ADVANCED COOLING TECHNOLOGIES

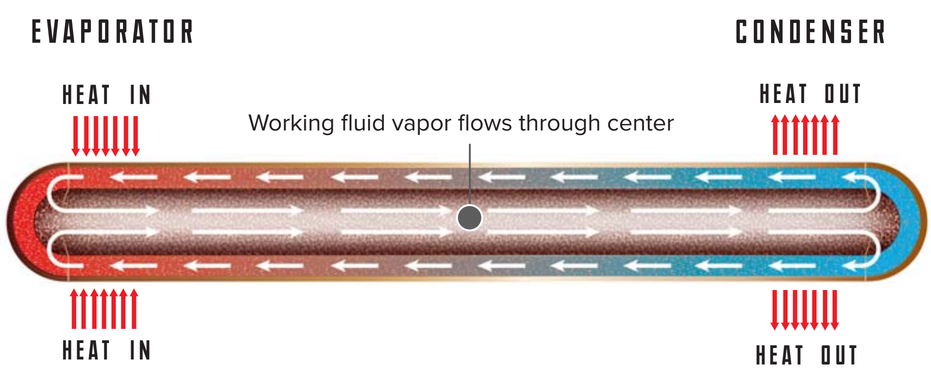
The Thermal Management Experts | www.1-ACT.com

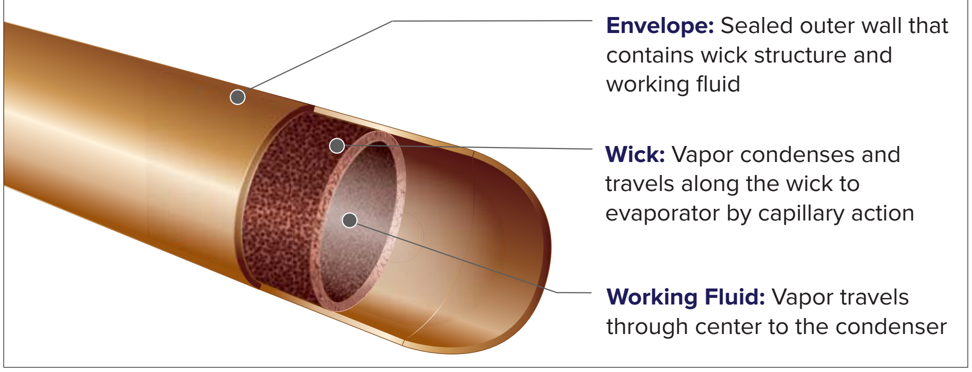
HEAT PIPE RELIABILITY GUIDE

GENERAL OVERVIEW

ADVANCED COOLING TECHNOLOGIES, INC. (ACT) HAS WORKED EXTENSIVELY ON HEAT PIPE PRODUCT RELIABILITY. This guide provides information for designing, modeling, and practical reliability surrounding copper/water heat pipes.

A heat pipe is a two phase heat transfer device with very high “effective” thermal conductivity. It is a vacuum tight device consisting of an envelope, a working fluid, and a wick structure. As shown below, the heat input vaporizes the liquid working fluid inside the wick in the evaporator section. The saturated vapor, carrying the latent heat of vaporization, flows towards the colder condenser section. In the condenser, the vapor condenses and gives up its latent heat. The condensed liquid returns to the evaporator through the wick structure by capillary action. The phase change processes and two phase flow circulation continue as long as the temperature gradient between the evaporator and condenser are maintained.

