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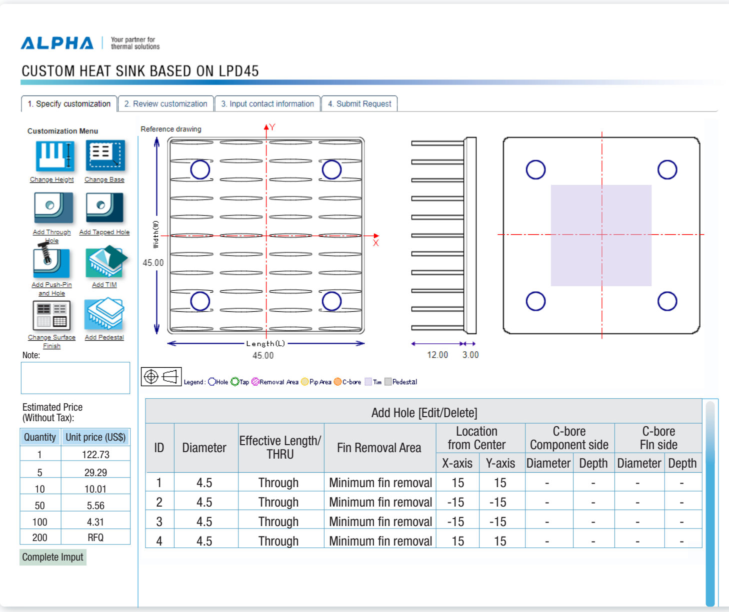

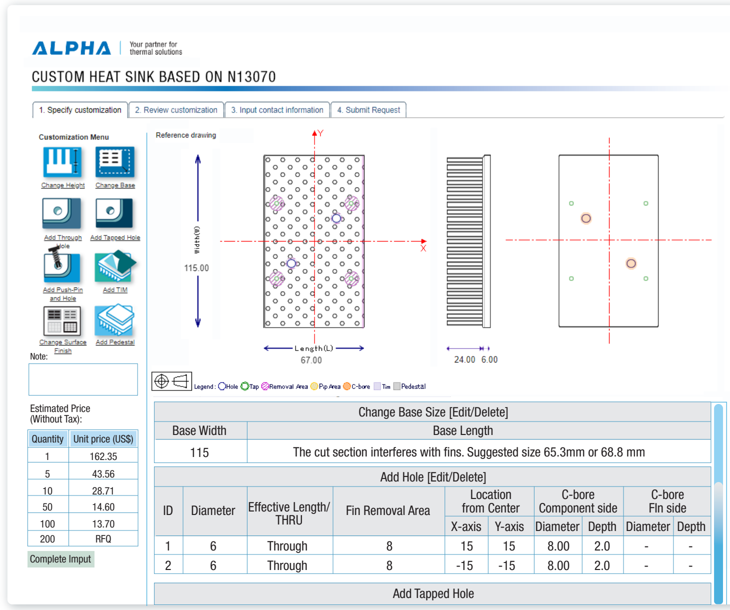

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CONTENTS

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LECTRIX

EDITORIAL

Genevieve Martin
Associate Technical Editor

An letter to our community and devoted readers: **How can our community contribute in this pandemic time?**

2020 has been a long and challenging year, both from professional and personal perspectives. We all know that Covid is still around and 2021 will probably remain difficult.

The technical editorial board wishes each of you and your beloved ones, a happy, healthy, and prosperous new year 2021. We are committing ourselves this year again to provide high quality issues that provide knowledge and insight. This issue of Electronics Cooling magazine includes articles on Innovative cooling solution for GaN-based components, discuss chemical material compatibility for your liquid cooling system, provide guidelines on how to determine flow rate of a fan based system, continue our calculation corner with statistic column, and last but not least deliver a tribute to Avi Bar-Cohen who left us October 10th, 2020 at the age of 74.

Let's start the year with a positive touch. As technology enthusiasts, we are creative enough to find solutions to problems. Worldwide, initiatives have emerged to help counter the virus; both by being innovative to react fast in the face of emergency and providing new product designs for healthcare workers and by supporting the development of new medical treatments and vaccines.

Recent pandemic shows once more how collaboration, multi-disciplinary approach is key to success. In this editorial, I would like to stay close to our community, which has a deep understanding of computer fluid dynamics simulations. Let's see how our expertise is helping solve the problems by working closely with other medical and lighting expertises.

Several studies are indicating that airborne transmission is a significant factor in the spread of the SARS-CoV-2 virus and of other viruses that cause diseases like SARS (severe acute respiratory syndrome), MERS (middle east respiratory syndrome), and influenza [1][2][3]. Natural air flow resulting from movement, temperature changes and recirculating air-conditioning in indoor spaces contributes to the rapid spread of viruses such as SARS-CoV-2. This is an obvious challenge in battling the virus, as air cannot be easily contained; however, risks can be mitigated by applying ultra-violet C (UV-C) light to reduce the virus concentration in the air while at the same time preventing human exposure to UV-C irradiation. Indeed, both in-duct and upper-air disinfection systems leverage air flow models to provide the right UV-C intensities to achieve effective disinfection.

Recently, both the WHO and CDC recommended [4][5] the use of upper-room ultraviolet germicidal irradiation (UVGI) systems as a supplemental air-cleaning measure to reduce the transmission of airborne bacterial and viral infections in public buildings, hospitals, military housings, and classrooms.

UV-C is an established measure for disinfection. UV-C light is a category of ultraviolet light with wavelengths between 100-280 nanometres (nm) and is the most effective UV light for disinfection. It has been applied ever since it was discovered to be an effective tool in preventing the spread of contagious diseases by disinfecting water, surfaces and air in very short time periods. UV-C light inactivates viruses and microorganisms such as bacteria, moulds, spores, fungi and yeasts by destroying their DNA or RNA. It is generated by well-known lamp manufacturing technology and it is sustainable and more environmentally friendly than several other disinfection methods.

Beginning in the mid-1800's, researchers realized that microorganisms responded to light, leading to the use of ultraviolet light as a germicide. Significant research over the past 150 years has led to numerous applications of UV-C light to disinfect air to reduce the spread of viruses.

The pandemic of 2020 has accelerated how our community has worked to reduce the spread of Covid through the combination of detailed CFD simulations, advanced optical systems and knowledge of viruses. A future issue of Electronics Cooling Magazine will include an article that describes the history of using light as a disinfectant, recent developments targeted at addressing the Covid-19 pandemic, and the technologies, which are enabled by advances in electronics cooling, that are used to generate the disinfecting light. Stay tuned!

As always, I encourage you to contact us if you have special wishes or want to publish yourself an article in one of the upcoming issues.

– Genevieve Martin

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[3] https://www.medrxiv.org/content/10.1101/2020.10.13.20212233v1

[4] WHO guidelines on tuberculosis infection prevention and control (2019 update)

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COOLING EVENTS

News of Upcoming 2021 Thermal Management Events

APRIL
26-29

INTERNATIONAL CONFERENCE AND EXHIBITION ON THERMAL & POWER SOLUTIONS

Online Event

NEW THIS YEAR – A TECHNOLOGY CROSS-OVER EXTRAVAGANZA! CICMT, High Temperature, and Thermal & Power Packaging come together for a great opportunity for you…One location | One registration | Three times the content, networking, and learning! The Thermal event has also been upgraded from a Workshop to a full Conference to allow for more attendees, exhibitors, speakers, and networking!

Previously, this event has been organized annually by IMAPS (since 1992 in Workshop format) to specifically address current market needs and corresponding technical developments for electronics thermal management. Presentations on leading-edge developments in thermal management components, materials, and systems solutions for effectively dissipating heat from microelectronic devices and systems are sought from industry and academia. The Workshop emphasizes practical, high-performance solutions that target current and evolving requirements in mobile, computing, telecom, power electronics, military, and aerospace systems. Single-company product development concepts are acceptable subjects; however, all abstracts will be judged on their novelty and innovative contributions to the industry knowledge.

Desc. source: electronics-cooling.com

► www.imapseurope.org/event/cicmt-2021/

MAY
10-14

THERMAL MANAGEMENT INNOVATION WEST-COAST 2021

Online Event

The Annual BEV Thermal Management Innovation USA Congress, West-Coast 2021 is the number one event to match buyer requirements with expert solutions during the Automotive sector's battery evolution. Following on from the tremendous success of the previous three events, Thermal Management Innovation USA has firmly established itself as the automotive industries first-class event to gain a clear and pragmatic view of the key challenges and current need to know learning objectives surrounding advanced battery thermal management systems; to increase efficiency, range, battery health, and optimize solutions for increasingly demanding advanced charging requirements.

The series analyzes innovative battery management solutions, explores the most crucial engineering and material challenges, and benchmarks strategic imperatives for next-generation BEV advancement. We welcome you to join the industry's largest technical meeting for Thermal Management professionals and foremost communication network for OEMs, technology and solutions providers, and leading Research Institutes alike; where powertrain experts will engage during a series of case study presentations, interactive panels and unparalleled networking opportunities.

Desc. source: electronics-cooling.com

► www.battery-thermal-management-usa.com/

JUNE
9-12

APEC 2021

Phoenix Arizona Convention Center

APEC is the leading conference for practicing power electronics professionals and addresses a broad range of topics in the use, design, manufacture, and marketing of all kinds of power electronics equipment. Join us June 9-12, 2021 in Phoenix, AZ.

The Applied Power Electronics Conference (APEC) focuses on the practical and applied aspects of the power electronics business. This is not just a designer's conference; APEC has something of interest for anyone involved in power electronics:

Equipment OEMs that use power supplies and dc-dc converters in their equipment
Designers of power supplies, dc-dc converters, motor drives, uninterruptable power supplies, inverters, and any other power electronic circuits, equipment, and systems
Manufacturers and suppliers of components and assemblies used in power electronics
Manufacturing, quality, and test engineers involved with power electronics equipment
Marketing, sales, and anyone involved in the business of power electronics
Compliance engineers testing and qualifying power electronics equipment or equipment that uses power electronics

Desc. source: electronics-cooling.com
► www.apec-conf.org

OCT
19-20

THERMAL LIVE™

Online Event

Electronics Cooling's Thermal LIVE™, the world's largest online thermal management event, returns for its 7th year this October. The two-day program features experts in the thermal management field, presenting live educational sessions on industry challenges, trends, and products. Past topics have included advanced thermal techniques in power electronics, design and manufacturing of blind mate couplings, selecting TIMs for different applications, calculations and design elements for liquid cooling, and more.

If you're an electronics or mechanical engineer who works with thermal management, this event is a can't-miss.

Desc. source: electronics-cooling.com
► https://thermal.live/

NOV
16

THERMAL MANAGEMENT INNOVATION USA

TCF Center | Detroit, Michigan

The Annual BEV Thermal Management Innovation USA Congress, Detroit is the number one event to match buyer requirements with expert solutions during the Automotive sector's battery evolution. Following on from the tremendous success of the previous three events, Thermal Management Innovation USA has firmly established itself as the automotive industries first-class event to gain a clear and pragmatic view of the key challenges and current need to know learning objectives surrounding advanced battery thermal management systems; to increase efficiency, range, battery health, and optimize solutions for increasingly demanding advanced charging requirements.

Desc. source: electronics-cooling.com
► www.battery-thermal-management-usa.com

Fan Cooling - Part 1: Determining Flow Rate

Ross Wilcoxon[1] and Genevieve Martin[2]
Associate Technical Editors for *Electronics Cooling*
[1]Collins Aerospace
[2]Signify

For a number of reasons, including cost, simplicity, power consumption, noise, etc., natural convection is the preferred approach for cooling electronic systems. However, it is often the case that natural convection is simply not sufficient to remove dissipated power while meeting other system requirements such as size. Therefore, cooling fans are commonly used to increase cooling capacity to achieve an adequate design. This series of two articles provides an overview of the basics of effectively integrating cooling fans into a system and understanding other impacts of the use of fans. This first article focuses on how the use of fans impacts the cooling system design and how to determine the flow rate that a fan can produce in a specific application.

Before describing how to design a fan-cooled system for electronics, it is useful to first ask the question 'why do fans improve cooling?'. While the benefits of a fan to improve cooling may seem obvious, a clear understanding of the physical mechanisms by which flow rate impacts thermal resistance is critical to developing effective designs.

