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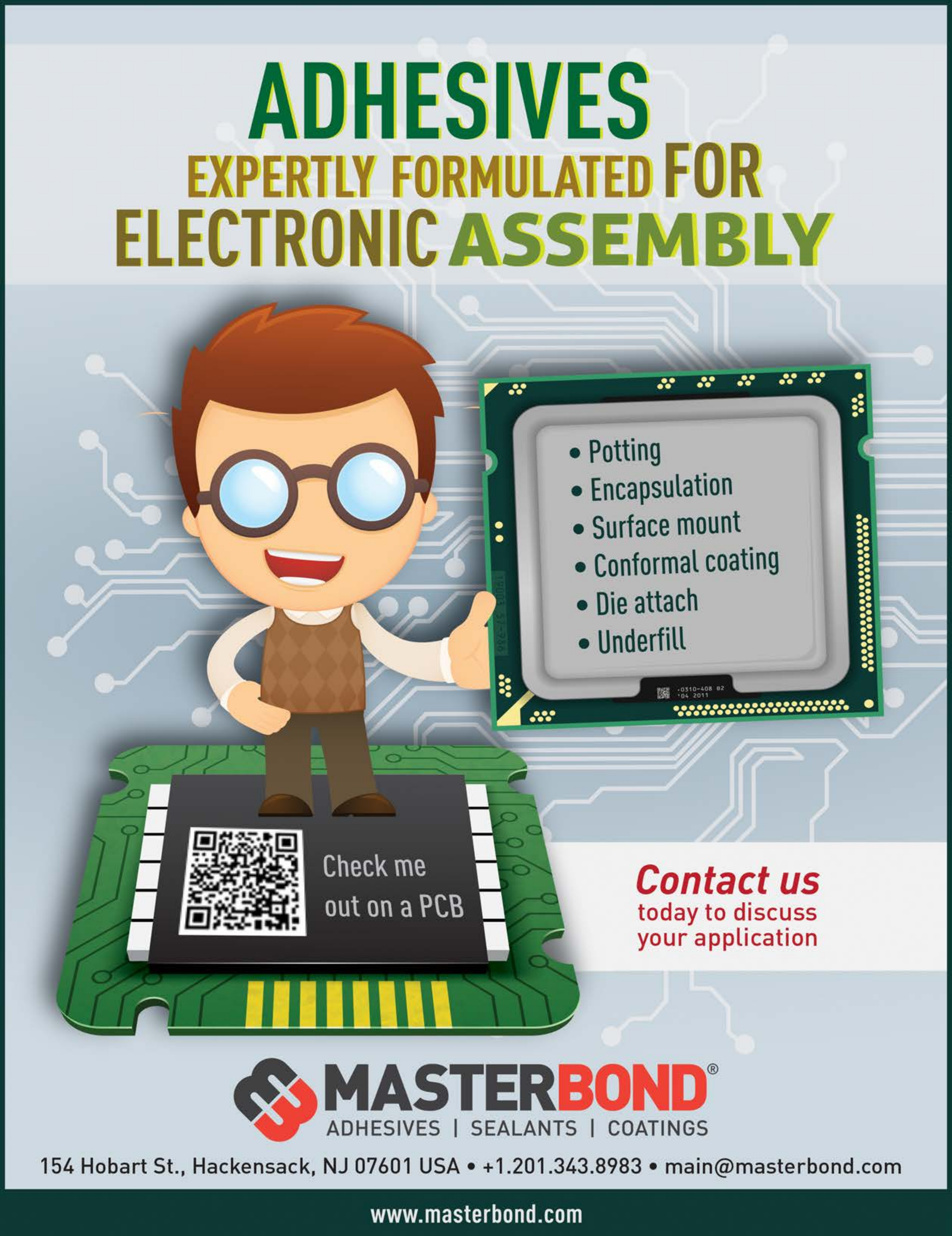
2017 IoT & CONSUMER ELECTRONICS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FOREWARD

In this inaugural issue of *Electronics Cooling*®'s series of digital guides, IoT & Consumer Electronics, we seek to supply you with the latest in thermal management of consumer electronics and the Internet of Things.

The intent of these digital guides is to bring you a collection of articles and information on thermal management materials. This issue features a brief description of the ecosystem for thermal management products, an overview of thermal management challenges, and some high-level descriptions of thermal design elements. We also feature more in-depth coverage in longer articles on select products.

There are many unique challenges that every thermal management professional has to address with respect to IoT and Consumer Electronics products. Most are in sync with the demands of ever increasing thermal dissipation. What makes the IoT and Consumer Electronics products even more challenging is the often conflicting and sometimes competing design requirements that have to be met while also insuring the products' functionality and reliability. From the concept of design, balance has to be sought between aesthetic and industrial vs. functional and utilitarian.

We are excited to take the first step in providing useful information to engineers to address thermal management problems.

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PRODUCT MATRIX

Continuing steep reductions in the prices of consumer electronics products have made them more affordable in developing and developed economies. Helped by innovations in sensor technology in the form of MEMS components and augmented by communications technology, recent years have witnessed yet another explosion of connected devices such as wearables, fashion-tech wearables, smart clothing, smart jewelry, fitness gadgets, virtual assistants, home security appliances, drones, virtual reality (VR) / augmented reality (AR) headsets, fashion-tech, and even more.

Not all the foregoing categories will need thermal management solutions, and many are well established product lines that are in their maturity and phase out stages of the life cycle. However, their newer versions and respins will inevitably use cost-effective thermal management solutions.

In the design of newer generation consumer electronics products that do use thermal management solutions, the choices are equally challenging for vendors and designers alike – offer the best solution for the problem that is reliable, manufacturable and cost-effective. In the context of increasing expectation and decreasing price tags, achieving this feat is no easy task.

The following tables list typical products, albeit partially, in the consumer electronics and IoT market place (the names were arbitrarily chosen and Electronics Cooling® is not recommending them in any way). Thermal management product component types are also listed.

Product Matrix of Consumer Devices (A Partial List)		Thermal Management Components														
Product Type	Product Examples	Electro-Active Polymers	Fans	Gap Pads	Heat Pipes	Heat Sinks	Heat Spreaders	Higher Thermal Conductivity Plastics	Lightweight Liquid Cooling Systems	Liquid Cooling Systems	Phase Change Materials	Resistive Heating Elements	Solders	Thermal Gaskets	Thermal Insulators	Thermal Interface Materials
Mobile Phones	Apple iPhone, Samsung S7, LG, Motorola, Xiaomi			X	X		X	X			X		X	X		X
Digital Cameras	Canon, Nikon, Sony, Olympus , Hasselblad			X			X	X					X			X
Wearables (arm/wrist wear)	Fitbit, Pebble, Apple Watch, Xiaomi, Garmin, Samsung Gear, Withings			X			X	X							X	X
Smart/Comfort Clothing	AiQ Smart Clothing, Sensoria	X							X			X				
Virtual Reality (VR) / Augmented Reality (AR) Headsets	Facebook Oculus VR, Microsoft Hololens, Sensic's OSVR, HTC Vive			X			X	X							X	X
Virtual Assistants	Amazon Echo, Amazon Alexa Device, Google Home		X	X	X		X	X					X			X
Drones	GoPro, Parrot, DJI		X	X	X	X	X	X					X			X
Television & Entertainment Hardware	4K Ultra High-Definition (4K UHD), OLED TV/Displays, Apple TV, Google Chrome, Harmon Kardon, TiVO		X	X	X	X	X	X					X	X		X
Gaming Desktops / Laptops	Acer, Velocity Micro, Lenovo, SkyTech		X	X	X	X	X	X		X	X		X			X
IoT Gateways, Nodes, Motes, Tags, etc. (A Partial List)		Thermal Management Components														
Mobile Phones	Apple iPhone, Samsung, LG, Motorola, Xiaomi			X	X		X	X			X		X	X		X
Smart Home IoT Gateways	Amazon Echo, Google OnHub, Motorola, Libelium Meshlium, Rigado IoT Gateways, Logitech Harmony		X	X	X		X	X		X	X		X			X
Edge Node: Occupancy Sensors	Libelium Plug & Sense, Lutron			X	X		X	X			X		X			X
Edge Node: Home alarm systems	Comcast, Libelium Plug & Sense		X	X	X		X	X		X	X		X			X
Edge Node: Power monitoring	Verdigris' Einstein system		X	X	X		X	X		X	X		X			X
Edge Node: Smart lighting	Philips Hue Bridge, Lutron		X	X	X		X	X		X	X		X			X

Thermal Management Manufacturers		Type of Product/Service					
Company	Contact Information - URL	Design: Software, Cameras, Etc.	Fans	Heat Sinks & Alternatives	Liquid Cooling & Thermo Electric	Monitoring	Thermal Interface Materials
AAVID THERMALLOY	https://www.aavid.com/			X	X		X
Advanced Energy Technologies, LLC. , a subsidiary of GrafTech International	http://www.graftech.com/products/egraf/			X			X
Alpha Novatech, Inc.	http://alphanovatech.com/en/index.html			X			
Amulaire	http://www.amulaire.com/			X			
Ansys, Inc.	http://www.ansys.com/products/fluids	x					
Autodesk	https://www.autodesk.com/products/cfd/overview	x					
Celsia	http://celsiainc.com/			X	X		
CPC (Colder Products Company)	https://www.cpcworldwide.com/Applications/Liquid-Cooling-of-Electronics				x		
Cradle North America Inc.	http://www.cradle-cfd.com/	x					
Delta Products Corporation	http://www.delta-fan.com/		x				
DUPONT	http://www.dupont.com/products-and-services/electronic-electrical-materials/thermal-management-materials.html						X
Ferrotec NORD	http://www.ferrotec-nord.com/				x		
FLIR Commercial Systems, Inc.	http://www.flir.com/instruments/display/?id=61313	x					
Fujipoly America Corp	http://www.fujipoly.com/usa/products/sarcon-thermal-management-components/						X
Henkel	http://www.bergquistcompany.com/						X
International Manufacturing Services	https://ims-resistors.com/therma-bridge/			x			
JARO Thermal (NRC Electronics)	http://www.jarothermal.com/		x	X	X		
Knight-Orion	http://orionfans.com/		x				
Laird	https://www.lairdtech.com/solutions/thermal-management						X
Leader Tech	https://leadertechinc.com/products/thermal						x
LMB Fans	http://www.alliedinter.com/lmb-fans.html		x				
Malico Inc.	http://www.malico.com/			X	X		
Master Bond Inc.	http://www.masterbond.com/industries/heat-sink-attachment						X
Mentor Graphics	https://www.mentor.com/products/mechanical/	x					
Mersen	http://ep-us.mersen.com/products/catalog/family/cooling-of-power-electronics/			X	X		
Panasonic	https://industrial.panasonic.com/ww/products/thermal-solutions						X
Polymer Science	http://www.polymerscience.com/product-type/thermal-management/						X
Rogers Corporation - Advanced Connectivity Solutions	https://www.rogerscorp.com/acs/products/74/COOLSPAN-Thermally-Electrically-Conductive-Adhesive-TECA.aspx			x			X
Rosenberg USA	http://www.rosenbergusa.com/		x				
Sanyo Denki	http://www.sanyodenki.us/		x				
Shin-Etsu MicroSi	https://www.microsi.com/product-category/packaging/						X
Siemens Industry Software Computational Dynamics Limited	http://mdx.plm.automation.siemens.com/	x					
SIKA	http://www.sika.net/en/products/flow-measuring-instruments.html					x	
Staubli	http://www.staubli.com/en/connectors/quick-couplings/cooling-line-coupling/				x		
ThermoElectric Cooling America Corporaton	http://www.thermoelectric.com/				x		
Techsil	https://www.techsil.co.uk/applications/thermal-management						x
T-Global Technology	http://www.tglobalthermal.com/						X
TRAN-TEC	http://tran-tec.com/			X			