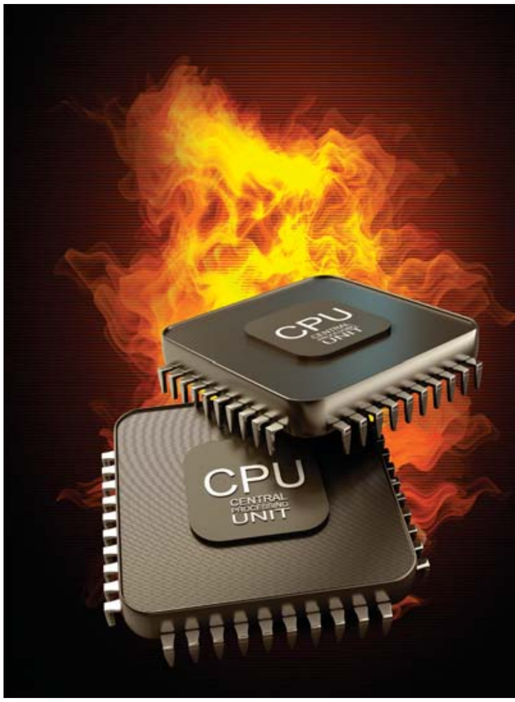




Copper/water heat pipes are used in a wide range of applications, most notably in electronics cooling. Water is an ideal fluid to operate and cool components nearing the maximum case temperature of electronics (70 to 100 C). Additionally, because water has favorable surface tension properties, heat pipes can be designed to operate in any orientation.

So when should you consider heat pipe technology?

Heat pipes will greatly reduce temperature rise from point to point. The two most common uses for heat pipes are:



1. Moving heat to a remote heat sink

a. In many cases, there is no room directly over a component for a large enough heat sink to successfully remove the waste heat. Heat pipes can be used to transfer heat to areas where more fin volume is available.

b. In electronics chassis that are externally cooled, the heat must move to the walls/edges while maintaining a dust/leak tight seal. Heat pipes can efficiently take heat to the wall and spread heat along the wall to make the external fins more efficient.

2. Enhancing heat spreaders

a. Anytime conduction is the limiting factor in a heat spreading system, heat pipes can be embedded to enhance 2D conduction. Heat pipes into aluminum can take thermal conductivities from 167 W/m-K (6061 aluminum) to 500+ W/m-K (HiK™ Plates)

Although thermal benefits are typically the focal point of heat pipe designs, ACT is experienced with adding value to other areas of the system:

- **Mass/Weight:** Since heat pipes can handle the thermal requirements, the need for thermal mass is often greatly reduced.
    - Reduce thickness/profile of metallic heat spreaders
    - Add weight reduction pockets
- **Noise:** Heat pipes are very effective at spreading heat which reduces hot spots and increases fin efficiency. You can increase workable fin volume to allow for less or no airflow while maintaining similar thermal performance.
- **Structural Integrity:** Although heat pipes themselves are thin walled copper and cannot be used for structural support, they are often fully embedded into aluminum to allow for a high thermal conductivity structural component.
- **Integration:** Heat pipes are versatile to implement into designs and interface with higher level assemblies. Pedestals and other mounting features critical to the heat spreader can typically be maintained. More detail on heat pipe attachment on pg 6, “Mechanical Design”.

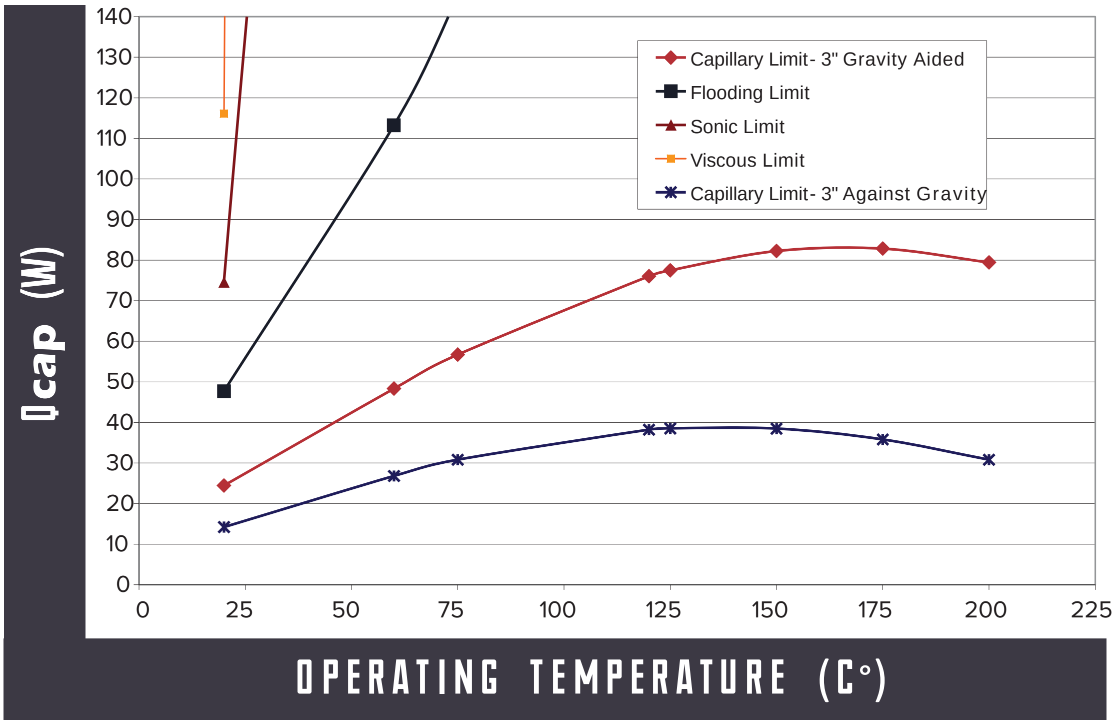
PERFORMANCE (LIMITS)

