

Thermal Management as a Force Multiplier within the Research, Development, and Engineering Command (RDECOM)

**by MAJ Brent Odom (Ph.D.), Nicholas R. Jankowski,
and Brian Morgan (Ph.D.)**

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14. ABSTRACT This report presents the information and conclusions gathered during a 6-month roadmapping effort at the U.S. Army Research Laboratory (ARL) and reaching out to partners in Research, Development, and Engineering Command (RDECOM). We identify common themes of thermal requirements encountered at the system level and provide short reviews of the primary technology candidates to achieve such functionality. We also suggest a new thermal management taxonomy for RDECOM's Power & Energy (P&E) Technical Focus Team (TFT) and recommend a related organizational shift within ARL to closely align and support this taxonomy. Finally, we summarize the fundamental thermal management research areas ripe to receive increased focus that we believe offer the highest potential payoff to current and future Army capabilities.					
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1. Introduction

Recent Power and Energy strategy reports by the U.S. Department of Defense (DoD) (1) and the Army (2) have emphasized the need to make every energy-using system and platform more fuel efficient to reduce the strategic and operational impact of the military's overall energy usage. These reports have identified improved system thermal management as a critical element to achieving these improvements, as any additional size, weight, and power (SWaP) used for cooling or temperature control is simply an overhead cost that detracts from the system's intended function. However, achieving the necessary thermal improvement for systems across the Army will require a change in the way the Army has traditionally handled thermal aspects of research and development.

Historically, thermal management has been considered a mature area where existing low risk solutions were selectively applied to an application after its core function had been fully designed. Thermal problems were addressed piecemeal as they arose, and engineering immediate solutions took precedence over research into improved technology. As a result, disparate groups have developed highly specialized thermal expertise, typically manifested as a thermally knowledgeable application expert rather than a trained thermal expert addressing a particular application. Though the thermal knowledge in an organization may be cumulatively substantial, its decentralized nature makes it difficult to access by groups with new problems, and limits the potential impact that the Army research and development community can make in solving future thermal problems.

Some first steps toward addressing this situation included the U.S. Army Research, Development, and Engineering Command (RDECOM) standing up a Power & Energy Integrated Product Team (P&E IPT) to better integrate the various Army programs developing advanced power and energy technology (3). The P&E IPT includes representatives from across RDECOM, where the U.S. Army Research Laboratory (ARL) provides crosscutting support to the mission-specific Research, Development, and Engineering Centers (RDECs) (figure 1). It quickly became apparent that in addition to poor coordination across the command, there exists a huge mismatch between (1) the plethora of thermal management problems and (2) the scarcity of thermal management experts across RDECOM in both basic and applied research. Thus, the P&E IPT initiated a thermal management roadmapping effort during the period of June to November 2011 to identify and group the primary areas of thermal management research and articulate a path forward for the Army to address thermal challenges in the future.

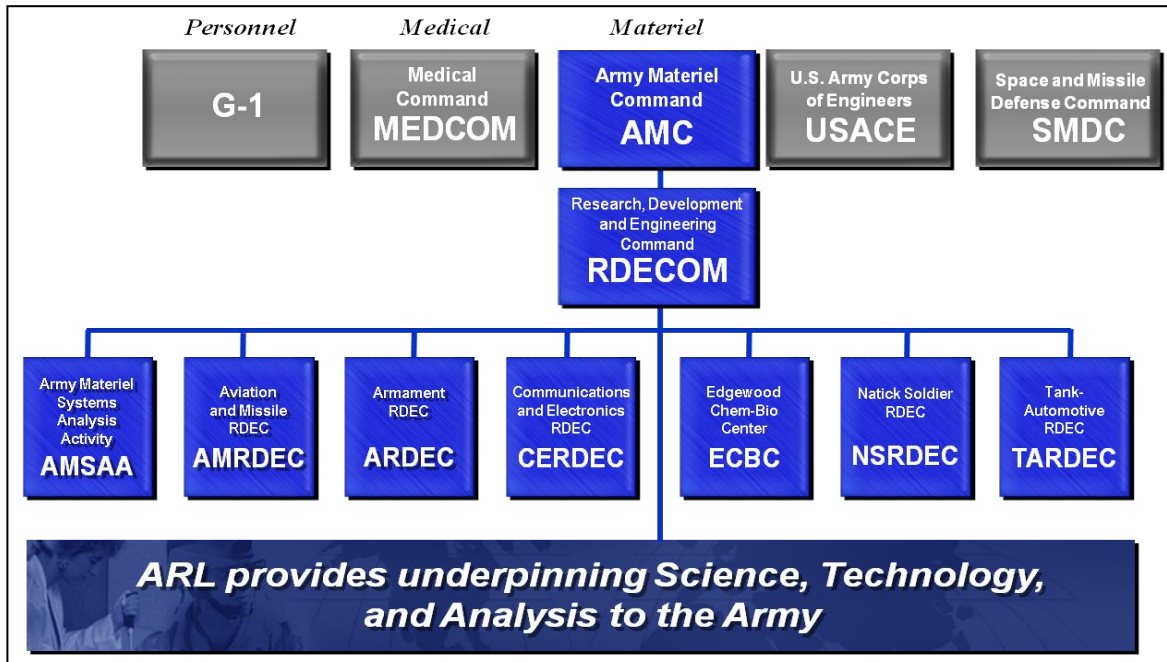


Figure 1. Army science and technology research and development organizations.