PRODUCT SELECTOR

The following sections provide some information on products for:

- TIMs, Gap Pads
- Heatsinks
- Heat Pipes
- Die Attach (Solders, Ag Epoxy, etc.)
- Thermal Compounds
- Conformal Coat

TIMs, Gap Pads
Find more information on TIMs here:
https://www.electronics-cooling.com/category/tims/

Heatsinks
Find more information on Heatsinks here:
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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.

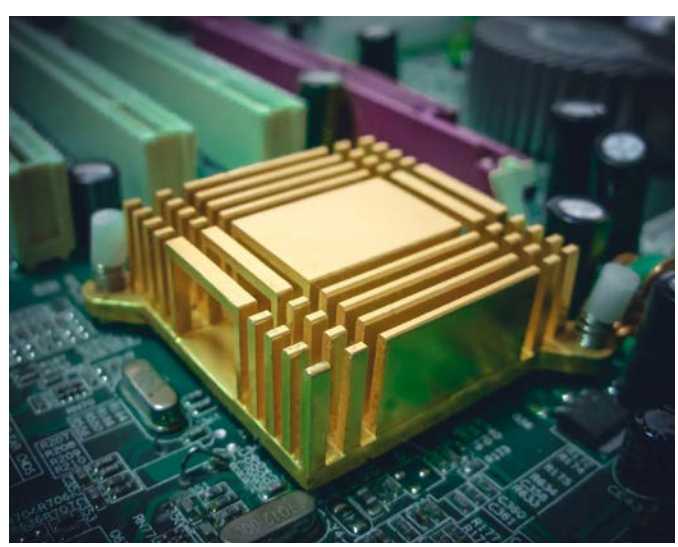
Die Attach Material	Thermal Conductivity Range (W/m-K)	Example Vendors
Silver Epoxy	2 to 20	Dow Corning, AI Technology, Henkel, Epoxy Technology
Lead Solders	40 to 50	Indium Corporation
Lead-free Solders	40 to 60	Indium Corporation
Gold-Tin (AuSn)	57	Indium Corporation
Gold-Silicon (AuSi)	27	Indium Corporation
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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ELECTRONICS COOLING OF HUMANS

MP Divakar, PhD
Stack Design Automation
Technical Editor, *Electronics Cooling®*

Introduction

In this article, we will explore the research trends underway in various research institutions and the industry to achieve further savings in energy by optimizing how human beings consume energy. While it is true that human beings lose a majority of the body heat from their head and chest areas, there are opportunities to optimize how human bodies respond to hot ambient conditions using smart clothing, a literal category of wearable electronics. Perhaps when Walt Whitman wrote one of his famous poems "I Sing the Body Electric," one of the twelve poems in the first edition of Leaves of Grass (1856/67), he had no clue that bidirectional thermoregulation of personal clothing on a human body would be enabled by the 'electric!'

ELECTRONICS COOLING IN HUMANS

Earlier in August of this year, Electronics Cooling® featured an article on energy efficiency of data centers where a review of the energy consumed by the IT and non-IT equipment and its optimization by deterministic (DCIM) and AI methods (Google's Deepmind) was presented. The 'occupants' of a data center, barring a few network techs and engineers, are all machines whose Silicon 'hearts' can withstand temperatures much higher than those of humans! As such, the cold and hot aisle temperatures in data centers have inched upward to achieve better power usage effectiveness. For the personnel servicing IT equipment, one of the workarounds of higher aisle temperatures has been to switch the airflow in cold aisle inlets as needed to insure personal comfort and then revert to a regular status when service is complete.

Since the early space age generation of personal heat and cooling, there has been a rapid progress in materials for making artificial fabric that enable better thermal regulation of human bodies while keeping or even improving the personal comfort levels. The end goal is to increase the set point for indoor energy regulation in office buildings, shopping malls, multi-tenant dwellings and homes.

If personal thermal management is addressed by facilitating heating or cooling only to a human body and its local environment, then the energy needed for heating and cooling an entire building can be significantly reduced. In comparison to buildings including homes, the human body has much smaller thermal mass and this difference is much larger in office buildings. The potential payoff from such savings will have a huge impact on energy costs, not to mention the impact on environment and climate change. This US Department of Energy (DoE) note explains that moving the thermostat temperature a few degrees higher or lower (in cooling / heating, respectively) for 8 hours a day can result in 10% energy savings.

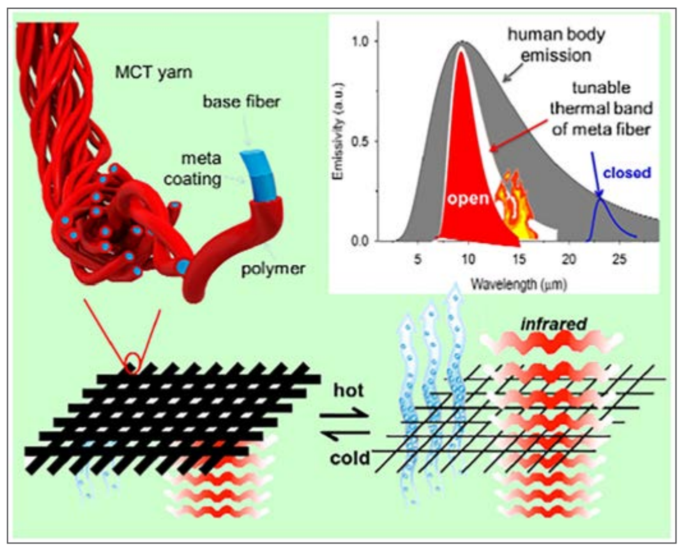
Materials like nanoporous polyethylene (nanoPE) are transparent to mid-infrared (IR) human body radiation but opaque to visible light because of the pore size distribution (50 to 1000 nanometers). This illustrious **Science** magazine article by Stanford University researchers (and sponsored by ARPA-E, see below) highlights more on the thermal characteristics of nanoPE materials. While such smart eTextiles have great benefits, the IR-transparent textile must also be wearable and allow water-wicking and air permeability, i.e., they must breathe! Nevertheless, such materials are the enablers of personal thermal management systems and thus represent a platform on which wearable cooling solutions can be developed.

ARPA-E Programs

The DELTA program (Delivering Efficient Local Thermal Amenities) has multiple R&D activities currently underway to address energy savings by personal thermoregulation. Starting with this edition, Electronics Cooling will publish a series of articles on this topic by inviting the participants of ARPA-E DELTA program. In this blog, more information on the work done at University of Maryland (UMD), a participant of the ARPA-E program is provided.

UMD's work on Meta-Cooling Textile (MCT) involves developing a thermally responsive clothing fabric to maintain personal comfort in hotter or cooler indoor settings. However, this program attempts to go a step beyond material innovation by providing clothing with active control over the primary channels for energy exchange between the body and the environment. This is done by increasing or decreasing the diameters of the nanopores as needed for regulating body temperature.

The technology being developed at UMD is shown pictorially in the figure below. Active IR emissivity control is achieved using a metamaterial coating and synergetic air convection. UMD researchers aim to achieve this in a self-powered mode whereas the state-of-the art (e.g. Nike Sphere React) smart clothing requires 2.5 to 5.0W of power and is bulky. Cost and weight of the fabric are other targets that favor the UMD researchers, should the research succeed –they only hope to add 2.5% increase in weight and a cost increase of $0.88 to $3.42.



Meta-Cooling Textile Characteristics

Electronics Cooling® is actively working with all researchers of ARPA-E's DELTA program for guest articles. Stay tuned as we will bring you more information on electronics cooling of people!

Your comments are welcome.
MP@electronics-cooling.com

THERMAL MANAGEMENT IN CONSUMER-GRADE DIGITAL CAMERAS

MP Divakar, PhD
Stack Design Automation
Technical Editor, *EElectronics Cooling®*

Introduction

The proliferation of digital cameras and their subsequent modular integration in mobile communication and hand-held devices has made today's photography almost trivial. The latter, i.e. the integration in mobile and hand-held devices is largely made possible by advancements in imaging technology as well as miniaturizing optics and the requisite electronics.

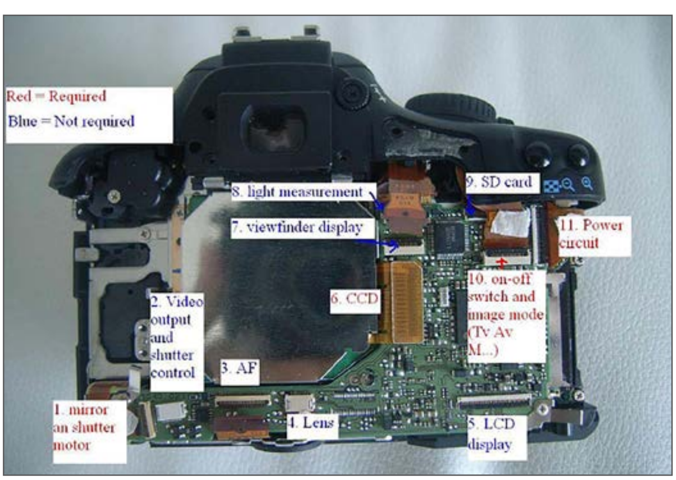
THERMAL MANAGEMENT IN CONSUMER-GRADE DIGITAL CAMERAS

Most camera modules in mobile phones are now a fraction of an inch in dimensions and their thicknesses are approaching those of chip packages. This costing and technology report on Samsung S7 phone states that the camera module with a set of 6 lenses, gyroscope and optical image stabilizer (OIS) driver with flash memory is only 12x12mm in size with a thickness of 5.3mm.

