Carbice Reliable cooling expertise.™

The secret to increasing data center performance lies at the interface.

The future of data center performance depends on manufacturing innovation and cooling expertise at the interface.

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PART 1: INTRODUCTION

The secret to increasing data center performance lies at the interface.

The future of data center performance depends on manufacturing innovation and cooling expertise at the interface.

The future of data center performance depends not just on compute power or cooling capacity—it hinges on what connects the two. As the demands of AI, high-performance computing (HPC), and energy-intensive applications continue to rise, data centers are confronting an overlooked bottleneck: the thermal interface.

While semiconductors become more powerful and cooling systems more sophisticated, the interface that links them remains stagnant. This small, often hidden layer—known as the thermal interface material (TIM)—plays a critical role in a cooling system's effectiveness. Yet for decades, innovation at the interface has been limited, fragmented, and undervalued across the electronics manufacturing ecosystem.

As data centers evolve to support the explosion of AI and ever-increasing power densities, thermal management is no longer just a design consideration—it's a strategic imperative. Power fluctuations, overheating, and inefficient cooling solutions aren't just technical nuisances; they drive unplanned downtime, inflate operational costs, and threaten long-term profitability. The question for data center operators isn't whether they'll face these challenges—it's how to solve them without compromising performance, sustainability, or serviceability.

At Carbice, we believe the interface isn't just a material problem—it's a system-level issue. Carbice's vertically aligned carbon nanotube technology transforms thermal interfaces from a liability into a scalable advantage, offering both performance predictability and manufacturing efficiency. With this breakthrough, Carbice is redefining the role of cooling in data center design, enabling more reliable systems that are easier to deploy, maintain, and scale.

This paper explores the hidden costs of legacy thermal interfaces, the systemic risks they pose to data center operators and IT suppliers, and how Carbice's material innovation and reliable cooling expertise solve a problem the industry has long ignored. The solution isn't just about better thermal conductivity—it's about building the foundation for faster deployment, more reliable operations, and a more sustainable digital future.

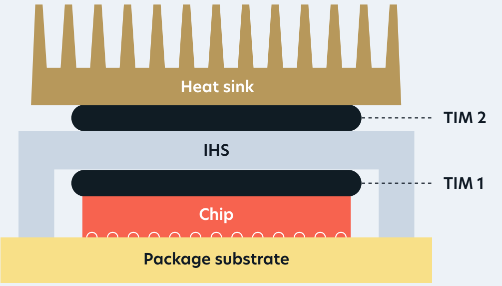
The importance of thermal interface materials in data centers

What is an interface material and why is it critical?

Thermal interface materials are critical for maintaining the thermal stability of electronic components by efficiently transferring heat from chips to heat sinks, cold plates, and other cooling devices. TIMs act as the bridge between heat-generating semiconductors and their cooling solutions, ensuring that the heat is effectively dissipated and preventing performance degradation. The device relies on the TIM to transfer heat to the cooling system at a higher temperature than the cooling medium—creating the temperature gradient that drives effective heat removal. In fact, the TIM contributes to more than 30% of the overall cooling efficacy[1], arguably making it one of the most critical components in any thermal system design. Without a reliable TIM, even the most advanced cooling technologies—whether air-cooled heat sinks or cutting-edge direct liquid cooling systems—would fail to perform as intended, leading to overheating, system throttling, and hardware degradation. In today's power-dense AI chips, poorly performing TIMs can result in up to 20°C of lost cooling potential between the chip and the cooling device—severely limiting power efficiency and compute performance in large data centers.

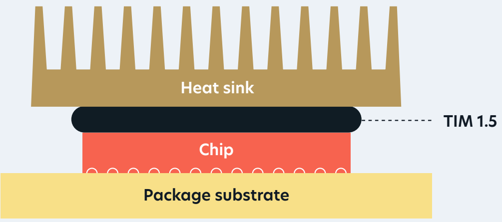
Modern data centers are pushing the boundaries of power density, with hyperscalers like Google, Amazon, and Meta deploying thousands of high-powered GPUs in massive clusters to support AI training, machine learning workloads, and cloud computing. To manage these extreme thermal loads, hyperscale data centers employ advanced cooling strategies such as chilled water cooling, direct-to-chip liquid cooling, and immersion cooling. These technologies are designed to remove vast amounts of heat efficiently, but their effectiveness is still fundamentally dependent on the performance of the TIM that sits between the processors and cooling elements. Without high-performance TIMs, even the most innovative cooling architectures cannot achieve their full potential, leading to costly inefficiencies, increased power consumption, and unexpected downtime events.

Key TIM categories in compute infrastructure:



TIM 1 – Between the chip and the lid

TIM 2 – Between the lid and the heat sink



TIM 1.5 Between the chip and the heat sink

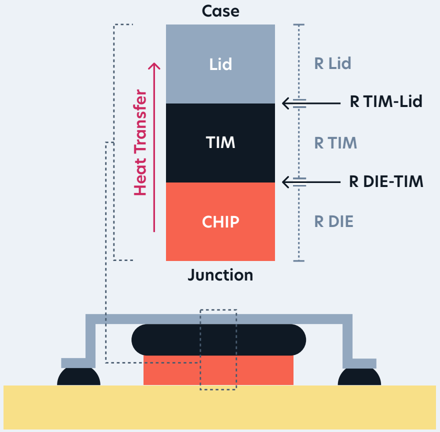


FIGURE 1: Thermal interface diagram.

Across an entire data center, there are thousands—if not millions—of TIM interfaces, all of which must function optimally to prevent thermal bottlenecks. As data centers continue to scale and deploy higher-wattage processors, ensuring the reliability, longevity, and serviceability of TIMs will be key to maintaining peak operational efficiency while minimizing costs and environmental impact.

Minimizing system risk through high-performance thermal interface design

In today's data centers and power electronics, thermal interface materials must do more than reduce temperatures at startup. As systems scale and power density increases, true high-performance is defined by how well they endure real-world operating stress—not just how they perform in early benchmarks. Yet system designers often optimize for low system steady-state temperature while giving less attention to more impactful system performance metrics driven by both dynamic thermal and mechanical stresses.

This focus on low steady-state temperature is often reinforced by the application of generalized models like the Arrhenius equation, which overemphasize steady-state temperature and overlook dynamic, real-world stressors. As Wilcoxon (2017) highlights, thermal cycling alone can reduce product lifetime by up to 8×—posing a much greater threat than modest increases in temperature[2]. Dasgupta (2024) further highlights how system degradation is driven by coupled mechanical, thermal, and material fatigue effects—none of which are captured in static models[3]. Establishing a new metric for true high-performance in electronics requires accounting for these more impactful thermal and mechanical failure mechanisms that conventional models and early benchmarks often miss.

To redefine what "true high-performance" means in thermal interface design, we must look beyond thermal conductivity alone. Many critical reliability issues—like fatigue, dry-out, pump-out, delamination, and contact stress relaxation—emerge over time due to a combination of thermal and mechanical stresses that aren't captured in conventional early-stage design and testing. These issues can show up in typical data center operations as soon as 3 months from initial startup.

Two industry recognized approaches, the Design Failure Mode and Effects Analysis (DFMEA) and Process FMEA (PFMEA) can be combined to define, analyze and address risks associated with thermal interface failure modes. While DFMEA highlights design-related vulnerabilities, PFMEA surfaces risks introduced during manufacturing and integration. On their own, each view is incomplete. Together, they offer a full-spectrum risk analysis that reveals the critical failure mechanisms in thermal interfaces that degrade performance, increase service costs, and reduce system life. True high-performance interfaces minimize these risks and allow systems to operate under their steady-state thermal limits.

