerospace
  - 2020 AHR Green Building
- Multiple Supplier Awards
- US SBA Tibbetts Award
- Three (3) time winner of Top 100 Best Places to Work in PA

OBJECTIVES

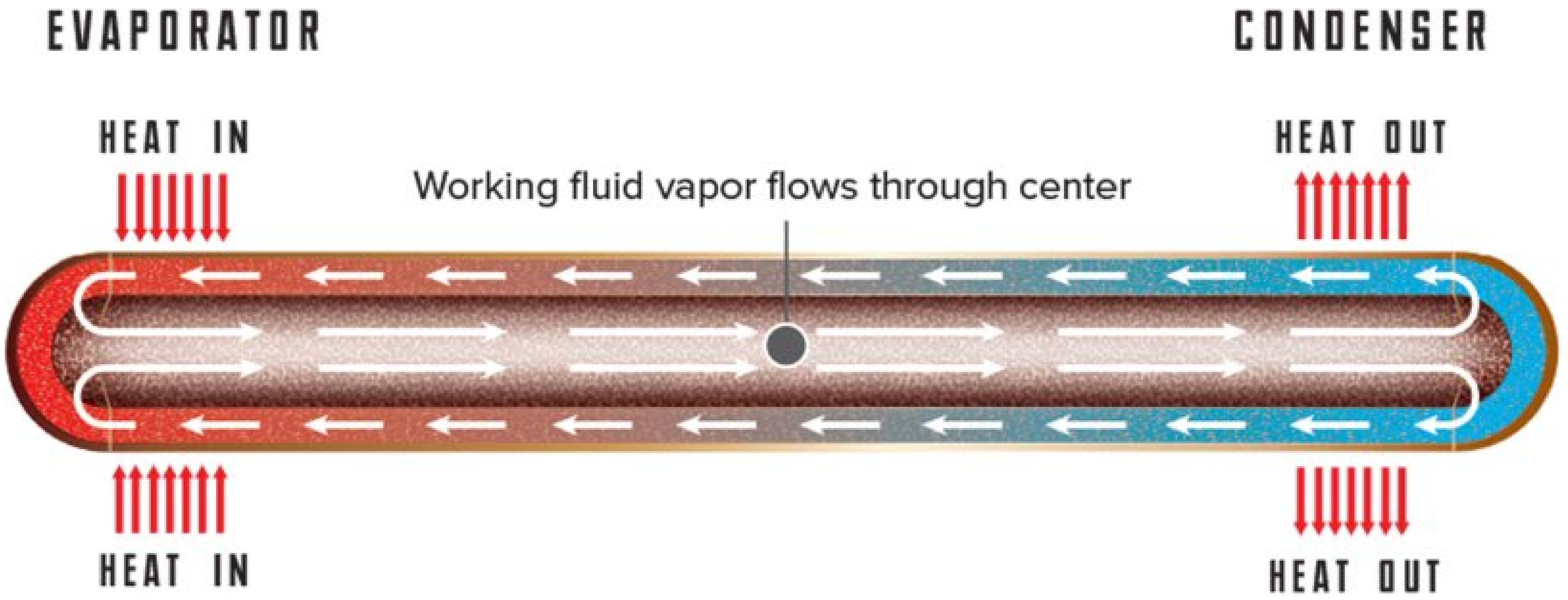
- Provide you with an understanding of heat pipe operation and performance
- Provide you with design guidelines to integrate heat pipes into your system
- Provide the necessary tools to run easy and effective thermal simulations with heat pipes

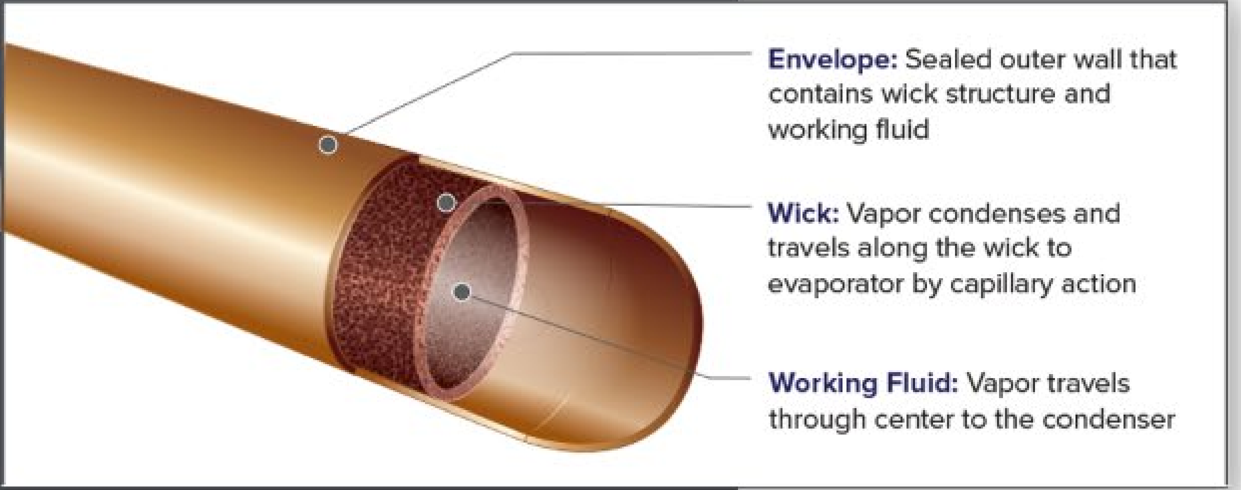


HEAT PIPE OVERVIEW

- Theory and Operation
- Advantages
- Embedded Heat Pipes (HiK™) Plates
- Product Examples

