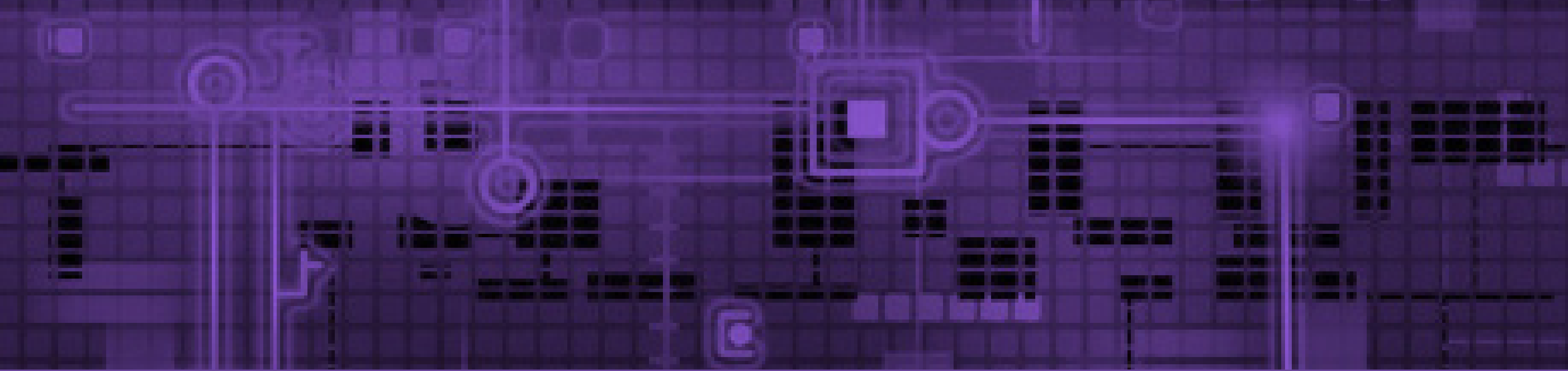


Experimental and CFD Analysis

of a Typical Telecom Board

In the multi-trillion dollar industry of electronics, the ever-rising demands on product capabilities are driving the importance of thermal management toward the leading edge of design cycles. To maintain spatial efficiency, engineering teams deploy products with higher complexity, more dense PCB topologies, higher power dissipations, etc. resulting in harsher operating conditions. Due to an abundance of competition and reduced design cycle times, program budgets continue to be reduced.

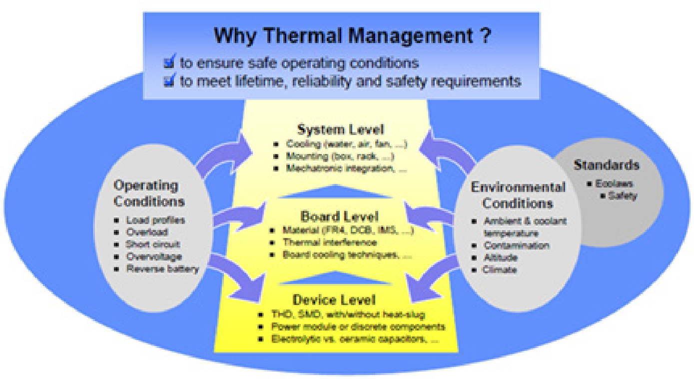


Figure 1. The Impact of Thermal Management at Every Level [1]

While system capabilities, and design budgets once followed parallels, now teams are pulled apart by departmental directives while implementing strategies to solve complex thermal management challenges that yield high ROI. When faced with solving a thermal design challenge, strategies may include: analytical modeling, computational Fluid Dynamics (CFD) and empirical testing. These approaches are subjective, often based on budgets, company culture, an engineer's background and training, etc. This article will investigate these three methodologies used to solve thermal management challenges found on common communications boards.

1st Order Approximations

When looking to determine a thermal solution, a 1st order analysis must be satisfied. As a team is working through optimizing a design, these 1st order calculations create the framework for a specific solution and enable engineers down verification paths using computational fluid dynamics (CFD) simulations and/or empirical testing. Not always are both these validation approaches followed due to resources, budget, time constraints, etc. however if they are, any potential errors are further reduced.

