THERMAL MANAGEMENT OF HARSH-ENVIRONMENT ELECTRONICS

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1. Introduction

As the trend of highly integrated electronics and simultaneous miniaturization escalates to include faster processors, more functions, and higher bandwidths, electronics continue to become more compact in response to size limitations and strict reliability requirements. The result is an increasing heat flux at both the component and circuit board levels. In the last decade, average power densities and heat dissipation rates have increased nearly two-fold [1]. It is expected that heat flux levels in excess of 100W/cm^2 for commercial electronics and over 1000W/cm^2 for selected military high power electronics will soon become a realistic and immediate challenge to overcome. There is also a growing demand for more sophisticated and capable electronics used in harsh environment applications such as those found in defense, automotive and oil exploration systems. Thermal management of harsh environment electronics is vital to the successful design, manufacture, and tactical operation of a variety of electronic systems to meet the high temperature, environmental, reliability, and cost effectiveness requirements.

This paper will look into fundamental characteristics and thermal management challenges for practical harsh environment electronics and will overview the most widely known, as well as emerging technology solutions for such applications. Future thermal management of harsh environment electronics at the chip, board and system levels will be also discussed. The paper concludes with a ranking of the potential applicability of these techniques according to several criteria, including cost, ease of use, thermal performance, and reliability concludes the paper.

2. Problem Statement

The main factor that distinguishes harsh environment electronics from commercial electronics is the environment in which they perform. Harsh-environment microelectronics operate at temperatures well above the traditional maximum allowable operating temperatures of 70°C for consumer electronics, as in Table 1.

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Table 1: Thermal operating environments

Electronics	Operating Temperature
Consumer	0 °C to +70 °C
Industry	-40 °C to +85 °C
Automotive	-40 °C to +125 °C
Military	-55 °C to +125 °C

The three main harsh environment electronics categories are: military electronics including land-based, shipboard, airborne, missile-based, and space-based applications; automotive; and oil exploration systems. Some applications in each of these categories in actuality require performance at even more extreme temperatures, ranging down to -65°C and lower for avionics in cold climates, and up to 225°C for avionics distributed control systems. For the drilling of well holes of 2 km or higher in length, temperatures often reach 200°C, with pressures up to 20,000psi. Under-the-hood temperatures in a car can be as low as -40°C in some areas of the world such as Alaska and above 200°C in other areas of the world such as Death Valley in the United States. Figure 1 shows typical automotive under-hood temperatures [2].

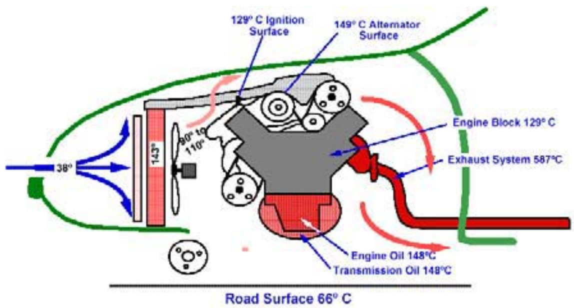


Figure 1: Typical automotive under-hood temperatures

The electronics products in vehicles, especially under-hood components, operate in a very harsh environment, including petroleum vapors, random vibration (up to 10G on engine), moisture, various fluids, dirt, and chemicals. High reliability and durability are simultaneously required, as the automotive manufacturers are offering extended warranties to consumers for 100,000 miles/10 years or even more. Added to these requirements is the fact that automotive applications are extremely cost sensitive and therefore require low cost targets referred to as the "convergence of automotive electronics and consumer electronics." In addition to the traditional engine management, comfort, and entertainment systems of the past, there is a growing market for office and entertainment systems that rival those in an office or home. Furthermore, more efficient thermal management is needed for increased power requirements that have made the automotive suppliers turn to 42 V sources.

In military environments, operating conditions are extremely harsh: the hardware must maintain reliability and ability in severe conditions, including thermal and mechanical shock vibration, cycling, humidity, corrosive, chemical/biological, and radiation degradation, and altitude changes [3]. Military electronics are required to have a functional lifetime of 20 to 30 years, more than that of rapidly obsolete consumer electronics, which have an average service life of less than 5 years. For example, missiles are required to be stored for 10 to 20 years in any location in the world and still meet safety and reliability requirements. Avionics must undergo severe changes in temperature, humidity, acceleration, and atmospheric pressure (altitude) within very short periods of time. Some military electronics require survivability when exposed to nuclear attack.

For more than three decades, military electronics have been governed by performance-based specifications. They are typically in the upper cost, high reliability, and high-density range, and only a small portion of the electronics industry in relationship to consumer electronics. Furthermore, the weight and volume occupied by cooling devices and hardware become even greater constraints in military electronics than in conventional applications. Since the electronics industry has been gradually shifting away from the production of military grade electronic parts, mainly due to high costs and very low volume production, the use of commercial off-the-shelf (COTS) electronic components, which have lower maximum temperature ratings than MIL-SPEC devices, has become more frequent, offering major benefits in the areas of supply and cost. The gradual shift in industry towards all COTS parts, the increasing chip-level temperatures, and the higher circuit density of next generation electronics, together with the need for high reliability and long life cycles of all the parts and materials, has introduced new challenges for harsh-environment applications. With miniaturization, the greatest dissipation requirement for high energy military lasers and MEMS devices is expected to be on the order of 100 W/cm^2 for high performance microprocessors and 1 kW/cm^2 for high power electronics components with a smaller allowable temperature difference (Figure 2). The heat flux associated with laser diodes is on the order of several kW/cm^2, comparable to the heat flux associated with ballistic missile entry.

