Thermal Management

of Defense Electronics

The biggest challenge to the thermal management of defense electronics stems from varied boundary conditions that are encountered in a short span of time. Military and space electronics live and operate in environments where extremes are seen in the course of a mission's operations. Consider a fighter jet stationed along the Caribbean Sea, now called on to perform a task. The plane that has been sitting in the sun at sea level, in moderately high temperature and humidity, is now forced to travel in high altitudes where the local ambient temperature is sub-freezing. This sudden change in boundary condition takes place in minutes, yet the plane's electronics must operate over this wide range of ambient conditions. Further, because of the mission-critical nature of such electronics, the processing speed and dataprocessing volume are both large. We know that once the frequency of transmission increases, the power dissipation increases accordingly.

Therefore, the combination of adverse and dynamic boundary conditions, and the excesses in power dissipation, have made thermal management of military electronics a major challenge to the design of a successful system. Along with the above concerns, the issue of weight and the unique reliability of such electronics adds complexity to the design of the cooling solution. For many air- or space-borne electronic devices, weight is a major gating factor. A lighter payload typically signifies longer mission duration and lower cost of operations, both of which play a pivotal role in a successful launch of the product. Obviously, the reliability of the electronics is a fact of life that designers live with, but because of the nature of a given system, e.g., a jet fighter, missile, tank, etc., the electronics' successful performance is essential for the safety of the operators and for avoiding collateral damage.

Figure 1 captures the impact of the environment and the role thermal design plays in a successful product lunch.

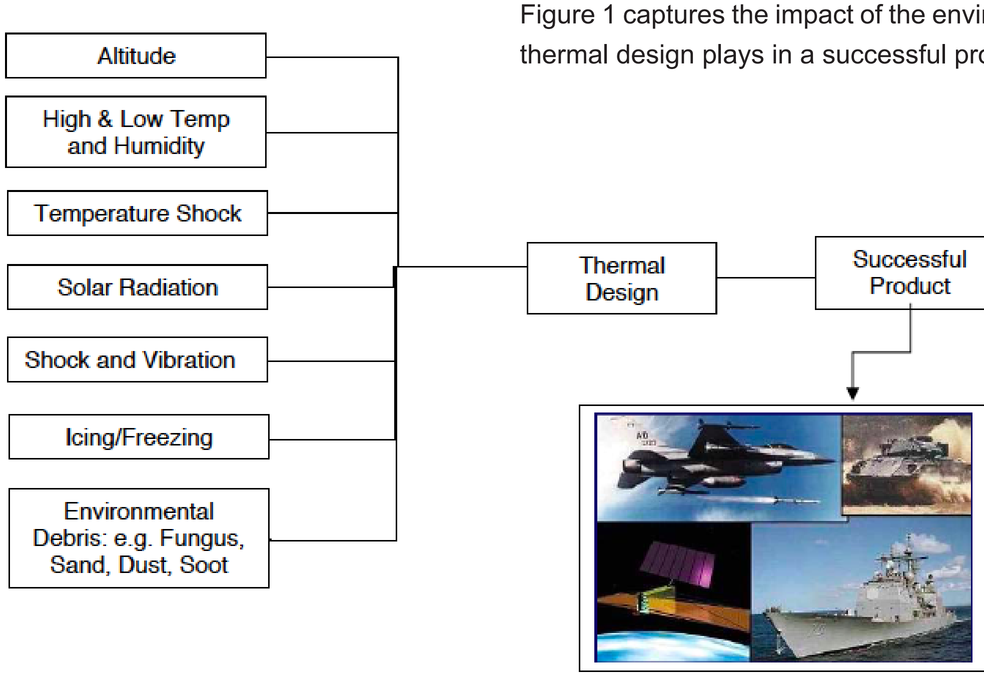

Figure 1. Impact of Environment and Role of Thermal Design in the Launch of a Successful Military Product. [1].

