FALL 2017
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THERMAL LIVE 2017 TECHNICAL PROGRAM

Avionics Thermal Management of Airborne Electronic Equipment, 50 Years Later

Advances in Vapor Compression Electronics Cooling

Thermal Management Considerations in High Power Coaxial Attenuators and Terminations

ESTIMATING INTERNAL AIR COOLING TEMPERATURE REDUCTION IN A CLOSED BOX UTILIZING THERMOELECTRICALLY ENHANCED HEAT REJECTION

RESEARCH ROUNDUP: OCTOBER 2017 EDITION

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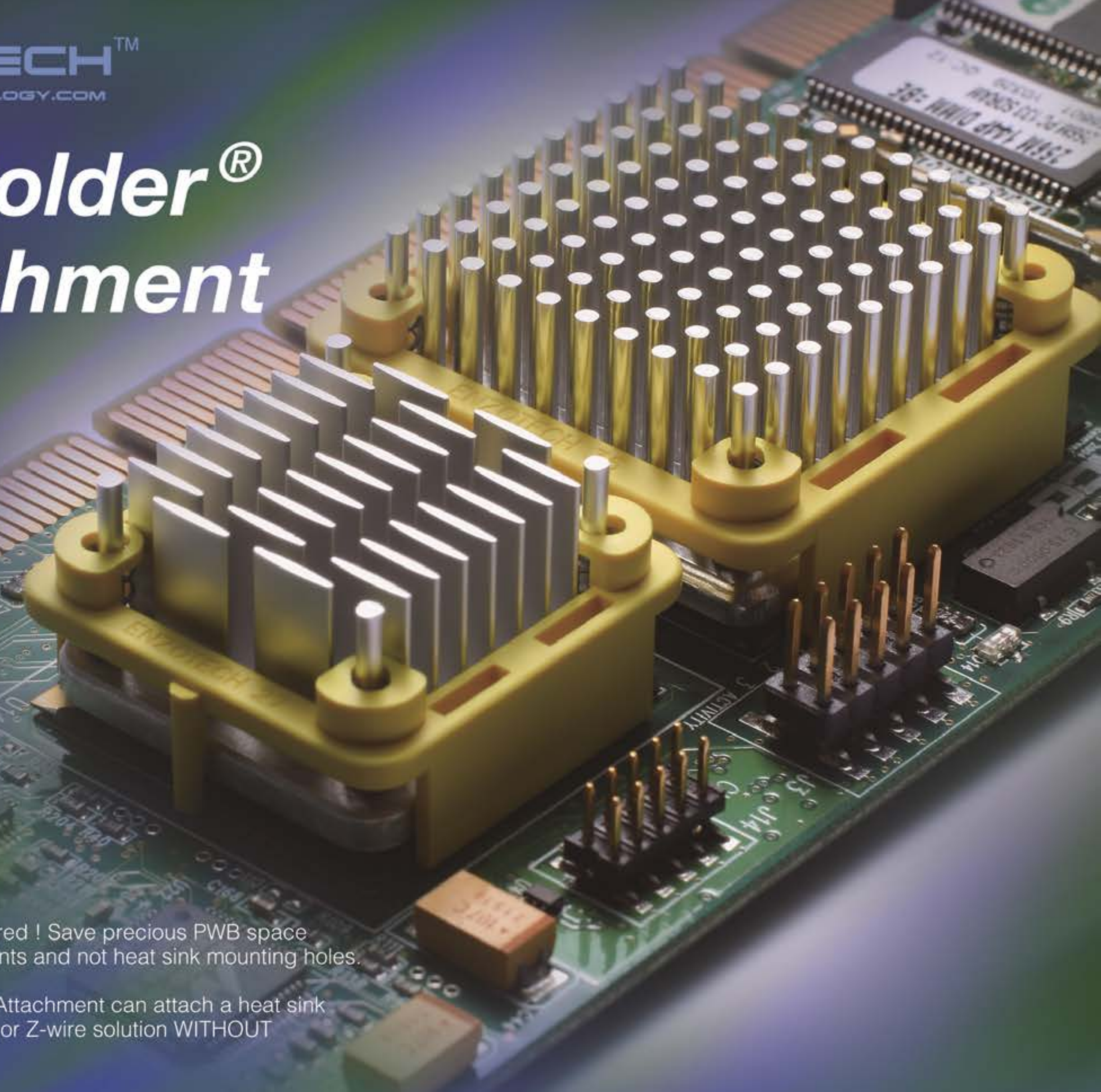
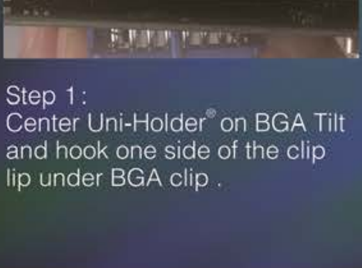
Uni-Holder®
-attachment

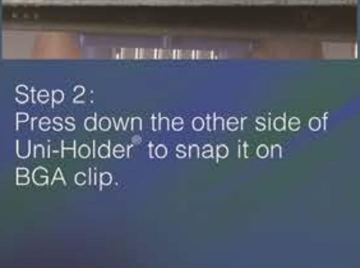


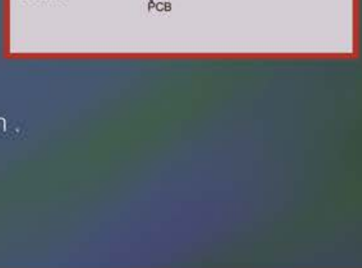
SPACE IS MONEY

No mounting holes required ! Save precious PWB space for routing and components and not heat sink mounting holes.

Enzotech's Uni-Holder® Attachment can attach a heat sink as reliably as a push pin or Z-wire solution WITHOUT the needed thru holes.







Step 1:
Center Uni-Holder® on BGA Tilt and hook one side of the clip lip under BGA clip .

Step 2:
Press down the other side of Uni-Holder® to snap it on BGA clip.

Step 3:
Installation completed. Snap on . Stay on .

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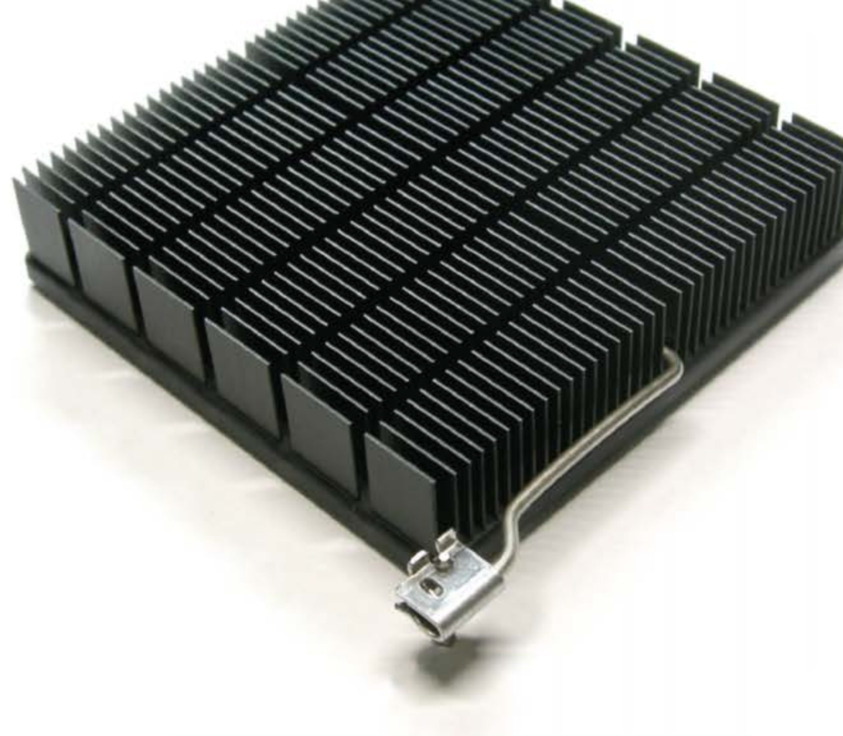
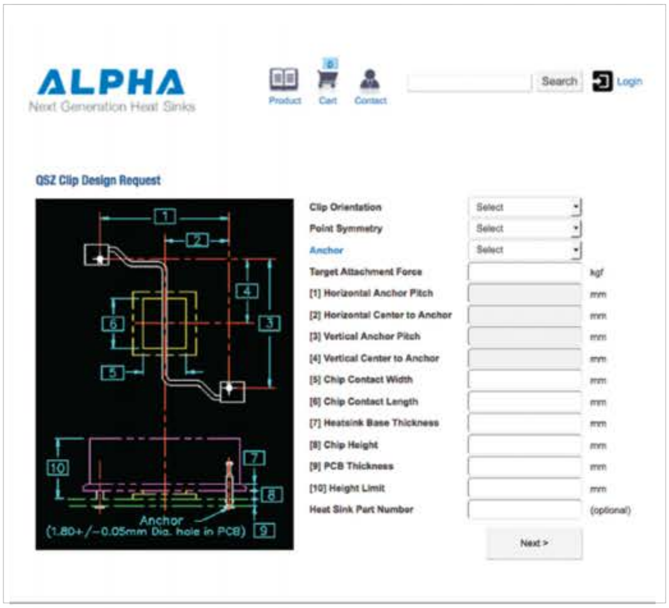


- Custom or off-the-shelf
- Simple to complex
- Prototype to mass production



QSZ Clip Design Request

Anchor
(1.80+/−0.05mm Dia. hole in PCB)

Clip Orientation	Select	
Point Symmetry	Select	
Anchor	Select	
Target Attachment Force		kgf
[1] Horizontal Anchor Pitch		mm
[2] Horizontal Center to Anchor		mm
[3] Vertical Anchor Pitch		mm
[4] Vertical Center to Anchor		mm
[5] Chip Contact Width		mm
[6] Chip Contact Length		mm
[7] Heatsink Base Thickness		mm
[8] Chip Height		mm
[9] PCB Thickness		mm
[10] Height Limit		mm
Heat Sink Part Number		(optional)

A custom clip is often required due to board layout issues or attachment force requirements.

+ Minimun order quantity: 1 piece
+ Prototype lead time: 2 weeks
+ Rapid design and quote process

QSZ Clip

Heat sinks are mounted directly to the PCB, but only take up a minimum of board real estate. Attachment force and shock loads are transmitted to the PCB instead of the chip and solder balls.

Advantages

Flexible Design

Custom clip/anchor pin spacing is compatible with standard heat sinks.

Easy-Install

Press and hook to install. Easy!

Minimum PCB Area

Pins only require 1.8mm diameter holes in the PCB.

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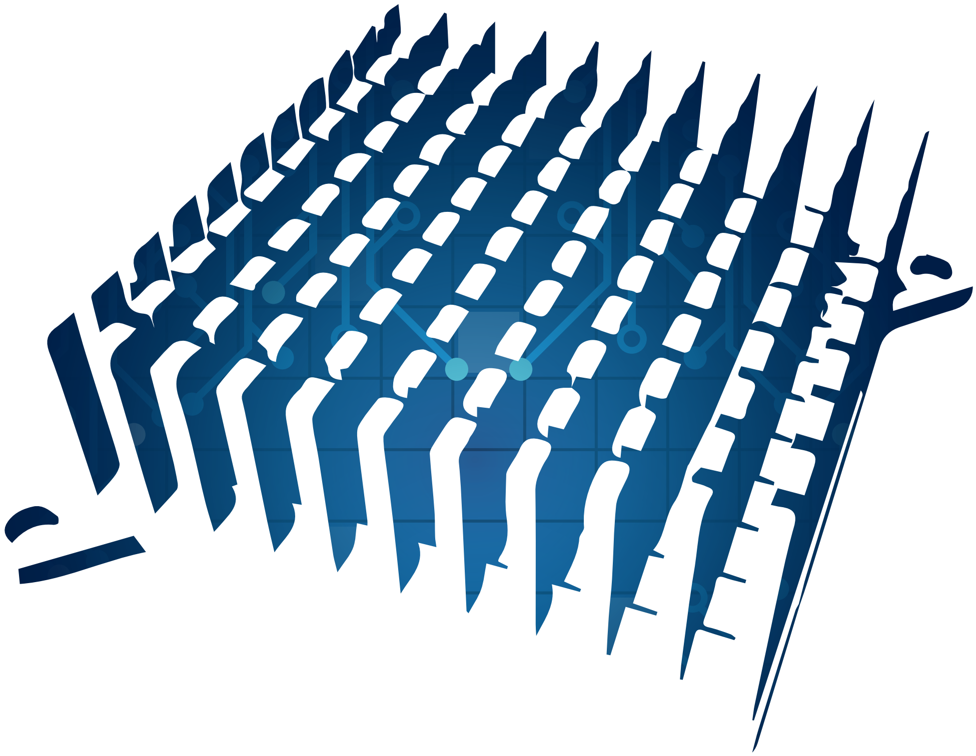

CONTENTS

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ITEM MEDIA

EDITORIAL

In the End, Entropy Always Wins… But Not Yet!

Greetings to All *Electronics Cooling*®'s Loyal Readership and Visitors,

I have recently had the privilege of joining the *Electronics Cooling*® team alongside the incredible Editorial Board and ITEM Media. My goal as part of the team is to help the experts on the Editorial Board and ITEM Media production staff to continue driving *Electronics Cooling*® to add the most value to its indispensable community. I say indispensable, because in the end, entropy always wins. The day we will no longer need electronics cooling and thermal management experts and engineers will be the day of the heat death of the Universe. My calculations might be wrong, but that is at least a few months off, at least.

Though my background is not formally in electronics cooling or thermal management, it is one of those unavoidable aspects of engineering that you only hide from if you are locked in a box-- the same box as Schrodinger's Cat. If you aren't sure if you are there or not, don't worry, you are probably there… or not. This has probably influenced my view that thermal management, especially in electronics, is similar to waste disposal. Please forgive the analogy, but I see it like managing sewage in a city. Everyone is making it, even if you don't want them to. Also, you have to dump it somewhere. If not, you are left with one hot mess.

Just like waste management in city planning, thermal management is also one of those factors that is forgotten until the last minute. That is where electronics cooling experts are really needed to save the day. All joking aside, proper thermal management is a key enabling factor to higher performing devices. We wouldn't have the latest high-speed computational chips, cell phones we can fit in our pockets without exploding, all-electric cars, telescopes that can capture the Cosmic Microwave Background Radiation, or essentially any modern electronics without the dedication of knowledge thermal management and electronics cooling experts.

Like a few other of the niche disciplines in electronics, there are very few with the knowledge and skills to be useful, and many more with just enough understanding to be dangerous. I am definitely in the category of the dangerous sort, which is why I am so glad *Electronics Cooling*® has such a competent, experienced, and collaborative Editorial Board.

This magazine has had solid and high quality content for years, due to the dedication of the Editorial Board. When many similar publications have waned in the quality of content, as a result of cost pressures or a lack of qualified experts to help take the reins, *Electronics Cooling*® has been standing tall. It is one of the few publications that I know of that a reader can still pick up, or click on, and find relevant articles worth reading. I also have to acknowledge and congratulate all of the determined contributors to the magazine for all of the high caliber articles. It is not always easy to get top notch content from already busy engineers and experts, but this community has really rallied behind the banner of advancing the art of thermal management and electronics cooling with some amazing submissions.

