Comparing Platform-Level Electronics Cooling Approaches At the System Level

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ABSTRACT

Military embedded systems must perform in harsh and rugged environments, with varying extremes in ambient conditions. Rising heat density in electronics exposed to harsh environments, coupled with size, weight, and power (SWaP) constraints, has forced key integrators to consider alternative cooling solutions from a platform perspective. The industry is challenged to provide solutions utilizing cooling products that provide excellent environmental isolation in small form factors for a broad range of power densities. A myriad of electronics options, enclosure alternatives, and environmental conditioning solutions are available today. This white paper will give an overview of the various platform-level approaches to electronics cooling, including SprayCool's direct-spray approach. A side-by-side quantitative comparison of competitive cooling approaches will be presented for air-cooled, conduction-cooled, and liquid-cooled subsystems.

BACKGROUND

Existing and emerging applications that are running on military embedded systems are demanding ever-increasing computational power and communications bandwidths. For example, airborne and ground mobile applications running vision systems and doing real-time processing are driving significant power densities at the board, chassis, and platform levels. Even more impressive are the demands created by electronic aircraft, directed energy, and radar processing systems with system-level power consumptions in the tens of kilowatts. Meanwhile, platform integrators are required to provide smaller, lighter, solutions on less cooling power with increased reliability all in the most extreme environments.

The most common approach to electronics cooling is air cooling. Due to increasing power densities, air-based systems require greater air flow rates, more complex heat sinks and larger environmental conditioning systems (ECS) than ever before. An advantage to air cooling includes lower-cost electronics and shorter lead times. In most cases, air-cooled cards are used in labs for integration and are deployed in more benign military environments.

Conduction-cooled systems provide a valuable alternative to air cooling by packaging rugged electronics in small form-factor enclosures for the most austere military environments. With the ability to completely seal enclosures, conduction-cooled electronics become impervious to sand, dust, rain, EMI, high pressure wash, etc. High-priced, lower-power and often-lower performing electronics are selected for conduction-cooled solutions due to higher operational components. For many military applications, conduction-cooled systems enable small, light-weight solutions that can withstand the rigors of the battlefield.

Increasingly, liquid-cooling products are used to further densify electronics, provide alternative heat rejection options and, in many instances, obviate the need for an ECS. Most familiar to end-users are conduction-cooled systems that deploy conduction-cooled electronics and circulate liquid in the walls of enclosure, often using polyalphaolefin (PAO) as the coolant. A newly emerging approach is called liquid flow-through (LFT) cooling. LFT also typically uses PAO as the coolant, but differs from conduction cooling by delivering coolant to cold plates mounted directly on the electronics. Applications such as direct spray offer significant life-cycle cost savings with the ability to use less rugged electronics in harsh environments without SWaP penalties.

COOLING SYSTEM ALTERNATIVES

AIR COOLING

As the most common approach to electronics cooling, air cooling provides an effective solution when environmental isolation is provided at some level. Figure 1 illustrates a typical platform hosting electronics subsystems. The platform could be a UAV, tracked vehicle, or manned airborne application. To remove heat from the electronics in an air-cooled enclosure, air is forced over hot components. Power densities vary from 20-200 watts per single slot 6U VME style board.

The waste heat is dumped to the internal air space and then rejected outside the vehicle to the ambient. There are many options for transferring heat to the ambient such as fuel prior to the engine, PAO, Ethylene Glycol and water (EGW) mixture, ram air or ambient air, and skin or hull. The mechanism often required with air-cooled systems is an ECS that both pressurizes (for airborne platforms) and cools the air inside the vehicle. Heat removal from the cab or fuselage is the primary role of the ECS. Air-cooled systems have the advantage of using less rugged, lower cost electronics; however, ECS SWaP negatively impacts useful load and/or range of the vehicle. In many airborne pod applications, for example, an ECS is infeasible due to space and weight constraints.

