WHITE PAPER

Enhanced cooling technologies for superior reliability, performance

abaco
SYSTEMS

Enhanced cooling technologies for superior reliability, performance

Providing the most capable rugged COTS products for demanding environments

Current Trends for Military Computing

The latest generation of processors, GPUs, switch fabrics, and memory has placed more computing power into the hands of the designer. The improved performance has come with the challenge of higher power and higher power density for the designer to manage.

This white paper will discuss the thermal challenges, as well as explore the next generation thermal solutions available to maximize the performance for applications.

Sophisticated military and aerospace applications have an almost unquenchable thirst for processing performance. Beyond intelligence, surveillance and reconnaissance (ISR), expanding autonomous operations, onboard diagnostics, time-sensitive logistics, and landing of UASs are driving the amount of performance that can be configured and deployed. As the military drives towards network-centric operations, the ability to quickly share data, voice, and video with almost any DOD entity becomes increasingly important. Supporting these operations will require advanced computing performance embedded within an airborne environment.

These military computing needs are further complicated by the trend for commercial suppliers to provide more powerful electronics in a smaller, thinner profile package. In recent years, electronic components have significantly reduced in size at maintained or increased functionality. Advances in semiconductor miniaturization lithography, development of multi-core architectures, and next generation multi-capable devices have boosted computational and graphics performance capabilities, outpacing former generations of embedded computers.

The situation is exacerbated by the cramped, confined spaces in which increasing numbers of military/aerospace solutions are being deployed. These trends pose unique challenges for the COTS (commercial off-the-shelf) solutions provider.

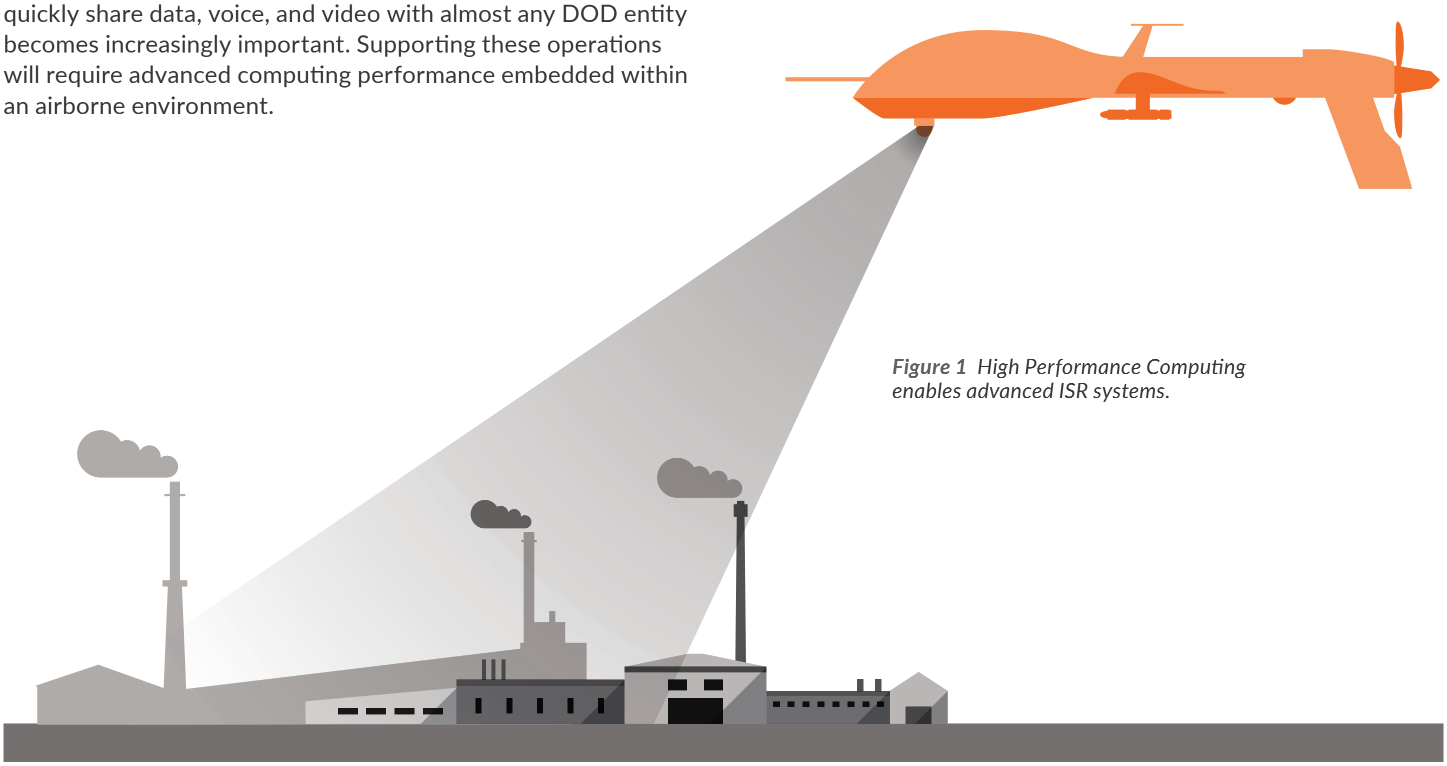


Figure 1 High Performance Computing enables advanced ISR systems.