A combined DFMEA/PFMEA framework identifies and ranks the risks associated with real-world failure modes in thermal interfaces. The chart below outlines common thermal interface failure modes, the underlying mechanisms that cause them, and the corresponding design and process controls used to manage risk. Each failure mode is assessed using a combined DFMEA/PFMEA approach and scored from low to high risk—highlighting which issues are most severe, most likely to occur, and hardest to detect, and therefore require accelerated reliability stress testing to fully characterize.

Design and Process FMEA Risk Analysis

FIGURE 2: FMEA Risk Priority Analysis for High-performance Thermal Interface Solutions

CATEGORY	FAILURE MODE	DRIVING MECHANISM	CURRENT DESIGN CONTROLS PREVENTION	RISK PRIORITY NUMBER (RPN)
Design	Contact Stress Relaxation	Mechanical creep	Thermal cycling, vibration, shock, high temperature storage, elevated humidity	High
Design	Interface Fatigue	Thermal-Mechanical gradients, cycling	Thermal cycling, vibration, shock, high temperature storage, elevated humidity	
Design	Grease Dry-out / Pump-out	Thermal cycling, viscosity changes	Thermal & mechanical cycling, vibration, shock, high temperature storage, elevated humidity	
Design	Polymers Stiffening	Elevated temps, time	Data sheet review, high temperature storage	
Process	Manufacturing Assembly Variance	Variance in dimensional tolerance	QA & visual inspection, final test	Medium
Process	Mechanical Damage During Rework	Stress concentrations from warped parts or misalignment	Visual inspection, rework procedure controls, functional testing	
Process	TIM Cleanliness	Poor quality control, environment, contamination causes scrapped parts	Visual inspection, process controls and isolation, downstream process detection	
Process	Vibration Contact Loss	Shipping/transportation, harsh environments	Shock, vibration, impact & drop testing	
Design	Metallic Connector Corrosion	Vibration, humidity, temperature cycles	High temperature, elevated humidity, salt fog	
Design	Delamination	Thermal-mechanical cycling	Thermal cycling, vibration, shock, high temperature storage, elevated humidity	Low
Process	Improper TIM application	Different application methods	Visual inspection	
Design	Electrostatic Discharge	Leakage, FOD	Data sheet review, dielectric materials, visual inspection and functional testing	
Design	Thickness out of Range	Application-defined	Engineering process development	
Design	Device Throttling	Insufficient variable or transient cooling	Initial system design, final test	
Design	Bulk Temperature Overload	Insufficient steady state cooling	Initial system design, final test	

RPN SCORE 🟥 High >250 🟨 Medium 150-250 🟩 Low 1-149

NOTE: See Appendix A for a Design and Process FMEA Risk Priority Score Comparison for Thermal Interface Solutions in Data Center Server Applications. The Carbice Design and Process FMEA presented in Appendix A reflects representative scenarios and potential failure modes based on standard electronics design and manufacturing practices. While the data is grounded in real-world engineering experience, it is intended as a reference model. For a tailored assessment aligned with your specific application or production environment, please contact the Carbice team.

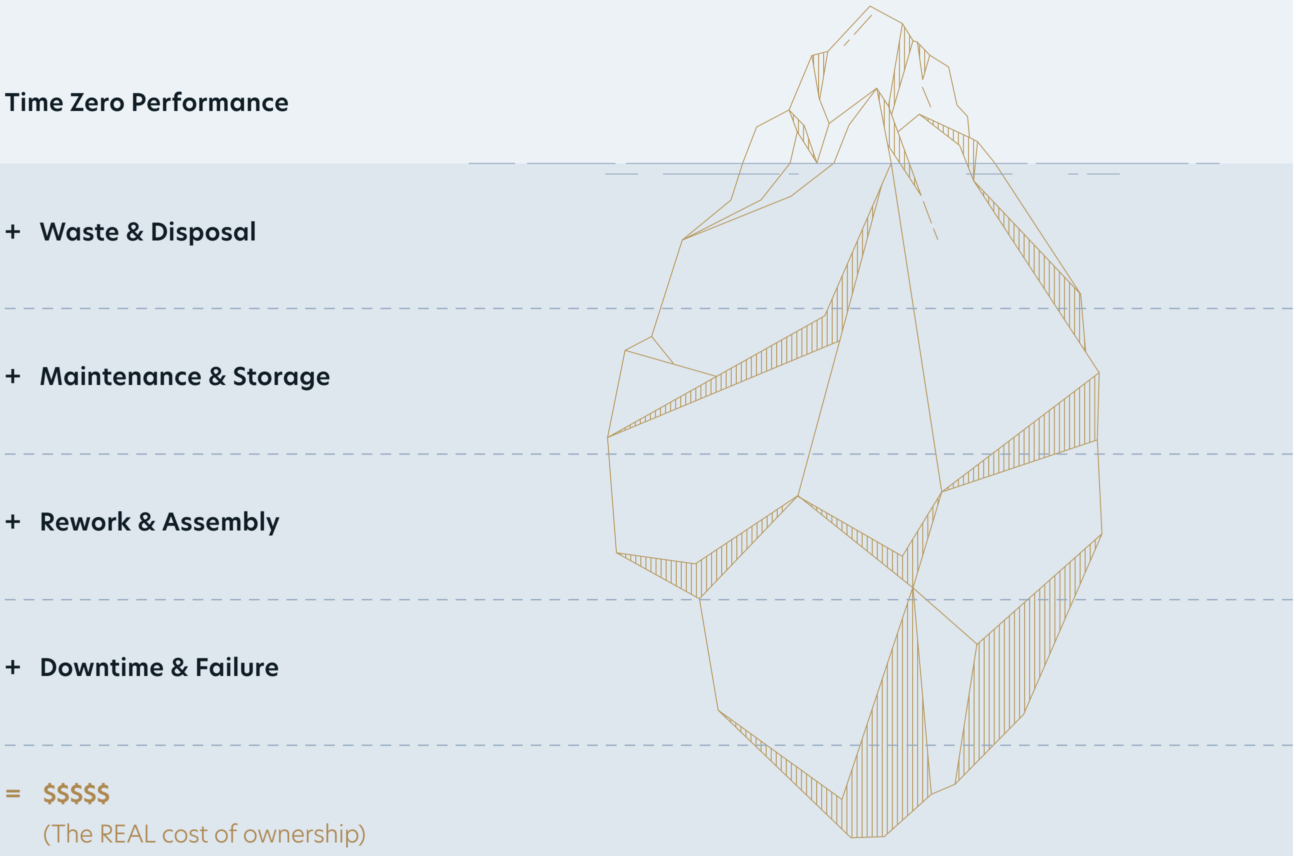
Data center operators, electronics manufacturers, and systems integrators who don't evaluate these key risk factors are likely missing the design and process controls necessary to achieve consistent, reliable, and long-term high-performance across their infrastructure.

Reducing data center costs through optimized thermal solutions

At first glance, ensuring desired temperature results at initial installation (Time Zero) might seem like the biggest challenge—solved in a laboratory evaluation with the right thermal interface material. However, as with an iceberg, the most significant costs of inadequate thermal solutions lie beneath the surface. We know this is true from just a brief search of "re-pasting" on the internet where gamers are constantly spending time, energy, and money adjusting for poor temperature stability in their systems.

FIGURE 3:

**Legacy TIMs:
The Iceberg of Hidden Costs**



Beyond the initial performance checks, unpredictable and unreliable TIMs can trigger downtime and excessive maintenance when products leave the factory, adding layers of operational inefficiencies and financial strain. Data centers rely on uninterrupted performance, yet many are unknowingly burdened by hidden costs tied to equipment recalls during initial build outs, rework, labor-intensive maintenance, waste and premature component wear and tear—all stemming from suboptimal thermal management. By adopting a serviceable, recyclable TIM that minimizes rework, simplifies assembly, is robust in shipping and storage, and eliminates wasteful disposal practices, data centers can significantly lower their long-term total cost of ownership while also reducing environmental impact.