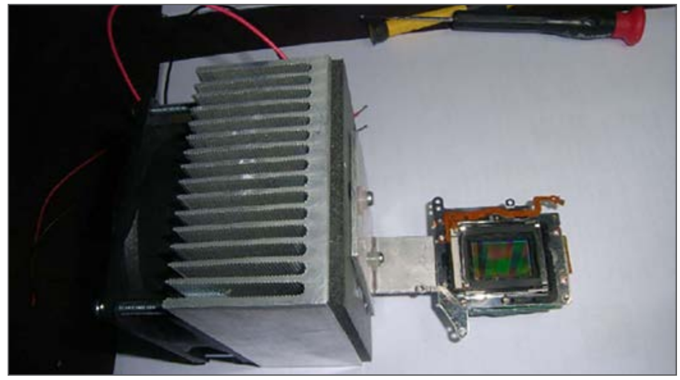
SLR (single lens reflex) cameras of yesterday are mostly mechanical and electromechanical devices requiring no thermal management during their operation. The material sets used in their manufacturing withstood the extremes of temperature and, for the most part, functioned as intended. However, this is not the same with digital cameras – both standalone SLRs and integrated camera modules. The main “light engines” in these devices largely fall into two broad categories: charged couple devices (CCDs) and CMOS imagers.

An excellent introduction to the digital camera technology can be found in this article which succinctly defines all of the underlying terms and technology of image capture with the two broad categories of sensors and their variants. CCDs and CMOS imagers each have their distinct advantages and performance metrics. Their comparison makes sense only in the context of an application; this paper provides a good comparison between the two types of sensors. In general, CCDs produce superior image quality but are bulkier to package and cool.

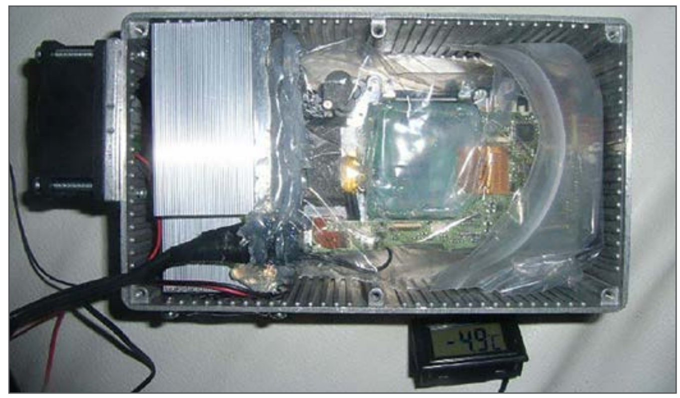
In an earlier article, I briefly covered the topic of dark currents in CCD imagers and the need for Thermoelectric (TE) modules to cool the CCD arrays minimizing dark currents. At lower temperatures of the CCD sensor, the ‘dark count’ pixels are lower. The CMOS sensors on the other hand are mostly uncooled, even in cases where the CMOS sensor array is a large one, like the Canon EOS 450D, which has a 12.2M pixel sensor measuring 22.2 x 14.8 mm.



Canon 450D (XSi) Camera with the back removed (source)



Canon 450D (XSi) CMOS fixed to the Peltier cooling assembly (source)



Re-purposed Canon 450D (XSi) with Peltier cooling assembly for astronomy imaging (source)

However, for astronomy imaging applications where the ‘dark count’ needs to be minimum, third party Peltier cooling adapters are available for most DSLR cameras. This hyper modification study details how one can disassemble the Canon 450D (XSi) Camera for cooling with heatsink augmentation.

For those of you who are hobbyists interested in building your own DSLR camera from scratch, there is an open source project that will be of interest. The “Build Your Own SLR Camera from Scratch” at SLR Lounge features an open source project for a SLR camera with full documentation and downloadable files. Some parts of the camera, including its body, can be 3D-printed. This project is perfect for designing a more elaborate cooling solution instead of a retrofit for the CMOS imager that can be perhaps integrated in the camera body. (Electronics Cooling would be very interested in hearing about your experience, perhaps in a blog. If interested, please contact me!)

In general, most digital cameras based on CMOS imagers are uncooled. The camera body is utilized as a heatsink with minimal compensation for dark currents in the imager. This has not stopped companies like Apple to get more creative in thermal management of consumer electronics devices. Apple patent “Multi-Level Thermal Management in an Electronic Device,” application #20120311357, 2012 is one such example.

THERMAL MANAGEMENT-ENABLED PRODUCTS AT CES 2017

MP Divakar, PhD
Stack Design Automation
Technical Editor, *Electronics Cooling*®

Introduction

The Consumer Electronics Show (CES) which concluded earlier this month is the largest annual conference and expo for anything or everything in electronics in the continental USA. By some estimates, CES 2017 exceeded the previous year record, topping 177K+ attendees. In such a large conference, enabling technologies like thermal management often take a backseat to the product-centric and consumer-appealing expo. However, this year that was not completely the case –there were many products enabled by thermal management.

THERMAL MANAGEMENT – ENABLED PRODUCTS AT CES 2017

The technology categories at this year's CES were mainly along two distinctions: emerging and maturing technologies. As outlined below, the product verticals identified are along expected lines over the last year or more. At *Electronics Cooling®* we would like to point out that we identified these categories in advance and our editorial calendar for 2017 well-reflects these trends.

Emerging Technology Category:

- Smart Home
- Digital Assistant Devices
- 4K Ultra High-Definition (4K UHD) TV/Displays
- Virtual Reality (VR) and Augmented Reality (AR)
- Drones
- Wearables

In the following paragraphs, some products shown at the CES this year are shown for the above category.

Smart Home Products

Evolving as consumers' most popular means of IoT engagement. The products here include smart thermostats, smart smoke and CO detectors, IP/Wi-Fi cameras, smart locks and doorbells, smart home systems, and smart switches, dimmers and outlets, etc. Of the foregoing, products requiring compute power like smart home gateways/edge nodes, etc., will demand lower cost thermal management solutions requisite in the consumer devices.

In addition to the 'main stream' smart home products, few others stood out as innovative and of interest to thermal management professionals. One of them claims to be an efficient an efficient water heater using selective heating of Graphite plates, shown below.

Ohmic Array Water Heater (Image Rights: Electronics Cooling®)

Another 'smart home' appliance is an inverter that serves as an emergency power backup with solar panels. This inverter has active cooling enabled by fans. The smaller version partly visible on the right is a portable one with passive cooling.

Solar-charging Inverters (Image Rights: Electronics Cooling®)

Digital Assistant Devices

These products present an opportunity to understand how home tech products will integrate artificial intelligence over time. Examples include Amazon's Echo and Google Home. These products are usually packaged with passive cooling solutions to keep costs lower, like this teardown shows for Amazon Echo.

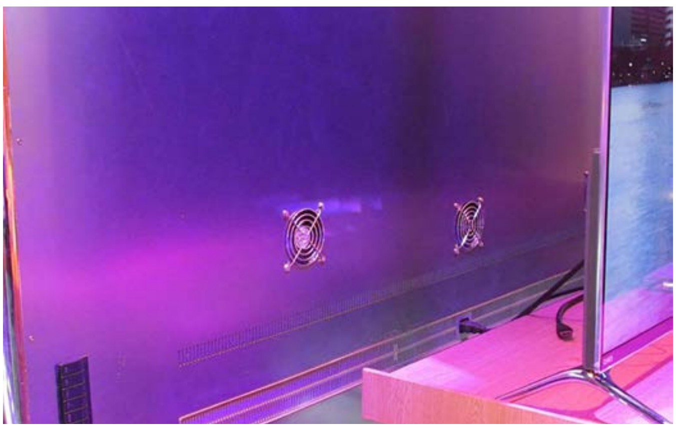
Amazon Echo (Cover Removed). Source: CNet

4K Ultra High-Definition (4K UHD) TV/Displays

One of the industry's fastest growing segments, driven in part by next-generation technologies like organic light emitting diodes (OLED), high dynamic range and wide color options.

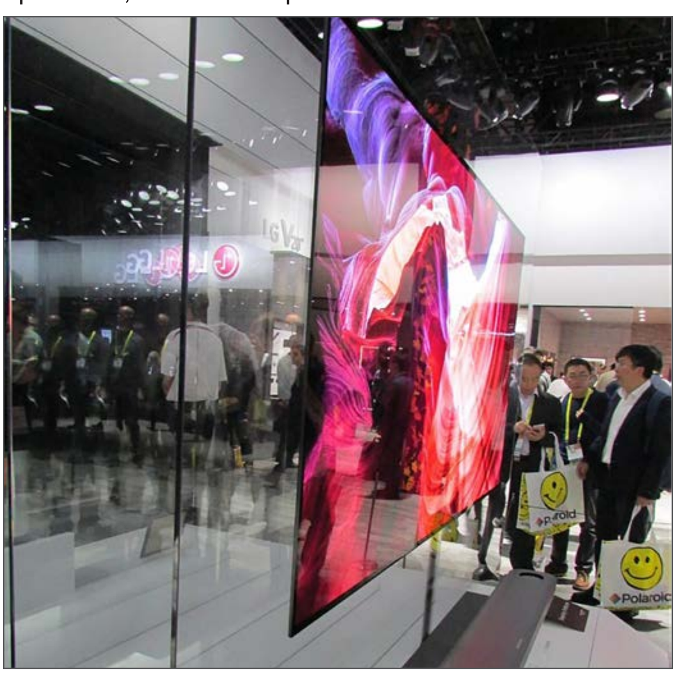
It was interesting to see that large format (>80inch) 4K UHD displays with LED technology were using strategically placed multiple cooling fans to address thermal management.

120inch 4K/8K UHD Display: Front Side (Image Rights: Electronics Cooling®)



120inch 4K/8K UHD Display: Back Side Showing Cooling Fans (Image Rights: Electronics Cooling®)

OLED displays on the other hand seemed to be using passive thermal management options like Graphite heat spreaders, thermal compounds etc.