Like I mentioned earlier, my goal is not to help entropy, but to help a good thing keep going. That being said, I am very open to learning from, engaging with, taking suggestions from, and supporting this great community of technical professionals dotted across the globe.

Cheers,

Jean-Jacques (JJ) DeLisle
Executive Editor
jj@electronics-cooling.com

THD Series - High Performance fans designed specifically for the following applications:

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THD series innovation with bionic blade

The THD series boasts newly designed bionic blades inspired by nature's most powerful winged predators. This fan series represents the most *quiet*, *fast*, *powerful*, and *efficient* design Delta has to offer. Engineers managed to apply the posture and wing structures of an osprey in flight to design fan blades via parameterized and simulated processes. By simulating the curve of an osprey's wing in flight, the new THD series fan reduces fan noise up to 6dB-A. THD fans offer different sizes of products, from SQ80mm to OD200mm.

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COOLING EVENTS

News of Upcoming Thermal Management Events

THERMAL LIVE™ 2017

October 24 (Tuesday) – October 25 (Wednesday)
Online

Thermal Live™ is an innovative concept in education and networking in thermal management – a FREE 2-day online event for electronics and mechanical engineers to learn the latest in thermal management techniques and topics. Produced by Electronics Cooling magazine, Thermal Live™ features webinars, whitepapers, and live product demos, all with no cost to attend.

www.thermal.live

FLOEFD SIMULATION CONFERENCE 2017

November 7 (Tuesday) 8:30 AM - November 8 (Wednesday) 5:00 PM
Mövenpick Hotel | Berlin, Germany

The FloEFD Simulation Conference 2017 is the second annual global event about FloEFD, the most popular frontloading Computational Fluid Dynamics (CFD) solution in the industry. The conference covers many types of applications and industries including automotive, aerospace, telecommunication, consumer products and general manufacturing.

https://www.mentor.com/events/floefd-conference

THERMAL DESIGN AND COOLING OF ELECTRONICS WORKSHOP

November 13 (Monday) - November 15 (Wednesday)
Eindhoven | The Netherlands

Industry trends towards ever increasing functionality, performance, miniaturization, and less cost result in higher heat density and corresponding higher temperatures. Unfortunately, these have a negative impact on the performance, reliability and lifetime of electronic products, and make thermal design more challenging than ever.

http://www.hightechinstitute.nl/en/training/electronics/thermal_design_and_cooling_of_electronics_workshop/

SEMICON EUROPA 2017

November 14 (Tuesday) - November 17 (Friday)
Messe München | Munich, Germany

The SEMICON Europa technology and business programs address the critical issues and challenges facing the microelectronics industries and provide the information, education, and guidance that needed to move your innovations and products to market. Connect with the facts.

http://semiconeuropa.org/

thermal LIVE 2017

October 24-25, 2017 | Online

Presented by Electronics Cooling®: Thermal Live™ is a **FREE** 2-day online event for electronics and mechanical engineers to learn the latest in thermal management techniques and topics.

Technical Program: Tuesday, October 24, 2017

CPC

11:00 am – 11:45 am ET

Liquid Cooling Quick Disconnects: Design Specs that Contribute to Cost-efficient and Reliable Thermal Management

Dennis Downs, liquid cooling of electronics expert at CPC, reviews the must-have features of Liquid Cooling Quick Disconnect Couplers in meeting the fluid handling requirements of thermal management systems. Using three actual customer examples, Dennis highlights connection design challenges and how to ensure reliability, safety, and effective safe cooling in heat removal.

Speaker: Dennis Downs

VILLANOVA UNIVERSITY

11:50 am – 12:05 pm ET

Transient & Steady-State Thermodynamic Modeling of Modular Data Centers

The data center industry focuses on initiatives to reduce its enormous energy consumption and to minimize its adverse environmental impact. Modular data centers provide considerable operational flexibility in that they (1) are mobile and (2) are manufactured using standard containers.

This study develops steady-state energy and exergy destruction models for modular data centers with the open-source EnergyPlus (EP) software package. Three different cooling approaches are examined: direct expansion cooling, direct evaporative cooling, and free air cooling (air-side economization).

This work shows that for hot and arid climates like those in the southwestern United States, augmenting direct expansion (DX) cooling with evaporative and free-air cooling can result in energy savings of up to 38% and 36% respectively. This study also applies exergy analysis to suggest that the Energy Reuse Effectiveness (ERE) of a data center increases with decreasing ambient (outdoor) temperature and increasing server inlet-outlet temperature difference. Furthermore, simulations indicate that the use of passive cooling techniques (e.g., direct evaporative cooling and free air cooling) decrease data center heating, ventilation and air-conditioning (HVAC) energy consumption, except in extremely hot and humid climates.

Lastly, a transient analysis is developed to answer the question of whether cooling demand needs to be revamped instantly if server demand is raised. The analysis shows that there is very little energy saving to be gained if cooling is ramped-up slowly when demand is instantly raised. Hence, the choice as to whether to ramp-up cooling instantly or slowly is up to the data center operator, without any significant energy and monetary savings.

Speaker: Rehan Khalid

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Please visit **www.thermal.live** for the most up-to-date schedule.

Tuesday, October 24, 2017

12:15 – 1:00 pm ET

Rapid Heat Sink Thermal Analysis and Design Utilizing Heat Pipes

The ability to analyze, design and optimize heat sinks for an application can be cumbersome and time consuming. In addition, it requires software that can be expensive and the user needs to have knowledge of heat transfer principles. To address these issues, a new heat sink software package (Aavid Genie) has been completed that allows for more rapid analysis and design of heat sinks. This session will cover how to use Aavid Genie and validate its design against FloTherm simulations and actual test results.

Speaker: Nelson J. Gernert, V.P. Engineering and Technology at Aavid Thermacore, Inc.

1:30 – 2:15 pm ET

Detailed PCB Thermal Modeling with Thermal Territories

Accurately modeling detailed PCB traces in a system level thermal analysis is challenging. Historically the process involved the manual conversion of 2D drawings to 3D MCAD geometry. More recently thermal analysis tools have been able to convert PCB layout files directly to explicit thermal models but generally lack the ability to control the models resolution of detail. The ability to resolve a PCB layout file directly greatly reduces the model development time but modeling an entire PCB with explicit traces is computationally inefficient for most system level thermal design scenarios. The current best approach balances thermal model accuracy with computational expense through the concept of Thermal Territories.

A brief overview of the methods of capturing PCB copper distribution is discussed including the advantages and disadvantages of each process. Examples of the thermal predictions based upon these methods will be shown. The concept of Thermal Territories will be introduced and examples shown that compare the relative accuracy gain when explicitly capturing the copper distribution from the heat source outwards.

Speaker: John Wilson, Electronics Product Specialist at Mentor Graphics

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Tuesday, October 24, 2017

phononic

2:45 – 3:30 pm ET

Thermal Design and Integration Considerations for Thermoelectric Devices in Cooled Optoelectronic Packages

The optical communications industry continues to increase data communication rates and bandwidth at an impressive rate. This progress drives increasing power densities and heat generation at both the transceiver level as well as the light source. This presentation will provide insight into the thermal challenges facing optoelectronic component designers and cover how thermoelectric devices can be optimally implemented to meet those challenges.

Speaker: Alex Guichard, Senior Product Manager of Optoelectronics Cooling Products at Phononic

Technical Program: Wednesday, October 25, 2017

fujipoly®

2:45 – 3:30 pm ET

In-depth Understating of Compression Characteristics of Thermal Interface Gap Fillers Materials

Using thermal gap fillers in a thermal solution is often more about managing stress in assemblies than about transferring heat. This webinar will provide the audience with a better understand of stresses and forces in an assembly, how to identify different regions on the compression curve, and understand the risk involved with operating in the given regions. We will also cover other characteristics such as plasticity and elasticity in gap fillers and how they impact stress.

Speaker: Christian Miraglia, Applications Engineering Manager

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What a Thermoelectric Cooler is *Really* Good For …

Roger Stout, PE
Senior Member of the Technical Staff
Corporate Research and Development, ON Semiconductor

Fairy tales … perpetual motion machines … Not all fairy tales are perpetual motion machines, but all perpetual motion machines are certainly fairy tales. Before I get into the specifics of thermoelectric coolers, however, it seems appropriate to set the stage for this particular category of fairy tales.

There are two classical types of perpetual motion "machines," called (not so creatively) "type 1" and "type 2" machines (or equally creatively, machines of the "1st kind" and "2nd kind"). Type 1 machines are the ones most likely immediately familiar to you. They violate the First Law of Thermodynamics, which states that energy cannot be created or destroyed, only transformed from one form to another. Typically, Type 1 machines involve some sort of rotating mechanism that through apparently clever design manages to always have torque generated in a constant direction (or perhaps alternates direction, but with an average favoring one direction). In the absence of friction (or a load), they would move forever without any addition of energy. Type 1 machines are so easy to come by that the U.S. Patent Office won't accept applications for machines of this type without a working model. In the rare cases one is provided, the "cleverness" invariably lies in hiding a small energy source somewhere, and the patent officer's job is to be smarter than the inventor and find it! The most blatant examples of Type 1 machines are where the inventor actually claims to be driving a load even though there's no energy source for the machine. Sneakier examples don't hide the fact that they have an energy source, they merely claim to deliver more energy out than they take in. For instance, a few years back I was asked to evaluate the "free-energy zero-cogging generator" which claimed to deliver more electrical power out, than the driving wind-turbine put in. (In this case, I believe the inventor wasn't intentionally deceptive, but he was woefully ignorant of how to measure electrical power!)

Type 2 machines are more subtle. They violate the Second Law of Thermodynamics, which states that entropy cannot be reduced (in a closed system). Entropy is a concept a bit difficult to grasp, let alone quantify, but very often it can be boiled down into the simple observation that heat can never passively flow from a colder place to a hotter place. If that appears to be happening, you've either missed something crucial, or else you've got a bona fide Type 2 perpetual motion machine. I recall (embarrassingly) an exam on my first undergraduate thermodynamics course. We were asked to evaluate a curious (and fishy-sounding) thing called a "vortex tube." In a vortex tube, compressed air is supplied into the base of a T-shaped pipe, and, amazingly, cold air comes out one branch of the T, and hot air comes out the other branch of the T. I was suspicious enough to realize that this implied that somehow some energy was moving "uphill" from the temperature of the incoming stream to the hotter output branch. The problem statement was very specific, and included mass flow rates and temperatures and pressures, so I proceeded to do the calculations showing that even though no net *energy* was being created, the net *entropy* of the outflowing air streams was less than the entropy of the incoming air stream, thus proving its impossibility. Turns out, vortex tubes are a real thing! I'd made a calculation error, though the professor was generous enough to grant me partial credit for at least thinking of looking for a violation of the 2nd Law. My point here is that the 2nd Law needs to be considered whenever you're trying to "pump" energy from a cold place to a hotter place.

Enter Thermoelectric Coolers (or TEC's). These are clever little gadgets that use the well-established Peltier effect. They're kind of like reverse thermocouples. You've probably seen them somewhere yourself in the form of a beer cooler or something similar. They obviously work (and have been patented). One of the niftiest things about them is that they have no moving parts and can be totally silent. You apply electricity at the terminals of the device, and one "side" of the gadget gets cold (the "inside" in the case of an RV refrigerator), while simultaneously the other side (or outside) gets hot. Obviously, if your surrounding environment's temperature is somewhere in between those two temperature extremes, heat will necessarily flow out of the hot side to the environment, and heat will flow into the cold side of the device from the environment (or whatever it's touching, e.g. your beer). If you're paying attention, you'll conclude two things: 1) this might be a really clever way of cooling electronics without having to use fans or liquid coolants; and 2) if this isn't violating the 2nd Law, there's some critical item we haven't yet bothered to consider (and it may bite us in the end).

Here's this thing: It's called the *Carnot efficiency* of a heat engine. In application, it gives you a quick assessment, based on the temperatures involved, of the amount of extra heat you'll have to add to a cooling system in order to move some of that heat from a colder place to a hotter place. (In fact, it's what allows you to avoid violating the 2nd Law). For the sake of argument, it might turn out that to move 1W out of a junction, you have to add an additional 1 W, meaning that your final heatsink has to reject 2 W to the environment instead of the original 1 W. Whence does the extra energy come? Through those nice, quiet, electrical terminals. Volts applied times amperes supplied equals extra energy that wasn't there before.

Aye, there's the rub! Sure, you can create a miniature Peltier cooler and lower the junction temperature (T_j , the "inside" of an electronic component) to something cooler than the surrounding environment, or even – let's not be greedy - just make it lower than it was without the cooler! The problem is, when you turn on the cooler you'll be *adding energy* to the overall system to get that lower T_j . From a macro-scale thermal analyst's perspective, this is usually the wrong thing to do, because more often than not, you were already having trouble getting all the heat out of your system in the first place. (Indeed, that problem is why your T_j was hotter than you wanted to begin with.) For instance, your PC board resistance might have to be 2x lower than it was before (bigger heat spreader, larger fan, etc.), to reject the heat *added* by the cooler in order to get the lower T_j. But if you could do that, then you should have just *done* that – in other words, *without* adding the cooler - and you'd have lowered your T_j a bunch anyway!

Now I can think of a couple of situations where a TEC might be an excellent choice, but you need to be very sure of your calculations. The first is, when you have a very small, localized, concentration of heat and you can afford to drive down the temperature of that spot at the expense of heating up everything else around it just a bit. The second is, when you actually need to control the temperature of a specific device within an electronics system, for instance, an image sensor (where so-called "dark current" is a serious problem and goes up rapidly with temperature). In this latter case, you have to have some margin in your system's "thermal budget," because from a system perspective you're going to have to get rid of some extra heat.

My advice is to think very carefully about whether a TEC is really the right thing for your electronics cooling problem. And using it to cool your beer may not be the best choice, either, if you're going to be trying to think carefully about cooling your electronics! You be the judge!

Avionics Thermal Management of Airborne Electronic Equipment, 50 Years Later

Ross Wilcoxon PhD
Rockwell Collins

This article is based on a keynote presentation that was made at the 2017 IMAPS Advanced Technology Workshop and Tabletop Exhibit on Thermal Management in Los Gatos, CA

BACKGROUND

In a proposal submitted to the Air Force in November of 1968, Collins Radio Company described ways to improve the electronic industry's understanding of thermal management and predictive techniques [1]. This article briefly describes that proposal and discusses what aspects of electronics cooling have changed over the past five decades and what things have not.

November 1968 was an interesting period in the histories of the aerospace and the electronics industries. The Space Race was on, and there was considerable funding available to support advances in both technologies. Apollo 7, which was the first manned flight after the tragic Apollo 1 fire of 1967, had occurred just a month earlier. Apollo 11 would successfully land on the moon in only nine months.

The Collins Radio company newsletters for November and December of 1968 discussed how the company's communication equipment had been used on the Apollo 7 flight and the Apollo 8 flight scheduled to orbit the moon in December, in addition to other events such as the upcoming first flight of the Boeing 747 in December [2]. Test activities in the heat transfer lab during the fall of 1968 included measuring the pressure drop and thermal performance of air cooled heat exchangers for high power radios, characterizing a vendor's fan, testing the performance of a liquid cooled heat exchanger, and demonstrating the fire resistance of a cockpit voice recorder. Other than the last test, which appears to have involved the use of a blow torch, all of these activities are still commonly done in the current Rockwell Collins Heat Transfer lab.

