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electronics COOLING

2017 BATTERY, AUTO, & POWER ELECTRONICS GUIDE

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FOREWARD

Welcome to Electronics Cooling's© miniguide for Battery, Automotive and Power Electronics.

The intent of these digital guides is to bring you a collection of subject-specific articles and information on thermal management materials and components serving the above categories of products. To that end, we are featuring a brief description of the ecosystem for thermal management products, an overview of the thermal management challenges in these verticals and some high level description of the thermal design elements.

As industrialization and the accompanying progress pervades developed and developing economies, our world today faces unique challenges in increased energy demand driven by affordability and population growth. There has been an explosion of consumer electronic devices with mobile phones at the center of that ecosystem. Coupled with these, large scale urbanization and increasing use of fossil fuel-based vehicles has led to the adoption of more electronic hardware in automotive industry. The technology sector has stepped up to do its part in enabling new energy sources, energy harvesting and energy storage systems like Lithium-ion batteries, Hydrogen fuel cells, Ultra-capacitors, regenerative braking, dynamic charging etc. These technologies are already introduced in the design and production of gasoline, electric and hybrid electric vehicles. In addition, electronic fuel injection, antilock brake systems (ABS), automated driver assist systems (ADAS), in-dash entertainment systems, electric motor drives, high-performance alternators, electronic control units, etc., are being incorporated in various vehicle architectures. Improving energy efficiency and management of waste heat remain as main challenges for hardware professionals to deal with. This miniguide focuses on Power Electronics and Automotive Electronics applications.

Your feedback about this miniguide is therefore very important to us and it will help us feature content that is most useful in your thermal management activities. With your participation, we may eventually positon these miniguides as both resource and design guides.

PRODUCT SELECTOR

The following sections provide some information on products for:

- TIMs, Gap Pads
- Heatsinks
- Heat Pipes
- Die Attach (Solders, Ag Epoxy, etc.)
- Enclosures

TIMs, Gap Pads

Thermal interface materials (TIMs) refer to a broad definition of a category of materials that are deployed between two components in order to enhance the heat transfer between the components. They include thermal glue, thermal grease, thermal tapes, thermal films, thermal pads, liquids and phase change materials (PCM). TIMs can also provide bonding functions between the two components.

There are important considerations when selecting a suitable TIM for your application. We refer you to the following articles in Electronics Cooling© for further information. Please visit the vendor websites for complete information on these products and datasheets.

- Thermal Interface Materials
- Recent Research in TIMs
- Calculations for Thermal Interface Materials
- Understanding Phase Change Materials
- Thermal Interface Materials: A Brief Review of Design Characteristics and Materials

Die Attach Material	Thermal Conductivity Range (W/m-K)	Example Vendors
Silver Epoxy	2 to 20	Dow Corning, Al Technology, Henkel, Epoxy Technology
Lead Solders	40 to 50	Indium Corporation
Lead-free Solders	40 to 60	Indium Corporation
Gold-Tin (AuSn)	57	Indium Corporation
Gold-Silicon (AuSi)	27	Indium Corporation
Indium Solders	30 to 40	Indium Corporation
Sintered Silver	>400	Alpha Advanced Materials
Non-Conductive	0.1 to 2.0	Epoxy Technology

Heatsinks

Electronics Cooling© features a rich selection of articles and calculators to guide you in selecting the appropriate heatsink for your applications. Elements of heatsink basics are explained in How To Select A Heatsink which serves as a starting point. There are many more articles in EC listed under Calculators that are quite useful in your projects requiring heatsinks.

Heatsinks are necessary to enhance the heat dissipation from a hot component to a cooler ambient environment, most often air. Heatsinks not only provide extended surfaces for natural / forced convection, they also enhance the heat transfer coefficient due to their design topologies –pin fin heatsinks for example.

Over the past several decades, heatsinks have witnessed very significant improvements in their performance and complexity. Depending on the methods of fabrication and/or the attachment process, heatsinks with fins can be stamped, extruded, bonded, skived, die-/sand-/vmold-cast and now a days 3D printed; the latter leading to previously challenging heatsink topologies once thought impossible to fabricate (see for example this article on Fractal Heatsinks). Many heatsinks are also available with phase change material (PCM) integrated.

Heatsink Vendor	Heatsink Types
AAVID THERMALLOY	Stamped, Extruded, Bonded, Cast, Folded Fin, Microchannel Integrated, PCM-Integrated, Fan-integrated, Heat Pipe-Integrated
Alpha Novatech, Inc.	Stamped, Extruded, Bonded, Cast, Folded Fin, Microchannel Integrated
Amulaire	Stamped, Extruded, Bonded, Cast, Folded Fin
Celsia	Stamped, Extruded, Bonded, Cast, Folded Fin, Microchannel Integrated, PCM-Integrated, Fan-integrated, Heat Pipe-Integrated
JARO Thermal (NRC Electronics)	Stamped, Extruded, Bonded, Cast, Folded Fin, Microchannel Integrated, PCM-Integrated, Fan-integrated, Heat Pipe-Integrated
Malico Inc.	Stamped, Extruded, Bonded, Cast, Folded Fin, Microchannel Integrated, Heat Pipe-Integrated
Mersen	Stamped, Extruded, Bonded, Cast, Folded Fin, Fan-integrated, Heat Pipe-Integrated
TRAN-TEC	Stamped Extruded Bonded Cast Folded Fin Microchannel Integrated PCM-Integrated Fan-integrated Heat Pipe-Integrated

Liquid Cooling, Heat Pipes & Thermo Electric Coolers (TEC)

Please refer to this introductory article on the basics of Heat Pipe Electronic Cooling© Applications. Basics of thermoelectric coolers can be found in this article: An introduction to thermoelectric coolers which steps you through the equations involved, number of stages and performance curves.

Vendor	Heatsink Types
AAVID THERMALLOY	Heat Pipe Assemblies, Blister Cold Plates, Tube Cold Plates, Vortex Cold Plates, Extended Surface Cold Plates
Celsia	Heat Pipe Assemblies, Blister Cold Plates, Tube Cold Plates, Vortex Cold Plates, Extended Surface Cold Plates
CPC (Colder Products Company)	Connectors / Couplings for Liquid Cooling
Ferrotec NORD	TEC (Single Stage), TEC (Multi Stage), Thermocyclers
JARO Thermal (NRC Electronics)	Heat Pipe Assemblies, Blister Cold Plates, Tube Cold Plates, Vortex Cold Plates, Extended Surface Cold Plates, TEC (Single Stage), TEC (Multi Stage), Thermocyclers
Malico Inc.	Heat Pipe Assemblies
Mersen	Heat Pipe Assemblies
Staubli	Connectors / Couplings for Liquid Cooling
ThermoElectric Cooling America Corporation	Heat Pipe Assemblies, Blister Cold Plates, Tube Cold Plates, Vortex Cold Plates, Extended Surface Cold Plates, TEC (Single Stage), TEC (Multi Stage), Thermocyclers

Fans

A summary article on thermal management with cooling fans can be found in this article, General aspects on fan selection and layout. You may also want to refer to this article All you need to know about fans for more on the basics of fans and blowers including fan curves and fan laws. The distinction between fans and blowers has to do with the direction of the air flow –in fans the air flow is parallel to the axis of the fans whereas in blowers it is perpendicular. The basic function is the same –designed air movement in the direction needed with the air flow rate required to keep the temperatures within limits while keeping the fan noise to a minimum!

There are essentially two types of fans: axial, radial and a combination of the two known as mixed flow. There are various considerations when it comes to selection of fans for electronics thermal management. Please consult articles under Calculators.

Fan Vendor	Fan Types
Delta Products Corporation	Axial Flow, Centrifugal Fans / Blowers, Fan Trays, Cabinet-integrated, Ventilation Fans (Data Center)
JARO Thermal (NRC Electronics)	Axial Flow, Centrifugal Fans / Blowers
Knight-Orion	Axial Flow, Centrifugal Fans / Blowers, Fan Trays, Cabinet-integrated
LMB Fans	Axial Flow, Centrifugal Fans / Blowers
Rosenberg USA	Axial Flow, Centrifugal Fans / Blowers, Fan Trays, Cabinet-integrated, Ventilation Fans (Data Center)
Sanyo Denki	Axial Flow, Centrifugal Fans / Blowers, Fan Trays, Cabinet-integrated, Ventilation Fans (Data Center)

Die Attach Materials

Depending on the severity of thermal gradients, every fraction of a degree counts when dealing with tight thermal budgets. The thermal conductivities of electrically-conductive and non conductive compounds become the primary metric to choose, followed by other considerations such as semiconductor substrate material, package type, required bond line thickness, die size, curing temperature, elastic modulus of the die attach material, CTE and the intended warpage control, thickness and size of the die attach pad relative to die size and thickness, flatness specification, etc.

The following table provides a summary of die attach material choices and some of the vendors to source from.

Die Attach Material	Thermal Conductivity Range (W/m-K)	Example Vendors
Silver Epoxy	2 to 20	Dow Corning, AI Technology, Henkel, Epoxy Technology,
Lead Solders	40 to 50	Indium Corporation
Lead-Free Solders	40 to 60	Indium Corporation
Gold-Tin (AuSn)	57	Indium Corporation
Gold Silicon (AuSi)	27	Indium Corporation
Indium Solders	30 to 40	Indium Corporation
Sintered Silver	>400	Alpha Advanced Materials
Non-Conductive	0.1 to 2.0	Epoxy Technology

Enclosures

The housings and enclosures for Consumer Electronics devices and IoT products are required to be light, durable, and aesthetically appealing while at the same time meet the electrical, thermal and mechanical requirements of these products. For the most part, the enclosures are rigid containers housing various modules and components of the products. How ever, with the proliferation of wearable devices and virtual reality headsets, flexible components encasing electronics are becoming increasingly common and in many cases require thermal management.

The common materials of choice for a majority of consumer electronics products are plastics: ABS Resins, Polycarbonate Resins, etc. When selecting plastics, attention should be paid to heat deflection temperature, specific heat (or heat capacity), thermal conductivity, coefficient of thermal expansion, and the operating range for temperatures, i.e., lower and upper working temperatures. Another important design attribute is whether the enclosure needs to be conductive for shielding purposes in which case conductive plastics are becoming more common.

Among metal enclosures, the application dictates the level of design complexity and environmental requirements. Outdoor electronic appliances must meet ingress protection (IP) requirements specified by IEC standard 60529 and more commonly NEMA-rated IP codes.

There are many choices for plastic enclosure vendors, too long to list! Metal enclosures including those meeting IP requirements can be sourced from vendors like Pentair, Sanmina, Elma, etc.

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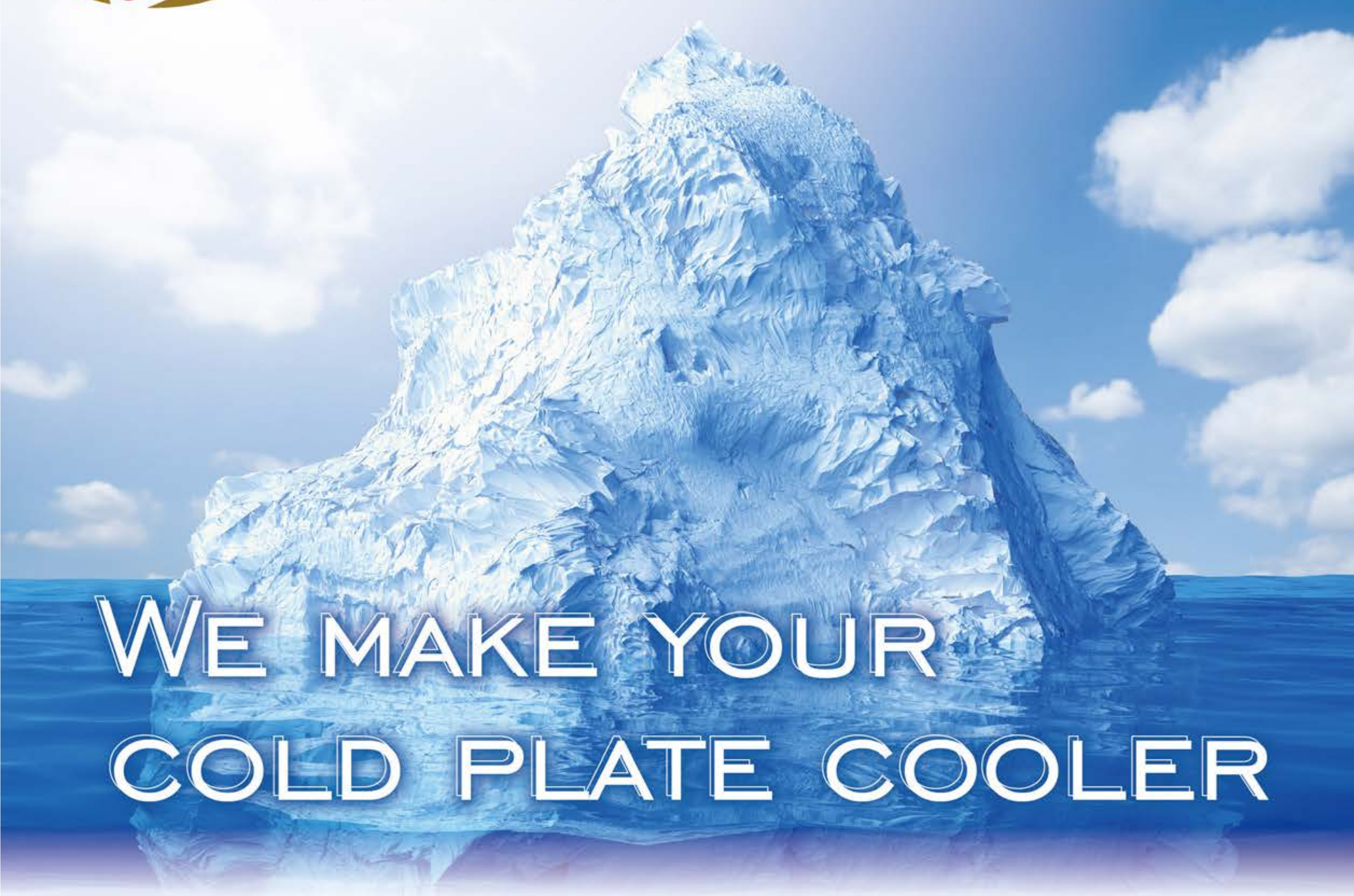
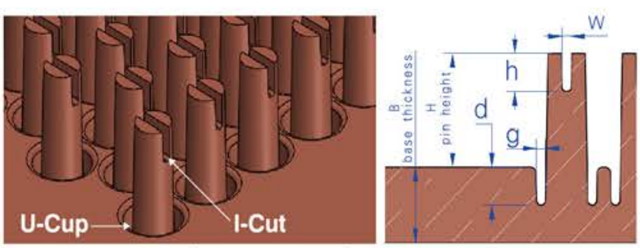
THERMAL TECHNOLOGY



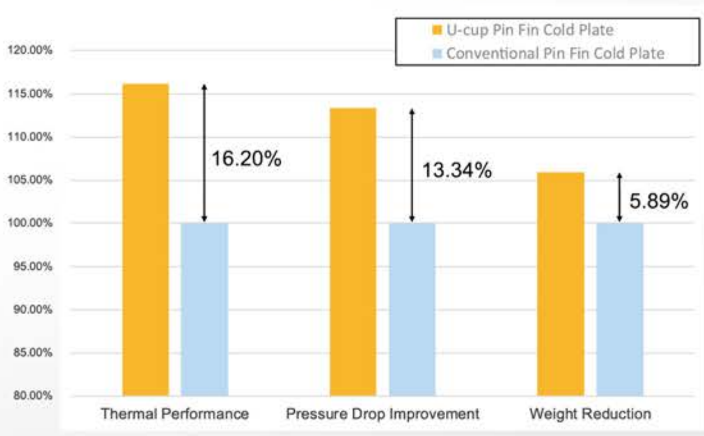
WE MAKE YOUR COLD PLATE COOLER

High Power Cooling System U-Cup & I-Cut



	Normal Pin Fin	U-cup	I-cut
characteristic width	n/a	g ≧ 0.5mm	w ≧ 0.5mm
characteristic depth	n/a	d ≦ Bx50%	h ≦ Hx50%
Thermal Performance	Normal	1.2% - 4.4 %	0 - 0.94 %
Pressure drop	Normal	9.79% - 15.2 %	0 - 16.1 %
Weight	Normal	2.7% - 9.23 %	0 - 2.87 %

U-cup Fin Advantage



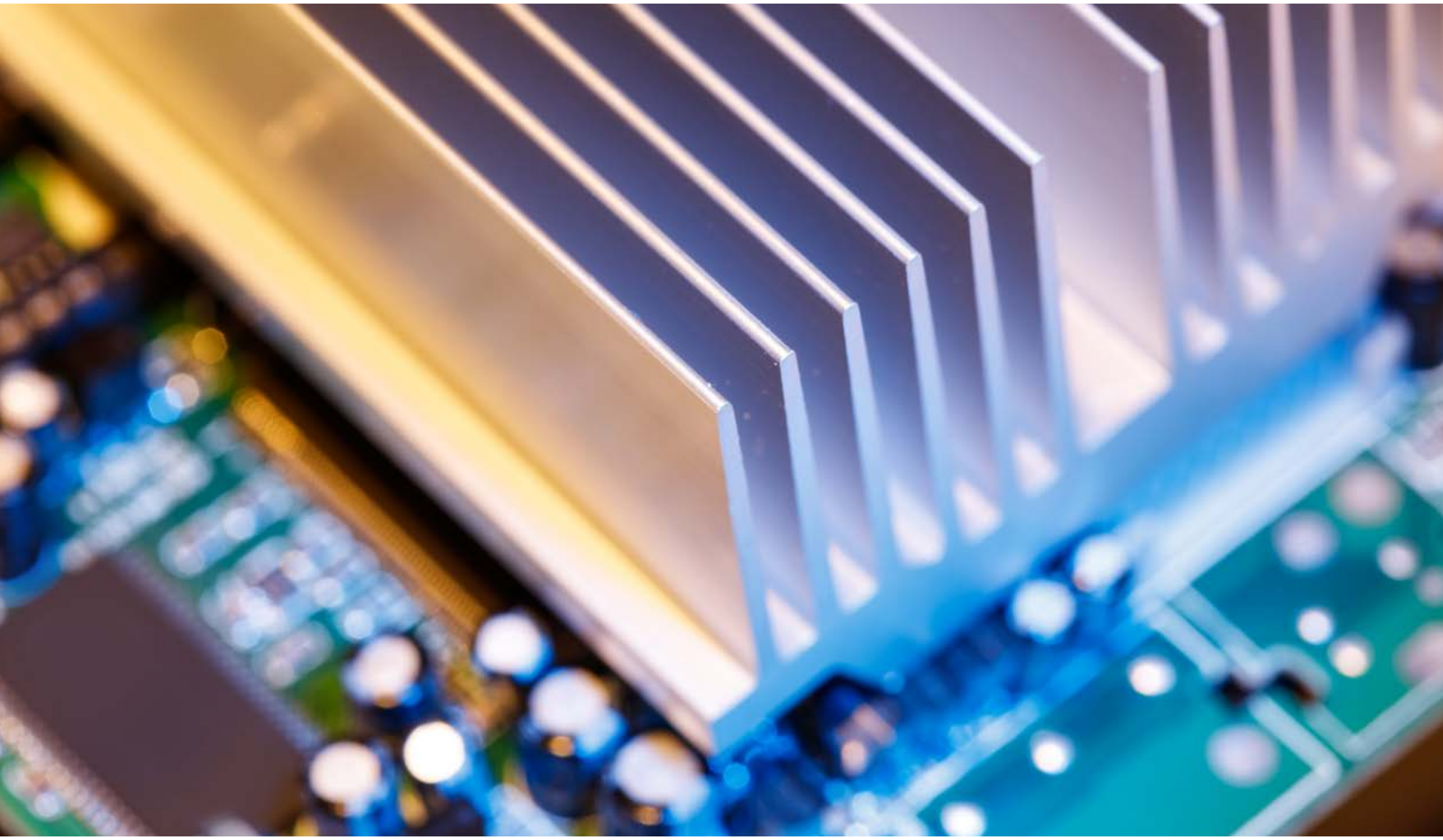
iNEMI ROADMAP IDENTIFIES TRENDS IMPACTING ELECTRONICS THERMAL MANAGEMENT

Azmat Malik

Preface

The International Electronics Manufacturing Initiative (iNEMI) is an industry-led consortium of approximately 100 leading electronics manufacturers, suppliers, associations, government agencies and universities. One of iNEMI's key initiatives is its biennial roadmap, which looks at the future technology requirements of the global electronics industry. It provides a 10-year outlook for electronics manufacturing, anticipating technology needs and identifying gaps.

The iNEMI roadmap is unique in scope. It covers the full electronics manufacturing supply chain and is an important tool for focusing research & development (R&D) priorities. This article discusses highlights from the Thermal Management Chapter of the 2015 Roadmap [1].



iNEMI ROADMAP IDENTIFIES TRENDS IMPACTING ELECTRONICS THERMAL MANAGEMENT

1. Introduction

The Thermal Management Chapter of the 2015 iNEMI Roadmap describes future thermal management technology needs across a broad range of product sectors, including: high-end systems, consumer/office systems, portable and wireless products, medical devices and systems, and light emitting diodes (LEDs). It assesses the current state of the art for all areas and then identifies the technology gaps that the industry will need to address to create tomorrow's products in these sectors.

The Thermal Management Roadmap also addresses the need to develop improved cooling technologies in terms of heat transfer processes, materials and innovative designs. If successfully implemented, enhanced thermal management will contribute to continued performance improvement trends and increased competitiveness of packaged electronic products. The roadmap identifies needs for further advances and developments in the following thermal technologies:

- thermal materials and thermal spreaders
- refrigeration cooling
- heat pipes
- liquid cooling
- thermal interfaces
- air cooling
- direct immersion cooling
- thermoelectric cooling, and
- thermal design modeling tools.

Here are highlights of some of these technologies, along with key challenges and R&D recommendations.

1.1 Overview/Situation Analysis

Demand for more effective and cost-efficient means of removing heat from electronic systems continues to grow across all segments of the industry—from compact, portable electronics to large, high-end systems. It is a particular concern for power electronics associated with transportation and the electrical grid. In the absence of major new breakthroughs in thermal management technology, this demand is being met by broader, more aggressive use of, and incremental improvements in existing techniques, along with increased emphasis on reducing the generation of heat through improved product design.

Aluminum and copper heat sinks, with forced or natural air circulation, continue to dominate in terms of unit volume in the high-volume personal computers and consumer electronics applications. The growing trend toward higher performance electronics in smaller packages is forcing designers and manufacturers to consider phase change and liquid cooling techniques, albeit at higher cost. These have not yet made it to high volume because of limited data about cost, reliability, and longer-term efficacy..

Increasingly, there is recognition that reducing system power (power in, heat out) will not only reduce the demands on thermal management technologies, hence their cost, but will also result in direct and indirect energy savings at system and facility/plant levels. This reduced energy consumption will eventually result in operating cost reduction—and is leading to improved design practices that focus more closely on reducing the sources of heat in electronic devices. One example of this is non-uniform heat generation on devices, which causes localized "hot-spots" and requires thermal management based on a worst-case scenario. In high-volume and critical applications, where cost is no object, custom designs of cold plates can effectively manage hot-spots locally, without need for the entire thermal solution being scaled for the worst-case hot-spot scenario.

Expanded adoption of multi-core central processing units (CPUs) continue to help lower the thermal impact of high-performance devices in computing applications and are helping to mitigate, though not eliminate, the need for even more costly and aggressive cooling solutions. Also, increasing acceptance of electric and hybrid vehicles, renewable energy solutions and evolution of the smart grid is placing growing emphasis on thermal management techniques suited to the unique requirements of power electronics. Most high-performance applications have specific thermal solution expectations and must be dealt with based on specific design requirements. High-volume customer solutions, where cost is a key concern, are still driving the technology toward simpler and lower-cost "elegant" solutions.

Cost and time-to-market continue to play a critical role in maintaining competitiveness for all product sectors. To keep pace with the shrinking design-cycle time and to reduce development costs, the industry will rely on advances in computer-aided thermal design tools.. Developments in thermal modeling tools to integrate electrical, thermal, fluid flow, and mechanical analysis and simulation in one user-friendly package continue to lag industry needs. The chapter identifies these tools as a major development need going forward. While many start-ups are addressing this gap, there have not been breakthroughs.