A simple analytical model for calculating thermal resistance, as shown in equation 1 is one such example.

$$\theta_{JA} = \frac{T_J - T_A}{P_D} \qquad (1)$$

Whereas:

θ_{JA} = Junction to ambient thermal resistance
T_J = maximum junction temperature
T_A = ambient temperature
P_D = power dissipation

The parameters of device are specified by the manufacturer, such as max junction temperature. If this is not available through the initial phases of the design cycle, a default of 125°C rating is typically used for analysis.

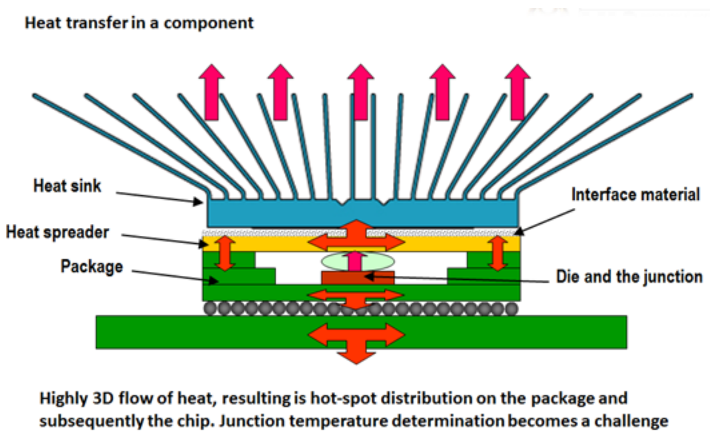


Figure 2. Heat Transfer Paths From Junction to Ambient [2]

Thermal transport from a device's core, to the ambient environment is highly three-dimensional as seen in figure 2. Heat generated at the die is removed through several paths and so the total resistance is made up of several separate thermal resistive paths. The thermal resistance inside the device package is labeled as θ_{JC} and θ_{Jb}. These resistance values are between the junction and case and the junction and PCB, respectively. Since it is within the device, θ_{JC} is under the control of the device manufacturer, and typically low as manufacturers desire the package to be as conductive as possible for efficient performance and increased reliability. Junction to board resistance is always higher, yet this resistance is also controllable by the design team and PCB manufacturers. Improvements can made to this thermal path when implementing features such as thermal vias or conductive slugs, that couple to increased copper planes within the PCB. Additional layers of resistivity are introduced between the device case and ambient environment. This is where the thermal solution resistance, θ_{CA} is comprised of θ_{CS} and θ_{SA}, where θ_{CS} is the thermal resistance of the thermal interface material (TIM) and θ_{SA} is the thermal resistance of the heat sink itself.

The junction to ambient thermal resistance is now defined as:

$$\frac{1}{\theta_{ja}} = \frac{1}{\theta_{jc} + \theta_{cs} + \theta_{sa}} = \frac{1}{\theta_{jb} + \theta_{ba}} \quad (2)$$

Disregarding the influence the PCB has, the formula is rendered down to this:

$$\frac{T_J - T_A}{P_D} = \theta_{jc} + \theta_{cs} + \theta_{sa} \quad (3)$$

Heat sink resistance, θ_{SA}, can be lowered by changing the geometry and choosing a material with a higher thermal conductivity. Convection resistance can be lowered by optimizing the heat sink surface area or the heat transfer coefficient.

Heat sink resistance is found using the following equation:

$$\theta_{SA} = \frac{1}{h\eta_o A_{tot}} + \frac{1}{\dot{m}C_P} \quad (4)$$

Here:
η_o = overall surface efficiency
A_{tot} = total heat sink surface area (m^2)
h = heat transfer coefficient ($W/m^2{\cdot}K$)
$\dot{m}$ = mass flow rate (Kg/s)
C_p = heat capacitance (kJ/Kg·K)

Above calculations show how extensive the analytical modeling would be to ensure device thermal transport is satisfied. These calculations are representative of a thermal model including one device residing on a PCB. For complete modeling of the PCB, thermal coupling between the devices, and from PCB to PCB must be accounted for. For this analysis, and potential iterations through optimization a CFD tool may be simpler.

Computational Fluid Dynamics (CFD)

CFD is another tool in the thermal tool box used for analysis and evaluation of a telecom board and provides an engineer with the capability to manipulate the layout of a PCB in order to accommodate necessary heat sink size, improve airflow management, and will exploit the need for and home in on evaluated cooling solutions. Also, as complex geometries and/or performance demand of the heat sinks rise, the investigation of custom features can be easily evaluated within the CFD vs. spending additional resources for calculating conservation of energy calculations and empirical testing. As computers have become more capable, CFD packages have been able to improve their mathematical models for solving the Navier-Stokes equations. As a result, a higher reliance on these software tools has been evident, and the challenge has been shifted some to user interpretation, and software know-how.