To begin, convection heat transfer (Q), from a solid surface to a fluid, is described with the equation $Q = h*A*(T_{fluid} - T_{surface})$, where T is temperature, A is the surface area in contact with the fluid, and h is the convection coefficient. In laminar flow, the coefficient is constant, regardless of flow rate. At higher velocities, the flow becomes turbulent and the heat transfer coefficient increases with velocity. While the surface temperature of a heat sink may be approximately uniform, the fluid temperature increases as it absorbs energy, with the fluid temperature at any point in the system defined as $T_{fluid} = \dot{m} * c_p / Q' + T_{inlet}$, where $\dot{m}$ is the mass flow rate of coolant, c_p is the specific heat of the coolant, Q' is the heat absorbed by the coolant to that point in the system, and T_{inlet} is the temperature of the coolant when it enters the system. A larger flow rate can potentially affect heat transfer in two different ways: 1) by increasing the convection coefficient, which decreases the convective thermal resistance 1/hA, and 2) by reducing how much the fluid temperature increases as it flows through the system. This effectively adds an additional thermal resistance, which may be referred to as the advective thermal resistance, that can be approximated as $1/(2\dot{m}c_p)^*$.

To illustrate how these two effects can influence the overall thermal resistance in a forced cooling application, the thermal resistances for parallel plate heat sinks with different flow rates were estimated using the approach described by Simons [1] for air cooling a heat sink dissipating 100W with the geometries shown in *Table 1*. Thermal resistances for different heat sinks and different flow rates are shown in *Figure 1*.

Table 1 Example heat sink with plate fins

Geometry	Value	Unit
Base Width	12.7	cm
Fin Length	12.7	cm
Fin Thickness	0.12	cm
Fin Height	5	cm
Fin Pitch	1.42, 2.83, 4.25	fins/cm

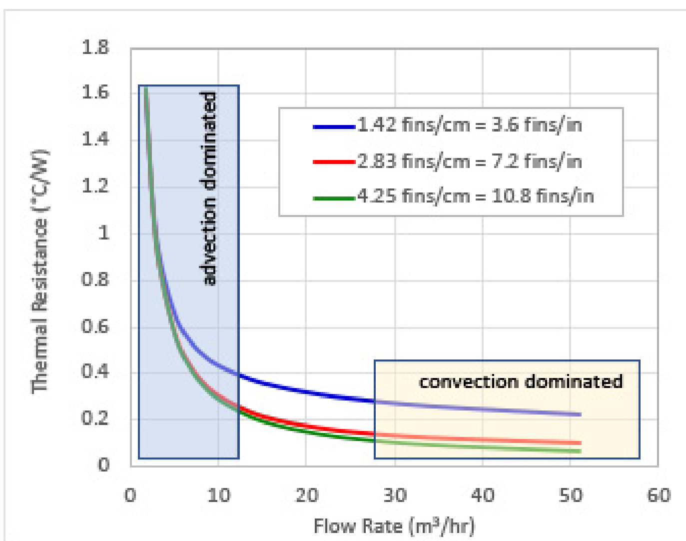

Figure 1: Example of the effects of flow rate and fin geometry on the thermal resistance of a heat sink

*A future issue of *Electronics Cooling Magazine* will include a Calculation Corner that provides a more general discussion on how to account for advective thermal resistance effects.

For this specific heat sink configuration, when the flowrate is less than ~5-10 m^3/hr, the thermal resistance is dominated by the flow rate, i.e., advection thermal resistance. In this flow rate regime, there will be little to no benefit of changing the fin design. At the other extreme, above ~30 m^3/hr, the benefits of increasing flow rate on the overall thermal resistance become quite small. Instead, the thermal resistance is dominated by the convection thermal resistance, which is decreased by increasing the heat transfer area by adding more fins. As described later in this article, the design of an air-cooled system typically begins by determining what flow rate corresponds to a target temperature rise for the cooling air and then determining fan and heat sink designs that are suitable for that flow.

In order to improve a fan cooled system, it is important that the designers know where they are on the flow rate / thermal resistance curve. If a design is in the advection-dominated regime, increasing the size or number of fins will have minimal benefit; more flow is needed. In contrast, if a system is operating in the convection-dominated regime, there is little to be gained by increasing the flow rate. Instead, the heat sink resistance needs to be reduced, typically by increasing the number of fins. *Figure 2* illustrates a typical result of modifying a heat sink to reduce its thermal resistance: the pressure drop through the heat sink increases. The pressure drop was calculated for the same three heat sink configurations shown in *Table 1*, using the approach described in Ref. [2]. In this case, the larger number of fins in the same space reduces the flow area, which directly increases the flow velocity and subsequently increases pressure drop.

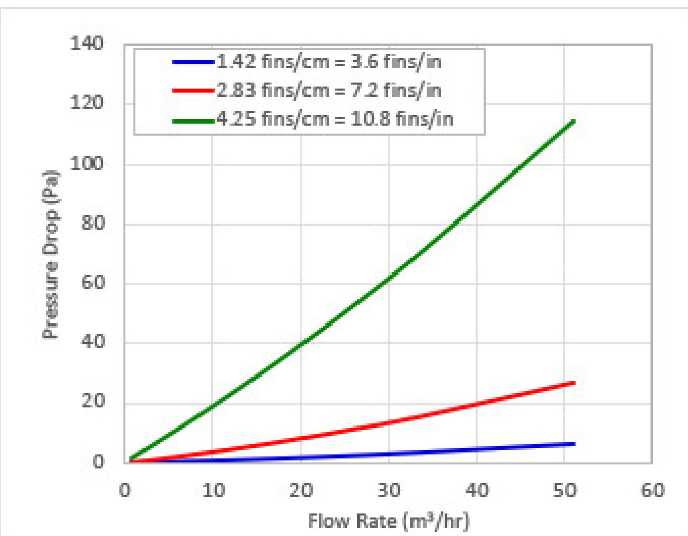

Figure 2: Pressure drop through different heat sinks as a function of flow rate

Thus, both the thermal and pressure drop characteristics of a heat sink can be influenced by the flow rate generated by a fan. While the previous figures and discussion apply to the thermal/fluid effects in a heat sink, the behaviors also apply to the overall thermal design of a system, in that the design generally requires a balance between reducing thermal resistance without excessively increasing pressure drop. The next section discusses the flow rate and pressure head generated by a fan and how system and fan characteristics are combined to determine the resulting system flow rate.

The pressure head generated by a fan as a function of the flow rate it generates are generally described in terms of fan curves; a few examples of which are shown in *Figure 3*. The different fans referenced in this plot all operate with the same 24VDC input power, but their physical geometries, expected use cases, price, noise, etc. are quite different.

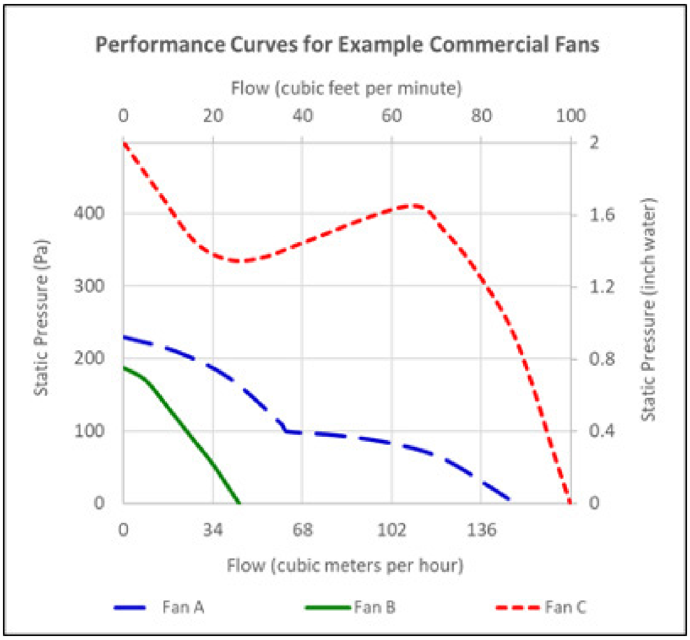

Figure 3: Fan performance curve for three commercial fans operating at 24VDC, as reported by manufacturers

In addition to fan curves, manufacturers also generally provide characteristic data to help users understand their performance. *Table 2* lists manufacturer-reported operating characteristics for the three air movers associated with the curves shown in *Figure 3*.

Table 2: Example fans

	Fan A	Fan B	Fan C
Type of Air Mover	**Axial Fan**	**Centrifugal Blower**	**Axial Fan**
Typical Use	**Commercial Systems**		**Aerospace**
Maximum Flow (m^3/hr)	146	44	170
Maximum Pressure (Pa)	230	287	498
Power Consumption (W)	9	9.6	43
Speed (rpm)	6,800	2,800	14,600

The quantified flow and pressure head parameters correspond to the extreme conditions (maximum flow is for zero pressure head, maximum pressure head is for zero flow rate), rather than actual use conditions in which the fan must generate both pressure head as well as flow. Thus, the actual operating point for a fan must be determined by comparing the fan curve to the system curve (also called system resistance curve).

The pressure drop that occurs when fluid flows through a heat sink, or any system, is a function of the flow velocity. If flow is completely laminar, the pressure drop is proportional to the square of the flow velocity; in completely turbulent flow, the pressure drop is proportional to the velocity. Actual flow through a system, which may include duct flow, turns, expansions, contractions, screens, etc., generally consists of regions of laminar and turbulent flow. As long as the flow of air is incompressible, local average velocities are proportional to the volumetric flow rate through a system and the pressure drop as a function of the volumetric flow rate, $\dot{V}$, generally follows the equation $\Delta P = C*\dot{V}^n$, where C is a constant and the exponent, n, is between 1 and 2. The specific values of C and n depend on the system. This relationship for pressure drop as a function of flow rate is referred to as the system curve and must be determined through testing, simulations, or flow resistance analysis.

The flowrate in a fan-driven system is determined by superimposing the system curve (pressure drop as a function of flow through the system) and the fan curve (pressure head generated by the fan as a function of the flow rate it generates). The intersection of these two curves is known as the operating point. *Figure 4* shows nominal operating points for the three fan curves shown previously for two system curves selected to represent low and high pressure drop systems*. The block arrows in the plot indicate predicted operating points for each combination of fan and system curve, with the numbers in the block arrows indicating the flow rate for each operating point.

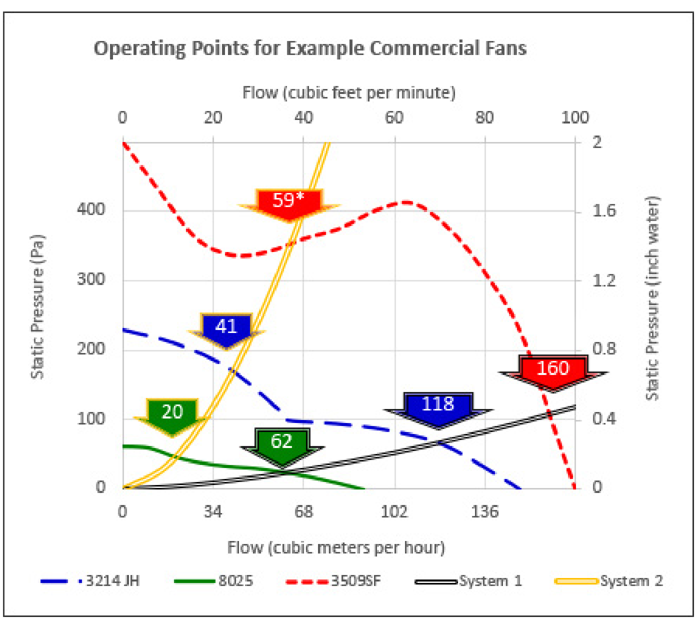

Figure 4: Predicted operating points for the three fans in two different systems

Table 3 summarizes the predicted operating points for the three different fans in the two different systems.

Table 3: Predicted operating points of fans

System/Fan Combinations		Fan A	Fan B	Fan C
System 1	Flow (m³/hr)	118	42	160
	Pressure Drop (Pa)	66	13	108
System 2	Flow (m³/hr)	421	27	59*
	Pressure Drop (Pa)	168	83	308*

In both *Figure 4* and *Table 3*, the operating point for Fan C in System 2 is shown with an asterisk. This is to indicate that the fan will not actually operate at this point in an actual system due to the fact that the system curve intercepts an unstable region of the fan curve. Under stable operation, a fan curve has a downward slope in which an increase in flow rate leads to a reduction in the pressure head generated by the fan. Under this condition, any small increase in the system pressure drop (imagine an insect flying past the system exhaust and temporarily creating additional pressure drop), the flow rate that the fan can generate is reduced. This reduction in flow leads to a reduction in the system pressure drop and once the perturbation has passed (the insect has flown away), the fan returns to its original operating point. In contrast, if the performance curve has a positive slope in which fan pressure head increases with flow rate, such as with Fan C in the flow range of ~40 and ~100 m^3/hr, any perturbations will cause the flow rate to increase, which increases the pressure head, which in turn leads to higher flow rate, and so on. When a fan is operated in an unstable region in which the fan curve has a positive slope, the flow rate can oscillate between the flow rates where the fan curve has a negative slope. These oscillations may generate substantial noise and significantly reduce the life of the fan.