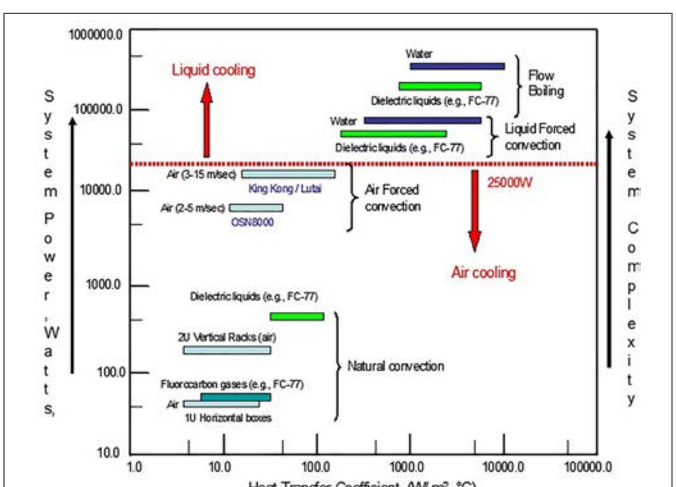
Thermal management has been a key enabling technology in the development of advanced micro-electronic packages and systems, and has facilitated many of the so-called Moore's Law advances in computers and electronic products. Thermal management entails a balanced combination of materials and techniques to optimize performance-cost designs. Increased complexity, density, and higher clock frequencies continue to push the thermal fluxes at chip level. These thermal demands propagate through the consumption chain (sub-system, system and facility).

The tradeoff between peak and average power is an important concern: high peak power will often mean a more expensive thermal management solution, while high average power will result in higher energy cost over the life of the system. There is reconsideration of the die junction temperature and there is a tendency to lower the acceptable temperature from previous norms. This will improve reliability and device life, while putting even greater demands on the thermal management system.

The state of the art of appropriate cooling solutions for electronics depends on the system power and the financial budget available for the cooling solution. There are thermal solutions to handle some of the most demanding needs, but the technology to do so does not always meet cost constraints.

Whenever possible, air-cooling is used, as it is the lowest cost. For cost-sensitive computing (desktop PC, a declining sector) this means air cooling of a heat sink, usually with fans to force air onto the heat sink to improve performance. Notebook computers often use a heat spreader with a heat pipe and a fan. However, weight and volume limitations constrain laptops' cooling performance, and that requires the use of lower power CPUs. Server computers use high-performance heat sinks and multiple fans to extend the limits of air cooling, and some medical equipment can afford liquid cooling. Acceptance of liquid cooling continues to increase as users get a better understanding of the costs and benefits associated with this solution.

The thermal management technology roadmap for typical power systems with different cooling schemes is shown in *Figure 1*. For 1U horizontal boxes with natural convection, systems now in the market are typically around 50W at ambient of 55°C at sea level.



Management Technology Requirements and Choices [Source: Huawei Technologies].

Thermal management costs have historically been a small percentage of total system cost, ranging from less than 1% for some PCs to 3-5% for some large servers, and approaching 10% on the largest supercomputers. Failure to consider thermal issues while the design is still flexible limits the ability to make design tradeoffs that might significantly improve thermal management cost, reliability and performance. System and chip-level product designers are now engaging the thermal design team early in the design cycles to take advantage of the potential to improve the performance contribution and cost of the thermal solution.

Additionally, from a design perspective, a unified approach, looking at the entire system design rather than "stacking" margins and specs at sub-system levels, may be another way of achieving a more efficient thermal management solution.

2. Thermal Management Technology Challenges

2.1 Power Electronics

Applications in power electronics have grown dramatically in the last few years because of greater need for electric power management and control (smart grid), renewable energy generation and control, and electric transportation—as well as a desire to improve operating efficiency of heavy systems, such as trains, industrial motors, and electric vehicles.

Power electronic converters are found wherever there is a need to modify the voltage, current or frequency. These range in power from few milliwatts (mW) in mobile phones to hundreds of megawatts (MW) in high-voltage direct current (HVDC) transmission systems. Usually, electronics are thought of in the framework of information technology, where speed is the primary interest. However, in the context of power electronics (*Figure 2*), there is a critical need for improved efficiency and reduced power losses.

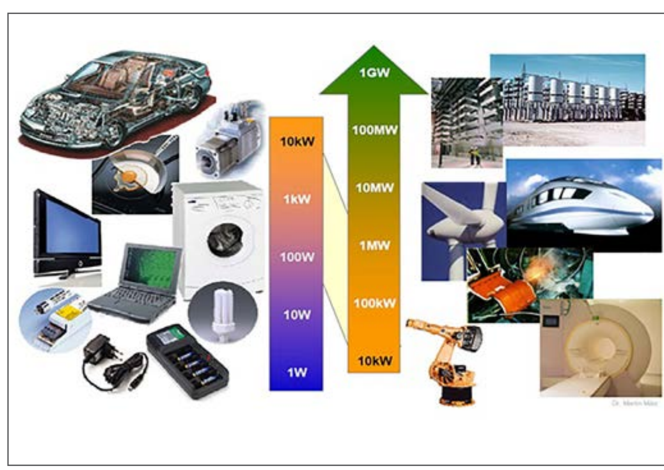


Figure 2: Range of power electronics applications [1].

There is a fundamental difference between planar microelectronics devices and power electronics devices. While microelectronics is essentially a surface-based technology (i.e., the active area is on surface of the chip), in power electronics the current passes through the chip. This means that electrical contacts are on both sides and, because of the high voltages, insulation is necessary. For higher power, the chips are often stacked or connected in parallel in a multichip module. As 3-dimensional (3D) chip solutions get incorporated into volume production, the need for bulk thermal management will drive the development of cooling techniques such as liquid channels and graphene[1] layers.

Designers call on materials in power electronics systems to provide electrical and thermal conduction, insulation, protection, and mechanical stability, all with the objective of achieving the desired reliability. These properties usually cannot be considered in isolation. The coefficients of thermal expansion (CTEs) of the semiconductors and insulators are fixed. Metals can be matched by adding fillers such as aluminum-silicon-carbide (AlSiC), a mixture of aluminum, silicon and carbon/graphite, where silicon-carbide (SiC) has the low CTE to interface with silicon. Clearly, it is important to use materials with high thermal conductivity and closely matched CTEs; applications using graphite must consider the fact that graphite is highly anisotropic with high thermal conductivity in the x-y plane only.

This metal-matrix composite (MMC) material is used in high-reliability traction applications because of the CTE match between the DCB/AMB (direct bond to copper-active metal braze) substrate to the AlSiC base plate, which protects the large area solder joint between them. Because of its lower weight, AlSiC may find use in aircraft applications.

2.2 LED Thermal Management Challenges

One particular challenge of light emitting diode (LED) thermal management is that, as with many semiconductor devices, the junction temperature of LED chips must be typically maintained well below 125°C — well below operating temperatures of traditional incandescent light sources.

The LED bulb is significantly more efficient in converting electricity to visible light, and the spectrum of that light is more effectively tailored to the photopic response of the human eye. As a result, the 60W equivalent LED bulb consumes only 13.5W of input power to deliver 2.5W of visible light power equivalent to 800 lm. This dramatic, 80 percent reduction in heat dissipation relative to the incandescent, 11W versus 55W, would seem to make thermal management of LED bulbs trivial. However, with a maximum allowable junction temperature of only 125°C, there is a much smaller temperature difference available to drive heat transfer from the source to the ambient. As a result, thermal management of the LED bulb is more challenging—requiring one-fourth to one-fifth the thermal resistance (°C/W). Making matters worse, natural convection and radiation heat transfer processes are significantly less effective at temperatures closer to ambient.

The vast majority of the waste heat in an LED system is generated in a very small volume within the millimeter-scale LED chip(s). While LED efficiency continues to improve, device manufacturers are packaging devices in increasingly smaller footprints, only exacerbating the heat density challenge.

2.3 Direct Immersion Cooling

It is possible that, in some cases, even with improved thermal interface materials, the internal temperature rise from the case-to-chip-junction may be too large because of the projected increase in power. In such instances it may be necessary to resort to direct immersion cooling with a dielectric liquid contacting the chip. Such cooling schemes could take the form of single-phase liquid-impingement jet cooling, pool boiling, or two-phase liquid spray cooling. Spray cooling of electronics within an enclosure has been implemented in military systems and in supercomputer modules. Whatever form the application of direct liquid immersion cooling may take, the major requirement will be that it is done at a reasonable cost, is reliable and occupies the minimum possible packaging volume.

2.4 Refrigeration Cooling

Both large servers and workstations have employed vapor compression cycle refrigeration to lower temperatures of the processor. Current technologies exhibit improvements of approximately two percent for every 10°C reduction in chip temperature. With this technology, the evaporator is mounted directly on the processor module. The remaining hardware (i.e., compressor, condenser, valves, etc.) is typically packaged in a separate enclosure attached to the bottom of the system (workstation) or mounted inside the rack (servers). This technology has achieved chip temperatures in the range of -20 to 40°C.. As with water cooling, the major requirement is to develop a refrigeration cooling technology that is low-cost, reliable, and occupies a minimum volume within the system.

2.5 Thermoelectric Cooling

Thermoelectric coolers (TECs) offer the potential to enhance the cooling of electronic module packages to reduce chip junction temperatures or accommodate higher power. They also offer the advantages of being compact, quiet, and moving-parts-free—and they can provide an active control of temperature. TECs are limited in the magnitude of the heat flux that can be accommodated. TECs also exhibit a lower coefficient of performance (COP) than conventional refrigeration systems. The COP of a TEC will vary depending upon the usage conditions, but will typically be less than unity. This means that the electrical power consumed by the TEC will be as great as, and often more than, the power dissipated by the component being cooled.

These limitations are due to the currently available materials and methods of fabrication. As a result, thermoelectric devices have been restricted to applications characterized by relatively low heat flux.

Efforts are underway to improve the performance of TECs by the development of new thermoelectric materials and thin film coolers. If successful, these efforts promise increased heat pumping capability and higher COPs, which could open the door to a much broader application of thermoelectric devices to augment electronic cooling.

2.6 Thermal Materials

Heat removal, thermal stresses, warpage, weight, and cost are critical packaging issues. Traditional thermal management / packaging materials all have serious deficiencies. In general, traditional materials with high thermal conductivities have high CTEs, and materials with low CTEs have high densities and thermal conductivities that are similar or modestly better than that of aluminum. Chemical vapor deposition (CVD) diamond is a key exception. In response to this problem, an increasing number of advanced materials have been investigated, and some are available for use. These materials offer: thermal conductivities up to more than four times that of copper, CTEs that can be tailored from –2 to +60 ppm/K, electrical resistivities ranging from very low to very high, extremely high strengths and stiffness, low densities, low cost and net-shape fabrication processes.

The payoffs are: improved performance or simplified thermal design, reduced power consumption, and reduced thermal stresses and warpage. Use of CTE matched materials allows direct solder attachment with hard solders (hard solders have better fatigue resistance than soft solders and fewer metallurgical problems), increased reliability, improved performance, weight savings up to 90%, size reductions up to 65%, reduced electromagnetic emissions, increased manufacturing yield and potential cost reductions. In addition, advanced materials make it possible to have low CTE, thermally conductive PCBs that can greatly increase the range of conductive cooling (in the aerospace industry, heat is removed entirely by use of PCB cold plates) and convective cooling.

A number of advanced materials are now being used in commercial and aerospace applications including: servers, plasma displays, notebook computers, printed circuit boards (PCBs), PCB cold plates, radio-frequency (RF) modules, power modules and optoelectronic packages. The rate of growth in the use of these materials has been dramatic. Components include carriers, heat spreaders, heat sinks, thermoelectric cooler substrates, LED packages and laser diode packages.

A significant need exists for new fluids that can be used for indirect liquid cooling (replacing water). That fluid would need to provide safer, more reliable operation in hostile environments, and also lower-cost direct (immersion) liquid cooling for the broad range of potential applications in commercial and military systems.

The critical issue of cost is complex and must be considered in the context of total cost over system life. Efficacy and appropriateness are prime factors, but beyond that, other issues needing to be evaluated include: reliability, life, mean time between failures (MTBF) and maintenance-repair-operating costs. Many factors also play a role in cost, such as complexity, size, flatness, surface finish requirements, and production run size.

Cost effectiveness depends on a particular application. For example, higher price and higher performance systems such as high-end servers and aerospace systems can tolerate higher thermal component costs than mobile phones. A key issue is the cost of competing approaches. For example, if the alternative is liquid cooling, an advanced material that is more expensive than a traditional one may be cost effective if it allows the use of convective air-cooling.

2.7 Thermal Design Modeling and Tools

Sophisticated thermal design tools are now an essential element in the day-to-day design of electronic components, packages and systems. These tools take a variety of forms. Thermal conduction codes are used to model heat flow and temperatures within a package. Computational fluid dynamics (CFD) codes are used to model fluid flow around and through package assemblies—along with the associated pressure drop and heat transfer from exposed package surfaces to the fluid stream. In addition, some CFD and thermal conduction codes have conjugate capability, making it possible to model thermal conduction within the package structure simultaneously with modeling fluid flow and heat transfer in the cooling fluid.

Over the past decade, much has been done to improve the graphical user interface for problem definition and data input, especially with CFD codes tailored for use to model electronic equipment. Nonetheless, the industry needs further improvements to reduce the time consumed in defining the package geometry and structure and to enter related data preparatory to running a model. Seamless integration of computer-aided design (CAD) solid modeling tools, electronic design automation (EDA) tools, and CFD tools is needed to provide thermal designers the ability to take CAD solid-modeling-generated data and EDA-generated data and move them effortlessly into finite element thermal conduction modeling tools or CFD modeling tools.

Other needs requiring further effort:

- An improved ability to optimize thermal analysis codes for parallel processing to reduce solution time and provide the capability to model more complex thermal problems;

- A better way to enable CFD codes to better model turbulence and convective heat transfer in the transition flow regimes; and More extensive benchmarking to validate the accuracy of CFD codes.

3.0 Summary of Technology Gaps & Show-Stoppers

The thermal technology improvements needed for each product sector to fill gaps and avoid show-stoppers are summarized in *Table 1*.

Table 1: Thermal improvements needed by product sector [1].

Product Selector	Requirements
Common Needs	• Improved thermal interfaces. • Improved thermal spreaders. • High-performance air cooling solutions. • Advanced modeling tools. • 3D designs cooling: ability to insert heat spreaders and phase change layers.
Portable/Wireless	• No significant improvements needed as long as battery power remains constrained.
High-End Systems	• Thermal integration with electromagnetic compatibility (EMC) shielding. • Low-cost, compact and reliable water cooling. • Low-cost, compact, reliable and efficient refrigeration. • High heat flux, efficient thermoelectric cooler. • Mechanically robust packages that minimize the thermal resistance path to air. • Low-cost, compact, and reliable dielectric liquid cooling. • Abatement of heat load impact on installation. • Outdoor structure (sheds) for remote stations: use materials that can passively reduce the need for active heating, ventilating, and air conditioning (HVAC)/fan load. • Quieter fans with efficient airflow design.
Automotive	• Low-cost, reliable heat pipe technology for automotive environment. • Passive electrical components/system level packaging materials capable of operating at 150oC. • Low-cost liquid or refrigerant cooling systems utilizing automotive cooling components. • Low-cost, self-contained, phase change materials to handle transient thermal events. • Analog and digital ICs capable of operating with TJ = 175oC. • Power transistor capable of operating with TJ = 200oC.
Medical	• Low-cost, compact and reliable water cooling. • High heat flux, efficient thermoelectric cooler. • Low-cost, compact, and reliable dielectric liquid cooling.
LEDs	• Development of LED packaging with low thermal resistance. • Low-cost, compact, and reliable dielectric liquid cooling. • SSI LED products have color shifts and lower lifetime performance – develop thermal management technologies to dissipate heat associated with high brightness light sources. • SSI-specific software and modeling tools to optimize assembly of LED and organic light-emitting diode (OLED) SSI devices are limited – develop SSI-specific software for designing and fabricating LED light engines and light sources within environmental and thermal constraints.
Power Electronics	• Geometries of electrolytic capacitors and magnetic components should be optimized to transfer and exchange heat better. • To best take advantage of the SiC junction field effect transistors (JFETs) (capability for higher voltages and higher operating temperatures in contrast to silicon devices) packages must be improved: materials, inductive wiring, creepage distances, etc. • Overall lower thermal resistance within power electronics system, especially in solders, glues, etc. – silver sintering as an attachment medium is in early stages of commercial use, and may offer other benefits. • Heat spreading: reliability of joining of heat pipes needs improvement; MMCs (such as aluminium/carbon) should be explored. • For optimization of heat exchange to ambient developments in two-phase cooling, pumpless liquid loops.

Recommendations

The following constitutes the major cooling technology areas identified for development and innovation by the Thermal Management Roadmap:

- Low-cost, higher-thermal conductivity packaging materials, such as adhesives, thermal pastes and thermal spreaders, for use in products ranging from high-performance computers to automotive applications.
- Advanced cooling technology, such as high-performance heat pipe / vapor chamber cooling technology, thermoelectric cooling technology, direct liquid cooling technology, as well as high-performance air-cooling and air-moving technologies.
- Closed loop, liquid-cooling solutions, which are compact, cost-effective and reliable.
- High-performance cooling systems that will minimize the impact on the environment within the customer's room and beyond.
- Advanced modeling tools that integrate the electrical, thermal, and mechanical aspects of package / product function, while providing enhanced usability and minimizing interface incompatibilities.
- Advanced 3D packaging techniques that can effectively remove heat from die not directly in contact with the PCB / substrate.
- Advanced experimental tools for flow, temperature and thermo-mechanical measurements for obtaining local and in-situ measurements in micro-cooling systems.

It is further recommended that industry participants should pool resources to fund cooling technology development, promote the involvement of university / research labs and establish a closer working relationship with vendors. Finally, the industry needs to consider and evaluate changes in design processes to optimize system performance by (i) eliminating margin redundancies so costs may be minimized, and (ii) modified partitioning of component / system building blocks.

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About the Author

Azmat Malik is President of Acuventures and Chair of iNEMI's Thermal Management Technology Working Group (TWG) for the 2015 Roadmap. He will also chair the TWG chapter for the 2017 Roadmap. Work is scheduled to kick off February 10 on the 2017 edition. Participation is open to the industry, and anyone interested in getting involved with the next Thermal Management Roadmap should contact Azmat (azmatmalik@acuventures.com) or iNEMI (info@inemi.org).

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[1] Graphene has been shown to have unusually high thermal conductivity. Multiple layers of graphene show strong heat conducting properties that can be harnessed in removing dissipated heat from multilayer electronic devices. This has led to dramatic improvement in thermal characteristics, leading to lower temperatures even at higher processing speeds and higher power dissipation.

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ELECTRONICS COOLING IN THE AUTOMOTIVE ENVIRONMENT

Bruce A. Myers

Introduction

By 2008 the electronics content of a typical consumer vehicle had grown to 20-25% of the total vehicle cost [1]. This content provides a wide range of functions and features for today's driver. Some features such as the radio/audio system and instrument cluster are quite familiar and visible to the driver and have been mainstays in the automobile for many years. Other functions such as engine controllers and body computers (passenger comfort and convenience feature control) are less visible to the driver but are vital to the operation of the vehicle..

ELECTRONICS COOLING IN THE AUTOMOTIVE ENVIRONMENT

Introduction

The need for high reliability in the harsh automotive environment demands robust and capable cooling designs. These cooling systems need to be manufactured for the very high volume automotive market (> 60 million vehicles per year) at a low cost and with high quality. In addition to being environmentally friendly and recyclable, automotive electronic products also require maintenance-free operation during their greater than 10-year lifetime. The automotive electronics market is characterized by a wide range of vehicle types with varied functional content. Each of these vehicle types (motorcycles, light-duty cars or trucks, heavy duty on and off-road trucks, and construction or agricultural equipment) has a different range of environmental and operational requirements. There is also a wide range of electronic applications within each of these vehicle types including but not limited to: powertrain and emission controllers; vehicle body, antitheft, and comfort controllers; communication, navigation, display and entertainment systems; vehicle braking, traction/stability, steering, low tire warning, collision warning and airbag systems. Three product areas are currently seeing significant product proliferation: electric powertrain control for hybrid and electric vehicles, passenger and vehicle safety systems, and driver connectivity, including anti-distraction systems.

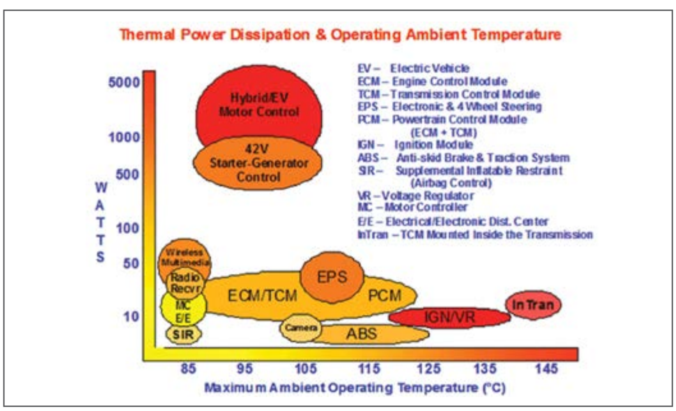

Figure 1.

Power Dissipation Challenges and Design Approaches

Most applications have waste power dissipation that ranges from milliwatts to 100 watts. However, waste heat for electric drive train controllers can be as high as several kilowatts. Also, electronic cooling designs are required to dissipate heat and be reliable in ambient temperatures ranging from -40°C to 150°C depending on the product mounting location within the vehicle. As a result, drivetrain applications require the use of high-performance cooling systems. The combination of high power dissipation and high ambient temperatures coupled with the previously discussed requirements for automotive applications create significant cooling design challenges. *Figure 1* shows the power dissipation/ambient temperature requirements for representative automotive electronic product families. Products mounted outside the passenger compartment are also exposed to a wide range of fluids, vibration, and thermo-mechanical shock conditions. *Figure 2* shows the full range of these vehicle environmental conditions.

Historically, most automotive electronics have been cooled convectively by ambient air. As indicated in *Figures 1* and *2*, maximum ambient air temperatures can vary significantly at various locations within the vehicle. As a result, even for products operating at comparable power levels, the design approach for electronics cooling will vary substantially in configuration and cost depending on the product mounting location within the vehicle. Whenever possible, the electronic product case, which in many instances is made of aluminum without cooling fins, is used as a thermal sink to ambient. If necessary, the case can be attached to a vehicle metallic structural member to conduct system heat to a larger surface area. Within the product enclosure, electronic devices are thermally attached to the case via thermally conducting grease or silicone pads, the choice being determined by the desired ambient-to-component junction temperature window. For power dissipations up to 30W, this approach can yield thermal resistance values for junction-to-case (θjc) in the 1°C/W to 2.5°C/W range, with case-to-ambient (θca) values of > 2°C/W.

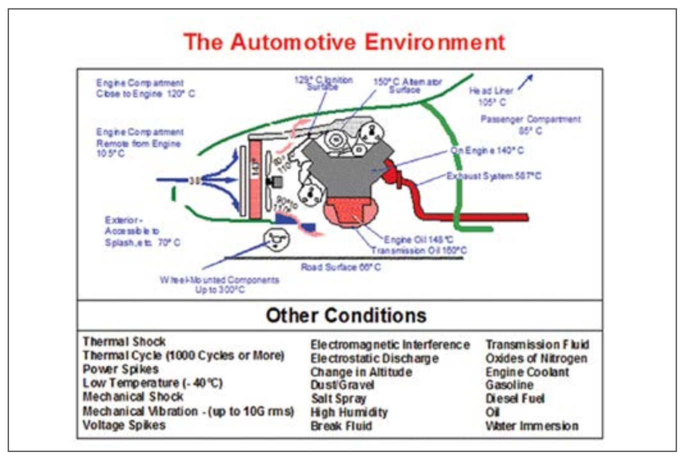

Figure 2.

As dissipation levels increase above 30 W, higher performance (higher cost) thermal interface materials and product case enhancements such as added cooling fins are required to reduce both θjc, θca into a range ≤ 1°C/W. In some instances, a bare chip die is attached to the product case with adhesives or thermal greases, which can also provide electrical isolation between the die and the case. *Table 1* shows the thermal resistance values of some typical semiconductor packages used in automotive applications.