Thermal challenges in data centers cause downtime

At the heart of every data center is an array of high-density servers, each housing thousands of GPUs, CPUs, memory modules, and networking components working together to process vast amounts of data. As AI workloads and high-performance computing (HPC) become more prevalent, these servers are pushing the limits of thermal design. The demand for higher power densities means components must dissipate more heat than ever before, making reliable heat transfer a critical bottleneck.

Inside a single compute rack, there can be hundreds of TIM interfaces, all of which must function optimally to avoid thermal throttling, increased fan speeds, higher energy draw, and even hardware failures. When TIMs degrade over time or fail to maintain uniform contact, hotspots develop, forcing servers to operate inefficiently. This leads to throttled performance, higher cooling loads and electrical power draws, and an increased risk of downtime—all of which translates to greater operational costs and a lower return on investment.

Downtime is a major concern for data centers, not only due to maintenance and repair costs but also the risk of lost revenue. Despite millions spent on redundancy, Uptime Institute reports that 45% of operators face outages costing $100,000 to $1 million per event[4]. Therefore, identifying all potential failure points, such as TIM degradation, is crucial to protecting productivity and profitability.

In an environment where uptime, efficiency, and sustainability are paramount, TIM performance directly influences the overall profitability and longevity of a data center.

Inconsistent TIM performance creates ripple effects throughout a data center:

- **Performance loss:** Thermal throttling reduces compute efficiency, forcing workloads to be distributed inefficiently across nodes and complex computations to be interrupted.
- **Higher energy consumption:** Fans, liquid cooling systems, and overall power draw must increase to compensate for thermal inefficiencies.
- **Serviceability challenges:** Any issue with the server components, for any reason, often requires the detachment of the heat sink and removal and reapplication of the TIM, leading to downtime and increased labor costs.
- **Premature hardware degradation:** Cyclic heat stress natural to regular operation leads to accelerated wear on semiconductor packaging interfaces, reducing their lifespan and increasing replacement costs.

Durable TIMs are crucial to reliable power operations

Beyond compute nodes, the power infrastructure of a data center also faces significant thermal challenges. Power modules, such as Insulated Gate Bipolar Transistors (IGBT) power modules and other semiconductor devices within UPS (Uninterruptible Power Supply) systems and inverter-based power infrastructure, are subjected to extreme electrical and thermal loads.

These components must not only handle high-voltage switching and fast transients but also maintain consistent performance under fluctuating power demands—whether from critical backup power applications or the surging energy needs of AI-driven workloads. As data centers and industrial power systems push higher power densities and efficiency standards, these power modules must operate with exceptional reliability, enduring intense heat cycles and mechanical stresses without degradation.

Challenges of TIMs in power infrastructure:

Electrical and thermal cycling degradation: Liquid TIMs dry out or pump out over time, leading to increasing resistance and heat buildup.

Increased power losses: Poor heat transfer leads to inefficiencies in power conversion, causing additional stress on cooling systems.

Service disruptions: Maintenance and replacement of power modules become time-intensive and costly, especially when entire systems need to be taken offline for rework.

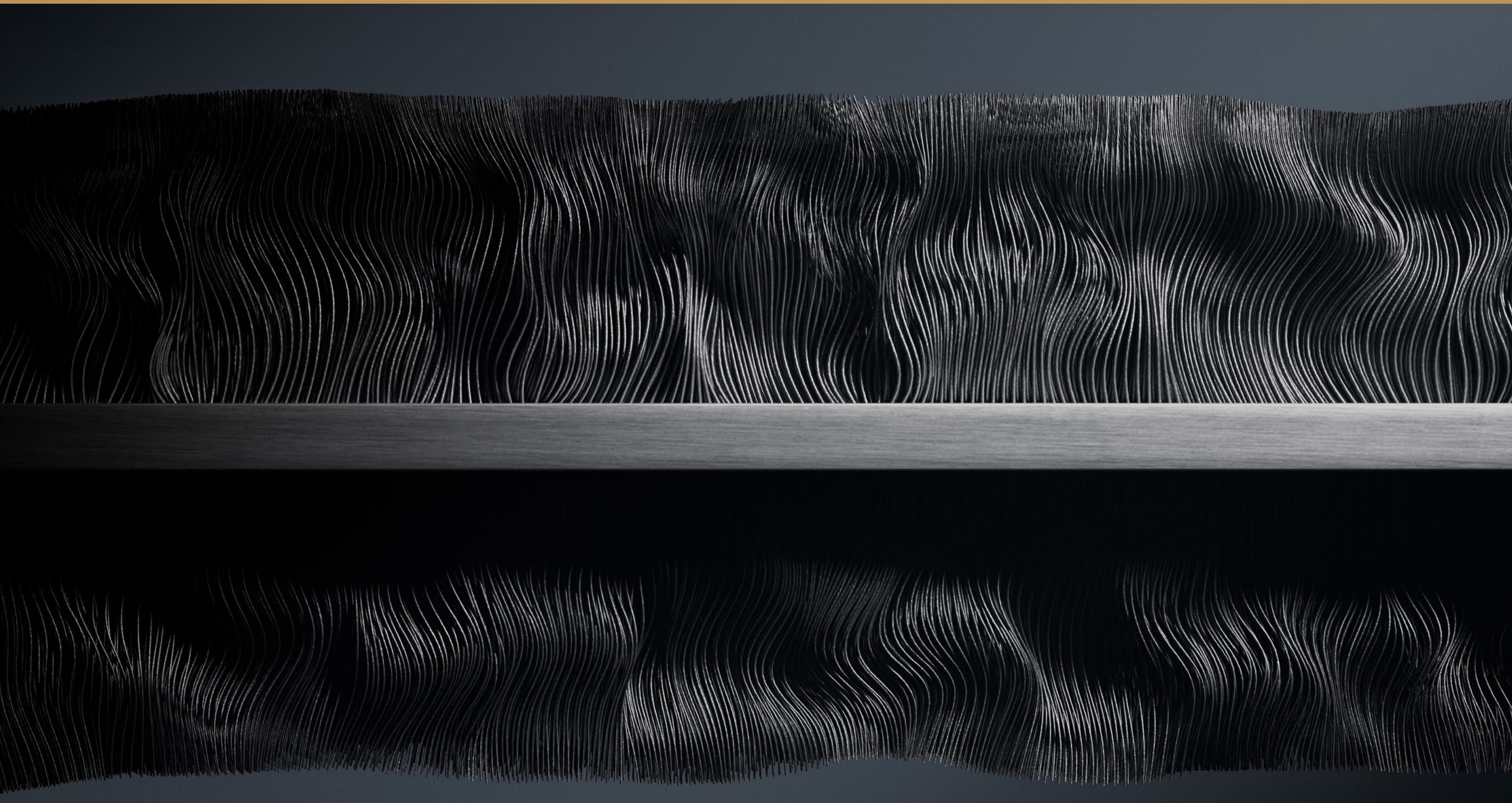
PART 2:

Maintaining high performance and reliability with Carbice

Carbice is revolutionizing thermal interface cooling with scalable, sustainable, and high-performance solutions designed to protect semiconductors and electrical components from heat stress in any environment. Unlike legacy TIMs that degrade over time, Carbice® Pads are built to last, ensuring consistent performance while reducing system costs and environmental impact.

At the core of the Carbice technology is a breakthrough use of vertically aligned carbon nanotubes (CNTs)—the most robust and conductive interface material available. Carbice® Pads feature a dense array of CNTs grown from waste carbon gas and bonded to both sides of a recycled aluminum substrate. These nanotubes behave like tiny flexible hairs, conforming to microscopic surface imperfections and filling voids much like a liquid TIM—***but with the durability and stability of a solid.***

FIGURE 4: Illustration of a Carbice® Pad highlighting the conductive aligned carbon nanotubes and aluminum substrate.