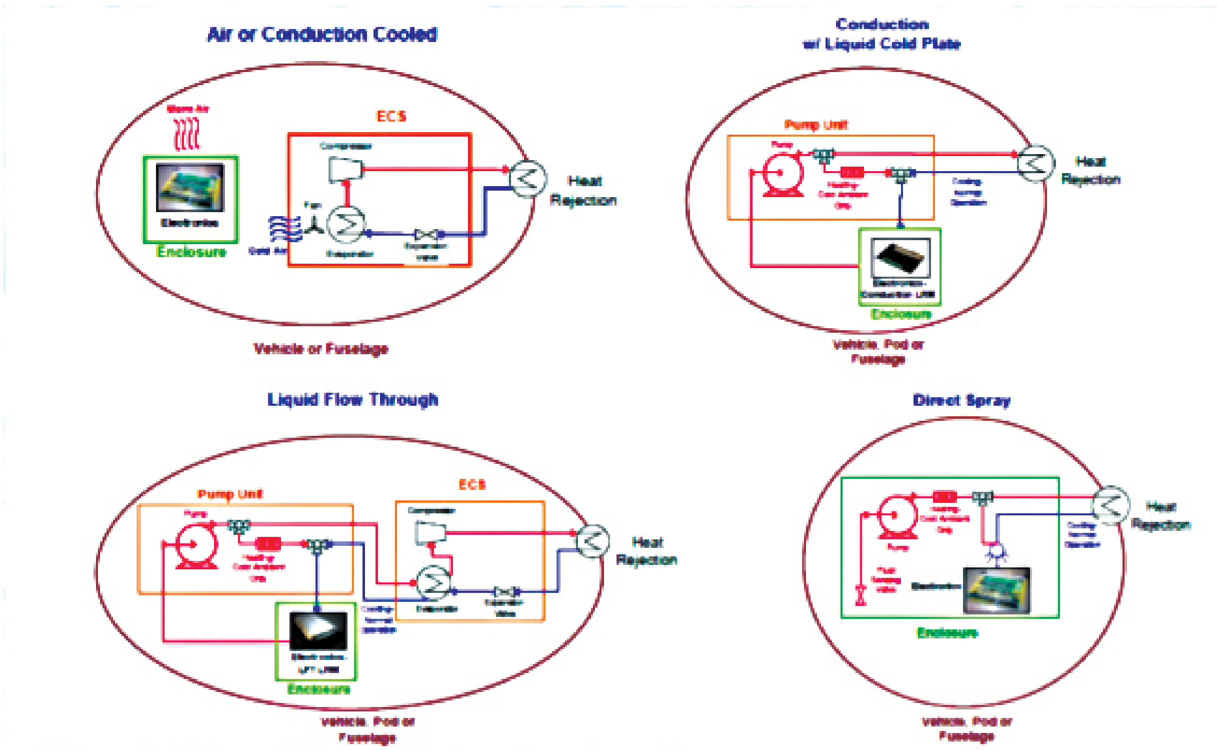

Figure 1 Architectural diagrams for alternative cooling solutions

CONDUCTION COOLING

In some applications, conduction-cooled systems are similar to air-cooled systems in their need for an ECS to remove heat from the fuselage or vehicle as shown in Figure 1. The greatest difference between air and conduction is the ability to completely seal enclosures, providing a barrier between the environment and the electronics. Whether it is sand, dust, rain, EMI, high-pressure wash, nuclear, biological, or chemical agents, the conduction-cooled electronics are isolated from the environment. The electronics are also designed, tested, and qualified for vibration and shock. Typical power densities range from 20 to only 100 watts per single slot 6U VME style board.

Like all cooling alternatives, there are trade-offs for conduction-cooled electronics. Long lead times for industrial grade components, lower performance, and significant cost premiums are common with rugged electronics. For many military applications, conduction-cooled systems provide small, light-weight solutions that can withstand the rigors of the battlefield.

For land-based applications where electronics are operational in enclosed spaces such a vehicle hull or shell, or pressurized airborne compartments, conduction enclosures require an ECS to reject heat to the ambient. In other cases where ambient air, ram air, or bleed air is available, conduction-cooled solutions provide SWaP benefits.

LIQUID COLD PLATE

At a system level, liquid-cooled electronics provide heat rejection options not available with pure conduction or air-cooled solutions. Most common are conduction-cooled systems that deploy conduction-cooled electronics and circulate liquid in the walls of the enclosure also known as liquid cold plate (LCP). A useful liquid for LCP is PAO. Figure 1 describes an architecture utilizing LCP on a conduction enclosure. The electronics transfer heat to the enclosure and the liquid transports the heat from the enclosure to the exterior of the platform. Pump units have better SWaP characteristics than an ECS while reducing the difference in temperature (ΔT) from component to ambient. Another benefit to LCP is the ability to heat the liquid for cold weather applications. Power densities range from 100-200 Watts per single slot 6U VME style board.