Once you determine that the system could benefit from enhanced conduction, the next step is to determine if heat pipes can move the total amount of power you must transport. There are several limits to heat pipe performance, described in the table below. In most applications, the most common limits that dictate performance are the capillary limit followed by the entrainment limit.

HEAT PIPE LIMIT	DESCRIPTION	CAUSE
Viscous (Vapor Pressure)	Viscous forces prevent vapor flow within the heat pipe.	Heat pipe operating near triple point with a very low vapor pressure – need to use a different working fluid.
Sonic	Vapor flow reaches sonic velocity when leaving the evaporator, choking the flow.	Too much power at lower operating temperature. Typically this is seen at start-up and will self- correct.
Heat Pipe Entrainment	High velocity vapor flow strips liquid from the wick.	Not enough vapor space for the given power requirement. Occurs at low temperatures.
Thermosyphon Flooding	High velocity vapor flow prevents liquid return in a gravity aided thermosyphon.	Not enough vapor space for the given power requirement. Occurs at low temperatures.
Capillary	The capillary action of the wick structure cannot overcome gravitational, liquid, and vapor flow pressure drops.	Power input too high. Wick structure not designed appropriately for power and orientation.
Boiling	Boiling occurs in the wick which prevents liquid return	High radial heat flux into the heat pipe evaporator

In electronics cooling applications, the primary goal is to make sure the max operating case (or junction) temperature of the electronics component is not exceeded. Therefore, as you approach that temperature, it's critical that the heat pipe is performing. The graph on page 5 provides a heat pipe limit curve for a given design. The goal during this phase of the design is to design an optimal wick structure to maximize transport power. ACT uses in-house tools with commonly available wick structures to quickly design the best available heat pipe for a given project. The Figure below shows that the design point is below all heat pipe limit curves, which means the heat pipe will function as intended.