An Evolving Thermal Management Landscape

Over the past decade, the automotive electronics thermal management landscape has changed dramatically with the advent of hybrid vehicle electric drive trains (see

Figure 3). The FET/IGBT semiconductor devices used in electrical power control systems, such as DC/AC inverters for electric motors and DC/DC converters for accessory power, can dissipate from several hundred watts up to tens of kilowatts of total power depending on the level of electric drive assist. Although conventional air cooling approaches can still be used for lower power mild hybrid vehicle assist systems, such as integrated starter/alternators, liquid cooling of the semiconductor devices becomes necessary for full hybrid systems. The most straightforward approach to cool these semiconductor devices is to use engine coolant, previously cooled by the vehicle radiator, flowing through cold-plates. In this situation, θjl (junction-to-liquid) thermal resistance values will be ≤ 0.5°C/W with maximum semiconductor junction temperatures of 150°C. However, this approach can add considerable cost, weight and volume to a hybrid vehicle drive system and there is a significant need for low-cost, high-performance cooling approaches.

For mild hybrid vehicles utilizing integrated starter/alternator systems, immersion cooling of power devices in a dielectric fluid has been used [3]. This is similar to the approach used for cooling the power system in locomotive engines in which the fluid provides convective and evaporative cooling. This method can reduce system volume and weight; however, ensuring fluid stability and containment integrity over vehicle lifetime presents additional technical and cost issues. Other possible approaches to liquid cooling include integrated liquid-cooled packages in which engine coolant is in contact with the electrically insulating power device substrate [4], or a secondary cooling loop using device packages where dielectric coolant flows directly over the power die [5]. These technologies can provide thermal resistance values of θjl < 0.2°C/W.

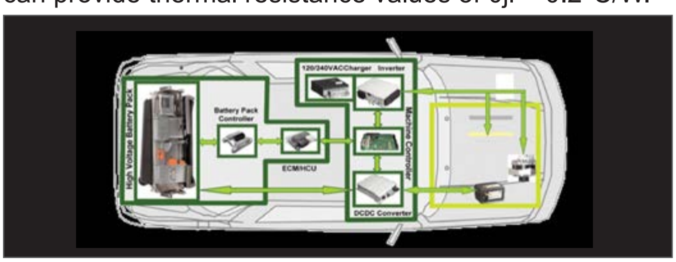

Figure 3. Electronics content of hybrid electric vehicle.

Many other components also require cooling. Bus capacitors and inductors can be effectively cooled by thermal conduction to the product case. The system battery pack can be cooled by forced-air convection through an appropriately designed package enclosure utilizing either ambient or passenger compartment air. In addition to air and liquid cooling technology, new developments in heat pipe/thermosiphon and thermoelectric cooling technology are being monitored.

Choosing Suitable Technologies and Materials for Cooling Structures

Just as crucial as the method of cooling are the materials used in cooling structures. Not only do they contribute to the thermal "stackup" resistance, packaging materials are also responsible for maintaining device integrity in a very demanding thermal environment. With power densities ranging from <1 W/cm2 to 400 W/cm2, the thermal management landscape in automotive electronics is very diverse. This requires a comprehensive approach for the selection of cooling technology, materials, and manufacturing processes.

A wide spectrum of compatible materials (metals, semiconductors, ceramics, plastics, composites and possibly dielectric fluids) are required for robust automotive thermal cooling systems. Many unusual materials with specific properties are required to provide critical performance functions including thermal conduction, insulation, fluid transport, surface passivation, bonding and sealing, structural support or low friction interfaces. Careful selection of these materials on the basis of cost, performance, stability and mutual compatibility requires a detailed understanding of their thermal, mechanical and chemical characteristics.

The key high-reliability requirements for operating temperatures spanning -40°C to 150°C are thermal performance and stability. Composite and polymeric materials must neither be brittle nor exhibit excessive thermal softening. A careful selection of material thermal expansion coefficient differences must be made to control possible bulk mechanical fatigue, fracture or delamination of electrical interconnect structures and bonded surfaces. The material combinations selected must also accommodate thermal shock caused by power spikes which can reach 30°C/sec ramp rates on or near silicon devices.

Similar to thermal creep and expansion is the concern for mechanical wear-out of seals and diaphragms at their interfaces. Thorough knowledge of material and function specifications coupled with experimental performance data can establish proper part geometries and the optimal material set for the required product life.

Thermal interface materials (TIMs) improve the thermal pathway at the interface of dissimilar materials by mitigating the effects of surface irregularities and air gaps. A variety of TIMs are available, such as semi-liquids, (thermal greases) and solid-state materials (pre-formed pads and curable TIMs) for this purpose. When using TIMs, potential areas of concern are mechanical pump-out of greases, dry-out of the continuous phase, and micro-structure fracturing.

When compared to radiation and conduction, liquid cooling offers improved thermal performance. The most common automotive cooling fluids are water-based. Water-based cooling fluids provide excellent thermal properties but also introduce significant design hurdles. Aqueous systems are notorious for promoting ionic corrosion. Additives and co-solvents address this concern and also provide freezing point depression and boiling point elevation while operating under pressures approaching 400 kPa (60 psi). However, high pressure and high flow rates in these fluid systems can cause mechanical wear of cooling system components.

In the future cooling systems may use heat transport fluids that come into direct contact with silicon power die. These high dielectric constant fluids (fluorocarbons) are not flammable and can be used in low pressure systems even under two-phase operation, but only provide a fraction of the heat transport capability of water-based systems. Chemical activity of these materials can be very low, but fluorine-based molecules pose significant compatibility issues with flexible tubing and many other halogen-based materials.

Therefore, it is important to use materials in the cooling system that have little to no interaction with these fluids.

Semiconductor Package Type	Std. 208 Leaded QFP on a PCB	256 Leaded BGA on a PCB	TO-220 Transistor with Electrical Isolation	Flip Chip with Top of Chip Heat Sinking	Custom High Power Transistor Package
Thermal Resistance	30-50 °C/W (j-a)	30-40 °C/W (j-a)	1-2 °C/W (j-c)	0.5-1.0 °C cm2/W (j-c)	<1 °C cm2/W (j-c)

Table 1. Typical Semiconductor Thermal Resistance (°C/W) or Unit Thermal Resistance (°C cm2/W) Values

Materials and Concerns	Thermal	Mechanical	Stability	Fluid Compatibility	Other	Environment
Metals	Thermal Resistance	Fatigue		Oxidation/Corrosion with Aqueous Systems	Mass	
Thermal Interface Materials	Thermal Resistance	Cracking, Pump-out	Dry-out	Leaching	Cost	
Electrical Interconnects		Fatigue				
Silicon		Brittle, Low CTE				
Insulators/Plastics		Fatigue	Brittle or Too Soft	Leaching or Swelling		
Adhesives/ Bonding	Thermal Resistance	Delamination, Cracking		Epoxy Very Good, Silicones Poor	Heat Cure	
Elastomers/Seals		Mechanical Wear		Swelling	Cost	Leakage

Typical Semiconductor Thermal Resistance (°C/W) or Unit Thermal Resistance (°C cm2/W) ValuesTypical Semiconductor Thermal Resistance (°C/W) or Unit Thermal Resistance (°C cm2/W) Values

Plasticizers and oligomers can be leached from flexible tubing or halogen-based seal materials and then deposited onto critical heating surfaces by the working fluid. Even low level absorption (~5%) of the fluids can cause material swelling, which indicates softening of the barrier material, dimensional change, and increased permeation of gases through the barrier. Dielectric fluids can absorb significant amounts of gases, especially carbon dioxide, which will evolve when the fluid is heated. Rapid de-aeration of the fluid will compromise the heat transport efficiency. Triboelectric materials in contact with a fast flowing dielectric fluid can also be an electrostatic discharge (ESD) generation concern. Conductive and semi-conductive materials (solids) may be used to control this ESD generation. *Table 2* summarizes many of the cooling system material selection concerns.

Conclusion

Most cooling system compatibility issues are those germane to the interior of the system. Externally, dust, debris and automotive fluids can foul heat exchanger surfaces and reduce heat transport efficiency.

Automotive electronic products are required to be reliable and maintenance-free in harsh operating environments for periods exceeding 10 years. However, these products also have to be produced in high volumes and at low cost. Some applications, such as hybrid vehicle drivetrain electronics, require liquid-cooling systems that can dissipate power levels exceeding 1 kW. The combination of these requirements is unique when compared to other consumer, commercial and aerospace electronic products. As a result, the design of the cooling systems required for automotive electronic applications demands careful technology development as well as long term material reliability and compatibility evaluations to ensure robust and reliable operation.

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ADVANCED COOLING FOR POWER ELECTRONICS

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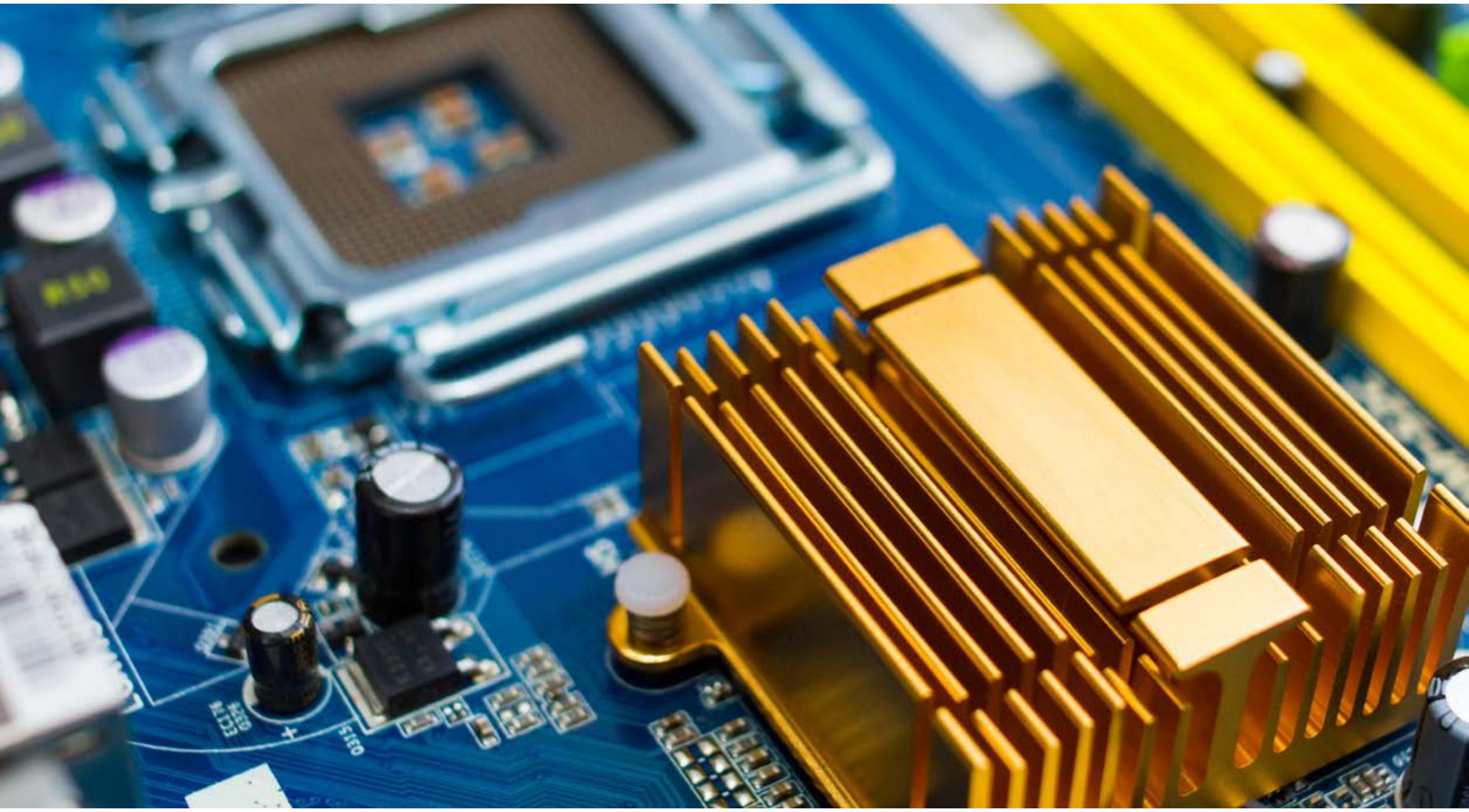
Abstract
Power electronics devices such as MOSFET's, GTO's, IGBT's, IGCT's etc. are now widely used to efficiently deliver electrical power in home electronics, industrial drives, telecommunication, transport, electric grid and numerous other applications. This paper discusses cooling technologies that have evolved in step to remove increasing levels of heat dissipation and manage junction temperatures to achieve goals for efficiency, cost, and reliability. Cooling technologies rely on heat spreading and convection. In applications that use natural or forced air cooling, water heat pipes provide efficient heat spreading for size and weight reduction. Previous concepts are reviewed and an improved heat sink con-cept with staggered fin density is described for more isothermal cooling. Where gravity can drive liquid flow, thermo-siphons provide efficient heat transport to remote fin volumes that can be oriented for natural and/or forced air cooling. Liquid cold plates (LCP's) offer the means to cool high heat loads and heat fluxes including double sided cooling for the highest density packaging. LCP's can be used both in single phase cooling systems with aqueous or oil based cool-ants and in two-phase cooling systems with dielectric fluids and refrigerants. Previous concepts are reviewed and new concepts including an air cooled heat sink, a thermosiphon heat sink, a vortex flow LCP and a shear flow direct contact cooling concept are described.



ADVANCED COOLING FOR POWER ELECTRONICS

Introduction

Power electronics devices and systems are vital in the ef-ficient generation, transmission and distribution, conver-sion, and a huge variety of end uses of electric power. More and more applications are adopting power electron-ics technologies to improve energy efficiency, reliability, and control and it is anticipated that in the fu-ture all elec-trical power will flow through a power semi-conductor de-vice at least once [1]. The state of art and future trends in power semiconductors and devices is re-viewed in [2, 3]. Silicon remains the workhorse material for power semi-conductors and to avoid device failure due to thermal run-away, effective cooling is critical. *Figure 1* shows the maximum safe junction temperatures for silicon devices [2]. Wide band gap semiconductors like SiC and GaN of-fer the advantage of high temperature operation. Howev-er, available packaging technologies, passives and periph-eral components, solder materials, reliability considera-tions and cost presently limit the junction temperatures to ~175 oC even though the semi-conductor device can, in principle, operate at much high-er junction temperatures [4]. The maximum safe junction temperatures in SiC could exceed 300 oC [5] so that even in high ambient temperatures, sufficient cooling may be provided by smaller and lower cost heat sinks resulting in improved volumetric power density.

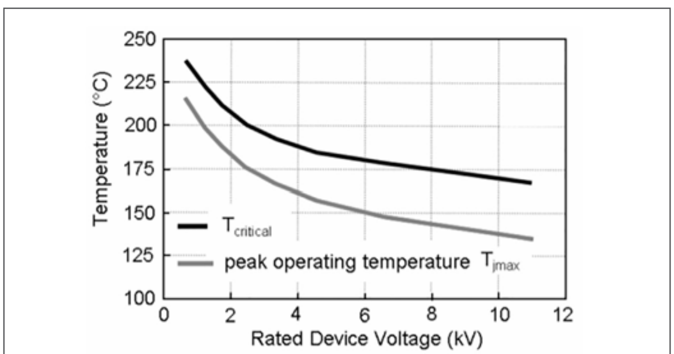


Figure 1. Critical thermal runaway temperature and esti-mated maximum safe operating temperature of Silicon devices [2]

A number of thermal management solutions in use for cooling power electronic modules in automotive appli-ca-tions are reviewed in [6, 7]. The coolant in such appli-ca-tions is available at temperatures above 100 oC so cooling must be accomplished with a low temperature difference between the semiconductor and the coolant. Many highly integrated cooling solutions are presented in [6] focused on the thermal management challenges in this severe ap-plication. Similar cooling concepts can be applied also to other applications like industrial drives, wind power con-verters, HVDC power transmission etc. depending on the constraints of each application. Various packaging de-signs and cooling solutions for reducing the thermal re-sistance of high power modules are de-scribed and com-pared in [8]. With micro-channel liquid cold plates [9, 10] the cold plate thermal resistance can be reduced to such an extent that the internal thermal resis-tance of the electronics package becomes the dominant thermal re-sistance. Phase change cooling using forced convection boiling of refrigerant fluids in cold plates is de-scribed in [11] including the more isothermal operation that comes from using the latent heat rather than the sensible heat of the coolant to provide the cooling effect.

Cooling solutions in use today include:

- Natural and forced convection air cooled heat sinks
- Single and double sided cooling with liquid cold plates
- Micro-channel liquid coolers built into power module base plates or integrated with the DBC substrate
- Jet impingement and direct contact liquid cool-ing of module base plates or DBC substrates
- Two-phase liquid cold plates with boiling of die-lectric refrigerant coolant

With the exception of underwater or marine applications, heat removed from electronics systems is ultimately dis-sipated to the air. Systems with air cooled heat sinks dis-sipate heat directly into the air that flows through the sys-tem either by natural or forced convection. Systems that use liquid cooling transfer heat from the electronics into the liquid that in turn transfers the heat to air in a liq-uid-to-air heat exchanger such as an automotive radiator. In two-phase systems, heat from the power electronics trans-forms liquid into vapor by boiling or evaporation and the vapor is then returned to liquid phase when it trans-fers heat to the air in an air cooled condenser.

This paper reviews some of the existing cooling solutions and presents new concepts for an air cooled heat sink, loop thermosiphon heat sink, a liquid cold plate, and a di-rect liquid cooling concept. Approximate performance levels are also presented.

Power Module Packages

Figure 2 shows two common packages used for power modules. The IGBT module on the left is commonly used in applications below 6.5 kV and exposes one flat sur-face for “single sided” cooling. The other module is well suit-ed for stacking in series for high voltage applications and provides both top and bottom surfaces for “double sided” cooling. Both these modules are designed to be mechani-cally bolted to heat sinks or liquid cold plates.

Figure 2. IGBT packages for single and double sided cooling

Interest in hybrid car and railway applications in recent years have led to customized packaging solutions with double sided cooling from Alstom [12], Denso [13] and oth-ers. These modules are shown in *Figure 3*. A number of other packaging concepts and related cooling solutions have previously been discussed in [6].

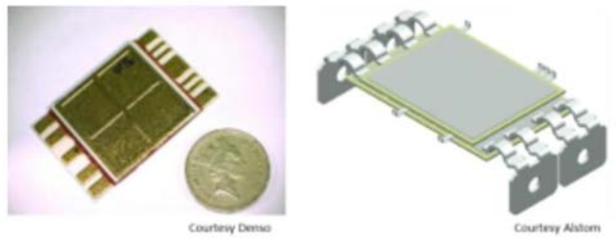


Figure 3. Custom power module designs for double sided cooling

Figure 4 shows a schematic of a standard power semi-con-ductor package mounted on a heat sink for cooling and the corresponding thermal resistance network. The key parameter for device cooling performance is the junc-tion-to-air thermal resistance, R_{ja}. This is the sum of the inter-nal thermal resistance within the device package, R_{jc}, the interface thermal resistance from the device to the heat sink, Rcs, and the heat sink to air thermal resis-tance, R_{sa}.

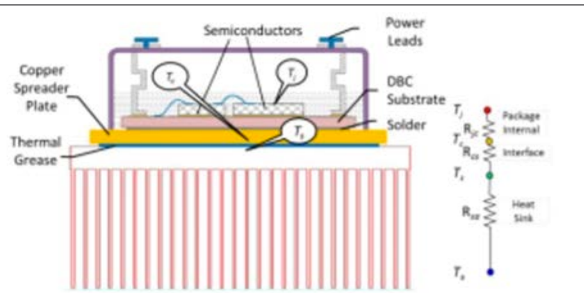


Figure 4. Schematic of standard IGBT package on a heat sink and key thermal resistances

The heat sink thermal resistance can be expressed through the following equation commonly used in heat exchanger design literature [14].

$$R_{sa} = \frac{1}{\dot{m}c_p\left(1-e^{-\frac{hA}{\dot{m}c_p}}\right)} \quad (1)$$

An examination of *equation (1)* shows that the heat sink thermal resistance can be improved by increasing the mass flow rate $\dot{m}$ of the fluid through the heat sink (e.g. forced convection rather than natural convection), the heat capacity c_p of the fluid (e.g. a liquid versus a gas), the heat transfer coefficient h on the heat sink surface (e.g. smaller channel dimensions like micro-channels, turbu-lent flow using turbulators and boundary layer inter-rup-tion rather than laminar flow, two-phase mechanisms such as evaporation and condensation rather than single phase convection) and the effective heat transfer area A. The ef-fective area is the actual heat transfer area in contact with the cooling fluid multiplied by the heat trans-fer efficiency of the surface (e.g. fin efficiency.) Area en-hancement by using closely spaced fins and small scale flow channels

(e.g. micro-channels) is the focus of many new devel-op-ments in heat sink manufacturing technologies.

The term in the parenthesis in *equation (1)* is the ef-fec-tiveness of the heat sink and is defined as follows

$$\epsilon = \frac{T_O-T_i}{T_S-T_i} \quad (2)$$

From *equation (1)* we can see that improving the effi-cien-cy of the heat transfer surface (making it more iso-thermal) will improve the effective area *A* and therefore the effec-tiveness $_E$ of the heat sink. This is also evident in equation (2) by noting that a more isothermal surface im-plies a smaller value of T_s in the denominator. The surface effi-ciency includes both the heat spreading resistance in the base and the fin efficiency of the fins.

Forced Air Cooled Heat Sinks

Table 1 shows an example of thermal resistances in the path from the IGBT dies to the air for the aluminum forced air cooled heat sink illustrated in *Figure 5*. The heat sink base is 236 x 230 mm in size and cools one econo-pack IGBT module (162 x 122 mm) with a DBC substrate sol-dered to a 3 mm thick copper heat spreading base. Alumi-num fins are pressed into grooves in the alu-minum base. The IGBT module is mounted on the heat sink using ther-mal grease to reduce thermal interface re-sistance. Air flow rate through the heat sink is 0.25 m3/s at 25 oC and 1 Bar and the IGBT dissipates a total of 2kW of heat.

Stack-up layer	Thickness (mm)	Resistance (°C/kW)	Resistance Percentage of total
Silicon	0.2	0.6	1.3%
Silver	0.1	0.2	0.4%
Copper	0.3	0.2	0.5%
Al-Oxide	0.38	4.0	9.7%
Copper	0.3	0.2	0.4%
Solder	0.1	0.6	1.3%
Copper base plate	3	0.7	1.6%
Thermal Paste	0.05	4.2	10.0%
HS-Base spreading	20	12	28.9%
HS-Fins convective	110	19	45.8%
Total		41.5	100%

Table 1 Approximate thermal resistances in IGBT air cooled assembly shown in Figure 5.

Data in *Table 1* shows that almost 30% of the thermal re-sistance is due to inefficient heat spreading in the base. With guidance from *equations (1) and (2)*, the base can be made more isothermal to reduce the heat sink thermal re-sistance. *Figure 6* shows an example of a heat sink with a copper base to improve heat spreading. For the same fin configuration as *Figure 5*, a copper base would enable an ~40% reduction in the spreading resistance in *Table 1* from 12 oC/kW to 7 oC/kW or a 10 oC reduction in junc-tion temperature.

Table 1 shows that the solder layer, copper base plate, and paste comprise 50% of the thermal resistance not associ-ated with the heat sink. This is even more significant in liquid cooling where the liquid cold plate resistance is ~0.1 to 0.2X the air cooled heat sink.