HEAT PIPE
SOLUTIONS





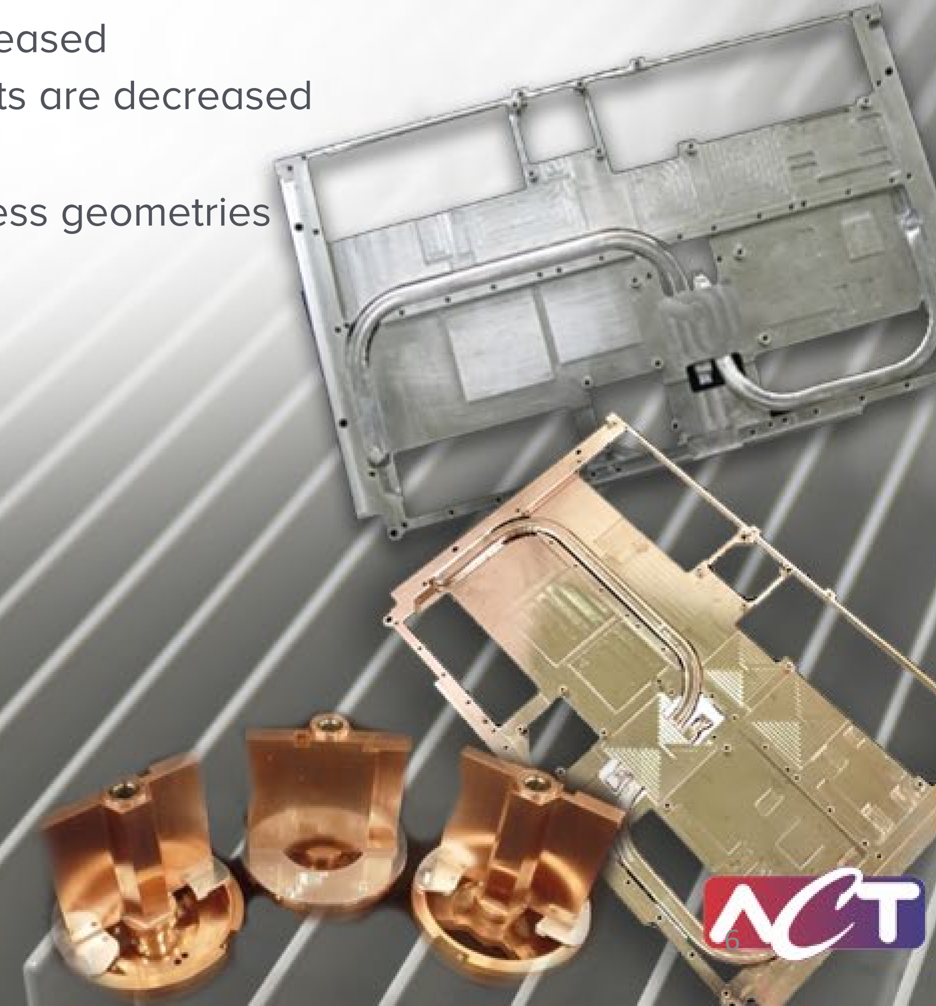
THERMAL SUPER CONDUCTORS

- Passive two-phase heat transfer device operating in a closed system
- Heat/Power causes working fluid to vaporize
- Vapor flows to cooler end where it condenses
- Condensed liquid returns to evaporator by gravity or capillary force
- Typically a 2-5 °C ΔT across the length of the pipe

HEAT PIPE BENEFITS

Primary Benefits (SWaP)

- **Size**
  - Can help reduce size by creating a more efficient heat transfer
- **Weight**
  - HPs are light weight devices and can reduce overall system weight
- **Power**
  - Hot spot power can be increased
  - Thermal power requirements are decreased
- **Flexibility**
  - Can be formed to fit countless geometries



Thermal Benefits

- Spreading heat along a surface
- Transferring heat to an external sink
- Isothermalization

HEAT PIPE RELIABILITY

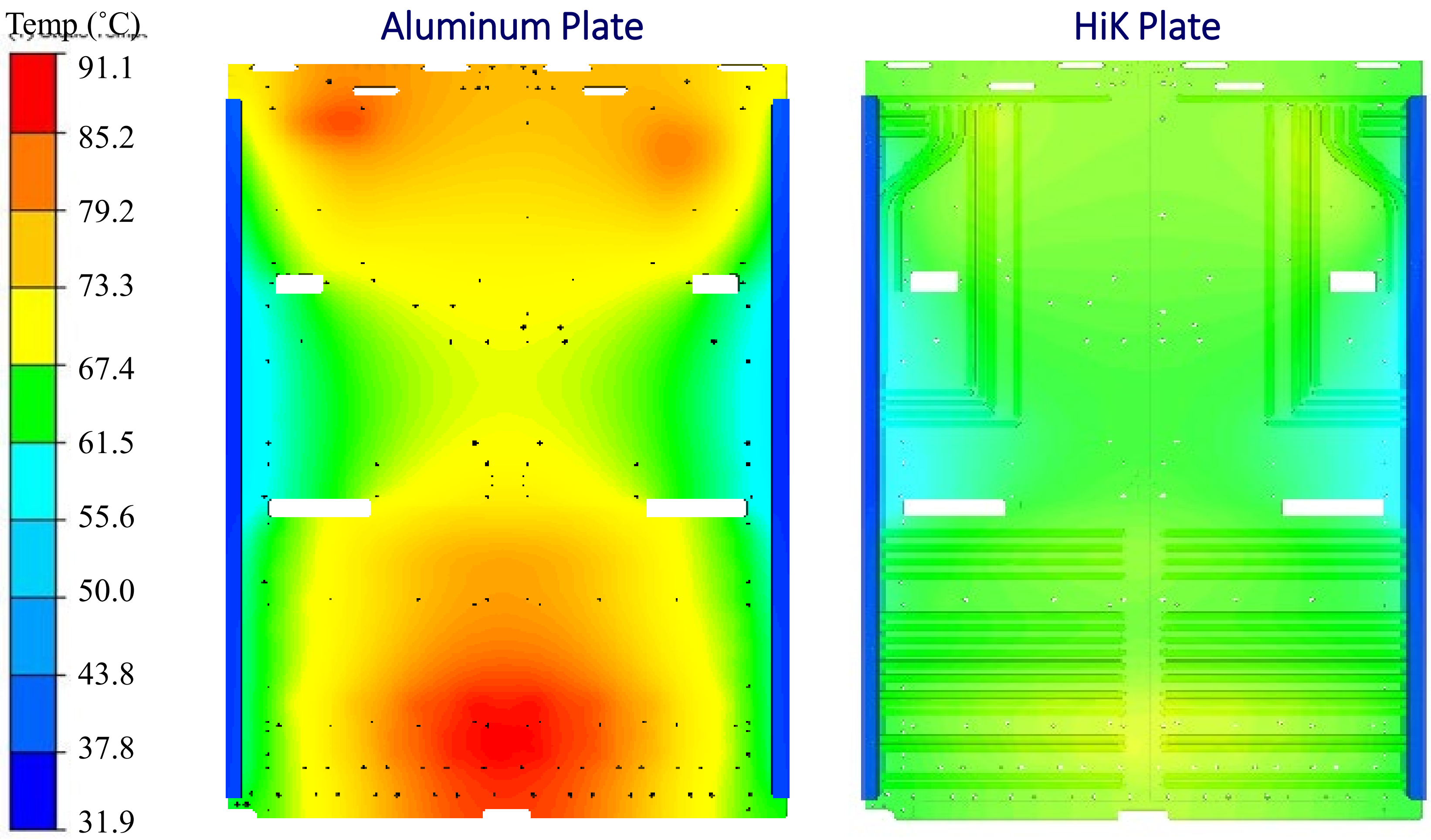
Long Life

- Proven Fluid/Envelope Combinations
- Passive Operation
- Innovative Manufacturing
- ACT's CCHP's have over 50 million hours on orbit