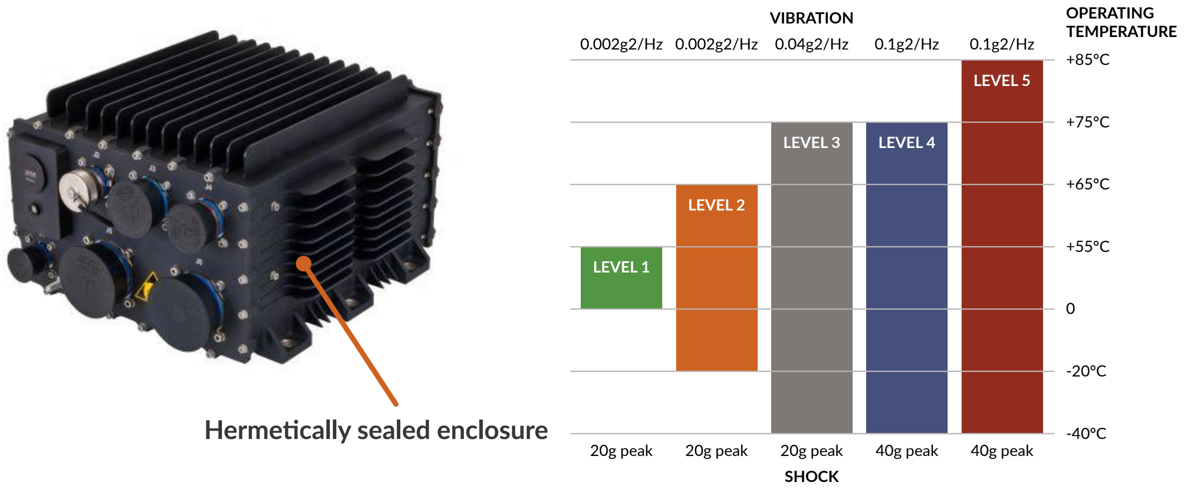


Figure 2 Abaco Systems ruggedization levels for circuit cards

As SWaP – size, weight and power – has come to be a dominant consideration in military and aerospace system design, performance/watt has superseded raw performance as a key indicator. Processor manufacturers have responded with lower power/lower heat dissipation technology – but this carries with it an understandable compromise in terms of performance.

A significant challenge becomes clear when analyzing the differences between consumer electronics and ruggedized military systems. Where consumer electronics applications are non-mission critical, operate in moderate environments and have an anticipated limited life of 5-10 years, military computing systems are the opposite of this in many ways. COTS ruggedized solutions for demanding environments – such as those developed by Abaco - often employ the same or similar components, but military systems operate in a much harsher environment than their consumer counterparts. Abaco Systems describes the qualification of ruggedized COTS products using a 5-level system (Figure 2). The five levels define various levels of vibration, shock and operating temperatures that can be experienced in mil/aero applications. At the harshest - level 5 - the card edge can reach 85°C with sustained 0.1g2/Hz vibration and 40g peak shocks. A rugged system containing these circuit cards can have an ambient of 71°C and vibration levels much higher than 0.1g2/Hz.

As an illustration, this can be described as taking a consumer electronics laptop, sealing the air vents with duct tape, placing it in an oven at 71°C, shaking the oven at sustained 0.1g2/Hz vibration and then dropping the oven on to concrete from four feet - and expecting the device to last for 20 years. This is the type of challenge a ruggedized military computer has to overcome.

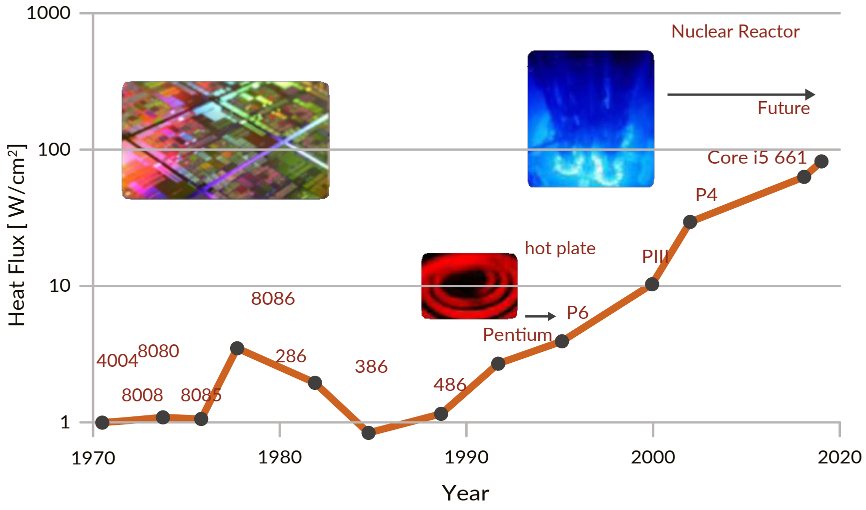


Figure 3 Heat flux for different processors [1]

Considering that, at the core, these systems might use similar COTS chips and electronics, there is a significant challenge in developing the mechanical and thermal designs to make these systems a reality.

The advances noted previously have meant that the heat dissipation per chip surface area (or heat flux) has increased significantly. Figure 3 illustrates this trend over recent years. It can be observed that current heat flux levels of 100 W/cm2 exceed heat fluxes of devices such as hot plates and are reaching heat fluxes similar to nuclear reactors.

Where hot plates and nuclear reactors are made of high temperature materials, typical semiconductor devices have well defined maximum operating temperatures, also referred to as maximum junction temperatures; these are typically in the 95°C-105°C range. Although many advanced semiconductor components have the capability to reduce performance if they exceed the recommended operational temperature, it is inefficient and wasteful to operate them at lower performance levels than those of which they are capable.

Advanced Thermal Management for COTS ruggedized computing systems

A typical rugged level 5 card with an edge temperature of 85°C, and the typical semiconductor junction limit in the 95°C-105°C range, allows between 10°C-20°C thermal budget to dissipate heat levels of 30-50W effectively from the die surface to the card edge. The efficiency of heat removal by the thermal management solution determines the final temperature of the die for a given power.

Advanced thermal management allows for a reduction in junction temperature or for the installation of more power chip architectures in ruggedized systems. Thermal management assists in two ways. By allowing chips to dissipate heat more efficiently, more powerful chips can be installed at the same power density; alternatively, if reliability is the primary customer requirement, a chip at the same power level can run at a lower operating temperature.

A chip that runs at reduced operating temperature has reduced leakage power loss and higher reliability as illustrated by Figure 4 and Figure 5 respectively.

Alternatively, if the customer desires, this would allow for the product to operate in extreme hot environments even exceeding the stringent level 5 85°C card edge (or 71°C system level ambient).