This report presents the information and conclusions gathered during that roadmapping effort. We first identify common themes of thermal requirements encountered at the system level, and then review the primary technology candidates to achieve such functionality. Given this landscape, we suggest a new thermal management taxonomy for RDECOM's P&E Technical Forcus Team (TFT) and recommend a related organizational shift to closely align and support this taxonomy. Finally, we summarize the fundamental thermal management research areas ripe to receive increased focus that we believe offer the highest potential payoff to current and future Army capabilities.

2. Cross-cutting Thermal Management Themes

In surveying the portfolio at the Army's RDECs, engineers were eager to discuss the key thermal management challenges that address a significant and current Soldier need or those in which their present state is a significant limiting factor in terms of cost and performance for a wider range of associated applications. We identified significant overlap between various agency program needs, and thus categorized findings into the following three areas (each of which is discussed below): heat-to-electricity, electronics cooling, and heat transfer. As shown, these thermal issues clearly cut across Communications & Electronics RDEC (CERDEC), Natick Soldier RDEC (NSRDEC), Tank-Automotive RDEC (TARDEC), Aviation-Missile RDEC (AMRDEC), and ARL programs.

2.1 Heat to Electricity

While the conversion of thermal energy to electricity for prime power remains of interest, many opportunities exist to improve system-level efficiencies by recovering and converting waste heat (typically of low quality) into supplemental electrical energy. By low quality thermal energy we mean energy that has low availability to do work (low exergy). The closer a system is to the condition of its surroundings in terms of temperature, the harder it is to produce work from that system. In most cases, the preferred output of converting thermal energy is to produce electricity, as electricity can be stored and/or used directly in Soldier equipment.

2.1.1 Heat to Electricity – Army Applications

As a rule of thumb, a typical vehicle with a gasoline internal combustion engine loses 40% of its fuel energy through the exhaust gas, which is still at a relatively high temperature (4). Similarly, inefficiencies in a turbine engine for an Abrams tank means that exhaust gasses can contain megawatts of thermal energy. Thus, the auto industry (5), Department of Energy (6–8), TARDEC (9), and others have all investigated waste-heat recovery as a way to improve overall system efficiency. Depending on the vehicle type and driving conditions, fuel mileage improvements on the order of 5% during highway cruising are expected (8, 10) Army vehicle modernization programs, which desire more onboard electrical generation, could potentially meet their targets by capturing and converting waste-heat energy to avoid increased fuel usage. As an example, to upgrade the onboard electrical generation for an Abrams tank from 18 to 28 kW (11), <1% of waste-heat recovery could supply the desired 10 kW of additional electricity without any increase in fuel consumption or changes in alternator hardware. For a military with an increasingly expensive logistics tail reliant on trucks, improved fuel usage could result in significant savings in lives and dollars. For example, according to an estimate provided by the Army G-4 office in October 2011, “18% of U.S. casualties in Afghanistan and Iraq were related to ground resupply.” (12).

Besides recovering waste heat, direct conversion of heat into electricity is of interest for small fueled generators (typically below 1 kW, where scaling down traditional generators becomes more difficult). Devices of this type are being pursued at both ARL and CERDEC. The goal of these efforts is to provide silent, low power sources for dismounted Soldiers or unmanned systems, as well as off-grid battery recharging. While fuel cells target a similar power range, they typically require specialized fuels like methanol. For small burners, because the goal is simply to provide heat, such systems are not tied to any particular fuel. They could potentially run on logistics fuels like JP-8, again reducing the logistics burden to the Army. If thermal-to-electric efficiencies of 10% or more can be achieved in a system using JP-8, the resulting energy density could approach 1200 Wh kg^{-1} , a ~10X improvement over current rechargeable batteries. This would provide a significant advantage to small mobile elements, dismounted troops, and potentially even unmanned vehicles.

Finally, NSRDEC is interested in simplifying some of their systems used for Soldier feeding and equipment by also converting thermal energy to electricity. Specifically, siphoning off a small amount of the heat generated to cook food in portable kitchen applications can simplify the required electrical subsystems to run the kitchen. NSRDEC also remains interested in producing a self-powered, solar hot-water heater, where some of the captured heat is repurposed to run the system pump. The NSRDEC Combat Feeding – Equipment and Energy Technology Team has small business innovation research (SBIR) awards exploring possibilities in these areas.

2.1.2 Heat-to-Electricity – Technology Options

Despite the intense desire to convert heat into electricity, there are only a few technologies relevant to this community, and the desired operating temperatures are the most limiting constraint.

At temperatures of ~ 1000 °C or higher, thermophotovoltaic (TPV) power generation is an attractive long-term option, where thermal blackbody radiation is converted by a photovoltaic cell to create electricity (13). Direct burner-generators have the potential to efficiently reach the high temperatures required by TPVs, but packaging at these elevated temperatures and controlling the efficiency within each energy conversion process (fuel-to-heat, heat-to-radiation, radiation-to-electricity) remains challenging. The Army has a long cyclic history of research in TPV, dating back to the 1960s, targeting kW-scale, silent, flexible fuel generators—with demonstrations of prototype systems circa 2001 with 2–2.5% net efficiency (14). In the past 10 years, improved component technologies like selective emitters based on photonic crystals (15), optical filters and reflectors (16), and improved understanding of low bandgap photovoltaic cells (17) have renewed optimism in this technology—including the fiscal year 2012 (FY12) start of an ARL program on TPV for Soldier power applications (POC: Dr. C. Mike Waits, ARL/Sensor and Electron Devices Directorate [SEDD]). Optimism remains high that if individual component efficiencies can be achieved and integrated, a net fuel-to-electric efficiency of 20% from temperatures below 1000 °C is feasible (13).