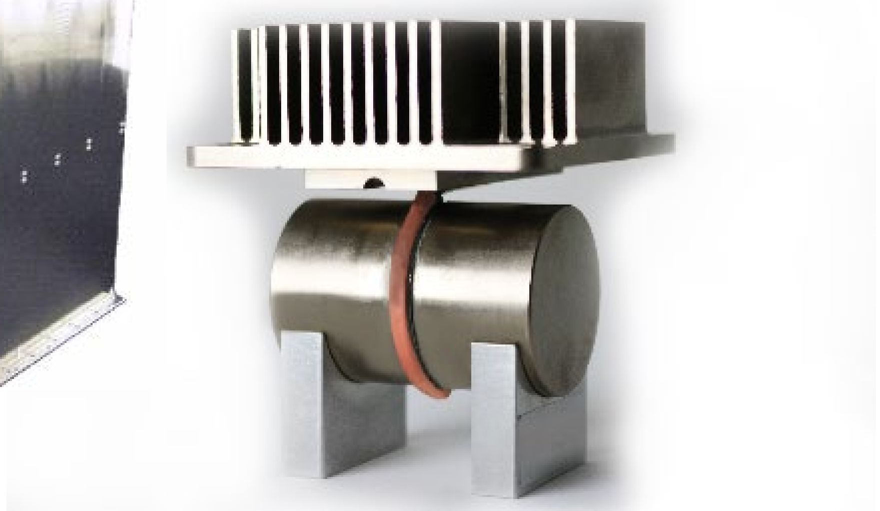
Able to withstand harsh environments

- Shock
- Vibration
- Temperature Extremes
  - Freeze/Thaw
  - Salt/Fog

THERMAL PERFORMANCE



PRODUCT EXAMPLES



Applications:

- Electronics Cooling
- Satellite Thermal Management
- Laser Diode Cooling
- Avionics
- LED Cooling
- Medical Devices
- Energy Recovery
- Temperature Calibration