OLED 4K Display: Notice the thickness of glass sheet on the edge, ~0.3inch! (Image Rights: Electronics Cooling®)

Virtual Reality (VR) and Augmented Reality (AR)

In addition those headsets augmenting smart phones, self-contained products like Microsoft's HoloLens, Oculus Rift, etc., were also present in good numbers. It is worthwhile to note that some of the wearables with good compute capability were noticeably warm when worn.

Wearable with Compute Capability (Image Rights: Electronics Cooling®)

Drones

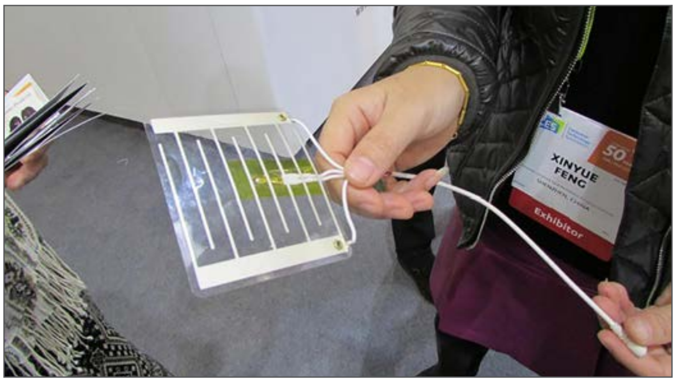
Drones are all the rage these days! But what would delight readers of Electronics Cooling is that thermal imaging cameras are becoming mainstream Drone applications. FLIR' Duo Thermal Drone Camera was particularly interesting as it was fitted into a Drone demonstrated at the show.

FLIR Duo Thermal Drone Camera (Image Rights: FLIR)

FLIR Duo Thermal Drone Camera (Image Rights: FLIR)

Wearables

Most readers would associate wearables with wrist-worn and in general body-worn electronic gadgets with communication capabilities but not smart fabrics used in comfort- and biomedical-clothing. Driven by the popularity of fitness activity trackers, products in this category include health and fitness devices, hearables and smartwatches as well as comfort clothing. At *Electronics Cooling*®, we have featured multiple articles (here, here) on comfort clothing in 2016. To see many commercial offerings of the comfort clothing and therapeutic 'wearable' products further validates our content strategy.



Embedded Heater for Comfort Clothing (Image Rights: Electronics Cooling®)

Comfort Clothing with Embedded Heaters in Market (Image Rights: Electronics Cooling®)

Comfort Clothing in Therapeutic Applications (Image Rights: Electronics Cooling®)

Maturing Technology Category:

- Smartphones
- Televisions
- Tablets
- Laptops
- Desktops

All of the products verticals above are now in the technology maturity phase of their life cycle. Though the forecasts for laptops and desktops indicate decline over the next few years, they appear to be in no near-term danger of extinction. Thanks to advances in thermal management and electronic packaging in general, more compute and memory can now be housed in the same form factors that make these products particularly attractive. Advances in computer gaming and virtual reality make compute platforms indispensable.

Smartphones

With more capable processors and better power management, newer smart phones are meeting the average user's computing demands. Most are using existing passive thermal management technologies which include efficient heat spreaders, heat pipes (in some handsets) and thermal compounds. Phones with OLED screens are making thin form factor realizable while at the same time keeping the power budget lower.

Televisions

LCD displays with full-array and edge-lit LED technology seems to be hitting the limits in scaling to larger sizes and higher resolution displays. Larger (>80in) format displays seem to favor OLED technology from a power and cooling perspective; some examples were shown earlier.

Laptops

Gaming seems to be the primary driver for high performance laptops. Vendors like Razr who provide high performance gaming laptops with i7 processors are augmenting compute capability by also using external GPU and memory banks with Thunderbolt interconnect. The external GPU unit (Razr Core) uses dual fans to cool the bank of GPUs and memory.

Razr Gaming Laptop with External GPU Unit (Image Rights: Razr)

Desktops

Gaming and high performance computing are also providing extended life to older compute platforms like the good old desktop. There were several vendors showing excellent thermal management enhancements for gaming desktops and servers.

The primary approach to meeting higher compute demands is augmenting existing cooling with liquid cooling loops and fans. To that end, companies like Calyos and ThermalTake show cased loop heat technology.

Calyos Loop Heat Pipe Augmentation for Servers
(Image Rights: Electronics Cooling®)

Some offerings of heat pipe-based thermal management provide retrofit capability where the existing chassis of the desktop / server require minimum or no modification (see figure below).

Retrofit Loop Heat Pipe Augmentation (Image Rights: Electronics Cooling®)

ThermalTake showcased colorful liquid cooling kits containing water blocks, colorful coolants, radiators, tubing, pneumatic fittings, cooling fans and other components.

ThermalTake' Complete Cooling Kit for Gaming Desktops
(Image Rights: Electronics Cooling®)

ThermalTake' Liquid Cooling implemented in Gaming Desktops (Image Rights: Electronics Cooling®)

In closing, it is worthwhile to note the following trends in the consumer electronics product-space:

- It may not be obvious, thermal management technologies are found in almost each and every consumer device available in the market. Without such enablement, such products would not be realized and accessed by the consumers.
- The primary drivers of thermal management in consumer devices are performance and cost –these are more critical in the CE sector than others.
- Newer / emerging CE products are using advances in electronics innovations such as faster processors, sensors, low power, newer fabrication technologies, electronics packaging and thermal management.
- Older / mature products such as laptops and desktops are seeing resurgence in growth due to gaming and VR. Thermal management is the core technological block in the design of these products.

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THERMAL MANAGEMENT OF IoT HARDWARE: GATEWAYS

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Stack Design Automation
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Introduction

As Electronics Cooling® engineers, we can say this unequivocally –the root cause of heat in electronics systems is power! Barring external and environmental influences, heat dissipation in electronic devices is an unavoidable side effect in any powered electronic device.

THERMAL MANAGEMENT OF IoT HARDWARE: GATEWAYS

In this article, we will take a look at the Internet of Things (IoT) Gateways, in particular Edge Gateways which connect to various “Things” that sense and report the data through these Gateways. And we will limit our discussions in this blog to Gateways that are deployed indoors, typically home IoT Gateways. These are typically Broadband Router and Gateway combinations without Cellular modems. *Electronics Cooling*® will feature more articles later on thermal management of outdoor and ruggedized / industrial IoT Gateways. Furthermore, the evolution of IoT Gateways is headed in a direction where computing capability is increasingly being integrated in these Gateways in what is now popularly known as Edge or Fog Computing Nodes which take cloud computing literally to the edge; we will limit our discussion in this blog to Gateways with no or limited compute capability; just be clear, computing in this context is alluding to the support of applications hosted at the Edge Gateway. As described in our Editorial Calendar, *Electronics Cooling*® will be releasing several thermal management miniguides throughout the year including one on the topic of Fog Computing which will also include coverage of Mobile Edge Computing (MEC).

What used to be simply known as embedded computing of yesteryears based on standards like PC/104, etc., is now a days supplemented with communication layer to make a completely self-contained connected product. Therefore, when it comes to discussing thermal management of IoT Gateways, the first thing to recognize is that we are dealing with thermal management of an embedded system with wired and/or wireless communication capabilities. Software has a primary impact on power consumption in an embedded system which is driven by the utility demands imposed on that embedded system. To reduce thermal dissipation, one needs to understand the power utilization in the device and develop new ways to aggressively reduce power in a dynamic manner.

Dealing with heat dissipation has long been the bottleneck in embedded systems design. To make matters worse, processing demands have increased in almost all categories of products, physical device sizes continue to shrink, and as if these were not enough, almost all embedded devices are passively cooled!

Software Thermal Management

Software-based Dynamic thermal management (DTM) techniques therefore form an essential piece of the runtime management stack in embedded systems. A good source to get started on DTM is this book “The Art of Software Thermal Management for Embedded Systems” (*Electronics Cooling*® review coming later this year!) which provides an excellent background to software-driven thermal management. Dynamic power dissipation is modeled by:

$$P = C V^2 f$$

where P is power, C is capacitance, V is volts, and f is switching frequency. The book emphasizes that software-based thermal management is primarily dependent on the above equation on dynamic power dissipation.

Intel Joule for example includes help on installing heatsinks as well as a detailed thermal management overview which is based on:

- User safety through thermal ergonomics that control exposed surface temperatures.
- Prevent thermal runaway.

The Joule module provides two (BIOS-based) methods that work together to maintain a thermal target. One is temperature limit setting and the second is Run-time Average Power Limit (RAPL). The module provides hardware thermal controls that are intended to maintain operation within a set temperature range by adjusting processor speed or capping the maximum power consumption. This is accomplished by a combination of Thermal Control Circuit (TCC) and Power Limit 1 (PL1) which is based on RAPL. However, PL1 is a static limit of the maximum module power while TCC is below set point. When module temperature is above the TCC set point, the TCC function dynamically lowers PL1 until the TCC value returns below the set point.

The IoT Gateways

Note that there are contrarian views and opinions on the need for a home IoT Gateway, some arguing that a smart phone can manage most of the functions provided by a home IoT Gateway. Such opposite views not withstanding, broadband internet providers like Comcast are indeed integrating multi-protocol radios into cable modems/routers thereby augmenting its function to that of a full-fledged IoT Gateway.

Today, with the naysayers on the market potential of consumer IoT not withstanding, there is a bewildering array of choices for IoT Gateways. Gadgets from Intel for example include a series of Gateway solutions like the DK100 Series for Industrial and Energy, DK200 Series for Transportation and the DK300 Series for Industrial, Energy, and Transportation. On the consumer side, there are IoT Gateways available today from Amazon (yes, the Echo is now a days positioned as a IoT Hub!), Logitech, Google (OnHub), Motorola, etc., are some of the vendors to choose from.

In the following paragraphs, we will present the thermal management approaches adopted in the Google OnHub product from a teardown.

Google's OnHub router which comes in two versions promises a new robust way to Wi-Fi and Bluetooth connectivity with the following specs:

- Dual-core 1.4 GHz CPU
- 4 GB e-MMC flash storage
- IEEE 802.11 b/g/n/ac
- Dual band 2.4 GHz and 5 GHz 12-antenna array
- Congestion-sensing radio and antenna
- USB 3.0 port + Bluetooth 4.0
- 1 GB DDR3L RAM

One OnHub version's teardown and the thermal design attributes thereof are presented in the following figures.