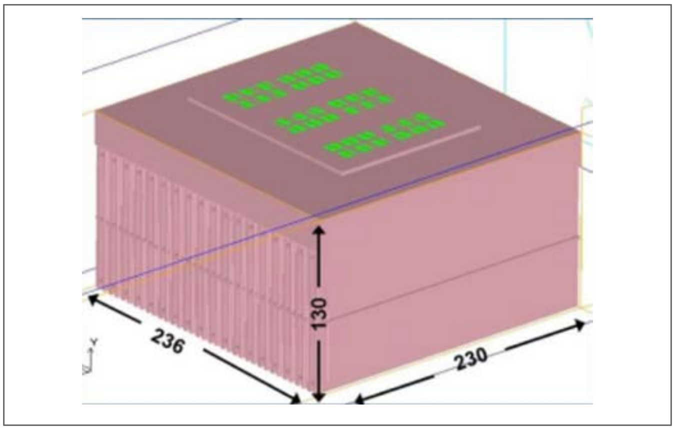


Figure 5. Illustration of IGBT module attached to an alu-minum press-fin forced air cooled heat sink

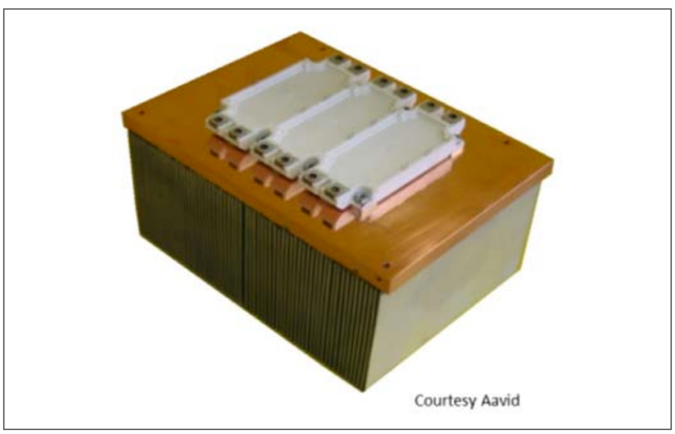


Figure 6. Air cooled heat sink with copper base

Figure 7 shows an example of a heat sink with heat pipes embedded in the aluminum base. The copper-water heat pipes use copper powder wick and are embedded in the base using Aavid's hi-contact technology. The heat pipes are oriented along the fin direction to even out the front to back temperature gradient due to heat up of the air. An ~60% reduction in the spreading resistance to 5 oC/kW or a 14 oC reduction in junction temperature can be achieved. The better heat spreading with heat pipes is achieved at a smaller heat sink mass compared to using a copper base. Recent advances using carbon nanotubes

grown on copper mesh and powder wick enable heat fluxes in excess of 500 W/cm2 [15] and reduction in thermal resistance. Such nanotechnology is expected to be avai-la-ble in commercial products based on market demands.

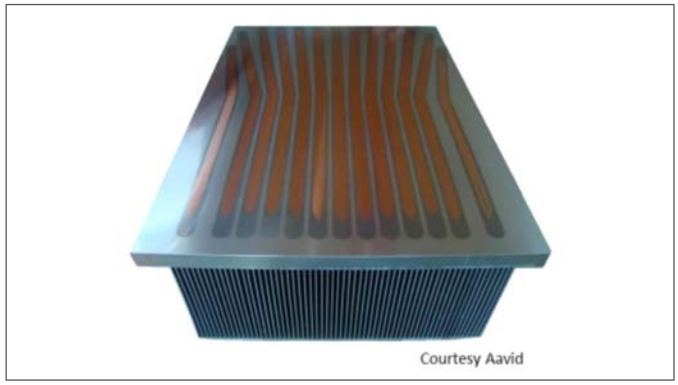


Figure 7. Air cooled heat sink with heat pipes embedded in an aluminum base

A further advance in heat sink performance is achieved if the press-fin joint is replaced by a metallurgical joint made by soldering or brazing the fins to the base. This decreases the thermal resistance by ~4 oC/kW enabling an additional ~8 oC reduction in junction temperature. Both the heat sinks pictured in *Figures 6 and 7* incorporate such an improved base to fin joint.

A recent innovation consists of a heat sink design with fin density increasing in the flow direction as shown in *Figure 8*. The fin surface area is lowest in the upstream re-gion where the cold air enters the heat sink and increases in a stepped fashion towards the downstream region as the air heats up. In this way, the base of the heat sink can be kept more isothermal so that power modules mounted at different distances from the edge where the air enters can be cooled to similar temperatures. Furthermore, the total pressure drop through the heat sink and the total mass is reduced because of the lower fin density in the upstream region. This type of design is manufactured by bonding or brazing the fins to the base.

Loop Thermosiphon Air Cooled Heat Sinks

The heat sink concepts discussed thus far position the heat sink to air heat transfer surface area in the physical space adjacent to the power module. This can limit the electrical design and packaging flexibility of the power electronics system. Heat pipes have been used to extend the heat sink fins some distance from the heat sink base but when grav-ity can be used advantageously, two-phase thermosiphons can provide a higher performance solution. The simplest thermosiphons are just gravity aided heat pipes with a groove type wick surface. In this type of design, the vapor flow in the tube is in the opposite direction to the liquid flow along the wall of the tube. This limits the maximum power that can be carried because of liquid entrainment in the high velocity vapor flow [16]. A loop thermosiphon avoids this limitation by transporting vapor in one tube and returning the condensed liquid through another tube.

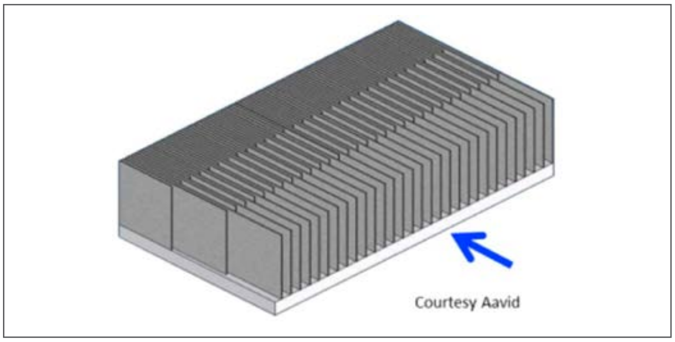


Figure 8. Advanced heat sink with increasing fin density along air flow direction

Figure 9 shows an air cooled heat sink that uses a loop thermosiphon to transport heat away from the immediate space around the power electronics package. An evap-ora-tor is provided with a flat surface where the power mod-ule is mounted and an enhanced boiling surface on the inside to enhance heat flux capability and reduce thermal resistance. The air cooled condenser is similar to an au-tomotive radiator with vapor flow inside extruded flat aluminum tubes and aluminum folded fins outside the tubes to provide a large cooling surface area on the air side. The liquid in the evaporator of the thermosiphon ab-sorbs heat from the electronics module and changes into its vapor phase. Vapor travels through the vapor tube to the condenser where it rejects heat to the air and con-dens-es back into liquid phase. The liquid condensate then re-turns to the evaporator through the liquid return tube to complete the cycle.

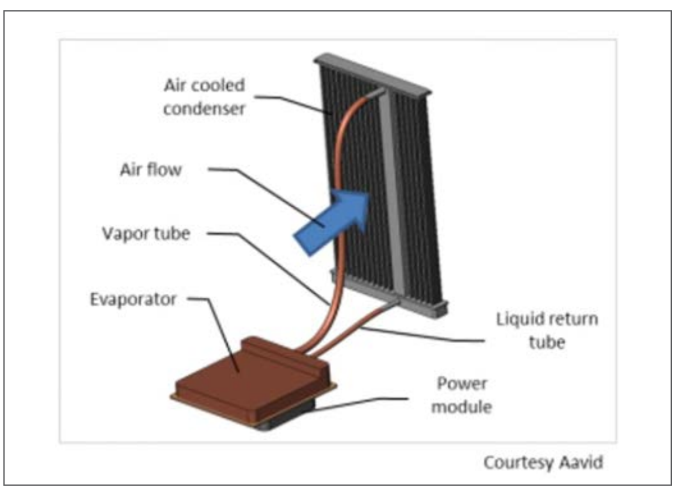


Figure 9. Air cooled heat sink using loop thermosiphon

Thermal resistance of the thermosiphon heat sink can be determined by using the heat transfer coefficient of the boiling surface inside the evaporator per *Figure 10* and a condensation heat transfer coefficient of ~1 kW/m2-K in-side the condenser tubing. Assuming a 122 x162 mm IGBT dissipating 2 kW of heat, the heat flux on the evap-orator wall is ~10 W/cm2 and the boiling heat trans-fer co-efficient is ~5.5 W/cm2-K. Including a 3 mm thick copper wall thickness, the evaporator thermal resistance is 1.3 oC/kW. Assuming a 230 x 230 mm by 30 mm thick air cooled condenser with 0.25 m3/s air flow rate (same as in *Table 1*), the estimated condenser thermal resistance is 9.1 oC/kW so that the total thermal resistance Rsa is 10.4 oC/kW, about a third of the 31 oC/kW value for the press-fin heat sink studied in *Table 1*. This huge improvement in thermal performance comes with the added benefits of lower mass, lower pressure drop, and an essentially iso-thermal heat sink base for good static current balance be-tween parallel IGBT dies.

The main limitation of the two-phase loop thermosiphon is that it is not suitable for moving platforms such as au-to-mobiles where external body forces other than gravity could potentially move the liquid out of the evaporator and cause dryout.

Since the working fluid inside the thermosiphon is di-elec-tric, in principle the power semiconductor can be im-mersed inside the fluid in the thermosiphon. *Figure 11* shows a prototype thermosiphon heat sink based on this type of "immersion cooling" concept [17]. Periodic two-phase thermosiphons can transport heat against gravity using vapor pressure to drive the flow [18].

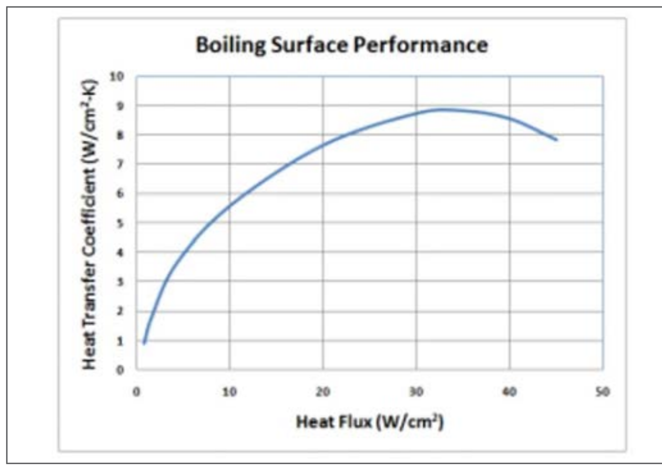


Figure 10. Heat transfer coefficient on thermosiphon evaporator boiling surface

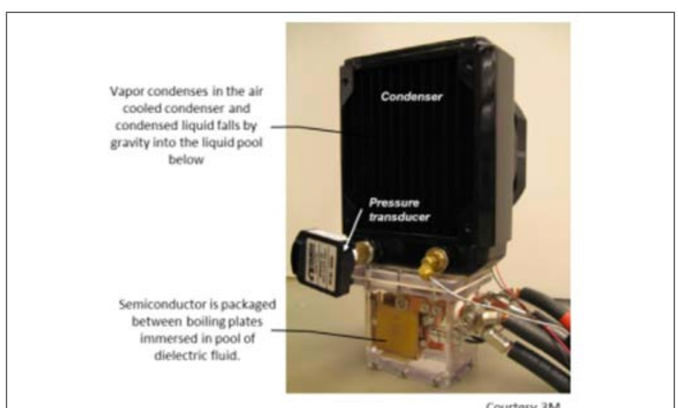


Figure 11. Thermosiphon air cooled system with power electronics immersed in dielectric fluid. IGBT is clamped between enhanced boiling plates.

Liquid Cooled Cold Plates

In liquid cooled systems, liquid cold plates provide lo-cal-ized cooling of power electronics by transferring heat to liquid that then flows to a remote heat exchanger and dis-sipates the heat to air or to another liquid in a sec-ondary cooling system. Liquid cold plates provide more efficient cooling and enable greater levels of integration and major reductions in the volume and weight of pow-er electronics systems. Existing and emerging liquid cold plate solutions in 2008 were extensively reviewed in [6] in-cluding:

- Tube type and fin type liquid cold plates to cool pack-ages with DBC substrates with and without copper base plates.
- Liquid flow through fins formed directly on copper and AlSiC base plates.
- Single and double sided cooling using liquid jet im-pingement.
- Direct cooling of the base plate or DBC substrate us-ing concepts such as the Danfoss "shower pow-er" design using jet impingement or liquid flow through meandering channels.
- Direct double sided cooling of back to back mod-ules with and without fins integrated with DBC substrates.
- Micro-channel coolers built into base plates or in-te-grated with DBC substrate or into specially cus-tomized package designs.
- Stacked power modules and liquid cold plates us-ing extruded channel type, folded fin type and mi-cro-channel type cold plates.

The paper [6] showed the great potential for achieving very high levels of cooling performance and system inte-gra-tion using liquid cold plates.

As noted earlier, *equation (1)* guides us towards higher heat transfer coefficients using turbulent flow or small channel dimensions such as micro-channels to reduce thermal resistance. Two recently developed concepts that apply these principles effectively are presented next.

In many applications where liquid filtration is not desira-ble, flow channels are required to be of a sufficiently large size (~2-3 mm) to avoid clogging by particles and precipitates in the cooling liquid. High liquid velocities and turbulator inserts are commonly used to enhance the heat transfer coefficient in such large size channels in-cluding in tube type liquid cold plates. This type of ap-proach provides limited opportunity for heat transfer area enhancement. An alternative approach developed recently [19] uses heli-coidal flow paths to create strong secondary flow with high vorticity to achieve high heat transfer co-efficients at the flow channel wall and parallel flow paths to reduce liquid velocities and the corresponding pressure gradient. Area enhancement is achieved by orienting the helical path so that its axis is normal to the base. This de-sign concept, named the "vortex liquid cold plate" or VLCP, is shown in *Figure 12* in the double sided cooling version. This design is ideal for cooling a stack of press pack IGBT's, thyristors or diodes in series as shown in *Figure 13*.

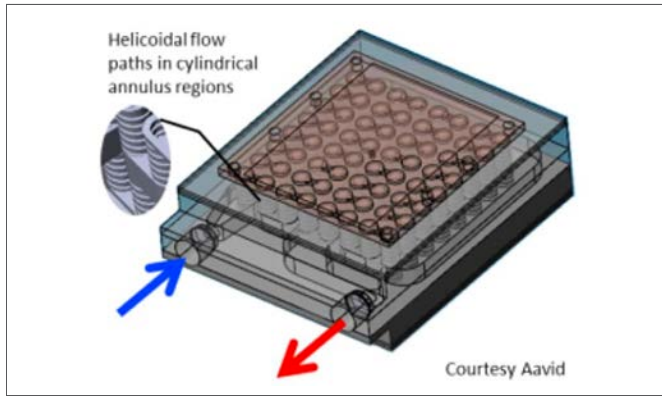


Figure 12. Vortex Liquid Cold Plate in a double sided cooling version.

In the example considered to illustrate performance, an IGBT dissipating 1600 W is attached to each side of the VLCP with thermal grease at the interface. The IGBT base plate size is 140 x190 mm and uniform heat flux is as-sumed on the VLCP over the IGBT contact area. Cool-ing is provided by a water-glycol coolant with 50% gly-col by volume flowing at 11 liters per minute (LPM) at a temperature of 80 oC at the cold plate inlet. Under these conditions, the maximum temperature on the cold plate surface is 91.5 oC, yielding a thermal resistance of Rsf = 3.6 oC/kW. Using *equation (2)*, the effectiveness is 47%. By comparison, the thermal resistances of suitable tube type and offset folded fin type liquid cold plates for the same application conditions were 19 oC/kW and 5.6 oC/kW respectively. The pressure drop of the VLCP was 52 kPa versus 10 kPa for the tube type and offset folded fin type designs.

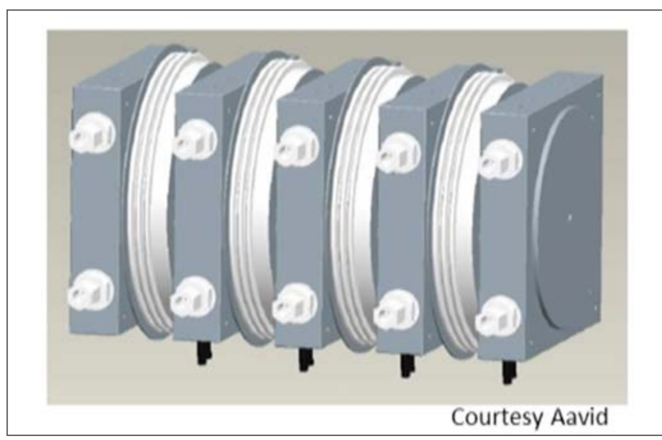


Figure 13. Stack of press pack diodes cooled using Vortex Liquid Cold Plates

For liquid cooling systems where liquid filtration is pos-sible, high heat transfer coefficients may be obtained us-ing high shear flow in narrow channels. *Figure 14* shows a high shear direct contact (HSDC) cooling approach us-ing a cooling plate that enables direct contact between the liquid and the surface to be cooled. An elastomeric O-ring (not shown) is provided between the cooling plate and the electronic package to seal the liquid flow volume. Liquid is distributed through a highly parallel manifold system and made to flow at a low velocity through narrow flow channels in direct contact with the surface to be cooled as shown in *Figure 15*. Ribs (not shown) are provided on the surface of the cooling plate that contact the cooled surface and set the height of the narrow flow channels. The com-bination of low liquid velocity and small channel height insures laminar flow in the channels. By adjusting the spacing between the liquid supply and return channels in the manifold, the flow length of the cooling channels and liquid velocity can be set to achieve the desired pressure drop characteristics.

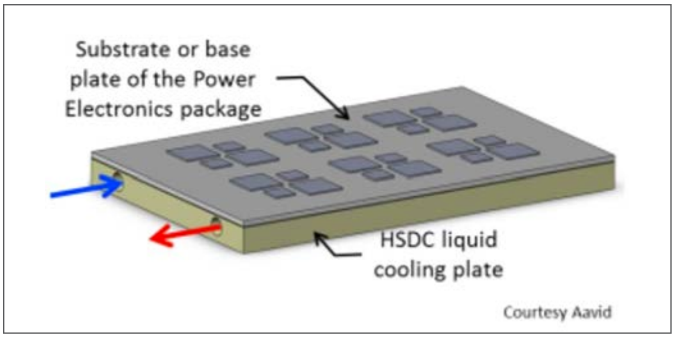


Figure 14. Liquid cooling of Power Electronics package using High Shear Direct Contact concept

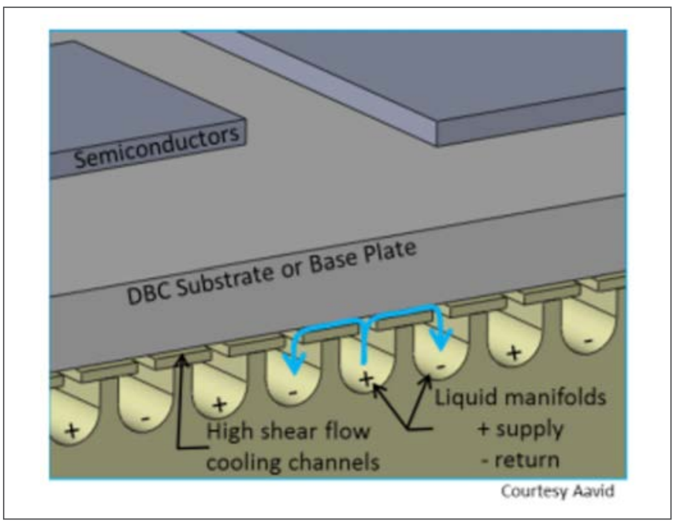


Figure 15. High shear flow cooling channels and flow pat-tern in the HSDC liquid cooling plate

It is obvious that the HSDC cooling plate may be designed to provide double sided cooling so that power electronics devices may contact the cooling plate on both the top and bottom surface. Furthermore, depending on the requirements of the application, the cooling plate may be made from non-conducting plastic or electrically conducting metal.

An attractive feature of the HSDC design is that the incoming cold liquid is supplied uniformly to cooling channels over the whole cooling plate so that temperature gradients over the power electronics package are considerably reduced. In its simplest implementation, there is no area enhancement on the base plate. However, the design can work well with enhanced surfaces as well. *Figure 16* shows the heat transfer coefficient on a flat base plate depending on flow channel height assuming fully developed laminar flow in the channels. The actual heat transfer coefficient will be higher because of entrance length effects.

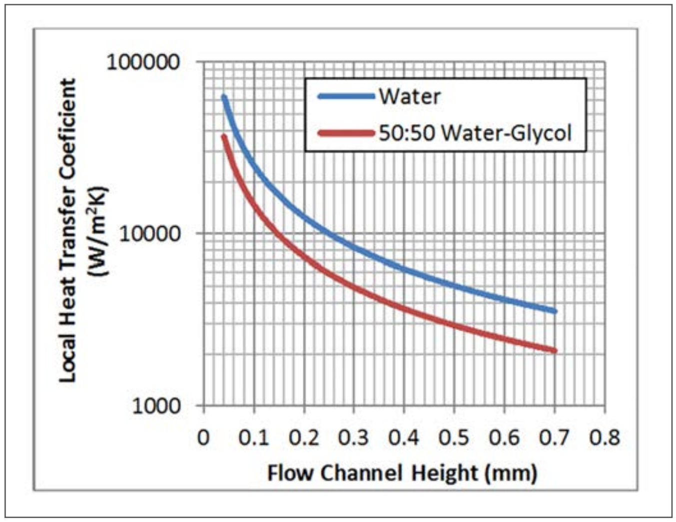


Figure 16. Local heat transfer coefficient on power mod-ule base plate at 80 C coolant temperature

We will use the same application example as for the VLCP to illustrate the performance of the HSDC liquid cooling concept in a double sided cooling configuration. The liquid contact area with the IGBT base plates on each side is 140 x190 mm and uniform heat flux is assumed over this area. Cooling is provided by a water-glycol coo-lant with 50% glycol by volume flowing at 11 LPM at a temperature of 80 oC at the cooling plate inlet. We assume a flow channel height of 0.15 mm so that the local heat transfer coefficient is ~9800 W/m2K. From *equation (1)*, the thermal resistance is ~2.8 oC/kW so the maximum temperature rise on the cooled surface relative to the li-quid inlet temperature will be ~9 oC. Assuming each flow channel is 10 mm long, average liquid velocity in the channels will be ~0.5 m/s and the pressure drop will be ~3-5 kPa. This level of performance is very competitive with the other cold plate designs mentioned earlier but this concept does require coolant filtration to avoid clog-ging the very narrow channels. By reducing the flow channel height, the thermal resistance can be improved even further but at the expense of higher pressure drop.

Conclusions

Significant advances have been made in cooling techno-logy for power electronics. This paper has discussed im-provements in applications ranging from air cooling to liquid cooling. A simple equation was described to helps guide design choices. Copper bases and heat pipes em-bedded in bases can significantly improve heat spreading in air cooled heat sinks. Even more dramatic gains can result from using loop thermosiphons to more efficiently pick up heat over the full base area in contact with the power module and passively transport the heat for dissipa-tion in an air cooled condenser. New liquid cold plate concepts are discussed that are well suited for single side cooled packages as well as double sided cooling of stacked press-pack type modules. Performance estimates are provided through application examples.

Emerging nanotechnology is mentioned that has the po-tential to significantly improve thermal performance of evaporative and boiling surfaces in future products. Although reliability of some technologies need to be proven, it seems that cooling technology will keep up nicely with increasing power dissipation levels and compactness of power electronics.