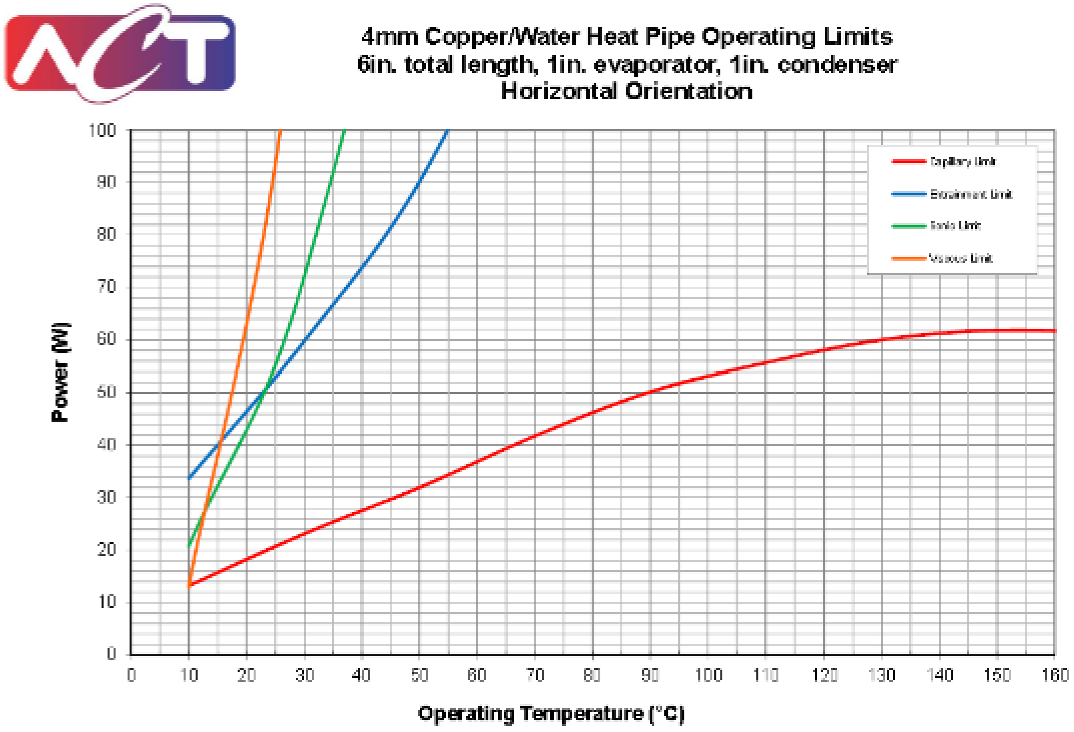
DESIGNING WITH HEAT PIPES

- Power Capacity
- Design Guidelines

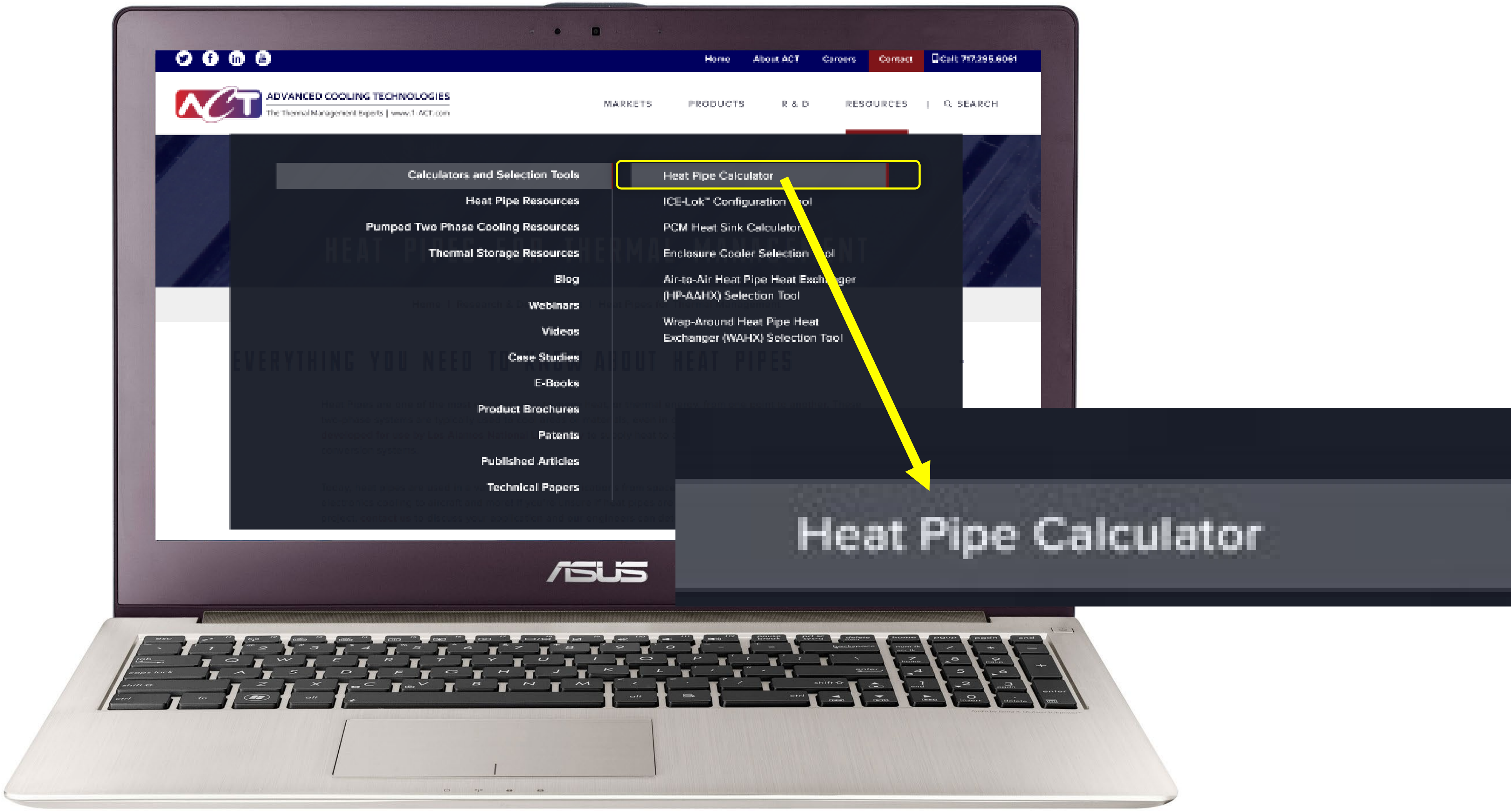
POWER CAPABILITIES

- Heat Pipes are governed by several limits that determine total heat transport capacity
  - **Capillary Limit** is most important for terrestrial applications
  - Others: Sonic, Entrainment, Viscous, Boiling

- Limits are a function of:
  - Diameter
  - Length
  - Orientation
  - Fluid Properties
  - Wick Properties



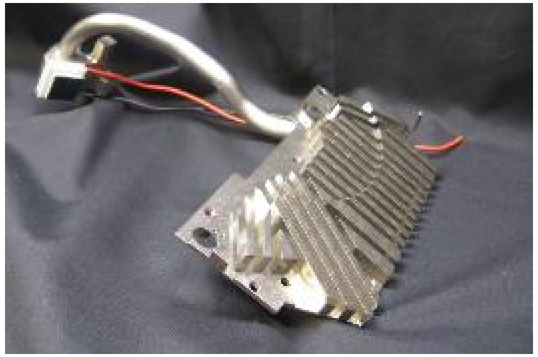
HEAT PIPE CALCULATOR

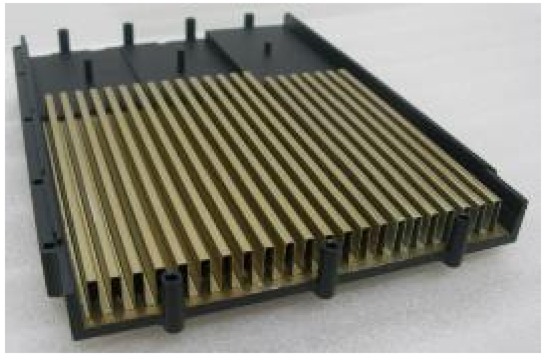


HEAT PIPE DESIGN GUIDE

Heat Pipe Routing

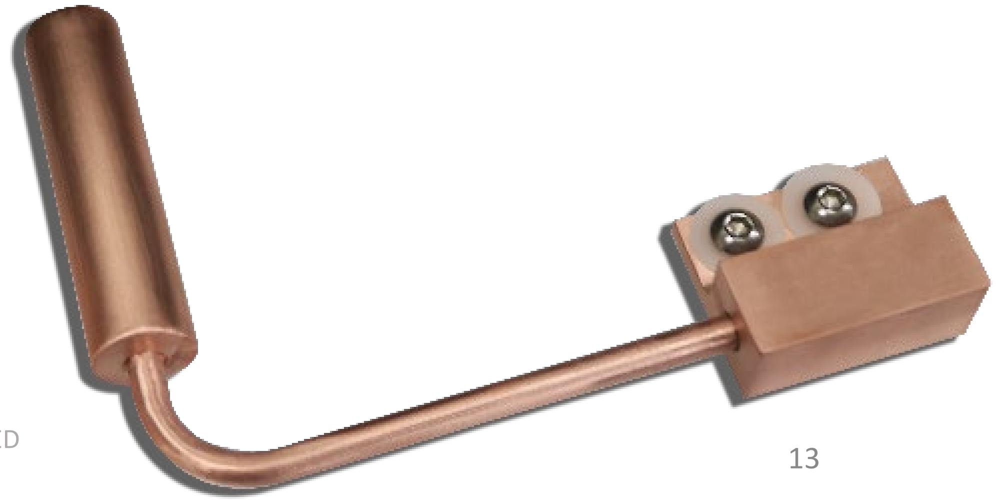
- Standard Pipe Sizes:
  - 3,4,5,6,8 mm
  - 1/8, 1/4, 3/8, 1/2 in.
- Bending: Typically 3 x OD
- Flattening: Typically 2/3 x OD