Figure 1. OnHub with the cover removed. The IoT Hub is passively cooled with slits for air circulation

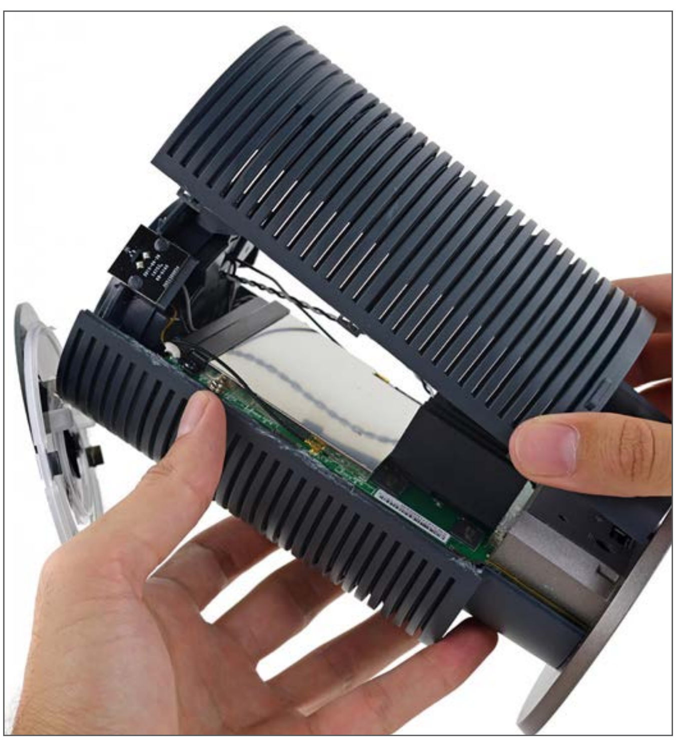

Figure 2. OnHub with the inner cover removed.

Figure 3. OnHub with the cover removed, revealing the smaller heat sink.

Figure 4. Larger heat sink contacting multiple components.

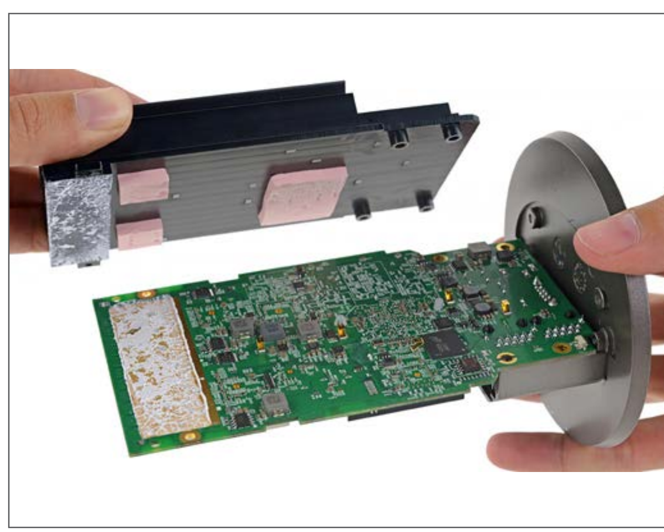

Figure 5. Underside of the larger heat sink with thermal / gap pads for contacting multiple components

Figure 6. Final tally of components: two heatsinks, cooling-capable cover and most importantly a software-enabled dynamic thermal management environment (not shown!)

In closing, passively cooled embedded thermal hardware components and systems pose a unique challenge to thermal management. What we consider as thermally adequate with sufficient margins under static operating conditions may not be sufficient to address the reliability of the product. The thermal design has to meet the dynamic operating conditions of the device wherein it is not just the maximum temperature limits of the components, the number of cycles also figures prominently.

Your comments are welcome!
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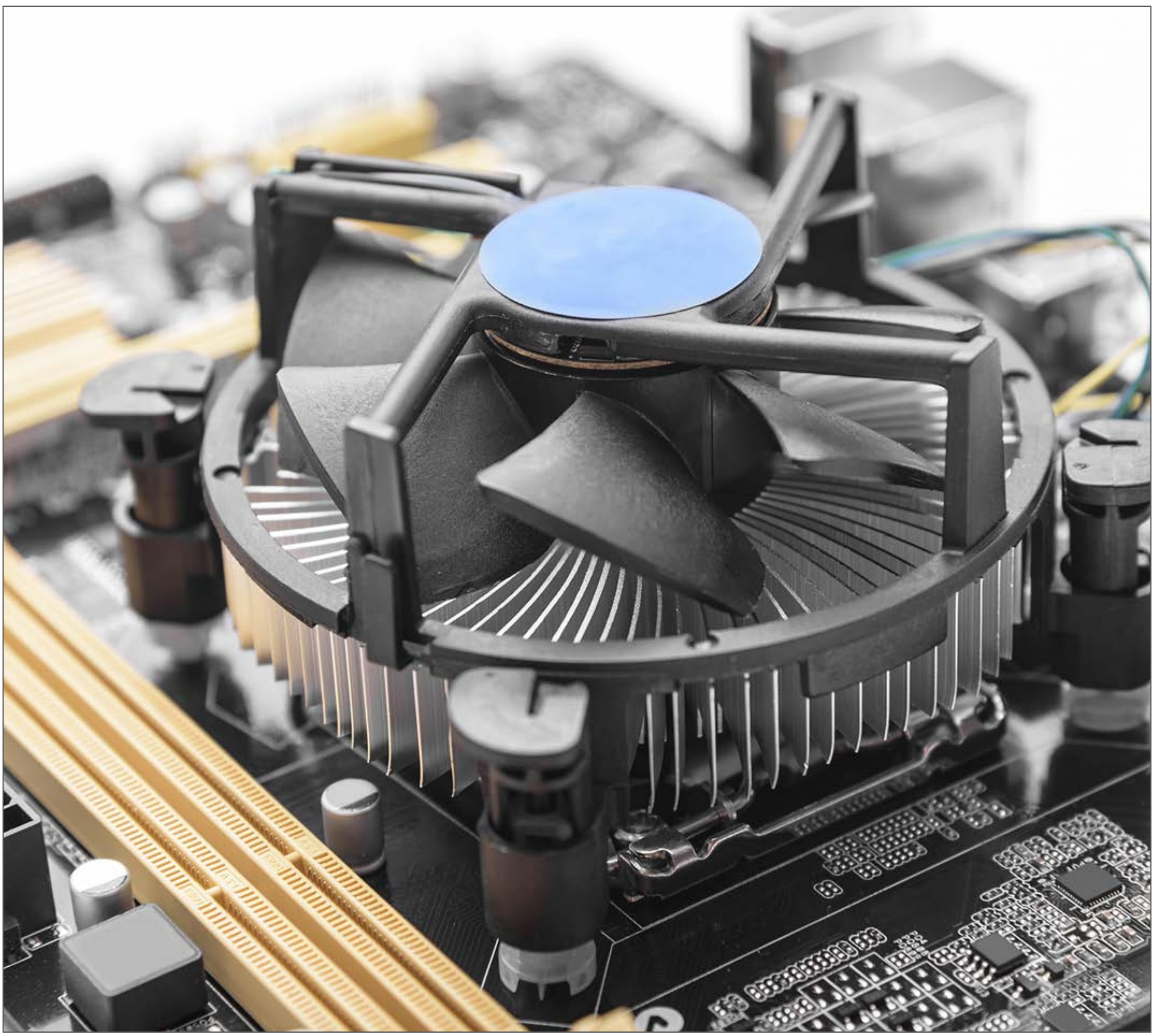

INDUCTIVE WIRELESS CHARGING IS NOW A THERMAL DESIGN PROBLEM

Dr. Vinit Singh
NuCurrent, CTO

Introduction

It is interesting how different parts of a value chain speak differently, sometimes wildly differently, about a product or feature but they may use the exact same words. For example, both the consumer and the thermal engineer want the device to have "cool" features. Wireless charging is one such hardware feature [1].

Wireless charging was included in over 250 million devices in 2016, expected to grow at a 85% CAGR until 2019. As of today, around 15 automobile models have announced the inclusion of consoles within the vehicle for wirelessly charging devices such as smartphones [2], and Dell has demonstrated the world's first laptop charging solution [3] at CES 2017 with a projected product release in mid-2017.

INDUCTIVE WIRELESS CHARGING IS NOW A THERMAL DESIGN PROBLEM

While several handset manufacturers already include it in their flagship devices, it is expected that both of the top two smartphone manufacturers of the world will include this feature by the end of 2017. The key technical attributes of the wireless power solution, especially for the antenna, include spatial (xy) freedom, high performance regardless of environment, and being minimally invasive. High performance implies high charge rates without causing heating concerns.

This article pertains to wireless charging of devices using Near Field Magnetic Coupling (NFMC) in the consumer electronics industry; more specifically it refers to devices that operate in the high-coupling (k> 0.5) regime, commonly referred to as the inductive mode.

There are wireless power standards working towards ensuring interoperability between devices [4,5]. This brief addresses the sources of thermal concerns and some common design practices and material choices to help implement ultra-thin form factors that are also thermally robust, especially on the receiver (device) side. Thermal effects are extremely important because it may lead to consumer inconvenience, device malfunction, and in extreme cases, device damage.

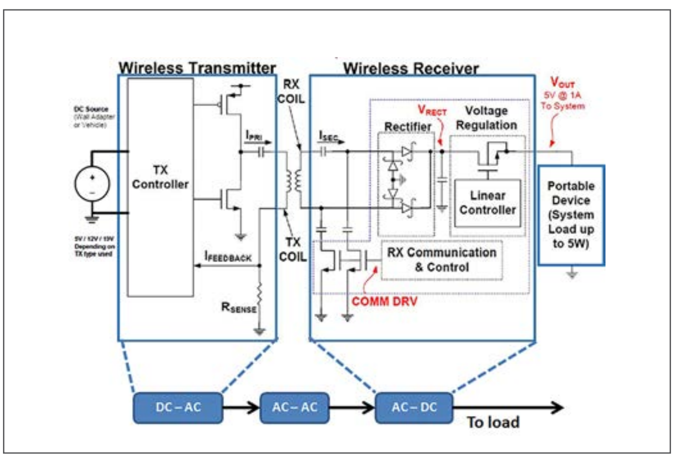

Fig. 1: A wireless power system with a DC input and DC output of 5V at 1 A resulting in a 5W system [6]. A simplistic 3-block description of the system is also provided.