OVERVIEW OF THE PROPOSED RESEARCH

The proposed research for the Air Force included four primary tasks. The first task was to gather and collate data from the published literature to better understand which areas needed further work. The second step was to conduct fundamental research to fill in those areas that were found to be lacking in a complete knowledge. The third would be to integrate the combined literature and test data into sub-routines to extend the capabilities of existing computer-based modeling. Finally, test structures would be built and tested to validate the new computer analysis capabilities.

The proposal's authors felt that there were two primary factors that inhibited accurate electronics cooling predictions. The first of these was the need to experimentally assess the heat transfer characteristics of different fluids and develop methods to compare the effects of the combined properties of different fluids when used in boiling heat transfer.

The researchers felt that two-phase cooling using new liquids, would be essential to meet severe thermal challenges and that the use of these new liquid coolants would require new methods to assess their performance in a given application so that the optimal fluid could be selected for a specific design.

The second gap identified in the proposal was the limited

Ross Wilcoxon PhD

Ross Wilcoxon is a Principal Mechanical Engineer in the Rockwell Collins Advanced Technology Center. He conducts research and supports product development related to component reliability, electronics packaging and thermal management for communication, processing, displays and radars. Prior to joining Rockwell Collins in 1998, he was an assistant professor at South Dakota State University.

knowledge of component level thermal resistance values. While the researchers were confident in their ability to predict system level temperatures, they lacked accurate methods to determine component-level temperature rise. In effect, they were proposing methods to better define component thermal resistance values, such as the terms $\theta_{j\text{-}c}$ and $\theta_{j\text{-}a}$, that we use today. Accurate prediction of component thermal resistance continues to be a challenge, although the types of packages for which these values applied have changed. In the 1968 proposal, the package style for which thermal resistances that were to be to experimentally determined were flatpacks, TO transistors and carbon resistors.

A primary goal of the research was to gather data to improve a modified version of the "Thermal Network Analyzer Computer Program" that was developed by Lockheed in the 1950's. That program may have been the same as one that was described by NASA, which reported that it could solve steady and transient thermal problems defined by up to 400 nodal points and 700 resistors [4]. The original program, which had been developed for airframe analysis, was modified to include subroutines that accounted for heating of the coolant, radiation effects, phase transition at nodes, and aerodynamic heating. The proposal stated that this thermal analysis tool had predicted component temperatures within 10% on equipment used in the Mercury, Gemini and Apollo systems.

The proposed work would seek to enhance the program's analysis capabilities through experimental testing that better defined the thermal resistances at each end of the thermal path, i.e. the convective thermal resistance as a function of local boundary layer effects for different fluids and component level thermal resistances. Ultimately, the proposal envisioned a general analysis approach that would be accessible to the entire avionics industry. This analysis capability would allow designers to accurately determine component temperatures so that the thermal management system cost and weight could be minimized such that temperatures would be just low enough to meet reliability requirements.

Figure 1 – C-8500 Computer

CHANGES SINCE 1968

It is illuminating to compare the information provided in the proposal, as well as other contemporary material, to today's state of the art. The most significant change over the past ~50 years has to be in computational capabilities. The proposal indicated that the available computer facilities consisted of two Collins C-8500 computers (*Figure 1*) that had a "memory size of 65,536 words, each word having 32 bits or 4 bytes", i.e. memory of 256kB. Input took place through punch cards and tape drives. Another computer, a Univac U-1108, was available through a data link and had a memory size of 65,536 words, each with 36 bits.

A primary reason for the significant advances in computing capabilities relative to 1968 is the evolution of integrated circuits and their packaging. *Figure 2* shows a 24 lead hermetically sealed package with a wire bonded silicon die that was featured as the cover picture on the November 1968 issue of the company magazine, Pulse [2].

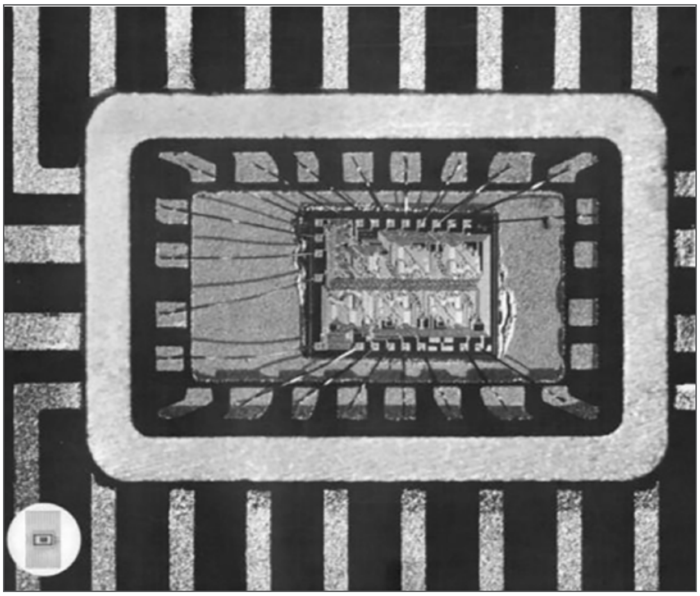

Figure 2 – State of the Art Microelectronics Package, circa 1968

In contrast, *Figure 3* shows a system in package currently used in avionics products. This package includes two flip chip Application Specific Integrated Circuits (ASICs) under a silicon interposer onto which memory die are wirebonded. The entire package is packaged as a Ball Grid Array (BGA).

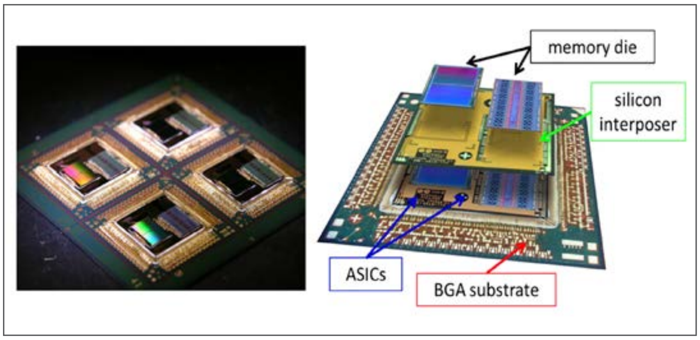

Figure 3 – Stacked Package Currently used in Mil/Aero Electronics Systems (courtesy, Russ Tawney, Rockwell Collins)

Figure 4 shows a transponder unit from the late 1960's. The electronic packages used thru-hole technologies, were primarily analog, and likely had relatively uniform power dissipation across all the circuit cards in the assembly.

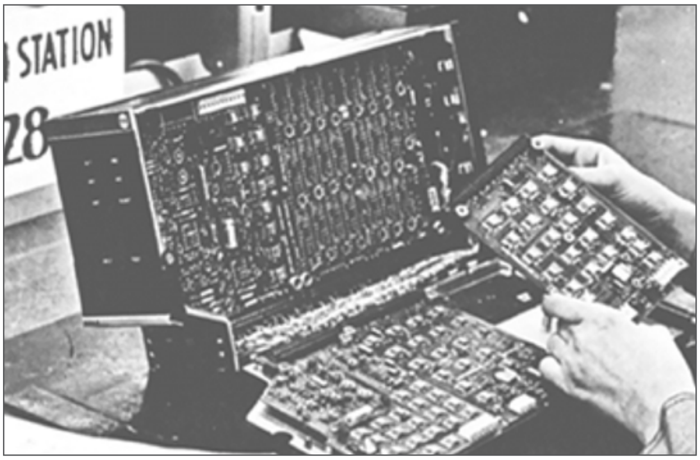

Figure 4 – Transponder, circa 1968

Figure 5 shows a system currently used on the Boeing 787 that includes weather radar, terrain collision avoidance, terrain awareness, and transponder functions. The system has much larger digital content and the circuit card assemblies use surface mount components.

Power dissipation in these types of systems tends to be less uniform than in its predecessors; instead much of the power dissipation tends to be isolated to a few components. Because the systems shown in *Figure 4* and *5* were both designed to conform to standard interfaces between aircraft and avionics, they have the same general size and shape. Advances in microelectronics did not lead to smaller individual avionics chassis, but instead allowed multiple functions to be integrated into a single module.

Figure 5 – Airborne Collision Avoidance System/Traffic Computer

While many things have changed since 1968, others have not. *Figure 6* shows a picture of the Collins Radio centrifuge described in the 1968 proposal and the same centrifuge that is still used by Rockwell Collins. Of the five specific pieces of test equipment shown pictorially in the proposal, three are still being used today. The primary change apparent for these three test units (the centrifuge, an explosion chamber, and an environmental chamber) after nearly 50 years is that computers are now part of the test equipment.

Figure 6 – Centrifuge Test Facility

DISCUSSION

Reviewing historical technical documents such as this proposal provide insight into what aspects of technology have changed over time or, in the case of test equipment like the centrifuge, have not. One clear change has been the level of dependence of design on computer resources. It is unlikely that any modern tool could operate on a system with only 256kB of memory, let alone do detailed analysis that predicts temperatures within 10% of test values. The fundamental analysis approaches in the analysis software have probably not changed all that significantly since 1968.

The primary changes are increased resolution with more detailed models, the algorithms that allow for efficient solution of these much higher resolution analyses, significantly faster processing, and the more flexible user interfaces. The proposal described that computer-based thermal analysis was conducted by experts who were well trained in how to use the software.

Many of today's most popular thermal analysis tools are designed for more casual user who may have limited understanding of the detailed nuances of the code's functions. Expert analysts are more likely to be needed to address complex optimization challenges that involve multi-disciplinary solutions that address topics as diverse as thermal, materials, structural, reliability, electrical, and optical engineering. Future improvements to software will likely continue to exploit the increasing processing capabilities to bring these multi-disciplinary analyses into the hands of the more casual user. Perhaps they will someday achieve the goal of the proposal and fully optimize thermal designs to meet reliability requirements, and no more than that, while minimizing cost and weight.

Looking back at information from that era, it is also clear that electronics miniaturization has made great strides over the past ~50 years. This has been accomplished in large part through advances in semiconductor technologies, but improved packaging has also played a significant role. The combination of new semiconductor technologies, such as Indium Phosphide and Gallium Nitride, and greater use of 3-D packaging will undoubtedly lead to continued device-level miniaturization. However, functional miniaturization does not inherently lead to system miniaturization. As shown in the transponders shown in *Figure 4* and *Figure 5*, smaller components do not necessarily lead to smaller systems.

As has occurred in mobile electronics over the past decade, miniaturization instead increases the amount of functionality that is packed into the same space. This is particularly true in cases like commercial avionics, which must be designed to interface standards so that common equipment can work in future as well as legacy platforms. Changing standard interfaces between sub-systems can be quite difficult once those standard interfaces have been adopted; consider, for example, how many light bulbs continue to use light bulbs with the Edison screw socket more than 100 years after it was first licensed.

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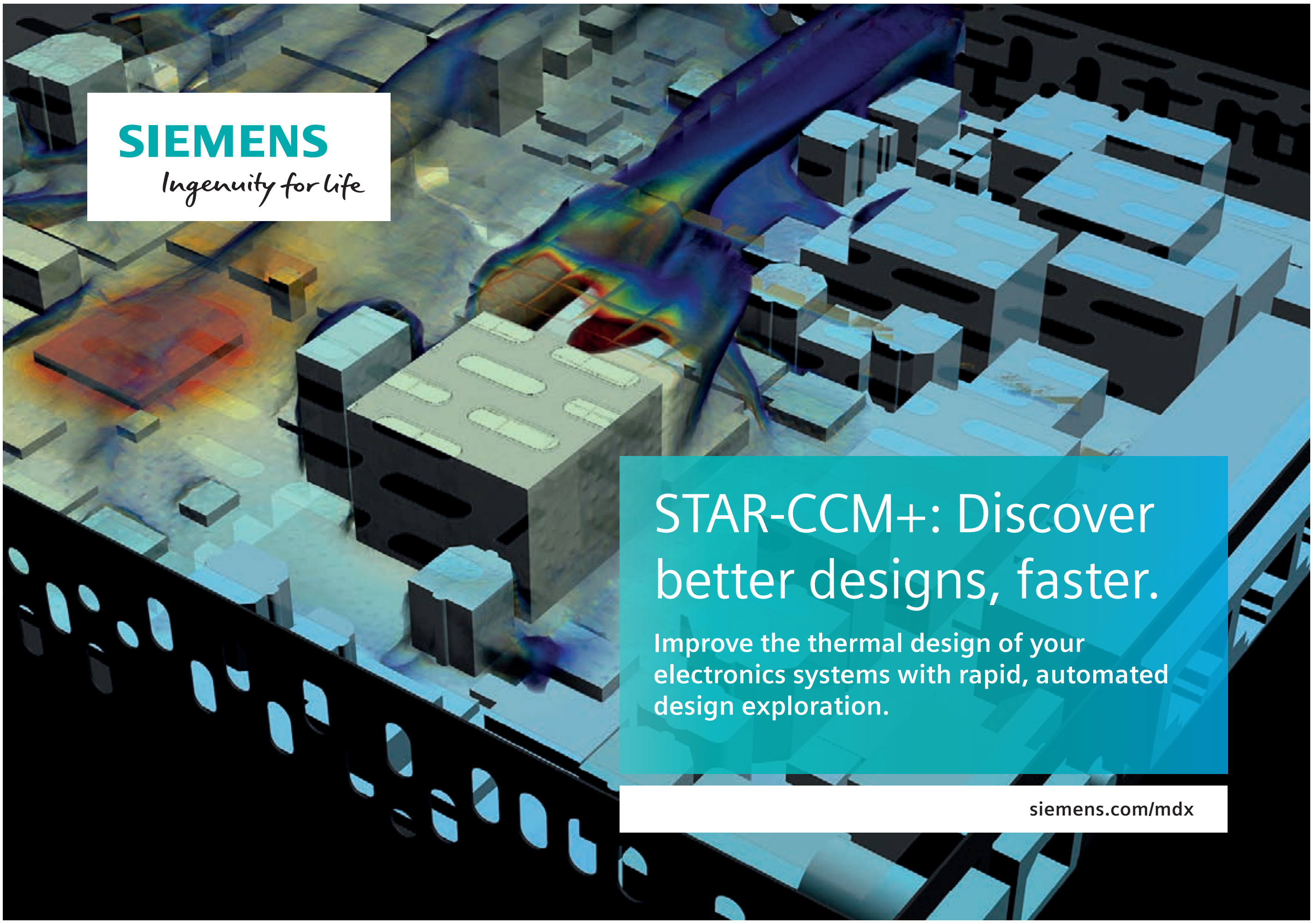

Advances in Vapor Compression Electronics Cooling

James Burnett
Aspen Systems

This article has been reprinted from the June, 2014 issue.

INTRODUCTION

Over the last 10 years, there has been a well documented increase in the energy density of electronic devices. As this energy density has gone up, so has the heat dissipation on electronics packages. In response to this challenge, significant research has taken place to develop chip level cooling systems to meet heat fluxes in excess of 1000W/cm2. As stated by Phelanetal [1], "Calculations indicate that the only possible approach to meeting this heat flux condition, while maintaining the chip temperature below 65°C, is to utilize refrigeration." While research has focused on achieving heat transfer rates at the chip level, the resistance to heat transfer to ambient air is often more critical [2]. In fact, the heat transfer resistance to ambient air as the final heat sink is the dominating factor in system performance. Certain classes of components such as field programmable gate arrays, diode laser and mobile network systems are being deployed in environments where passive cooling systems cannot maintain junction temperatures below required upper limits. Programs such as the US Army's Warfare Information Network–Tactical (WIN-T) fall into this category [3]. These factors place additional constraints on designers to meet the thermal management challenges of their electronics systems.