This structure creates ultra-efficient heat transfer highways that move heat away from high-power components such as CPUs, GPUs and other powerful electronics. The result? Superior thermal conductance, ultra-low resistance, and unmatched reliability over time, even in the harshest environments.

Designed for reliability, scalability, and ease of use
Unlike greases and phase-change materials that often degrade, dry out, or create air pockets leading to performance drops of 20-40%, Carbice® Pads remain stable and improve in performance over time. There is no degradation. They withstand thermal cycling, eliminating the need for frequent reapplications or costly maintenance.

Scalable manufacturing:
Carbice is the *only* TIM that can scale to hundreds of billions of square inches across industries without creating supply chain or environmental burdens.

Easy-to-apply:
Carbice® Pads come as cut-to-spec, assembly-ready sheets that can be applied by hand or integrated into automated production lines—no complex tools or messy reapplications required.

Reworkable and recyclable:
Carbice® Pads can be easily removed, reused, or recycled back into raw aluminum stock, reducing e-waste and lowering total cost of ownership.

By ensuring stable and efficient heat dissipation in both compute and power systems, across the entire product lifecycle, advanced TIM solutions like Carbice® Pads enable data centers to operate with greater efficiency, lower energy consumption, and reduced operational risk. Carbice's proven durability and consistent performance stand out when compared to traditional TIMs. This has been demonstrated in several recent customer qualification evaluations. A few examples to discuss here include two different server platforms and a high-performance power module used in Uninterruptible Power Supply (UPS) systems.

The first evaluation was conducted on a Dell PowerEdge G16 server—equipped with an Intel Xeon CPU—where a Carbice® Pad was tested against the stock thermal paste under power cycling conditions that simulate real-world operational loads. Carbice outperformed the server's stock thermal interface material, exhibiting lower thermal resistance and more uniform thermal contact. This results in better heat spreading and improved cooling reliability—critical in high-performance, high-uptime environments like data centers.

In a second evaluation using the Cisco UCS C240 M4 Rack Server—equipped with dual Intel Xeon CPUs—A Carbice® Pad was tested against the stock thermal paste under high-temperature thermal shock conditions. While the thermal paste began to degrade after just six thermal cycles, leading to increased thermal resistance and reduced cooling performance, Carbice remained stable, showing no degradation and maintaining reliable thermal conductance throughout the test—even under repeated, intense thermal shocks. Such shocks are becoming increasingly common in data center operations, driven by power constraints that force some computer nodes to stay off (cold) while others run overclocked (hot), creating abrupt transitions between these states.

In another test, Carbice was compared to the stock phase change material (PCM) on a high-power Infineon 62mm power module designed for UPS systems. The evaluation, which measured thermal resistance under application-typical vibration and thermal cycling between 20°C and 125°C, showed that Carbice outperformed the PCM by over 30%. This lower thermal resistance translates to more efficient heat dissipation, which improves power efficiency and enhances long-term reliability of the power module throughout the device's lifetime.

These findings reinforce the importance of long-term consistency in high-performance thermal solutions. As electronics increase in power density and thermal demand, traditional TIMs can't withstand the cycling, pressure, and thermal loads required. Carbice® Pads deliver sustained performance without pump-out, drying, or degradation—offering day-one reliability a truly high-performance solution over the lifespan of the system.

The ability to deliver consistent, long-term thermal performance is no longer a luxury—it is an operational necessity for modern data center sustainability and profitability because the cost of just one computing node failing is too high.

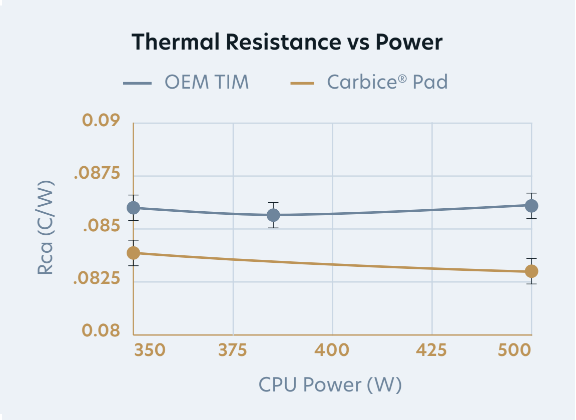


FIGURE 5: Improved thermal performance compared to stock TIM in in Dell PowerEdge G16 data center server.

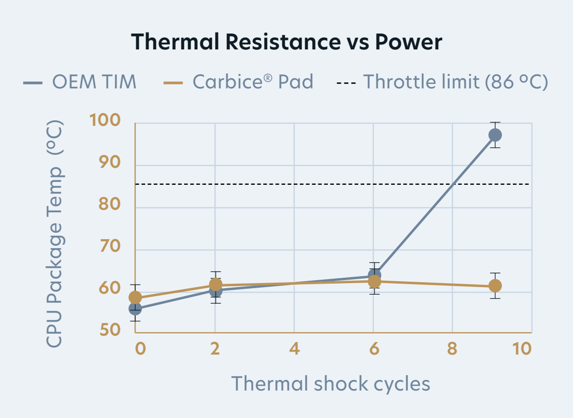


FIGURE 6: Proven reliability compared to the stock TIM on a Cisco UCS C240 M4 Rack Server—Carbice delivers long-term performance across server systems.

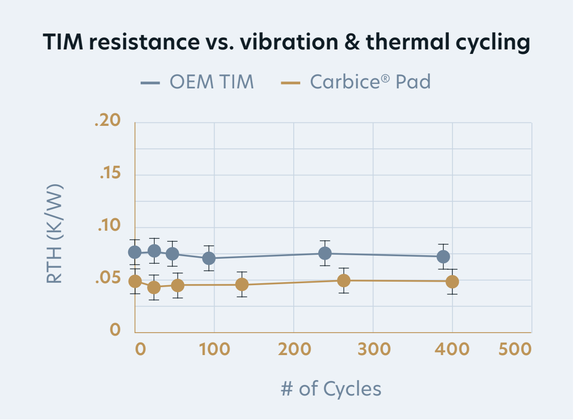
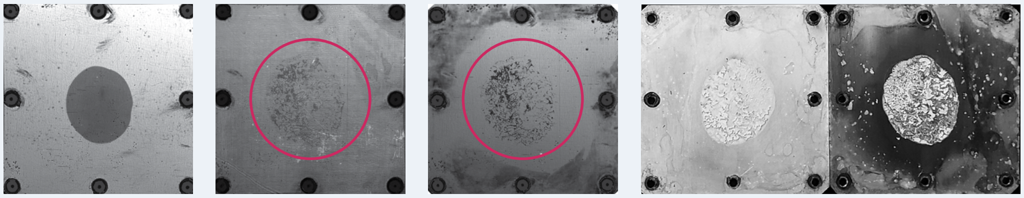


FIGURE 7: Outperformed the stock PCM by over 30% in thermal resistance during cycling (20°C–125°C) with vibration (50-70Hz) on a 62mm IGBT power module.

Carbice offers consistent performance

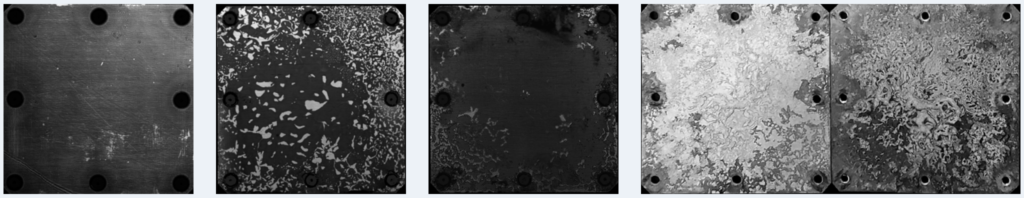
Carbice® Pads enable best-in-class thermal conductance that supports the increasing power densities of modern data centers. Unlike legacy TIMs that degrade with time and repeated thermal cycling, Carbice ensures stable performance for even the most powerful devices and difficult environmental conditions.