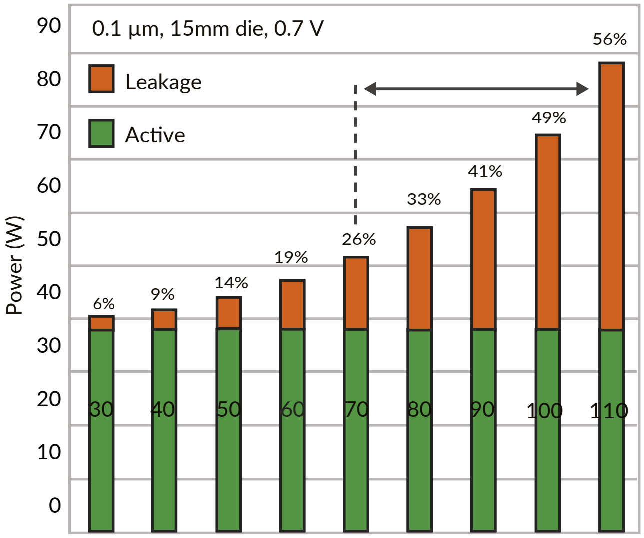


Figure 4 *Heat flux for different processors [2]*

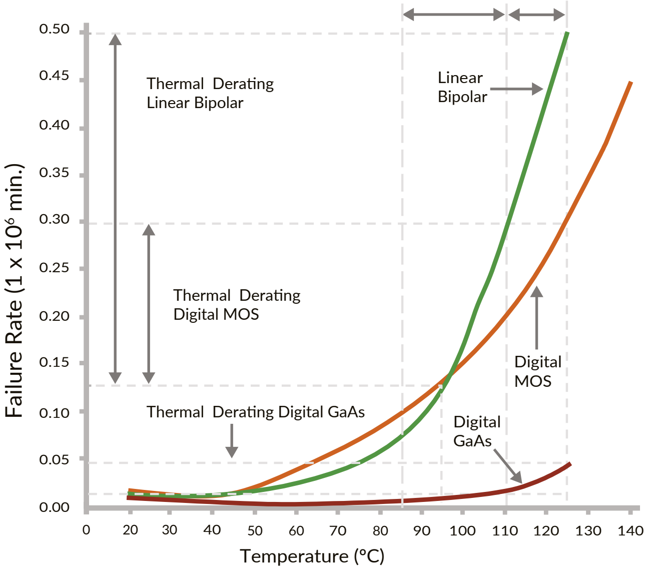


Figure 5 *Heat flux for different processors [3]*

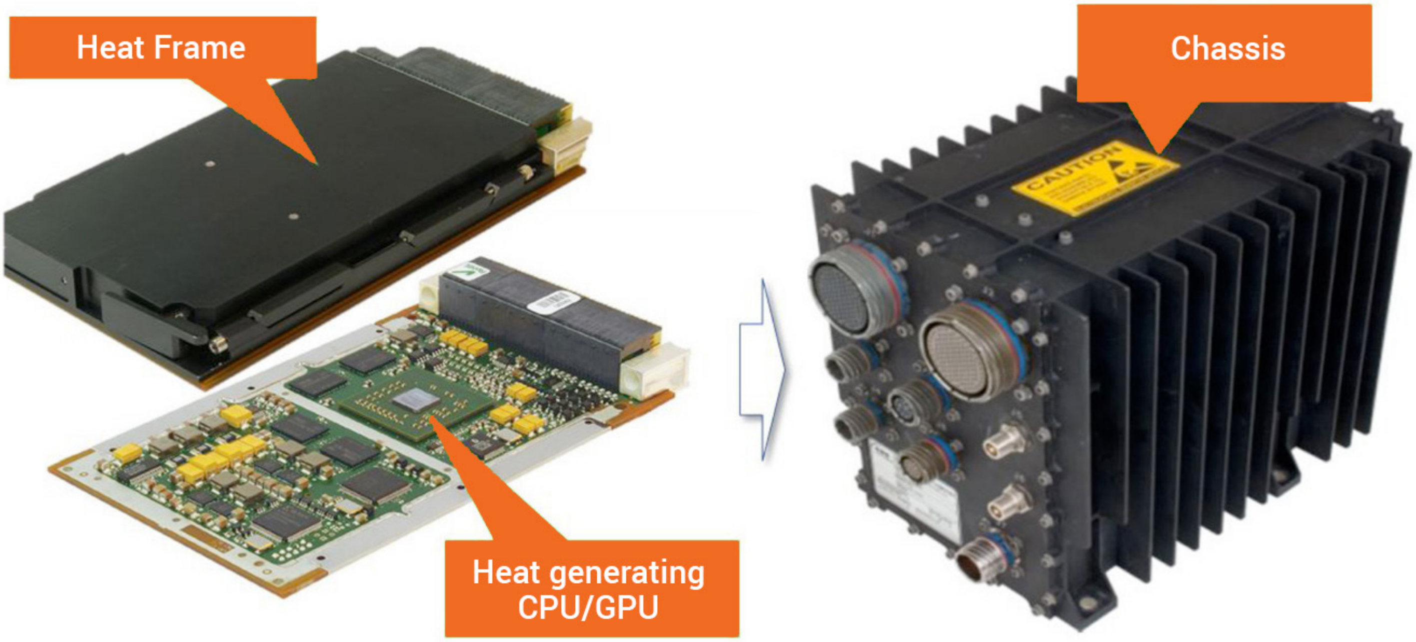


Figure 6 Components of a 3U ruggedized military computing system

The components of a typical military ruggedized solution include a series of computing cards with heat frames installed inside a chassis (Figure 6). The computing card can host a GPU, CPU or other component. The heat frame and wedge locks provide mechanical support to the card and serve to conduct heat from the heat- generating components to the chassis. Typically, multiple card assemblies are installed inside a ruggedized chassis to provide complex functionality in a ruggedized environment.

Characteristic heat transfer path for conduction cooled solution

Clearly, the benefits of advanced thermal management solutions are significant. Thermal management for advanced military computing systems impacts performance, reliability and power consumption.

The typical heat transfer path for a conduction-cooled high performance computing solution consists of three main elements as sketched in Figure 7.

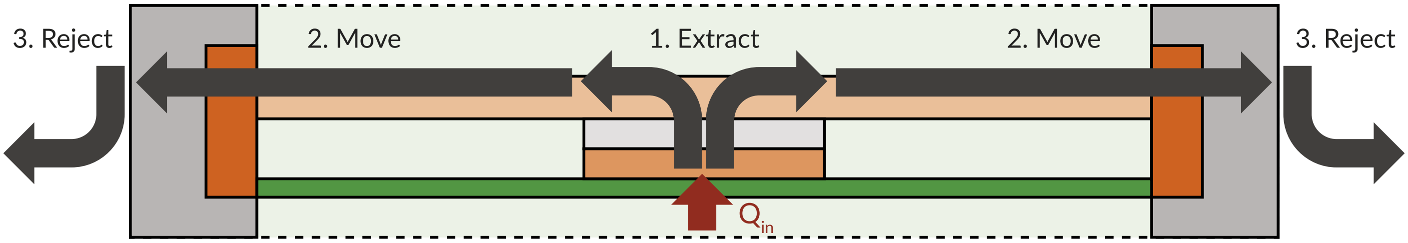


Figure 7 Overview of characteristic heat transfer path for typical ruggedized solution

1. Extract. Efficient heat connection between mechanical heat spreader and chip mounted on PCB, taking into account chip mounting and planarity tolerances while providing a high efficiency thermal connection. As heat fluxes are highest near the chip, the performance of this part of the thermal path has a significant impact on the thermal performance of the system. Note: some of the heat will move into the PCB and is a less efficient thermal path.