Figure 2 shows the temperature gradient and air composition of the earth's atmosphere to outer space, where a typical electronics design for military and aerospace applications may apply. [2]

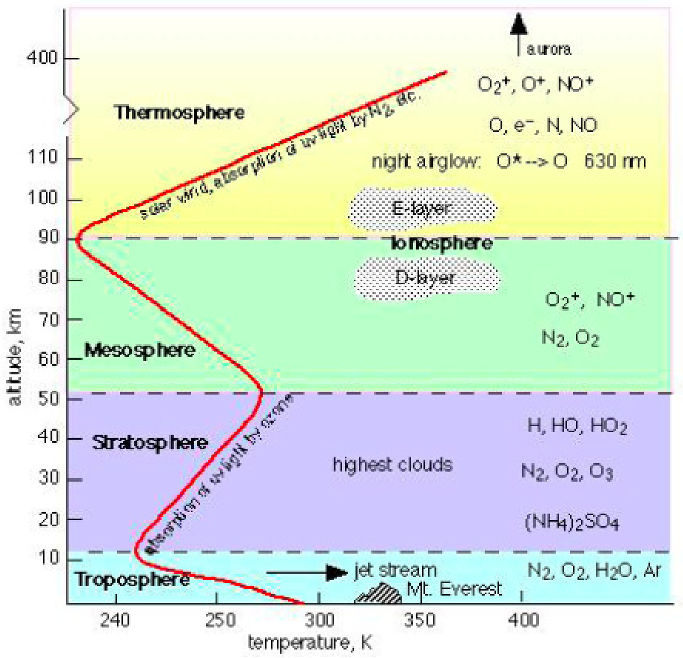

Figure 2. Atmospheric Temperature and Composition as a Function of Altitude [2].

The twin challenges of the lack of atmosphere and change of density, as they impact thermal management, is shown in Figure 3, which clearly depicts the behavior of air as a function of altitude. The challenge of varying boundary conditions, and the design of the cooling system to meet those requirements, is quite evident.

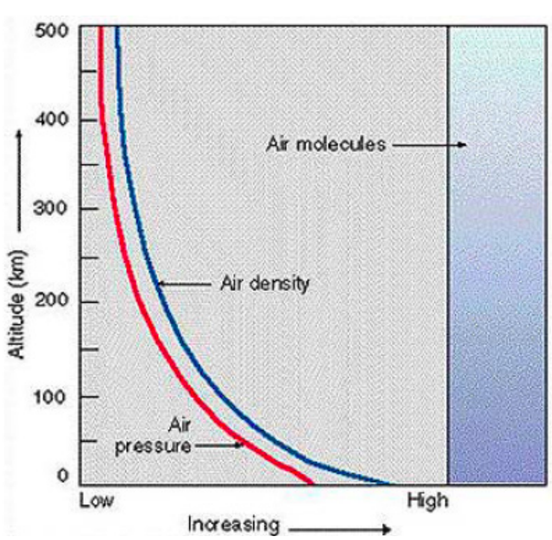

Figure 3. Variation of Air Pressure and Density as a Function of Altitude [2].

Cooling Systems

Similar to other electronics, defense related electronics have been cooled by a variety of systems [3]. These range from a thermal transport mechanism like a heat pipe for taking the heat to another location, to cryogenically cooled systems that are perhaps the most complex in architecture and packaging. The major parameter is to recognize that, as with other electronics, there is no "one-solution" that will address every need. A cooling system is dictated by size, weight and power requirements and will vary from system to system. A common theme in many electronics systems, however, is that they tend to be closed systems.

The designers of more sophisticated electronics have attempted to isolate the cooling system and the electronics from the environment. Based on the boundary conditions described earlier, this is certainly a prudent practice. Imagine a Humvee in a desert environment where the ambient elements, e.g., sand and debris, can paralyze electronics that are not isolated.