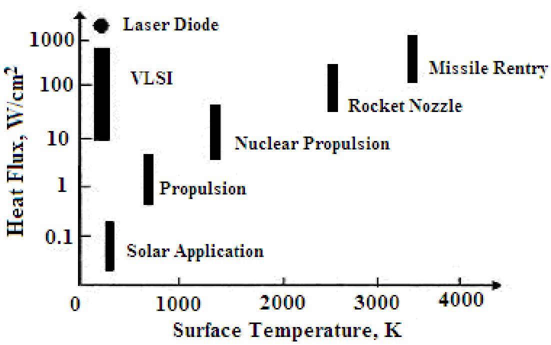


Figure 2: Heat dissipation for various events

Therefore, thermal management is now becoming increasingly critical to the design of harsh environment electronics to satisfy the increasing market demand for faster, smaller, lighter, cheaper and more reliable products. More aggressive thermal management techniques are required to handle the high heat loads on the all-electric military systems, which are expected to increase by several fold compared to existing electronic technologies [4]. In this paper an overview of the current thermal management technologies, as well as emerging solutions will be offered, with additional details available in Ohadi et al [4].

3. Overview of thermal management for harsh environment electronics

In a typical electronics system, heat removal from the chip may require the use of several heat transfer mechanisms to transport heat to the coolant or the surrounding environment. There are three basic heat transfer modes (including phase change): conduction, convection, and radiation.

Thermal management techniques can be characterized as passive, active, or a combination of the two (hybrid). The passive techniques, absence of external power, are relatively reliable and simple to implement. However, they are performance-limited for many high power applications. The main passive thermal management techniques are:

- *Conduction* (metal spreader, interface materials, adhesives, pads, pastes, epoxy bond)
- *Natural convection* (finned heat sinks, ventilation slots, liquid immersion cooling)
- *Radiation* (paints, coatings, mechanical surface treatments)
- *Phase change* (phase change materials, heat pipes, thermosyphons, vapor phase chambers)

Active thermal management techniques, requiring input power, provide increased performance/capacity, but also reduced reliability and added complexity. The essential active techniques include:

- *Forced convection* (fans, nozzles)
- *Pumped loops* (heat exchangers, cold plates, jet/spray)
- *Refrigerators & coolers* (vapor-compression, vortex, thermoacoustic, thermoelectric/Peltier)

Figure 3 shows the values of thermal resistance for a variety of coolants and heat transfer mechanisms with a typical component wetted area of 10 cm^2 [5]. Thermal resistances vary from 100K/W for natural air convection to 33K/W for forced air convection, to 1K/W in FC forced liquid convection, and to less than 0.5K/W for boiling in FC liquids.

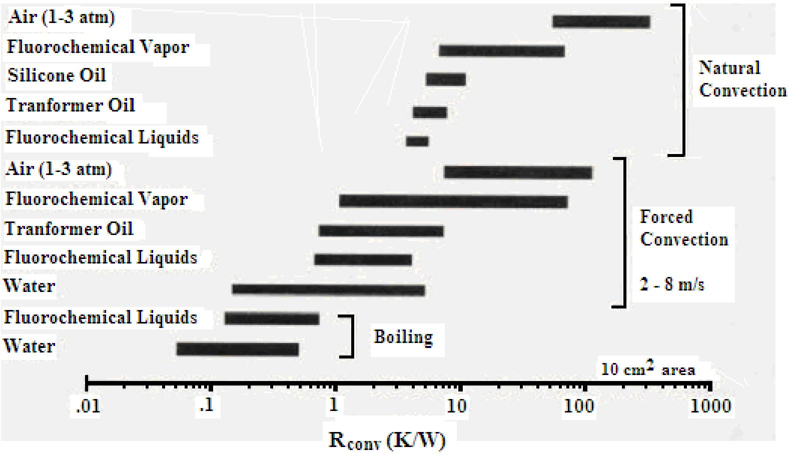


Figure 3: Typical thermal resistances for various thermal management modes.

Although the primary thermal transport mechanisms and the commonly used heat removal techniques vary substantially from one packaging level to the next, in general, heat removal can be addressed hierarchically. The first level of the hierarchy is at the chip package (IC) level where heat conducts from the chip or component to the package surfaces through interface materials and is then rejected from the outer surfaces (heat sink and the board) into ambient air (Figure 4).

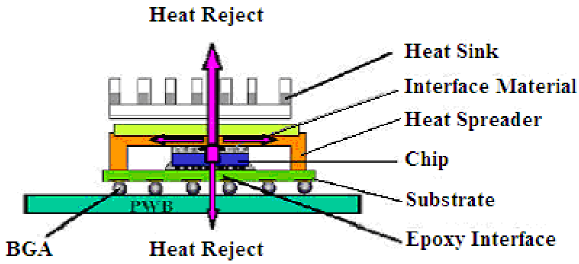


Figure 4: Schematic of thermal packaging architecture

Reduction of thermal resistance between the die and the outer surface is the most effective way to lower the chip temperature. A variety of passive techniques are available to reduce the interface thermal resistance, such as using die-attach adhesives with diamond, silver, or other highly conductive material, or thermal greases, thermal epoxies, and phase change materials (PCMs). Successful thermal management requires the development of a Thermal Interface Material (TIM) that connects the die and heat sink. Alternatively, attaching metal-plate heat spreaders to the chip while using thermally-enhanced molding compounds, embedded heat slugs or heat pipes for printing wiring board (PWB) and lead frame packages can improve heat spreading effectiveness by one order of magnitude. The Integrated Heat Transfer Spreader (IHS) is a good example of this option (Figure 4), which is used in the packaging for Pentium® 4 processors as integrated heat pipe lids in the Itanium™ processor.