Selecting a specific fan for a specific system requires sufficient knowledge of both the fan and system to avoid design problems. This may require an iterative process of selecting a fan, determining what its performance will be in a system, and then potentially modifying the system to improve its thermal resistance and/or pressure drop, operating the fan at a higher voltage/speed, or selecting a different fan until performance specifications are met. Generally, one way to begin a design is to define an allowable coolant temperature rise for the system, i.e., the dif-

*For reference, the system curves used in this plot were System 1: $\Delta P = 0.032*\dot{V}^{1.6}$, System 2: $\Delta P = 0.25*\dot{V}^{1.75}$ with pressure drop in Pascals and flow rate in cubic meters per hour.

ference between the inlet and exit air temperatures, and determining the mass flow rate needed to achieve that condition. The appropriate target temperature increase depends on the specific application and thermal budget available to the designer[3]. Simulations or rough analysis, such as with a spreadsheet or a flow resistance tool, can then be used to estimate the pressure drop through the system for that flow rate. An initial fan selection can be made by identifying fans that have a maximum (zero pressure drop) flow rate that is ~130% of that flow rate and a maximum pressure head that is ~150% of the estimated system pressure drop. Once the candidate fan has been selected, a more detailed comparison between the system curve and the fan curve can be used to identify the operating point for the fan and the resulting thermal conditions.

[3]For example, the flow rate of cooling air supplied to avionics commercial aircraft is set to establish a 15°C difference between exhaust and inlet temperatures.

The next article in this series will discuss specific issues related to integrating fans into systems. This includes how, when and why to use multiple fans, type of fans, how fan orientation (positive or negative pressure) can influence designs, issues related to fan noise, efficiency, power, etc.

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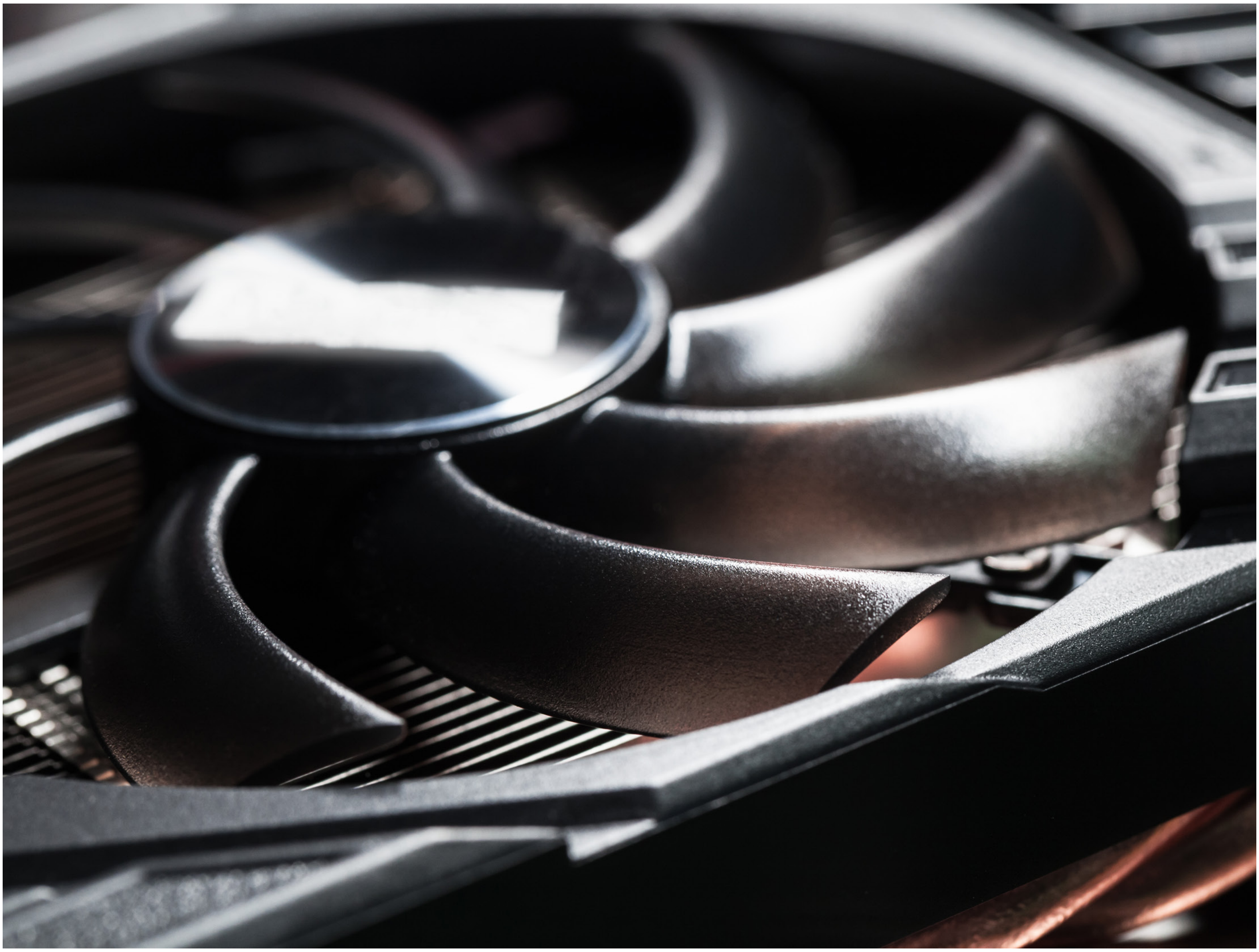

Confidence Intervals

Ross Wilcoxon
Associate Technical Editor for *Electronics Cooling*
Collins Aerospace

The previous articles in this series [1, 2] described how the mean and standard deviations of a set of data are calculated and how they can be used to estimate the characteristics of a population using the normal distribution. Since measured data typically represents only a subset of an entire population, one should recognize that the estimated mean and standard deviation values determined from a sample set are not likely to be exactly equal to the true values of the entire population. In other words, when we calculate the mean, i.e., average, of a data set, we should recognize that there is actually a range of values in which the true population mean lies – and the size of that range depends on the confidence level that we assign to our estimate. This article describes a process that can be used to determine that range as a function of the number of data points and confidence level. More generally, this outlines the overall process for linking probability distributions with confidence levels that is the basis of a variety of statistical analyses.

Figure 1 shows an example of a normal distribution in which the mean value is 8 and the standard deviation is 0.75. Two lines are included in this plot: the probability distribution corresponds to the probability of any specific value occurring within the population while the cumulative distribution indicates what portion of the population is less than or equal to a given value[1]. The cumulative distribution curve is equal to the area under the curve of the probability distribution.

Z-value is defined as the difference of a value from the mean, normalized by the standard deviation. For example, with the mean of 8 and standard deviation of 0.75, a measurement of 9 would have a Z-value of (9-8)/0.75 = 1.33. The cumulative normal distribution for this value is 90.9%[2]; in other words, 90.9% of the population with a normal distribution would have a Z-value that is less than or equal to 1.33. This is illustrated in Figure 1 as the area under the cumulative probability curve for values of 9 and below.

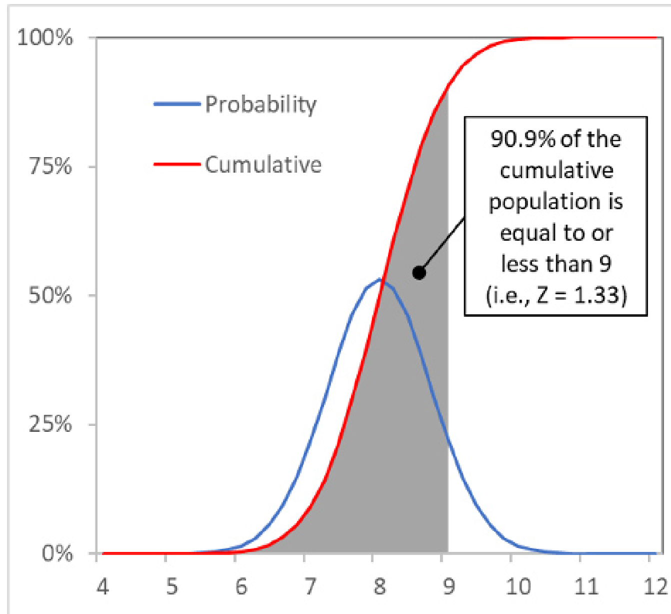

Figure 1: Normal distribution for mean of 8 and standard deviation of 0.75

As mentioned previously, we don't generally know the true mean and standard deviation of an entire population because we only make measurements of a subset of it. The larger the subset (the more samples we use in making our estimates), the more accurate our estimates of the true values should be. When we use a small sample size in an analysis, we can account for the additional uncertainty due to sample size by 'flattening' the bell curve of the standard normal distribution and increasing the size of the 'tails' (the areas under the curve that are far from the midpoint) using the Student t-distribution.

The t-distribution looks very similar to a normal distribution, but its specific shape depends on the number of degrees of freedom.

[1]To use Excel to calculate the values of these curves, use the function =norm.dist(x, mean, stdev, dist), where x is the x-axis value, mean and stdev are the mean and standard deviation of the population respectively, and 'dist' is FALSE for the probability distribution and TRUE for the cumulative distribution.
[2]This value can be calculated with Excel in two different ways (at least). The simple approach is the function =norm.dist(9,8,0.75,TRUE). Another approach is to use the Z-value with a standard normal distribution, which has a mean of 0 and standard deviation of 1. Thus, the function would be =norm.dist(1.33,0,1,TRUE). Both of these functions will return the same value of 0.9088.

The degrees of freedom (DoF) for a sample set corresponds to the number of independent values used in the analysis. In this case, we can consider a data set of n data point to be comprised of n-1 independent values; the difference between the sample size and DoF is due to the use of the data points to estimate the population mean [3]. Thus, one data point is not independent and the other data points can be used to assess to assess the uncertainty. *Figure 2* shows t-distributions for 2, 4 and 10 DoF and compares them to the normal distribution, again for a mean of 8 and standard deviation of 0.75. As the DoF increases, the t-distribution converges to the normal distribution; above 30 DoF, the t-distribution is virtually identical to the normal distribution.

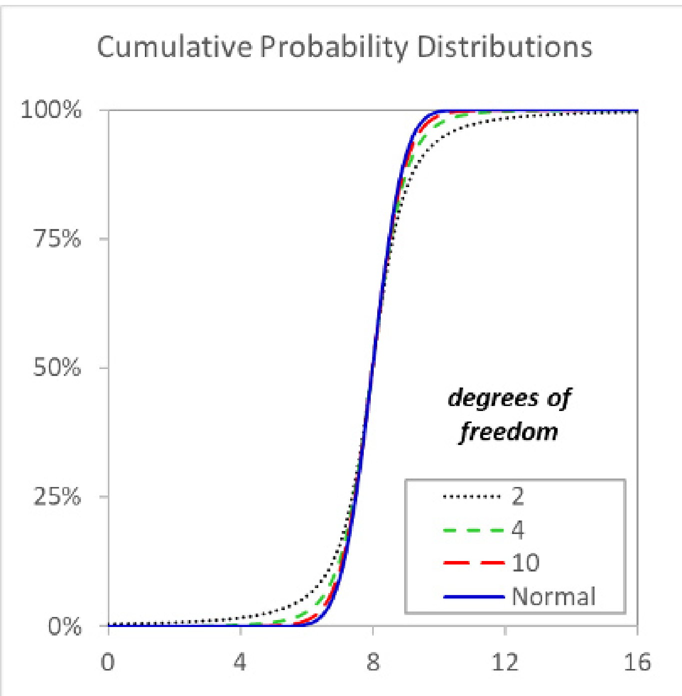

Figure 2: Normal and t-distributions for mean of 80 and standard deviation of 0.75

With this baseline information on distributions established, we can now describe how they are used to define what range of values the true mean of a population is based on a small number of measurements. The Central Limit Theorem is a critical component in establishing this. The Central Limit Theorem states that a population of terms $(X-\mu)/(\sigma/n^{1/2})$ tends towards being normally distributed, where X is a value in the population, μ is the mean, σ is the standard deviation and n is the number of samples used to estimate the population characteristics. This applies not only to the data, but also to the distribution that we use to assess our confidence in the mean that is calculated from a sample set.