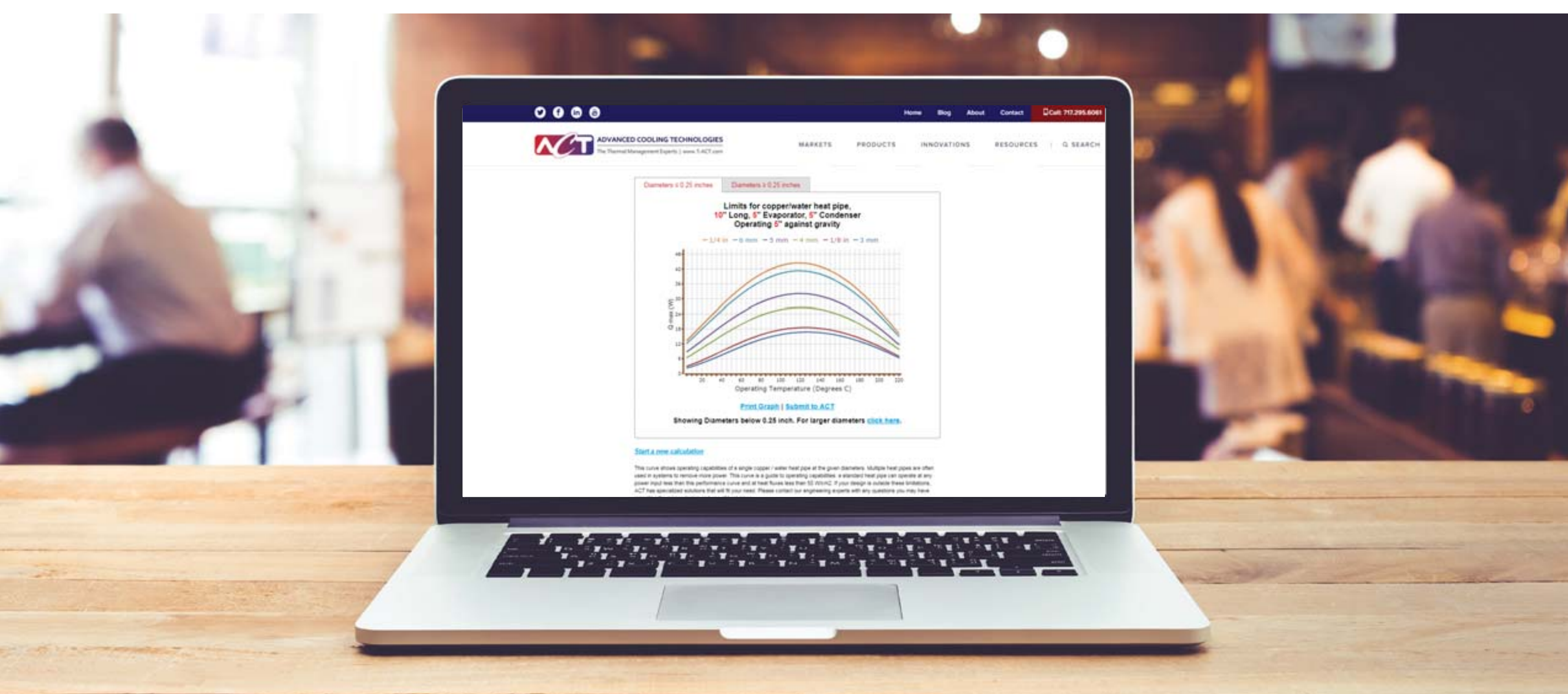
10" Copper / Water Heat Pipe
3" Evaporator and Condenser



This graphs shows the various heat pipe limitations for a typical copper/water heat pipe. These limitations are a function of the operating temperature, due to the change in the fluid properties as a function of temperature. It is important to ensure that the appropriate performance limit curve adequately cover the performance requirement for the entire specified temperature range.

ACT HEAT PIPE CALCULATOR

ACT provides this free online tool to calculate the capillary limit. This assumes a certain wick structure but can give a ballpark estimate of power transport capability. Contact ACT for further optimization.



This section provides a step by step guide to designing heat pipes into your system.

1. Analyze your system:

- Does your design suffer from hot spots or large conduction gradients?
- Do you have a need to remotely locate your heat sink?

2. Identify your highest heat flux:

- Typical heat pipes can handle heat flux up to 50 W/cm2. For higher heat fluxes, advanced wick structures may be required.
- Is your heat flux less than 50 W/cm2?

3. Determine the size and number of heat pipes required:

- Run ACT's Heat Pipe Calculator.
- Notes:
  - Each curve represents capacity of a single heat pipe. Therefore, if you can transport 10 W with a 4mm heat pipes, using two (2) 4mm heat pipes will transport up to 20 W.
  - The calculator uses an assumed wick structure- in many cases, we can optimize the wick. If you're close to your goals, please contact ACT for more detailed/optimized curves.
- Can you transport the total of your waste heat?

4. Quick Thermal Analysis

- Heat Spreaders: If utilizing a metallic heat spreader, one simple way to model a HiK™ (embedded heat pipe) design is to change the bulk thermal conductivity of your base material to 600 W/m-K. K values of 500-1,200 W/m-k have been validated through various designs and correlated test data. 600 W/m-k is a valid starting point that can usually be met with optimized heat pipe layout.
- Remote Heat Sink: Model the heat pipe as a solid rod and adjust the bulk thermal conductivity until the delta T (hottest point to coldest point) is between 2 and 5 C. Start with 10,000 W/m-K.
- Did you meet or are you close to your thermal performance objectives?