LIQUID FLOW THROUGH

A relatively new approach is called liquid flow through (LFT) cooling. LFT also often uses PAO as the coolant, but offers superior thermal performance compared to LCP because LFT delivers coolant closer to the source of heat. By placing cold plates on the electronics instead of the enclosure, the thermal resistance is greatly reduced enabling higher power densities under the same ambient conditions. LFT board densities of 750 watts per single slot 6U VME COTS could be a future reality, more than tripling the thermal headroom of LCP. Availability of LFT boards is a challenge today, but if adoption of LFT boards increases, prices should be similar to that of conduction-cooled electronics.

Current power densities, up to perhaps 300 watts per slot, can be cooled using a pump unit delivering liquid that is directly rejected to the ambient similar to the architecture for conduction LCP in Figure 1. For cooling electronics with power densities above 300 watts per slot, LFT will require an ECS to sub-cool liquid going into the pump unit. At the system level, high power densities impact SWaP and cost by requiring both a pump unit and an ECS.

DIRECT SPRAY

A direct spray system applies non-conductive liquid directly on electronics removing heat via forced convection and phase change from liquid to vapor. Because liquid is applied directly to the heat source, component temperatures operate cooler than alternative cooling solutions. This also provides significant thermal headroom with projected densities as high as 1000 watts/slot. Realistically, most program requirements won't exceed 500 watts/slot for some time.

One advantage of direct spray systems is the flexibility to cool a wide range of electronics. Many integrators today offer solutions to the military with a combination of custom and COTS electronics from 20 to 200 watts/slot. Figure 2 illustrates a direct spray enclosure from SprayCool® called multi platform Enclosure (MPE) used on many UAV and airborne applications. The ability to mix rugged and commercial grade and/or mix proprietary and COTS boards provides integrators more options when deploying systems.

Figure 2 SprayCool Multi-Platform Enclosure (MPE)

Like LCP and LFT systems described above, direct spray enclosures can heat the electronics reducing extreme temperature fluctuations. In fact, temperature variation is further reduced with direct spray systems due to low thermal resistance between the fluid and components. By reducing the maximum temperature of the components by even 10C, the reliability of the electronics doubles (IEEE, 2004).

Flexible heat rejection options also decrease integration time and effort. With fluid as the transport mechanism, heat from electronics can be rejected anywhere on the platform to bleed air, PAO, EGW, ram air, ambient air, skin/hull, fuel, etc. Unlike alternative liquid solutions, direct spray systems offer thermal headroom without SWaP or cost penalties. Direct spray systems do not require an ECS or separate pump unit to transport heat from electronics to the ambient. Due to low operating pressure (15-20psid) and flow rates (1-3 L/min), the SWaP overhead of small pumps, controller, and valves can easily be co-located with the electronics inside the enclosure as shown in figure 1.

ARCHITECTURAL ASSESSMENT

A detailed system level, quantitative analysis is presented in figure 3. Each alternative cooling system was evaluated based on an equivalent power density (100 watts/slot) and card set (eight 6U x 160mm 0.8" pitch slots). Non-rugged electronics MTBF is estimated to be 50,000 hours per card using Airborne Inhabited Cargo (AIC) as defined by MIL-HDBK-217F with the understanding that the cooling solution must provide isolation from vibration and temperature. For pure conduction electronics 25,000 hours is assigned due to intrinsically higher component temperatures (at least 10C higher than non-rugged boards) per the Arrhenius equation. LFT electronics MTBF is assumed to be 37, 500 hours with some expected reduction in component temperatures relative to conduction-cooling.

Values for price, volume, weight, and reliability were sourced from vendor datasheets, whitepapers, websites, conference proceedings, and correspondence. The values categorized by electronics include backplane, power supply, and electronics. The enclosure contains fans, filters, and fluid where applicable. Also, internal cabling, I/O connectors, access covers, and provision for mounting were considered. A pump unit encompasses pumps, valves, filters, heaters, quick disconnect fittings, tubing to/from enclosure, fluid, sensors, and controller. Heat exchangers include the core, manifolds, tubing, fittings, and fluid. ECS is a self-contained unit purchased off the shelf. The ECS does not consider platform systems necessary to pressurize the fuselage for airborne applications. Categories are the same for all alternative-cooling solutions unless otherwise noted.