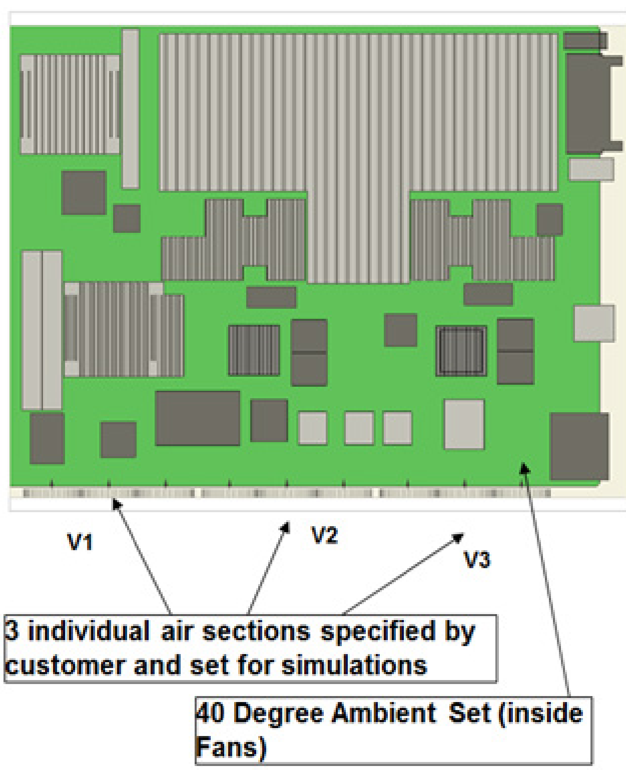


Figure 3. Simplified Board For CFD Analysis And Heat Sink Optimization [2]

As seen in Figure 3, board geometries need to be simplified, with small – non impeding features removed to allow for effective use of CFD (time to converge). While some features bear no impact on the airflow/thermal coupling on the board, some in fact do. Knowing that there are impacts on the flow regimes, can be imputed based on one's experience and knowledge, or preliminary testing on the board via flow visualization. If initial empirical testing is not done, assumptions will have to be made which could lead to inaccurate results, and adverse consequences in the final solution.

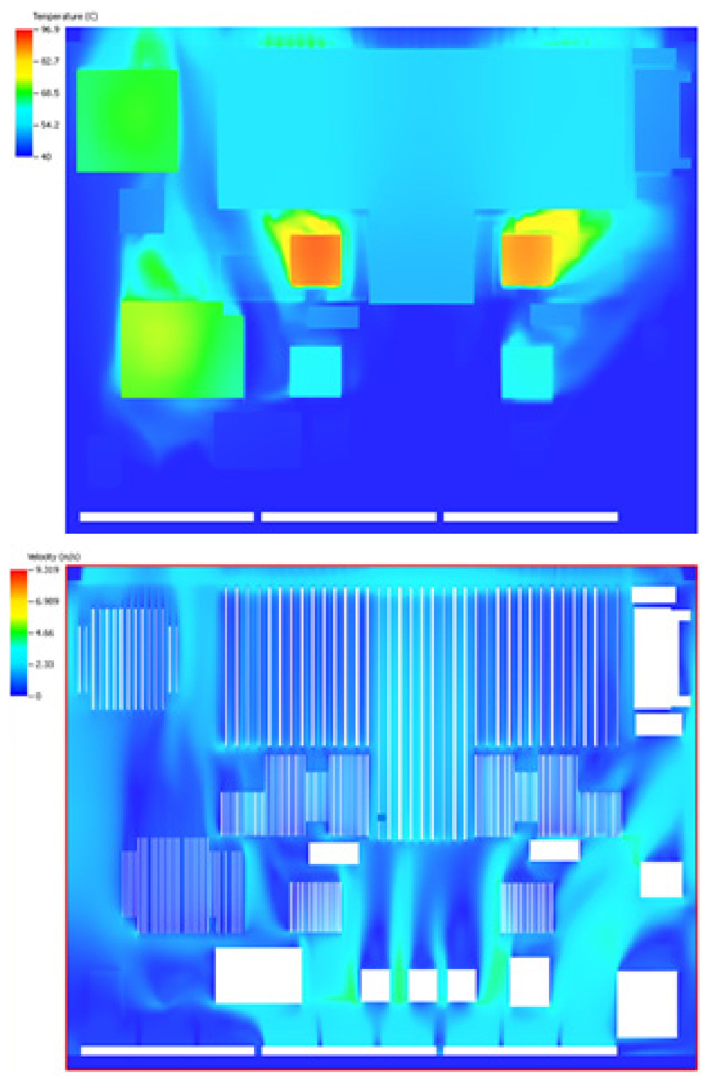
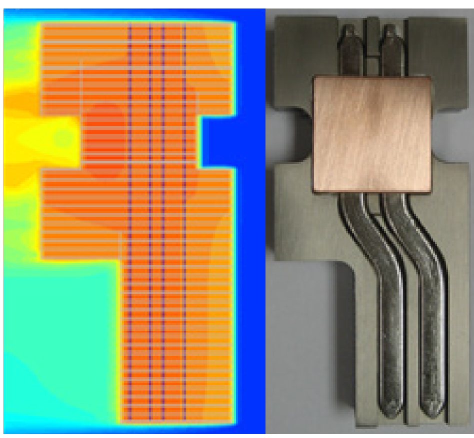