5. Mechanical Design

- At this stage you should have a good feel for if heat pipes are a suitable solution, but you still need to integrate them into your design which may have challenging geometric constraints. Often times you'll need to bend and/or flatten heat pipes to properly integrate.
- Use the following guidelines to integrate heat pipes into your design
  - Bend Radius > 3x OD of the heat pipe
  - Flatness > 2/3 OD of the heat pipe (Note: flattening heat pipes reduces vapor space and may require rerunning heat pipe curves)
- Attaching heat pipes:
  - Solder: Highest thermal and mechanical properties
  - Epoxy: Easy assembly, good for lower heat flux applications

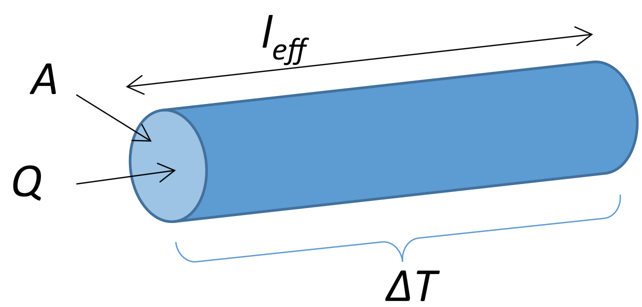
Some other modeling techniques include using a complex model where you model the liquid vapor interface, envelope wall, wick structure and vapor space separately. This is usually done for smaller models with high heat flux and custom wick structure. The two main resistances associated with heat pipes are the radial resistance and the axial resistance. The radial resistance is the conduction through the wall, the wick and the two phase heat transfer at the vapor-condensate interface. This value is typically around 0.2 degrees C centimeters square per watt. The axial resistance is the vapor temperature difference across the length due to the temperature across the length due to the internal pressure difference. This is typically a very low number, about 0.02. This modeling technique is fairly challenging, especially in applications that must include several interfaces (gap pads, greases, etc.) and can lead to long computational run times.

One technique to cut down on computation time is a Mixed Model, which is a method which lumps the interface, wall and wick material into one material and uses a very highly conductive vapor space. This method again simplifies the two phase heat transfer into effective conductivity, but accounts for the radial resistance more accurately than the simplified model. The user can use hand calculations to determine the "lumped" thermal conductivity / radial resistance. To calculate the k_{EFF} of the vapor space, use Fourier's Law as shown in the example below:

Use Fourier's law to determine k_{eff} for vapor space

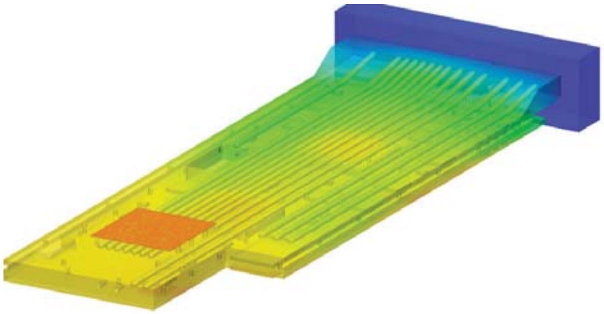
- Known geometry
- Assumed power and ΔT
- Power (Q)
  - Known to be 25 W
- Effective Length (l_{eff})