PASSIVE VERSUS ACTIVE COOLING SYSTEMS

Passive cooling will be defined herein as a cooling approach that cannot achieve an electronic system operating temperature at or below ambient temperature. In contrast, active cooling systems use added energy to drive the electronic system temperature below that achieved by passive means.

In passively cooled systems, the electronics temperature will rise until the enclosure interface with the ultimate heat sink, usually ambient air, warms up enough to dissipate the heat to the environment as shown in the left half of *Figure 1*. Methods to reduce the internal temperature rise in these systems include liquid coolant loops, pumped phase change systems, high conductivity chassis and heat pipes. Although these methods reduce the resistance to internal heat transfer, they do not help overcome the thermal resistance associated with the transport of heat to the ambient air. Fan cooling aides in heat transfer to air by increasing convection, but this approach cannot lower the enclosure surface below the ambient air temperature. As a result, passively cooled electronics used in high temperature ambient environments run at high temperature, sometimes above recommended operational limits.

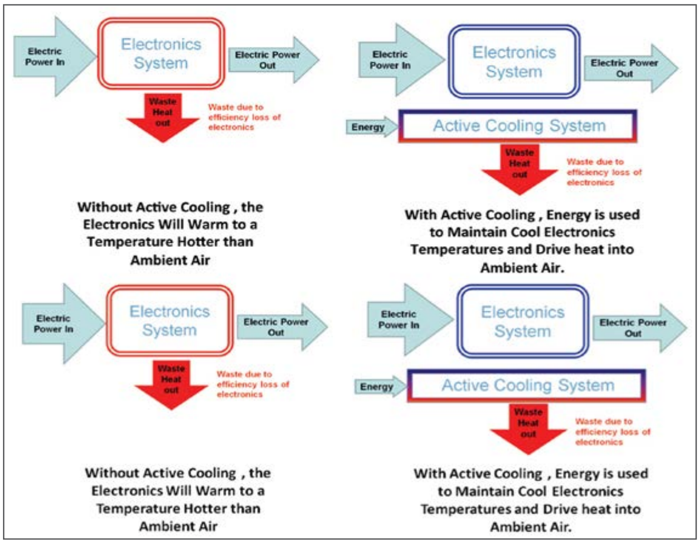

Figure 1. Passive and active electronics cooling.

Active cooling uses energy to lower the electronics temperature to acceptable levels as illustrated in the right half of *Figure 1*. Active

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cooling systems raise the temperature of the surfaces exposed to air, increasing heat transfer to the air, while simultaneously lowering the temperature of the surfaces exposed to the electronics, thereby increasing heat transfer on both sides of the system. The major advantage of active cooling is that desired chip junction temperatures can be maintained independently of the ambient air temperature. The disadvantage is that additional power is required to accomplish this task. Therefore, the packaging engineer should use passive cooling techniques only in ambient conditions suitable for passive cooling and use active techniques under all other ambient conditions.

The maximum allowable junction temperature (Tjmax) is provided by the manufacturer. To determine the junction temperature in the system (Tj), the sum of the ambient air temperature, the temperature rise from air to the package and the conductive temperature rise internal to the package are calculated. If Tj ≥ Tjmax , then an active cooling system is required. If Tj ≤ Tjmax , then a passive system is sufficient. The decision path to determine the need for active cooling is shown in the flow chart in *Figure 2*.

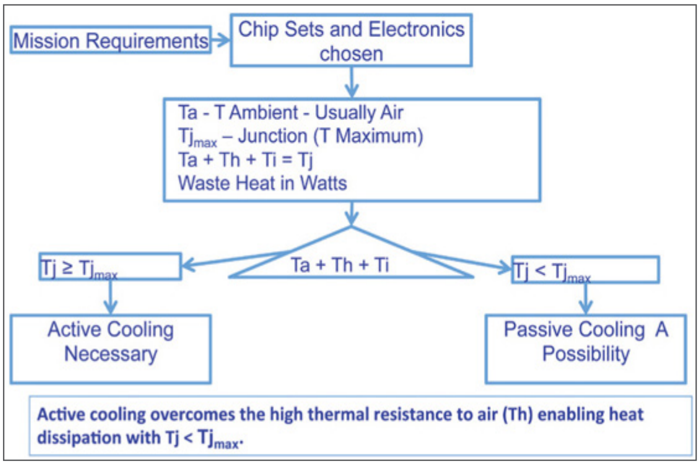


Figure 2. Active-passive cooling decision flow path.

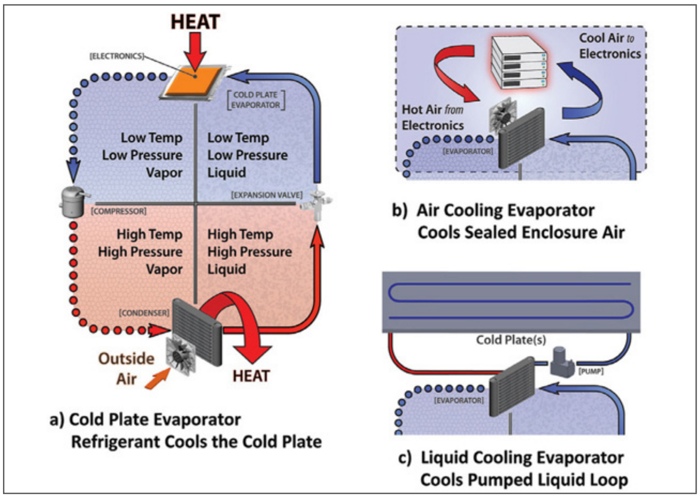
The least costly and most efficient time to address such thermal management issues is during the concept development phase of the program. Applying these decision process steps early in the effort can clarify and simplify discussions with program managers and customers, enabling effective thermal management solutions to receive the attention required.

ACTIVE COOLING METHODS

There are several technologies that can be used for active cooling of electronics systems. Government studies have included thermoelectric, thermotunneling, magnetic and others in their comparisons. The general consensus is that vapor compression is more efficient and lighter than alternative technologies in most applications. A Department of Energy sponsored study carried out in 2010 [4]. compared vapor compression systems with five competing technologies including thermoelectric, thermoacoustic and magnetic technologies. The study focused primarily on efficiency and concluded that vapor compression systems are at least three times more efficient than all available alternatives. An earlier study conducted by the Environmental Protection Agency [5]. concluded that "vapor compression refrigeration using non-CFC refrigerants is the most desirable technology of those considered for use in the five application areas considered in this study (domestic, commercial, and mobile air conditioning; and domestic and commercial refrigeration). This conclusion is supported by the first place ranking that vapor compression received in the technical assessment of each technology."

VAPOR COMPRESSION SYSTEM OPTIONS

Vapor compression systems take advantage of the latent heat of vaporization of liquids that have a boiling point lower than the desired temperature to be managed. The four major elements of the system are the compressor, condenser, expansion valve, and evaporator, as shown in *Figure 3a*. In the evaporator, the refrigerant vaporizes at a low temperature, absorbing heat from the electronics. At the evaporator, the refrigerant is a low temperature vapor, as shown in the upper left quadrant of the vapor cycle diagram. The vapor then passes through the compressor, where it is brought to high pressure and a temperature typically 10°C to 15°C higher than ambient. This hot vapor is converted to liquid in the condensing heat exchanger where heat is rejected to ambient air. The hot liquid refrigerant then exits the condenser and passes through an expansion valve, dropping the refrigerant to a low pressure and temperature. The low-temperature, low-pressure liquid refrigerant then enters the evaporator and the cycle begins again.



a) Cold Plate Evaporator Refrigerant Cools the Cold Plate

b) Air Cooling Evaporator Cools Sealed Enclosure Air

c) Liquid Cooling Evaporator Cools Pumped Liquid Loop

Figure 3. Vapor compression system schematic.

Vapor compression environmentally controlled units (ECUs) are routinely customized to meet the specific requirements of an integrated design. Three evaporator options available for vapor compression systems include direct expansion, air cooling, and secondary liquid loop as shown in *Figure 3*.

The direct expansion option is shown with the complete vapor compression schematic in *Figure 3a*. With no separate fans or pumps on the evaporator side of the system, this approach has the advantage of relatively few components for light weight and simplicity, and is the most efficient of the three options. The disadvantage of this approach is that the cold plates and the condenser need to be in close proximity to one another to be effective.

The liquid cooled system shown in *Figure 3c* uses an evaporator that cools a pumped liquid, typically glycol and water. The coolant is passed to a cold plate to remove heat from the electronics. This approach has the advantage that the refrigeration system can be remotely located from the system to be cooled, and disconnected in the field if desired. The disadvantage of this system is the additional temperature rise at the evaporator, and the line losses that can be expected if the refrigeration unit is a great distance from the thermal load.

The air cooling refrigeration system uses a refrigerant to air heat exchanger as shown in the upper right quadrant of *Figure 3b*. Fans are used to move air through the evaporator and circulate the chilled air across the electronics in the enclosure. This method is used when rack mounted electronics are placed in outdoor environments and need to be protected from the elements and from heat.

MINIATURE VAPOR COMPRESSION SYSTEM TECHNOLOGY

The main barrier to using vapor compression cooling systems at the enclosure level has been the availability of refrigeration compressors small enough for the application. In 2007, a miniature refrigeration compressor came onto the market and is now being used in applications ranging from mobile military electronics to laser cooling on manufacturing floors. This compressor and the first prototype experimental cooling systems utilizing it were introduced in an article in the May 2008 issue of Electronics Cooling®.

The compressor shown in *Figure 4* was developed specifically to enable the miniaturization of vapor compression cooling systems for personnel and electronics cooling. This miniature compressor is one-tenth the weight and one-tenth the volume at the same capacity as a competing standard reciprocating compressor. This is the key enabling component in miniature refrigeration systems with cooling requirements up to about 1,000 watts. Vapor Compression System Components Other enabling miniaturized components include controllers and drive boards that are designed to meet electromagnetic interference (EMI) requirements are shown in the left picture of *Figure 5* along with a direct expansion evaporator, shown in the middle picture, and an aluminum condenser and air evaporator with microchannels as shown in the right picture.


Figure 4. Miniature compressor is 1/10th the volume and weight of conventional systems.

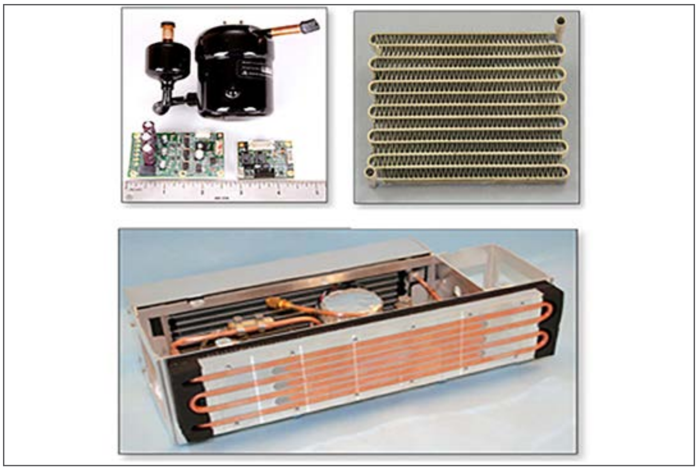


Figure 5. Components in a miniature refrigeration system.

COOLING SYSTEM EXAMPLES

Examples of direct refrigerant, liquid cooling and air cooling vapor compression systems are shown in *Figure 6*. The direct refrigerant cooling system (*Figure 6a*) is for an industrial application. The liquid cooling system (*Figure 6b*) is a military hardened liquid chiller. This system uses two-phase evaporative cooling on the cold plate to efficiently remove heat from a pumped diode laser. The liquid cooling system is a military hardened liquid chiller that was designed, developed and is now in initial production for applications with the US Army. It provides 350 watts of cooling to a cold plate via a pumped water glycol solution. The system measures 27.9 cm (11 in) by 21 cm (8.25 in) by 14 cm (5.5in) and weighs 5.44 kg (12 lbs).

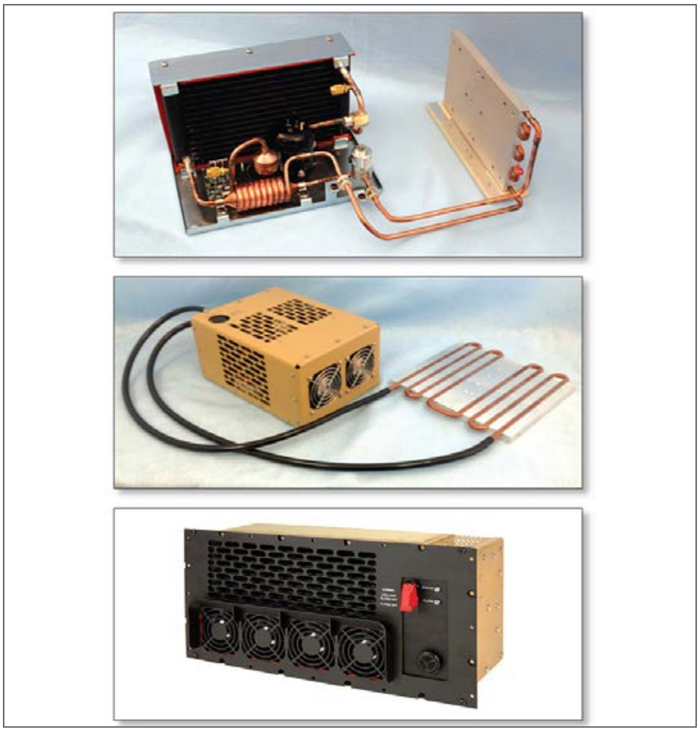


Figure 6. Direct, Liquid, and Air Cooling Vapor Compression Systems: (from top) a) Direct Refrigerant System; b) Liquid Chiller System; c) Air Chiller System.

The air cooling system shown in *Figure 6c* is a ruggedized vapor compression cooling/heating system designed specifically to meet military requirements for harsh, high vibration environments. This system has been in service on multiple Department of Defense programs. Most notably, over 1,000 of these systems have been in use on Special Operations Command (SOCOM) Mine Resistant, Ambush Protected (MRAP) vehicles for nearly three years.

The air flow patterns for the condenser on the outside surface (left) and evaporator (right) inside the enclosure are shown in *Figure 7*. The unit maintains a sealed electronics enclosure at or below ambient temperature, enabling Commercial Off-The-Shelf (COTS) electronics to be safely and effectively used in hot, dirty environments.

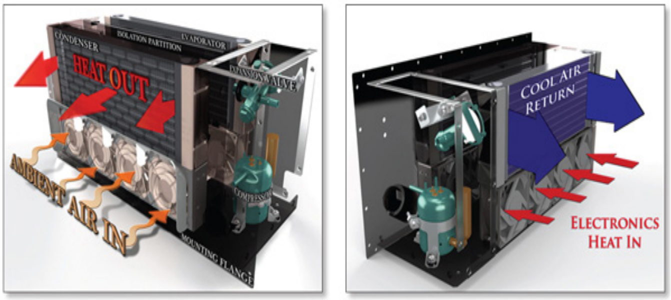


Figure 7. Air flow patterns outside (left) and inside (right) the air cooling environmental control unit.