Integration

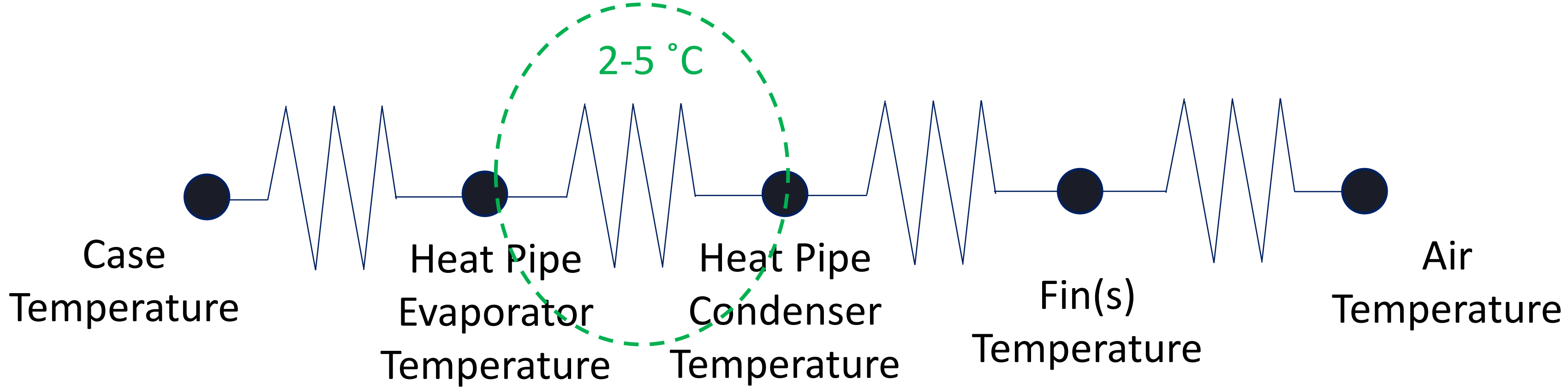
- Epoxy
- Solder
  - Thermally, mechanically superior
  - Aluminum must be nickel plated



BASIC THERMAL MODELS

- Heat Pipes
- HiK™ Plates

THERMAL RESISTANCE MODELS

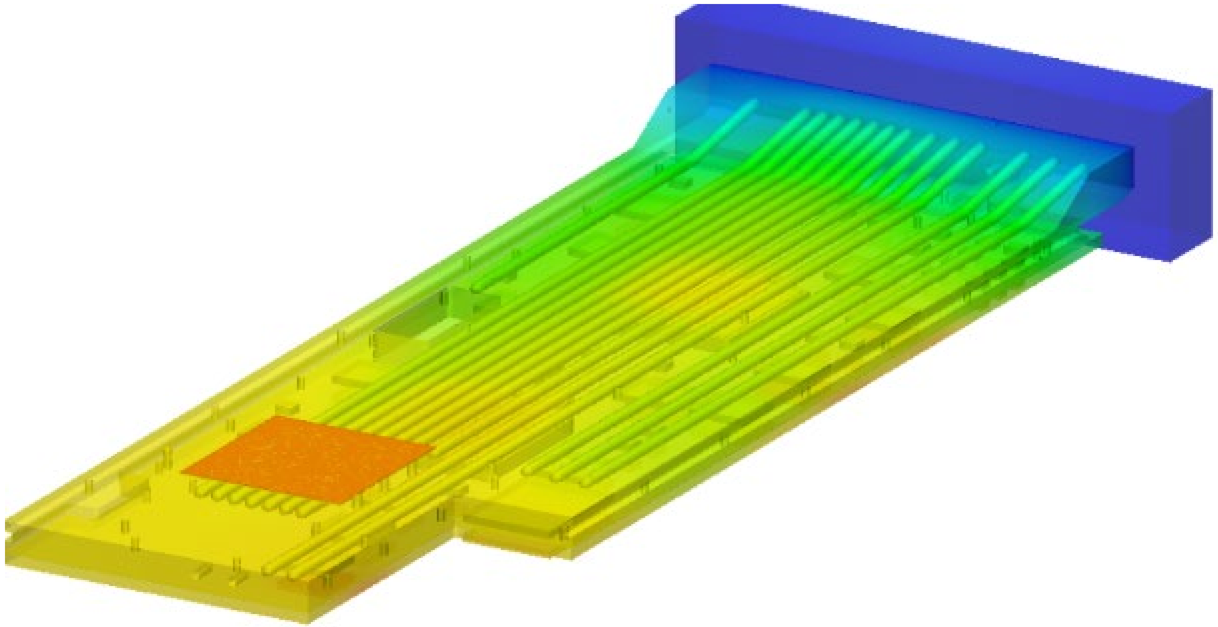


- When looking at your preliminary thermal stack-up, you can easily integrate a 2-5 ˚C temperature rise to account for your heat pipe

BASIC CONDUCTION ROD

- Bend and Flatten heat pipe so that it fits into your system
- Model heat pipe as a solid rod in your system and assign a thermal conductivity

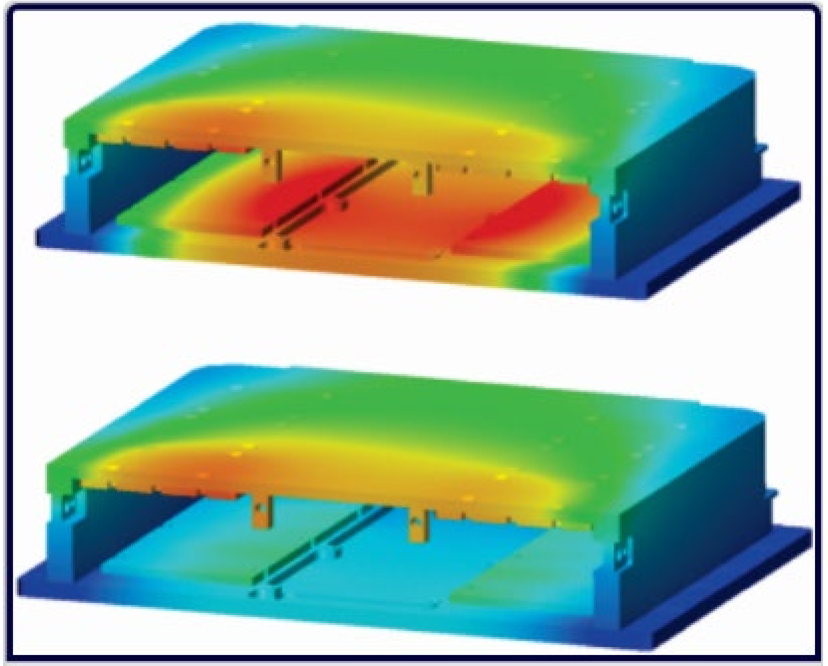
1. Start with k=10,000 W/m-K
2. Check max temperature on heat pipes
3. Iterate until max temperature difference 5 ˚C