2. Move. Once in the heat spreader, heat is moved into the heatframe and conducted to the sides of the heatframe and to the card edges. At the card edge, heat is conducted through the heatframe-wedge lock interface into the chassis wall where the wedge lock serves as a mechanical retainer. The chassis wall spreads the heat to a number of fins on the exterior surface or to a customer-supplied cold wall.

3. Reject. At the exterior surface a coolant, typically air, removes the heat through forced or natural convection.

Abaco Systems and GE Global Research Center (GRC) Development of Next Generation Thermal Management Solutions

Through its participation in Defense Advanced Research Program Agency (DARPA) projects, Abaco Systems, in collaboration with the GE Global Research Center (GRC), (Abaco was spun out of GE in 2015) has established itself as a leader in developing innovative heat dissipation technologies.

GE is known as a strategic differentiator on DARPA programs due to the successful migration of thermal technologies from the lab to operational environments. Examples of DARPA programs include Thermal Ground Plane (TGP) and Nano Thermal Interface (NTI).

In addition to the DARPA program developments, internal GE-funded programs, such as Thermal Management Technology Bridge and Dual Cool Jets (DCJ), have been deployed in overall best in-class performance systems. These technologies have been either transferred or licensed to Abaco Systems.

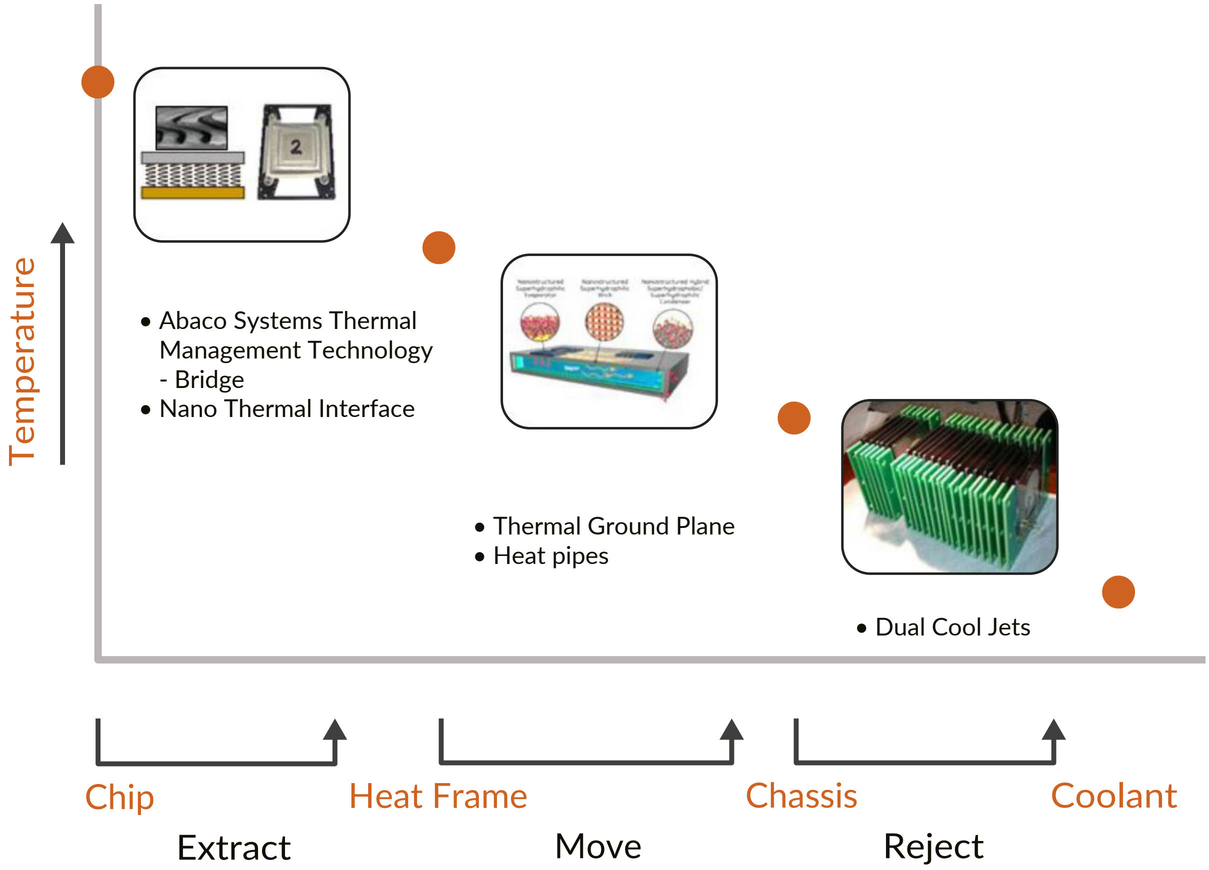


Figure 8 Advanced thermal technologies overview

Nano Thermal Interface (NTI)

The objective of the Nano Thermal Interface program was to develop a thermal interface material (TIM) with a 10x improvement in thermal resistance over state of the art interface materials. The ultimate goals of the 3-phase program were to achieve less than 0.01 cm2-C/W thermal resistance, enable reworkability and assembly processing at less than 240°C, and stable life with >1,000 hours at 130°C and more than 100 temperature cycles from –40°C to 150°C.

The NTI provides a compliant interface, capable of filling micro-gaps in the surface, between coefficient of expansion mismatched materials such as a silicon chip and a copper heat sink while an efficient low thermal resistance connection is made between the two surfaces.

Traditional compliant materials such as polymers and silicone have low thermal conductivity, while high thermal conductivity materials such as copper, silver or solders have low compliance - making this a significant challenge.

NTI introduces an innovative new interface by utilizing a high thermal conductivity material such as copper that is tailored in a precise compliant shape of a nano spring (Figure 9).