The unit is rated to maintain an internal temperature of 52°C (125°F) in an ambient environment at 52°C (125°F) while dissipating 550 watts of heat. In cold environments, the ECU heats the electronics from as low as -40°C to preheat the system for cold starts. The system weighs 9.1 kg (20 pounds) and measures 47 cm (18.5 in) wide by 22.9 cm (9 in) tall by 17cm (6.7 in) deep.

CONCLUSION

Miniature vapor compression thermal management systems are being custom designed to meet Original Equipment Manufacturer (OEM) and end user specifications for a wide array of electronics thermal management applications. A transit case cooling system has been developed and refined to meet stringent military program requirements for mobile network applications and is currently operating worldwide. A liquid chiller system has been developed for use on radio and computer cooling in mobile environments and several direct refrigerant systems have been developed for end users and OEMs. An airborne cooling system was developed to meet mission critical requirements for cooling infrared cameras. Miniature refrigeration technology is now mature, qualified and fielded for effective application to electronics systems that require active cooling.

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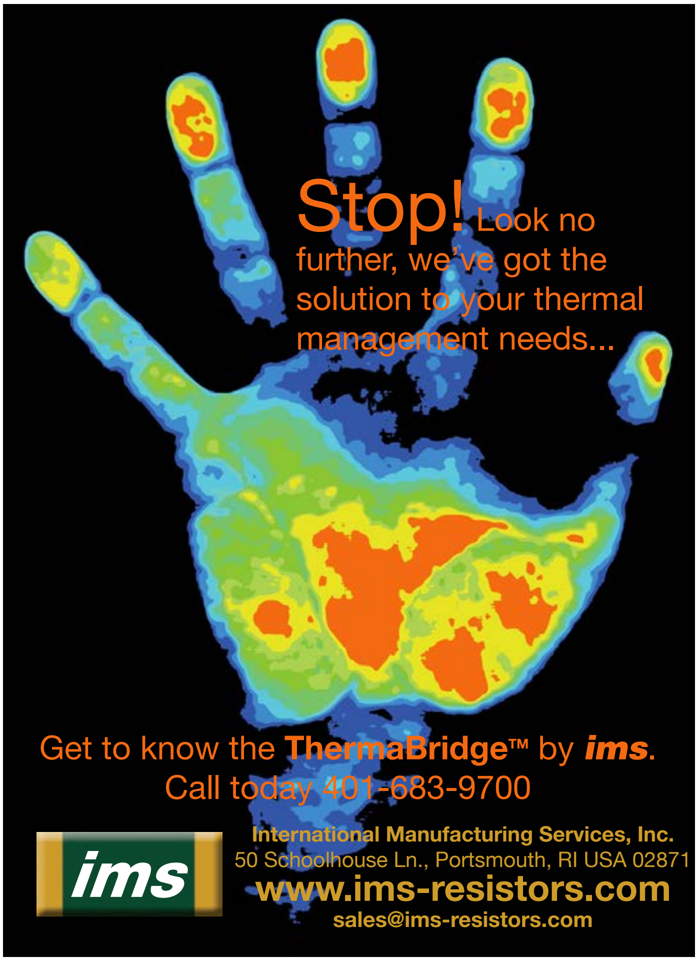

Thermal Management Considerations in High Power Coaxial Attenuators and Terminations

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The testing and troubleshooting of high power and high frequency systems such as distributed antenna systems (DAS), base stations, and various radar applications require buffering to prevent a power overload to the testing equipment and sensitive subsystem internal circuitry. With powers as high as 60 dBm (1000 Watts), radio frequency (RF) terminations and attenuators are relied upon to dissipate much of this microwave energy. A number of factors must be taken into account in the design of these high power handling components, including designing the internal resistive network with minimal reflections and a low Voltage Standing Wave Ratio (VSWR), which is a measure of power reflected back at the source, even at high temperatures as well as minimizing the thermal resistance of the device.

WHAT IS A TERMINATION/LOAD?

Terminations are one-port devices meant to absorb microwave energy by dissipating it as heat. This has to be accomplished with little reflections; in other words, the termination must be impedance matched (often 50 ohms) to the device under test (DUT). High powered coaxial terminations leverage heat sinks to dissipate heat while the 50 ohm impedance is often generated with precision thin film resistors. Loads can be used to test the frequency response of a multi-port component, such as a 3-port switch, where one (or more) ports can be terminated in order to properly measure the transmission of a signal in the two active ports. When testing a T/R (transmit/receive) module, high power terminations are often used as "dummy loads" in place of an antenna to protect the sensitive internal circuitry of the equipment that would be damaged by the power reflections resulting from a temporary open-circuit.

WHAT IS A FIXED RF ATTENUATOR?

Whether being used for microwave power measurements or to minimize reflections in a RF signal chain, attenuators are immensely valuable for protecting sensitive equipment. Attenuators are 2-port components that essentially reduce the amplitude of a signal traveling from the input to the output of the device by means of an internal resistive network or transistor-based network. These high utility components can come in many forms based on the application. For instance, transistor-based programmable attenuators can be used to control the gain of a system while fixed attenuators are more often used as 'padding', or protection.

To dissipate power on the order of 100W or more, such as in radar systems, fixed RF attenuators have a large advantage over the other constructions (*Figure 1*). Significant losses occur in the switches of programmable attenuators causing deviations in the attenuation flatness over frequency. In high power scenarios, the parasitic capacitance from the high-power internal resistors and ground plane as well as the reactance of PIN diodes in programmable and continuously variable attenuators lead to these deviations. While methods to mitigate these sources of error do exist, they are generally impractical due to enormously more complex and expensive system thermal management requirements.

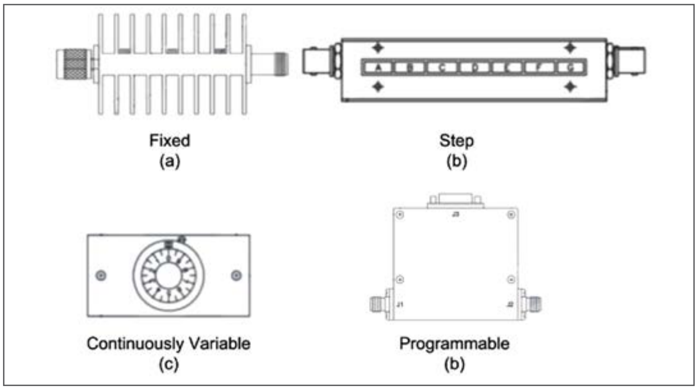

Figure 1: Various attenuator configurations such as (a) Fixed attenuators rely upon an internal resistive network while (b) step attenuators comprise of various resistive networks to generate an attenuation value based on preallocated increments. Made with transistors or with PIN diodes, (c) continuously variable attenuators are often adjusted manually to yield any attenuation to a degree of resolution by controlling the voltage across the semiconductor device. Programmable attenuators (d) contain a series of switches that can be programmed to follow a specific signal path for a predetermined attenuation value.

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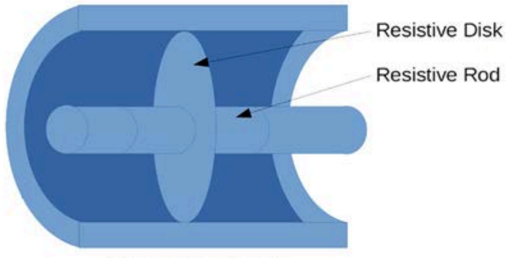
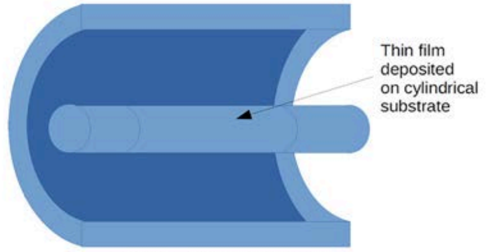
Prior to joining Pasternack, Mr. Blackwood held management positions in engineering, program management, product marketing and business development with some of the industry's most recognized corporations including TriQuint Semiconductor, Texas Instruments, Anritsu and others. Mr. Blackwood holds advanced degrees in electrical engineering and physics.

HOW RF ATTENUATORS AND TERMINATIONS DISSIPATE HEAT

The design of fixed coaxial attenuators has evolved significantly since the T-pad and Pi-pad attenuator with distributed internal resistive disks and rods and the lossy in-line style attenuator where the center conductor consisted on a cylindrical element with resistive film deposited on the surface *Figure 2*. These constructions were effectively replaced by the 'card' coaxial attenuator design by Weinschel, in which the inner resistive element became what is essentially a thin film resistor--this greatly increased the bandwidth of the device [1]. Replacing the barrel-shaped outer conductor with a heat sink increased the power handling capability beyond 10 W as the larger surface area could better dissipate heat to the environment through radiation. This design for a high powered attenuator has been widely adopted for fixed RF coaxial attenuator designs due to its simple approach for thermal management.



Coaxial T-pad Attenuator



Coaxial Lossy Line Attenuator

Figure 2: Schematic model of coaxial T-attenuator designs with resistive rods and disks and lossy line attenuators where a thin resistive film is deposited onto the cylindrical center conductor.

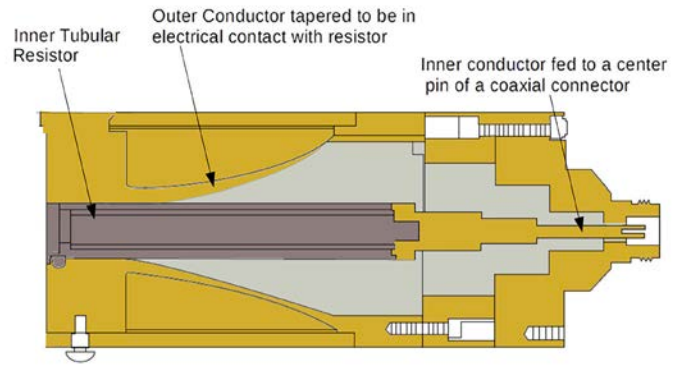


Figure 3: Basic schematic of prior coaxial termination designs with internal tubular resistor.

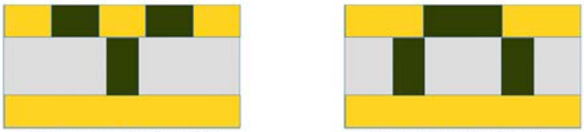
Similar to attenuators, early design methodologies for coaxial terminations included an inner conductor comprised of a tubular film resistor that often included a ceramic tube with resistance film coated on the outer surface while the surrounding metallic outer conductor was tapered at one end to electrically connect with the resistor (*Figure 3*). Current termination designs are similar to attenuators with internal precision resistor networks and an external heat sink and outer conductor.

CENTRAL RESISTIVE ELEMENT

While prior designs for the central attenuating element included tubular resistors or a Pi- or T-pad attenuator topologies (*Figure 4a/4b*), more recent constructions employ a distributed thin film topology in which precision laser trimmed resistors sit on a dielectric substrate to accomplish the internal resistive topology as shown in *Figure 4c* where the characteristic impedance is given in *Equation 1*.

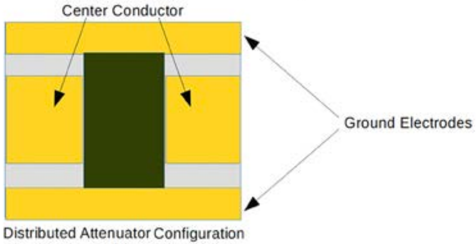
$$Z_o = \rho\sqrt{\frac{D-a}{4a}} \tag{1}$$

Where Z_o is the characteristic impedance, ρ is the resistivity of the thin film, D is the distance between the ground electrodes, and a is the thickness of the center electrode.



'T' Attenuator Configuration
(a)

'Pi' Attenuator Configuration
(b)



Distributed Attenuator Configuration
(c)

Figure 4: Various attenuator topologies.

RF Attenuators and terminations have evolved in design with thin film technology and resistive materials such as Nichrome, Tantalum Nitride, and Silicon Chrome, as drastically higher frequencies can be achieved with extremely high tolerance resistances. The sheet resistance is dependent on the thickness of the resistive film, its resistivity, and its dimensions (length and width). Since the resistivity of the material is a constant and there is a reliably homogenous layer of film across all resistors, the real variables are essentially the length and width. Additionally, the temperature coefficient of resistance (TCR) values of the thin films can now be manufactured with values of less than 10 ppm/°C absolute [2], which is significantly better than discrete resistor counterparts. Ceramics are often the substrate of choice as materials such as Aluminum Nitride, Beryllium Oxide, and 99% Alumina exhibit a low coefficient of thermal expansion (CTE) and high thermal conductivity. Materials with a high CTE are likely to change in impedance where a small impedance change from 50 ohms can cause significant reflections at high powers, choosing resistive and dielectric materials with a similar CTE can mitigate this effect.

The ceramic insulating substrate often sits on milled grooves directly in the heat sink, or outer conductor, forming a connection between the ground electrodes on the substrate and outer conductor ground path as well as a conductive path for heat dissipation. Further cooling can be accomplished by joining the ground planes with solder, or by integrating bonded fins (*Figure 5*) with the ceramic's ground to enhance convection and reduce the thermal resistance. The dimensions of the resistors and respective contacts/flanges increase in order to better conduct thermal energy generated from joule heating whereby the energy is channeled through the heat sink. The interconnections in the central attenuating element are typically gold-plated. While metals such as copper or silver offer higher thermal conductivity gold's low contact resistance and imperviousness to corrosion/oxidation make it a better plating surface for high frequency systems. Since gold is also a malleable metal, it requires significantly less pressure to form the functional internal spring loaded contacts often form the electrical connection between the substrate and the RF connectors.

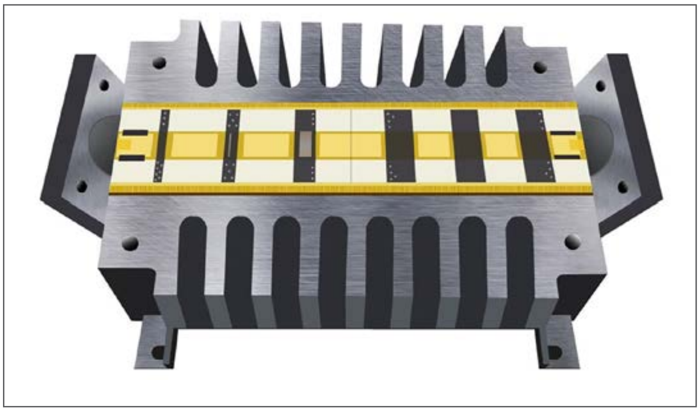


Figure 5. Attenuator with integrated fins bonded with the ground plane of the ceramic substrate.

HEAT DISSIPATIVE OUTER CONDUCTOR

Often made of black anodized aluminum, the fixed attenuator and termination outer conductor is composed of various extruded heatsink topologies. The black coating increases the surface emissivity so that the conductor can more readily radiate the heat from the internal resistive elements; this only slightly improves the thermal management since most of the radiated heat radiated falls on adjacent fins [3]. A commercially extruded aluminum surface typically has emissivity in the range of 0.09; anodization increases the emissivity to 0.77-0.85 [4]. Additionally, the thin oxidized layer of anodization metal's microscopic pores inhibit corrosion of the component.