Grease


INITIAL INSTALL | 50 CYCLES | 2000 CYCLES | INSPECTION AFTER DISASSEMBLY

After only ~50 cycles, grease is completely dried out.

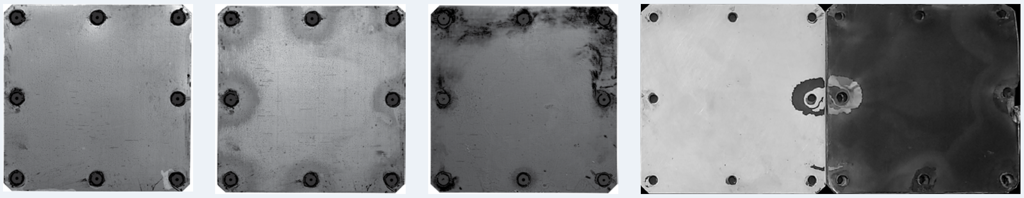
PCM


INITIAL INSTALL | 50 CYCLES | 2000 CYCLES | INSPECTION AFTER DISASSEMBLY

Air voids migrate around interface with PCM.

Carbice® Pad

150 MICRONS THICK


INITIAL INSTALL | 50 CYCLES | 2000 CYCLES | INSPECTION AFTER DISASSEMBLY

Carbice® Pad maintains consistent contact and performance.

FIGURE 8: 3rd party performance study, NREL. Carbice® Pad vs. Grease vs. PCM for accelerated lifetime testing via thermal cycling from -55 °C to 110 °C. The effect of the air voids in the PCM resulted in 16% increase in thermal resistance after just 50 cycles and 44% at 2000 cycles.

This applies not just to compute racks but also to UPS systems and other inverter-based power systems, where Carbice enhances reliability, reducing power infrastructure disruptions and unplanned downtime. Power modules in these systems are critical for maintaining continuous operation, and their reliability is directly impacted by thermal management. Carbice® Pads mitigate thermal stress, ensuring stable performance and extending the lifespan of key components in UPS and industrial inverters.

Carbice offers reliable performance

Traditional TIMs suffer from shear stress and compressive stress failures, leading to degraded heat transfer and component defects. Carbice® Pads eliminate these risks by:

- Withstanding mechanical stress from repeated power cycling
- Maintaining integrity under compressive loads
- Offering long-term durability without degradation

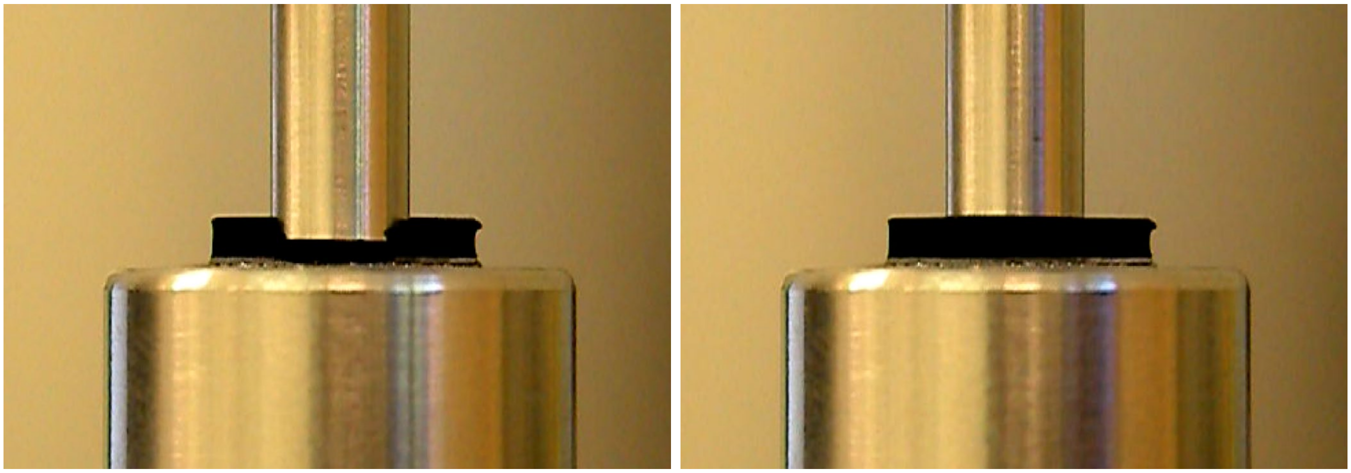


FIGURE 9: Mechanical stress test showing aligned carbon nanotubes are always elastic, predictable, resistant to tears and failures.[5]

Carbice® Pads are engineered to absorb mechanical stress while maintaining elasticity, ensuring long-term reliability for electronic devices. Unlike traditional TIMs that degrade under shear and compressive stress, Carbice remains stable and predictable under repeated power cycling and mechanical loads. Its highly compressible structure conforms to surfaces without tearing or failing, reducing the risk of thermal degradation over time. This elasticity not only enhances heat transfer efficiency but also protects components from mechanical damage caused by expansion, contraction, and vibration. By deploying Carbice, data centers and high-performance computing environments can extend equipment lifespan, minimize downtime, and maintain peak operational stability.

Reducing design time, assembly, maintenance and rework cost with Carbice

The unpredictability of traditional TIMs

Traditional thermal interface materials often come with specifications that fail to align with real-world performance, requiring extensive testing and optimization for each new deployment.

These challenges introduce major inefficiencies in both manufacturing and long-term operations, making TIM selection a critical factor in electronic device costs and reliability.

The true cost of TIM-related maintenance

Every time a heat sink is removed to enable servicing in the field, the TIM must be reapplied, adding both downtime and cost. This process is particularly complex when using thermal pastes or phase change materials, which often require specialized equipment and heating procedures to soften and remove the material. On average, this rework takes up to an hour per device.

Even after the removal process is complete, residual paste often remains on the heat sink, the device surface, and surrounding components. If not cleaned properly, leftover material can degrade performance upon reinstallation, leading to higher thermal resistance, reduced efficiency, and potential hardware damage.

Liquid-based TIMs like thermal pastes or PCMs commonly used in today's data centers and power electronics—require precise application methods to ensure proper thermal conductance. This involves:

- Complex stencil patterns that control paste thickness and volume
- Strict process tolerances to meet device-specific requirements
- Advanced monitoring and inspection to verify accurate application
- Additional costs for stencils, paste overages, and waste management
- Excessively large packaging and special shipping and storage to protect surfaces

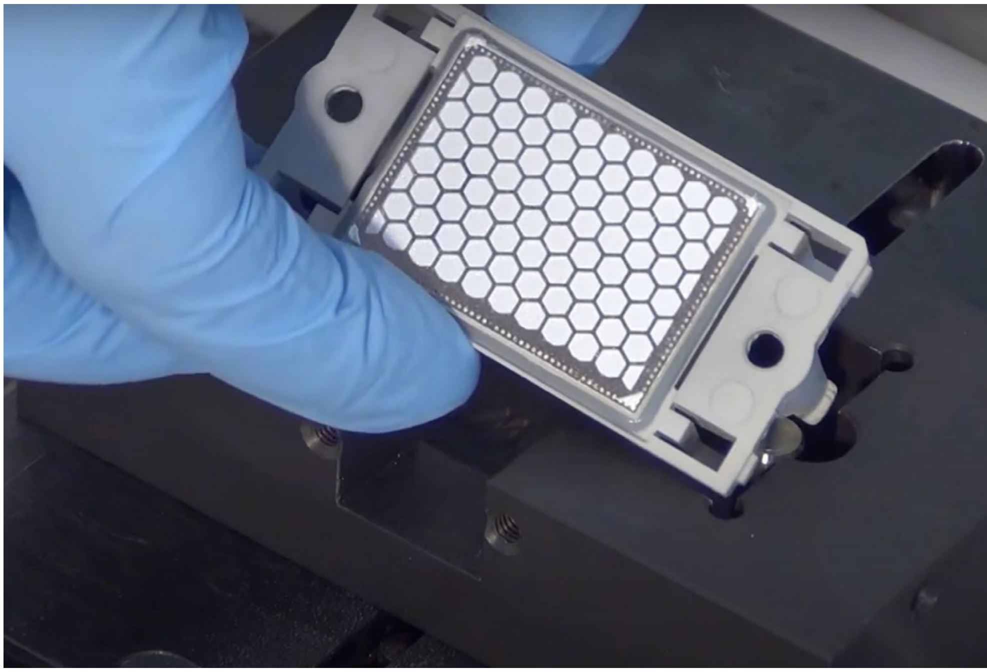


FIGURE 10: Stencil pattern for power module. Source: Vincotech[6]