Wireless Power and the Mobile Device

The Wireless Power system can be viewed as a DC-DC converter with an air-core transformer as illustrated in *Fig. 1* [6]. The figure illustrates a circuit schematic of an exemplary low frequency (around 100-400 KHz) system using a half-bridge type inverter to drive the transmitter antenna (equivalent to the primary coil of the transformer). The system may utilize antennas that are highly resonant, mildly resonant, or not resonant at all; it depends on the use of capacitors to alter the reactive impedance looking into the antenna. In the consumer electronics realm, the frequency of operation ranges from approximately 100 KHz to about 13.56 MHz.

Refer to *Fig. 2* for a schematic of a generic cross-section of a handset device that has the wireless charging feature included. As indicated in this figure, the typical location of the device side antenna (the receiver antenna) is close to the backcover (also called backplate), which allows for minimum separation from the transmitter antenna. As a side note, for wireless charging, it is almost mandatory that the backcover be dominantly non-conductive. "Almost" because there are techniques that may allow for useful power transfer through a dominantly conductive backcover; however, this is not a commercialized technology yet.

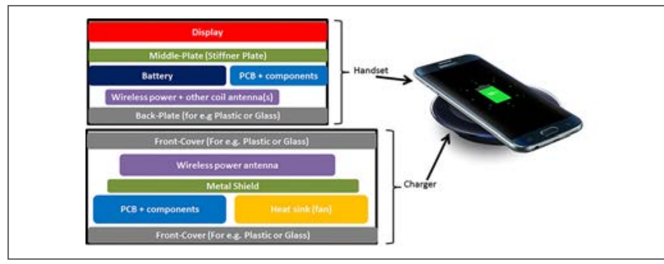

Fig. 2: A generic cross-section of the contents within a smartphone and the charger. Portions of this figure have been obtained from [7]. On the right is a photograph of a generic device placed on a wireless charger that shows the physical equivalent of the schematic.

The proximity of the battery to the antenna the will add to the stress of the thermal management system. The battery, typically Li-ion based, is considered to operate safely (i.e. charging and discharging) in the temperature range of 00 C– 450C [8]. This has also led to a generally accepted maximum temperature on the skin of the device to be about 450C [6].

Thermal Sources in a Wireless Power System

The major sources of heat in this system are the I2R losses (Joule heating) in the antennas, joule heating due to eddy currents in the shielding material and any metallic components that are in the path of magnetic flux lines, switching losses in the power stage, and losses in passives (e.g. rectifiers). Further, it should be noted that the heat is generated by both the transmitter system and the receiver system, and a portion of the heat from the transmitter side will flow to the receiver via a combination of conduction and convection. Here, we will focus on the magnetics (i.e. antennas + shielding) on the receiver side which is one of the primary sources of heat in the device.

Consider the following equations:

$$V_{Rx-ind} \sim j\, \omega\, k \sqrt{L_{Tx}\, L_{Rx}}\, I_{Tx} \tag{1}$$

$$I_{Rx} = \frac{V_{Rx-ind}}{R_{AC(coil)} + Z_{AC\ load}} \tag{2}$$

Where VRx-ind is the voltage induced in the receiver antenna, ω is the angular frequency, k is the coupling coefficient, LTx is the inductance of the transmitter antenna, LRx is the inductance of the receiver antenna, ITx is the current through the transmitter antenna, IRx is the current through the receiver antenna, RAC (Coil) is the AC resistance of the antenna at the operating frequency, and ZAC load is the effective impedance looking into the receiver circuit.

The I2R losses in the antennas generate heat. This can be minimized by reducing the current, IRX and/or by reducing the RAC(Coil). To reduce the current, one could need to use a higher voltage receiver Power Management IC (PMIC) topology. The RAC(Coil) can be reduced by using high-Q antennas that have a lower ESR (Equivalent Series Resistance). These two aspects result in better performance as seen in *Fig. 3*.

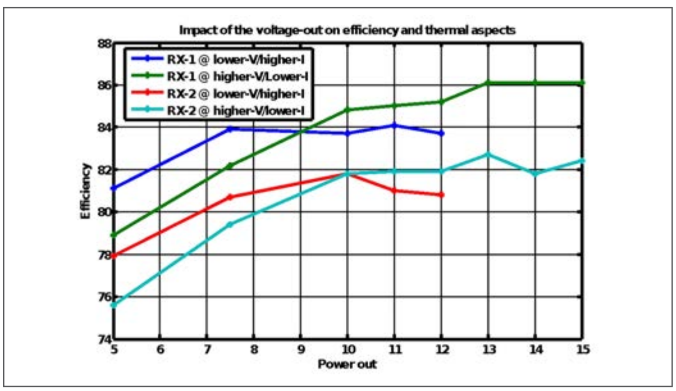

Fig. 3: First, for both receiver antennas, Rx-1 and Rx-2, the higher-V/lower-I topology yields higher efficiency. Second, the ESR of Rx-1 is about 180 milliohms lower than the ESR of Rx-2; this results in a 4% improvement in efficiency (the overall power dissipation is reduced by 850 mW at 15W delivered DC power). This will lead to more than 2 degrees drop in maximum temperature in the device, all things equal.

In general, for antennas for mobile devices, apart from being high-Q, they also need to be of small form factor and low profile (sometimes as thin as 250 um including shielding). Additional requirements of non-standard shape and integration of multiple antennas (for e.g. NFC) are often placed on the antenna designer to reduce overall cost and thickness. The requirements of thinness, flexible form factors, integration and robustness have resulted in flexible circuit antennas becoming the dominant technology for devices; printed antennas on a flex substrate are found in more than 75% of the handsets shipped (~ 200 million) in 2016 [9].

Wireless Power is a Thermal Problem

Most installed wireless power systems are designed to transfer a maximum of about 5W to the load (typically battery). With the advent of fast charge technologies, the need to charge at 10W and higher is imminent. In fact, devices from Samsung and Motorola are already shipping with the FastCharge feature.

With the move towards higher power levels, wireless charging in the consumer electronics domain will be viewed increasingly as a thermal problem, if not already, with the general electrical system architecture becoming quasi-commodity. The implication of the last statement is that thermal design will dominate the electrical design of the wireless charging system.

Consider the following numerical example: An inductive system delivering 5W operating at 75% efficiency dissipates about 1.67W, while a system that delivers 10W operating at 82% efficiency and dissipates about 2.19W. Alternatively, the 10W system will need to operate at nearly 86% (a 15% increase) to dissipate the same amount as a 5W system. If the system is broken down into 3 parts as shown in *Fig. 1*, assuming identical efficiencies, each block will need to operate at 95% efficiency. Now, assuming a typical inductive system with QTx ~ 80, QRx ~ 15, and coupling ~ 0.62, results in antenna to antenna efficiency of ~ 91%. To obtain the 86% efficiency, this will require the other two blocks for this inductive system to operate at 97%!

In other words, we are pushing physics in terms of efficiency. We saw a similar example in the previous section for a 15W system where a 4% efficiency drop to 82% resulted in an additional 850 mW dissipated power. To put things in perspective, a typical WiFi modem in a handset consumes ~ 700 mW power, the handset drains about 320 mW power during an audio playback, and about 1.05 W in a 1-minute phone call with display off [11,12].

Solving the Thermal Problem

The fundamental problems that product engineers think about are, first, how do we minimize heat generation, and second, once heat is generated, how do we spread it quickly from the main heat centers to prevent localized heating.

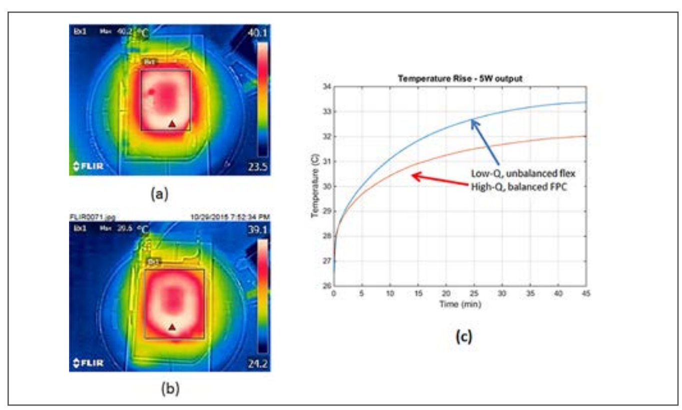

Fig. 5(a) and (b): The heat map on the coil surface during the charging process. Both solutions have antennas ~ 0.3 mm thick. Fig. 5(c) shows the time domain plot at the max temperature location for ~ 45 minutes.

Per the assertion in the previous section regarding the quasi-commoditization of the system architecture, the answer to the first question is "relatively" straightforward, i.e. choose the best components (IC's and antennas) and ensure optimum implementation for the use cases being considered. For example, consider *Figures 5 a, b* and *c*; they present the thermal data using two systems that are identical in every respect, except in the design and the technology of the wireless power antenna. The antenna in *Fig. 5b* offers a higher Q (by about 20%) that results in an efficiency improvement by ~2 percent, and runs about 1.3 degrees cooler. Incidentally, the higher-Q antenna is also cheaper to fabricate since it uses a standard flexible circuit technology unlike the unbalanced FPC fabrication utilized for the coil in *Fig. 5a*.

The challenge is further exacerbated as devices become thinner; batteries get larger thereby reducing the space available for the components associated with wireless charging. By far the largest component of the wireless charging system is the antenna.

It should be noted that for smaller devices such as wearables, significantly lower power dissipation will be allowable before temperatures start touching the magical limit of 45 degrees C [6,8].

Therefore, there is a high demand for ultra-thin antennas that deliver maximum performance. Often, a heat spreader material is placed, for example, between the antenna and the backcover of the device. These heat spreaders demonstrate an anisotropic thermal conductivity, i.e. they conduct heat more easily in the xy direction than in the z-direction [13].

The use of Phase Change Materials (PCM) and heat pipes is also a way to direct heat away from thermal sources. Samsung engineers implemented this in the Galaxy 7 [14]. While the primary purpose of this is to drive heat away from the power intensive Application Processor, it is conceivable that the concept could be applied to the wireless charging coil, especially for higher power solutions.

Concluding Remarks

This article provides a high-level discussion on the thermal effects of wireless charging on consumer electronics devices. A key takeaway is that the wireless charging problem, at least in the realm of near field magnetic induction, is fast becoming a predominantly thermal problem. For starters, the highest performing components will be required and magnetics design will need to be optimized for maximum coupling (k) and efficiency (Q); however, the design will need to be driven from a thermal perspective. This need will become more pronounced as the devices become thinner, have more components, and house large batteries. Further, components that have worked in the past will not work in the future – higher power densities will warrant improvements in antenna materials and fabrication technology, magnetic shielding materials and heat spreaders.