For example, assume that 50 measurements of a heat sink show that its thermal resistance is 8°C/W with a standard deviation of 0.75°C/W. How confident can we be that the actual population mean is somewhere between 7.9 and 8.1°C/W? Using the Central Limit Theorem, we calculate a test statistic as (7.9-8)/(0.75/501/2) = -0.943. We can look this value up on a standardized normal distribution table, which shows that 17.3% of a normal population that has a mean of 0 and standard deviation of 1 will have a value of -0.943 or less[3]. Since the normal distribution is symmetric, we will also find that 17.3% of the population will have value of 0.943 or greater. Thus, 34.6% of the normal distribution is either less than 7.9 or greater than 8.1 and there is a confidence band of ~65% that the true mean is between 7.9 and 8.1.

Typically, we are more interested in conducting the reverse analysis – namely, what range of values corresponds to a prescribed confidence band. Also, we may not have the luxury to have a sufficient number of measurements (more than 30) to justify using a standard normal distribution, rather than a t-distribution, in our calculations. The steps for determining the range of mean values correspond to a specified confidence band are shown in *Table 1*. This table includes example calculations for testing on ten heat sinks that again showed a mean thermal resistance of 8°C/W with a standard deviation of 0.75°C/W. The goal of the analysis is to

#	Step	Example (with Excel functions)
1	Measure n samples and calculate the nominal mean, μ, and standard deviation, σ	n = 10, μ = 8°C/W, σ = 0.75°C/W
2	Define confidence interval, C.I. that defines the range of means, leading to the size of the tails outside the C.I., α/2	C.I. = 90%; two tails (one on each side of the distribution) => area in each tail is (1-0.9)/2 = α/2 = 0.05
3	Calculate the inverse t-distribution for the tail size and degrees of freedom, $t_{\alpha/2}$	$t_{\alpha/2}$ = t.inv((1- α/2),(10-1)) = t.inv(0.95,9) = 1.833 *t.inv inputs: probability of being outside the tail (1-α/2), DoF (sample size – 1)*
4	Calculate the distance from the lower limit of the confidence interval to the mean, Δ	$\Delta = t_{\alpha/2} * \sigma / n^{1/2}$ =1.833 * 0.75 / sqrt(10) = 0.43
5	Calculate the range that corresponds to the confidence interval = μ ± Δ	Confidence interval: 8 - 0.43 to 8 + 0.43 C.I. = 7.57 to 8.43°C/W

Table 1

[3] Or, we can use the Excel function =norm.dist(-0.943,0,1,true) if that seems easier…

determine the range of values that we can be 90% confident that the true mean lies within.

Figure 3 shows the 90% confidence intervals calculated for the t- and normal distributions for data with the same mean and standard deviations, but different sample sizes. As the sample size increases, the lines for the confidence intervals come converge. At small sample sizes, the confidence bands that are calculated using the more appropriate t-distribution are much wider than those calculated using the standard normal distribution. In general, it may be questionable that an extremely small sample size of 2-3 samples is necessarily representative of a population – and that small of a sample size also leads to an uncomfortably large confidence interval. But when dealing with typical sample populations with 5-20 measurements, the t-distribution provides a reasonable approach for estimating the confidence interval and can be evaluated for whether it is likely from a normal distribution (a discussion for a future article). When the sample size is greater than 30, the normal distribution can be used to assess the confidence interval. However, since the t-distribution converges to the normal distribution at large sample sizes, one can continue to use the t-distribution even with larger populations. So in general, if these equations are incorporated into a tool such as Excel, it is appropriate to use the t-distribution even for very large sample sizes.

In summary, the goal of the first three articles in this series has been to provide a sufficient background to allow readers to better understand future articles aimed at providing practical statistical analysis approaches. Hopefully, the articles did not achieve a 'worst of both worlds' status in which they included more theory than engineers might want to see and less theory than statisticians would expect. Regardless of whether they achieved that or not, with a basic statistical foundation in place we can now move on in future articles to describe tools and analysis methods for solving the types of statistical problems that engineers may encounter.

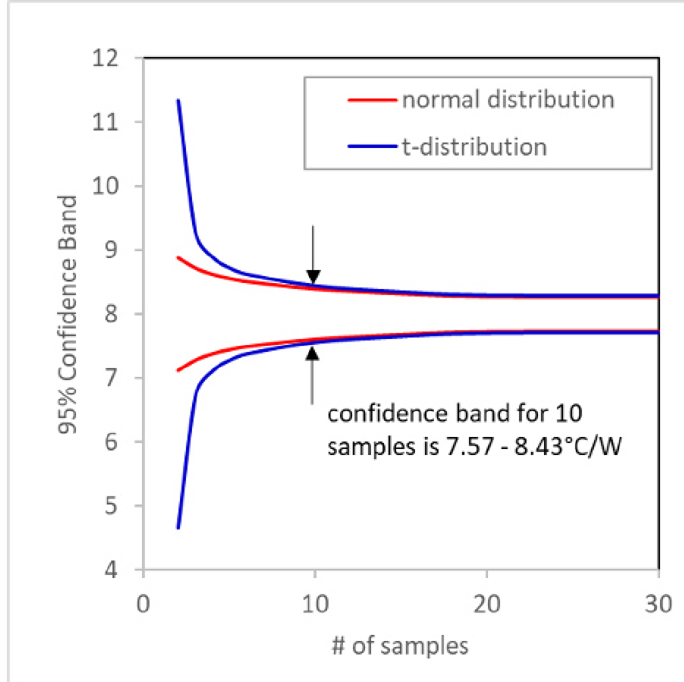

Figure 3: Confidence bands calculated for different sample sizes of heat sink resistance

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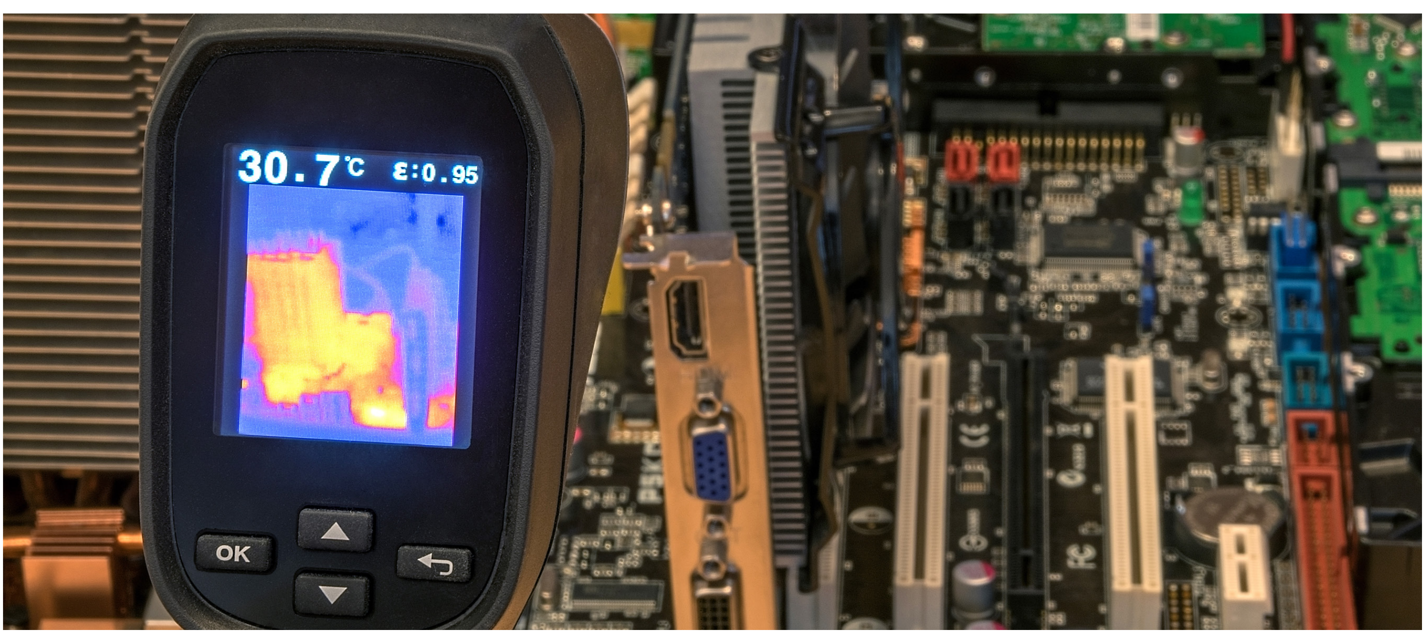


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Why Chemical Compatibility Is Vital To Your Liquid Cooling System

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Power densities in electronic subsystems continue to increase, driving demand for more extreme cooling power alternatives that increasingly include liquid cooling as a viable candidate. To optimize thermal management efficiency, sustainability and reliability, designers of systems that use liquid cooling are exploring innovative combinations of component materials, including advanced thermoplastics, specialized elastomers, metal alloys and engineered fluids.

Whether designing a closed-loop, single-phase immersion, two-phase immersion or direct-to-chip cooling system, component material compatibility is critical to performance. This article provides general guidance regarding selecting the right ingredients for a liquid cooling solution.

THINK HOLISTICALLY WHEN SELECTING COMPONENTS

A variety of subsystems and components make up the architecture that is critical to the successful and reliable operation of any cooling system.

Each system component has the potential to interact with other component materials. Therefore, materials interactions and dependencies warrant detailed analysis during design and specification.

Coolants are of particular interest, not only as the primary conduit of thermal transfer, but because they are in contact with all wetted materials within a particular cooling system, as indicated in *Figure 1*. Some fluids may promote corrosion or biofouling in the presence of certain materials, creating the potential for flow blockage or failure of the cooling system. It is essential to understand what all the materials are and the interactions that they might have. Specifically, when assessing concerns related chemical compatibility, potential permeation and diffusive losses, it is important to identify critical points of connection – such as tubing junctions, manifold ports, and quick disconnect fittings – and evaluate each one for risks to reliability and performance.

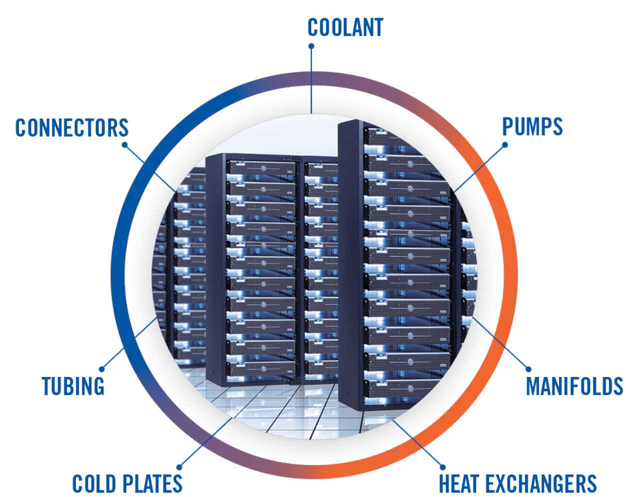

Figure 1

Overall, when it comes to material selection, one must think holistically. This includes accounting for all system components and considering the potential effects of the environment, working fluid, temperature, pressure, and mechanical loading, which might adversely impact performance.

This article will discuss liquids commonly used in liquid cooling

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applications and present an overview of the materials of construction. Finally, we'll provide guidance regarding the potential compatibility of these fluids and materials when used together.

COOLANTS *Fluids commonly used in electronics cooling applications.*	
Water	Excellent heat transfer, low viscosity, non-flammable and low cost. Relatively narrow operational range and susceptible to freezing or boiling. Susceptible to biological fouling which inhibits heat transfer. May contain impurities with potential corrosive effects; deionization may reduce initially, though impurities may be extracted over time from wetted surfaces.
Ethylene glycol (EG)	Controls biological growth, lowers freezing point and elevates boiling point when used in solution with water, ranging from 10% to 90% EG. Lower cost than refrigerants or dielectrics. Water in solution may still promote corrosion, degrading coolant over time. Highly toxic, requires careful handling.
Propylene glycol (PG)	Controls biological growth when used in solution with water, ranging from 10% to 90% PG. Lower cost than refrigerants or dielectrics. Lower thermal conductivity and higher viscosity than EG. Water in solution may still promote corrosion, degrading coolant over time. Low toxicity for easier handling and disposal.
Mineral oil	Odorless, non-toxic and chemically inert. No evaporation or volatility. Enables immersion applications. Potential incompatibility with copper or some elastomers.
Refrigerants	Lightweight with excellent thermal transfer properties. Incompatible with some plastics and elastomers. Higher cost than water, EG, PG or mineral oil. Examples include R-1234yf and R-1336.
Dielectrics	Non-conductive engineered fluids that enable full immersion of electronics in single-phase, two-phase and direct-to-chip applications. Low boiling points. High chemical stability. Higher cost. Potential incompatibility with thermoplastics or heavily plasticized elastomers.