However, most applications discussed in the previous section have hot-side temperatures of 500 °C or below, leading RDECOM to focus more on improving thermoelectric generator technology. Thermoelectric devices can work over a wide range of temperatures, from room temperature up to ~ 1000 °C, with varying levels of effectiveness. In general, thermoelectric modules are solid-state devices consisting of n- and p-type materials (figure 2) that directly convert heat into electricity via the Seebeck effect. Their effectiveness is captured through the material and temperature dependent figure-of-merit, $Z\bar{T}$ (18):

$$Z\bar{T} = \frac{\sigma S^2}{k} \bar{T} ; \quad (1)$$

$$\eta_{TE} = \frac{T_h - T_c}{T_h} \frac{\sqrt{1 + Z\bar{T}} - 1}{\sqrt{1 + Z\bar{T}} + \frac{T_c}{T_h}} \quad (2)$$

Here, $\bar{T}$ is the average of the hot (T_h) and cold (T_c) side temperatures for the device, σ is electrical conductivity, S is the Seebeck coefficient, and k is thermal conductivity. For high efficiency, one must maximize the temperature gradient, while essentially engineering the materials to transfer heat from hot to cold via electrons rather than phonons.

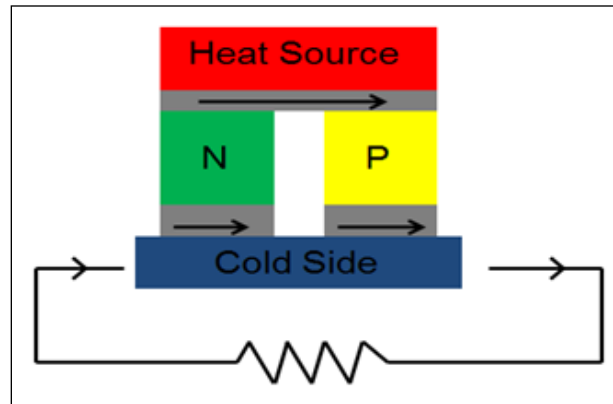


Figure 2. Basic thermoelectric generator concept.

Thermoelectrics are generally reliable and scalable from mW to kW's, but commercial products tend to be limited to low temperature ($<250\text{ }^{\circ}\text{C}$) and low efficiency ($<5\%$), resulting in low utility up to this point. Figure 3 shows the results of an informal survey of measured thermoelectric module performance taken by ARL in 2011 (data in the appendix). Research modules clearly show that efficiencies of $>8\%$ are reasonable to expect in the mid-term for temperature gradients in the $400\text{ }^{\circ}\text{C}$ range (6). Thornton & Smith (6) estimate that these efficiencies will be roughly halved by parasitic losses in a system, for example, temperature drop when transferring heat from hot gasses to the device, or the power used to maintain low cold-side temperatures. Therefore, careful modeling of materials, modules, and the requisite thermal ancillaries (heat exchangers, fans, etc.) is an absolute requirement to evaluate the cost-benefit proposition for such technologies and to reach the more relevant $\sim 10\%$ efficiency range desired for many Army applications.

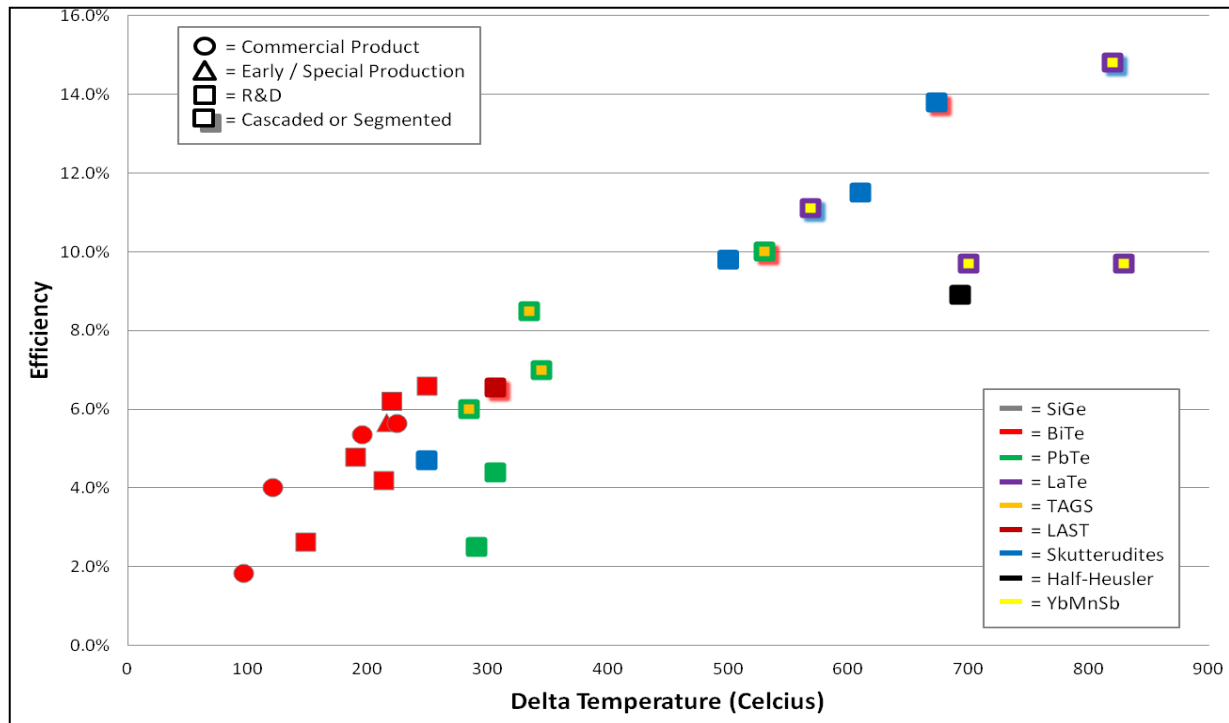


Figure 3. Survey of thermoelectric modules in 2011. Most power levels were <5 W electric.