Figure 4. CFD Output Showing Temperatures (Top) and Airflow Velocity (Bottom) [2]

As a case in point the CFD capture in Figure 4 shows that there is a high degree of spreading resistance within the heat sink base (left) and under utilized airflow regions just above the heat sink base (right). In the figure, red arrows call out the heat concentration areas and airflow velocities so the heat sink can be optimized with additional features and/or different profile. Figure 5 shows an up close view of the heat sink in question and the performance improvement when integrating heat pipes into the base. Comparing figures 4 and 5, show that the heat sinks were not utilizing the width of the heat sinks effectively, and so the effective cooling solution is much smaller than assumed through 1st article approximations. The solution in this case was the use of heat pipes for more efficiency, while still maintaining the ability to directly attach the heat sink to the component with a frame and spring clip assembly.



Parameter	Settings/Results		
	OLD	NEW	Yield
Fan setting	25	25	
Device Power (W)	42	42	
Ambient (°C)	22.0	22.0	
Upstream air (°C)	45	45	
Upstream air (m/s)	1.2	1.2	
Device T_J (°C)	84.0	74.0	10.0
θ_{JA} (°C/W)	1.48	1.24	0.24 (16.2%)

Figure 5. Heat sink Redesigned with Heat Pipes [2]

The benefits of accurate CFD modeling for virtual prototyping and creating a 1st – 2nd order cooling solution approximation are unquestionable. Note, at this stage of the design cycle productivity typically outweighs accuracy, and so care must be taken in relying on CFD results to drive prototyping. Inaccuracies in modeling can lead to under/over-performing solutions that may turn into custom designs after empirical validation. [3]

Empirical Validation

As discussed for input into a CFD model, to support the investigation of heat transfer in a forced convection application, it is imperative to know the flow composition around a potential heat sink solution. There are several ways to do this empirically, one can set up an existing board, or a 3D printed version within a quality wind tunnel and introduce smoke at the inlet, as seen in figure 6, or if equipment is available use hot-wire anemometers to directly measure airflow, and temperatures.

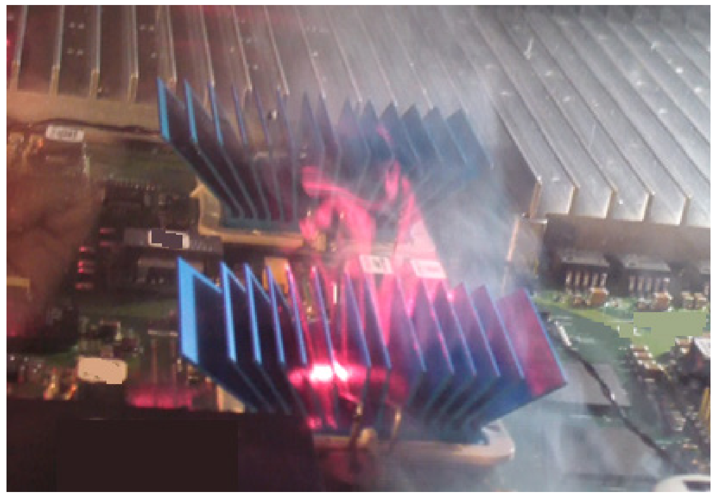


Figure 6. Video Analysis/Smoke and Laser Visualization [2]

PCB topologies create complex flow structure and the variation in layout will also create different airflow resistances from card–to–card within a card cage. Once heat sinks are approximated in CFD, the most accurate way to evaluate actual performance, and optimize the thermal solution is by testing using replica boards within a wind tunnel, or if available, live boards within their specific card guides in a system chassis.