Also, there is always a discussion of the illusive "next generation" cooling system. Clicking through pages on cooling options on the Internet, we see a large variety of designs that have been deployed in the market. The next generation design is often meant as a higher capacity, more compact cooling system; a so-called HCMC system. Irrespective of the electronics, the desire is to have HCMC systems that can readily and reliably be deployed anywhere. Until we create a new generation of materials and fluids, while developing manufacturing technologies that can fabricate compact systems with higher performance, our challenge will be more on the packaging of the existing technology and identifying ways to minimize resistances on the path of heat transfer. Let us see what is available on the market.

Because of the required high heat flux of military electronics, there has been a lot of focus on spreading the heat at the device level. These remedies include higher thermal conductivity substrate materials, substrate level heat pipes, a micro-Pelletier (thermoelectric) embedded on the die itself, or spray or direct liquid cooling where the heat is transported by the fluid to a heat exchanger on the system. Figure 4 shows one such system. [3]

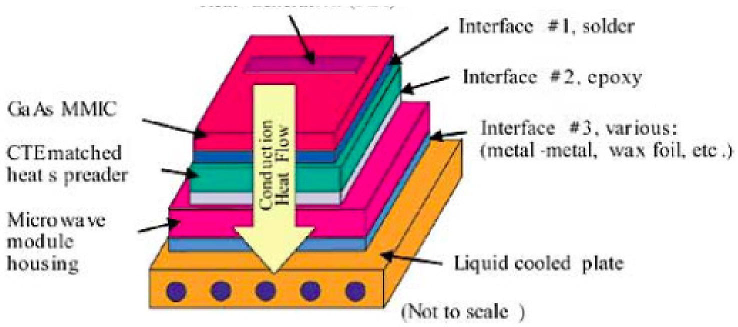

Figure 4. Control Volume around the Enclosure Wall.

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New thermal management materials that have come to light over the past decade include composites, such as diamond particle-reinforced aluminum, silver and copper; a ceramic matrix of silicon carbide reinforced with diamond particles; diamond particle-reinforced cobalt; and carbon-based materials like natural graphite and highly oriented pyrolytic graphite (HOPG). [4]

The reader's attention should be drawn to the complex packaging required to manage such a task. The physical packaging of the cooling system itself is one aspect of the challenge. The second aspect is managing the coefficient of thermal expansion of such a complex yet sensitive composite structure. These all must happen, while we need to ensure that the boundary conditions are satisfied where the electronics will function.

Board and System Level Cooling

Confronting growing power dissipation and harsh boundary conditions, many designers are gravitating toward higher capacity cooling options. Yet, the attractiveness of air cooling with the lighter weight and ease of field repair continues, and rightfully so. With the push toward using commercial off-the-shelf (COTS) components, many designers are looking to and deploying hybrid cooling. This is because many traditional components are able to tolerate the harsh ambient conditions that most ground based military electronics experience. However, many CPUs and GPUs will fail in such environments. Therefore, many designers have deployed a hybrid system, where most of the electronics is cooled by air and the critical components carry a cold plate system often tied to the vehicle's cooling system or an independent heat exchanger.

However, for airborne and space electronics, such an option is not available. Designers must develop closed loop liquid systems whose complexity and means of heat removal vary from total immersion, to coldplate, to liquid in contact with the component via spray or stream, to refrigeration and cryogenics. All these systems require a liquid-to-air or liquid-to-space heat exchanger to remove the heat from the liquid. These cooling solutions are as broad and varied as the designers who design them and the systems that deploy them. However, one area is certainly common, irrespective of the selected cooling solution: packaging.

The challenges of packaging are readily seen in Figures 5 and 6. [5]