At the low end of the temperature spectrum, organic Rankine generators are attractive as they are a mature technology capable of thermal-to-mechanical (shaft) power efficiencies of >10% at low temperatures ($T_h < 200$ °C); electrical power could be derived via an additional generator or the shaft power could be used directly to run something like a vapor compression cooling system. These efficiencies are significantly higher than those available from thermoelectrics in a similar temperature range; however, organic Rankine systems are complicated, with many moving parts, and therefore are best suited to moderate scale applications where kW's or more power is desired. Detailed models have been developed in the literature to analyze potential coupling of organic Rankine engines with thermoelectric generators for combined thermal-to-power systems with high efficiency (figure 4) (19, 20).

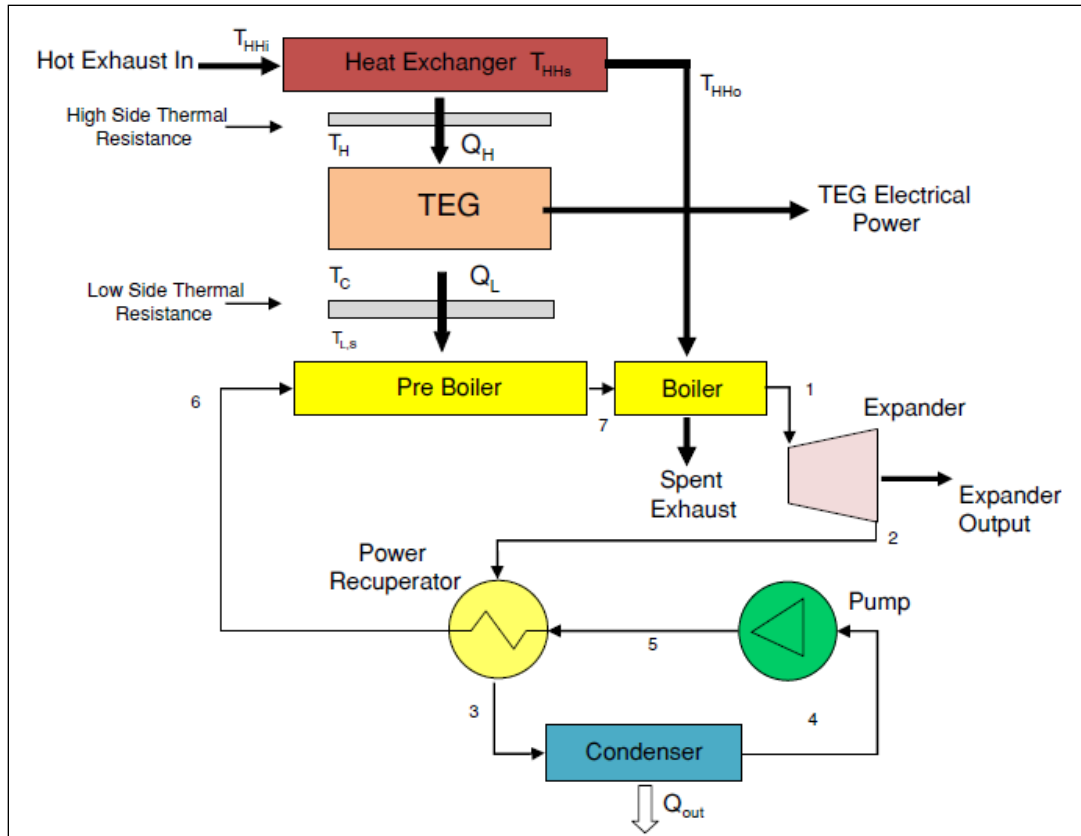


Figure 4. Combined thermoelectric/organic Rankine waste heat recovery, from reference 19.

Considering the options discussed previously, the highest impact research areas in the short term definitely reside in the development of new thermoelectric materials showing a $Z\bar{T}$ of $\sim 1\text{--}2$, the commercialization of high temperature materials and devices, as well as improved engineering and packaging of thermoelectric modules and systems to reduce parasitics and enable scale-up to the appropriate level. In the far term, high temperature, direct generation applications could benefit from further TPV development.

2.2 Electronics Cooling

The ubiquity and increasing complexity of electronic components within Army systems creates significant platform challenges related to waste-heat removal. These include power conversion electronics, optical devices, radio frequency (RF) components, and even consumer electronic devices on vehicle, Soldier, and weapons systems. While the performance of many of these components is often strongly dependent on temperature, the thermal management elements themselves are considered part of the system overhead. Thus, the goal for the platform is to reduce this overhead by minimizing the SWaP required by the thermal system to ensure adequate operating conditions for the electronic components.

2.2.1 Electronics Cooling – Army Applications

The majority of electronics cooling efforts within the Army have focused on the thermal management of power conversion electronics in vehicle systems. As with the commercial vehicle sector, increasing electrification of the ground vehicle platform is seen as a way of boosting both efficiency and capability. This was most recently demonstrated in the now discontinued Future Combat Systems (FCS) program, which had hybrid and electric manned ground vehicle (MGV) platforms as a primary deliverable. Even future non-hybrid drivetrain vehicles are being designed with more complicated power electronics elements than current vehicles, with the primary goal of more efficient non-drive vehicle systems and enabled use of advanced offensive and defensive payloads. Figure 5 shows an example of the representative electronic power conversion elements within either mechanical or hybrid Army vehicle systems.