Hot-wire Anemometry/Thermocouples

Ambient air and components will be heated by adjacent board components and so it is crucial to understand what the boundary conditions are directly upstream of the component requiring a thermal solution. As seen in Figure 7; sensors that reads both air temperature and air velocity can be placed directly upstream of the sample solution. When placing sensors in this region it is important that the sensor itself isn't blocking/redirecting the flow as this will lead to inaccuracies and altered thermal solution design. Sensors such as those in Figure 7 are capable of temperature measurements ranging from -20° to +120°C ±1°C and velocity measurements range from 0 to 50 m/s ±2%.

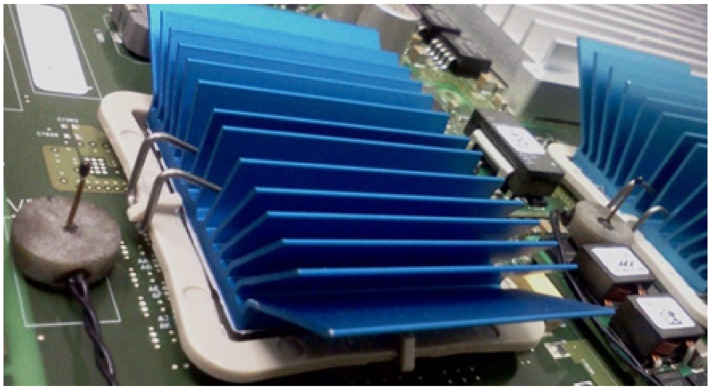


Figure 7. Two Sensors Measuring Boundary Conditions

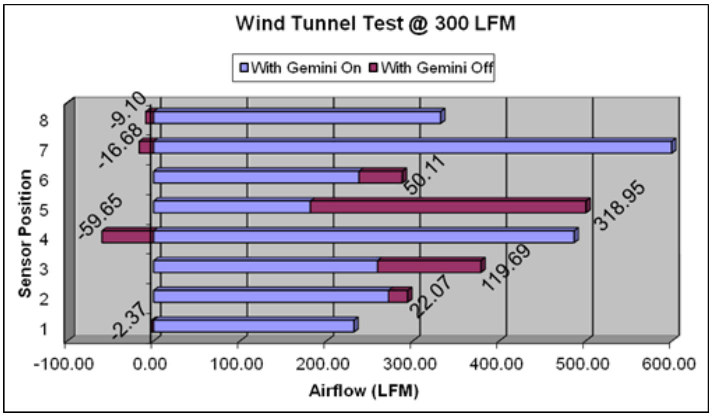


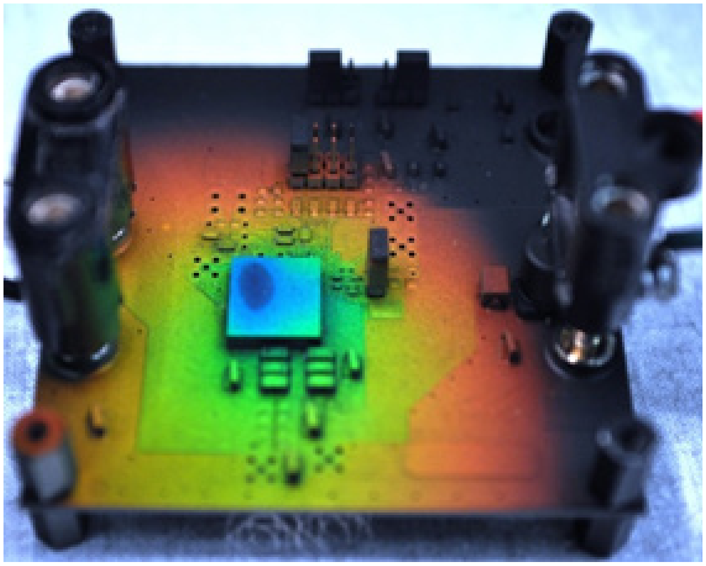
Figure 8. Airflow Measurements Across a Telecom Board