The process is labor-intensive and requires specialized technicians with the right tools—usually only available at the manufacturing site. As a result, reworking components in the field is extremely difficult, often risking device performance. Operators face a tough choice: attempt reapplication and risk unpredictable performance, or remove entire boards or servers and send them out for repair. Over a data center's lifetime, these inefficiencies **accumulate into millions of dollars in unnecessary labor, damaged components, and underperforming systems.**

Carbice® Pads eliminate this costly cycle by providing a reliable thermal interface that remains effective throughout the lifetime of the device. By reducing the need for TIM reapplication, Carbice minimizes service disruptions, lowers long-term operational costs, and ensures sustained system performance and reduced maintenance.

High costs of rework and assembly

Liquid-based TIMs often introduce process variability in manufacturing, usually requiring 5-10% of units to be reworked due to application inconsistencies. If a heat sink must be removed for any reason, the labor-intensive reinstallation and validation process further **drive-up costs - $200-400 for each occurrence.** Beyond manufacturing, any component servicing that requires disassembly may also necessitate TIM replacement, adding extra costs and complexity. This challenge is further compounded by the supply chain process—TIM is typically applied by the heat sink provider before being shipped elsewhere for final system assembly. At this stage, proper labor skill sets are often lacking, making it difficult to re-stencil thermal

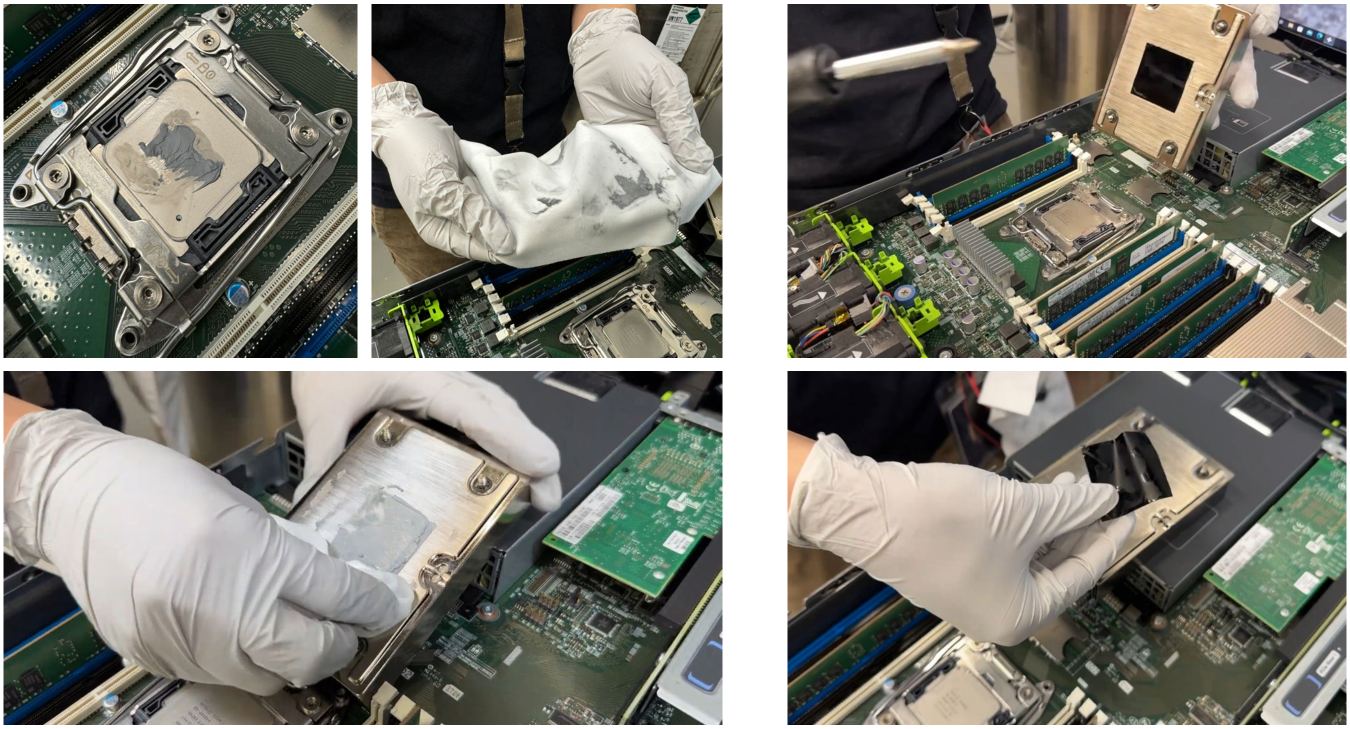


FIGURE 11: Messy thermal paste (left) vs. clean Carbice solution (right).

paste correctly, increasing the risk of performance issues and rework. Because this process is so messy, contamination of other components in the factory with the residue of the replaced liquid TIM is a substantial problem. Once contaminated with TIM residue, parts will sometimes have to be scrapped due to challenges with bonding or soldering to the stained surface.

Carbice® Pads solve these issues by providing a uniform, pre-engineered thermal interface that eliminates variability. Unlike liquid-based TIMs, which can degrade or pump out over time, Carbice remains stable, reducing the need for rework and ensuring every device meets performance expectations from the start. If a heat sink needs to be removed for any reason, Carbice detaches cleanly in seconds without residue, mess, or risk of damage—allowing the device to return to service with no loss in performance.

Carbice® Benefits:

- Enables quick, tool-free heat sink swaps without reapplication costs
- Reduces technician dependency, improving assembly consistency
- Lowers annual maintenance and service costs related to TIM degradation
- Simplifies removal and replacement, accelerating rework and repair processes
- Minimizes component waste, improving sustainability

Reducing waste and disposal costs with Carbice

The environmental cost of legacy TIMs

The transition to a 100% renewable energy grid requires more than just cleaner energy sources—it demands a shift toward operational efficiency and material sustainability. Legacy thermal interface materials, prone to thermal cycle and shock failures, accelerate component wear, leading to frequent replacements, increased waste, and higher operational costs. Data centers relying on these legacy materials generate massive amounts of electronic waste (e-waste), contributing to landfill accumulation and straining global recycling systems. Data centers are responsible for over 2 million tons of e-waste per year[7].

Carbice solves this problem by providing a durable, serviceable, and recyclable TIM solution that withstands elevated thermal cycling and shock, extending component lifespan while reducing downtime, waste, and energy consumption.

Green manufacturing & circular production

Carbice is redefining sustainability in thermal management. Manufactured through a low-energy, fully electrified process, Carbice® Pads use recycled aluminum and waste carbon gas in a circular production model. At end-of-life, they can be repurposed into high-value materials, further reducing the environmental footprint of electronics.