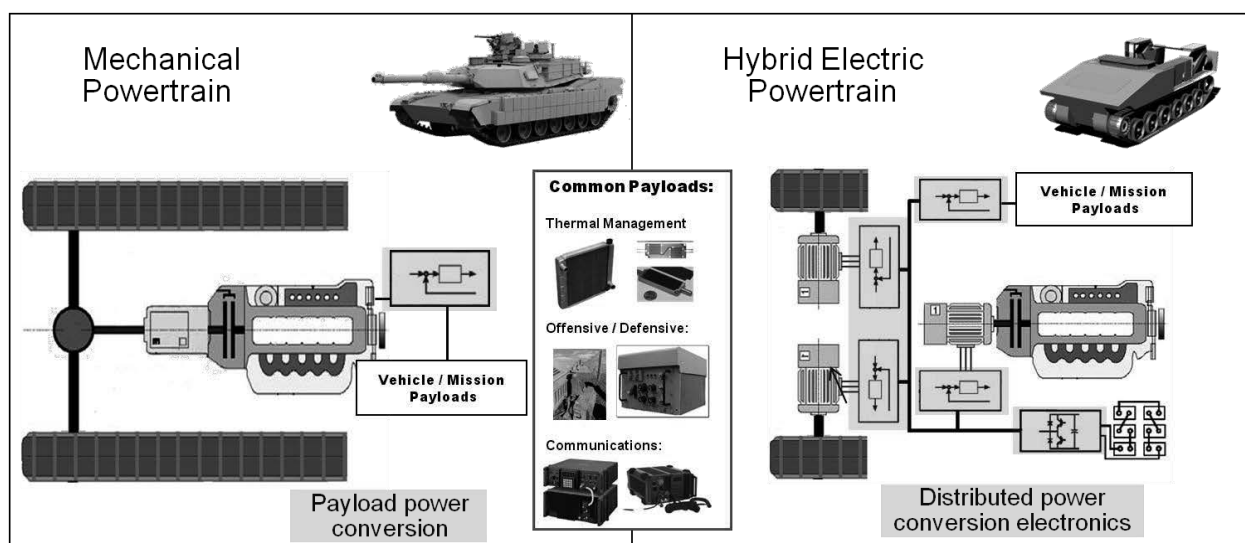


Figure 5. Representative electronic power conversion elements within either mechanical or hybrid Army vehicle systems.

While a more-electric approach to vehicle design can lead to increased overall efficiency and/or performance, platform size and weight limitations can make the electronics themselves a thermal problem as designers increase power density and remove space for associated cooling. Maintaining device temperatures within acceptable limits becomes a challenge that requires proper thermal engineering from the device package all the way to where the heat is rejected from the platform cooling system. Power devices are typically silicon, with associated operating temperature limits of 125–150 °C (21). In combination with the trend toward increasing coolant temperatures (~100 °C) to reduce vehicle radiator size, there is little temperature margin for these devices under normal operation. As a result, device heat fluxes typically have to be kept below 100 W cm⁻², meaning more die and larger modules must be used for a given application. Because of limited success in improving vehicle cooling, the Army has been investing heavily in wide bandgap electronic materials, mainly silicon carbide (SiC) but also including new programs

in gallium nitride (GaN), which can survive much higher temperatures (200–400 °C) (22). Recent SiC demonstrations at ARL have shown sustained operation at heat fluxes just under 200 W cm⁻² (23). Such devices can ease temperature restrictions, but may still result in increased heat fluxes imposed on the rest of the thermal management system. However, successful handling of these fluxes via high quality thermal management permits increased device heat flux, which translates into lower total device area for a given power level requirement—reducing overall cost.

While in some ways similar to cooling power conversion electronics, high power RF electronics have operational and system constraints that make them a unique thermal challenge. These can include tighter temperature limits (typically <80 °C) and packaging designs meant to avoid interfering with RF signal propagation. In the Army, these devices can be found in high frequency radio, radar, electronic warfare (EW), and other hardware systems primarily on mobile platforms. The amplifiers used in these systems are typically the highest power components, and the high operation frequency necessitates the use of extremely small device features with local heat fluxes much higher than in other power conversion electronics (24). These hotspots are the primary impediment to RF device progress as they limit total system operating power and reduce the effectiveness of cooling techniques used for traditional power devices (25). In addition, many RF devices are implemented in large array configurations that limit practical options for packaging and coolant delivery. Recent advances in wide bandgap semiconductor technology, specifically GaN-based electronics, have allowed order-of-magnitude increases in both total power and power density over competing technologies (26), but this also further increases the challenge of removing the heat and maintaining proper device operating temperatures.

Even electronics with lower total heat can create significant cooling problems in some systems, especially those with challenging constraints imposed by the rest of the platform. Recent composite material improvements have resulted in fuel and weight savings for airframes, but this is creating a thermal challenge for missile systems being developed by AMRDEC. Changing missile skins from aluminum to composites can cut weight in half, but it also reduces structure thermal conductivity by a factor of 25–100. This essentially eliminates the primary heat removal path of the missile guidance electronics, whose heat load may only amount to 10's of watts, but the resultant heating is enough to make electronics survivability a primary concern (27).