Figure 8 shows the impact that one heat sink may have on the velocity distribution on an ATCA form factor telecom board. Here we see that 8 sensors scattered throughout the card are taking measurements with all heat sinks attached to select components, and also with one heat sink "Gemini" removed. As seen by the empirical measurements, the air flow profile just above the top of the PCB can change dramatically based on the removal of a single heat sink. This is why it is critical to understand the relative impact of heat sink geometries and location within the board layout, evaluate the challenge holistically, and not focus on cooling one component at a time.

Analysis of flow through a telecom board can be executed in a timely fashion with various ways to mitigate dead zones and exploit high flow regimes for improvements to overall layout. Such measures include baffling, refining heat sink geometries, using heat pipes to transport heat to positioned condensers, or even PCB re-layout. From an experimental standpoint, there are two straight forward methods for temperature mapping including infrared and liquid crystal thermography.

IR/LCT

The use of IR and Liquid Crystals (LCs), or Liquid Crystal Thermography (LCT) for PCB surface thermal mapping provide visual insight into thermal coupling between devices and substrates and uncover hidden hotspots, display the thermal spreading during transient stages, and absolute surface temperatures at steady state. As seen in figure 9, the visual output from using liquid crystals and IR vary slightly. Comparing these two images side by side, one can see that the LCs display the hotspot and temperature gradients more clearly. An increase in clarity via IR could have been attained with an alternative magnification/ resolution lenses. The LC temperature gradients may be easier to see, but must to be correlated based on the system's calibration information. The IR isn't as clear, but uses software that requires surface emissivity be specified for absolute temperature measurement. For this reason, the use of LCs provides results at a substantially lesser cost. No additional equipment is needed when using LCs, and temperature mapping is visible through enclosures such as wind tunnel test



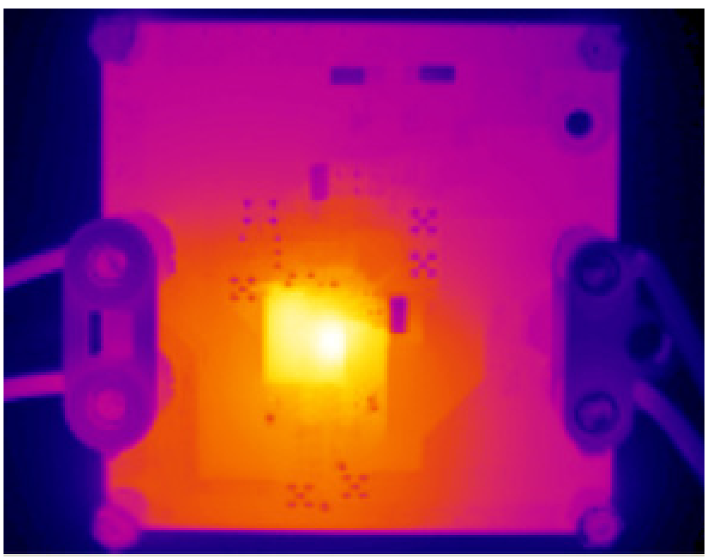


Figure 9. Investigation Using Liquid Crystals (top) and IR (bottom) [2]

sections, whereas the use of IR requires hardware and software, and special IR viewing panels, etc. For high resolution, IR thermography can warrant pricing of 5x that of LCT systems.

Conclusion

Overall, the purpose of thermal management is to satisfy performance and lifetime reliability requirements for various systems, within specified operating conditions. Despite that electronics are subjected to different environmental conditions and power outputs during operation, interpretations are typically made once systems have reached steady state conditions. This may have been due to aged reliability prediction methods for continuous operation however, as reliability predictions become more acute, transient temperatures may have to be increasingly investigated to ensure product sustainability. As synergy is created between these investigative methodologies presented here, teams can more accurately determine cooling solutions, and realize reduced hardware costs, improved reliability, and shorter time-to-solution intervals.

References:

1) März, Martin "Thermal Management in High-Density Power Converters," 2003

2) Advanced Thermal Solutions, www.qats.com

3) Eveloy, Valerie C., M.Sc., "An Experimental Assessment of Computational Fluid Dynamics Predictive Accuracy for Electronic Component Operational Temperature," August 2003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