BASIC HiK(TM) PLATES

- Over many programs, ACT has matched test data to a range of effective thermal conductivities for HiK™ Plates.
  - k = 500 to 1,200 W/m-K
  - Depends on
    - Geometry
    - Sink conditions

- Model HiK™ plate as solid plate
- **Assign a thermal conductivity of 600 W/m-K**
  - If you're close to your desired results, heat pipes can probably be optimized to meet your goals

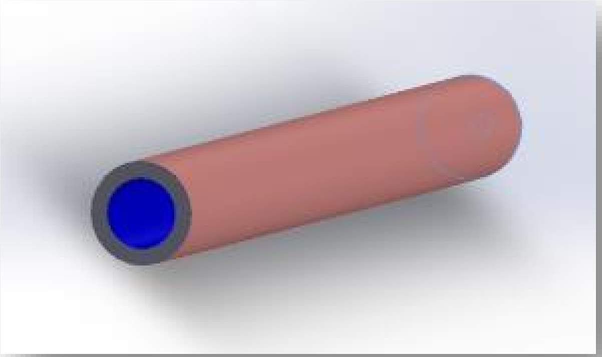


Replaced Baseplate w/ HiK™ Plate

DETAILED THERMAL MODELING

Model the heat pipe using two components

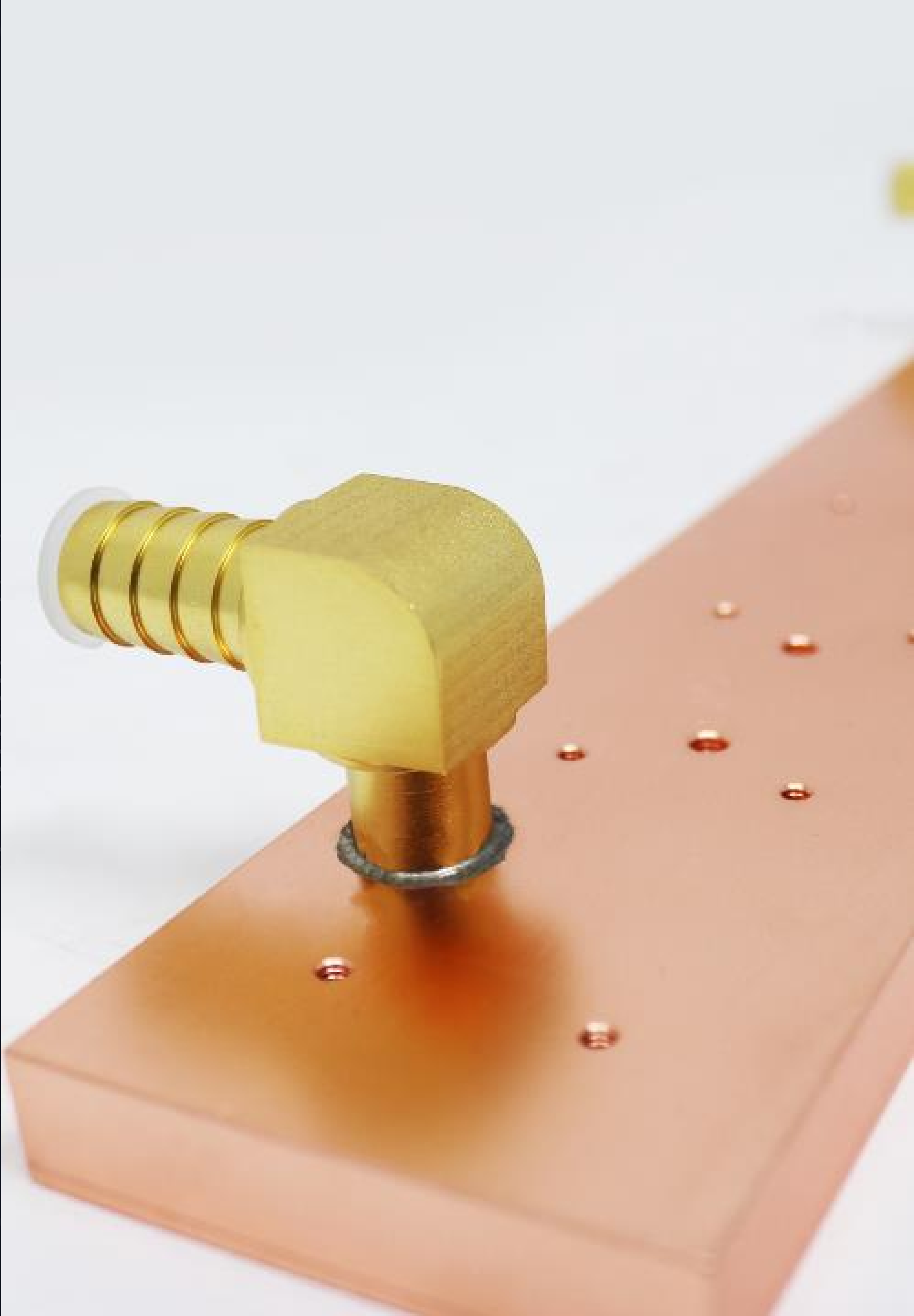
- Heat Pipe Envelope
  - Captures radial thermal resistance
  - Includes TIM, Heat Pipe Wall, Wick, and Evaporation/Condensation Thermal Resistance
  - Relatively low effective thermal conductivity