Other applications are seeing problems with using lower-power electronics in systems and platforms with heat removal capabilities below desired levels. Examples of this include Signals Intelligence (SIGINT), command and control (C2), and communications electronics systems placed in ground and vehicle platforms with inadequate cabin air cooling, which decreases lifetime and reliability as the electronics are operated well above design temperatures (28, 29). This is a concern for both CERDEC, which is one of the primary electronic systems research groups, and TARDEC, which is attempting to develop vehicle platforms to accommodate these systems.

2.2.2 Electronics Cooling – Technology Options

The goal of electronics cooling is to reduce the temperature rise associated with removing heat from the device, also called the device's thermal resistance (R_{th}). Minimizing this thermal resistance requires addressing several aspects of both the device itself and the method by which it is integrated into the system. Here we limit discussion to where it interfaces with the platform, while section 2.2.3 discusses the technology required to get the heat off of the platform.

Figures 6 and 7 display a representative power electronics module and a cross-sectional depiction of its layer stack. Heat is produced at or near the top surface of the semiconductor devices, or die, and it is removed through conduction via the module baseplate. This baseplate is usually connected to either an air-cooled heat sink or a liquid-cooled cold plate depending on what is available in the system. The numerous layers in the thermal path, also called the thermal stack, are the first impediment to heat removal. Thermal improvements in package design include reducing the thickness of these layers, using alternative materials to increase layer thermal conductivity, or removing the layers from the stack entirely. The goal of all of these approaches is to reduce total thermal resistance, including the thermal stack conductive resistance and the fluidic convective resistance, given in one dimensional form by

$$R_{th} = \sum_i \left(\frac{t}{k_{th} A_c} + R_s + R_{int} \right) + \frac{1}{h A_s} \quad (1)$$

Each material layer imposes a conductive resistance, $t/k_{th}A_c$, comprised of the layer's thickness (t), thermal conductivity (k_{th}), and layer cross-sectional area (A_c), in addition to the layer spreading resistance (R_s) and the interface resistance between layers (R_{int}). The convective resistance, $1/hA_s$, is defined by the systems convective heat removal coefficient, h , and the wetted surface area, A_s . It should be noted that minimization of R_{th} can be non-intuitive due to interaction of the individual terms. Excessive thinning may reduce heat spreading and artificially increase interface or convective resistance due to the higher heat flux. Maximizing convective performance may have diminishing returns in the absence of decreasing the package conductive resistance.

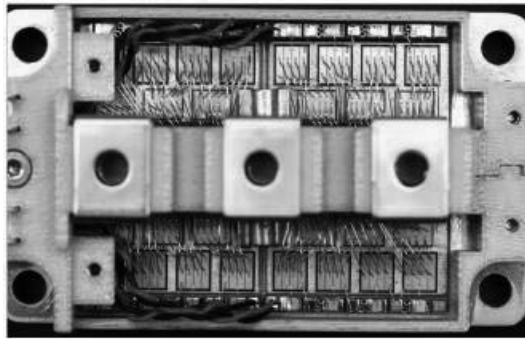


Figure 6. Photograph of a representative power electronics module (23).

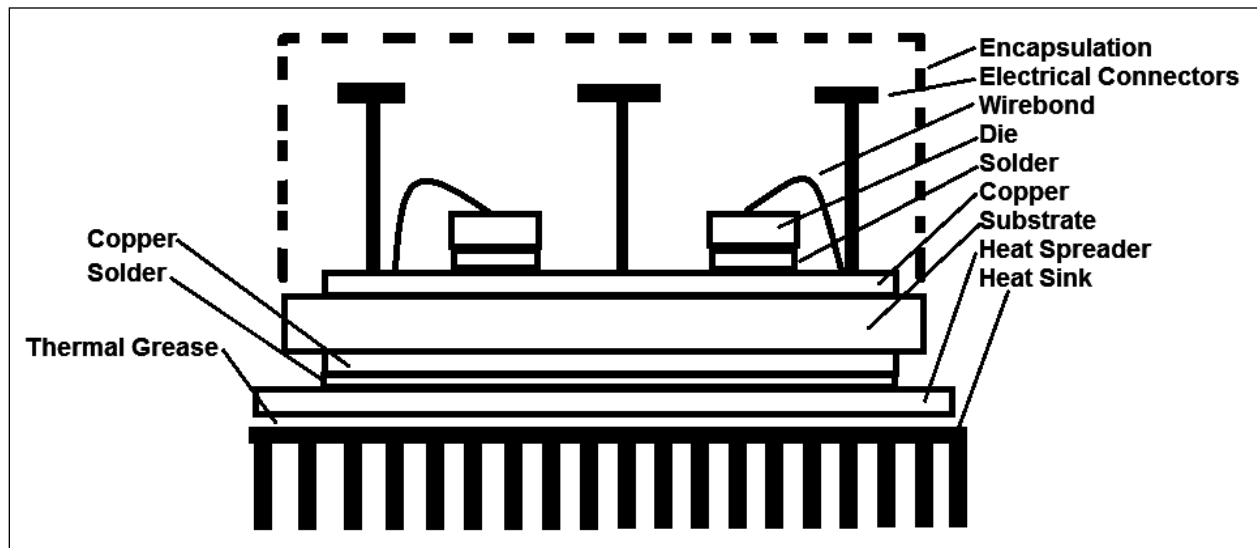


Figure 7. A typical power electronics stack (not to scale).