Heat sinks are commonly attached to the surface of the spreader to provide additional surface area for heat removal by convection. The convection may be natural air convection or forced air convection via a fan or duct. For very high power applications, it may be necessary to cool the chip directly with a heat pipe attachment, high-speed air jets, a direct heat sink attachment (cold plate), or dielectric liquid immersion.

The second level is at the board, which provides the means for chip-to-chip communication with the backplane or motherboard to interconnect PWBs where heat removal typically occurs (through conduction in PWBs and convection to the ambient air). Use of PWBs with thick, high conductivity power and ground planes that include insulated metal substrates and/or embedded heat pipes provides improved thermal spreading at this level of packaging. Heat sinks are often attached to the back surface of PWBs. In systems designed for very harsh environments, e.g., avionics systems, the convective air-cooling is limited due to low gravity and air density at high altitudes. Instead, heat is transported to the edge of the PWB via conduction and removed by a cold plate or a heat exchanger attached at this edge (Figure 5), where wedge locks are used to ensure complete contact and efficient conducting. “System on a chip” or “computer on a chip” heat sinks, or finned surfaces protruding into the air, can be applied at the first and second levels to directly dissipate heat into ambient air.

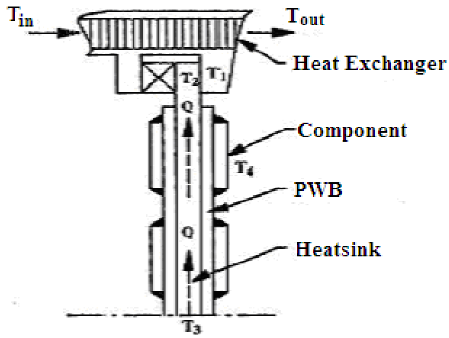


Figure 5: Heat transfer path to the cold wall of heat exchanger [6]

The third level is the system level, such as the box, rack, or cabinet, which provides the anticipated operating environment for the electronic device. An air-cooled chassis, shown in Figure 6, with modular integrated racks (MIR) to accommodate a complement of Line Replaceable Modules (LRMs), is suitable for shallow avionics. The thermal-mechanical interface to the LRMs is provided by removable, air/liquid cooled rack heat exchangers (top and bottom). Heat dissipated by the LRMs is conducted into each heat exchanger and is removed by coolant that is supplied from the aircraft's environmental control system (ECS). The coolant circulates through the MIR. The rack heat exchangers contain an internal serpentine channel that the coolant passes through [7]. Offset fins [8] or pin fins [9] are attached between the walls of the channel to provide structural integrity and enhance thermal performance.

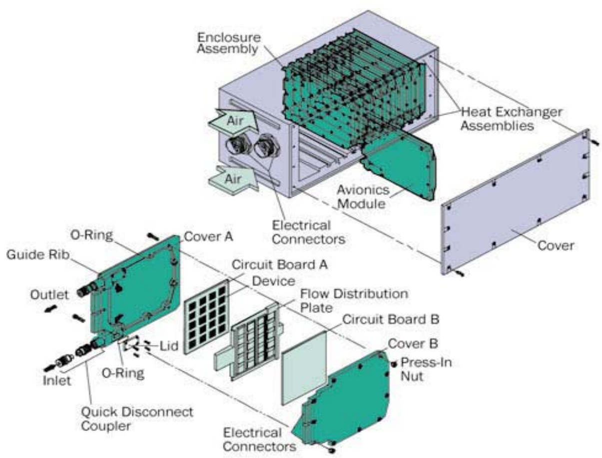


Figure 6: Air-cooled chassis system [6]

When the third level exists, thermal packaging generally involves the application of active thermal management techniques, such as air handling systems, refrigeration systems, or heat pipes, heat exchangers, and pumps. Routine fan cooling will still be maintained among the next generation electronic cooling solutions due to its simplicity and cost-effectiveness.

However, rapidly increasing heat flux, low junction temperatures and high ambient temperatures, and concerns over volume, weight, cost, and acoustic noise are limiting the successful application of fan cooling, particularly in harsh environment electronic systems. Therefore, the cooling resolutions will be focused on performance optimization for a particular application (system package level) and in some cases integrated into the electronics themselves (chip package level) to meet the junction temperature and power dissipation requirements. Enhanced air-cooled heat sinks, direct liquid cooling, phase change cooling, and refrigeration, along with design for manufacturability, sustainability and availability, can be expected to play pivotal roles in future electronic systems. In the following section more specific thermal management methodologies for selected harsh environment electronics are discussed.

3.1 AUTOMOTIVE ELECTRONICS

Currently, most of the thermal management solutions used in automotive applications rely on a combination of passive cooling such as conduction, and active air/liquid cooling. Most designs use conduction to transport heat from electronic components to the surface of the electronic enclosure and natural and/or existing convection to dissipate this heat into the ambient air. Figure 7 shows a typical automotive cooling system that works by moving coolant (water plus antifreeze) through the engine, and moving that heated coolant through the radiator, where its heat is transferred to the surrounding air.

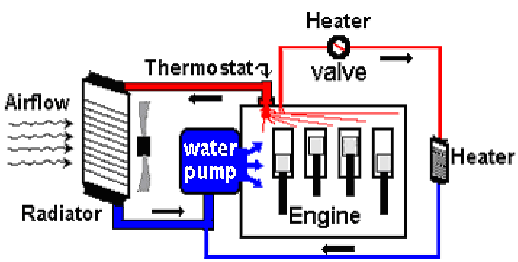


Figure 7: Typical automotive cooling system

The engine cooling system keeps the engine at its most efficient temperature at all speeds and operating conditions. It consists of a radiator, radiator pressure cap, coolant recovery tank, hoses, thermostat, water pump, fan and fan belt. The water pump sucks cooled coolant from the radiator and pushes it into the engine. The coolant flows through the engine, absorbing the engine's heat. The thermostat is an automatic valve to control the coolant circulation to keep the engine at a normal operating temperature. It closes when engine is cold and opens when engine is hot. If the thermostat is open, coolant flows into the radiator for cooling. At low speeds, airflow is maintained by the fan, and at high speeds, it is maintained by the relative velocity of the vehicle in relation to the outside air.