Acknowledgments
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Nomenclature

Q	Heat Load (W)
R_{ja}	Junction to air inlet thermal resistance [= (Tj-Ta)/Q (oC/W)]
R_{sa}	Heat sink contact surface to air inlet thermal re sistance [=(Ts-Ta)/Q (oC/W)]
R_{sf}	Heat sink contact surface to fluid inlet thermal re sistance [=(Ts-Tf)/Q (oC/W)]
R_{cs}	Thermal interface resistance [=(Tc-Ts)/Q (oC/W)]
T	Temperature (oC)

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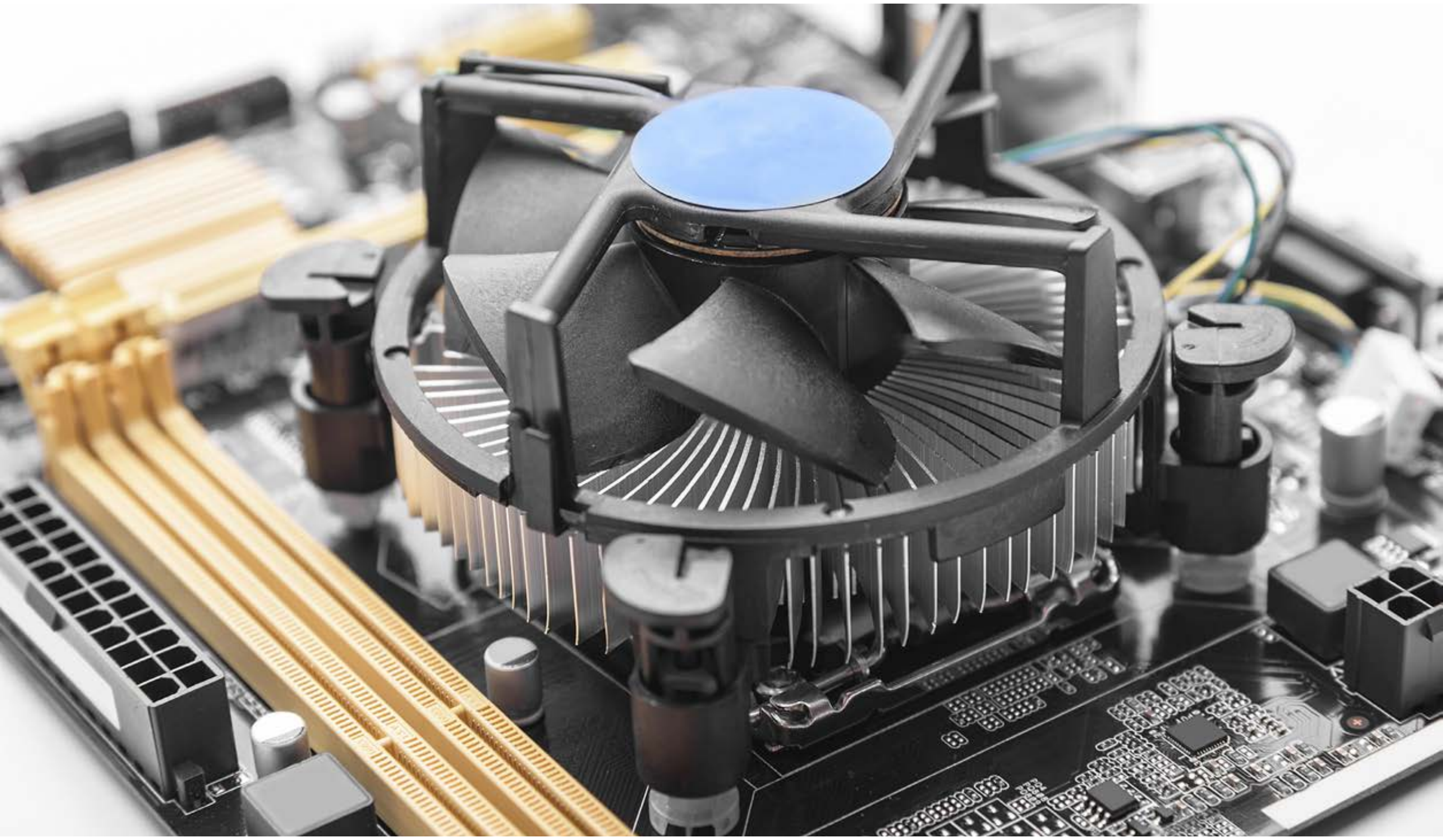
ADVANCES IN HIGH-PERFORMANCE FOR ELECTRONICS

Clemens J.M. Lasance

Introduction

The need for new cooling techniques is driven by the continuing increases in power dissipation of electronic parts and systems. In many instances standard techniques cannot achieve the required cooling performance due to physical limitations in heat transfer capabilities. These limitations are principally related to the limited thermal conductivity of air for convection and copper for conduction.



THERMAL MANAGEMENT – ENABLED PRODUCTS AT CES 2017

Introduction

Figure 1 shows a comparison of various cooling techniques as a function of the attainable heat transfer in terms of the heat transfer coefficient. To accommodate a heat flux of 100 W/cm^2 at a temperature difference of 50 K requires an effective heat transfer coefficient (including a possible area enlarging factor) of 20,000 W/m^{2}K. From *Figure 1* it can be concluded that there will be a need for liquid cooling in the future of thermal management. This article briefly discusses a number of promising thermal management technologies that are emerging for possible electronics applications.

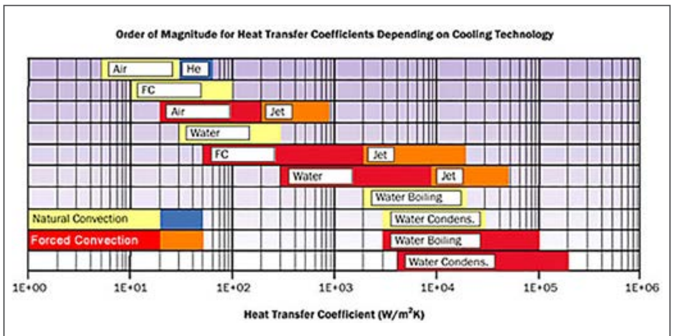


Figure 1. Heat transfer coefficient attainable with natural convection, single-phase liquid forced convection and boiling for different coolants [1].

Conduction and Heat Spreading

In all cooling applications, heat from the device heat sources, must first travel via thermal conduction to the surfaces exposed to the cooling fluid before it can be rejected to the coolant. For example, as shown in *Figure 2*, heat must be conducted from the chip to the lid to the heat sink before it can be rejected to the flowing air. As can be seen thermal interface materials (TIMs) may be used to facilitate thermal conduction from the chip to the lid and from the lid to the heat sink. In many cases heat spreaders in the form of a flat plate with good thermal conductivity may be placed between the chip and lid to facilitate spreading of the heat from the chip to the lid or heat sink. Vapor chambers are also used to spread heat from a concentrated chip or module heat source to a larger heat sink.

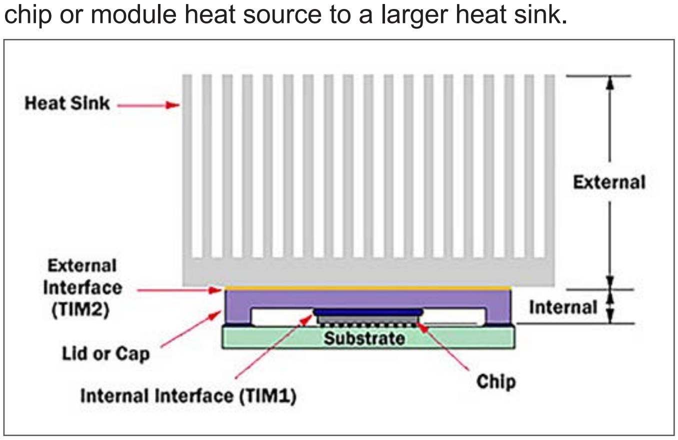


Figure 2. Chip package with thermal conduction path to heat sink via TIMs.

For high-power applications, the interface thermal resistance becomes an important issue. Direct soldering (e.g., reflow soldering) is often difficult, certainly when copper is used because of the large CTE mismatch between Cu and Si. However, a few promising materials are entering the market. Diamond-filled greases have been tested to have an effective thermal conductivity of over 20 W/mK; however, the vendor claimed 60 W/mK [2]. Even more interesting is a nanostructured foil, which utilizes a very fast exothermic reaction to create a soldered connection virtually at room temperature [3]. Extensive long-term reliability studies are in progress [4].

Heat spreading is a very effective way of mitigating the need for sophisticated high-heat flux cooling options. Of course, to be effective the benefits of decreasing the heat flux density by increasing the area should outweigh the penalty of adding another layer that the heat must be conducted across. This is an optimization problem as discussed below. The options for advanced heat spreading solutions are two-fold:

- Novel materials such as carbonaceous materials, metal-matrix composites, ceramic matrix composites (e.g., diamond-particle-reinforced silicon carbide), or ScD (Skeleton cemented Diamond), all of them with much higher thermal conductivities than copper, much less weight and tunable CTEs [5].

Novel heat spreader technologies such as Novel Concept's Isoskin [6] and Enerdyne's Polara [55] that claim effective thermal conductivities that compete with diamond.

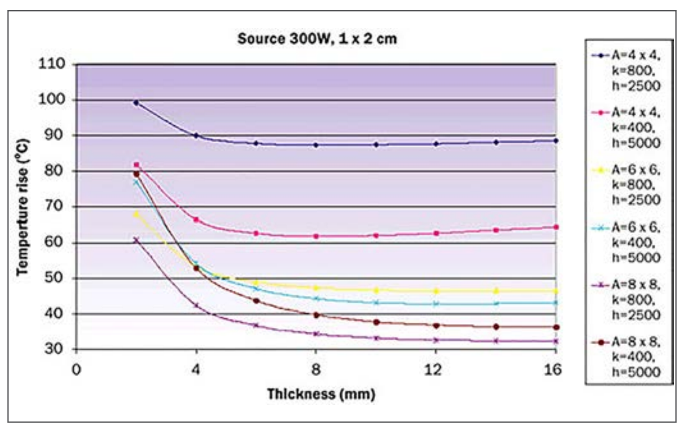


Figure 3. Example of effect of thickness on heat spreading for various heat source areas, material thermal conductivities, and heat transfer coefficients (A in cm2, K in w/mK, h in W/m2K).

By applying heat spreaders cooling methods such as loop heat pipes and low-flow liquid cooling may be augmented to accommodate higher heat flux applications. *Figure 3* provides a graph showing heat spreading results for a 300 W heat source of 2 cm^2 area as a function of thermal conductivity, thickness and cooling boundary condition (i.e., heat transfer coefficient). Looking at the results it becomes obvious that heat spreading is a complex phenomenon.

This is because the conduction and convection effects cannot be separated and the two effects compete: increasing the thickness increases the through-plane resistance but decreases the in-plane thermal resistance. For example, comparing the two upper curves with the two lower curves, their order is changed. The results also show that it is very well possible to use heat spreaders to decrease the required fluid-side heat transfer coefficient to easily manageable values, below 5000 W/m^2K, which could be fairly easily realized with hydrofluoroether (HFE) cooling fluids. For example, using an 8 x 8 cm^2 heat spreader of some advanced composite with a k of 800 W/mK and a thickness of 4 mm results in a temperature rise of 40°C with a heat transfer coefficient of only 2500 W/m^2K.

Air Cooling

It is generally acknowledged that traditional air-cooling techniques are about to reach their limit for cooling of high-power applications. With standard fans a maximum heat transfer coefficient of maybe 150 W/m^2K can be reached with acceptable noise levels, which is about 1 W/cm^2 for a 60°C temperature difference. Using 'macro-jet' impingement, theoretically we may reach 900 W/m^2K, but with unacceptable noise levels. Non-standard fans/dedicated heat sink combinations for CPU cooling are expected to have a maximum of about 50 W/cm^2, which is a factor of 10 higher than expected 15 years ago. However, some new initiatives have emerged to extend the useful range of air-cooling such as piezo fans, 'synthetic' jet cooling and 'nanolightning'.

Piezo Fans

Piezoelectric fans are low power, small, relatively low noise, solid-state devices that recently emerged as viable thermal management solutions for a variety of portable electronics applications including laptop computers and cellular phones. Piezoelectric fans utilize piezoceramic patches bonded onto thin, low frequency flexible blades to drive the fan at its resonance frequency. The resonating low frequency blade creates a streaming airflow directed at electronics components. A group at Purdue reports up to a 100% enhancement over natural convection heat transfer [7].

'Synthetic' Jet Cooling

An approach using periodic microjets coined 'synthetic jets' has initially been studied by Georgia Institute of Technology and is being commercialized by Innovative Fluidics. Due to the pulsating nature of the flow, synthetic jets introduce a stronger entrainment than conventional-steady jets of the same Reynolds number and more vigorous mixing between the wall boundary layers and the rest of the flow. One of the test set-ups is shown in *Figure 4*. A synthetic jet entrains cool air from ambient, impinges on the top hot surface and circulates the heated air back to the ambient through the edges of the plate. A radial counter current flow is created in the gap between the plates with hot air dispersed along the top and ambient air entrained along the bottom surface. The idea was further explored by the development of flow actuators using MEMS technology [8].

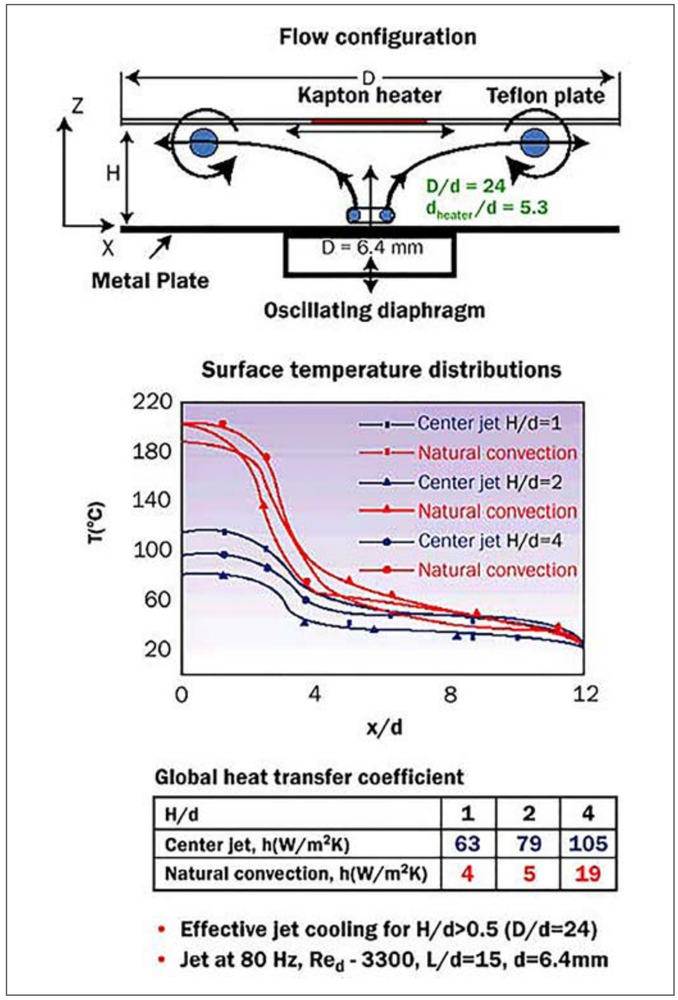


Figure 4. Flow dynamics of normal jet impingement with an oscillating diaphragm.

'Nanolightning'

An interesting new approach to increasing the heat transfer coefficient called 'nanolightning' is being pursued by researchers from Purdue. It is based on 'micro-scale ion-driven airflow' using very high electric fields created by nanotubes. As shown in *Figure 5*, the ionized air molecules are moved by another electric field, thereby inducing secondary airflow [9]. Cooling a heat flux level of 40 W/cm2 has been reported. The technology is being commercialized through a start-up company (Thorrn).

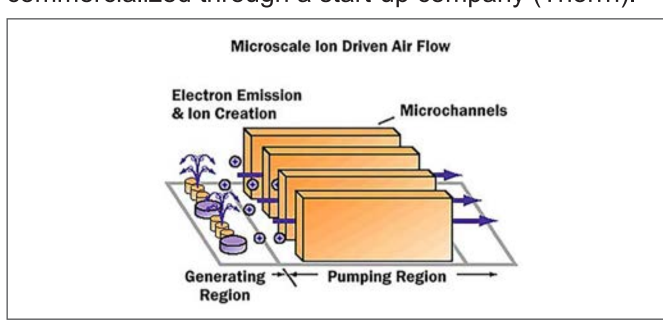


Figure 5. 'Nanolightning' sketch.

Liquid Cooling

The widely known heat transfer guru John Lienhard [10] once raised the question: "How much heat could possibly be carried away by boiling?" The answer is: 2000 kW/cm2 (based on water molecules turning into vapor without influencing each other). The highest reported experimental value is over 200 kW/cm^2, using high velocities and high pressures. Some commercially available microcoolers can handle about 1 kW/cm^2 so there is some room for improvement. Liquid cooling for application to electronics is generally divided into the two main categories of indirect and direct liquid cooling. Indirect liquid cooling is one in which the liquid does not directly contact the components to be cooled. Direct liquid cooling brings the liquid coolant into direct contact with the components to be cooled. The following sections discuss the categories of indirect liquid cooling in the form of heat pipes and cold plates and direct liquid cooling in the form of immersion cooling and jet impingement.

Heat Pipes

Heat pipes provide an indirect and passive means of applying liquid cooling. They are sealed and vacuum pumped vessels that are partially filled with a liquid. The internal walls of the pipes are lined with a porous medium (the wick) that acts as a passive capillary pump. When heat is applied to one side of the pipe the liquid starts evaporating. A pressure gradient exists causing the vapor to flow to the cooler regions. The vapor condenses at the cooler regions and is transported back by the wick structure, thereby closing the loop. Heat pipes provide an enhanced means of transporting heat (e.g., under many circumstances much better than copper) from a source to a heat sink where it can be rejected to the cooling medium by natural or forced convection. The effective thermal conductivity of a heat pipe can range from 50,000 to 200,000 W/mK [11], but is often much lower in practice due to additional interface resistances. The performance of heat pipes scales from 10 W/cm^2 to over 300 W/cm^2.

A simple water-copper heat pipe will on average have a heat transfer capacity of 100 W/cm^2. An example of a typical application of a heat pipe for an electronics cooling application is given in *Figure 6*.

Figure 6. Examples of heat pipes used in a notebook application.

Although there is virtually no limit to the size of a heat pipe, the effectiveness of a heat pipe decreases with decreasing lengths. For heat pipes with a length less than about 1 cm the performance of a solid piece of metal (e.g., copper) is often comparable. They are very effective as efficient heat conductors to transport heat to locations were more area is available. 2D heat spreaders (otherwise known as vapor chambers) based on the heat pipe principle can achieve much higher effective thermal conductivities than copper. For example, a thin planar heat spreader has been developed that is claimed to have a thermal performance greater than diamond [12].

Besides standard heat pipes, loop heat pipes (LHP) such as those shown in *Figure 7* are attracting increased attention. LHPs have the advantage over conventional heat pipes that the vapor and liquid paths are separated enabling much better performance of the liquid return loop. For example, Kim et al. [12] showed the ability to accommodate a heat flux of 625 W/cm^2.

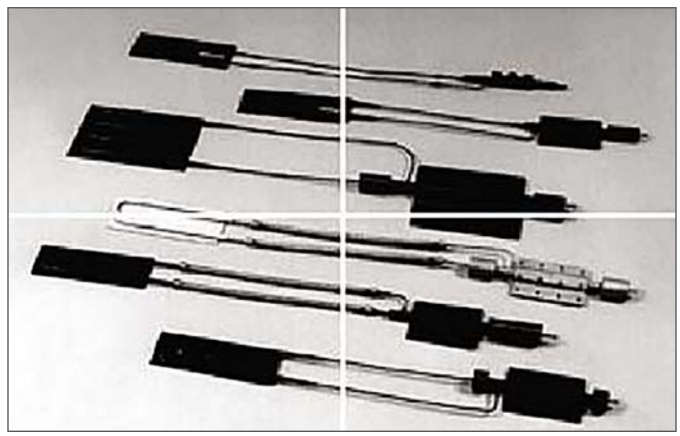


Figure 7. Examples of loop heat pipes.

Cold Plates

Liquid-cooled cold plates perform a function analogous to air-cooled heat sinks by providing an effective means to transfer heat from a component to a liquid coolant. Unlike heat pipes they may be considered active devices in that liquid is usually forced through them by the action of a pump. For many years water-cooled cold plates were used in mainframe computers to cool high-powered multichip processor modules. Vacuum-brazed finstock coldplates are standard practice in defense electronics, and copper-based superalloy structures are used in high-energy lasers. In 1981, in an effort to significantly extend cooling capability, Tuckerman and Pease [13] demonstrated a liquid -cooled microchannel heat sink that removed 790 W/cm^2 with a temperature increase of 71°C for a 600 ml/min flow rate with a pressure drop of 207 kPa. As a result of the continuing increases in heat flux at the chip level, microchannel cold plates are receiving renewed attention.

Microchannels and Minichannels

The term 'micro' is applied to devices having hydraulic diameters of ten to several hundred micrometers, while ‘mini’ refers to diameters on the order of one to a few millimeters. In many practical cases, the small flow rate within micro-channels produces laminar flow resulting in a heat transfer coefficient inversely proportional to the hydraulic diameter. In other words, the smaller the channel, the higher the heat transfer coefficient. Unfortunately, the pressure drop increases with the inverse of the second power of the channel width, keeping the mass flow constant, and limiting ongoing miniaturization in practice.

Garimella and Sobhan [14] published a very good review of the microchannel literature up to 2000. They concluded, among others, that “Given the diversity in the results in the literature, a reliable prediction of the heat transfer rates and pressure drops in microchannels is not currently possible for design applications such as microchannel heat sinks.” Mudawar [15] reviewed high-heat-flux thermal management schemes, including ultra-high-heat-fluxes in the range of 1000-100,000 W/cm^2. A recent overview was also provided by Mohapatra and Loikitis [16].

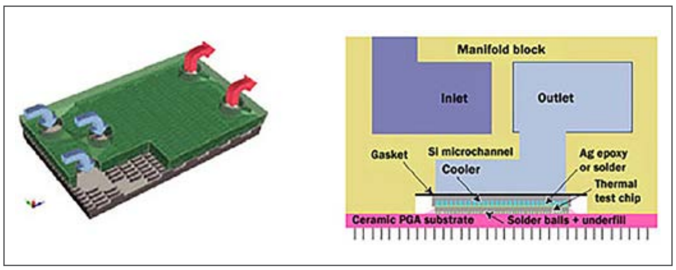


Figure 8. Pictures from IBM paper showing high-performance liquid cooling technology using microchannels [21].

Lee and Vafai [17] compared jet impingement and microchannel cooling for high heat flux applications. One of their conclusions is that microchannel cooling is more effective for areas smaller than 7 x 7 cm. Integrated single and two-phase micro heat sinks are treated by Gillot et al. [18]. They were able to cool about 450 W/cm^2 using both single and two-phase heat transfer. For two-phase flow the pumping power is about ten times lower and the required flow rate is considerably lower. Kandlikar and Upadhye [19] showed enhanced microchannel cooling by using off-set strip fins and a split-flow arrangement. Cooling of over 300 W/cm^2 at 24 kPa is claimed with a flow of 1.5 l/min. A paper devoted to pumping requirements has been written by Singhal et al. [20]. Useful graphs compare the performance of a whole range of pumps that could be considered for microchannel cooling. Colgan et al. [21] at IBM published a practical implementation of a silicon microchannel cooler (as shown in *Figure 8*) for high-power chips. They argued that it is not practical to form the microchannels directly on the chip given the high cost of high-performance processor chips. Instead, a separate microchannel cold plate is bonded to the back of the chip. This requires a very low interface thermal resistance. If the microcooler is based on silicon, a rigid bonding means that silver-filled epoxies or solder should be used. Power densities in excess of 400 W/cm^2 are reported, for a flow of 1.2 l/min at 30 kPa.

It may be possible to push microchannel heat transfer even further by utilizing boiling. In addition to offering higher heat transfer coefficients, boiling convection in microchannels is promising because it requires less pumping power than single-phase liquid convection to achieve a given heat sink thermal resistance. For the same heat flux the pressure drops by a factor of 20. A review has been published by Bergles et al. [22]. A prototype of a 1000 W/cm^2 cooling system based on boiling heat transfer in microchannel heat sinks using a flow rate of 500 ml/min has been described in [23]. The main practical problem with two-phase flow is its unpredictability. Local heat transfer coefficients may change appreciably over time leading to local temperature changes of 10-15 °C [24]. Also backflow of already heated flow due to expansion of bubbles is observed.

Increasingly, microchannel-like cold plates are becoming commercially available. Mikros [25] claims 1000 W/cm^{2}K, 14-21 kPa and 0.05 K/W/cm^2 for its patented technology in which the fluid impinges on the surface to be cooled. ACT (Advanced Cooling Technologies) [26] offers pumped liquid (both single and two-phase) cooling technologies in addition to loop heat pipes for space applications. Their single-phase solution (see *Figure 9*) incorporates a ‘unique oscillating flow heat transfer’ mechanism, capable of cooling over 1300 W/cm^2.