Recently, ARL has investigated several approaches to developing higher thermal conductivity attach layers (30, 31) and moving the cooling mechanism closer to the devices. This has included cooling integrated into baseplates (32) and ceramic substrates (33, 34) and even directly cooling the backside of the packaged devices (35). A number of other investigators have pursued alternative substrate (beryllium oxide [BeO] [36]) and composite heat sink materials (aluminum-SiC (37), aluminum-carbon (38), etc.) to decrease total conduction resistance while reducing weight and mechanical package stresses.

The other portion of the thermal resistance equation that typically gets the most attention is the convective heat removal component, i.e., the heat sink or cold plate. Briefly, the function of this component is to transfer the heat generated by the electronic devices into a moving fluid for removal from the system. Low power devices may be air-cooled, but higher power devices will generally require liquid cooling because of the improved heat removal capability. Methods of decreasing the convective resistance involve either increasing the fluid convective rate, h , or increasing the wetted surface area, A . The former can be achieved by increasing fluid flow rate, introducing turbulence and mixing, or choosing fluids with higher thermal performance, such as a liquid over air cooling. The effects of different cooling choices can be seen in figure 8.

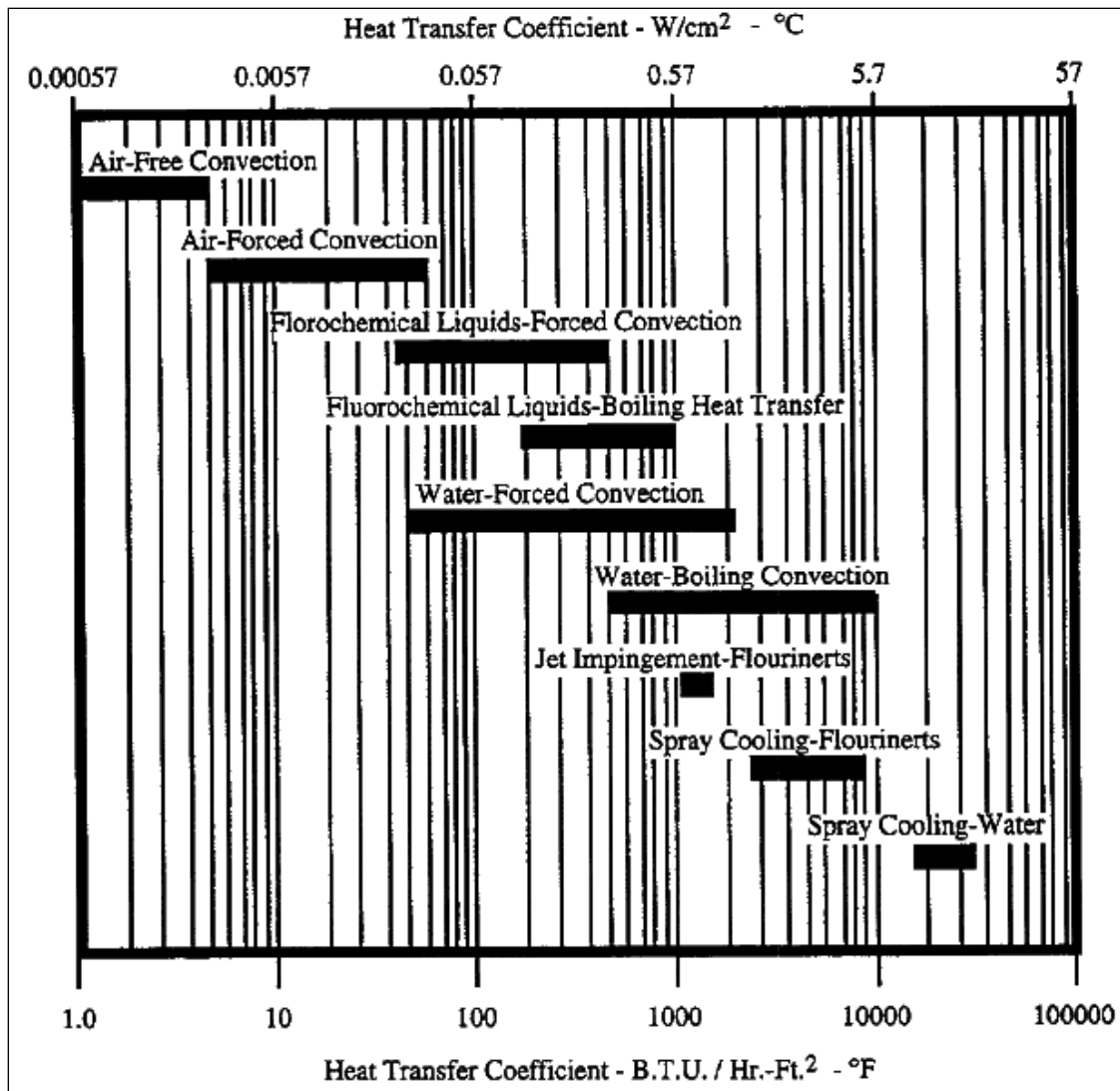


Figure 8. Available convection rates from different fluid delivery technologies (39).

As shown in figure 8, high convective performance can be achieved with alternative fluid delivery schemes such as jets or sprays (39). Even within improved Army systems, however, forced convection has been the primary cooling mode for several reasons, including similarity to conventional systems, lower system requirements, and well-managed fluid containment. Another detail shown in the figure 8 is that almost an order of magnitude increase in heat removal can be achieved by making use of boiling mode heat transfer. In fact, more recent data have shown boiling mode convective rates in excess of $100 \text{ W cm}^{-2} \text{K}^{-1}$ (40). These boiling mode increases are due to a combination of the liquid's latent heat of vaporization promoting isothermal absorption and the mixing of the multiphase fluid boosting convection. In recent demonstrations, ARL has taken a single phase cold plate and operated it in boiling mode, showing a 2–6 times increase in heat removal capability as well as a 2–10 times increase in temperature uniformity across a 12-device module (41).