Generally, the maximum temperature ratings of high power RF attenuators and terminations are on the order of 125°C while the length, width, and height can range from 10 to 20 inches (25 to 50 cm). Due to these constraints radiation alone is insufficient to cool fixed RF attenuators and terminations by more than a few degrees [5].

Figure 6: A sampling of attenuator and termination heat sink topologies with varying power handling. The (a) annular fin heat sinks are often used on attenuators up to 50 W while parallel plate attenuators can be used for higher power handling attenuators such as (b) 100W, (c) 200W, and (f) 1000W. Flared fin heat sink designs (d)(e) are often employed for improved natural convection cooling over parallel plate heatsinks.

The main source of cooling for these components come from the combination of the conduction, through contact between the PCB and the heatsink, and natural convection cooling from the external conductor's fins. Nevertheless, the heatsink topologies of attenuators come in a plethora of shapes and sizes. *Figure 6* introduces a number of fixed attenuator topologies with high power capacities ranging from 50W to 1000W. For up to 50W of continuous wave (CW) power, the annular (radial) fin topology (*Figure 6a*) is generally used. Since the convective thermal resistance of these fins depends on the fin diameter and fin spacing, lower power rated attenuators and terminations have significantly smaller diameters than those with 50W or more. It should be noted that there are also broadband, high-powered fixed attenuators with radial fin configurations that have a long length. The dimensionally smaller resistors have better high-frequency performance and-the resistive stages are cascaded to achieve a particular insertion loss requirement. Dimensionally larger resistors generally have better power handling; since their increased surface area and larger geometries better spread the dissipated power across the device.

The commonly used straight fin heat sink (*Figure 6c*) operates with the power dissipating central component located at the center of the structure. The central component can either be placed on a solid aluminum baseplate (*Figure 6c*) or another identical parallel plate heat sink structure (*Figure 6b*). As shown in *Figure 6d* and *Figure 6e*, flared fins can be leveraged for higher powered components as they can improve heat transfer by at least 20% better than the straight fin topology, even with approach velocities as low as 1 m/s. This improvement can be particularly beneficial when relying on natural convection [6]. *Figure 6f* shows another larger parallel plate topology with a gap between the extruded heat sinks for improved airflow. *Figure 7* further illuminates the relationship between size and power handling, where the various heat sink topologies shown in *Figure 6* are labeled for clarity.

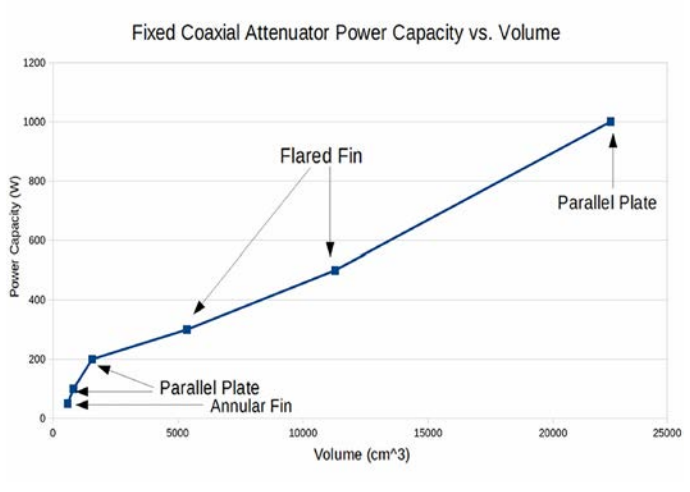


Figure 7: A plot of power capacity over volume of the various heat sink configurations shown in Figure 6.

CONNECTOR CONSIDERATIONS

Since the main purpose of the connectors in a coaxial RF attenuators and terminations are to channel the microwave energy, the choice and design of the connector depends heavily upon the maximum frequency for the given application as that decides the maximum allowable diameter for the outer conductor. Naturally, there is a trade-off since the larger diameter increases the maximum input power but limits frequency while the smaller diameter increases the maximum frequency but limits the input power. For this reason, connector heads such as 7/16 DIN and N-type are rated for much higher power than SMA, or TNC connectors.

CONCLUSION

RF attenuators and terminations must ultimately strike a balance between maximum frequency and power handling. Once the internal dimensions of the resistive network have been devised there are a number of other factors to maximize heat dissipation including:

- Choosing insulating and resistive materials with a similarly low CTE and a high thermal conductivity.
- Designing a distributed resistive topology in order to better spread heat.
- Optimizing the heat flow from the substrate to the mounting base by means of fins on ground planes, soldered connections, milled grooves, silver-plating, etc.
- Choosing heat sink topology for optimal thermal dissipation (flared fins, plate fins, black, anodized, etc).

Fixed RF attenuators are one of many attenuator topologies, but offer the best thermal management. High powered RF terminations are similarly designed to attenuators as they are both passive devices meant to absorb and dissipate RF energy.

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Research Roundup: October 2017 Edition

The significance of thermal management constraints on the next generation of electronics is increasing as package and electronics assembly densities continue to reduce circuit dimensions. The demand for ever greater performance and features of aerospace, military, rf/microwave, and high-speed digital applications compound the challenges of thermal management for these new technologies. Researchers at Universities, companies, and organizations from around the world are struggling to overcome these limitations and unleash levels of device and system performance impossible with prior understanding and technology. *Electronics Cooling*® is also striving to highlight researchers by featuring some of the latest research from around the globe.

GENERALIZED HEAT FLOW MODEL OF A FORCED AIR ELECTRIC THERMAL STORAGE HEATER CORE [1]

Researchers from the Departments of Computer and Electrical Engineering and Mechanical Engineering at the University of Alaska Fairbanks, Nicholas T. Janssen, Rorik A. Peterson, and Richard W. Wies, have recently published a paper that highlights work done to develop a generalized charge/discharge, high-resolution, and 3D finite element model of a forced air electric thermal storage (ETS) heater core [1]. The results of the research could be used to aid in grid demand load-leveling and off-peak domestic space heating. Furthermore, a proposed use of the model is to efficiently simulate and estimate the economic evaluation and performance of such systems for cold climate communities that may benefit from distributed thermal energy storage. The results of the work were a numerical model of a room-sized ETS heater core useful in studying the effects of various parameters of the heater cores design and operation. The relative significance of these parameters was revealed, with material properties, core dimensions, and bulk air velocity found to have the strongest impact on overall performance. Lastly, an energy balance equation, in relation to the findings, was also presented in the research.

ANISOTROPIC THERMAL RESPONSE OF PACKED COPPER WIRE [2]

Andrew A. Wereszczak, Hsin Wang, Rand H. Wiles, and Timothy B. Burress of the Oak Ridge National Laboratory, J. Emily Cousineau and Kevin Bennion of the National Renewable Energy Laboratory, and Tong Wu of the Department of Electrical Engineering and Computer Science at the University of Tennessee, all contributed to a study on the thermal conductivity of packed copper wire [2]. This research could contribute to understanding thermal management considerations for packaged copper wire in electric vehicle, transportation, aircraft, and military applications. The study revealed that the apparent thermal conductivity of packed, insulated copper wire was roughly two orders of magnitude greater along the parallel direction compared to perpendicular to the wires. The apparent thermal conductivities of the parallel and perpendicular directions with 50% packing efficiency were found to be 200 W/mK and 0.5-1 W/mK, respectively. It was also found that the anisotropic apparent thermal conductivity of packed copper wire could be adequately estimated with laser flash and transmittance tests, with transient hot disk methods being less consistently accurate. The Kanzaki model, also supported by FEA analysis, was found to provide a satisfactory numerical estimation of the apparent thermal conductivity in the perpendicular direction of the packed wire.

PROSPECTS FOR IMPLEMENTING VARIABLE EMITTANCE THERMAL CONTROL OF SPACE SUITS ON THE MARTIAN SURFACE [3]

Thinking ahead to manned exploration of Mars, Christopher J. Massina and David M. Klaus with the Aerospace Engineering Sciences department of the University of Colorado, studied a proposed method of heat rejection in space suits using a full suit, variable emittance radiator [3]. The study leveraged surface environmental parameters generated with the same method as the one used in the Mars Science Laboratory's initial landing site. Environmental and planetary rotation variations at a latitude of 27.5°S of the Martial Surface exploration site were used. The study includes parametric variations of metabolic rate, radiator solar absorption, total radiator area, and wind speed.

The final results of the study supported the assumption that the new heat rejection design could dissipate a standard nominal extravehicular activity (EVA) load of 300 W in all conditions, with the exception of summer noon hours. A supplementary heat rejection system capable of 250 W capacity would need to be included to account for summer noon hours. The results of the study may also be valuable in determining the best opportunities to conduct EVAs, and in designing Martian-ready EVA suits.

THERMAL ANALYSIS AND FLOW VISUALIZATION OF A FLAT LOOP HEAT PIPE [4]

To overcome the limitations that conventional electronic cooling systems have when removing high heat flux from compact electronics, researchers, Md Monir Hussain of the Department of Biomedical Engineering and Mechanics with Virginia Tech, and John Kizito of the Mechanical Engineering Department with North Carolina A&T State University, investigated loop heat pipe (LHP) technologies [4]. It is proposed that LHP passive device features capable of self-starting and operating in any orientation, which have already been successfully employed in space programs, PC cooling, and other systems, could be viable for many other applications if the operation of LHPs was better understood.

For a variety of heat loads, the researchers studied the loop performance of an LHP, with an emphasis on visualization, using a flat evaporator and flat gap condenser. The startup process and temperature profiles of several loop components were also compared at different heat loads. The researchers also used an acrylic plastic block that enabled visualization of the startup process and component performance, specifically the startup process of the vapor line and bubble formation inside the condenser and compensation chamber. The study found that a disc shape copper wick in the evaporator was able to withstand a 100 W heat load with an evaporator thermal resistance of 0.14°C/W and heat transfer coefficient of $14.1 W/m^2$.

BALANCING THERMAL AND ELECTRICAL PACKAGING REQUIREMENTS FOR GaN MICROWAVE AND MILLIMETER-WAVE HIGH POWER AMPLIFIER MODULES [5]

As gallium nitride (GaN) power amplifier (PA) devices are able to achieve high power densities at microwave and millimeter-wave frequencies, researchers with the Department of Electrical and Computer Engineering at Colorado State University and MPT Inc. have investigated a GaN heat spreader thickness that balances between optimum thermal design and device system requirements [5]. The researchers discovered that an optimum thermal configuration of the electrical interconnects for the input and output ports for GaN PAs impacted the electrical performance of the device. This was in part due to the signal coupling and ground path inductance of these contacts. Hence, the research predominantly pursed package and module integration considerations. It was found that the optimum heat spreader design negatively impacted the electrical design, and that a balanced approach can be made to meet all system requirements. The optimum design achieved the required maximum junction temperature, minimized the ground inductance, and resulted in a heat spreader thickness between 1 mm and 2 mm.

PROPOSAL AND VERIFICATION OF SIMULTANEOUS MEASUREMENT METHOD FOR THREE THERMOELECTRIC PROPERTIES WITH FILM-TYPE THERMOCOUPLE PROBE [6]

The following research by Takumi Yamazaki with the Department of Aerospace Engineering and Ai Ueno and Hosei Nagano with the Department of Mechanical Science and Engineering at Nagoya University, proposed and verified a new technique in which three thermoelectric properties of a film-type thermocouple probe could be simultaneously measured [6]. A known reference material, constantan, was used to verify the effectiveness of the methods, and Bi 0.3 Sb 1.7 Te 3 thermocouple material was the primary focus of the investigation.

The Seebeck coefficient was measured with the steady-state condition of the differential method, electrical resistivity was measured with the four-probe method, and the periodic heating method was used to determine the thermal diffusivity.

The resulting experiment demonstrated that the physical properties of the reference material measured with the new method were within +/- 10% of the reference values, an acceptable margin to verify the validity of the method. Furthermore, the Bi 0.3 Sb 1.7 Te 3 material was measured at a temperature of 300 K, with the resultant values of the new test being within 0.3%, 11.7%, and 14.8% for the Seebeck coefficient, electrical resistivity, and thermal diffusivity, respectively.

METAL-ORGANIC–INORGANIC-NANOCOMPOSITE THERMAL INTERFACE MATERIALS WITH ULTRALOW THERMAL RESISTANCES [7]

As part of an interdisciplinary, intercollegiate, international, and government sponsored research program (DARPA) and a collaboration with NREL, researchers at several universities and DARPA studied a new class of thermal interface materials, metal-organic- inorganic, that has demonstrated ultralow thermal resistances [7]. The potential of this technology is to help optimize high performance electric drive vehicles (EDVs) and high performance electronics, which are limited by current thermal interface materials (TIMS).

The new class of TIMs leverages the chemical integration of boron nitride nanosheets (BNNS), a copper matrix, and soft organic linkers to decrease the thermal resistance to one-third that of other high performance TIMs. The research resulted in nanocomposite TIMs composed of a metal matrix with enhanced mechanical properties, which was augmented by covalently integrating BNNS. BNNS was chosen as the material for its demonstrated high in-plane thermal conductivity, superior thermal and chemical stability, and a low coefficient of thermal expansion.

The final results of the study produced a material with thermal resistivity values between 0.38 mm 2 K/W and 0.56 mm 2 K/W for a typical bond-line thickness of 30 um to 50 um. The coefficient of thermal expansion for the material was found to be 11 ppm/K, which results in low thermally induced axial stress for compact electronic packages.