This compliant thermal interface material allows for thin solder bondlines using a compliant structure within the bondline to achieve a thermal resistance of less than 0.01 cm2C/W. The structure uses an array of copper nanosprings sandwiched between two plates of materials to match the thermal expansion of their respective interface materials (ex. silicon and copper). Thin solder bondlines between these mating surfaces and the high thermal conductivity of the nanospring layer results in a thermal resistance of less than 0.01 cm2C/W, exceeding DARPA’s requirement. The compliance of the nanospring layer (Figure 10) is two orders of magnitude more compliant than the solder layers, so thermal stresses are carried by the nanosprings rather than the solder layers. The nanospring wires are three times stronger than bulk copper. The TRL (technology readiness level) and MRL (manufacturing readiness level) of this approach is at level 4.

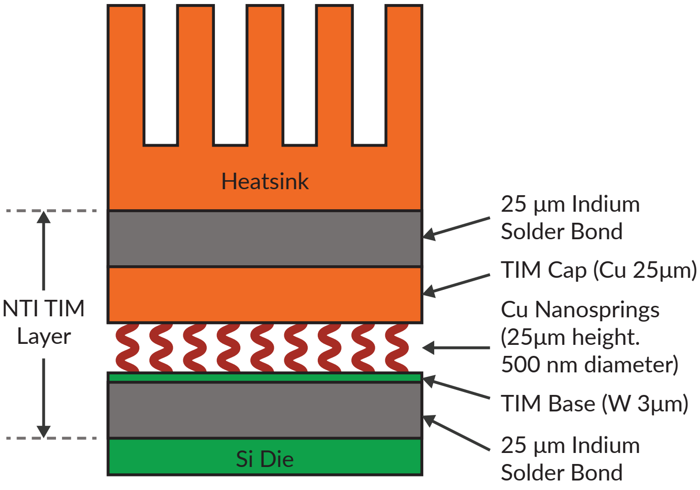


Figure 9 NTI concept illustration

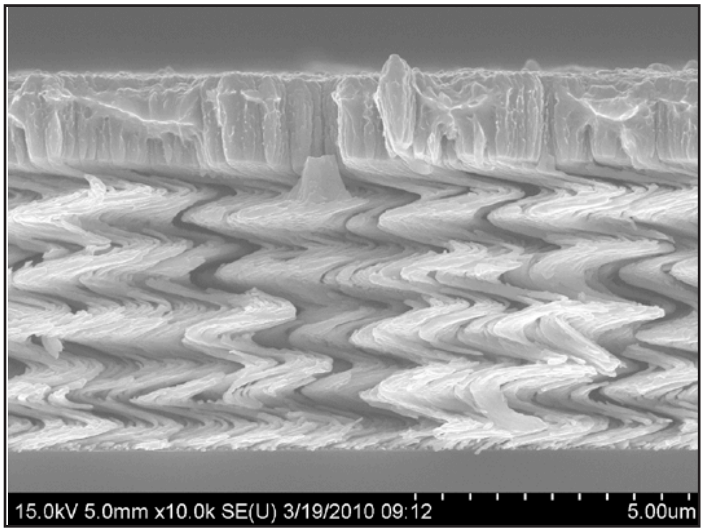


Figure 10 SEM image of copper nanospring structure

Abaco's Thermal Management Technology Bridge

For demanding conduction-cooled applications, today's state of the art solutions utilize a metallic heat frame that is attached to one or more high power processors using a stack-up of thermal interface materials, including grease on the device surface (TIM1), and metallic heatspreaders and gap pads (TIM2). Such a configuration is cumbersome to assemble and introduces alignment constraints during PCB-heatsink assembly. By using traditional gap pads, stress on the die can potentially crack solder balls and die if variation in assembly is not controlled.

Abaco Systems' Thermal Management Technology Bridge addresses these shortcomings by providing a 'perfect' passage for heat to transfer from the underlying electronic device – typically, a CPU – to the heatsink, and on out through the subsystem chassis. Figures 11 and 12 depict the Thermal Management Technology Bridge thermal solution.

Thermal Management Technology Bridge is a 2mm thick self-contained cartridge that can be attached in seconds to a heat sink during the manufacturing process. The cartridge contains a flexible membrane which encloses a low melting point solder. The flexible membrane also incorporates a high performance heat spreader with a metallic spring providing pressure to directly interface to the device to be cooled. The Thermal Management Technology Bridge is mounted to the underside of the heatspreader in a preassembled "frozen" state where the spring is compressed and contained inside the low melting point solder in a solid state. After assembly, the system is taken through a short moderate temperature excursion, melting the low melting point solder and allowing for the spring to align the internal heat spreader flush to the die surface. When the low melting point solder spreads, the space behind the flexible membrane is filled, thereby creating a perfect bond between the two surfaces that allows the efficient transfer of heat. This results in the Thermal Management Technology Bridge achieving its "engaged" state as depicted in Figure 12.