Table 1. Liquids Commonly used in Liquid Cooling Systems for Electronics

TAPPING COOLANT ALTERNATIVES

Obviously, choosing a coolant is a focal point when designing a liquid cooling system. From a compatibility standpoint, it is important to recognize that the fluid links virtually every component as it circulates through the liquid cooling system. *Table 1* provides a brief overview of a number of fluids typically used in cooling electronics.

The first step in selecting a coolant is to consider operating and storage temperatures. Fluid properties must be appropriate to the application environment, such as a boiling point that satisfies the thermal load and thermal efficiency needed without exceeding the critical heat flux. Fluids must also have suitable low temperature characteristics during storage and shipping, environmental exposures, particularly engineered dielectrics such as fluorochemicals, as well as refrigerants. It is often necessary to understand the environmental impact of the fluid throughout the life cycle – how it's manufactured, the potential impact of it leaching into the facility or atmosphere during use, and end-of-life fluid reclamation requirements.

When selecting fluids, the ozone depletion and global warming potentials need to be considered, particularly for refrigerants and dielectrics. Over the last decade or so, the World Health Organization guidelines have increased emphasis on these parameters, prompting the development of greener alternatives, such as 3M Novec™, HFE coolant, and more environmentally friendly, fourth generation hydrofluoroolefin refrigerants like R-1234 or R-1336.

CONSTRUCTION MATERIALS *Commonly used in electronics cooling applications.*	
POLYMERS	
Commodity plastics	Includes HDPE, POM, PP, PS, PVC. Relatively low cost and readily available. Potential flammability in high-temperature applications. Potential thermal degradation and shrinkage in some environments.
Engineered thermoplastics	Includes PEEK, PEI, PESU, PPSU, PSU. Improved mechanical and thermal properties. Higher cost than commodity plastics.
Elastomers	Includes CR, EPDM/EPM, FKM, HNBR, silicone. May be modified to enhance flame retardance, durability or chemical resistance. Some types may leach into fluids during thermal cycling or exposure to certain solvents, negatively impacting coolant performance.

Table 2. Construction materials that are commonly used in electronics cooling applications

CONSTRUCTION MATERIALS *Commonly used in electronics cooling applications.*	
METAL ALLOYS	
Aluminum	Durable, lightweight metal. Strong thermal properties. Potential for galvanic corrosion, especially with water-based coolants and in presence of copper. Anodization increases corrosion resistance.
Brass	Durable. Strong thermal properties. Relatively low cost. Often plated with nickel and/or chrome for improved corrosion resistance.
Copper	Durable. Strong thermal properties. Galvanic corrosion potential, especially with water-based coolants in the presence of aluminum.
Stainless Steel	Highest in durability and stability. Lower thermal conductivity. Higher cost. Passivation increases corrosion resistance.

Table 2. *Continued*
Construction materials that are commonly used in electronics cooling applications

In addition to thermal stability and chemical compatibilities, properties such as coolant toxicity, flammability, cleanliness requirements, environmental impact, and cost should be considered. And of course, when comparing coolant types and options, all materials that the fluid may come in contact with throughout the system should be evaluated.

SIZING UP MATERIALS OF CONSTRUCTION

Electronics cooling system components are, in general, comprised of three types of polymers – commodity plastics, engineered thermoplastics, and elastomers – and four types of metal alloys – aluminum, brass, copper and stainless steel. *Table 2* provides a high-level comparison of liquid cooling system component materials of construction.

Polymer Strengths

Polymer properties can vary widely based on processing, additives, fillers, and where they are on the spectrum, from commodity to ultra-high-performance thermoplastics and elastomers.

Polymers can replace metal in many areas, and often provide additional benefits. For example, engineered thermoplastics like PPSU and PEEK can meet higher thermal, chemical and mechanical requirements compared to metals while providing the added benefits of reduced weight and better corrosion resistance at a potentially lower cost.

Engineered thermoplastics can be an excellent choice, especially when considering effects of weight, chemical compatibility, and price over metal counterparts. When specifying thermoplastic materials look for mechanical strength, chemical compatibility, and thermal stability characteristics.

Polymer Limitations

Polymers, in particular commodity plastics and some thermoplastics, may present issues in certain applications.

Given the emerging prevalence of warm-water cooling systems, polymer resistance to hydrolysis has become an important factor. Polymers with hydrolyzable links may be at risk for severe property degradation in hot water environments. The same risk may apply for fluorochemicals in contact with fluorinated polymers. As we know, like dissolves like, and there could be a risk of solubility of certain plasticizers or additives into the coolant fluid.

Since flammability may also be a concern with some polymers, designs should include inherently non-flammable materials, specifically non halogenated thermoplastics. Long-term exposure to a wide range of temperatures is certainly a key consideration for material selection in cooling systems.

Additional risks associated with thermoplastics include chemical attacks and crazing, cracking, discoloration, and, as previously mentioned, extraction or leaching into the coolant. Fluid absorption, swelling and certainly thermal aging and degradation effects over time and also mechanical loading and an internal pressure stresses are potential threats to integrity as well.

Elastomers

Elastomers can be engineered to meet a wide range of performance requirements.

Elastomers are polymers that have the property of viscoelasticity – they are rubbery and flexible – and are primarily used in components for fluid transport, such as tubing and hose, as well as sealing components such as O-rings and gaskets. To understand how elastomers tend to behave, we can look at how they're made.

Vulcanization, or the process of curing, creates permanent cross-links in long polymer chains in elastomers. These chains ensure that when stresses are loaded and unloaded, the elastomeric component will return to its original position. In the case of an O-ring and a quick disconnect, for example, an elastomer will maintain its seal.

At a high level, specifying elastomers for use in a liquid cooling application requires detailed analysis and evaluation with the selected unique coolant to ensure compatibility and long-term reliability.

For discussion purposes, some common material compound categories that might be seen in these applications can be identified as hydrogenated nitrile, ethylene-propylene or EPDM, and chloroprene. HNBR has great chemical resistance, excellent mechanical properties, including tensile strength, tear modulus to the wide temperature range and can be compounded for excellent resistance for high pressure applications. EPDM has excellent hot water and steam resistance characteristics. However, because it has lower resistance to hydrocarbon, it is not well suited for any refrigerant type application.

Chloroprene, which is commonly known as neoprene, is very resistant to many chlorofluorocarbons or CFCs that are used as refrigerant. It has low cost but moderate chemical resistance and limited temperature resistance.

Some additional things to consider when specifying elastomers are to consider the hardness (the durometer), the thermal robustness under both continuous and intermittent exposures, and certainly the compounding as it relates directly to chemical compatibility.

Metal Alloys

Compared to commodity plastic polymers, metal components in liquid cooling systems are generally more stable, more durable and have a perception of longer-term reliability. Metal components also tend to be heavier and can be more expensive. In many applications, the enhanced performance characteristics of metals warrants the additional investment. In other applications, the right polymer may actually provide the best solution.

When considering metal alloys for use in systems, one should account for mechanical strength, surface treatment, and cleanliness. While many refrigerants and engineered fluids are low- to non-corrosive to metals, designers still must consider the operating environment with regard to corrosion.

PUTTING IT ALL TOGETHER: CHEMICAL COMPATIBILITY

With a foundational understanding of the fluids, plastics and metals that might be employed in a given liquid cooling application, one can assess potential chemical compatibility of system components, based on their make-up, to ensure reliable, long term operation.

While polymers and metals can be effective in any combination when appropriately specified, it is critical to distinguish wetted materials of construction from structural materials. Wetted materials include all components that are directly exposed to the coolant and therefore, are indirectly exposed to one another. Structural materials are not exposed to coolant during normal operation. Creating a list of wetted and structural materials early in the design cycle can help avoid complications down the road. A given component might potentially be built of a combination of polymers and metals. Thus, it is important to distinguish the wetted materials from structural materials within a given component. For example, a quick disconnect, such as those shown in *Figure 2*, may be constructed of nickel-plated brass and include an elastomeric O-ring seal, a polysulfone thumb latch and stainless steel springs. However, only the interior surface of the connector and the elastomer seal would be wetted in a closed-loop cooling system and those materials need to be considered for compatibility relative to the selected coolant.

Figure 2

At a high level, fluids can affect polymers in two different ways: physically and chemically. The first is generally reversible while the other is not. For example, an O-ring compound in a quick disconnect might have an affinity for a certain coolant, causing the O-ring to swell, which creates connection and disconnection issues that potentially lead to leaks. Replacing the O-ring with an alternative plastic or specifying a different fluid could correct the problem.

However, in a chemical interaction, in which a plasticizer is extracted from a component such as tubing, the effects of that dissolved plasticizer on the fluid's performance can be dramatic and are irreversible, which can be a critical issue in sensitive high-value applications.

General guidance can provide a good starting point. *Table 3* provides an overview of relative compatibility between various materials and coolant options. Remember, a holistic view of the full application details is the best way to ensure that the right materials are specified. It is incumbent on system designers to test components under expected operating extremes for their applications to assess fluid and material interactions at application-specific temperatures, pressures, and other environmental conditions.

A key to successful liquid cooling design is to engage with component suppliers early. This allows for the identification of any materials that might be exposed to coolant, and any other variables that might be present so that a design solution that is optimized for the specific system requirements can be developed.

Table 3. Typical fluid and material compatibilities

Material and coolant compatibility

When considering wetted components in a liquid cooling system, the following combinations are:

A = **Recommended**. Little or no potential for chemical reaction or corrosion.
B = **Good options**. Minor potential for chemical reaction or corrosion, with limited effect on system performance.
F = **Not recommended**. Mild to severe chemical or corrosive reactions likely. May impede system performance.

		WATER	ETHYLENE GLYCOL	PROPYLENE GLYCOL	MINERAL OIL	REFRIGERANTS	DIELECTRICS
POLYMERS	Commodity plastics	A	A	B	A	F	B
	Engineered thermoplastics	A	A	B	A	A to F[1]	B
	Elastomers	A	A	A	A[2]	A to F[3]	A to F[3]
METALS	Aluminum	B	A	B	A	A	A
	Brass (plated)	A	A	B	A	A	A
	Copper	B	B	A	B	A	A
	Stainless steel	A	B	B	A	A	A

[1]Thermoplastics may be engineered to enhance compatibility with specific refrigerants.
[2]Most elastomers are compatible, however EPDM is not recommended for use with mineral oil.
[3]Elastomers may be engineered to enhance compatibility with specific refrigerants and dielectric fluids.

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Better Cooling by Removing Material, Instead of Adding Material, to Unlock the Full Power of GaN Electronics

Remco van Erp

As society is moving from fossil fuels to more sustainable electrical power, the systems for converting and delivering this electrical power are becoming increasingly important. These power electronic systems are responsible for controlling and shaping the electricity between the sources, such as solar and wind, and the end-use destination, such as driving a motor or charging the battery of your phone. The transistor is the fundamental building block of these converters. While silicon transistors thrive in computing applications, they have limitations when it comes to handling high power and high voltages. Many applications are very constrained in space and weight and the challenge is to get more power in a smaller package. Gallium nitride (GaN) transistors are key in achieving this goal, but its full potential remains untapped due to thermal limitations. The paradigm of cooling has long been about adding more material and going bigger: more metal, bigger heat sinks. Yet, the limitation on heat extraction often lies at the interfaces between these components. Instead, in this article we discuss the alternative path to improve cooling by not *adding* material, but by *removing* it. We evaluate several approaches of microchannel liquid cooling of GaN power devices and show the benefits of moving the cooling inside the chip.

Gallium nitride (GaN), a wide-band-gap semiconductor, has favorable material properties compared to silicon for power conversion. It enables faster-switching, smaller converters with lower losses. GaN technology, which originated from the Nobel-prize winning research on blue-light LEDs, has steadily matured over the last years. One such development is the capability to grow a thin, epitaxial layer of GaN on a low-cost silicon substrate, making the material cost effective in growth as well as in processing, since established silicon fabs can be utilized. This low-cost GaN-on-Si is the driving force behind the commercial adoption of GaN in power electronics.

Aside from the benefits of faster switching and lower losses, a unique property that distinguishes the GaN power transistor from its silicon counterpart is its lateral device structure. Transistors can be placed side-by-side on the same chip and assembled together into a power integrated circuit (Power IC), creating the potential of high-power converters integrated on a small chip. To fully appreciate this feature, we have to jump back to the early discovery of the transistor. Shortly after Shockley, Brattain and Bardeen demonstrated the first transistor, then-vice-president of Bell Labs, Jack Morton, spoke about the *tyranny of numbers*. For each extra component soldered together on a circuit, the system becomes more complex and likely to fail. The same factors hold for power converters: more complex topologies with multiple devices can improve efficiency, add functionality and reduce reliance on bulky passive components such as inductors. However, the higher component count is usually faced with reliability concerns. Just as the integrated circuit helped to manage the tyranny of numbers for processors, the GaN-based power IC may do the same for power conversion. One could imagine a centralized chip that contains all active high-voltage power switching components, potentially co-packaged with passive components such as capacitors [3]. A system like this could be a disruptive technology for power conversion, leading to more compact and powerful systems.