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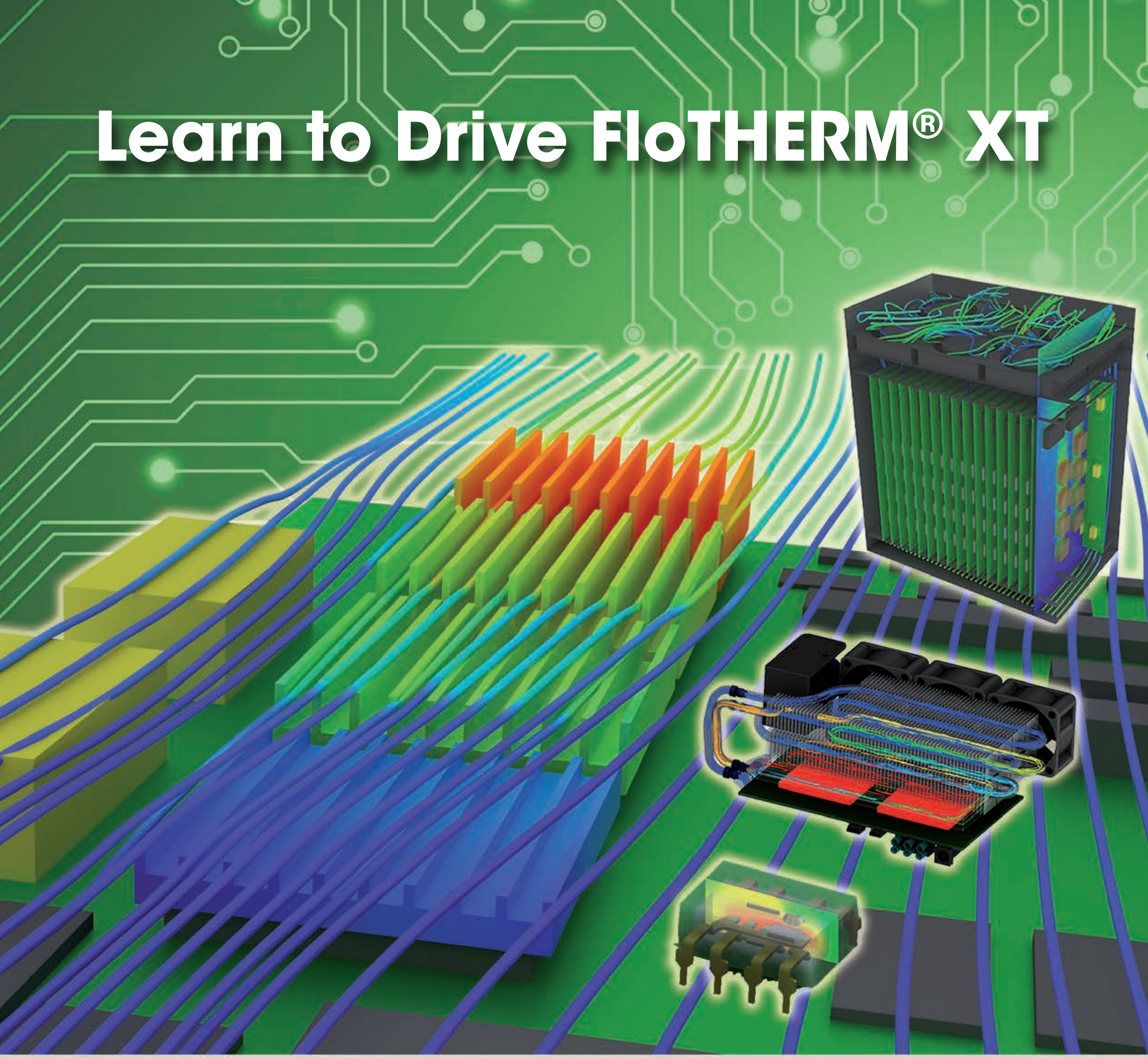

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Estimating Internal Air Cooling Temperature Reduction in a Closed Box Utilizing Thermoelectrically Enhanced Heat Rejection

Previously published in February, 2013

Bob Simons
IBM Retired

The following article was originally published in the February 2013 issue. It is being republished here because of its significant tutorial value. Bob served as an Associate Technical Editor of this publication from January, 2001, to December, 2011.”

An earlier article in this column considered the problem of cooling electronic components in a closed box [1]. In outdoor applications for example, it may be necessary to totally seal the box to prevent exposure to airborne particulates, water droplets or other substances in the air that could be injurious to the electronic components. In such an application, heat picked up by the air circulating over the electronic components within the box is rejected to outside air by means of an air-to-air heat exchanger mounted in one of the walls of the box. Such a heat exchanger may be as simple as two plate-fin heat sinks (or a heat sink with fins on both sides) mounted base to base in an opening in the wall of the box. Of course in such cases, the air that is cooling the electronics components will always be higher in temperature than the outside air being used for heat rejection from the box. If this does not provide a satisfactory cooling solution, an alternative that might be considered is augmentation with thermoelectric cooling (TE) modules sandwiched between the heat sinks as shown in *Figure 1*.

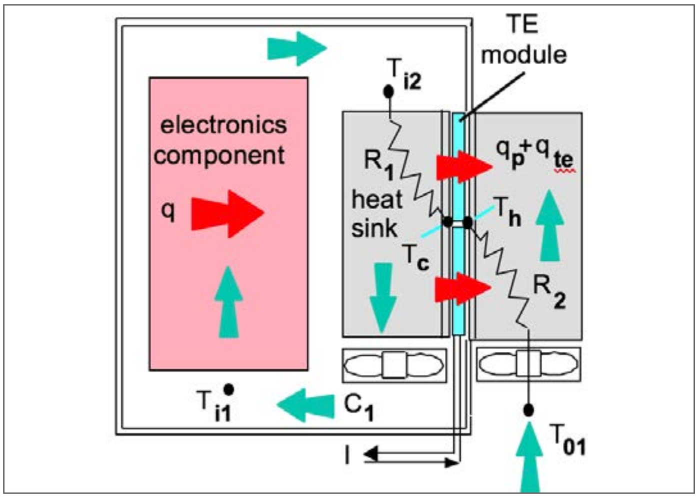

Figure 1. Closed box electronics enclosure with thermoelectrically enhanced heat rejection.

For those that are unfamiliar with TE modules, a thermoelectric cooler, sometimes called a Peltier cooler, is a solid-state heat pump that transfers heat from one side of the device to the other side depending on the direction of the applied electric current [2]. For example in *Figure 1*, electric current, I, may be applied to the thermoelectric modules such that the side in contact with the base of the heat sink within the box becomes cooler, thereby augmenting the transfer of heat from the air circulating within the box to the internal heat sink. The opposite side of the thermoelectric module becomes hotter and both the heat pumped by the thermoelectric cooler (q_p), and the heat dissipated (q_{te}) by the thermoelectric cooler in performing its heat pumping function, is transferred to outside cooling air via the external heat sink.

This article is intended to present to the reader, by example, a methodology to estimate the cooling air temperatures that can be achieved by thermoelectric augmentation. However, to illustrate the value of thermoelectric augmentation, we will first consider some equations to calculate the air temperature (T_{i1}) entering the portion of the box housing the electronic components without thermoelectric augmentation. Working from the air temperature (T_{o1}) outside the box to the temperature of the wall (T_w) of the box (or a base temperature common to the external and internal heat sinks) gives,

$$T_w = T_{o1} + qR_2 \tag{1}$$

where q is the heat dissipation of the electronic components and R_2 is the thermal resistance of the external heat sink. It should be noted that throughout this analysis and in the subsequent calculation examples, heat sink resistances, R_1 and R_2, are assumed to include any associated thermal interface resistance between the heat sinks and the wall or later in the article, the TE modules. The air temperature entering the internal heat sink passages is given by,

$$T_{i2} = T_w + qR_1 \tag{2}$$

which, substituting in *eq. (1)* for Tw, gives

$$T_{i2} = T_{o1} + q(R_1 + R_2) \tag{3}$$

The temperature drop of the air passing through the internal heat sink is given by,

$$T_{i2} - T_{i1} = \frac{q}{C_1} \tag{4}$$

where C_1 is the air heat capacity rate inside the box, given by the product of the mass flow rate, $\dot{m}$, and specific heat, c_p, of the inside air cooling stream. So, the temperature, T_{i1}, of the cooling air entering the electronics compartment (without thermoelectric augmentation) becomes,

$$T_{i1} = T_{o1} + q\left(R_1 + R_2\right) - \frac{q}{C_1} \tag{5}$$

Now, we will proceed to determine the temperature of the air entering the electronics compartment when thermoelectric cooling augmentation is incorporated. To do this we must include equations to account for thermoeletric heat pumping and the heat dissipation of thermoelectric modules. In an earlier article, Luo [3] presented the following equation for heat pumping with a thermoelectric cooling module

$$q_p = S_m T_c I - \frac{1}{2} I^2 R_m - K_m\left(T_h - T_c\right) \tag{6}$$

and another equation for the corresponding TE heat dissipation

$$q_{te} = I S_m \left(T_h - T_c\right) + I^2 R_m \tag{7}$$

in terms of the TE parameters at the module as defined in the nomenclature and discussed by Luo [3]. In addition to the above two thermoelectric equations we have the following heat transfer equations,

$$q = C_1\left(T_{i2} - T_{i1}\right) \tag{8}$$

$$T_c = T_{i2} - q R_1 \tag{9}$$

$$T_h = T_{01} + \left(q + q_{te}\right) R_2 \tag{10}$$

q_p = Heat pumped by TE modules
q_{te} = Heat dissipation of TE modules
q = Electronics heat dissipation in box
T_h = TE module hot side temperature
T_c = TE module cold side temperature
T_{01} = Air temperature outside box
T_{i1} = Air temperature into electronics package
T_{i2} = Air temperature out of electronics package
T_w = Base temperature of heat sink(s) w/o TEs
I = Electric current supplied to TE module
S_m = TE module effective Seebeck coefficient
K_m TE module thermal conductance
R_m = TE module electrical resistance
R_1 = Thermal resistance of cold side heat sink
R_2 = Thermal resistance of cold side heat sink
C_1 = Air heat capacity rate within box ($\dot{m} c_p$)

Table 1 - Nomenclature

It should be noted here that under steady-state conditions heat load, q, in *Equations (8-10)* is equal to the heat pumped, q_p, by the thermoelectric cooler. Considering *Equations (8–10)* together with thermo-electric *Equations (6)* and *(7)* we have five linear algebraic equations. Given that we know or can assume values for q, R_1, R_2 , C_1, S_m, K_m, R_m and I, we are left with five unknown variables. The unknown variables are q_{te}, T_h, T_c, T_{i2} and T_{i1} (which is the variable we are really after). It is possible to solve these equations via algebraic substitution, as the author has done with the aid of software [4] capable of performing symbolic algebraic manipulation. However, the author found that the algebraic solution obtained for T_{i1} by this method was so long (about two or three screen-widths) and so complex as to be of practically no value other than demonstrating that a solution could be obtained.

A method of practical utility is to solve these equations for numerical values using a matrix method as employed in an earlier article addressing the solution of a thermal resistance network [5]. To do this we first rearrange the *Equations (6-10)* so that the unknown variables are on the left-hand side of the equation and the constant terms are on the right-hand side,

$$S_m T_c I q_p - K_m T_h + K_m T_c = q + \frac{1}{2} I^2 R_m \tag{6a}$$

$$q_{te} - I S_m T_h + I S_m T_c = I^2 R_m \tag{7a}$$

$$C_1 T_{i2} - C_1 T_{i1} = q \tag{8a}$$

$$T_c - T_{i2} = -q R_1 \tag{9a}$$

$$T_h - q_{te} R_2 = T_{01} + q R_2 \tag{10a}$$

In matrix notation these same equations can be compactly represented as

[Coeffs] x [Unknowns] = [Constants] (11)

The coefficients of the unknown variables and the corresponding constant terms for each equation may be grouped in a tabular form as shown in *Table 2*. So doing, the top row represents the column vector of unknowns, the columns beneath each unknown variable make up the coefficient matrix and the rightmost column the constant vector.

T_{i1}	T_{i2}	T_c	q_{te}	T_h	Constant
0	0	S_m+K_m	0	$-K_m$	$q+I^2R_m/2$
0	0	$I\ S_m$	1	$-I\ S_m$	I^2R_m
$-C_1$	C_1	0	0	0	q
0	-1	1	0	0	$-q\ R_1$
0	0	0	$-R_2$	1	$T_{01}+q\ R_2$

Table 2 – Coefficients of Unknown Variables and Constants in Equations

The coefficient matrix below comprises the known coefficients of the unknown variables of the equations, as shown in *Table 2*,

$$\text{Coeffs} = \begin{bmatrix} 0 & 0 & S_m + K_m & 0 & -K_m \\ 0 & 0 & I S_m & 1 & -I S_m \\ -C_1 & C_1 & 0 & 0 & 0 \\ 0 & -1 & 1 & 0 & 0 \\ 0 & 0 & 0 & -R_2 & 1 \end{bmatrix}$$

the column vector of unknown variables which we seek to solve is,

$$\text{Unknowns} = \begin{bmatrix} T_{i1} \\ T_{i2} \\ T_c \\ q_{te} \\ T_h \end{bmatrix}$$

and the column vector comprising the known constants on the right hand side of each equation is,

$$\text{Cons tan ts} = \begin{bmatrix} q + I^2 R_m/2 \\ I^2 R_m \\ q \\ -q R_m \\ T_{01} + qR_2 \end{bmatrix}$$

A matrix equation such as *(11)* may be solved for the unknown variables by multiplying the constant vector by the inverse of the coefficient matrix,

$$[\textbf{Unknowns}] = [\textbf{Coeffs}]^{-1} \textbf{ x } [\textbf{Constants}] \qquad (12)$$

Many computational aids such as MathCad [4], Matlab [6], and EXCEL [7] can be used to obtain the matrix inverse of the coefficient matrix and multiply by the constant vector to obtain the desired solution vector.

To demonstrate the potential enhancement with thermoelectrically augmented cooling, we now turn our attention to some numerical results obtained using the method described above. For purposes of illustration, a small enclosure with an allowable opening in one side of 100 mm x 100 mm is assumed. It is further assumed that the base dimensions of the internal and external air-cooling heat sinks are 100 mm x 100 mm. Before proceeding further it is necessary to assign values to the thermoelectric module cooling parameters, S_m, K_m,and R_m. The same 40 mm x 40 mm TE module considered by the author in an earlier article[8] will be considered here. In the earlier article, the author illustrated the calculation of single module TE parameters from vendor data, using the method discussed by Luo *(3)*. The values for the example TE module were found to be:

$$\begin{aligned} S_m &= 0.068 \text{ V/K} \\ K_m &= 0.712 \text{ W/K} \\ R_m &= 2.307 \text{ ohms} \end{aligned}$$

However, to increase the overall heat pumping capacity, four of these TE modules can be sandwiched in a 2 x 2 array between the bases of the internal an external heat sink and wired electrically in series. Consequently, the parameters for the array of TE modules will simply be four times the value for a single TE module or,

$$\begin{aligned} S_m &= 0.272 \text{ V/K} \\ K_m &= 2.848 \text{ W/K} \\ R_m &= 9.228 \text{ ohms} \end{aligned}$$

Calculations were performed for a range of heat sink resistances to show the effects of this parameter, coupled with the thermoelectric cooling effects. The heat sink thermal resistances used in the calculations were 0.075, 0.125 and 0.175 oC/W and were considered to have the same value for the heat sink within and outside the box (i.e. $R_1 = R_2$). The internal air flow rate within the box was assumed to be 0.00944 m3/s (20 CFM).It should be remembered that *Equations (6)* and *(7)* are in Kelvin temperature units (i.e. Kelvin temperature = Centigrade temperature + 273.16. So the temperature of the outside cooling air, T01, used in the calculations, must also be in degrees Kelvin and the temperatures obtained from *Equation (12)* will be in degrees Kelvin. However, for ease of understanding, the temperatures reported in the following figures have been converted to degrees Centigrade.

Figure 2 illustrates both the effect of increasing electric current through the TE modules and heat sink thermal resistance, with a heat load of 100 watts from the electronics and an outside air temperature of 35 ^{o}C. The solid lines represent the cooling air temperature within the box with the TE modules sandwiched between the heat sinks and the dashed lines represent the temperatures obtained without the TE modules. As can be seen, at low values of electric current, the presence of the TE modules result in higher cooling air temperatures within the box. This is because at low electric current, the Peltier heat pumping effect is offset by the thermal resistance across the TE modules. As current is increased the Peltier heat pumping effect becomes more significant and the inside cooling air temperature can be decreased significantly. However, as electric current continues to be increased, the Joule heating (i.e. heat dissipation) within the TE modules becomes increasingly significant causing the inside cooling air temperature to bottom out and if current is increased still further begin to rise.