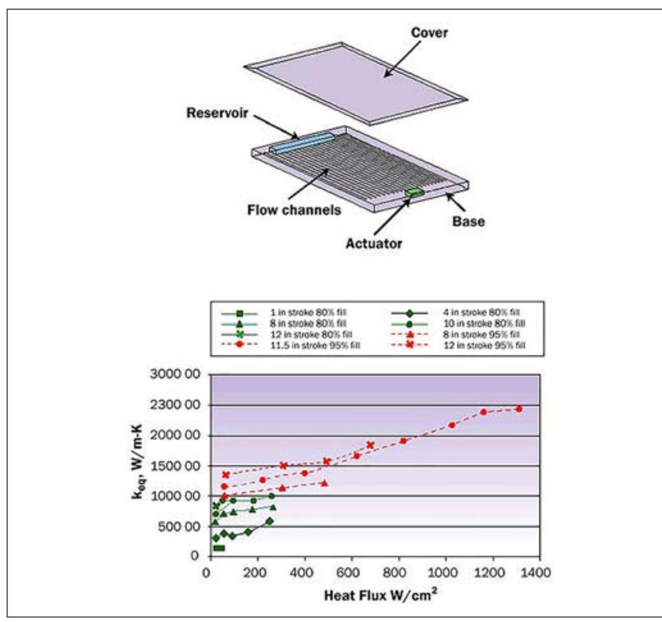


Figure 9. Vendor’s heat spreader and test results.

Another company, Cirrus, sells microchannel high heat flux heat sinks, claiming over 100 W/cm^2 heat flux capability and reduced pressure drops. Recently another player, iCurie [27], entered the market. They claim a pumpless microchannel cooling system based on capillary pumping with separate liquid-vapor loops. The layout can be very flexible, only 300 micrometer thick. At least 200 W/cm^2 can be cooled, with the additional advantage of a negligible effect of gravity. It is not a heat pipe because the principle of operation is based on flow boiling, not evaporation. Other companies offering microchannel coolers include Lytron, Novel Concepts, Curamik, Microcooling Concepts (MC2), and Koolance.

A completely different way of making microchannels is by using metal foams or metal made porous otherwise. Engineers from Thermacore have described a family of liquid -cooled heat sinks using porous metal. They accommodated a heat flux of 500 W/cm^2 for a 50 K difference at a pressure drop of 115 kPa using water [28].

On June 21, 2005, Georgia Tech [29] announced a novel monolithic technique for fabricating liquid cooling channels onto the backs of high-performance ICs. They also built a system that would allow the on-chip cooling system to be connected to embedded fluidic channels built into a printed circuit board.

Electrohydrodynamic and Electrowetting Cooling

As an alternative to a continuous flow set into motion by either temperature differences or by mechanical means, liquid could also be formed and moved in droplets of nano-to-milliliter size (see for example a nice demonstration by Nanolytics [30]) by means of electric fields. Electrowetting on a dielectric film, in which the surface property of a dielectric film can be modified between hydrophobic and hydrophilic states using an electric field, can be used to provide the basis for a direct micropumping system. Electrowetting involves control of the surface tension of a liquid and can cause a droplet of liquid to bead (as shown in *Figure 10*) or spread out on the surface depending upon its surface state.

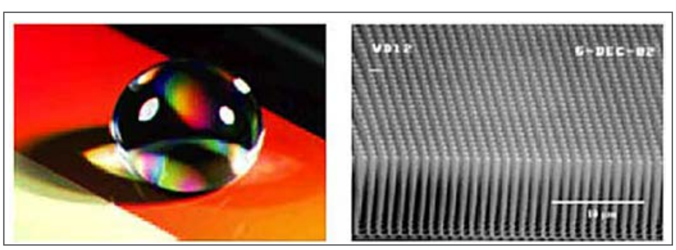


Figure 10. Water forms a nearly perfect ball, as shown in left photo, suspended on the tips of tiny blades of nanograss.

One of the possible applications is cooling on a micro scale. The recently published theoretical work of Pamula [31] has shown a possible configuration based on fast moving droplets under a chip. They showed that with 0.4 ml/min it is theoretically possible to cool 90 W/cm^2. Recently Leuven University in collaboration with Philips Research published two papers on this subject [32, 33]. The Philips approach differs from the Duke approach in that it concerns an oscillating flow. At Bell Labs researchers coupled electrowetting with nanostructured superhydrophobic surfaces (coined ‘nanograss’) to result in dynamically tunable surfaces [34]. One application is the movement of droplets to cool hot spots; however, no further heat transfer data are given.

A recent publication discussed another promising development, the application of electrowetting to liquid metals [35]. The main advantage besides a better heat transfer capability is the much lower voltage required (2 instead of 50 V). However, no experimental data have been presented.

The interesting aspect in combining microfluidics with electric control is that when all sizes scale down to micro scale, the electro/-kinetic/-wetting/-osmotic forces become comparable to pressure drop forces and therefore control of the liquid motion becomes easier. Of course, active cooling of a hot surface is one thing, to remove heat from the heated liquid in a closed loop requires additional heat exchange area.

Liquid Metal Cooling

Of special interest is the work ongoing in the field of liquid metal cooling. Apart from heat pipes based on liquid metals, mainly for the high-temperature range, an increasing amount of research is devoted to the use of Ga-Sn-In eutectics that remain liquid down to minus 19°C. In [36, 37] high-performance liquid metal cooling loops are described using magnetofluiddynamic pumps, claiming over 200 W/cm^2 cooling capacity, using a flow of 0.3 l/min at 15 kPa. Examples of liquid cooling loops for electronics cooling application are shown in *Figures 11* and *12*. Another advantage of liquid metal is its much lower CTE compared to water and the fact that freezing introduces fewer problems. Developments to extend the use in cold environments to -40°C are ongoing.

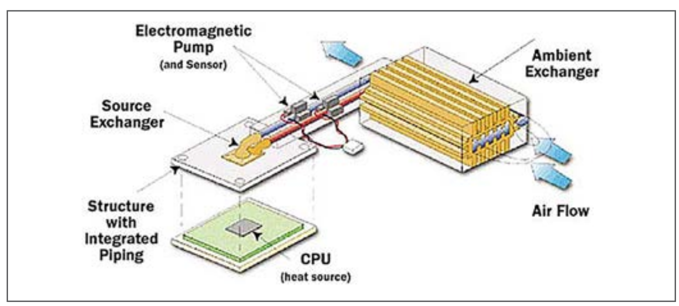


Figure 11. Sketch of liquid metal cooling loop.

Figure 12. Typical configuration of liquid metal cooling loop for mobile applications.

Immersion Cooling
Direct liquid or immersion cooling is a well-established method for accommodating high heat flux backed by over thirty years of university and industrial research. With natural convection two-phase flow, generally termed nucleate pool boiling, the critical heat flux using FC-72 is in the range of 5 to 20 W/cm2. However, much higher heat fluxes up to 100 W/cm2 can be accommodated with surface enhancement of the heat source. *Figure 13* illustrates a device submerged in a pool of dielectric liquid. The heat dissipated in the device produces vapor bubbles that are driven by buoyancy forces into the upper region of the container, where the vapor condenses and drips back into the liquid pool. One of the disadvantages of this technique is the need for a liquid compatible with the device. Most often, water cannot be used because of its chemical and electrical characteristics.

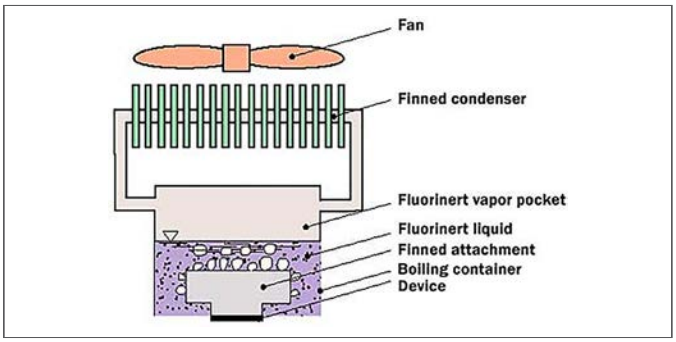


Figure 13. Example of pool boiling (thermosyphon) cooling.

Liquid Jet Impingement
Wang et al. [38] claim a cooling of 90 W/cm2 with a 100°C temperature rise using a flow rate of only 8 ml/min. Researchers at Georgia Institute of Technology studied a closed loop impingement jet [39]. Cooling of almost 180 W/cm2 has been realized using water, using a flow of 0.3 l/min at 300 kPa. The micropump used 7 W to drive it. At this point it is difficult to say which one is better, microchannels or microjets. Microchannels are easier to fabricate and implement but the temperature nonuniformity is larger and the nucleation is more difficult to control. Microjets achieve better cooling uniformity but more fabrication steps are required and an initial pressure is necessary to form the jet. An example of a commercial concept for liquid cooling is shown in *Figure 14* [40].

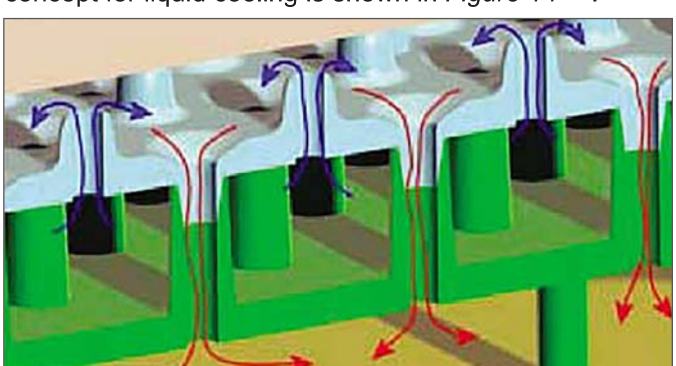


Figure 14. Commercially available multiple jet impingement liquid cooling.

Spray Cooling
In recent years spray cooling has received increasing attention as a means of supporting higher heat flux in electronic cooling applications. Spray cooling breaks up the liquid into fine droplets that impinge individually on the heated wall. Cooling of the surface is achieved through a combination of thermal conduction through the liquid in contact with the surface and evaporation at the liquid-vapor interface. The droplet impingement both enhances the spatial uniformity of heat removal and delays the liquid separation on the wall during vigorous boiling.

Spray evaporative cooling with a Fluorinert™ coolant is used to maintain junction temperatures of ASICs on MCMs in the CRAY SV2 system between 70 and 85°C for heat fluxes from 15 to 55 W/cm2 [41]. In addition to the CRAY cooling application, spray cooling has gained a foothold in the military sector providing for improved thermal management, dense system packaging, and reduced weight [42]. A research group at UCLA discussed chip-level spray cooling for an RF power amplifier and measured a maximum heat flux of over 160 W/cm2 [43]. Isothermal Systems Research manufactures SprayCool products [44].

Spray cooling and jet impingement (as shown in *Figure 15*) are often considered competing options for electronic cooling. In general, sprays reduce flow rate requirements but require a higher nozzle pressure drop.

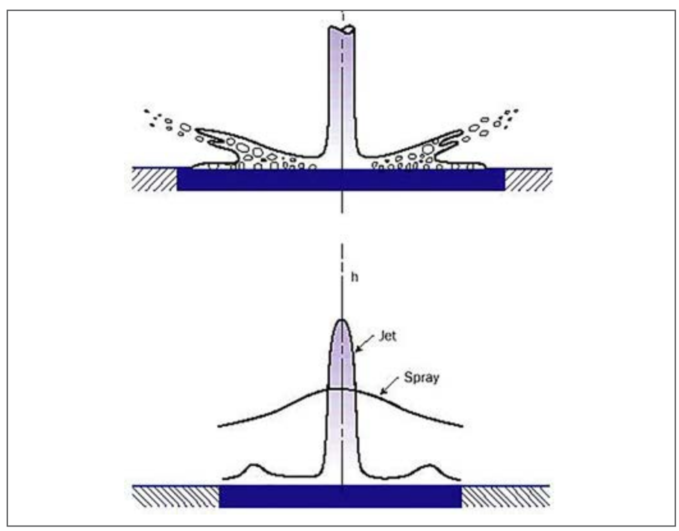


Figure 15. Illustration of spray and jet impingement cooling.

A final method to be mentioned is inkjet-assisted spray cooling. This method uses existing thermal inkjet technology. A critical heat flux of 270 W/cm2 is reported [45] using only 3ml/min, with a COP of 6, meaning that the inkjet pumping power is a factor of 6 lower than the heat removed.

Solid-State Cooling
A thermoelectric or a Peltier cooler (as shown in *Figure 16*) is a small electronic heat pump that has the advan-

tage of no moving parts and silent operation. Thermoelectric cooling enables cooling below ambient temperature. The coolers operate on direct current and may be used for heating or cooling by reversing the direction of current flow.

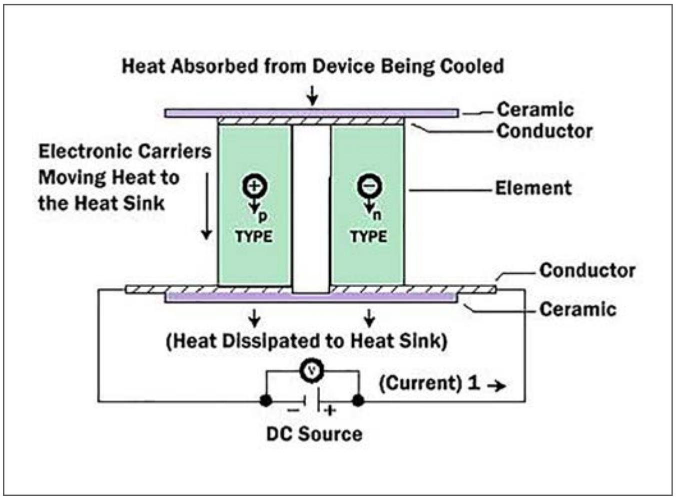


Figure 16. Schematic of simple Peltier cooler.

When a positive DC voltage is applied to the n-type thermoelement, electrons pass from the p- to the n- type thermoelement and the cold side temperature decreases as heat is absorbed.

The heat absorption (cooling) is proportional to the current and the number of thermoelectric couples. The main disadvantage is that the heat transferred to the hot side is greater than the amount of heat pumped by a quantity equal to the Joule heating (i.e., I2R loss) that takes place in the Peltier elements.

The three most important thermoelectric effects are the Seebeck, Peltier and Thomson effects. For thermoelectric cooling the Thomson effect can be neglected. The Peltier coefficient Π and Seebeck coefficient S are related to each other through Π = ST. Thermoelectric materials are usually characterized by their figure of merit ZT, defined by:

where σ= electrical conductivity
λ = thermal conductivity
T = temperature in absolute units

This equation shows why it is difficult to obtain good thermoelectric materials. A good thermoelectric material must achieve low thermal conductivity (to prevent heat losses through heat conduction between the hot and cold side) and a high electrical conductivity (to minimize Joule heating). Due to the dependence of σ and λ (Wiedemann-Franz law), it is almost impossible to optimize this ratio for the electron contribution to the thermal conductivity. Hence, the approach is to reduce the phonon thermal conductivity without a degradation of the electrical conductivity.

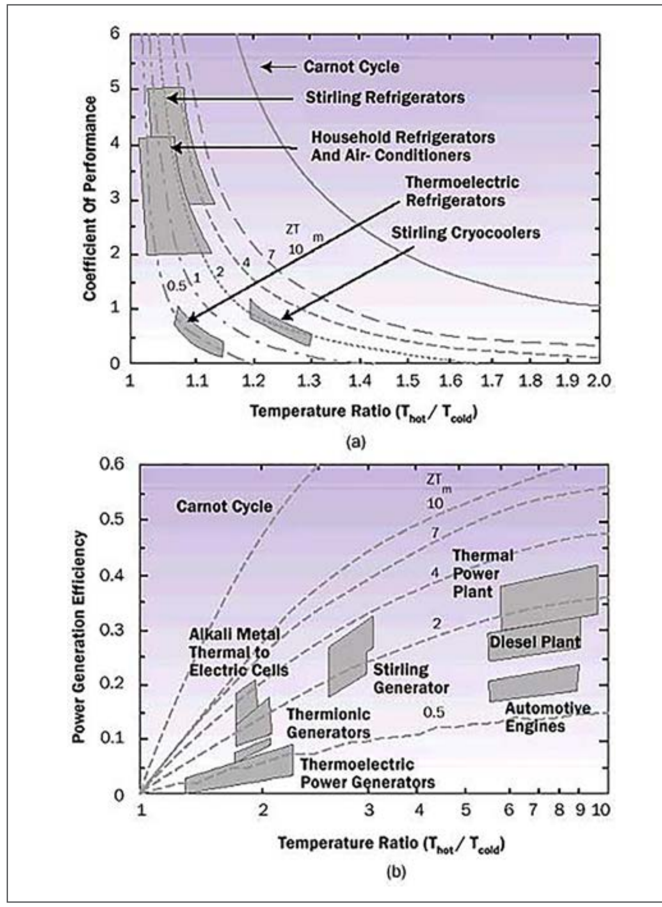


Figure 17. Comparison of thermoelectric technology with other energy conversion methods for (a) cooling and (b) power generation [46].

The best materials so far are alloys of Bi2Te3 with Sb2Te3 and Bi2Te3 with Bi2Se3. ZT is of the order of 1 at room temperature. This value gives a Coefficient of Performance (COP, a measure for the efficiency) of about 1 (see *Figure 17a*), which compared to household refrigerators and air conditioners (COP from 2 to 4), makes thermoelectric cooling generally not competitive. The same holds for power generation (see *Figure 17b*).

Despite the low efficiency, the application areas are increasing and include infrared detector cooling, charge coupled devices (CCDs), microprocessors, blood analyzers, portable picnic coolers. Principal applications are still accurate control of temperature and cooling below ambient temperature.

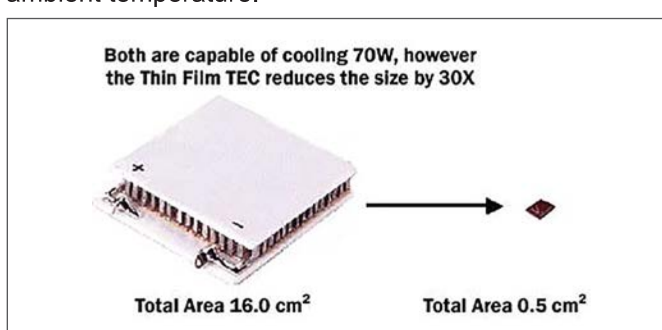


Figure 18. Comparison of standard and thin-film Peltier element.

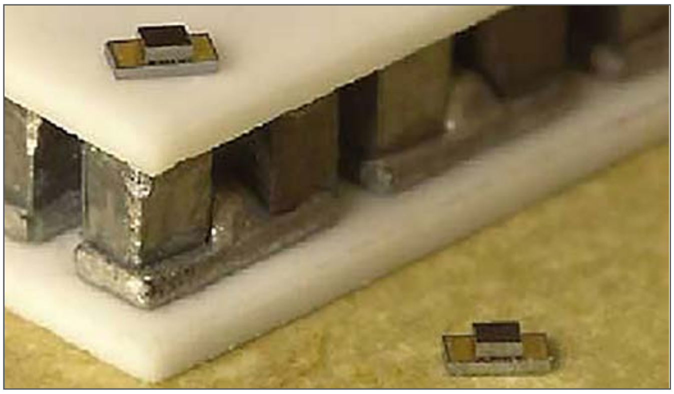


Figure 19. Thin film Peltier element.

One of the problems with traditional Peltier elements is their limited capability of cooling heat fluxes over 5-10 W/cm2. Because the cooling density of a Peltier cooler is inversely proportional to its length, scaling to smaller size is desirable. The material structure produced by conventional crystal growth techniques for producing bismuth telluride thermoelectric materials impose significant limitations on thermoelectric element dimensions due to poor manufacturing yields. This prevents thermoelectric elements from being made very short. Marlow Industries reported new fine-grain micro-alloyed bismuth telluride materials that do not suffer the element geometry limitation and can offer higher performance [47]. Another serious step forward has been realized by Nanocoolers through a proprietary wafer-scale manufacturing process. It concerns a monolithic process with thicknesses about 1-2 micrometers (see *Figure 18*). They claim a tunable performance of 10 – 1000 W/cm^2 with a single stage Δ T of 50-70 K [48]. MicroPelt, a spin-off company from Fraunhofer and Infineon also sells promising thin film thermoelectrics (see *Figure 19*). For their near-future products they claim cooling of 160 W/cm^2.

A number of other research projects directed at miniaturizing Peltier elements are worth mentioning. In 2004 Biophan Technologies [49] signed an agreement with NASA for characterization and joint development of high-density nanoengineered thermoelectric materials for use with implantable devices. They anticipate a breakthrough in power generation systems. A French/US consortium published a paper [50] on the fabrication and modeling of an in-plane thermoelectric micro-generator. They concluded that a heating power of about 100 mW may be enough to produce 1 mW of useful electrical power in vacuum, using thin film technology. A compact thermoelectric device may be able to produce 60 microwatt with an output voltage of 1.5 V in air.

Applied Digital Solutions uses its ThermoLife thermoelectric power generator to power its implantable chips [51]. It generates 3V, has a diameter of 9.3 mm and weighs 230 mg. DTS in Germany uses thin film technology for their Low Power Thermoelectric Generators (LPTGs) [52] that produce a few tens of microwatts in the volt range for a temperature difference of a few degrees C. The generators have a mass of 390 mg. Also in Germany, researchers at Dresden University [53] have found a way to make tiny thermoelectric generators using copper foil as a template. Antimony-Bismuth thermocouples are electro-deposited and after adding an epoxy film the copper is etched away. The result is a cheap, flexible and recycable generator that converts environmental heat into electricity. The growth by pulsed laser deposition of high-quality thermoelectric cobaltate thin films on silicon has been reported by Yu et al. [54]. In addition, TEM characterization revealed nearly perfect crystalline structures of the Ca3Co4O9 film formed on top of an SiOx amorphous layer, suggesting self-assembly might be a viable technique for cobalt oxide-based thermoelectrics.

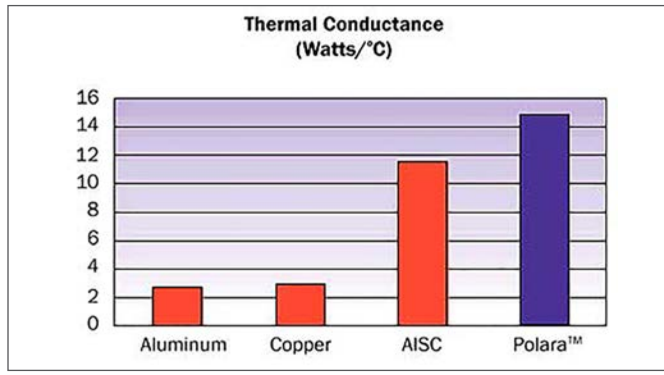


Figure 20. Comparison of effective thermal conductances.

If the application is limited to temperatures above ambient temperature matters are quite different. Because the heat flow paths of the cooling and the conduction have the same direction, high-thermal conductivity materials are preferred. Enerdyne's Polara heat spreaders are based on this principle [55]. A factor of five improvement compared to copper is claimed as shown in *Figure 20*. However, no samples are available as of July 2005.

Superlattice and Heterostructure Cooling

For a number of years now, the strategy to improve thermoelectric cooling has taken a new turn [46] giving hope for the future. On a nano scale level, coherent and incoherent transport plays an important role in the electron and phonon diffusion. Extensive research is going on in this field. For example, Venkatasubramanian [56] at RTI reported ZT values between 2-3 at room temperature obtained with Bi2Te3/Se2Te3 superlattices. Cooling power density is estimated as high as 700 W/cm^2 at 353 K compared to 1.9 W/cm^2 in the bulk material (see *Figures 21* and *22*).

THOT refers to the heat sink temperature.Thin-film related work is also being conducted at the University of California Santa Cruz, based on SiGe/Si. The most recent paper [57] quotes a cooling power density of nearly 600 W/cm2 for a temperature difference of 4K below ambient for a 40 x 40 micrometer size area. The superlattice efforts of RTI are being commercialized through a spin-off company called Nextreme. Recent information reveals that despite their claimed value of ZT = 2.4, they are not able to manufacture production samples with a ZT larger than 1.4. The focus is to reduce the parasitics and to reduce even further the current 100 micrometer thickness.