As more automotive mechanical functions are converted to electronic and electrical functions, and as recently introduced hybrid vehicles (which use internal combustion engines in conjunction with electric drive motors) and emerging fuel cell based electric vehicles (which use electric motors alone without internal combustion engines) become more common, these vehicles will use high power motor controls and drive electronics that will likely dissipate kilowatts of thermal energy. A thermal power dissipation summary for many current and future automotive electronic systems is shown in Figure 8.

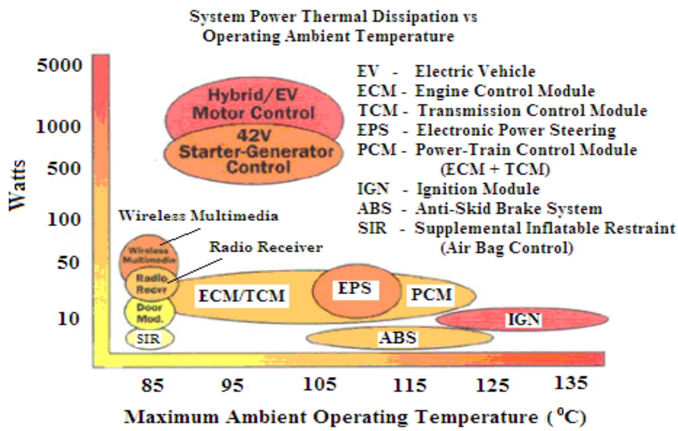


Figure 8: Current and future thermal power dissipation in automotive electronic systems [10]

The applications that operate in the highest ambient temperatures (i.e., ignition) and that have the highest power dissipation (i.e., hybrid and electric vehicle motor controllers) present the greatest challenge to current thermal management system design. For low heat fluxes, passive thermal management techniques can be used that do not require expending external energy for the heat removal. Interest in such techniques is currently very strong, due to their design simplicity, low cost, and high reliability. New thermal packaging materials for electronic components and system level that can reliably operate at junction temperatures of 175°C for digital and analog devices and 200°C for power drivers are needed to reduce the need for higher cost and more complex thermal cooling systems. In order to meet future higher power densities, the use of more efficient and feasible cooling technologies are anticipated to update those used in most automotive electronic applications today. Several emerging cooling technologies include advanced thermal packaging materials (i.e., PWBs with high-efficiency, copper, power and signal plane layers), reliable heat pipes and self-contained PCMs with solid-to-solid, solid-to-liquid, or liquid-to-gas, thermo-siphons, and liquid or refrigerant cooling systems. For example, Thermocore proposed one integrated cooling concept using heat pipe technology as a more efficient remote heat dissipating solution in automotive electronics systems (Figure 9). However, the greater challenge will lie in applying these available technologies in high volume and low cost, low weight and high reliability.

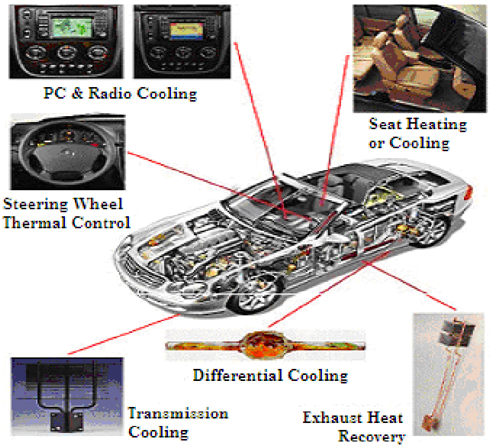


Figure 9: Application of heat pipe technology for automotive electronics [11]

3.2 MILITARY ELECTRONICS

Currently, heat flux at the chip level is in the range of 1-10W/cm^2 for avionics. Generally, conduction cooling has been widely used in military thermal management. For example, circuit boards in missiles are typically attached on one side to an aluminum structure resulting in a conduction path through the board. Many avionic-based electronics are conduction cooled using the military standard electronic module-format E (SEM-E) module that consists of conducting the heat away from the board through a thermal path parallel to the plane of the boards and rejecting the heat through air or liquid heat exchangers along two edges of the module (Figure 5). The most commonly known thermal management techniques for harsh environment electronics are summarized in Table 2.

Table 2: Overview of current thermal management techniques for harsh environment electronics

	Techniques	Comments
Passive Technology	High conductivity thin materials - thin diamond film - grease/adhesive with high k fill material (i.e., silver, graphite, diamond, MMC)	Simple and conventional High pressure between contact surfaces. Limited capability Inefficient for a non-uniform heat flux (i.e., hot spot)
	Heat sink	Sensitive to gravity and altitude Not feasible due to space limited
	Heat spreader	Effective and reliable Advanced MEMS heat spreader needed
	Phase change materials (PCMs)	Effective for intermittently operated avionics
	Heat pipe	Effective heat transport Miniature needed insensitive to gravity
Active Technology	Air jet impingement	Require cleaning and dehumidification Difficult integrated at chip level
	Indirect liquid cooling (cold plate)	More efficient than thermal conduction Require pump to overcome overall pressure drop in the loop Require low thermal resistance packaging at component level
	Immersion in dielectric liquid	Direct contact with chip surface Require high reliable liquid, complex hardware and high cost

Passive cooling is prevailing in current harsh-environment application because it is simple and reliable. However, as discussed in next section, passive cooling may not be sufficient to satisfy future generation high flux electronic cooling.