The author would also like to point out that, while efficiency is an important metric, it should be considered in concert with the desired consumer use case, technology robustness and cost, and most importantly, the thermal increments in the devices. It is possible that a system operating at a lower efficiency leaves a lower thermal footprint on the device than the higher efficiency device because the product implementation and/or thermal design.

Acknowledgements

The author would like to thank Pavel Shostak, for his help with the data, and Michael Gotlieb, Jacob Babcock, Bob Giometti and Ryan Grieves for their inputs on the article.

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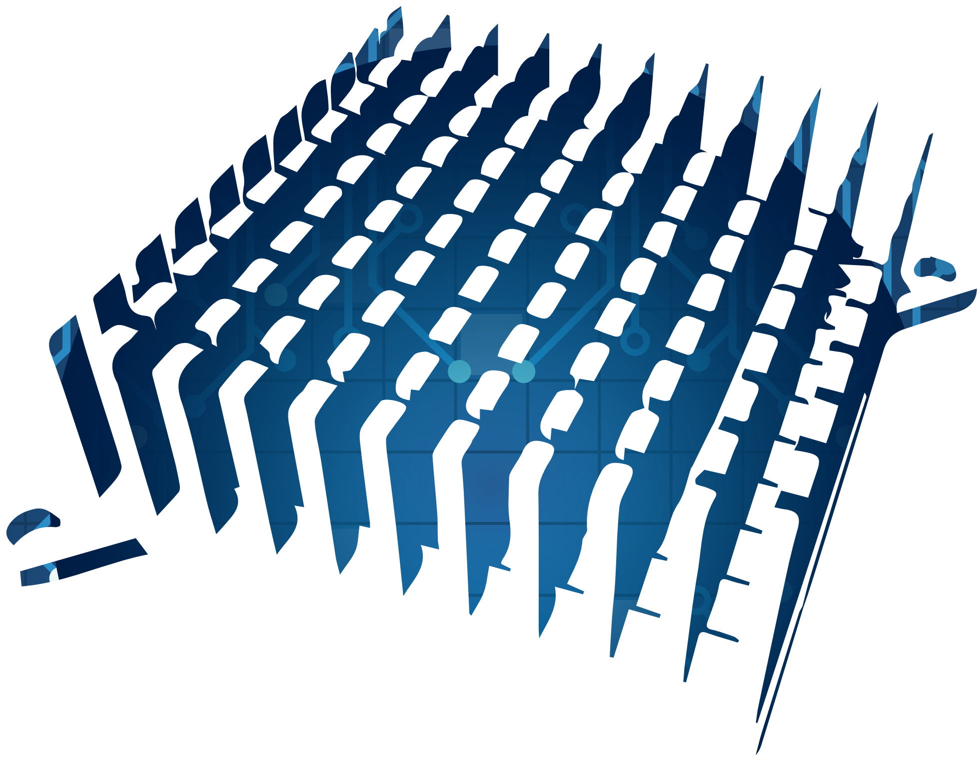
Editor’s Note

Electronics Cooling® featured some results of Dr. Vinit Singh’s PhD dissertation work in an earlier article “Thermal Management in Body-Embedded Electronics” published in December 2016.



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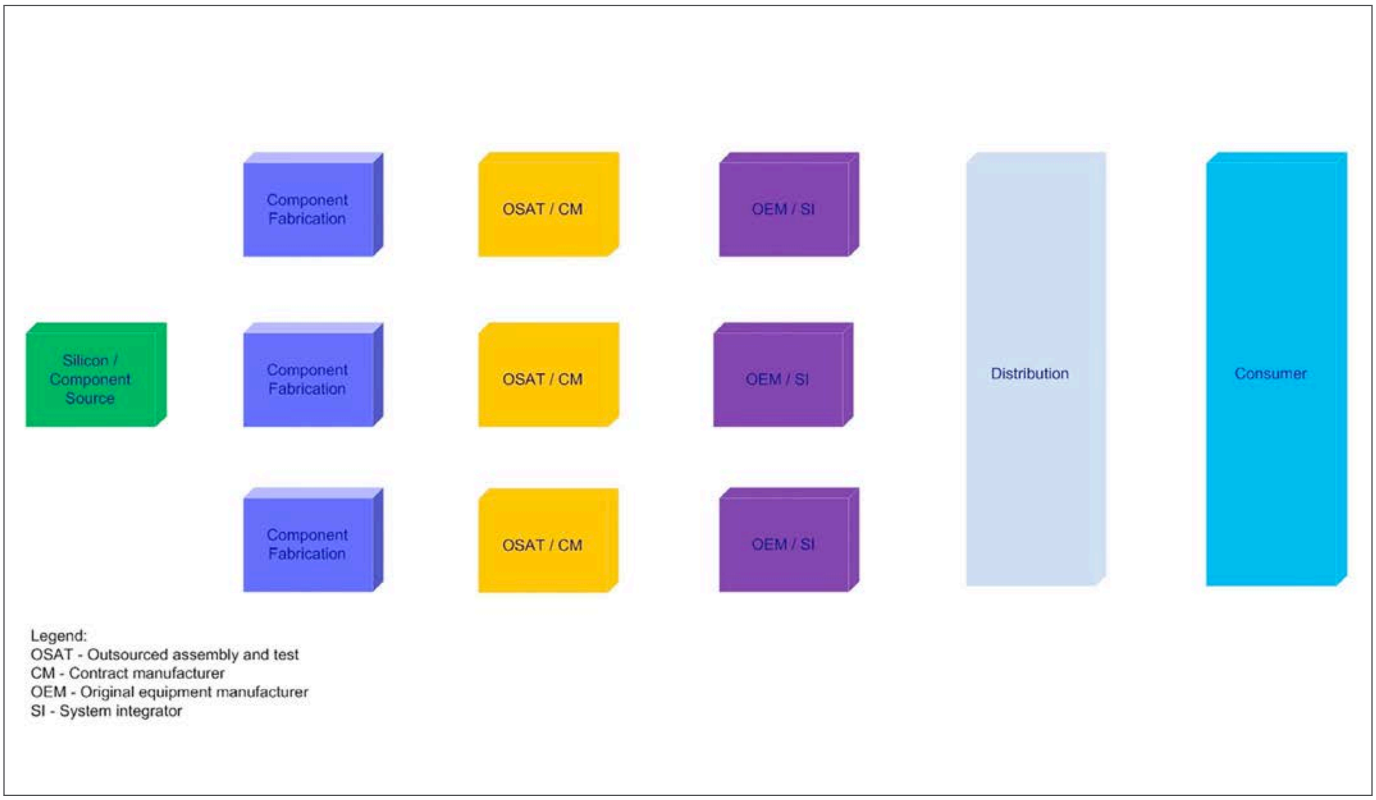
ECOSYSTEMS

The ecosystem for consumer electronics and IoT products closely follows that of the general electronics hardware ecosystem. This can be understood with the help of the value chain illustrated below, starting from the left. Opportunities for electronics thermal management components exist predominantly in the first four stages, though one could argue that there is significant opportunity for after-market products (ie. add-on heatsinks or liquid cooling systems for over-clocked gaming systems). With that exception, for each stage of the aforementioned electronics value chain, the ecosystem varies slightly for thermal management solutions. For example, in the fabrication of chip components, including passives, the type of thermal management solutions address process parameters including high temperature excursions and insure the components' integrity.

For each of the first four stages in the value chain below, 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



OVERVIEW OF COMPONENTS OF IoT & CONSUMER ELECTRONICS PRODUCTS

As is well known, the growth in electronics hardware in recent decades is primarily driven by consumer electronics devices and appliances. With advances in information and communication technologies (ICT) and in recent years the trend toward connecting people and enterprises with " things" , further escalation in electronics products is being realized.

In the following pages, we present a sampling of consumer electronics products including IoT appliances from the perspective of thermal management. The types of products covered include:

- Smart Phones
- Digital Cameras
- Virtual Assistants (Amazon Echo, Google Home, etc.)
- Home IoT Gateways
- Desktops / Laptops (Microsoft Surface)
- Television

The challenges for thermal management professionals working on products like those above are manifold, some of which are:

- Form factor and available space –most common in the thickness direction but also shrinking in-plane dimensions.
- Cost and performance targets.
- Ever increasing thermal dissipation!
- Conflicting and at times competing design requirements, for example EMC vs. thermal, DFM vs. optimal thermal management, design to cost vs. thermal management, etc.
- Aesthetic industrial design vs. functional / utilitarian approach of thermal management

A good way to understand how thermal management is addressed is to look at the approaches to thermal management in some examples of teardowns. A few of them are covered more in depth in separate articles.

In the following paragraphs, we present elements of thermal management in some of the consumer electronics products highlighted above.

Desktops / Laptops

The Microsoft Surface Studio is a integrated desktop with 28-inch adjustable PixelSense display featuring 6th-Gen Intel Core i5 or i7 CPU with 8 GB, 16 GB, and 32 GB RAM configuration options. It is GPU-augmented with NVIDIA GeForce GTX 965M GPU (paired with 2 GB GDDR5) or GTX 980M (paired with 4 GB GDDR5) chips. As can be imagined, thermal management while maintaining a slim overall form factor is one of the primary challenges in its design. The Surface features peripheral air vents for circulation of the hot air to the ambient as shown in the picture below.

Peripheral Vents for forced air cooling of Microsoft Surface (Image from iFixit)

Microsoft uses Brushless DC (BLDC) motor-based fans with low form factor and noise for cooling the CPU and GPU. The fans also have damping pads to isolate vibration to other components in the Surface.

DC Brushless motor-based fans for forced air cooling of Microsoft Surface (Image from iFixit)

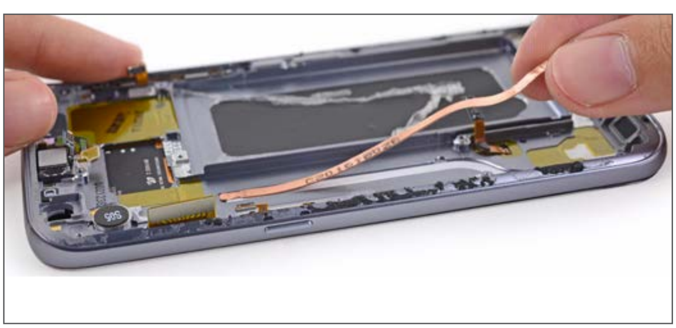
The surface also features heat pipe-integrated heat sinks depicted in the picture below.