- Recycled aluminum and carbon waste gases are used to create high-performance Carbice products, turning industrial byproducts into cutting-edge thermal solutions.
- Carbice materials allow easy reuse and rework, enabling electronics to be disassembled and recycled cost-effectively rather than discarded.
- At the end of a device's life, Carbice products can be recovered and reprocessed into raw recycled aluminum stock and carbon source gas, or high-value composite fillers like carbon nanotubes and aluminum flake powders, closing the loop on material reuse.

By integrating sustainable manufacturing with long-term performance and recyclability, Carbice ensures that next-generation data centers and electronics operate with minimal environmental impact—aligning with global sustainability goals and the economics of a renewable-powered future.

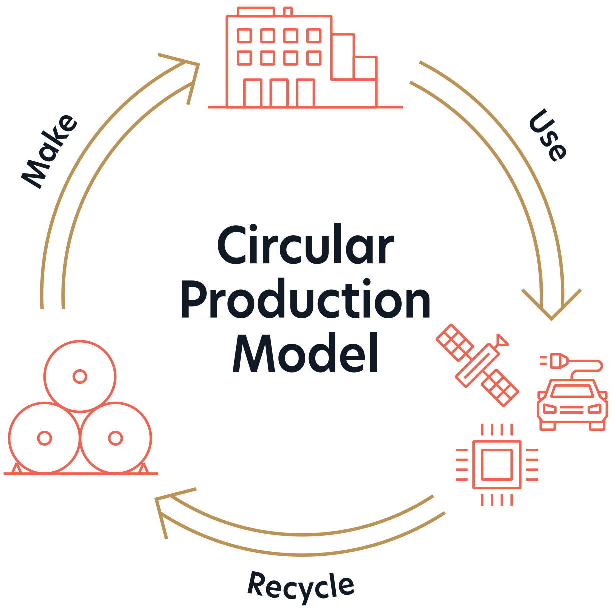
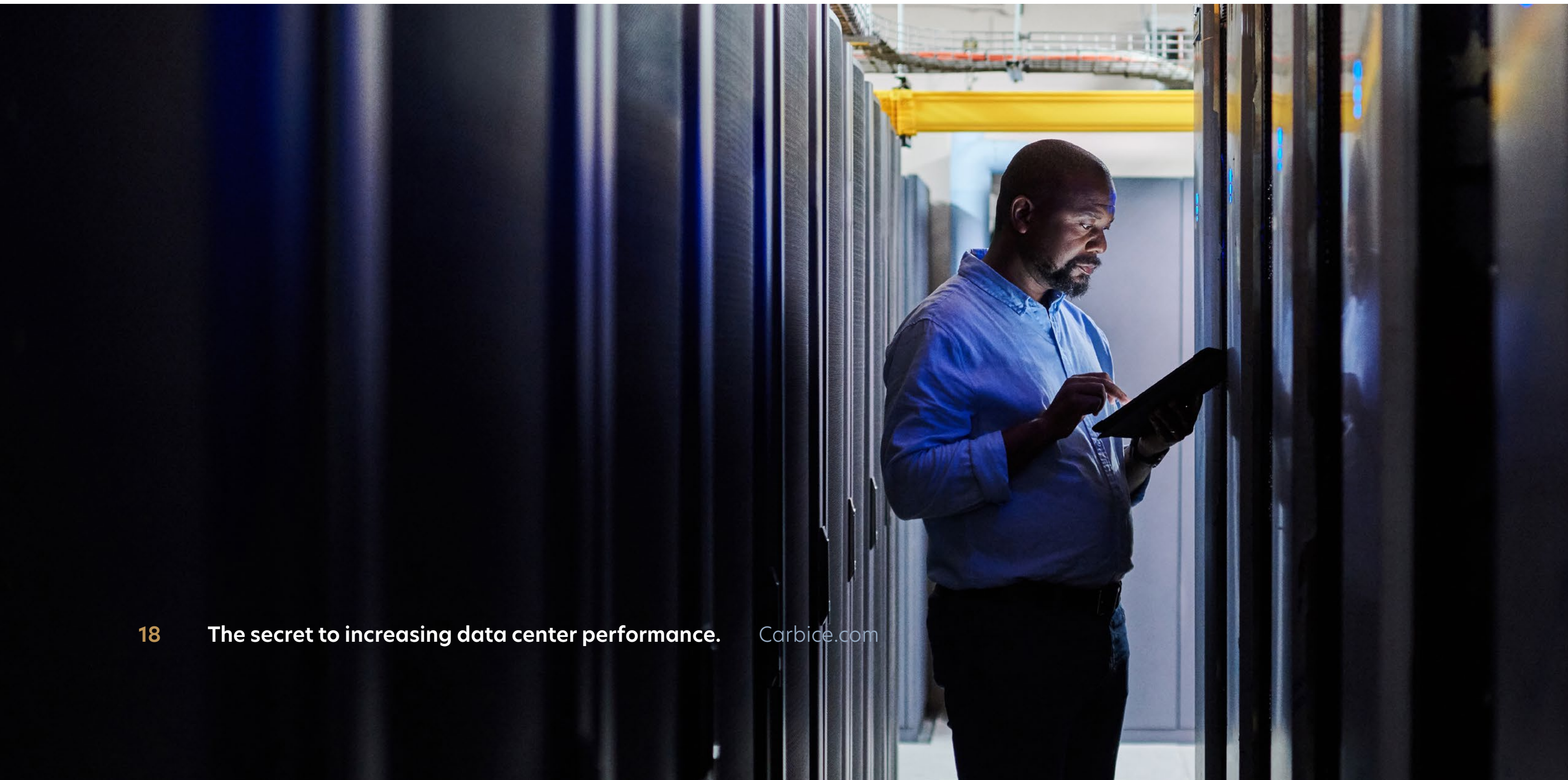


FIGURE 12: Carbice® Circular Production Model

Sustainability & energy savings with Carbice

Cooling systems account for **over 40% of data center electricity use[8], and TIM degradation leads to hotspots, inefficiencies, and increased energy demand.** Low-performance TIMs degrade within a year, forcing cooling systems to work harder and limiting operators' ability to optimize temperatures.



Carbice® Pads provide stable, predictable thermal performance that never degrades and can reduce cooling energy use by up to 30%—equivalent to cutting 90 million metric tons of CO_2 emissions globally. Carbice helps data centers run more efficiently by enabling reliable heat transfer for cooling systems, reducing power losses in distribution infrastructure, increasing compute power, and minimizing e-waste through longer lasting and more serviceable electronics. With **no maintenance, no reapplication, and no performance loss over time**, Carbice enables **more compute with less energy waste**, making it the most sustainable and scalable TIM solution for the future of data centers.

The true cost of sticking with legacy TIMs

Organizations that continue relying on outdated TIM solutions will face escalating costs, reduced system performance, and increased downtime. Thermal throttling will create bottlenecks in AI workloads, HPC environments, and next-generation computing. Additionally, poor serviceability and frequent rework will drive up the total cost of ownership, creating long-term financial and operational burdens.

A side-by-side comparison: Legacy TIMs vs. Carbice

Issue	Legacy TIMs	Carbice® Solution
Performance	Degrades over time, leading to throttling	Stable, long-term heat dissipation
Maintenance	Frequent rework, labor-intensive application	No rework needed, easy swaps
Serviceability	Risk of damaging components during removal	Clean, reusable interface
Sustainability	Wasteful, contributes to e-waste	Circular manufacturing, recyclable, indefinite shelf life

Continuing to rely on outdated TIMs can lead to significant financial losses for data centers. One analysis looking at data center infrastructure vulnerabilities estimates the average cost of data center downtime is approximately $5,600 per minute[9], with typical incidents lasting around 90 minutes, a single downtime event can cost over $500,000. In AI-focused data centers, the impact is even greater: just one TIM failure in a single GPU could bring down an entire server rack and affect the performance of every node involved in training.