3.2.1 AIR COOLING

For decades, air cooling has been preferred for cooling military electronics ranging from PWBs to chips, multichip modules, and rack heat exchangers. Although air has less attractive thermophysical properties than most liquids, such as a low thermal conductivity (about 0.026W/mK) and a small Prandtl number (about 0.70), air has advantages over other coolants: it is available on most platforms, it is simple and inexpensive to implement, and it is easy to maintain and highly reliable without complex and expensive sealing devices. It appears that until two-phase and liquid cooling systems reach a stage where they can be inexpensively fabricated and packaged with high reliability, air-cooling will continue to be the primary choice for most of military thermal management systems where possible. As shown in Figure 10, four air-cooling schemes are used in today's military electronics, including (a) indirect air conducting cooling, (b) direct air cooling, (c) air flow through cooling and (d) air flow around cooling [12].

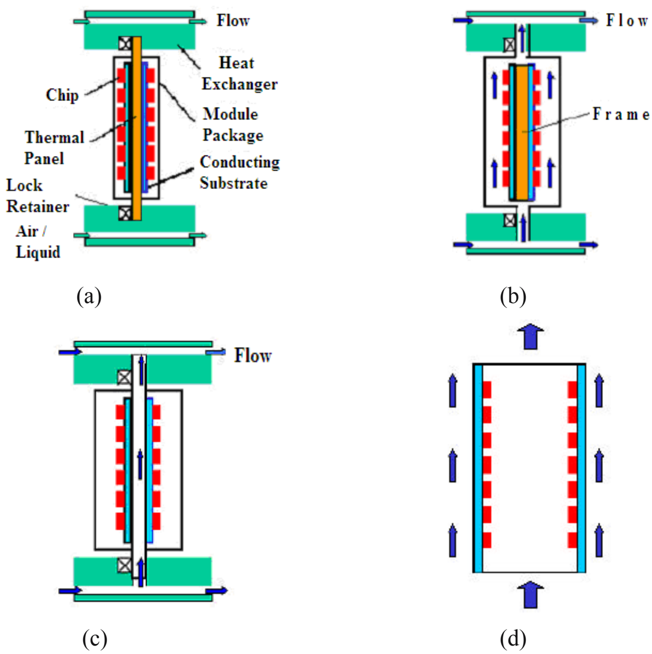


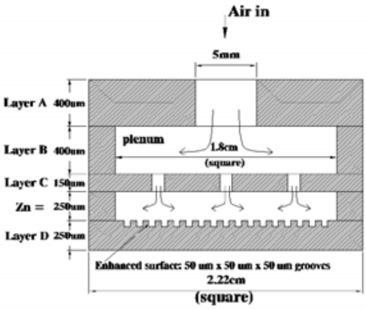
Figure 10: Main air cooling schemes for military electronics

Table 3 summarizes current air cooling techniques being used for military electronics modules. Due to increasing heat dissipation requirements, air cooling schemes are no longer capable of meeting demands of high performance military electronics modules, which require more than several hundred watts of cooling per module.

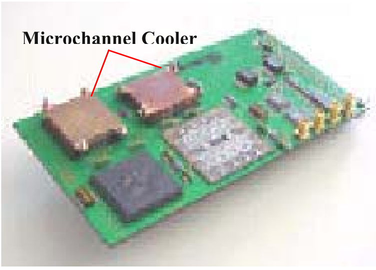
Table 3: Summary of available air cooling techniques

	Conducting	Air Flow Through (AFT)	Air Direction Flow (ADF)
Cooling Capacity (SEM module)	*< 50W*	*< 90W*	*< 100W*
Advantage	Low cost and high reliability Low mass and easy installation No pumps, ducting, filters, etc.	Abundant, free supply if taken from atmosphere No atmospheric altitude impact if using engine bleed air More efficient than conducting	Directly contact with components Eliminating thermal path resistance between air and components Some improvement in thermal performance than AFT
Disadvantage	Low cooling capacity Thermal contact resistance Substrate thermal conductivity dependant Need high pressure, intimate contact	Air supply need conditioning (throttling to low temperature) More complex cooling hardware Relatively large thermal resistance associated with edge heat exchanger	Atmospheric or cabin air need cleaning, filtering and dehumidification Component surfaces be free from corrosion
Comment	Air cooling schemes longer for demands of high performance avionics (up to 200 to 300W for SEM modules) Air cooling techniques are being replaced by liquid cooling systems. Single-phase fluid systems provide higher heat fluxes than conventional air cooling systems, phase change cooling system would provide even higher heat fluxes and allow compact packaging.		

One effort in air cooling seeks to improve air cooling's capability to reduce noise levels, pressure losses and heat sink volume, such as MEMS air cooling approaches, i.e., micromachined air jet arrays, or synthetic jets. A MEMS impinging-jet cooling device was developed for chip level cooling with a single-phase direct air cooling, or micro-jet array (MJA) (Figure 11a).



(a) Micro-jet air impingement



(b) Microchannel air cooler

Figure 11: MEMS based air cooling technologies

Single and multi-jet arrays with orifice diameters ranging from 50-800 micron were investigated including integration with actuation by magnetically driven membranes [14]. Heat transfer coefficients of 2500W/m^{2}K were reported with a 1.3×10^{7}ml/min air flow rate [15], which showed better than conventional air forced convection (around 50W/m^{2}K). An innovative cooling concept using a micro-channel air cooler was proposed for highly integrated avionics modules [12]. The micro cooler was fabricated by stacking precision etched thin copper foils that were fused together by direct bonded copper (DBC) technology. Several microcoolers can be integrated into one board to directly cool heat generating components (Figure 11b), which saves space and reduces system weight.