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While this will be beneficial from a power density point of view, it aggravates the thermal challenges involved in maintaining junction temperatures at acceptable levels. Power dissipation will be concentrated in a single chip, so it cannot be spread to multiple large heat sinks. To fully exploit the possibilities of GaN-based power ICs, new strategies for effectively extracting the heat are required. Since GaN is grown as a thin layer on a silicon substrate, and this substrate has no functionality except for being an inexpensive carrier, it is possible to tap into the developments of in silicon microchannel heat sinks from past decades [1]. Microscopic cooling channels etched directly in the silicon substrate can function as a high-performance heat sink. The large surface-to-volume ratio of such microchannels provides high heat extraction while the absence of thermal interfaces ensures a low overall thermal resistance. In other words, it can turn the silicon substrate from a low-cost substrate into a high performance heat sink (*Fig. 1*).

In this work we evaluate several embedded microchannel cooling approaches for GaN-on-Si power devices, and benchmark their performance. A useful non-dimensional metric for such benchmarking of cooling performance is the ratio of extracted power ($Q_{max} = \Delta T_{max} R_{total}$)to pumping power ($P_{pump} = f\Delta p$) at a certain flow rate. This is known as the coefficient of performance (COP) and is given by the following formula:

$$\mathrm{COP} = Q_{max}/P_{pump}R_{total} = \Delta T_{max}/f\Delta p R_{total}$$

R_{total} is a summation of the individual contributions of thermal resistances between the power dissipating hot spot and the coolant at the system inlet. As the flow rate increases, R_{total} decreases, but P_{pump} quadratically increases due to dependency on both flow rate (f) and pressure drop (Δp). Ignoring any entrance effects, the COP can be seen as independent of die size. For example, two chips can be placed side-by-side, doubling both the maximum heat load and the flow rate, resulting in an equal COP. Plotting the COP against the maximum heat flux, q_{max}, provides a benchmark of heat extraction efficiency versus heat extraction capability.

$$q_{max} = Q_{max}/A_{die}$$

Figure 2 shows an overview of three approaches we compared using this approach. The first, in *Fig. 2a* shows an indirect cooling approach in which a silicon microchannel heat sink is attached with an intermediate thermal interface material (TIM) to a commercial packaged GaN transistor [4]. A one-dimensional thermal resistance network can be used to model the heat transfer between the device's junction and coolant inlet. The junction-to-case thermal resistance ($R_{j\text{-}c}$) is given by the device manufacturer and consists

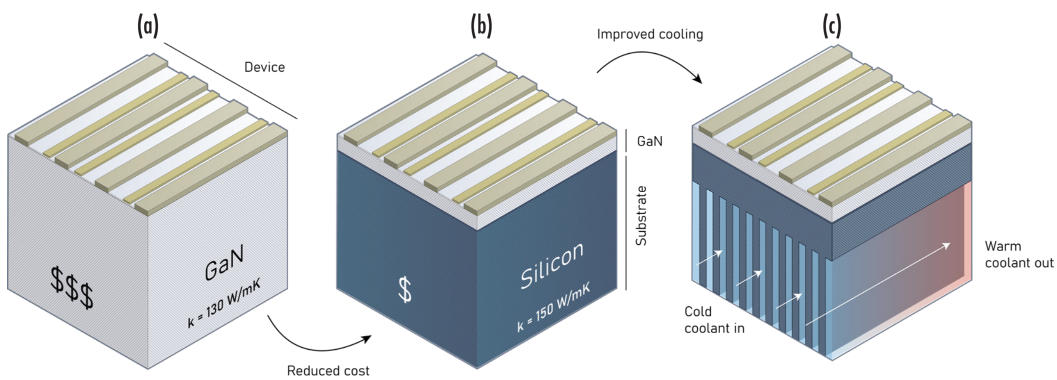

Figure 1: (a) Bulk GaN, (b) GaN-on-Si reduces cost, (c) Embedded microchannels for improved cooling.

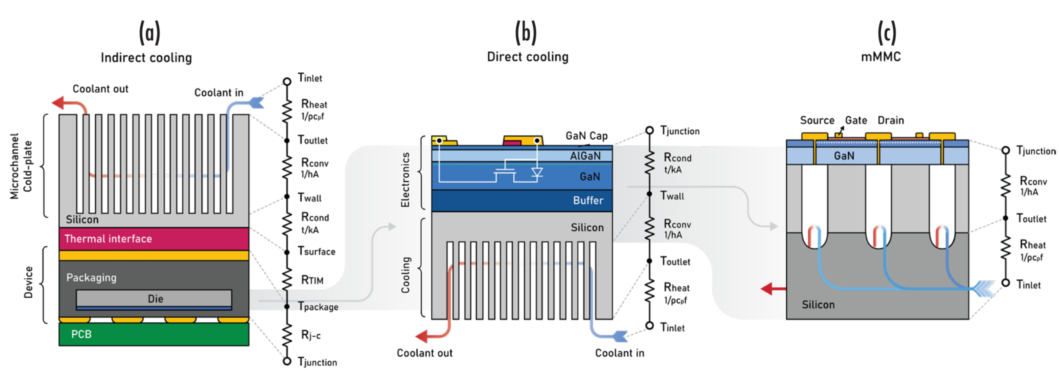

Figure 2: (a) Indirect cooling, a microchannel cold plate is attached to a packaged die with an intermediate thermal interface material. (b) Direct die embedded microchannel cooling, cooling channels are etched inside the backside of the silicon substrate. (c) GaN-on-Si device with a monolithically integrated manifold microchannel inside the silicon substrate, co-designed with the electronics. Cooling channels are positioned below and aligned with the pads of the electronic device.

of the various conductive elements between the hot-spot, die, and packaging layers.

- R_{TIM} describes the thermal resistance due to the TIM,
- R_{cond} accounts for the conduction in the silicon cold plate
- and R_{conv} accounts for the convective heat transfer between the solid silicon domain and the liquid coolant.
- Finally, R_{heat} is the thermal resistance due to the heat capacity of the coolant. R_{heat} scales with the flow-rate of the coolant ($R_{heat} = 1/\rho c_p f$) and does not depend on the geometry of the chip.

All the other thermal resistance components scale directly with the surface area of the chip, i.e., increasing chip size reduces these thermal resistances.

To compare multiple designs, we show the thermal resistance normalized by surface area in *Fig. 3a*. This shows that the major contributions in thermal resistance are related to the packaging and TIM, which account for more than 80% of the total. If the pressure drop of *Fig. 3b* is accounted for, this indirect method enables the extraction of about 55 W/cm^2 at a COP value exceeding 10^4.

From this finding, it becomes clear that the most effective way to improve cooling is not by adding a better heatsink, but by removing the packaging and thermal interfaces. In the approach shown in *Fig. 2b*, similar 50 µm microchannels are directly embedded into the silicon substrate in the same approach initially proposed by Tuckerman [1]. The second column in *Fig. 3a* highlights the effectiveness of this approach: the contributions of $R_{j\text{-}c}$ and R_{TIM} are eliminated, resulting a substantial reduction in thermal resistance. Since similar channel dimensions are used as in the indirect approach, the pressure drop between the indirect and direct approach remain comparable (*Fig. 3b*). As a result, at a comparably high COP of 10^4, this direct approach achieves a 10-fold increase in maximum heat flux up to 500 W/cm^2 (*Fig. 3c*) [5]. Furthermore, *Fig. 3a* reveals that the convective thermal resistance actually represents the limiting factor for heat extraction. We cannot scale the heatsink since the dimensions are constrained by the chip size. In order to reduce R_{conv}, smaller channel sizes can be utilized. However, this comes at a cost of increased pressure drop, which reduces COP and may add to system integration challenges.

One potential approach to decouple R_{conv} and pressure drip is by utilizing a third dimension. The manifold microchannel heat sink (MMC) is a hierarchical design that addresses these issues. In a MMC, manifold channels distributes the liquid efficiently over the chip, reducing pressure drop and increasing temperature uni-

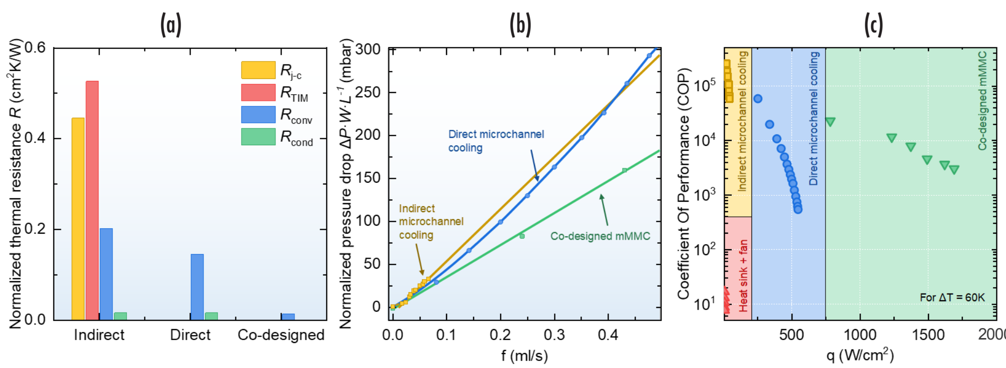

Figure 3: (a) Normalized thermal resistance components of indirect microchannel cooling, direct microchannel cooling and co-designed mMMC cooling. The components of R refer to the thermal resistance network diagrams illustrated in Fig. 1. (b) Normalized pressure drop (pressure drop multiplied by chip aspect ratio *W/L*) versus flow rate for the three configurations. (c) Benchmark of cooling efficiency (COP) versus maximum heat flux capability (*q*) for a maximum temperature rise of 60 K.

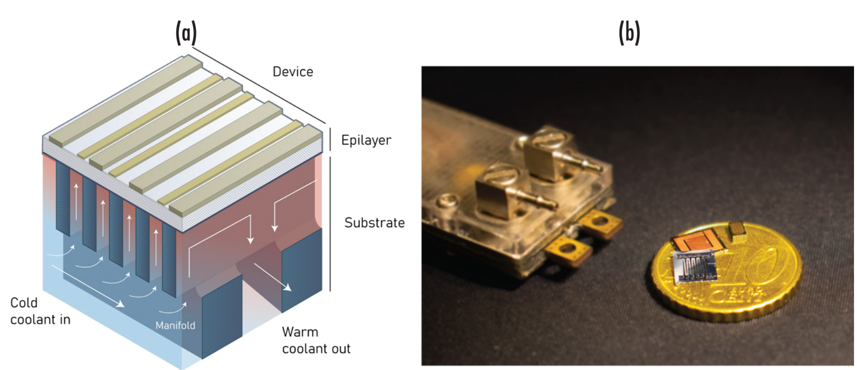

Figure 4: GaN power device with microfluidically co-designed mMMC. (a) Schematic of the mMMC structure. (b) Picture of a fabricated GaN power device with mMMC cooling.

formity. However, design of such flow-hierarchy in MMC heat sinks traditionally require multiple bonded layers together. This is not only a cumbersome fabrication step, but also raises reliability concerns under repeated thermal cycling. In the third approach in *Fig. 2c*, we explored a new design approach, where the design of the cooling and electronics go hand-in-hand from the start of the fabrication. We monolithically integrated an MMC structure in a GaN-on-Si device, which we call mMMC, using a new fabrication method that exploits the etching selectivity between silicon and GaN [6]. The typical source-drain spacing of GaN transistors and the optimal range of microchannel pith are both in the range of 15 to 25 microns. We exploited this fact by etching small trenches through the GaN epilayer, realizing a cooling channel in the underlying silicon substrate, and finally sealing the trenches in the GaN epilayer during the metallization step. Using this approach, each source and drain of the transistor is linked to an individual cooling channel (*Fig. 4a*). We refer to this approach as a microfluidic-electronic co-design. The bonding interface between the manifold and the microchannels was eliminated and the entire 3D cooling structure was realized in a single silicon crystal. This monolithic structure ensures structural integrity as well as excellent heat transfer. Fig. 3a shows the substantial reduction in R_{conv} realized using this approach, as well as the reduction in pressure drop (*Fig. 3b*). Combining these properties, we can show an additional increase in maximum heat flux of almost 3-fold at a COP of 10^4, relative to the microchannels etched in the back of the substrate.