Beyond the immediate costs, downtime also results in lost revenue. For enterprises whose revenue models depend on continuous data center operations—such as telecommunications service providers and e-commerce companies— the same analysis shows that the highest cost of a single event can exceed $1 million, averaging more than $11,000 per minute[9]. The lost revenue per event could be substantial.

Moreover, inefficient TIMs can lead to thermal throttling, reducing compute power by up to 30%. For data centers selling compute power, this reduction directly impacts revenue. Assuming a data center requires $100 million annually to achieve a 10% internal rate of return (IRR), a 30% reduction in compute power could result in a revenue loss of approximately $30 million per year[10]. Over a 15-year period, this amounts to a staggering $450 million in lost revenue.

While a low-performance TIM may appear low-cost at the point of purchase, its true impact is far more expensive when viewed across the entire data center ecosystem. From assembly complexity to performance inconsistencies and long-term reliability failures, the hidden costs accumulate quickly—especially at scale. In the example below, we examine the full lifecycle cost of a typical thermal paste for 50,000 AI servers (100,000 CPUs), quantifying the financial burden of overprovisioning for IT, rework, assembly defects, downtime and waste. This analysis reveals how conventional thermal materials silently drive-up operational expenses and risk, reinforcing the need for a more robust, engineered solution.

Hidden costs of paste: Product Lifecycle

Based on 100,000 AI CPUs. 50K servers.

	Overprovisioning for IT	Rework	Assembly	Downtime	Disposal & E-waste
Paste	**$21M**	**$2M**	**$38M**	**$5.6M**	**$153K**
Carbice					

Total Impact of Paste Per Year:

$66M+

**Based on 5% server failure rates in the first year. $250K per Ai server.*

FIGURE 13: Example Data Center Ecosystem Cost Impact of Thermal Paste on 50K AI servers.

This cost analysis highlights how reliance on legacy thermal interface materials extends far beyond simple material expenses—it compounds into significant financial and operational strain across the data center lifecycle. From increased failure rates to unsustainable maintenance demands, these hidden costs threaten long-term profitability and efficiency. Transitioning to a high-performance TIM solution is not just an upgrade—it's a strategic investment in reducing risk, enhancing uptime, and enabling sustainable, scalable infrastructure performance.

The Carbice® Advantage: Performance, reliability, and cost savings

Carbice sets a new standard in thermal management by delivering superior performance, unmatched reliability, and significant cost savings. Unlike traditional TIMs, which degrade over time and require costly rework, Carbice ensures long-term thermal stability while simplifying assembly and manufacturing. By reducing total cost impact by up to 80% compared to legacy solutions and cutting rework costs by up to 5X, Carbice provides a scalable, serviceable, and future-proof solution.

Here's how Carbice transforms thermal management:

- **Maximizes performance:** Stable thermal conductance enables AI, cloud computing, and HPC systems to run efficiently without throttling.
- **Ensures long-term reliability:** No degradation over time, reducing costly downtime.
- **Reduces assembly, rework and maintenance costs:** Unlike liquid-based TIMs, Carbice allows for simple Peel-and-Stick assembly and fast, tool-free heat sink swaps without reapplication.
- **Enhances energy efficiency:** Reduces operational costs while enabling high-density compute infrastructure to scale without thermal constraints.
- **Sustainable and recyclable:** Designed with a circular manufacturing approach, reducing material waste and environmental impact.

As industries push the limits of AI, HPC, and cloud computing, the demand for reliable thermal solutions has never been higher. Yet, legacy TIMs continue to fail under real-world conditions, creating an urgent need for a scalable, high-performance alternative. Enter the Carbice® Ecosystem—a solution designed for long-term reliability, operational efficiency, and environmental sustainability.

The Carbice® Ecosystem: A future-proof approach to thermal management

Unlike legacy TIM solutions, which force companies into rigid designs, Carbice fosters a collaborative ecosystem that delivers unmatched performance, reliability, and sustainability across the entire technology value chain – for a new era of design without painful business compromise. From OEMs streamlining their design cycles to data center operators reducing costs and sustainability leaders driving circular innovation, Carbice transforms the industry by providing a predictable, reusable, and high-performance TIM solution.

The future of AI and high-performance computing demands more than just better cooling—it requires a fundamental shift in how we manage thermal challenges. Sticking with legacy TIMs means increasing maintenance costs, frequent disruptions, and performance limitations. But with Carbice, companies gain a future-proof solution that:

- Delivers stable, high-performance thermal management for the lifespan of the device
- Reduces total cost of ownership through reliability and efficiency
- Minimizes environmental impact with a sustainable, recyclable design

Legacy thermal interface materials are holding back your customers' performance—and your reputation. Whether you're building for AI, high-performance computing, or next-gen power infrastructure, Carbice helps you deliver solutions that run cooler, last longer, and drive measurable value. Stay ahead of thermal challenges and future-proof your designs with Carbice.

Future-proof your hardware. Elevate your offering.

Visit Carbice.com to learn more.

APPENDIX A

Design and Process FMEA Risk Priority Score Comparison for Thermal Interface Solutions in Data Center Server Applications.

				RISK PRIORITY NUMBER (RPN)				
CATEGORY	FAILURE MODE	DRIVING MECHANISM	CURRENT DESIGN CONTROLS PREVENTION	CARBICE	PCM	ALIGNED GRAPHITE	METAL	LIQUID METAL
Design	Contact Stress Relaxation	Mechanical creep	Thermal cycling, vibration, shock, high temperature storage, elevated humidity	84	294	175	210	294
Design	Interface Fatigue	Thermal-Mechanical gradients, cycling	Thermal cycling, vibration, shock, high temperature storage, elevated humidity	63	392	105	210	343
Design	Grease Dry-out / Pump-out	Thermal cycling, viscosity changes	Thermal & mechanical cycling, vibration, shock, high temperature storage, elevated humidity	7	294	245	245	294
Design	Polymers Stiffening	Elevated temps, time	Data sheet review, high temperature storage	12	288	6	6	6
Process	Manufacturing Assembly Variance	Variance in dimensional tolerance	QA & visual inspection, final test	20	245	150	180	240
Process	Mechanical Damage During Rework	Stress concentrations from warped parts or misalignment	Visual inspection, rework procedure controls, functional testing	8	240	8	160	448
Process	TIM Cleanliness	Poor quality control, environment, contamination causes scrapped parts	Visual inspection, process controls and isolation, downstream process detection	24	216	54	54	96
Process	Vibration Contact Loss	Shipping/transportation, harsh environments	Shock, vibration, impact & drop testing	98	294	245	245	294
Design	Metallic Connector Corrosion	Vibration, humidity, temperature cycles	High temperature, elevated humidity, salt fog	9	180	18	180	216
Design	Delamination	Thermal-mechanical cycling	Thermal cycling, vibration, shock, high temperature storage, elevated humidity	42	126	56	56	56
Process	Improper TIM application	Different application methods	Visual inspection	12	144	120	120	168
Design	Electrostatic Discharge	Leakage, FOD	Data sheet review, dielectric materials, visual inspection and functional testing	64	120	64	192	240
Design	Thickness out of Range	Application-defined	Engineering process development	36	144	120	96	144
Design	Device Throttling	Insufficient variable or transient cooling	Initial system design, final test	72	72	72	72	96
Design	Bulk Temperature Overload	Insufficient steady state cooling	Initial system design, final test	84	63	84	63	84
			Design Average RPN Score	47	197	71	111	187
			Process Average RPN Score	32	228	115	152	249
				Design	4x Higher Risk	1.5x Higher Risk	2x Higher Risk	4x Higher Risk
				Process	7x Higher Risk	4x Higher Risk	5x Higher Risk	8x Higher Risk

RPN SCORE

🟥 High >250

🟨 Medium 150-250

🟩 Low 1-149

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