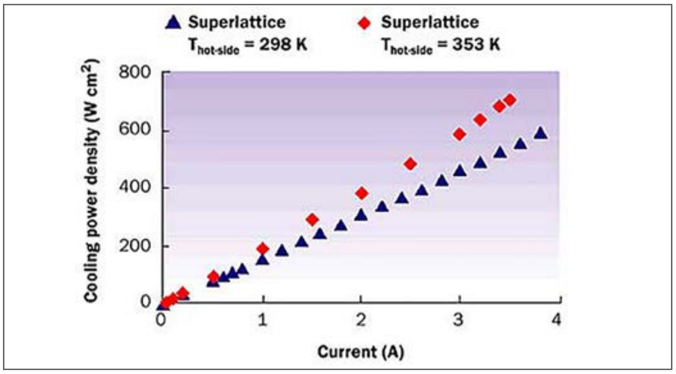


Figure 21. Estimated power density for superlattice devices as a function of current.

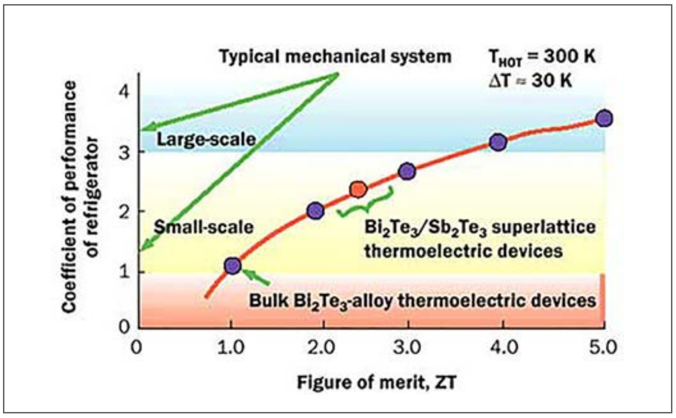


Figure 22. Potential COP as a function of ZT with various technologies.

However, there is still hope for a serious breakthrough. Very recently, Humphrey and Linke [58] published a paper called 'Reversible Thermoelectric Materials'. They argue that nanostructured materials with sharply peaked electronic density of states (such as quantum wires) may operate reversibly, challenging the view that thermoelectric devices are inherently irreversible heat engines. In this case, ZT values could reach a value of 10 at room temperature, much above the value of 5 that is required for economical adoption of thermoelectric technology for mainstream refrigeration and power generation.

Thermionic and Thermotunneling Cooling

Thermionic cooling is based on the principle that a high-work-function cathode preferentially emits hot electrons [46]. Materials available have a work function of 0.7 eV or higher, which limits the use to the higher temperature ranges (>500 K). Vacuum thermionic devices based on resonant tunnelling have been proposed more recently [59]. Cooling capabilities of 20-30°C with kW/cm2 cooling power density can be achieved. However, since the operating currents for the device are as high as 105A/cm^2, effects such as Joule heating at the metal-semiconductor contact resistance and reverse heat conduction have limited the experimental cooling results to <1°C.

Devices based on quantum tunnelling through a small gap are being commercialized [60]. The spacing between the cathode and the anode should be of the order of 10 nm providing quite an engineering challenge. Much larger cooling power than thermoelectric superlattice coolers are predicted by Hishinuma et al. [61] (e.g.10 kW/cm^2 for 50 K cooling at room temperature). Recently a study has been devoted to their potential use as energy scavenging or power conversion devices [62]. Unfortunately, the conclusion is that a gap an order of magnitude lower must be achieved to be of interest for these application fields. Even more worrying is another recent study [63] showing that contrary to the results of Hishinuma only about 16 W/cm^2 can be reached with a Δ T of 40°C, while the maximum COP is only 0.25. More or less the same conclusion can be drawn from a paper presented at THERMINIC 2005, September 27-30 [64]. Herein, some weaknesses in prior studies are discussed and it is clear from the conclusions that nanogap solutions without significant improvements in lower work function materials have no future.

Phase Change Materials and Heat Accumulators

Phase change materials are successfully used as heat-storing materials for air conditioning, cool boxes, efficient fire-retarding powders, as functional materials for self-heating insoles for boots and many other industrial applications. Their use for electronics thermal management is limited to applications where time-dependent phenomena play a role. For example, reference [65] discusses the use of phase change materials as compared to copper for use in a power semiconductor unit.

Chemical heat accumulators should also be mentioned. For example, the use of composite materials based on granulated open-porous matrix filled with a hygroscopic substance can be seen as a new approach to accumulate heat [66]. The advantage is a significant increase in the heat that can be stored as compared to sensible heat and latent heat. For example, for a 100°C temperature rise copper absorbs 40 kJ/kg. Evaporation of water is associated with an absorption of 2260 kJ/kg. The enthalpy of a reversible chemical reaction can reach a value of 7000 kJ/kg. A principal advantage of reversible chemical reactions for heat accumulation is their ability to store the accumulated energy for a long time, if the reaction is controlled by the presence of either a catalyst or a reagent. Hence, the major applications are in the field of summer-winter heat storage for buildings, etc. Chemical heat accumulators could potentially be used for outdoor electronic applications when a night-day rhythm is present.

Conclusions

A number of approaches show interesting industrial potential for the cooling of high-power electronics. This prospect is attested to by the number of small companies that are entering the market. For example, there are now companies engaged in the development and commercialization of microchannels, spray cooling, synthetic jets, thin film Peltier elements. For heat flux densities up to and maybe even beyond 50 W/cm^2 air-cooling may remain the cooling option of choice. For heat fluxes over 100 W/cm^2, some form of liquid-cooling appears to be the most viable option. Several papers have demonstrated solutions that may be industrially feasible for application in the range between 500 and 1000 W/cm^2. Considering the range of efforts underway to extend conventional cooling technologies, as well as develop new ones, the future seems bright for accommodating high-heat flux applications.

(Note: We deemed it instructive to include examples of commercially-available thermal solutions. However, it should be clearly stated that we do not intend to promote any of the mentioned products. Finally, we have tried to cover the state-of-the-art as known to us. However, given the broadness of the field, we may have overlooked some important new developments for which we apologize.)

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SIMULATION DRIVEN DESIGN OPTIMIZATION FOR REDUCTION OF TEMPERATURE ON A HIGH CURRENT DENSITY PCB

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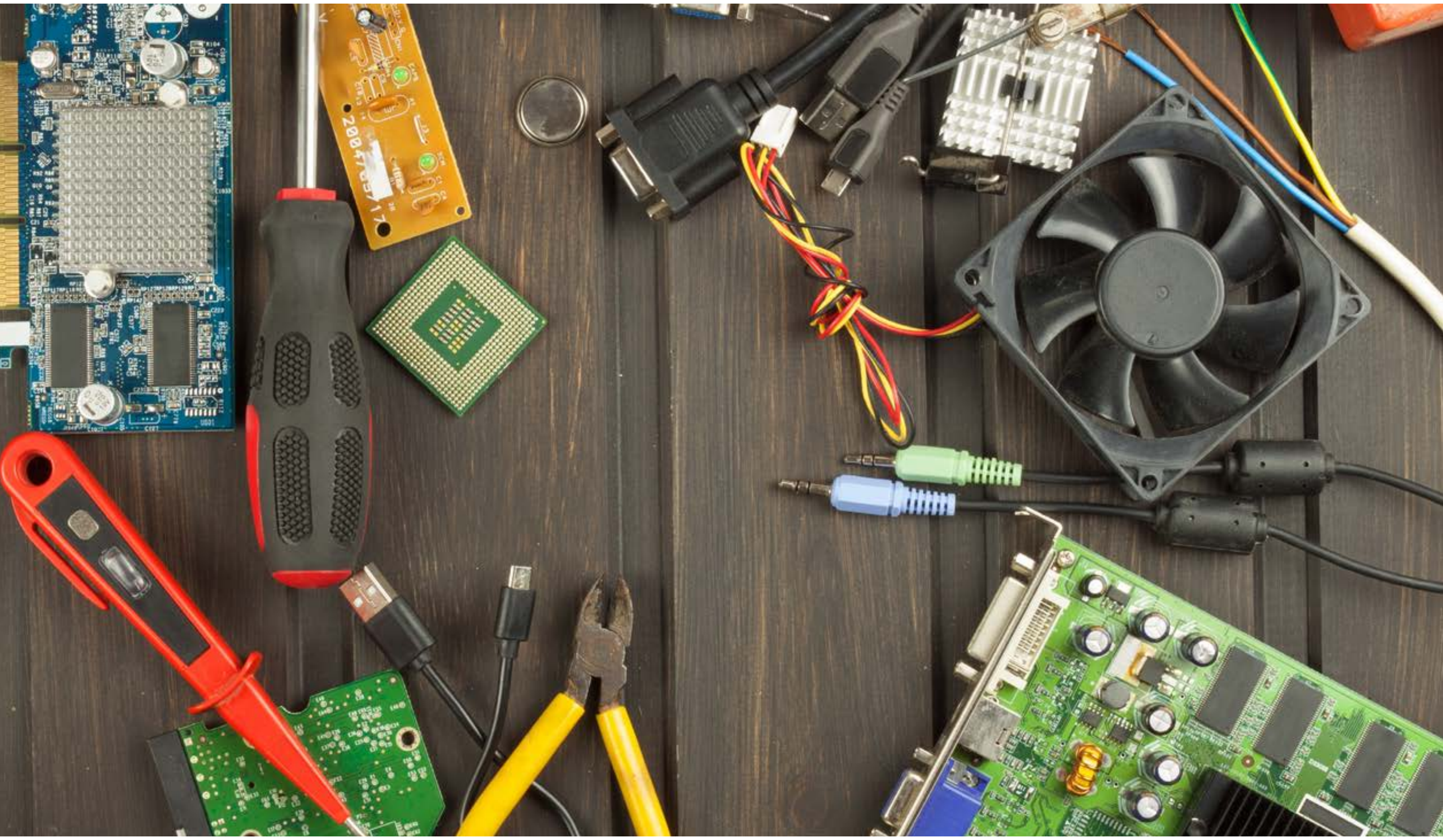
Introduction

The market demand for lightweight and cost effective electronic products with multi-functional operations leads to the introduction of plastic housing and high current density on board. In general, automotive electronic products operate in harsh environment. With high current demand, Joule heating in copper traces on the board is highly pronounced. Managing heat dissipation from components and traces without the use of cooling banks on the plastic housing is a thermal challenge.



SIMULATION DRIVEN DESIGN OPTIMIZATION FOR REDUCTION OF TEMPERATURE ON A HIGH CURRENT DENSITY PCB

For this study, the product consists of a plastic enclosure that houses printed circuit board (PCB) and electronic components that are capable of operation at higher current. The product consists of multiple inputs and outputs to support a variety of loads. The high current is distributed across multiple copper layers in PCB. These copper layers (due to constraints on their dimensions) experience high current densities leading to higher Joule heating. In addition, there are several heat dissipating components on board. As a result, the components are exposed to higher operating temperature. Electrical-Thermal simulation helps to (i) visualize the thermal field, (ii) identify bottlenecks to current flow, and (iii) identify hot spots in order to optimize the circuit layout for reducing the Joule heating.

In this study, Electrical-Thermal simulation is carried out using Thermal Risk Management tool (TRM). The model consists of lumped components with their respective power dissipation, thermal vias in PCB underneath the heat dissipating components, PCB base material (FR4), copper layers with discrete traces for current flow and heat conduction, and electrical nets for current flow among copper layers, input-output pins and components. The effect of enclosure is manifested in the overall heat transfer coefficient that is applied on PCB and components as boundary condition. Overall heat transfer coefficient is derived from a system-level conjugate heat transfer model accounting for conduction, convection and radiation for the entire product. Electrical current (I) is assigned to input and out pins. Ambient temperature is applied to PCB and components as boundary condition.

Measurement at board-level is carried out in the lab via Thermal imaging and thermocouple measurements for thermal field and component temperatures respectively. Simulation and measurement results are found to be within ± 3%.

After validating the simulation model, parametric study via simulation is carried out to optimize the copper traces geometry and location of components and power dissipation of the components, PCB stack up and PCB base material properties. These parameters are evaluated against the cost of the product due to each change. This optimization helps in reducing the hot spots and temperature on the PCB, during the early development phase itself, and reduces the development cost as well as the product cost.

Keywords: Design Optimization, Electrical-Thermal Simulation, Joule heating, High Current Density, PCB

Introduction

With the rise in usage of electronics in automobile industry, the demand for light weight and cost effective electronics has increased exponentially in the past few decades. Along with the packaging requirements, the functionality of electronics has increased, posing challenges for thermal management of electronics. To cater to numerous functions required by the application, component density and current in the Printed Circuit Board has increased too.

These requirements have led to the introduction of plastic housing and high current density on board.

The amount of heat generated in copper traces on board due to flow of current is

$$Q = I^2R \quad (1)$$

Where,

Q: Joule heating, W

I: current flow in copper traces on board, A

R: electrical resistance of copper traces, W

Electrical resistance, R, is related to geometry and resistivity of the copper traces:

Where,

$$R = pL/A \quad (2)$$

p: Electrical resistivity of the copper trace, W×m

L: length of the copper trace, m

A: cross section of the trace carrying current, m^2

With increase in current, Joule heating poses bigger thermal challenges. The thermal challenges are amplified if the internal heat generation is relatively high and compounded with aggressive external environment [1].

Product

The product in analysis is an automotive electronic unit that supports multiple applications in the vehicle. Catering to all these demands require high current flow on board. The product consists of a plastic enclosure that houses PCB and high current capable electronic components. It consists of multiple inputs and output pins to support a variety of applications. The high current is routed out in multiple copper layers.

The Copper layers, due to the constraint in their size, experience high current density that leads to higher Joule heating. Apart from this, there are several heat dissipating components on the board. As a result, components are expected to be at higher temperature.

Electrical-Thermal Simulation

Electrical-Thermal simulation helps to (i) visualize the thermal field, (ii) identify bottlenecks to current flow, and (iii) identify hot spots in order to optimize the electronic layout for reducing the Joule heating. In this study, Electrical-Thermal simulation is carried out in Adam Research's Thermal Risk Management tool (TRM). The tool is used to calculate temperature of components and PCB due to electrical current flow in copper traces and component heat dissipation.

Simulation Model

The model consists of lumped components with their respective power dissipation, thermal vias in PCB underneath the heat dissipating components, PCB base material (FR4), copper layers with discrete traces for current flow and heat conduction, and electrical nets for current flow among copper layers, input-output pins and components. The effect of enclosure is manifested in the overall heat transfer coefficient that is applied on PCB and components as boundary condition. Overall heat transfer coefficient is derived from a system-level conjugate heat transfer model accounting for convection and radiation for the entire product. Electrical current (I) is assigned to input and out pins. The model allows the current to flow in the entire circuit depending upon connectivity and routing between input and output pins. Ambient temperature is applied to PCB and components as boundary condition.

Validation of Simulation

In order to assess the thermal risk and enhance the life time of the product by removing thermal bottlenecks, temperature of components, PCB and plastic housing is compared with their limits [2]. Since the life time of an electronic product is reduced by half for every 10°C increase in temperature, it is necessary to have safe operating temperature for components.

Life time and operating temperature of component are related by

$$t= e^{c}/T \qquad (3)$$

Where,

t: life time, hr c: constant

T: operating temperature (junction or ambient) of components, K

For validating the simulation results, measurement at board- and component-level is carried out in the lab via IR thermal imaging and thermo-couple measurements for thermal field and component temperature respectively. Simulation and measurement results are found to be within ± 3%. *Table 1* shows the temperature of few operating components that were measured and their predicted temperature in simulation.

Table 1: Comparison of Simulation and Measurement Results

Reference Designator	Temperature Rise in Testing (°C)	Temperature Rise in Simulation (°C)
C1	55.3	57.3
C2	51.2	53.0
C3	56.6	59.3
C4	49.0	53.9
C5	56.0	61.5
C6	50.0	51.7
C7	62.7	69.7
C8	48.5	56.1

Base Model

Once the simulation model is validated with the lab measurement, a full blown model is simulated with complete loading, where PCB experiences maximum current and power dissipation of the components. Copper layer thickness in the base model is considered as below:

Table 2: PCB Copper Layer Thickness in Base Model

Cu Layers	Thickness (Normalized)
Top	1.0
Inner 1	1.0
Inner 2	1.0
Inner 3	1.0
Inner 4	1.0
Bottom	1.0

The maximum temperature rise (DT) on the board is observed at 88.8 ˚C. This temperature is observed on the top side of the PCB. The total joule heating is calculated as 13.03 W.

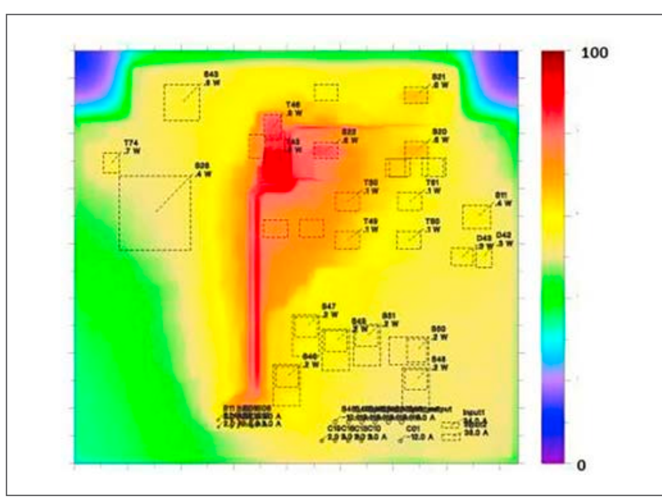


Fig. 1: Temperature rise on the top side of PCB for Base design

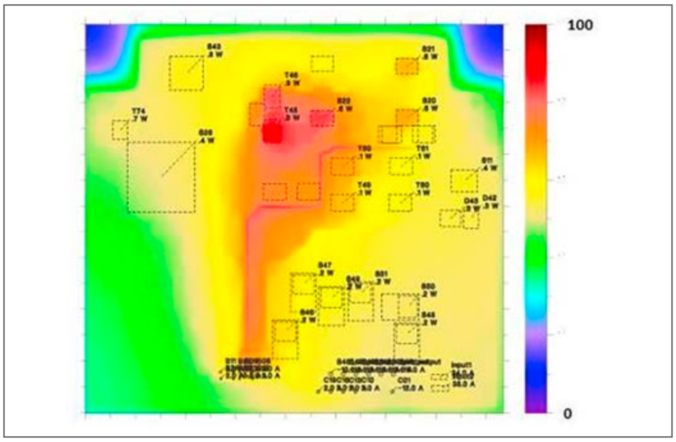


Fig. 2: Temperature rise on the bottom side of PCB for Base design

Design Modification 1

Since the Joule heating is quite high (i.e. 13 W) and contributes to heating the PCB and components, modifications are done on copper traces to reduce it. As the first step of reducing Joule heating, modifications are done to increase the cross section area of the copper trace by increasing the copper layer thickness. The copper layer thickness is considered as below:

Table 3: PCB Copper Layer Thickness in Design Modification 1	
Cu Layers	Thickness (Normalized)
Top	2.0
Inner 1	2.0
Inner 2	2.0
Inner 3	2.0
Inner 4	2.0
Bottom	2.0

The maximum temperature rise on board in this case is observed to be 59.8 ˚C. Joule heating reduces from 13.03 W to 6.81 W. With the increase in copper layer thickness by twice, the cross section area is increased to double. This reduces the joule heating by half.

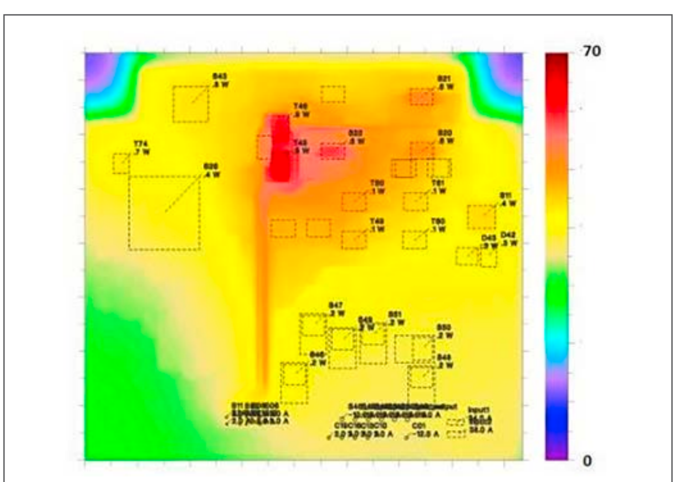


Fig. 3: Temperature rise on the top side of PCB for Design modification 1

Design Modification 2

With the increase in Copper layer thickness, the cross section area increases which is an effective way of reducing the Joule heating and maximum temperature on the PCB. In the next design modification, PCB with maximum copper layer thickness available for prototyping is chosen. The copper layer thickness used is mentioned in below

Table 4: PCB copper layer thickness and joule heating in corresponding layers for design modification 2		
Layer	Thickness (Normalized)	Joule Heating (W)
Top	1.6	4.76
Inner 1	1.0	0.06
Inner 2	3.0	0.44
Inner 3	3.0	0.31
Inner 4	1.0	0.06
Bottom	1.6	2.44

In design modification 2, maximum temperature rise on PCB is observed as 62.5 ˚C. Total Joule heating is calculated to be 8.23 W.

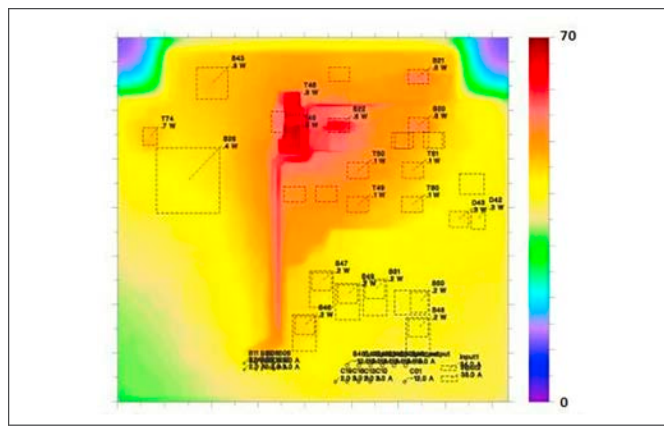


Fig. 4: Temperature rise on the top side of PCB for Design modification 2

Design Modification 3

Once the PCB with maximum copper layer thickness is utilized, routing is done for increasing the current carrying traces in fourth inner layer. This leads to distribution of joule heating to inner layer. Maximum PCB temperature on board reduces by 7 K only due to distribution of current to inner layer.

Table 5: PCB copper layer thickness and joule heating in corresponding layers for design modification 3		
Layer	Thickness (Normalized)	Joule Heating (W)
Top	1.6	2.86
Inner 1	1.0	0.07
Inner 2	3.0	0.43
Inner 3	3.0	0.34
Inner 4	1.0	0.48
Bottom	1.6	1.89

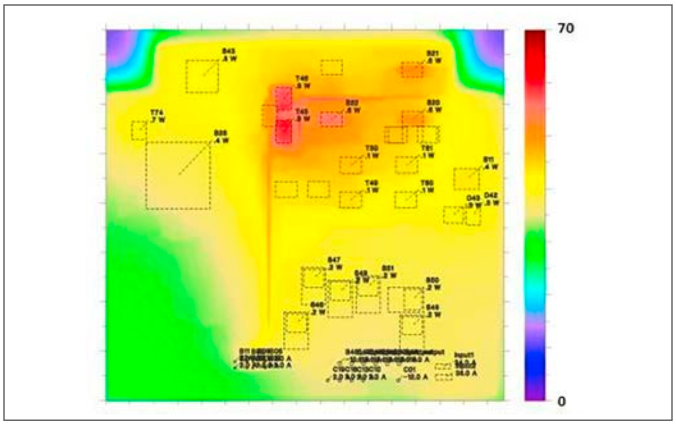


Fig. 5: Temperature on the top side of PCB for Design modification 3

In this design, maximum temperature rise on PCB is 55.8 ˚C. Total Joule heating in inner layer 4 increases from 0.06 W to 0.48 W.

After utilizing the inner layers for carrying current, the traces with maximum current density are widened to increase the cross section. This reduces the joule heating and hence reduces the temperature on PCB.

Table 6: PCB copper layer thickness and joule heating in corresponding layers for design modification 4

Layer	Thickness (Normalized)	Joule Heating (W)
Top	1.6	2.35
Inner 1	1.0	0.05
Inner 2	3.0	0.38
Inner 3	3.0	0.28
Inner 4	1.0	0.46
Bottom	1.6	2.08

In this case, the maximum temperature rise on PCB is observed to be 53.3˚C. Maximum current density is reduced from 140 A/mm2 to 120 A/mm2 in top layer and from 73 A/mm2 to 62 A/mm2 in inner layer 4.