GaN has the potential to reshape power electronic, and improved cooling can be an enabling technology that facilitates this technology. The silicon substrate on which GaN is grown does not need to merely be an economic choice; in addition, it can become an efficient heat sink that pushes the boundaries of what is possible in terms of integration and power density. As an example, *Fig. 5* shows an integrated GaN-based power rectifier with embedded microchannel cooling. Here, the GaN chip contains multiple power diodes, which are all cooled with water flowing inside the chip. Several challenges need to be addressed in terms of packaging and reliability in order to see such technology materialize, but at least it's sure that cooling doesn't need to be the limiting factor in a future with more compact and efficient power conversion.

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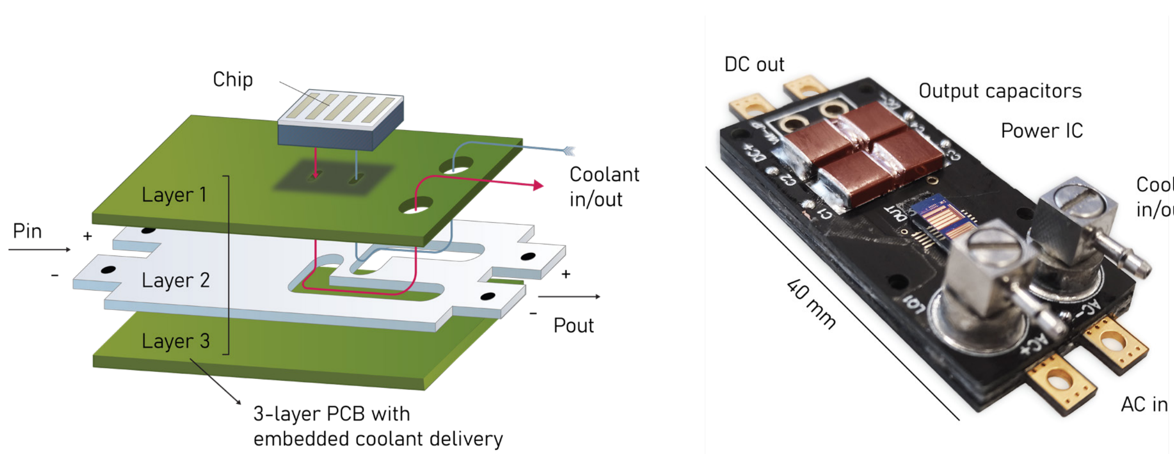

Figure 5: 1.2 kV/120 W GaN-based full-wave bridge rectifier (FWBR) power IC with embedded microchannel cooling. Schematic (left) and prototype (right)

Thermal Packaging – From Problem Solver to Performance Multiplier

Reprinted from Electronics Cooling website, December 5, 2013

Avram Bar-Cohen

The increased integration density of electronic components and subsystems, including the nascent commercialization of 3D chip stack technology, has exacerbated the thermal management challenges facing electronic system developers. The sequential conductive and interfacial thermal resistances associated with the prevailing "remote cooling" paradigm in which heat must diffuse from the active regions on the chip to the displaced coolant, have resulted in only limited improvements in the overall junction-to-ambient thermal resistance of high-performance electronic systems during the past decade. These limitations of Commercial Off-The-Shelf (COTS) thermal packaging are undermining the cadence of Moore's Law and leading to a growing number of products that fail to realize the inherent capability of their continuously improving materials and architecture. Continued application of this "remote cooling" paradigm has resulted in electronic systems in which the thermal management hardware accounts for a large fraction of the system volume, weight, and cost and undermines efforts to transfer emerging components to small form-factor applications.

To overcome these limitations and remove a significant barrier to continued Moore's Law progression in electronic components and systems, it is essential to implement aggressive thermal management techniques that directly cool the heat generation sites in the chip, substrate, and/or package. The development and implementation of such "Gen-3" embedded thermal management technology, following on the Gen-1 air-conditioning approaches of the early years and the decades-long commitment to the Gen-2 "remote cooling" paradigm, is the focus of the current DARPA Intra/Inter Chip Enhanced Cooling (ICECool) thermal packaging program. Launched in 2013, ICECool aims to develop and demonstrate "embedded cooling" techniques capable of removing kW/cm^2 chip heat fluxes and kW/cm^3 chip stack heat densities, while suppressing the temperature rise of multi-kW/cm^2 sub-mm hot spots [1,2]. The ICECool program is composed of two thrusts: a 3-year ICECool Fundamentals effort, involving several university teams which are developing embedded cooling building blocks and modeling tools, and a 2.5-year ICECool Applications effort, led by several aerospace performers and culminating in functional electronic demonstration modules. ICECool performers are pursuing the creation of a rich micro/nano grid of thermal interconnects, using high thermal conductivity, as well as thermoelectric, materials to link on-chip hot spots to microfluidically-cooled microchannels. Such intra/inter chip enhanced cooling approaches are required to be compatible with the materials, fabrication procedures, and thermal management needs of homogeneous and heterogeneous integration in 3D chip stacks, 2.5D constructs, and planar arrays. A conceptual ICECool device is shown in *Figure 1*.

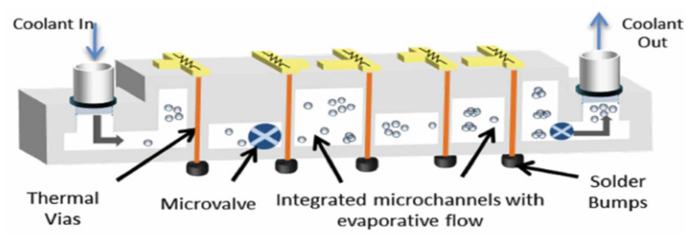

Figure 1: A Cross-Sectional Conceptual Schematic of an Embedded Cooling, Gen-3 (ICECool) device.

An *intrachip* approach would involve fabricating micropores and microchannels directly into the chip [3,4] while an *interchip* approach would involve utilizing the microgap between chips in three-dimensional stacks [5,6], as the cooling channel. In addition to the inclusion of an appropriate grid of passive and/or active thermal interconnects, it is expected that a combination of *intrachip* and *interchip* approaches, linked with thru-silicon and/or "blind" micropores, will confer added thermal management functionality. These microchannels and/or micropores will be integrated into a fluid distribution network, delivering chilled fluid to the chip or package and extracting a mixture of heated liquid and vapor to be transported to the ambiently-cooled radiator.

Some 30 years of thermofluid and microfabrication R&D, driven initially by the publication of the Tuckerman & Pease microchannel cooler paper in 1981 [1] and more recently by compact heat exchanger and biofluidic applications [7,8], has created the scientific and engineering foundation for the aggressive implementation of the "embedded cooling" paradigm. Nevertheless, substantial development and modeling challenges must be overcome if Gen-3 techniques are to supplant the current "remote cooling" paradigm. Successful completion of the DARPA ICECool program requires overcoming multiple microfabrication, thermofluid and design challenges, including:

- Subtractive and additive **microfabrication** in silicon, silicon carbide, and synthetic diamond of high aspect ratio, thin-walled microchannels and high aspect ratio micropores; low thermal boundary resistance, high thermal conductivity thermal interconnect grids; on-chip, high power factor, high COP thin-film thermoelectric coolers; and hermetic attachment of liquid supply and liquid/vapor removal tubes.

- Convective and evaporative **thermofluid transport** in microchannels and micropores– removal of 1 kW/cm^2 chip heat fluxes with 2-5 kW/cm^2 sub-millimeter “hot spots”; low pumping power liquid-vapor manifolds with Coefficients-of-Performance (CoP) between 20 and 30; high-exit-quality, greater than 90%, evaporative flows without flow instabilities and/or local dryout; and high fidelity thermofluid models for single- and two-phase flow in microchannels, microgaps, and micropores.

- Thermal/electrical **co-desig**n which moves progressively from passive, thermally-informed designs, which recognize the impact of temperature on functional performance, to active thermal co-design which places functional paths and blocks in the most favorable locations on the chip, to fully-integrated co-design which deals with the impact of microfluidic channels and thermal interconnects on the electrical design and placement of electrical devices and cells, to mature designs that interactively balance the use of resources to optimize layout for energy consumption/functional performance.

- **Physics of Failure** models that address the failure mechanisms and reliability of the Gen-3 thermal management components, including erosion and corrosion in microchannels, microgaps, and micropores; failure modes induced in the electrically active areas of the chip and/or substrate; and the impact of microfabrication and embedded cooling operation on the structural integrity and stress profile of the microchanneled substrate (intrachip) and/or the chip-to-chip bonding (interchip).

Successful development and implementation of this Gen-3 thermal packaging paradigm places thermal management on an equal footing with functional design and power delivery, transforming electronic system architecture and unleashing the power of nanofeatured device technology, while overcoming the SWaP (size, weight, and power consumption) bottleneck encountered by many advanced electronic systems. After decades of mere “problem solving” with Gen-1 (HVAC) and Gen-2 (spreaders, heat sinks, and TIMs) thermal management technology, it is expected that widespread adoption of Gen-3 “embedded cooling” techniques will provide a significant performance multiplier for advanced electronic components.

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In Memoriam of Avram Bar-Cohen

– Victor Chiriac, *Electronics Cooling* Co-Editor, January 8, 2021

It is with sad feelings that I am compiling this remembrance article for Professor Avram Bar-Cohen, who departed this world too soon. Avi inspired many scientists, educators and practicing engineers with his deep understanding of the thermal field and excitement in seeking new technical breakthroughs. He mastered the secrets of combining the fundamentals of the academic field with the practicality of novel technology implementation into the industrial products… I remember Avi's infectious smile and enthusiasm when I first met him during his visit to Motorola in 1997, while I was a summer student. Over my career I had the privilege to interact professionally with Avi in my technical leadership roles at Motorola and later at Qualcomm. He was an inspiration to many of us who were peers, colleagues and friends. There are many more things that could be said, but I would like to share here with our readership a collection of memories from several distinguished educators and scientists who worked with and knew well Avi… God Bless and Rest in Peace Avi. You are living through your Work and through the People who you helped shape into today's thermal community leaders…

See below a collection of thoughts from some of Avi's peers

A few personal notes by Clemens Lasance, Philips Research Emeritus

On October 11, I was shocked by being informed about prof. Avram Bar-Cohen's sudden death, and I still am. Avi inspired everyone in our thermal community, first of all by the impressive number and quality of his books, chapters and papers, but also for the people who had the privilege to meet him in person by his enthusiasm and his presence. I will always remember his irresistible smile. Allow me a few words on his achievements without even trying to be complete. He was a thermal engineering pioneer since the early seventies, from both an academic and a practical point of view. He is worldwide recognized as a leader in thermal science and technology. He authored and co-authored over 400 publications, delivered over 100 keynotes, and guided more than 70 masters and PhDs at the universities of Maryland, Minnesota and Beer Sheva (Israel). He was honored by over 10 institutions (amongst with the THERMI Award in 1997) and became recently a member of the EU Academy of Sciences. I agree totally with the words of Mike Pecht at the U. of Maryland: ''Avi's scientific accomplishments are prodigious, but it was his commitment to helping others that will be his enduring legacy.''

I first met Avi at the IHTC in San Francisco in 1986, attending a course presented by him and Allan Kraus on heat sinks. Then again at the IHTC in Jerusalem in 1990, and in 1993 for two weeks at the NATO Advanced Study Institute on Cooling of Electronic Systems held in Cesme, Turkey, where we both lectured and participated in the closing panel session. I recall vividly not only our get togethers, with a whole bunch of famous thermal experts, among others Arthur Bergles, Frank Incropera, Allan Kraus, Dick Chu, Al Ortega and Wataru Nakayama, but especially our snorkeling adventures in the Mediterranean. When I together with the U. of Delft organized the first thermal management conference in Europe in 1993, I invited Avi as a keynote speaker which he happily accepted. For sure he brought the conference at a higher level with his active participation.

The most important result of the successful EU project DELPHI was the compact thermal modeling philosophy. Avi, who was involved in this subject in those days, and me agreed to write a book on this topic together with three other authors, a serious start was made but it never was finished. Then, some 10 years later, as the editor of the famous Encyclopedia of Thermal Packaging, Avi invited me to contribute a volume on Compact Thermal Modeling, so I asked him what's in for me, and he said: All volumes of the Encyclopedia.I replied that I liked the proposition, the problem being that my bookshelves couldn't carry their combined weight. He answered: No problem, I am an excellent carpenter, when I am in the neighborhood, I give you a call. In 2011, I was very honored by being asked to write a contribution to the Festschrift celebrating Avi's 65th birthday. The subject I chose was about heat sinks, exactly the same subject that started our relationship back in 1986. Avi, I will miss you as a scholar, friend and carpenter. I offer my deepest condolences to his wife, children and family.