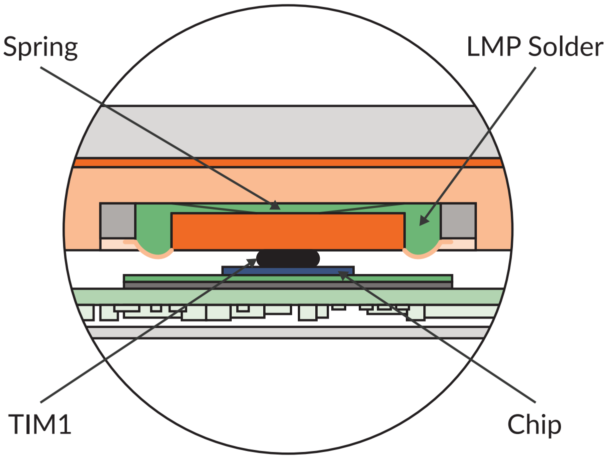


Figure 11 Thermal Management Technology Bridge in "frozen" configuration

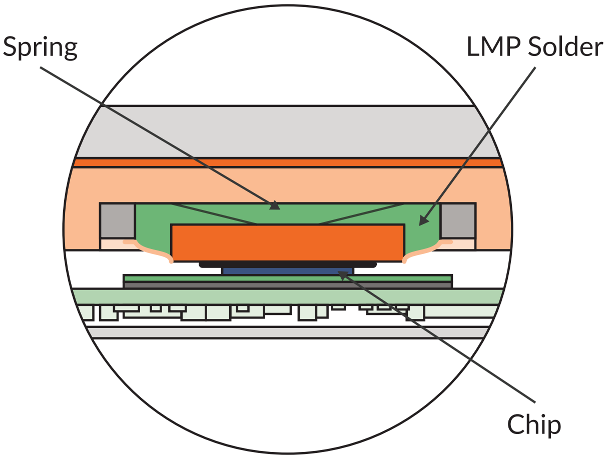


Figure 12 Thermal Management Technology Bridge in "engaged" configuration

Figure 13 Thermal Management Technology Bridge cartridge assembly prototype

Abaco Systems' Thermal Management Technology Bridge resolves the issue of cumbersome assembly in three ways. Firstly, the entire thermal interface material stack (TIM1, heatspreader and TIM2) is incorporated within a single bridge cartridge. Secondly, the bridge cartridge is pre-assembled on the heatsink surface in the precise location of the processor. This eliminates the potential for alignment errors. Finally, given the 'self-adjusting' nature of the bridge cartridge, die height and non-planarity measurements are not required. In addition, contact pressure to the die can be precisely controlled. As a result, costly and time-consuming metrology and alignment steps can be entirely eliminated during the PCB –heatsink assembly process.

Like many of the most brilliant inventions, Abaco Systems' Thermal Management Technology Bridge is characterized by its simplicity. It is flexible enough to be easily deployed across a range of devices and platforms – yet it is truly a "one size fits all" solution, without compromise. Whatever the application, the optimum heat path between device and heat sink is created, regardless of imperfections in the surfaces to be joined. The result is more efficient cooling of the device – creating the ability for systems designers to specify higher performance devices than would otherwise be possible.

Thermal Ground Plane

Abaco Systems' Thermal Ground Plane (TGP) greatly enhances heat dissipation capability and supports more complex computing operation in a rugged environment.

In most current rugged computing systems, heat spreading is achieved through solid conduction using either aluminum- or copper-based heat frames. While these readily available heat frames can adequately address the heat dissipation need of existing systems, the thermal resistance of these heat frames is limiting the next generation of rugged computing systems. Abaco Systems, in collaboration with GRC, DARPA, Air Force Research Laboratory (Dayton, Ohio), and the University of Cincinnati, has developed TGP-based heat spreader technology that replaces aluminum- or copper-based heat frames and offers better than 2x the potential for heat dissipation and performance enhancement than is possible with current systems.

TGP technology achieves effective high thermal conductivity performance by utilizing two-phase heat transfer rather than the solid conduction of aluminum- or copper heat frames. Shown in Figure 14, the inside of the TGP is partially filled with a working fluid under saturation conditions. As heat enters the TGP, the liquid evaporates, creating a local increase in vapor pressure. The vapor then travels inside the device to lower temperature regions where it condenses. In the heat rejection area the vapor releases heat to an outside cold wall through condensation. The condensed working fluid flows back to the hot section due to the capillary forces induced by the micro/nano-engineered internal surface of the TGP casing. This heat transfer cycle continues as heat sources continue to generate heat and vaporize the working fluid.

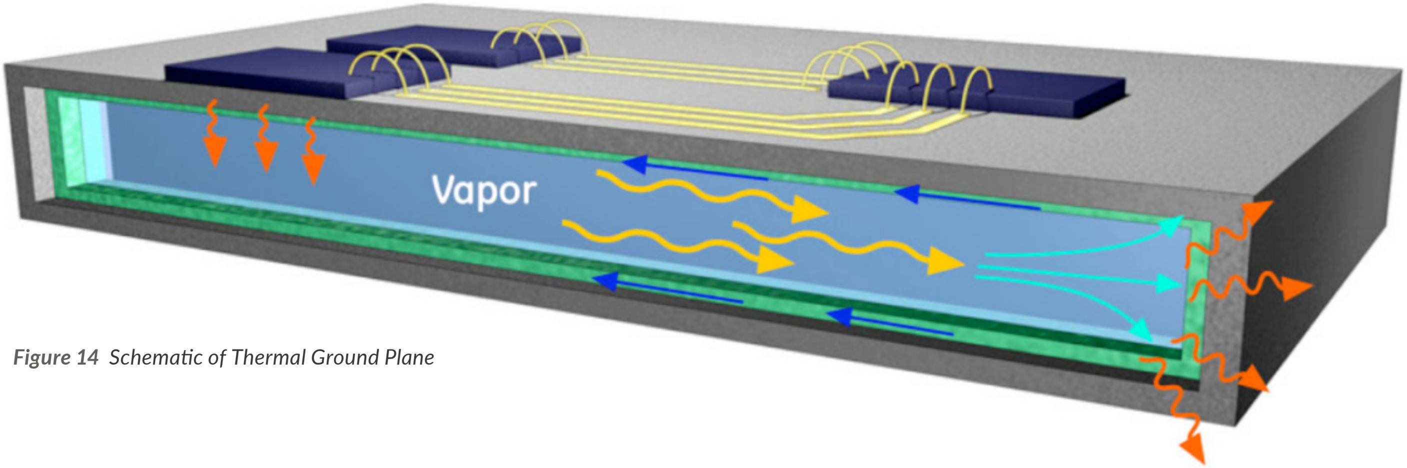


Figure 14 Schematic of Thermal Ground Plane

GRC has demonstrated TGP heat spreaders capable of:

- >50x the solid thermal conductivity of copper
- Ideal matching of the coefficient of thermal expansion with the semiconductor materials used in the heat sources
- Operation at >10 g continuous acceleration

Through the application of TGP-based heat spreader technology, GRC demonstrated significant enhancement (Figure 15) in the Abaco Systems MAGIC1, a 3U VPX compact rugged computer that combines state of the art CPU technology with the latest graphics processing unit technology to deliver unprecedented levels of performance for rugged applications.