3.2.2 LIQUID COOLING

Due to the limits of air cooling, air cooling technology will be no longer capable of meeting the demands of future high performance military electronics in harsh environments. The rapidly increasing thermal management requirements of advanced electronics in harsh environments have lead to the use of liquid cooling techniques with the superior thermal transport properties of liquid coolants and the merits of phase change. For example, unlike other fighter aircraft, the next generation military aircraft, the F-22, successfully uses Polyalphaolefin (PAO) liquid flow through (LFT) cooling, rather than air cooling for its mission avionics. The LFT cooling configuration is similar to air flow-through (AFT) cooling scheme as shown in Figure 10c, except that liquid instead of air is circulated in the LRM core. The main difference with AFT is the need for quick disconnect couplings between the LRM and the rack distribution network. Currently, LFT using polyalphaolefin (PAO) liquid can cool several hundred Watts for today's military Standard Electronic Module-format E (SEM-E) modules. The use of the porous metal matrix as a heat exchanger core and as chassis racks and aircraft sandwich structures combines structural efficiency, heat transfer efficiency, and reduction in the volume of the heat exchanger core [16]. Mudawar (2001) investigated various liquid cooling schemes compatible with the existing SEM-E military enclosures. Figure 12 shows the removal capabilities for different liquid cooling arrangements.

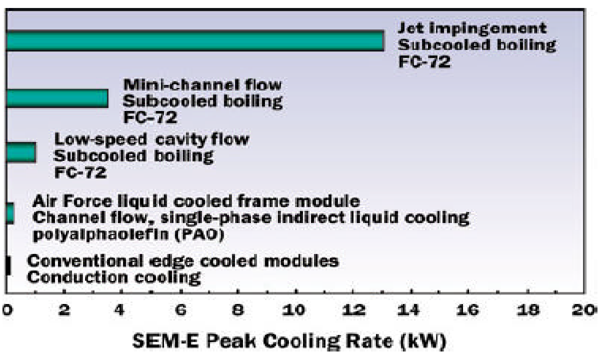


Figure 12: Heat removal capacity for different liquid cooling modules [6]

The single-phase PAO flow-through module demonstrated heat removal capability around 250W, and about 1000W heat dissipation was achieved with an FC-72 immersion cooling clamshell module. Mini- and micro-channel cooling techniques enabled heat removal capability over 3000W, one order of magnitude greater than the single-phase PAO flow-through module. The performance of the subcooled jet impingement showed great advantage over a conventional immersion cooling technique by approximately a factor of 13. Over the past decade, the Air Force Research Laboratory and Navy have invested in the development of a spray-cooled chassis integrated into the environmental control system on an advanced aircraft or other military electronic systems [17]. Isothermal Systems Research (ISR) proposed a spray-cooled chassis to the U.S. Marine Corps for the Advanced Amphibious Assault Vehicle (AAAV) [18]. A comparison of power consumed per 1kW of cooling between traditional air refrigeration and spray cool systems is shown in Table 4.

Table 4: Comparison of power consumption for air refrigeration cooling and spray cooling

Cooling System Power for 1 kW Elect. System	Air + Refrigeration	Spray Cooling
Fan Power	250/1000	30/1000
Pump Power		20/1000
ACU Power	412/1000	0
Total Power	662/1000	50/100

Using spray cooling, the total power consumption is much lower than a fan-cooled electronics system in an air-conditioned environment. Other candidates for spray cooling include the U.S. Navy's EA-6B carried-based jet and the U.S. Air Force's F-16 jet fighter. While jet impingement and spray cooling have been proven in the laboratory, they still require significant development before they are ready for application to a real, military, harsh environment system. Their practical application is dependent on the reliability of fluid pump and the variation in nozzle performance due to contamination, corrosion, and clogging.

Although pool boiling has been shown to yield cooling rates well above 50W/cm^2, its use is limited by several concerns, such as a minimum superheat required for boiling inception, a relatively thick thermal boundary layer, and an inherently low critical heat flux. These limitations can be overcome if a thin film (several microns) of the working liquid continuously covers the heated surface. In operation, a temperature gradient forms across the film via heat conduction and the liquid simply vaporizes at the liquid-vapor interface. This process has the potential to remove a very large amount of heat because the amount of heat removed is inversely proportional to the thickness of this thin liquid layer. Emerging Ultra Thin Film (UTF) evaporation is perhaps one of the most effective methods of heat removal from a high heat flux surface. One prototype of an EHD pumped UTF evaporator was reported to achieve a maximum cooling capacity of 65W/cm^2 at an applied voltage of 150V for a 50 micron electrode gap when using R-134a as the working fluid. The total EHD power consumption was less than 0.02% of the total power input to the device, translating into a few mille Watts for the application at hand [19]. A comparison of cooling performances of the thin film evaporator with the performances of pool boiling and spray cooling techniques is shown in Figure 13 [20].