- Vapor Space:
  - Simulates the effects of two phase heat transfer using conduction elements
    - Significantly simplifies model
  - Uses known geometry (l_{eff} and A), power (Q), and typical heat pipe ΔT to back-calculate k_{eff}
  - High axial conductivity

$$k_{eff} = \frac{Q l_{eff}}{A \Delta T}$$

CASE STUDY / EXAMPLE

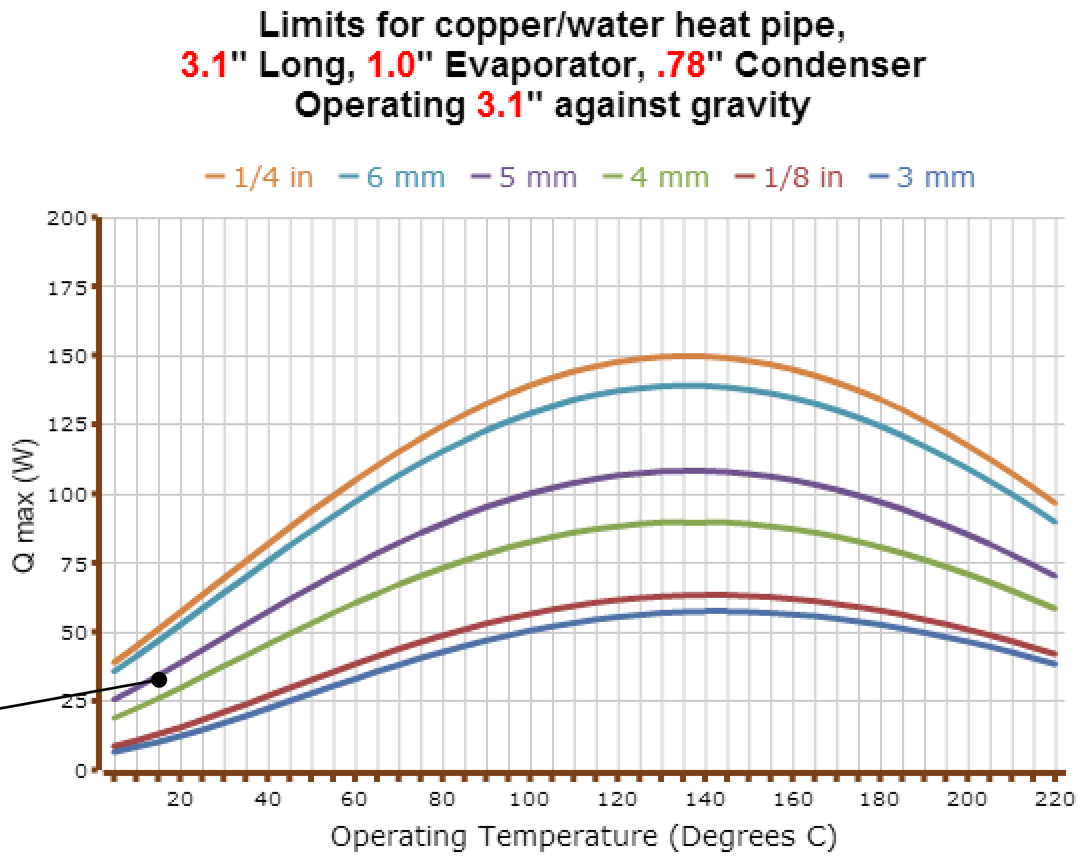


THERMAL MODELING EXAMPLE

- We need a heat pipe to transfer 25W against gravity at room temperature

- Geometry
  - Total Length = 3.10"
  - Evaporator = 1.00"
  - Condenser = 0.78"
  - (Adiabatic = 1.32")

- Select a 4mm heat pipe

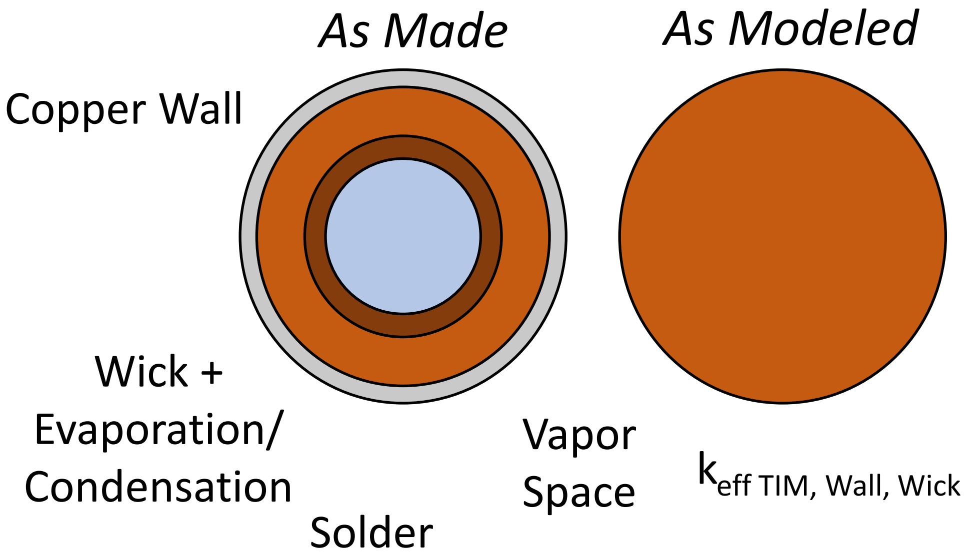


Operating Point

At a minimum, a 4mm heat pipe is needed

THERMAL MODELING EXAMPLE

- Calculate k_{eff} for TIM-Wall-Wick
  - Sum Radial Thermal Resistances
    - 0.004" of Bi/Sn solder (19 W/m-K): R=5.347x10^{-6} °C-m^2/W
    - 0.012" Copper Wall (380 W/m-K): R=8.021x10^{-7} °C-m^2/W
    - Wick Material and Evaporation/Condensation: R=3.195x10-5 °C-m^2/W
  - Model as .040" thick (keep thick to further simplify meshing)



4mm pipe selected

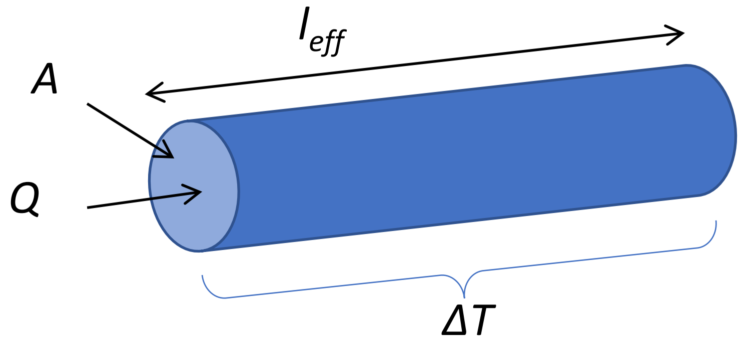
$$k_{eff} = \frac{0.040\ in \times 0.0254\frac{m}{in}}{\left(5.347 \times 10^{-6}\frac{℃\,m^2}{W} + 8.021 \times 10^{-7}\frac{℃\,m^2}{W} + 3.195 \times 10^{-5}\frac{℃\,m^2}{W}\right)} = 26.7\,\frac{W}{m-K}$$