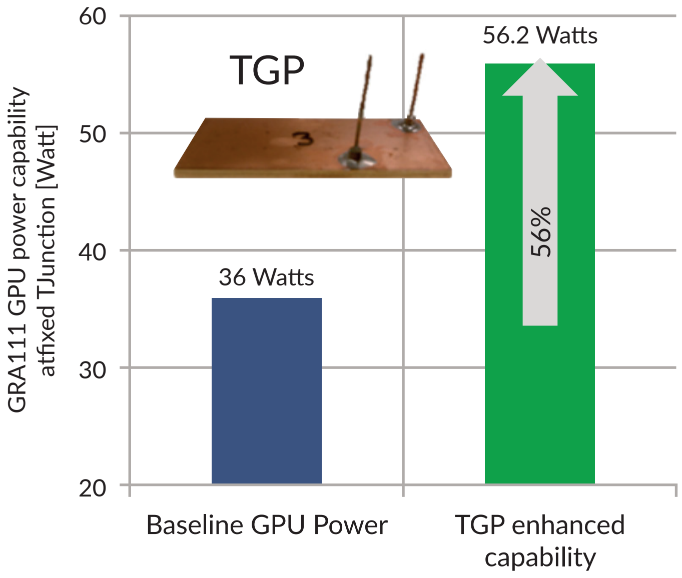


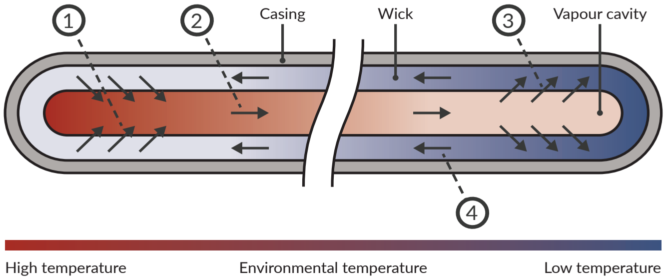
Figure 15 TGP performance demonstration result

Heat pipes

Adding a mezzanine card to a SBC card is a significant thermal challenge. Not only do XMC or PMC cards add heat load, but they also reduce the effective heatframe cross section needed to spread heat from the processor to the card edges (Figure 17). Abaco Systems has qualified heat pipe technology utilized inside heatframes of processor cards which also carry mezzanine cards. These heat pipes meet rugged military environments. A 2.5x thermal improvement has been demonstrated when compared to a solid copper heatframe. This allows for processors to run at maximum capability and/or a reduction in operating temperature to increase reliability.

Heat pipes have been around for decades and are used in aerospace and space applications. They are highly reliable, and can work during acceleration loads when designed correctly and/or oriented in certain configurations. The principles of heat pipes are similar to the Thermal Ground Plane described earlier, except they are in the shape of a tube (Figure 16). Heat pipes are used to move heat from a surface with a heat load to another cool surface to reject the heat. Their ability to move heat is dependent on a number of variables such as diameter, length, wicking structure, path, and bonding. GRC has helped size heat pipes for Abaco Systems applications, ensuring the optimum solution is used.

Heat pipe principle (source: internet)



Heat pipe thermal cycle

1. Working Fluid evaporates to vapour absorbing thermal energy
2. Vapour migrates along cavity to lower temperature end
3. Vapour condenses back to fluid and is absorbed by the wick, releasing thermal energy
4. Working fluid flows back to higher temperature end

Figure 16 Heat pipes used in boards and systems

Abaco Systems has the option of using heat pipes inside chassis walls to move heat from hot areas to areas that are cooler. This allows for the chasses to run at a reduced temperature and ultimately the internally mounted cards can either be allowed to run hotter or it can allow for the outside ambient of the chassis to be increased. The use of heat pipes in a system is truly a SWaP improvement since more processing can be done in a smaller volume, or power input can be reduced to give the same performance.

Dual Cool Jets

As heat is moved to the chassis wall more effectively by the aforementioned advanced thermal management technologies, a significant challenge remains in effectively removing heat from the exterior surface of the chassis. As reliable performance in a ruggedized environment is a key requirement for a military computing system, convection options are limited. Use of fans for air movement is typically not desired since limited life components such as bearings are used. Natural air convection cooling provides a challenging thermal barrier as hot air can envelope a chassis surface and, in a way, insulate the chassis from connecting thermally with cool air surrounding the envelope.

Developed initially for airfoil fluidics and cooling of LED lighting solutions, Dual Piezo Cooling Jet (DCJ) technology provides an efficient and effective cooling technology that has demonstrated reliable operation in harsh environments (Figure 18). The DCJ is a piezoelectric micro fluidic device that does not require a bearings or lubricant system, making it well suited for an environment that may contain sand or dust.

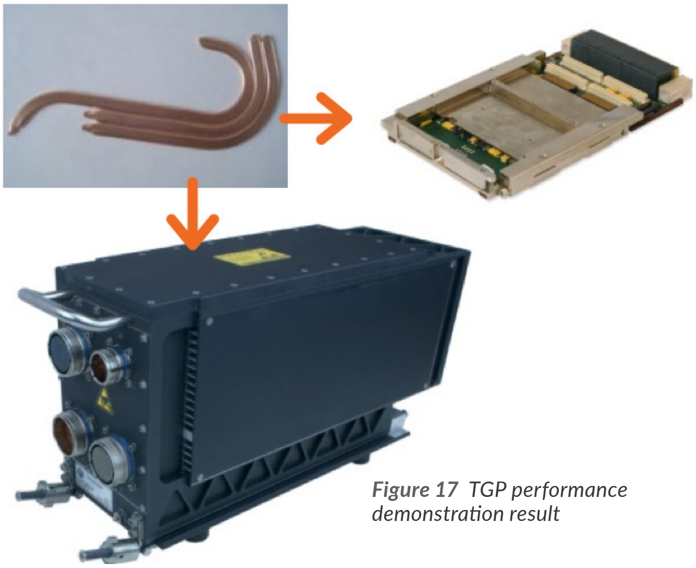


Figure 17 TGP performance demonstration result

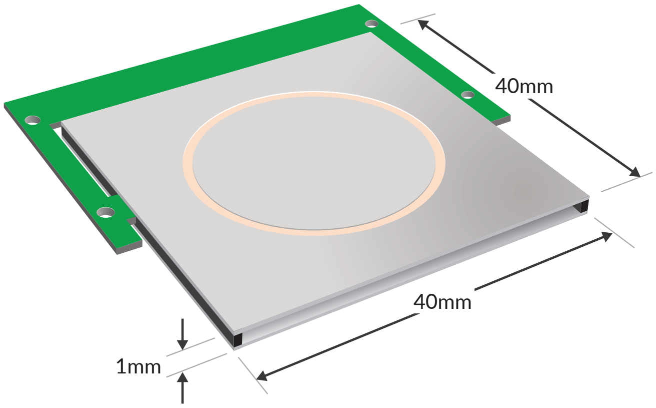
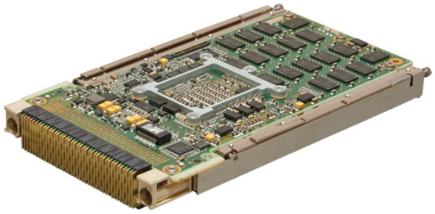


Figure 18 DCJ microfluidic device

The SBC347D benefits from Abaco's advanced cooling expertise.