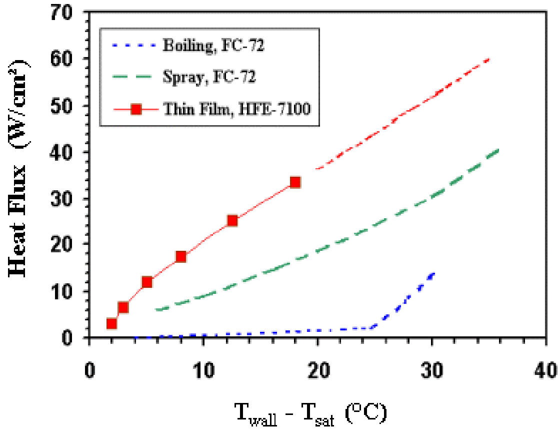


Figure 13: Comparison of cooling performances of thin film evaporator with the performances of pool boiling and spray cooling techniques

The data for pool boiling and spray cooling are reported by Bar-Cohen et al. [21] and Mudawar [6] for the 3M thermal fluid FC-72, which is quite similar to the 3M thermal fluid HFE-7100 used in the thin film evaporator test data shown in Figure 13. The thin film evaporator can remove heat fluxes of 20-40W/cm^2 with a temperature difference that is about 10-15°C less than spray cooling and about 30°C less than pool boiling. Further optimizing the electrode pattern and gap on the thin-film evaporator will generate ultra thin (micron-size) films on evaporator surfaces with higher cooling rates, low voltage and a more robust operation.

3.2.3 SPACE-BASED ELECTRONICS

On Earth, heat travels by conduction, convection, and radiation. However, conduction and natural convection are almost entirely nonexistent in the vacuum of space. Radiation is the primary method of heat transport in space. Space-based electronics that need to be kept cold are attached to radiators that face deep space and radiate excess heat into space. These electronics (i.e., space based phased-array-radar and laser systems) and radiators are thermally insulated from the rest of the spacecraft. Cooling is achieved through surface thermal radiation to deep space. Space-based electronics thermal management encompasses not only the removal of waste heat, but also the conservation of heat to provide a benign environment for the instruments and on-board electronic equipment.

The three types of cooling used for the extreme environmental requirements in space applications are compared in Table 5.

Table 5: Three types of space cooling technologies

Cooling Type	**Advantage**	**Disadvantage**
Passive cooling *- Blankets and barriers* *- Louvers* *- Heat pipes, pumped loops* *- Radiators*	*- simple* *- reliable* *- long lifetime (15yrs)* *- low cost and mass* *- proven technology*	*- limited cooling range (>80K)* *- depends on surroundings (orbit condition)*
Stored cryogen *- Superfluid helium* *- Solid nitrogen*	*- stable and passive* *- low temperature (1.3K using sup He)*	*- limited lifetime (1-2 yrs)* *- massive and bulky* *- complex interfacing (storage)*
Active cooling *- Mechanically pumped loops* *- Recuperative cryocooler (Joule-Thomson and Brayton)* *- Regenerative cryocooler (Stirling and Pulse-Tube)* *- Adiabatic demagnetization refrigerator (ADR)* *- Optical cryocooler*	*- low temperature (down to 10K now)* *- good lifetime (5-10yrs)* *- easily regulated, flexible, stable and uniform* *- enabling technology (Oxford 80K Stirling cooler succeeded in the late 1980s)*	*- power consuming* *- low efficiencies (1 to 3% of Carnot)* *- expensive/impossible to repair produce vibrations*

Currently, space-based radar (SBR) systems have a time-averaged power dissipation level in the 50 W/m^2 to $100W/m^2$ range. The heat dissipation of future radar systems is anticipated to reach 1 kW/m^2 to 2 kW/m^2 in response to greater function and higher density packaging [22]. Because the dissipated power from the SBR modules is highly distributed, one cost- effective thermal solution is to use the large antenna area as a thermal radiator. The more concentrated heat dissipation from the other electronics (such as the power converters) is about 20% or less of the total dissipation and can be controlled with local heat spreaders. Moreover, low weight requirements will necessitate new materials of low weight and high thermal conductivity like graphite and/or phase change materials. Thermal performance of PCMs can be further improved by filling them with metallic foams [23].

Future high power SBR, space-based laser (SBL), Integrated Power Systems (IPSs), and electromagnetic weapons (EWs) will require the utilization of two-phase thermal management systems that employ capillary-pumped-loops or loop heat pipes with thin, flat evaporators and multiple parallel evaporators [24 and 25] or even more aggressive use of refrigeration (i.e., thermoelectronic devices, magnetic or thermo-acoustic refrigeration and cryogenic coolers) [26, 27 and 28] and emerging MEMS based cooling techniques (Microchannel cooling and ultra thin film cooling) [29, 30 and 31]. The potential application of such cooling techniques will depend largely on the development of low-cost, use-based technologies that can be proven suitable and reliable for long-life, harsh-environment applications [32].

4. Summary

Continued electronic circuit miniaturization, coupled with increased performance requirements and severe mechanical/environmental constraints in harsh environment systems, has resulted in ever increasing circuit power densities and dissipation levels. Furthermore, the future electrical generation for the all-electric ships, more-electric aircraft (MEA), and more-electric vehicles (EV) will require higher levels of power generation and increased thermal management challenges. Power conditioning circuits will switch from silicon substrates to silicon carbide (SiC) substrates with a five-times increase in heat flux for air-cooled applications and a more than three-times increase in heat flux for liquid cooled applications [NEMI 2002]. These increases result in the need for advanced and more efficient thermal management techniques. With the current emphasis on the use of COTS components in military electronics systems, there will be an increased emphasis on utilizing commercially available cooling technology to meet these demands and reduce costs.

The authors' qualitative ranking of the potential applicability of various thermal management technologies for harsh environment electronics is shown in Figure 14. The potential applicability of these techniques in terms of criteria such as cost, ease of use, thermal performance, and reliability is compared.