A few personal notes by Professor Michael Ohadi, U Maryland/ARPA-E

I first came to know Avi first in 1986, when I was a graduate student at the University of Minnesota and attended Avi's newly offered Electronics Cooling course there. Later Avi moved to the University of Maryland to chair the Department of Mechanical Engineering at the University of Maryland (UMD) between 2001 and 2010. Avi brought much enthusiasm and momentum to UMD's mechanical engineering department. Among his many contributions, the Department's national rankings vastly improved, and its research expenditures increased by 63%.

At the international level, under Avi's leadership in 2002 UMD's mechanical engineering participated in a sponsored international research and educational collaboration with the United Arab Emirates (UAE). Through this multi-year collaboration, UMD's College of Engineering helped establish an engineering institution in the UAE, which included six engineering programs, a mechanical engineering program which boasted the highest student enrollment of the six. The programs included both undergraduate and graduate programs. In 2012, the six engineering programs were granted ABET accreditation and became the only institution in the UAE at the time with such high recognition.

Avi's administrative duties did not stop him from his active research, collaborative, and scholarly activities. He reached out and collaborated with many of the faculty in mechanical engineering and across the campus. His scholarly work between 2001 to 2010 included more than 150 journal articles, peer-reviewed conference papers, and invited plenary/keynote/other major lectures. The Mechanical Engineering faculty, staff, and students at UMD will miss Avi's engaging and intellectual presence, momentum building character, and his affable smile.

A few personal notes by Madhu Iyengar, Google

Professor Avram Bar-Cohen was a giant in the fields of electronics packaging and cooling, and a pioneer who has significantly influenced academia, industry, and governmental research. Beyond his technical accomplishments and leadership, he was a fantastic mentor for individuals and the community. He fostered a culture of innovation, collaboration, and high technical achievements for several decades, and founded vibrant and healthy international conferences, such as the IEEE ITherm and the ASME InterPack. Avi's more recent leadership as the leader of the DARPA IceCool program has led to breakthrough research on embedded cooling of ultra-high performance chips, and I expect this achievement to be a beacon that shines light for future progress in the field.

For me personally, Avi was a teacher, mentor, and friend over the last 25 years, and whose passing I mourn and grieve deeply. Avi inspired fearlessness and total commitment towards the progress of the field, with a cheerfulness and exuberance that was infectious. He will be missed, but will continue to guide us through our memories.

A few personal notes by Bob Simons, IBM Emeritus

I knew Avram Bar-Cohen during most of his professional career, having first met him in 1976 when he was at IBM for a short while. Since that time he became an internationally recognized leader in the electronics cooling and packaging community. Through his many publications, lectures, short courses, and research, he contributed significantly to establishing a scientific foundation for the thermal management of electronic components and systems. Those who had the opportunity to know him and interact with him professionally, will remember him for his energy and passion for promoting both the art and science of cooling electronics.

A few personal notes by Professor YC Lee, U of Colorado at Boulder

Avi had been my mentor since the beginning of my professional career in Bell Labs. In 1984, I took my first short course taught by him. In 1988, I attended the first ITherm organized by him. In 1995, Avi made a strategic move to hold the InterPACK in Maui, and I supported this conference as a coordinator of international liaisons and a session chair. In 2010, Avi began his service as a DARPA Program Manager, and I had a chance to work with him closely as the PI of a Thermal Ground Plane (TGP) project. In 2014, I started serving as the Editor of the Journal of Electronic Packaging (JEP), and the first person I asked for help was Avi. Avi and his DARPA team members contributed three reviews on TGP, Nanothermal Interface Materials, and Cooling for Wide Bandgap Power Amplifiers. These articles made a major impact. I was blessed to have Avi as my mentor, and I was fortunate to witness and support Avi's truly outstanding service to the packaging community. Avi, we miss you!

A few personal notes by Jim Wilson, Principal Fellow, Raytheon Technologies

Avi's contributions to the field of electronics cooling are numerous and found in many places including this magazine. His influence extended beyond the many technical contributions to include the mentoring and collaboration and support he showed to his colleagues and friends. I had the privilege of knowing Avi from professional society interactions, as an associate editor of Electronics Cooling, as a coworker at Raytheon, and most importantly as a friend. His first exposure to the challenges of cooling electronics came when he was a new mechanical engineer at Raytheon and this helped motivate further graduate studies and Raytheon made an excellent investment helping support his graduate work.

Avi was a true trail blazer who enjoyed pushing for disruptive ideas that challenged the way things are done and was a fearless advocate for the voice of thermal engineers all over the world. While he could be a challenging and persistent leader, he was a genuinely kind person. He always found time to review a paper or discuss the latest technical topic (sometimes with emails that were sent in the middle of the night). Avi found joy in selflessly helping others succeed and hopefully passed this characteristic on to others as part of his legacy. He is deeply missed.

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- Automotive/Aerospace/Outdoor
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- Two-Phase Cooling II
- Data Centers
- Liquid Cooling
- Measurement Techniques / CFD
- Thermal Interface Materials

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Keynote Speaker

Tuesday March 23, 9:00 a.m.

Opening Opportunities for Thermal Design through Innovations in CFD

Presenter: Lieven Vervecken
Diabatix

Over the past decades, computational fluid dynamics (CFD) has evolved from a purely research discipline to a reliable engineering practice. This evolution was driven by continued innovation in multiple domains, ranging from hardcore mathematics to HPC architecture development. Concurrently with this evolution, CFD has gradually taken on great importance in the thermal design process which has resulted in a countless number of products that could not have been realized otherwise. Yet, the potential for discovering new possibilities in thermal design through innovations in CFD remains enormous. This talk touches on a number of recent and upcoming innovations in CFD which have the potential to set this in motion.

Lieven Vervecken is co-founder and CEO of Diabatix nv where he is responsible for the general management development of the company. Diabatix is a Belgian technology scale-up specialized in generative design for cooling components that helps multinationals all over the world to push the boundaries in thermal design.

Short Courses Monday, March 22

These two-hour classes provide practical, interactive training on a variety of specific skills on topics ranging from thermal design & modeling to system level validation testing. Attendees can choose one Short Course in the morning and one in the afternoon. All times PDT.

7:00 a.m. Short Course 1

Let's Work Together: How Co-Design Leads to Better Solutions in Thermal Management

Presented by: Lauren Boteler, Army Research

7:00 a.m. Short Course 2

Design and Optimization of Heat Sinks

Presented by: Marc Hodes and Georgios Karamanis, Transport Phenomena Technologies, LLC

9:20 a.m. Short Course 3

Micro-Two-Phase Electronics Cooling…Getting it on its Way

Presented by: John R. Thome, J.J. Cooling Innovation

9:20 a.m. Short Course 4

Introduction to Electronics Cooling

Presented by: Patrick Loney, Northrop Grumman Mission Systems

SEMI-THERM 37

Liquid Cooling Panel Monday, March 22 11:40 a.m.

Join us Monday afternoon for the Liquid Cooling Panel. This panel will provide a broad perspective on the current usage of liquid cooling across a range of industries, including data centers, ground vehicles and aerospace. We will also look forward to the near-term trends according to these experts, then looking further out, with each panelist given the opportunity to describe the technological advances in liquid cooling that they would most like to see.

Panelists:

Moderator:

Tim Shedd, Ph.D.
Director of R&D, Motivair Corporation

Emre Gurpinar, Ph.D.
R&D Staff, Electrical and Electronics Systems

Alfonso Ortega Ph.D.
James R. Birle Endowed Chair Professor of Energy Technology, Villanova University Director, Villanova site of the NSF Center for Energy Smart Electronic Systems

Suresh Pichai
Director, Innovation and Development
Research Division Oak Ridge National Laboratory
Equinix Data Centers

Debabrata Pal, Ph.D.
Technical Fellow
Collins Aerospace

Bapi Surampudi, Ph.D.
Staff Engineer, Electric Powertrain
Southwest Research Institute

Technical Sessions

Tuesday March 23

Technical Session - Track 1: Consumer Electronics

Increased System Performance and Reduced Surface Touch (Skin) Temperature in Mobile Electronics Utilizing Composites of Graphite with Ultra-High Spreading Capacity and Insulation with Ultra-Low Thermal Conductivity
Mitchell Warren, W. L. Gore & Associates

An Analysis of Temperature Variation Effect on Response and Performance of Capacitive Microaccelerometer Inertial Sensors
Jacek Nazdrowicz, Lodz University of Technology

Thermal Acceptability Limits for Wearable Electronic Devices
Mark Andrew Hepokoski, ThermoAnalytics

Technical Session - Track 2: Automotive/Aerospace/Outdoor

Effects of Solder Voiding on the Reliability and Thermal Characteristics of Quad Flatpack No-lead (QFN) Components
Ross Wilcoxon, Collins Aerospace

Characteristics of Practical CTE-Matched Composites for Electronics Thermal Management: Comparative Study
Dave Saums, DS&A LLC

Technical Session - Track 3: Two-Phase Cooling I

Numerical Investigation of Coolants for Chip-embedded Two-Phase Cooling
Pritish R Parida, IBM T.J. Watson Research Center

Numerical Investigation of Thermal Spreading Resistance of Vapor Chambers
Farzan Kazemifar, San Jose State University

Wednesday March 24

Technical Session - Track 4: Data Center

Determination of Cost Savings Using Variable Speed Fans for Cooling Servers
Nicole Okamoto, San Jose State University

Effects of Different Coolants on the Cooling Performance of an Impingement Microchannel Cold Plate
Cong Hiep Hoang, Binghamton University - SUNY

Sensitivity Analysis of a Calibrated Data Center Models to Minimize the Site Survey Effort
Saurabh Singh, University of Texas, Austin

Technical Session - Track 5: Liquid Cooling

Unified Method to Model Closed-Loop Liquid Cooling
Albert Chan, Cisco Systems, Inc.

Thermohydraulic Performance of Heat Sink with Sinusoidal Microchannels Embedded with Pin-Fins for Liquid Cooling of Microelectronic Chips
Bobby Mathew, United Arab Emirates University

Technical Session - Track 6: Measurement Techniques/CFD

Cross Correlation Method for Images Alignment: Application to 4 Buckets Calculation in Thermoreflectance
Metayrek Youssef, IFSTTAR

Including Electrothermal Effects in Electronics Design with Connected FANTASTIC BCI-ROMs
Byron Blackmore, Mentor, A Siemens Business

Thursday March 25

Technical Session - Track 7: Thermal Interface Materials

CVD Polycrystalline Diamond for Laser Diode Applications
Firooz Faili, Element Six Technologies

Experimental Investigation of the Impact of Squeezing Process on the Microstructure and Performance of Thermal Interface Materials (TIMs)
Rajath Kantharaj, Purdue University

Metallic TIMs for Liquid Immersion Cooling and Cryogenic Temperatures for Quantum Computing
Dave Saums, DS& A LLC

Technical Session - Track 8: Two-Phase Cooling II

Design and Optimization Array of Micropillar Structures for Enhanced Evaporative Cooling of High-Powered Electronics
Kidus Guye, Washington State University, St. Louis

Actively Cooled Two-phase Cold Plate for High Heat Flux Electronics
Michael C. Ellis, Advanced Cooling Technologies, Inc.

THERMI Award Presentation, Wednesday March 24, 9:00 a.m.

Each year, SEMI-THERM honors a person as a Significant Contributor to the field of semiconductor thermal management. The THERMI award is intended to recognize a recipient's history of contributions to crucial thermal issues affecting the performance of semiconductor devices and systems. The 2020 THERMI award is proudly presented to:

Ross Wilcoxon, Ph. D.
Collins Aerospace

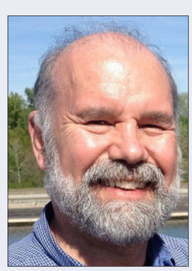
Join us Wednesday morning for Dr. Wilcoxon's presentation.
Apollo – The Dawn of Semiconductor Thermal Management

Hall of Fame Award Presentation, Thursday March 25, 11:50 a.m.

Dr. Dereje Agonafer
University of Texas at Arlington

This year's recipient is Dr. Dereje Agonafer.
Join us Thursday afternoon for the presentation by this years Hall of Fame award recipient.
Each year the SEMI-THERM Educational Foundation Thermal presents the Hall of Fame Lifetime Achievement Award in recognition of significant contributions to the field of electronics thermal management.

Embedded Tutorial, Thursday March 25, 9:00 a.m.



Bruce Guenin, Ph.D.
Join us Thursday morning for the Embedded Tutorial, presented by Bruce Guenin, Ph.D.
Realistic Thermal Model for Human Skin in Contact with a Wearable Electronic Device

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