THERMAL MODELING EXAMPLE

- Use Fourier's law to determine k_{eff} for vapor space
  - Known geometry
  - Assumed power and ΔT

$$k_{eff} = \frac{Q l_{eff}}{A \Delta T}$$

- Power (Q)
  - Known to be 25W
- Effective Length (Leff)
  - $l_{eff} = \frac{l_{evap}+l_{cond}}{2} + l_{ad} = 2.21in = 0.056\,m$
- Vapor Area (A)
  - 4mm Diameter less the .040" modeled wall
  - $A = 3.004 \times 10^{-6} m^2$



- Vapor ΔT
  - Temperature drop of vapor is only due to pressure drop of vapor from evaporator to condenser (very low)
  - Conservatively assume 2K

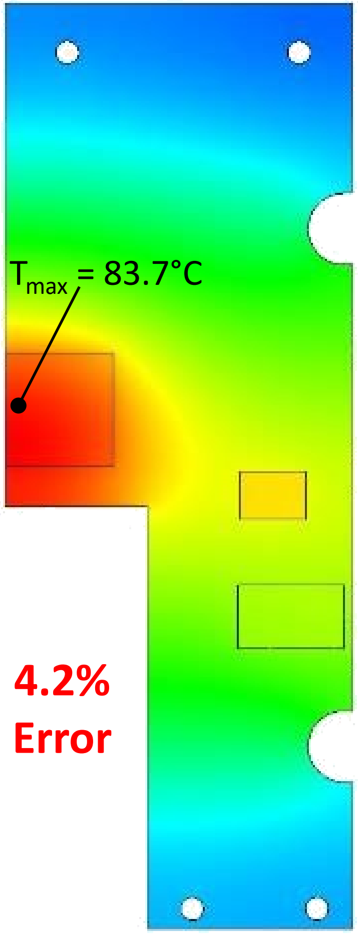
$$k_{eff} = \frac{25W \times 0.056m}{(3.004 \times 10^{-6}) \times 2K} = 233{,}000 \frac{W}{m\,K}$$

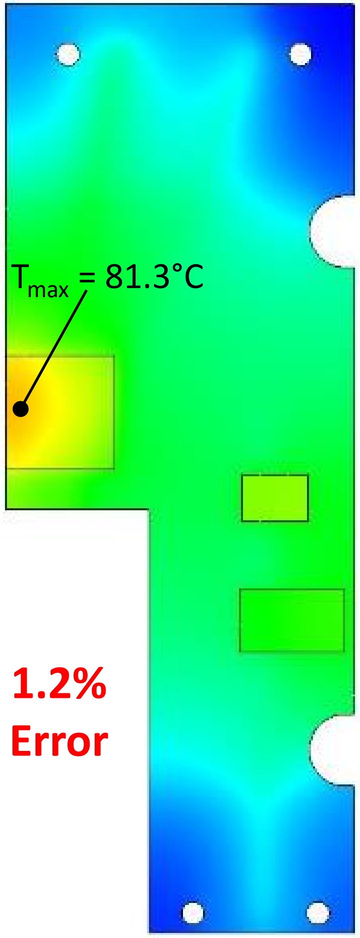
THERMAL MODELING EXAMPLE

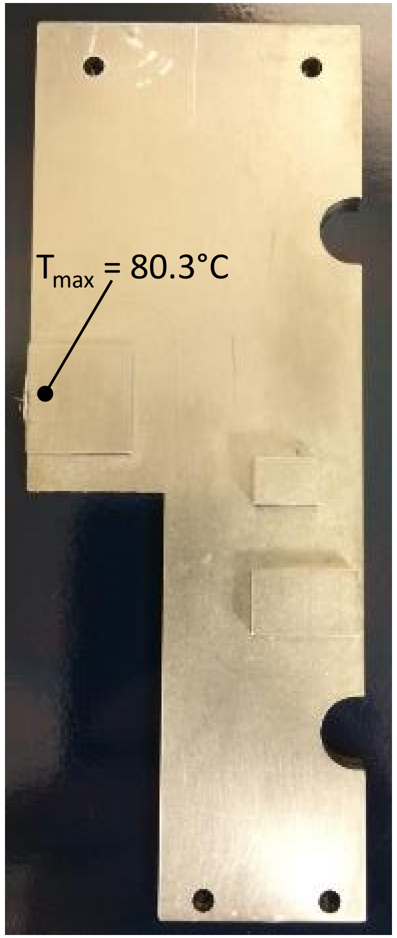
- Will a heat pipe transfer the required power?
  - Yes (confirmed using ACT's online calculator)
- Incorporate the heat pipe into the 3D model to confirm the diameter is acceptable
- Determine effective conductivity for the heat pipe wall and vapor space
  - $k_{eff\ TIM,\ Wall,\ Wick}$ = 26.7 W/m-K
  - $k_{eff\ vapor}$ = 233,000 W/m-K
- Assign model boundary conditions to perform simulation
  - Heat load conditions
  - Heat sink conditions

RESULTS COMPARISON

Modeled k_{eff}= 500 W/m-K







CONCLUSION

- Heat pipes are reliable and effective components in a thermal design
- They can be easily integrated into new or existing systems
- There are several techniques to effectively model heat pipes based on the level of detail needed
- ACT, your trusted partner, is available as needed to support!

ACT QUALITY SYSTEMS

ISO 9001:2015 Certified
General Product Design and Manufacturing

AS9100D Certified
Aerospace Product Design and Manufacturing

Customer Success is the best measure of our ability to execute our core values

"ACT HAS A GREAT REPUTATION WITH ALL THE ENGINEERS I KNOW IN MY COMPANY. I HAVE RECOMMENDED YOU TO MANY OF MY FELLOW ENGINEERS HERE BECAUSE OF YOUR ATTENTION TO DETAIL, EXPERTISE, CUSTOMER SERVICE, AND WILLINGNESS TO TAKE ON LITTLE JOBS AS WELL AS BIG JOBS."

"IT WAS A REAL PLEASURE TO WORK WITH ACT DUE TO THEIR TECHNICAL CAPABILITY, PRODUCT PERFORMANCE, AND PROFESSIONALISM."

"THROUGHOUT THE WHOLE PROJECT, IT WAS CLEAR THAT ACT CARED ABOUT THE SUCCESS OF THE PROJECT AS MUCH AS WE DID."

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1046 NEW HOLLAND AVENUE,
LANCASTER, PENNSYLVANIA 17601, USA

717.295.6061

SOLUTIONS@1-ACT.COM

WWW.1-ACT.COM

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