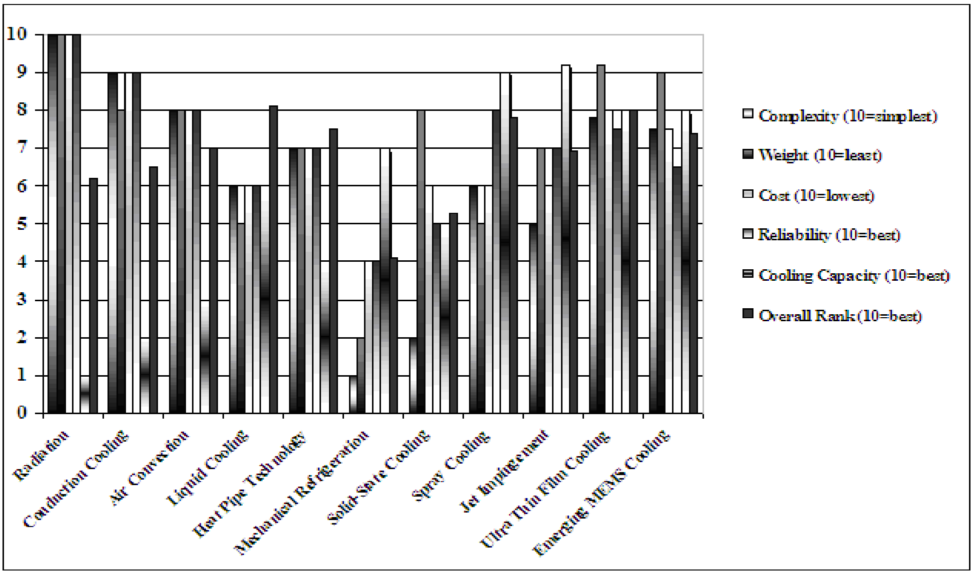


Figure 14: Summary of thermal management techniques for harsh environment electronics

For low heat flux systems, passive cooling (no machinery to move coolant) for new-generation electronics is as an attractive approach that can produce overall improvements in system reliability and reduced costs of operation. High conductivity materials and lightweight micro-heat pipes may possibly be used as thermal backplanes within circuit cards or enclosures. Since heat pipes do not rely on gravity, heat pipes can be used in any orientation. High thermal conductivities such as those found in graphite composites impregnated with unidirectional carbon fibers can be up to 800 W/mK, which can be used as heat sinks or for efficient heat removal.

For high heat flux high performance systems, a combination of active and passive techniques can be used. These may include using a high thermal conductivity substrate at the board level, along with forced air cooling or direct-contact liquid cooling at the board level. For this range of heat fluxes, the use of single phase cold plate technology and flow through cooling are also possible. For example, when current air cooling methods couldn't meet the future high performance military electronics system, single-phase liquid cooling methods (Liquid Flow-Through Cooling) became available in the next generation of military aircraft (the F-22). For even higher heat fluxes, a variety of cooling techniques are available that require the use of external power for cooling and can operate a coolant circulator (forced convection), direct liquid-immersion, spray/jet impingement, and ultra thin film evaporative cooling techniques which have recently been examined for removal of very high heat fluxes to meet future cooling requirements in harsh environment systems.

Future thermal management technology for harsh environment electronics will be focused on the following areas.

1. At the chip level, thermal management solutions need high performance heat spreaders to minimize thermal contact resistance:

- low CTE and low-coat, high thermal conductivity packaging materials, i.e., metal matrix composite and AlSiC
- embedded micro-heat pipes or vapor chamber cold plates
- micro- or mini-channel heat sinks
- micro-machined air-jet array impingement
- high performance thermal interfacial materials, such as thin film thermal grease, thermal pastes and PCM interfacial materials.

2. At the board level, compact single or phase change cooling methods have potential application in future high heat-flux avionics:

- single phase micro cooling, i.e., single-phase micro/mini-channel liquid cooling
- phase change cooling, i.e., spray or jet impingement cooling, and ultra thin-film evaporative cooling (UTF)
- refrigeration cooling, i.e., high COP micro-refrigerators and advanced thermoelectric cooling.

3. At the system level, several important criteria should be considered for selecting a suitable thermal management solution for a particular harsh environment system:

- heat dissipation potential
- cost and reliability
- packaging concerns, i.e., weight, volume and power
- complexity and flexibility, i.e., enhanced usability and minimal interface incompatibilities
- integration of thermal subsystem in the existing environmental control system
- minimal impact to the environment.

NOMENCLATURE

AAAV	Advanced Amphibious Assault Vehicle
ABS	Anti-Skid Brake System
ADR	Adiabatic Demagnetization Refrigerator
AFT	Air-Flow-Through
BGA	Ball Grid Array
COP	Coefficient of Performance
COTS	Commercial Off-The-Shelf
CTE	Coefficient of Thermal Expansion
DBC	Direct Bonded Copper
ECM	Engine Control Module
ECS	Environmental Control System
EHD	Electrohydrodynamics
EPS	Electronics Power Steering
EV	Electric Vehicle
EWs	Electromagnetic Weapons
FC	Fluorochemical
HEF	Hydro-Flouro-Ether
HEV	Hybrid Electric Vehicle
IC	Integrated Circuit
IGN	Ignition Module
IHS	Integrated Heat Spreader
IPS	Integrated Power System
LFT	Liquid-Flow-Through
LRMs	Line Replaceable Modules
MEA	More Electric Aircraft
MEMS	Micro-Electro-Mechanical System
MIR	Module Integrated Rack
MJA	Mciro-Jet Array
NEMI	National Electronics Manufacturing Initiative
PAO	Polyalphaolefin
PCM	Powertrain Control Module (ECM+TCM)
PCMs	Phase Change Materials
PWB	Printing Wiring Board
SBL	Space-Based Laser
SBR	Space-Based Radar
SEM	Standard Electronic Module
SiC	Silicon Carbide
SIR	Supplemental Inflatable Restraint (Air Bag Control)
TCM	Transmission Control Module
TIM	Thermal Interface Material
UTF	Ultra Thin Film
VLSI	Very Large Scale Integration

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