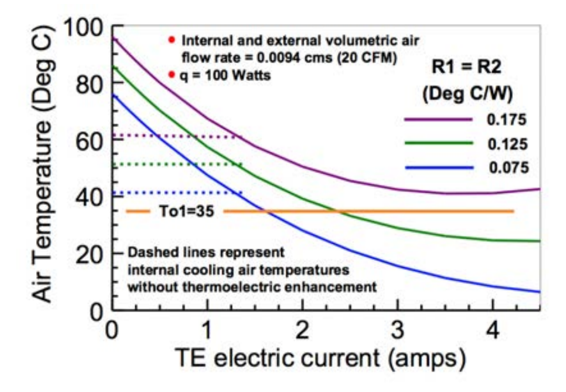

Figure 2. Effect of increasing electric current to TE modules on internal cooling air temperature

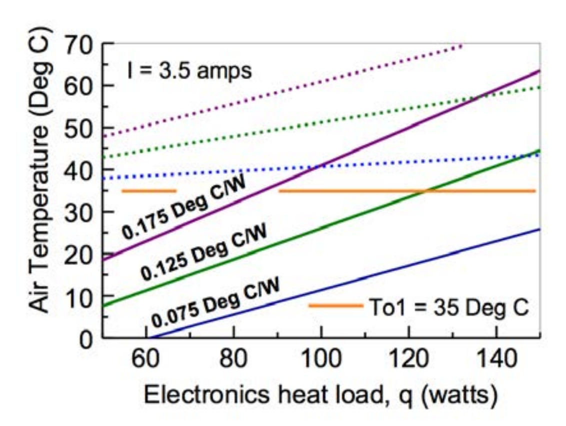

Figure 3. Effect of electronic heat load on internal cooling air temperature with (solid lines) and without (dashed lines) thermoelectric augmentation.

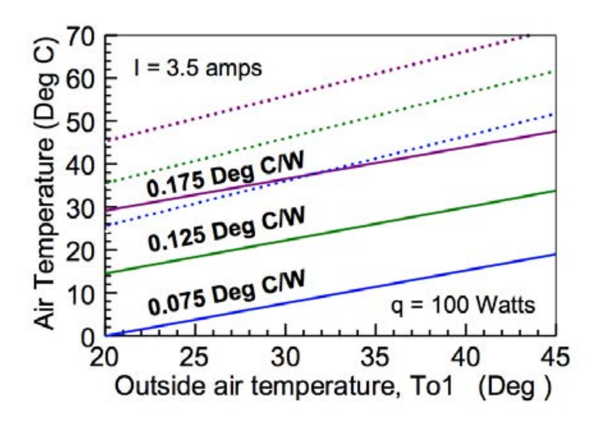

Figure 4. Effect of outside air temperature on internal cooling air temperature, Ti1, with (solid lines) and without (dashed lines) thermoelectric augmentation.

Figure 3 illustrates the effect of the electronics heat dissipation on cooling air temperature within the box, with a constant current of 3.5 amperes through the array of TE modules and an outdoor temperature of 35 °C. As can be seen, the cooling air temperatures obtained in all the cases are lower than could be achieved without employing TE enhancement. It should also be noted that, depending on heat load and heat sink thermal resistance in many cases the cooling air temperature is even lower than could be obtained using outside air for cooling.

The results in *figure 4,* show the effect on cooling air temperature within the box due to supplying a fixed current of 3.5 amperes to the TE modules at a fixed electronics heat load of 100 watts. As in the preceding figures, it can be seen that the resulting cooling air temperatures are always below the cooling air temperatures that could be achieved without thermoelectric enhancement.

The equations and solution methodology presented in this article can provide a useful tool with which to obtain a preliminary estimate of the effectiveness of thermoelectric augmentation in providing cooling to electronic components in a closed box.

Of course, when considering the use of thermoelectrics for cooling applications, the designer should be cognizant of the electrical power required to drive the thermoelectric elements, which is given by *Equation (7)*. The cooling efficiency of thermoelectric devices relative to their power consumption, as with other types of heat pumping devices, may be characterized in terms of Coefficient of Performance (COP). COP is defined as the ratio of cooling (q) provided over the electrical energy consumed (qte) to produce the cooling effect.

For example, for the results shown in *Figure 3*, the COPs ranged from 0.3 to 0.4 at heat loads of 50 or 60 W to around 1 at a heat load of 150 W. The range of heat sink thermal resistance values had only a little effect on the COP realized. Similarly, considering the results shown in *Figure 4*, COPs ranged from 0.6 to 0.7 with little effect due to heat sink thermal resistance or outside air temperature.

As one might expect from *Equation (7)* the principal effect on COP is caused by the electrical current required to drive the thermoelectrics. This is amply demonstrated considering the results presented in *Figure 2*.

At electric currents around 1.25 A, the COPs calculated ranged from 6 to 6.4 depending on the value of heat sink thermal resistance. Although these COPs may seem good, in this case the cooling air temperature within the box is no lower than could be achieved without thermoelectrics. As current is increased in *Figure 2*, the COP realized decreases rapidly to about 0.65 at a current of 3.5 A. However, even though the COP has dropped, this coincides with the maximum reduction of air temperature within the box by as much as 20 to 30 Centigrade degrees below those achieved without thermoelectric augmentation. For comparison, the COP values realized by conventional vapor compression refrigeration systems may typically vary from 1 to 4.

Finally, it should also be noted that a number of vendors provide thermoelectric heat exchangers for cooling air in a closed box.

The interested reader may find a number of vendor products and examples by conducting an internet web search using the terms "thermoelectric air cooler" or "thermoelectric air conditioner."

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KEYNOTE **Tuesday March 20, 2018**

Thermal Challenges and Industry Trends of Consumer Electronic Devices.

There are many thermal design challenges in consumer electronic devices including wearables, portable computing platforms and IOT communication devices. This talk covers industry trends in the consumer electronics hardware business and the role that thermal management and design plays, as well as how to cope with the trends to overcome power and thermal challenges.

Dr. Andre Ali currently heads thermal engineering for Google HW. He is a former chief thermal architect at Apple where he is credited for leading and innovating thermal technologies and design architectures for Apple's MacBook, MacBook Pro, MacBook Air, iPhone and iPad. He is a former thermal technologist at Intel's mobile product group. His interests and research focus are in electronics thermal management and control, energy efficiency, renewable energy. Dr. Ali invented and published numerous patents and papers in the field of thermal management, CFD and two-phase heat transfer. He also served as keynote speaker, panelist and chair at various conferences and forums worldwide. He has a PhD in Mechanical Engineering from University of Maryland.

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Contact Bob Schuch : rschuch@semi-therm.org

Panel Discussion
“Challenges in Consumer Electronics Cooling”
Thursday, March 22 2:00p.m. - 4:00p.m.

“Challenges in Consumer Electronics Cooling” will address how current challenges are being met and will emphasize future challenges, how they are framed, and what approaches and technologies might be applied to overcome them. Each panelist will give a 10 minute presentation from their perspective, with 30 minutes for audience questions.

Moderator: Mark Carbone, Intel

Co-Topic Champions: Consumer Electronics
William Maltz, President, Electronic Cooling Solutions, wmaltz@ecooling.com
and Mark Carbone, Senior Thermal Engineer, Intel, mark.carbone@intel.com

PANELISTS:

Andy Delano, Microsoft, andel@microsoft.com
Amip Shah, HPE Labs Director, Internet of Things, Hewlett Packard Labs, amip.shah@hpe.com
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Air Mover Technologies with Low Acoustics • David Nelson, Nelson Acoustics
Automotive / Aerospace / Outdoor • Eric Dede, Toyota Research Institute
Computational Fluid Dynamics (CFD) • Robin Bornoff and John Parry, Mentor Graphics, a Siemens Business
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Consumer Electronics • William Maltz, Electronic Cooling Solutions and Mark Carbone, Intel
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Mohammad I. Tradat, Binghamton University

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SEMI-THERM 34

SHORT COURSES Monday, March 19, 2018

Short courses are offered on Monday prior to the formal opening of the symposium. Concurrent short courses at SEMI-THERM 34 will be held in the morning and afternoon of March 19, 2018. These sessions are free to regular paid attendees. Short courses for SEMI-THERM 34 are under development.

A partial listing includes:

Power Electronics & Energy Harvesting: Unleashing the Potential of IoT
Brian Zahnstecher, PowerRox
Managing Cooling Fan Noise
David Nelson, Nelson Acoustics
Experimental Methods in Thermal Sciences
Al Ortega, Santa Clara University
LED Thermal Design
Genevieve Martin, Philips Lighting
Shock and Vibe
Nick Clinkinbeard, Rockwell Collins

Additional Short Courses will be given by:
Suhkvinder Kang, Aavid Thermalloy
Peter Raad, SMU

Short courses at SEMI-THERM 33 included:

A History of Commercial CFD from Bernoulli to Spalding and Beyond, with a Focus on Electronics Cooling Simulation
Robin Bornoff, Mentor Graphics John Parry, Mentor Graphics
Fundamentals of Liquid Cooling: From Fluid Selection to Phase Change
Timothy Shedd, Ebullient Inc
Transient Thermal Analysis using Linear Superposition
Roger Stout, ON Semiconductor
Spreadsheet Based Thermal Analysis Method
Ross Wilcoxon, Rockwell Collins
Design of Experiments for Thermal Engineering
James Petroski
Fundamentals of Power in the Data Center
Brian Zahnstecher, Power Rox

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SEMI-THERM is known as an application-oriented symposium. The How-To Courses are designed for those new to thermal technology and also as a review for more experienced thermal professionals. SEMI-THERM's How-To Courses are meant to allow an expert overview of various engineering disciplines that relate not only to thermal phenomena, but also include topics on electrical, mechanical, design, materials, processes, manufacturing, and more. The focus is on real world practices and techniques from the chip and package to the board, backplane and system level. The tutorials are presented by experienced and well-known specialists from industry and academia.

SEMI-THERM 33's How-To Courses Included:

Thermocouple Theory and Practice
Robert J. Moffatt, Stanford Emeritus
Design of Liquid Cooled Systems
Pablo Hidalgo, Aavid Thermacore
Design Consideration for Heat Sink Mounting Solution
Dr. Milena Vujosevic, Intel, Juan L. Cruz, Light
Practical Guidelines for Using Heat Pipes and Vapor Chambers in Heat Sinks
George Meyer, Celsia

SEMI-THERM's Technical Committee is currently developing the How-To Courses for SEMI-THERM 34. The courses will be held concurrently from 6:30p.m. - 8:30p.m on Wednesday March 21, 2018.
Please check the website for updates: www.semi-therm.org

THERMI Award

Each year, SEMI-THERM honors a person as a Significant Contributor to the field of semiconductor thermal management. The THERMI award is intended to recognize a recipient's history of contributions to crucial thermal issues affecting the performance of semiconductor devices and systems.

From left to right: Dereje Agonafer, SEMI-THERM 33 Thermi Winner Chandrakant Patel, Devin Patel, and SEMI-THERM 33 General Chair Veerendra Mulay.

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Bernie Siegal's first involvement in semiconductor thermal matters came in 1966 while working at the microwave semiconductor group within Hewlett-Packard Associates (HPA). Bernie and an associate developed an automated system for making thermal resistance measurements on microwave diodes and authored a feature article describing the method, which appeared in the October 1967 issue of the HP Journal. From that beginning to today, Bernie has been an active participant in the semiconductor measurement, modeling and management field. In 1974, Bernie founded SAGE Enterprises, Inc. and began offering test equipment for measurement of thermal resistance for many different types of semiconductor devices. The thermal testing techniques Bernie developed eventually became incorporated into many of the industry (SEMI and EIA/JEDEC) and US military measurement (Mil Std 750) standards. Besides being actively involved in many of the various standards-creating committees, Bernie is co-founder and primary force behind the start of SEMI-THERM, the premier technical symposium in the field. He has authored over 40 technical papers, presented seminars to world-wide audiences, and conducted several short courses for the UC Berkeley Extension program. His current company, THERMAL ENGINEERING ASSOCIATES, INC. (TEA), maintains his involvement in the field. Bernie holds M.B.A. (Santa Clara University), M.S.E.E. (San Jose State University), and B.S.E.E. (Cornell University) degrees. He was elected a Fellow of the IEEE and received the IEEE Significant Contributor Award for his work in the semiconductor thermal field. He currently serves as the Chairman of the IEEE CPMT Silicon Valley Chapter.

SEMI-THERM Electronics Cooling App Development Challenge

Call for Apps

The goal of the Development Challenge (ADC) is to encourage SEMI-THERM attendees to develop mobile apps that would be useful to those in the electronics cooling industry. The ADC is open to all individuals and companies within the electronics cooling community. Students are particularly encouraged to develop apps, either individually, as part of a class project, or in collaboration with industry partners.

Submitted apps will be reviewed and scored by members of the SEMI-THERM program committee. The developer of the highest scoring app will receive a FLIR One IR imaging attachment for smartphones. Developers of the three highest scoring apps will be invited to SEMI-THERM, with a reduced registration fee, so that they can present their app to the rest of the community.

Apps submitted for the ADC will be made available to SEMI-THERM attendees at no cost. Developers only need to provide the executable code for their apps and have no obligation to provide any support for its use. Please contact AppDevChal@semi-therm.org for more information or to submit your app.

Schedule:

- October 27, 2017 - Individuals who are planning to submit an app for the ADC are requested (not required) to inform SEMI-THERM of their 'intent to submit' by this date
- January 12, 2018 - Apps are to be submitted to SEMI-THERM by this date
- February 5, 2018 - The SEMI-THERM committee will announce which six apps received the highest scores from the reviewers and invite the top three winners to present at SEMI-THERM (if the developer of any of these three selected apps cannot travel to SEMI-THERM, the next highest scoring developer will be invited)
- March 2018 (at SEMI-THERM) - Three apps will be demonstrated by their developers at the SEMI-THERM symposium as part of a special session

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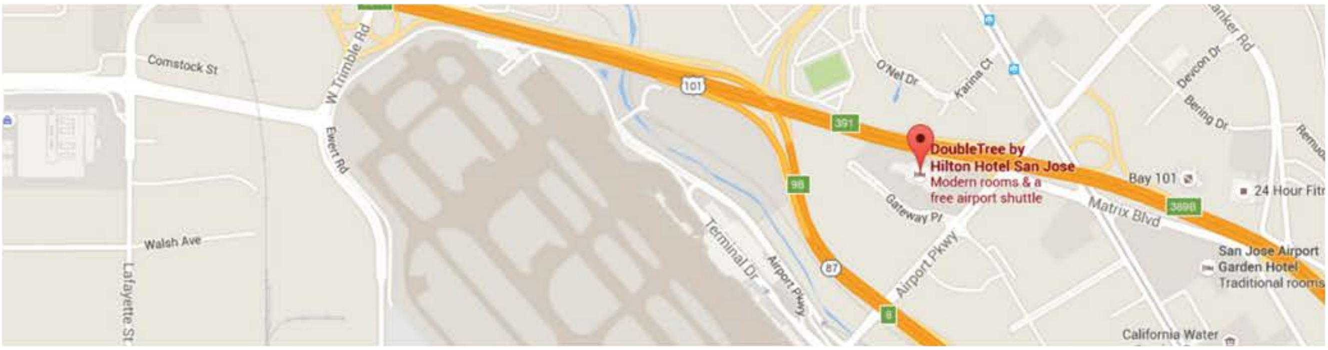

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