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



$$l_{eff} = \frac{l_{evap} + l_{cond}}{2} + l_{ad} = 2.21\ in = 0.056\ m$$

- 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

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

	COMPLIANCE METHOD	ACT EXPERIENCE
Power (W) Transport	Analysis	ACT has in-house tools to quickly determine heat transport capabilities and optimal wick structure.
	Test	ACT provides 100% start up testing to show the heat pipe is functioning. Detailed power and delta T testing can be added as required.
Thermal Performance	Analysis	ACT utilizes in-house thermal resistance calculators as well as commercial FEA & CFD tools to verify system level performance.
	Test	ACT designs prototype test sets to mimic boundary conditions and verify performance. This can be executed during qualification as well as acceptance level testing.
Thermal Cycling / Freeze-Thaw	Design	To assure freeze/thaw capability, the fluid charge must be precise to assure all fluid is captured within the wick structure. Wicks act as a sponge and can withstand the expansion of water from liquid to solid phases.
	Test	Most heat pipes that are implemented into environments where the ambient temperature range spans below 0° C go through thermal cycling to prove the wick structure can absorb water's expansion from liquid to solid. Typical requirements are -20° to +20° C. Extreme tests have gone from -45° to +125° C. ACT has tested at the heat pipe and assembly level for 10s to 100s of cycles depending on customer requirements.
Frozen Start-up	Design	Frozen start-up can be an issue if the system thermal mass and heat transfer are such that the fluid in the evaporator is thawed and vaporized by the heat input, travels to the condenser and freezes there. This is a system design consideration, not a heat pipe limitation. There are four ways to address this issue: (1) Design that the vapor transport and input power are sufficient to thaw the entire system. (2) Use active controls (such as turning off fans) to limit heat transfer in freezing conditions. (3) Design a secondary heat transfer mechanism so that the heat pipes are not needed to prevent device from overheating in the freezing conditions. (4) Add NCG to the system to ensure "orderly" freezing and thawing.
Shock / Vibration	Design	Design so that mechanical failure is not an issue in shock and vibration environments. For instance, assure evaporator and condenser mounting features provide adequate mechanical attachment so that the assembly does not encounter significant mechanical stress during shock or vibration.
	Test	ACT has in-house mechanical shock and vibration test equipment (Shock Test Table & Vibration Test Table). ACT has tested to the following conditions: 4,500 lbf force sustained vibration loads. Up to 9,000 lbf shock loads. 0-3,000 Hz frequency range. Over 100 g's peak acceleration. Vibration: Sine, random. Shock: Haversine, Half Sine, Saw-Tooth & Trapezoid. Replication of Measured Field Data. Gunfire Vibration. Shock Response Spectrum. ACT heat pipe assemblies are routinely tested at the system level using MIL-STD 810.
Other Environment (Salt Fog, Fungus, etc.)	Test	ACT heat pipe assemblies and HiK™ plates can utilize coatings for various environments. Coatings include nickel plating, chem film, powder coat, black anodize, tin plating and other paints/coatings based on customer requirements.

SPECIFIC INDUSTRIES / ENVIRONMENTS	
Space	ACT received heritage for copper/water heat pipes in space in April 2017 and has now delivered 100s of copper/water heat pipes for space applications. This typically requires thorough performance, freeze-thaw and life testing during qualification/acceptance testing. Additionally, Aluminum-Ammonia CCHPs are used frequently at the spacecraft level and go equally rigorous testing protocols. ACT has over 20 million hours on orbit with aluminum-ammonia CCHPs.
Aircraft	ACT routinely delivers to defense and commercial aircraft. Assemblies must survive harsh environments including shock, vibration, and extreme temperature ranges. Most commonly, heat pipe/assemblies are tested to thermal performance and verified to environmental requirements at the higher level assembly level. ACT has delivered over 1,000 heat pipes that have been integrated into aircraft systems.
Power Electronics	In many cases, water is a suitable working fluid for power electronics applications. However, certain customers require dielectric fluids to be utilized. ACT has built large scale thermosyphons and loop thermosyphons with refrigerants to meet demands of the power electronics industry.

NOTES

ADVANCED COOLING TECHNOLOGIES
1046 New Holland Avenue
Lancaster, PA 17601, USA

Phone: 717.295.6061
Fax: 717.295.6064

ISO 9001 & AS9100 Certified
ITAR Registered

www.1-ACT.com

MARKETS

Automotive
Avionics/Aircraft
Electronics Cooling
Enclosure Cooling
HVAC Energy Recovery
LED Thermal Management
Materials Process
Medical Devices
Military
Power Electronics
Solar
Spacecraft Thermal Control
Temperature Calibration & Control

PRODUCTS

Heat Pipes for Thermal Management
Heat Pipe Assemblies
Vapor Chambers
High Performance Power Electronics Coolers
HiK™ Plates
Constant Conductance Heat Pipes
Variable Conductance Heat Pipes
Loop Heat Pipes
Isothermal Furnace Liners (IFLs)
Heat Pipe Blackbody Cavity
Pressure Controlled Heat Pipe Furnaces
Pumped Liquid Cooling
Pumped Two Phase Cooling (P2P)
Phase Change Material (PCM) Heat Sinks
HVAC Heat Pipe Heat Exchangers
Sealed Enclosure Coolers
Custom Thermal, Fluid and Mechanical Systems
Isothermal Card Edge (ICE)-Lok™

RESEARCH & DEVELOPMENT

TECHNICAL SERVICES