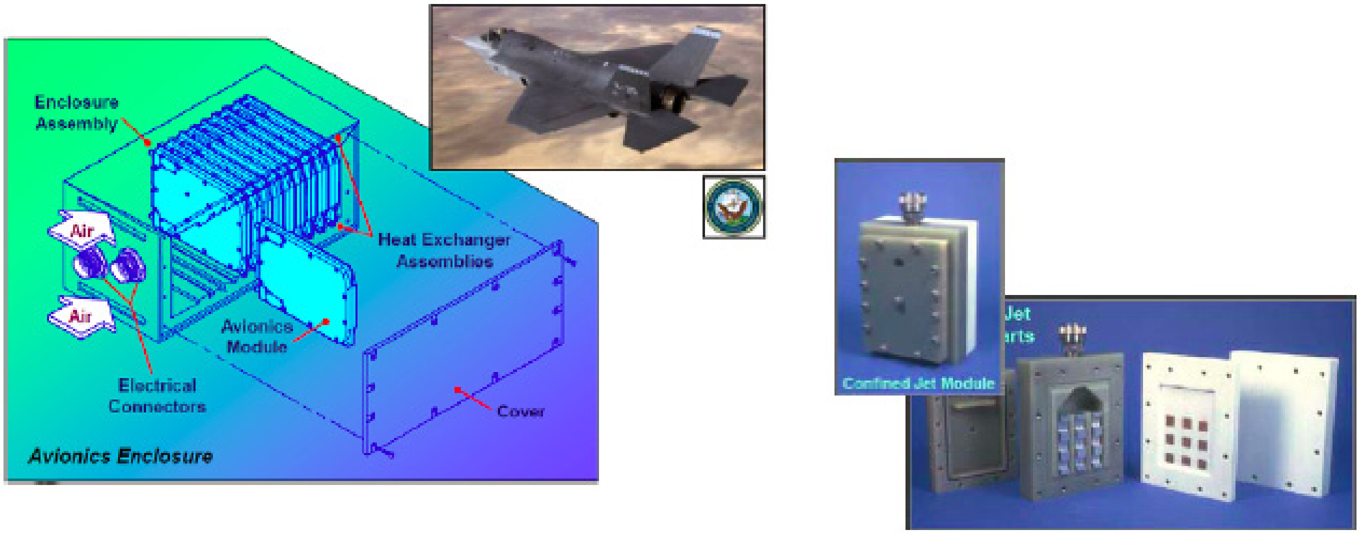

Figure 5. High-Flux Thermal Management of Military Avionics – Closed Loop Hybrid Cooling [5].

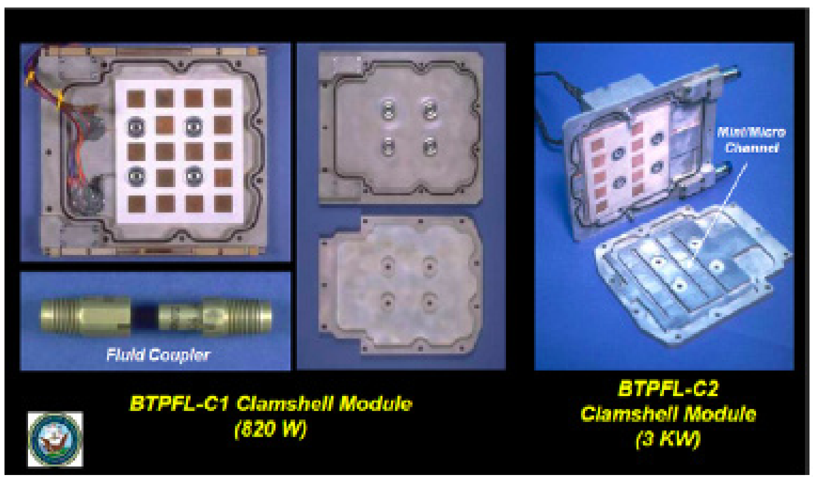

Figure 6. Phase Change Avionics Cooling Modules Used in Avionics Enclosures [5].

Considering the fail-proof requirements for a successful design, along with environmental, shock, vibration and weight requirements, it is clear that the mechanical packaging of these systems takes a dimension of its own and is an integral part of the solution.