		Air Cooled	Conduction Cooled	Conduction (w/ECS)	LCP	LFT	LFT (high Density)	SprayCool Enclosure
Weight (lbs)	Electronics	20	25	25	25	25	25	20
Assume (8) 6U VME	Enclosure	20	25	25	25	25	25	35
Assume 100 W/slot	Pump Unit	-	-	-	15	15	15	-
SprayCool pump,	Heat Exchanger	-	-	-	9	9	-	12
controller, valves	ECS	50	-	50	-	-	50	-
included in enclosure	**Total**	**90**	**50**	**100**	**74**	**74**	**115**	**67**
Cost ($)	Electronics	$64,000	$120,000	$120,000	$120,000	$120,000	$120,000	$75,000
Assume (8) 6U VME	Enclosure	$15,000	$25,000	$25,000	$30,000	$35,000	$35,000	$45,000
Assume 100 W/slot	Pump Unit	-	-	-	$10,000	$10,000	$10,000	-
SprayCool pump,	Heat Exchanger	-	-	-	$1,000	$1,000	-	$1,000
controller, valves	ECS	$5,000	-	$5,000	-	-	$5,000	-
included in enclosure	**Total**	**$84,000**	**$145,000**	**$150,000**	**$161,000**	**$166,000**	**$170,000**	**$121,000**
Volume (in^3)	Electronics	(8) 6U, 160mm, 4HP	(8) 6U, 160mm, 4HP	(8) 6U, 160mm, 4HP	(8) 6U, 160mm, 4HP	(8) 6U, 160mm, 4HP	(8) 6U, 160mm, 4HP	(8) 6U, 160mm, 4HP
1 ATR short	Enclosure	975	975	975	975	975	975	1076
Assume 100 W/slot	Pump Unit	-	-	-	560	560	560	-
SprayCool pump,	Heat Exchanger	-	-	-	200	200	-	338
controller, valves	ECS	975	-	975	-	-	488	-
included in enclosure	**Total**	**1950**	**975**	**1950**	**1735**	**1735**	**2023**	**1414**
Total Power (Watts)	Electronics	800	800	800	800	800	800	800
Assume (8) 6U VME	Enclosure	100	-	-	-	-	-	30
Assume 100 W/slot	Pump Unit	-	-	-	120	120	120	-
SprayCool pump,	Heat Exchanger	-	-	-	-	-	-	-
controller, valves	ECS	450	-	400	-	-	450	-
included in enclosure	**Total**	**1350**	**800**	**1200**	**920**	**920**	**1170**	**890**
Reliability - MTBF (hrs)	Electronics	6,250	3,125	3,125	3,125	4,688	4,688	5,479
Assume (8) 6U VME	Enclosure	14,000	27,000	27,000	27,000	27,000	27,000	14,000
Assume 100 W/slot	Pump Unit	-	-	-	18,000	18,000	18,000	-
SprayCool pump,	Heat Exchanger	-	-	-	100,000	100,000	-	100,000
controller, valves	ECS	18,000	-	18,000	-	-	18,000	-
included in enclosure	**Total**	**3405**	**2001**	**2424**	**2366**	**3165**	**2767**	**3709**

Figure 3 Comparison matrix for cooling alternatives

SUMMARY

When platforms have ECS infrastructure and SWaP budget, air-cooling is the least expensive alternative as shown in figure 4. For low power electronics exposed to pressure wash, chemicals, rain, dust, or vibration, while operating without an ECS, conduction cooling is a practical solution. LCP extends the power density of conduction cooling and improves SWaP with minor price and reliability impact. With broader industry adoption, LFT offers improved thermal headroom. When electronics power density exceeds approximately 300w/slot, the need for sub-cooled liquid drives additional SWaP on the platform using LFT. Direct spray solutions offer a unique advantage in deploying today's 20-500w/slot commercial grade or rugged, proprietary or COTS electronics in unpressurized and unconditioned environments. Intrinsic heat rejection flexibility for the integrator is an added value. Direct spray solutions offer the lowest cost alternative to air-cooling, the best reliability and greatest thermal headroom of any cooling alternative for SWaP constrained applications.

System Summary

Option	System Price	Weight (lb)	Volume (in^3)	Total Power (W)	Performance (Watts/slot)	Reliability (hr)
Air cooled	$84,000	90	1,950	1,350	100	3,485
Conduction	$145,000	50	975	800	100	2,801
Conduction (w/ECS)	$150,000	100	1,950	1,200	100	2,801
LCP	$161,000	74	1,735	920	200	2,366
LFT	$166,000	74	1,735	920	300	3,165
LFT (high density)	$170,000	115	2,023	1,370	750	2,767
Spray	$121,000	67	1,414	890	1000	3,789

Figure 4 Summary of baseline assessment of cooling alternatives

REFERENCES

1.IEEE Transactions on Device and Materials Reliability, VOL. 4, NO. 4, December 2004

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