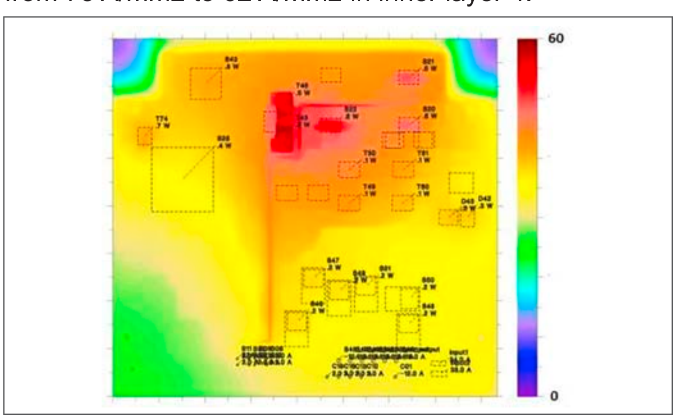


Fig. 6: Temperature rise on the top side of PCB for Design modification 4

Conclusion

Reduction in temperature of components and PCB is an important design goal to increase the lifetime of electronic product. To achieve the safe operating temperature on a high current density board, joule heating needs to be minimized. Reduction in joule heating is obtained through optimization of trace geometry as exhibited in design modification 1, 2 and 4. To further reduce the maximum temperature of component and PCB, inner layers are utilized to carry the current as in design modification 3. Overall maximum temperature rise of PCB reduces from 88 ˚C to 53 ˚C, which enhances the lifetime of the electronics. This simulation also helps in identifying hot spots at early stage of development and provide measures to mitigate them.

Table 7: Summary of various design modification studied

Design	Description	Max Temperature Rise of PCB, °C
Base Model	Nominal Copper Layer Thickness = 1	88
Design Modification 1	Nominal Copper Layer Thickness = 1	59
Design Modification 2	PCB with maximum copper layer thickness available for testing	62
Design Modification 3	Routing to inner copper layer	55
Design Modification 4	Widening of copper traces on PCB	53

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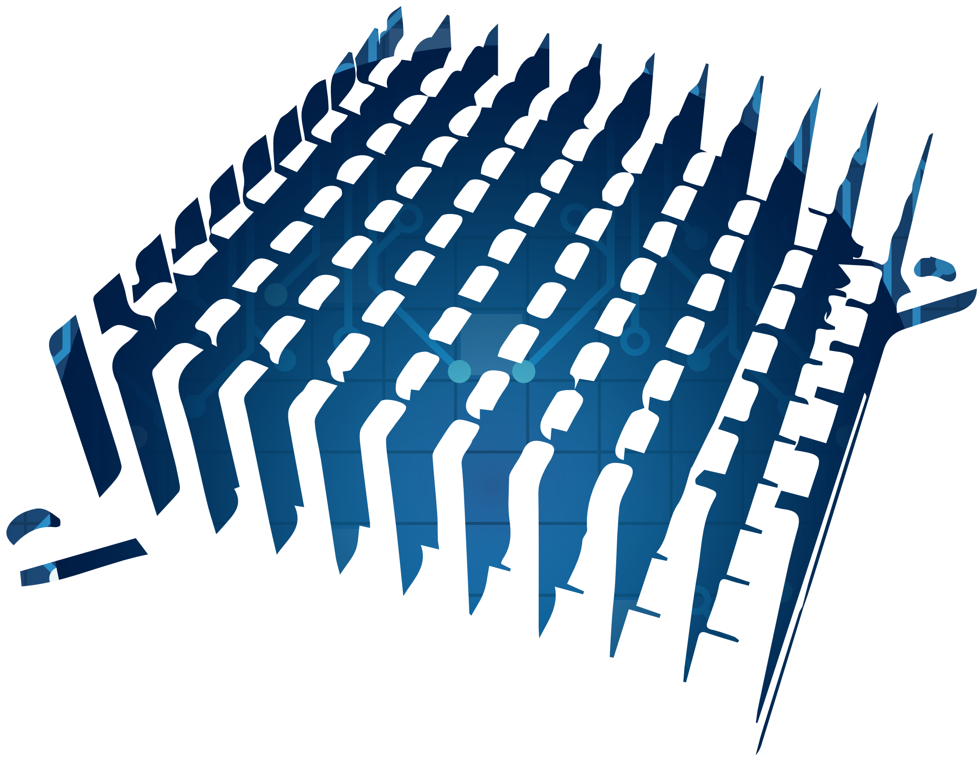


ECOSYSTEMS

Automotive and Power Electronics are perhaps two of the most demanding areas for thermal management professionals. With advances in fully electric vehicles (EV), hybrids and fuel cell automobiles, they also represent product segments with very active contemporary R&D of which thermal management is the primary focus.

Electronics has a long history in the automotive ecosystem. In the earlier generations, electronic systems were used to control the engine (EFI -electronic fuel-injection systems; a system that atomizes the fuel through a small nozzle under pressure). Following this, electronic components entered the domain of driving safety (e.g. antilock brake system, ABS, etc). More recently, completely new fields of application have emerged in the areas of driving assistance, infotainment and communication as a result of continuous advancements in semiconductor technology. ABS is now days integrated as a component of the electronic stability program (ESP) owing to advances in information and communication technology (ICT).

Though largely unnoticed and unappreciated, power electronics is the primary enabling technology for all of electronics. As growth in electronics is primarily driven by consumer electronics and more recently by alternative fuel vehicles continues, the technology of power electronics has grown increasingly complex. Its applications have scaled at both ends of the scale –from small personal devices to large datacenters. Thermal management is most often the primary limit or the enabler of the capabilities of a power conversion / inversion / regulation system. The broader power electronics product landscape is therefore quite diverse, multiscale and has products which are either complete systems or components and modules coexisting with other electronics components. With advances in electronics for EVs, there are many overlapping applications of power electronics in the automotive sector where the main stream thermal management methods are being adapted to address new challenges.

Automotive Ecosystems

Power and automotive electronics are closely interconnected ecosystems with the former enabling the latter. Though the automobile ecosystem is a long-established and seemingly mature ecosystem, it is undergoing rapid changes where electronics now accounts for nearly 50% of the components by the year 2020.

Description of the general automotive ecosystem is beyond the scope of this miniguide and will not be covered. In what follows below, we cover an electronics-centered ecosystem for automotive electronics. This somewhat dated figure below shows the four main categories of electronics hardware in a modern automobile; a fifth on In-dash Entertainment appears plausible to add.

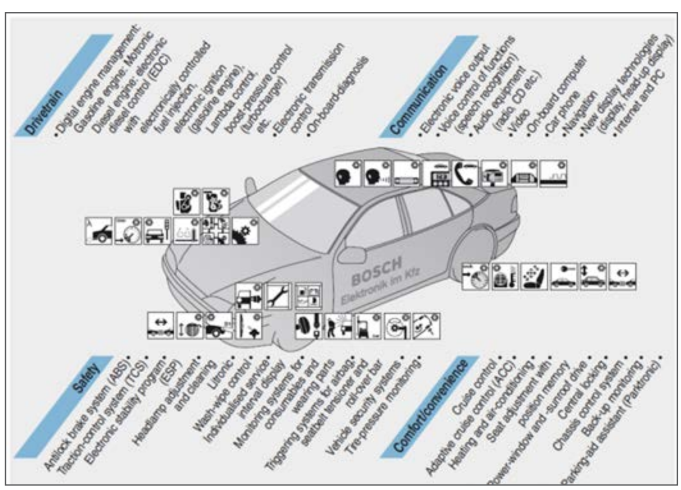
· Drivetrain
· Communication
· Comfort / Convenience
· Safety
· In-dash Entertainment

For each of the above five categories, the components of thermal management ecosystem can be broadly defined as follows:

· materials vendors
· component vendors
· process equipment vendors
· test equipment and services
· CAD and simulation software tools
· CAD and simulation services
· design services
· consultants

From a thermal management perspective the ecosystem for the broader power electronics products is the same as that for consumer electronics;

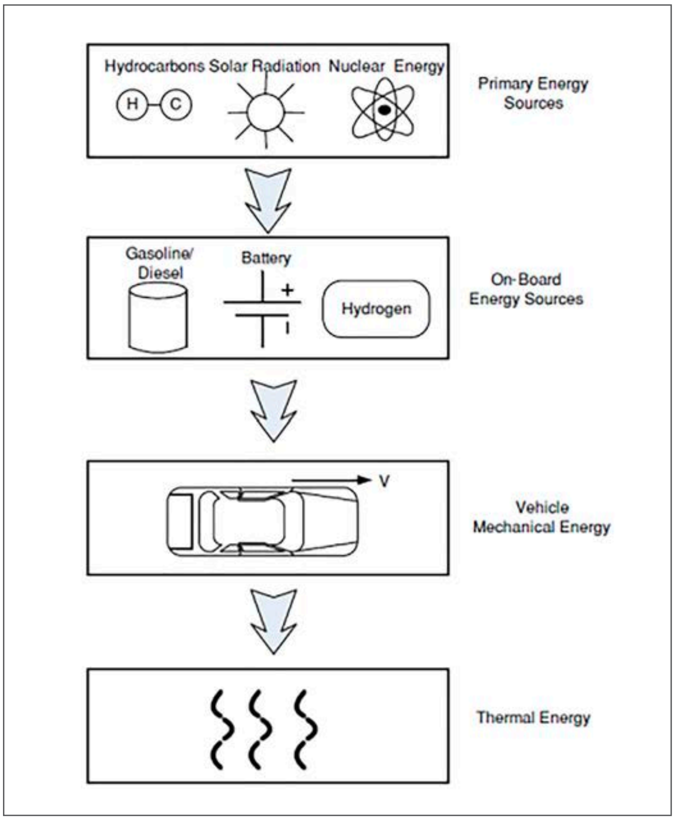
you can access that here: http://learn.electronics-cooling.com/2017-iot-and-consumer-electronics-guide/



OVERVIEW OF THERMAL MANAGEMENT COMPONENTS OF AUTOMOTIVE & POWER MANAGEMENT PRODUCTS

In this section, few elements of thermal management in power and automotive electronics are presented. This miniguide also features detailed articles on these topics.

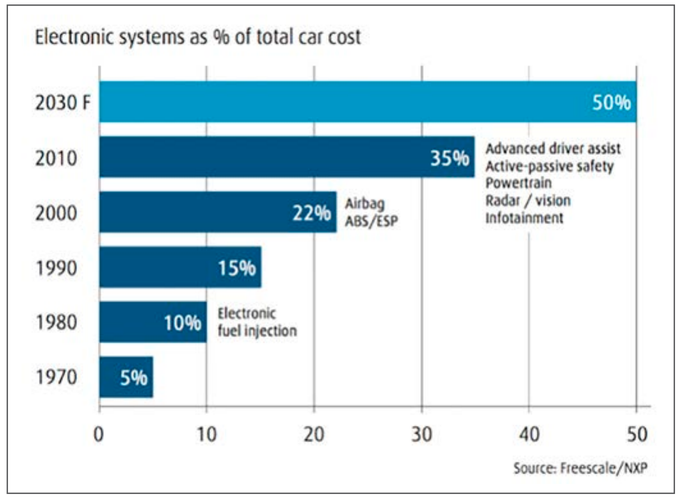
From a thermal management perspective, it is important to understand the energy conversion steps in automotive as shown below.



Energy conversion steps for vehicle energy consumption (Source: Vehicle Power Management (2011))

Energy losses exist at every stage of the energy conversion, aided by electronics in most cases. However, power electronics in energy conversion is most significant in the second and third stages: on-board energy sources and its conversion to mechanical energy. Current focus in the industry on electrification of the automobile in an effort to shift away from fossil fuel-based vehicles has led to increased application of power electronics. In addition to the batteries and fuel cells in EVs and hybrids, increasing complexity of automobiles has also led to the growth in the use of electronic control units (ECU) and communication modules.

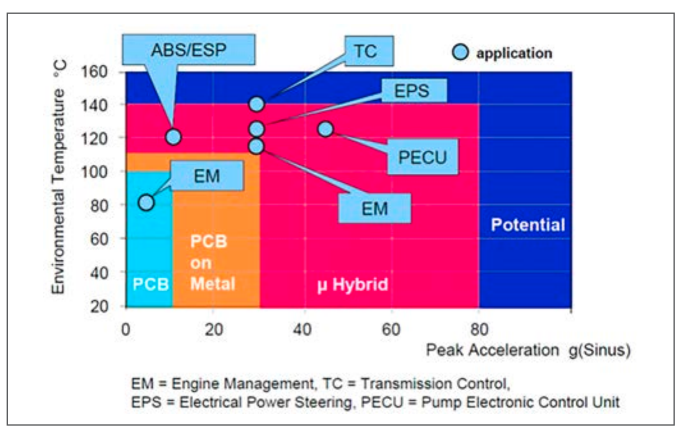
IC Insights forecasts automotive sector as the market with the highest growth rate between the years 2015 and 2020 with a market share of $16B in 2016. Furthermore, the cost of electronic systems in vehicles is expected to reach 50% of the total cost by the year 2030, as indicated in the figure below.



Cost Share of Electronic Components in the Bill of Materials for a Typical Automobile (Source: Freescale/NXP)

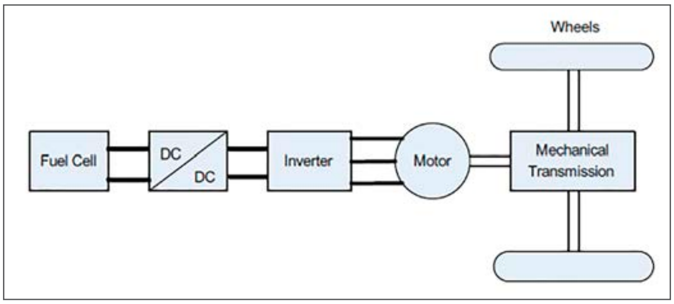
Some important trends in thermal management of automotive (depicted in the figure below) and to some extent broader power electronics applications are:

- Rising temperatures under the hood
- Increasing power dissipation
- Higher number of components into smaller SiPs
- More applications in challenging locations



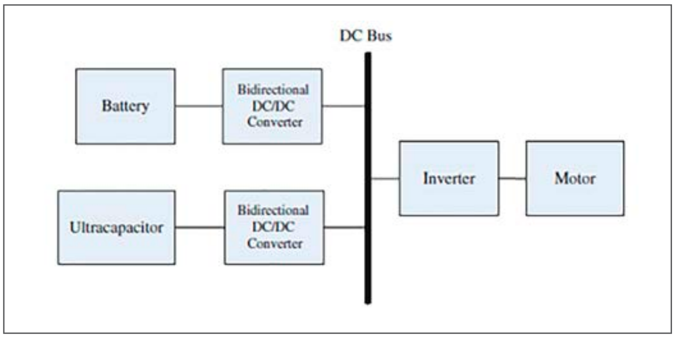
Environmental Temperature for Automotive Applications (Source: Bosch)

Typical configuration of a battery / fuel-cell-powered vehicle is as shown below. For both configurations (battery replaces fuel cell in the first block), the configuration consists of an energy source, DC/DC converter, inverter, motor and mechanical transmission. During braking, the batteries are charged by regenerative braking. Plugin hybrids and other alternative fuel-based vehicles have similar and more complicated configurations.



Configuration of a Typical Fuel Cell / Battery Vehicle (Source: Vehicle Power Management (2011))

In most applications using the above configuration, the powertrain structure also consists of ultracapacitors to accommodate power surges and/or transients (see figure below). Joule heating in the DC bus, thermal management of the batteries, ultracapacitors and inverters are some of the constituent components requiring special attention.



Powertrain Structure in a Battery-Powered Electric Vehicle (Source: Vehicle Power Management (2011))

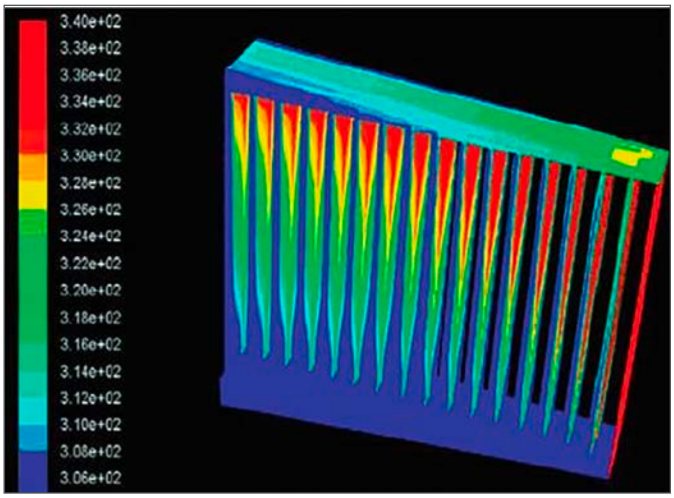
All powertrain components, including the energy storage systems (ESS) generate heat. One of the important factors with regard to thermal management is that temperature gradient inside a battery pack can cause inconsistency in the cell capacity and internal impedance. Hence, the available capacity of the pack may be limited by cells that are at the highest or lowest temperatures.

In fuel cell vehicles for example, power demands during vehicle operations include random and rapid transient cycles. The fuel cells and batteries in EVs and hybrid electric vehicles can hardly handle these power demand cycles due to many limitations of which thermal management is an important part. When the power demands fluctuate as the vehicle is operated, local current increases and the accompanying temperature rises are dramatically influenced by the loading rates. With quicker the loading rates, there is also the possibility of temperature accumulation and thermal runaway.

In Li-ion and NiMH batteries, the transient surge current through the battery results in dramatic temperature increases even if the average current is not high. As a collateral effect, the dramatic temperature increase leads to severe diffusion increase and uncontrollable ion concentration.

The figure below shows simulated temperature distribution inside an air-cooled battery pack. From the temperature contours, it can be seen that the difference between the maximum (340 K) and minimum temperature (314 K) is 26degC which is quite significant. With liquid cooling, the maximum and minimum temperature can be reduced to be within a few degrees inside the battery.

Another important consideration when it comes to thermal management of batteries is that the internal impedance will increase very quickly with the drop of temperature below zero Celsius. Experiments have shown that Li-ion batteries can barely deliver any power below -20degC. Internal heating elements are included in battery pack designs so that the battery can be warmed up during cold-weather.



Temperature distribution inside an air-cooled battery pack (temperature in Kelvin). Source Bosch

Another important aspect of thermal management of automotive components is in the charging the batteries. Batteries require cooling while charging. Tesla and GM for example are looking at ways to increase the rate at which batteries are charged and are incorporating thermal management systems into the process. Higher levels of charging shorten the time for full charge but result in heat introduced to the system. To quickly remove as much heat as possible with a simple, cost effective solution, Tesla and GM are using glycol distributed through the battery pack to cool the cells.

DESIGN AIDS & TOOLS

This section provides a brief overview of the design and simulation tools for thermal management of electronics products. It is worthwhile to note that many computer aided design (CAD) tools also feature embedded simulation capabilities including thermal simulations. Many of these tools can also be accessed on the cloud, requiring no dedicated hardware resources. The following tables show a partial list of these tools commonly used in electronics thermal management discipline.

Thermal Management CAD Tools

Vendor	Product Name	Cloud Access	Embedded Simulation
Ansys SpaceClaim	SpaceClaim	•	•
Autodesk https://www.autodesk.com/	AutoCAD IronCAD Inventor Fusion360	•	•
Dassault Systemes https://www.3ds.com/	SolidWorks Catia DraftSight	•	•
FreeCAD (Open Source) http://www.freecadweb.org/	FreeCAD		
IronCAD http://www.ironcad.com/	IronCAD Mechanical		•
PTC http://www.ptc.com/cad/creo	Creo		•
Siemens	NX Unigraphics SolidEdge		
Trimble https://www.sketchup.com/	Sketchup		
...many others			

Component / Vendor Repositories & Design Reuse

These portals are ideal for reusing existing designs and / or modifying a design to get a jump start. Many are also available in neutral file formats (IGES, STEP, STL, etc.) for easy porting to simulation tools listed above.

In addition to vendor websites where CAD files are available for download, the following portals offer CAD files of many chip packages, heatsinks, heatpipes, enclosures, cabinets, racks, etc.

- 3D Content Central (operated by Dassault Systemes) https://www.3dcontentcentral.com
- GrabCAD https://grabcad.com/

In addition to the above, for performing thermal simulations many vendors provide built-in, parametric and configurable component libraries –for example Mentor Graphics' Flotherm users can access Flopack for many standard packages, heatsinks, fans, etc. Similar features are also accessible in Ansys' Icepak and Future Facilities 6SigmaET & 6SigmaDC.

Remember to visit the manufacturers of the component itself –most component manufacturers now offer CAD files for download. You may also want to search in electronics component distributors like Arrow, Element14, DigiKey, etc. for older / discontinued components' CAD files not found on the manufacturer's site.

Thermal Management Simulation Tools

Vendor	Product Name	Cloud Access	Embedded Simulation
Ansys Suite https://www.ansys.com/	Icepak ICEM CFD Ansys Mechanical	•	•
Autodesk https://www.autodesk.com/	Fusion360 NEi Nastran	•	•
Comsol https://www.comsol.com/	Heat Transfer Module CFD Module	•	•
Daat Research Corp. http://www.daat.com/index.php	Coolit	•	
Dassault Systemes https://www.3ds.com/	SolidWorks Professional Simulia	•	•
ESI Group https://www.esi-group.com/software-solutions/virtual-environment/cfd-multiphysics/ace-suite/cfd-ace	CFD-ACE+	•	
Future Facilities www.futurefacilities.com/	6SigmaET 6SigmaDC	•	
Maya HTT https://www.mayahtt.com	NX Thermal AMESim	•	•
Mentor Graphics www.mentor.com	Flotherm FlothermXT Flovent	•	•
OpenCFD (Open Source CFD) https://openfoam.org/	OpenFOAM	•	
PTC http://www.ptc.com/cad/creo/simulate	Creo Simulate		
Siemens https://www.plm.automation.siemens.com/en_us/products/simcenter/nastran/	NX Nastran	•	
Software Cradle Co., Ltd. www.cradle-cfd.com	scSTREAM SC/Tetra HeatDesigner	•	
...many others			

CALCULATIONS

In this section, we feature a selection of articles on calculations you will find useful when working with consumer electronic devices and IoT products. Over the last two decades or so, Electronics Cooling© has been publishing calculation tips and suggestions which have benefitted design engineers and thermal management professionals to a great extent. Even though there has been great progress in software tools for thermal management, the articles featured in this section are invaluable in that they provide a backup as sanity checks and first order calculations early in the product conceptualization and design cycles.

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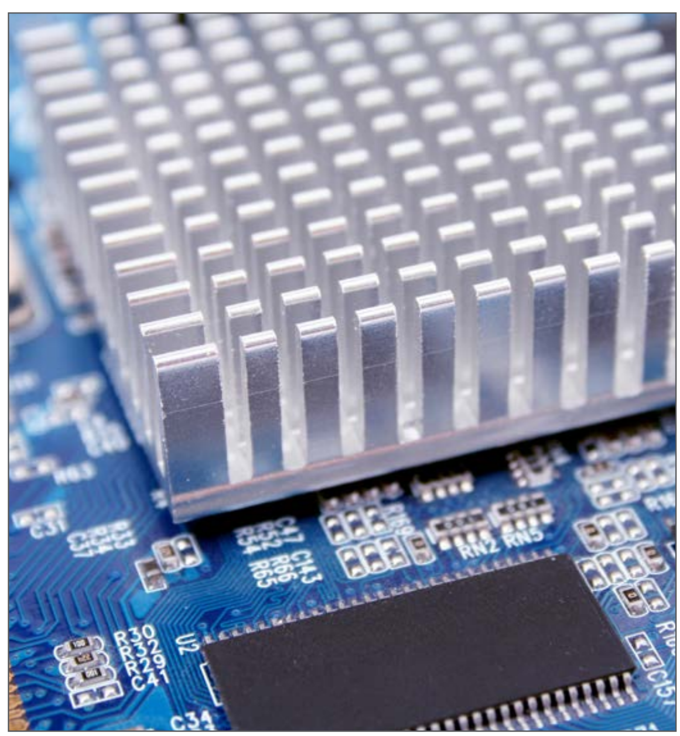

CALCULATIONS (CONTINUED)

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SYSTEM COOLING ANALYSIS, APPLICATIONS AND TRADE-OFFS

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