In many cases, advanced cooling is required in deployments in which excessive heat – either due to an extremely constrained physical location or challenging operating environments, or a combination of both – must be eliminated in order to prevent processor failure and mission jeopardy.

For this reason, Intel processors are specifically designed to automatically de-rate their performance in response to rising ambient temperatures. Inevitably, however, this has a negative impact on application performance – an impact that is not always tolerable in, for example, applications that rely on real-time determinism.

The Abaco SBC347D 3U VPX single board computer, however, is designed to eliminate this performance degradation: uniquely in the embedded computing industry, it can maintain 100% of its specified operating frequency at temperatures as high as 75°C.

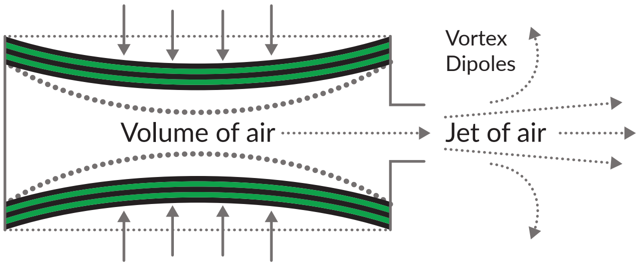
It benefits from a combination of Abaco's traditional solution for removing/spreading heat with a reliable space grade technology to move heat through the heat frame with a low temperature drop while maintaining 500V electrical isolation.

This means that not only is the SBC347D able to perform at maximum speed in higher temperatures, but also it is a light weight solution compared to traditional solid metal heat sinks- improving its SWaP characteristics.

The front side of a DCJ is open for air ingestion and expulsion. The DCJ operates by application of a 100-175Hz AC voltage to the piezo elements, exciting a resonance mode of the system. The low frequency range of operation of the device results in low acoustic A-weighted noise output of 25-35dBa depending on mode of operation. As both piezo elements experience the same mirrored bellowing resonance shape, fluid is expelled at high velocity during the out stroke and ingested into the device on the intake stroke as illustrated by Figure 19.

Integration of six of these devices, on ruggedized mil/aero chassis, has demonstrated convection enhancement in excess of 3.4X as illustrated by IR measurement images in Figure 20 and Figure 21.

a. Compression/Expulsion



b. Expansion/Ingestion

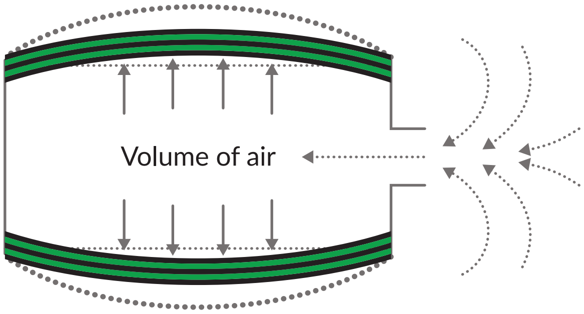


Figure 19 DCJ Operation

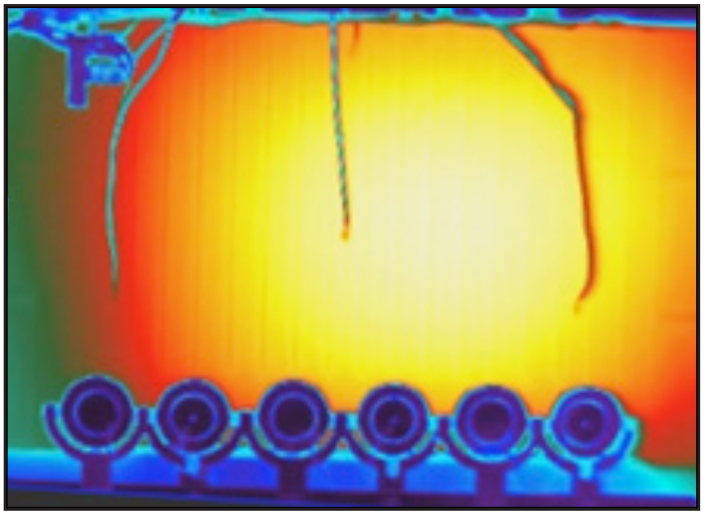


Figure 20 Chassis heated, DCJs in "off" configuration avg temp. rise 46°C

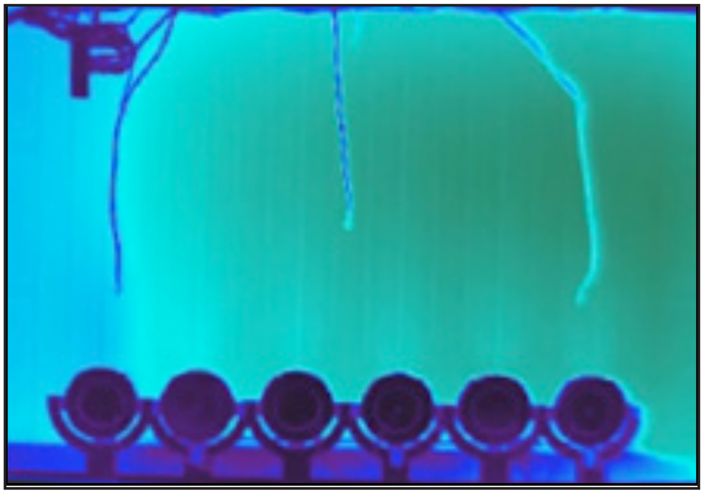


Figure 21 Chassis heated, DCJs in "on" configuration avg temp. rise 17°C

Summary

Abaco Systems has long been an acknowledged leader in the development of truly rugged COTS solutions. The new cooling technologies described above will allow Abaco Systems to extend that leadership, bringing with them the ability to dissipate significantly more heat than has previously been possible, permitting more capable processors to be used, or existing processors to be deployed at higher clock speeds.

In recent years, military/aerospace systems performance has been constrained by the limited ability to provide cooling in confined, space-restricted (and weight-restricted) environments. Abaco Systems' advanced thermal technologies promise to allow the creation of a new high performance embedded computing (HPEC) paradigm for military/aerospace organizations, setting the stage for inclusion of higher performance processors than has historically been possible.

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