There is very little to no limitation on the cooling capacity of liquid assisted cooling systems (whether direct contact or cryogenics). The limits stem from system deployment rather than cooling capacity. They are seen in the following, as observed in [4]. "While most systems are sealed and no fluid actually touches any electronic component, there remains a desire to use a liquid that would not damage a component in case there is a leak. When you have an electrically non-conductive fluid, it also tends to be thermally non-conductive. This is the best from a non-toxic standpoint, but not the best otherwise. In general, a fluid that has good insulating properties also tends to be a poor thermal fluid. The market has been loud and clear with its complaints that liquid cooling is more expensive than air or conductive cooling. Still, the expectation is for liquid cooling to experience significant growth in the next few years.

Therefore, with such growth, albeit small, more resources and research will be committed to liquid cooling to develop better fluids and materials that meet the thermal and weight requirements.

Along with packaging challenges one needs to meet the reliability requirements, ease of field service repair and satisfaction of harsh shock and vibration requirements. One can only assume the weather induced turbulence or pressure shocks that a system may endure. And facing potential theater action and engagement, the verification and manufacturing of such systems must become the essential component of the design cycle.

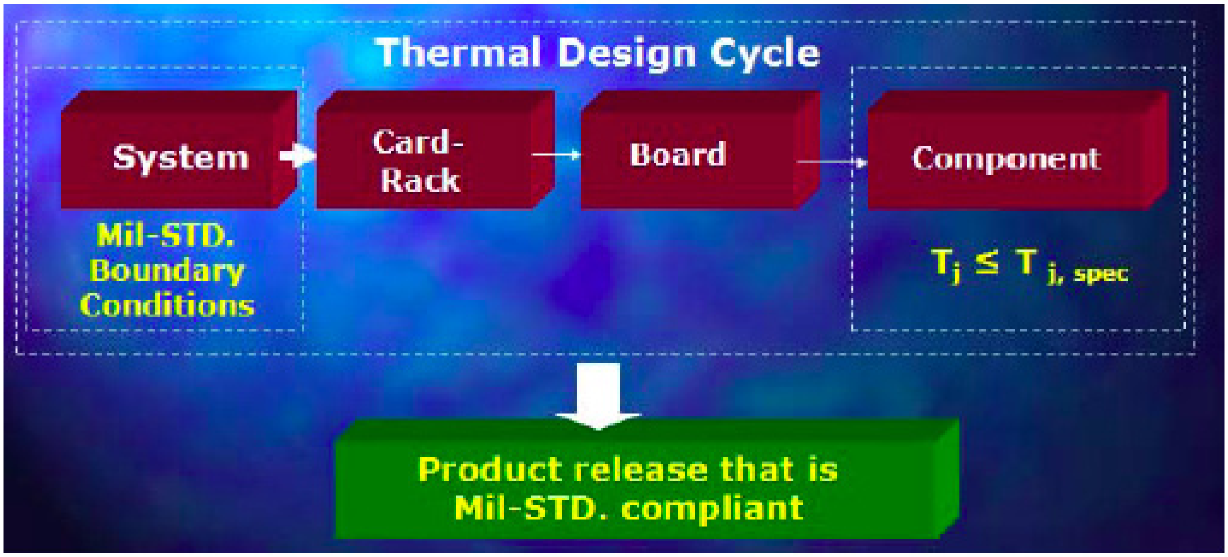

Figure 7. Design Cycle for the Thermal Design of Military Electronics with Mil-Spec Boundary Conditions [1].

Thermal Design Process

It is clear that the military market is rich with varied cooling options. Their dimensions or capabilities are sufficiently understood to provide a designer with a clear path. The illusion of the "next generation cooling system" is simply an illusion. What wins is simply good engineering and the understanding of the capabilities and capacities of different cooling options along with their effective deployment.

The basics of electronics cooling simply do not change because we are dealing with military or aerospace electronics. The system-down-approach (SDA) with proper boundary conditions is a must. At the end of the process, a cooling system must ensure all critical components have a junction temperature level that, for the worst possible ambient, is below the specification level that is provided by the device manufacturer, Tj, spec. Figure 7 shows such a process [1].

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2. Short, N., Meteorology – Weather and Climate: A Condensed Primer, http://rst.gsfc.nasa.gov/Sect14/Sect14_1a.html
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