Heat pipe-integrated heatsinks for forced air cooling of Microsoft Surface (Image from iFixit)

In addition to the above, there seems to be some clever air flow management and thermal containment like plastic channels in surface. Further more, the surface also makes use of a heat pipe bridging the CPU and GPU which may achieve some thermal load leveling. There could also be heat spreaders, in particular the Graphite-based ones that are not obvious in any of the pictures found on iFixit site.

Smart Phones -Samsung Galaxy S7 and S8

The travails of the Galaxy S7 are quite well known –thermal runaway of the battery resulting in the device catching fire and causing damage to property. The S7 employs Qualcomm Snapdragon 820 processor. The phone has IP68 water resistance rating provided by the adhesive shown below. It appears that Samsung tried to address the flak from consumers for reducing battery capacity in its earlier generation product S6. That seems to have led to the decision of using a lager (3000 mAh) battery in the S7.



Samsung Galaxy S7 showing heat pipe (Image from iFixit)

The S7 uses a thin Copper heat pipe with a wall half a millimeter thick. In the case of the S7, the heat pipe appears to transfer heat to the phone's metal mid-frame where it is efficiently conducted to spread over a larger area of the phone cover; see picture below.

There is a recent update to the product lines of the Samsung Galaxy series. The jsut released Galaxy S8 teardown starts with this pun " After the Galaxy Note7's fiery exit, Samsung is hoping to bring a different kind of heat with the Galaxy S8 series" and it may not sit well with many Electronics Cooling readers. After all, our community cares about thermal management topics and sets out to solve them whether or not it is a good problem or a bad one!

Heat pipe carrying the heat away from processor to the handset's mid-plane (Image from iFixit)

Copper foil in the handset's mid-plane to reduce thermal graidents (Image from iFixit)

The S8 is a smaller version of its sibling S8+ and comes in 5.8-inch, dual-edge, Super AMOLED display size. Similar to the S8+, it comes with Qualcomm Snapdragon 835 or Samsung Exynos 8895 processor.

The S8+ on the other hand is a 6.2-inch, dual-edge smart phone with Super AMOLED display with Qualcomm Snapdragon 835 (or Samsung Exynos 8895) processor, with 4 GB RAM and IP68 water resistance rating.

The S8+ also uses a heat pipe and appears to spread the heat uniformly by employing a copper foil, shown in the following pictures.

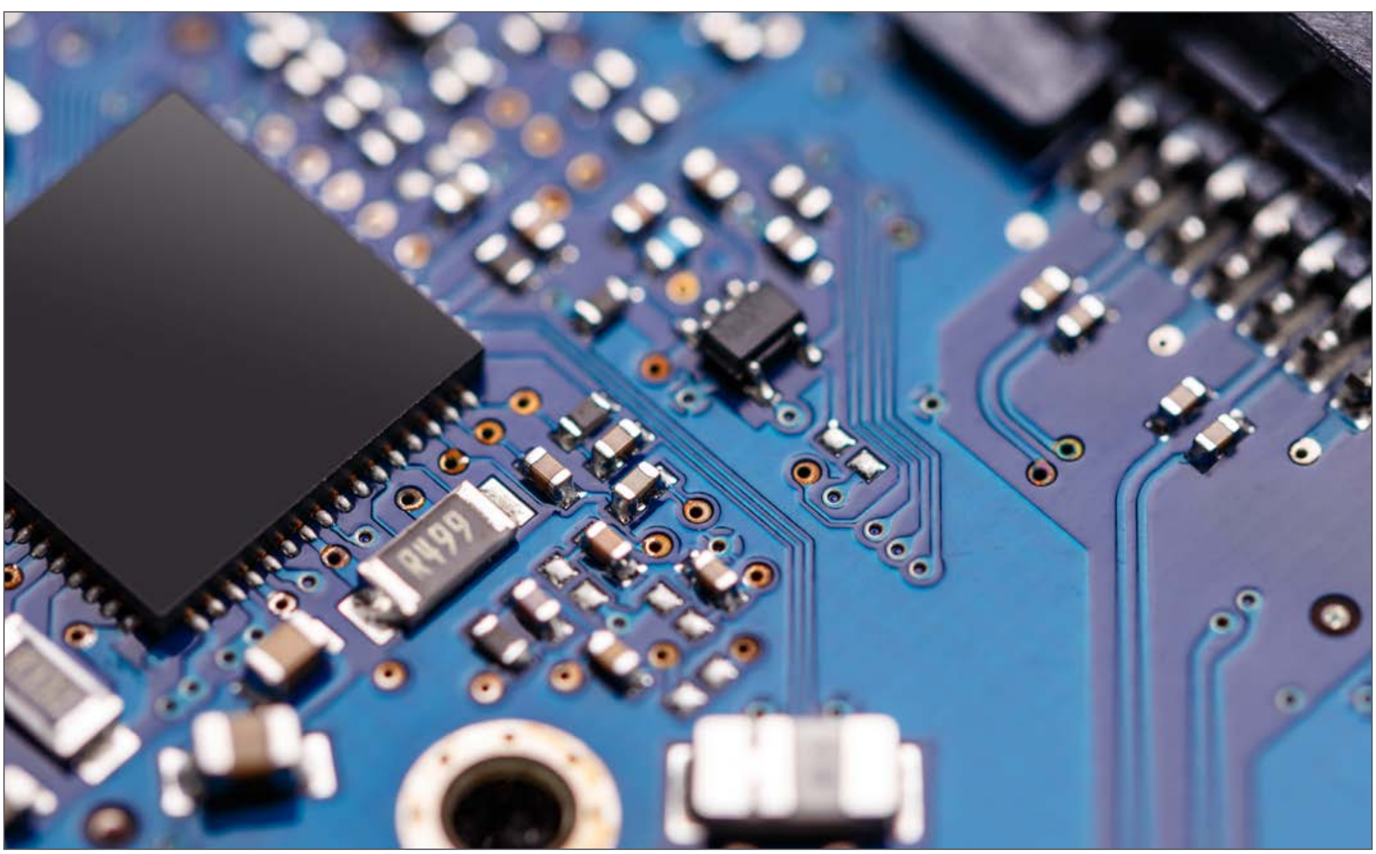
Sony XEL-1 OLED TV

The Sony XEL-1 is by now an older generation of flat screen TVs but it is worthwhile to study how it was packaged to meet thermal management requirements. It was credited with having the high color saturation, large viewing angles, high screen uniformity, and low power consumption.

Some of the power dissipating components includes Cyclone-II FPGA, three switching regulators, many op-amps and others. Because of the vulnerability of OLEDs to fail under thermal runaway, XEL-1 makes use adequate thermal management materials such as gap pads to evenly distribute the heat to the larger surface of the backcover.

Sony XEL-1 TV with back cover removed (Image courtesy of bunnies:studios)

Gap pads for thermal management (Image courtesy of bunnies:studios)



DESIGN AIDS & TOOLS

This section provides a brief overview of the design and simulation tools for the thermal management of electronics products. 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 nodedicated hardware resources. The following tables show a partial list of the tools commonly used in the electronics thermal management discipline.

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			

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/

Remember to visit the manufacturer 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.

CALCULATIONS

In this section, you'll find articles with calculations you can use 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.

HEAT TRANSFER FUNDAMENTALS

"One-Dimensional Heat Flow"
Bruce Guenin, September 1997
www.electronics-cooling.com/1997/09/one-dimensional-heat-flow/

"Convection and Radiation"
Bruce Guenin, January 1998
www.electronics-cooling.com/1998/01/convection-and-radiation/

THERMAL SPREADING FORMULAS AND CALCULATIONS

"Calculations for Thermal Interface Materials"
Bruce Guenin, August 2003
www.electronics-cooling.com/2003/08/calculations-for-thermal-interface-materials/

"The 45 Heat Spreading Angle — An Urban Legend?"
Bruce Guenin, November 2003
www.electronics-cooling.com/2003/11/the-45-heat-spreading-angle-an-urban-legend/

HEAT SINK ANALYSIS AND PERFORMANCE

"Estimating Parallel Plate-Fin Heat Sink Thermal Resistance"
Robert Simons, February 2003
www.electronics-cooling.com/2003/02/estimating-parallel-plate-fin-heat-sink-thermal-resistance/

"Estimating Parallel Plate-Fin Heat Sink Pressure Drop"
Robert Simons, May 2003
www.electronics-cooling.com/2003/05/estimating-parallel-plate-fin-heat-sink-pressure-drop/

"Thermal Interactions Between High-Power Packages and Heat Sinks, Part 1"
Bruce Guenin, December 2010
www.electronics-cooling.com/2010/12/calculation-corner-thermal-interactions-between-high-power-packages-and-heat-sinks-part-1/

"Thermal Interactions Between High-Power Packages and Heat Sinks, Part 2"
Bruce Guenin, March 2011
www.electronics-cooling.com/2011/03/calculation-corner-thermal-interactions-between-high-power-packages-and-heat-sinks-part-2/

PACKAGE AND COMPONENT ANALYSIS AND PERFORMANCE

"Conduction Heat Transfer in a Printed Circuit Board"
Bruce Guenin, May 1998
www.electronics-cooling.com/1998/05/conduction-heat-transfer-in-a-printed-circuit-board/

"Convection and Radiation Heat Loss From a Printed Circuit Board"
Bruce Guenin, September 1998
www.electronics-cooling.com/1998/09/convection-and-radiation-heat-loss-from-a-printed-circuit-board/

"Characterizing a Package on a Populated Printed Circuit Board"
Bruce Guenin, May 2001
www.electronics-cooling.com/?s=characterizing+a+package+on+a+populated+printed+circuit+board&x=36&y=12

SYSTEM COOLING ANALYSIS, APPLICATIONS AND TRADE-OFFS

"Estimating Temperatures in an Air-Cooled Closed Box Electronics Enclosure"
Robert Simons, February 2005
www.electronics-cooling.com/2005/02/estimating-temperatures-in-an-air-cooled-closed-box-electronics-enclosure/

"Using Vendor Data to Estimate Thermoelectric Module Cooling Performance in an Application Environment"
Robert Simons, July 2010
www.electronics-cooling.com/2010/07/using-vendor-data-to-estimate-thermoelectric-module-cooling-performance-in-an-application-environment/

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