The second term in the convective resistance component, wetted surface area, can be increased by using extended surfaces in the flow, such as longer fins in an air-cooled heat sink, or by shrinking the fluid passages to increase surface-to-volume ratio in a cold plate. An additional advantage of shrinking the fluid passages is that it permits a more compact cold plate design, but there is an associated cost of increased flow restriction and pumping power requirements, as well as an increased likelihood of fouling and clogging reducing system lifetime. These many factors necessitate proper thermo-fluid design to optimize system performance.

Up to this point, improving thermal performance has been treated as a steady-state problem where minimizing thermal resistance was the primary goal. In practice, however, many electronic components experience on- and off-state transients, as well as possible surge conditions, and there are a number of systems designed specifically for pulsed loads. When designing for a transient condition, not only the resistance but also the thermal capacity of the system needs to be taken into account. The system's thermal time constant defines the speed with which it responds to a transient input and can be expressed as the product of thermal resistance and capacitance:

$$R_{th} = \frac{t}{k_{th} A_c}, C_{th} = \rho V c_p, \tau = R_{th} C_{th} \quad (2)$$

Thermal improvements that reduce R_{th} for steady-state performance inherently reduce τ as well. A smaller thermal time constant means that the component will respond more quickly to a transient, and as shown in an ARL study, can result in hotter power device temperatures under certain conditions (42). Thus, it is necessary to design a transient system with sufficient thermal capacity to keep surge temperatures below acceptable levels. One technology being explored to address this are phase-change materials (PCMs) that melt on heating, thus using the latent heat of phase change to isothermally absorb heat. Because the amount of energy a material can absorb through phase change is much higher than through sensible absorption over an equivalent temperature range, PCMs can be used to thermally buffer electronic devices. ARL has been investigating the use of PCMs within microchanneled electronic substrates for use as thermal buffering components, with the goal of maintaining low thermal resistance while providing increased transient absorption (43). Material selection is highly application specific, however, and there is much work needed in developing materials and integration techniques to take full advantage of PCMs for electronics thermal buffering.

2.3 Heat Transfer

While electronics cooling focuses on improving heat transfer rates and material properties at the microscale, the Army's macroscale heat transfer capability needs abound. With recent conflicts occurring in parts of the world where extreme heat is the norm, heat removal from or effective insulation for platforms, living structures, and Soldiers has been paramount in terms of maintaining or improving operational effectiveness and reducing energy consumption. For the

same two reasons, heat retention is of equally high importance for Soldiers operating in cold environments. Improving the SWaP characteristics of microclimate control systems will always be of interest—whether within the engine compartment and cabin of a vehicle platform, inside a structure, or surrounding an individual Soldier on patrol.

2.3.1 Heat Transfer – Army Applications

TARDEC seeks to improve the efficiency of heat removal from platform engine compartments and cabin areas. Engineers there have looked toward advancing heat exchanger and fan design to impact the SWaP of cooling system radiators and vapor compression cycle (VCC) condensers and evaporators (9). For a VCC, an improved condenser could reduce compressor SWaP requirements.

As mentioned earlier, AMRDEC engineers are reducing missile weight by using a fiber-reinforced polymer composite shell material in place of metals (27). Onboard missile guidance and radar electronics generate heat that must be removed through the missile shell, and composites are not thermally conductive. Thus, there is a need for further research into modifying existing composites or developing lightweight but thermally conductive materials that can be used in the myriad applications where lighter composites are attractive, but the thermal benefits of metals should not be sacrificed.

Environmental control units (ECU) can account for 50% or more of energy usage for a tactical operations center (TOC) housed in a structure like the large Deployable Rapid Assembly Shelter (DRASH). This estimate was calculated using data from a structure powered at Fort Indiantown Gap, PA (44). Though this estimate depends on environmental conditions and assumptions, it indicates that even small ECU performance improvement could have significant energy savings. Winter ECU energy use tends to be even greater than in the summer. Temperatures are farther from humans' comfort zone and heating is typically accomplished with resistive heaters that are not as thermally efficient as the vapor compression cycles used in air conditioning (44). Improved insulation would decrease energy consumption in structures under both hot and cold conditions.

NSRDEC continues to advance the functionality of Army tents and portable structures, in both solid and flexible wall applications. Their engineers are looking towards high-tech insulation that is lightweight, durable, and effective to improve shelter performance. High tech insulation may also be useful in shipping containers where food might be stored and heat from solar loading affects shelf life.

For cooling individual Soldiers, NSRDEC has successfully fielded microclimate control systems, which use a liquid cooled vest for each Soldier in platforms such as the Blackhawk and the Stryker that use a VCC. These systems, called the Air Warrior Microclimate Cooling System, are capable of removing up to 180 W from an individual. Systems intended for use by a dismounted Soldier still need reduction in size and weight.

2.3.2 Heat Transfer – Technology Options

For improvement in any of the heat transfer application areas mentioned in section 2.3.1, there must be improvement in the fundamental heat transfer physical mechanisms associated with their designs. Essentially, improvement would be constituted by increasing or decreasing conduction through a solid, convection in a fluid, or radiation emitted to or from a surface. Conduction rates are dependent on the thermal conductivity, k , of a material, while heat transfer from a solid to a fluid is dependent on a proportionality constant called the convection heat transfer coefficient. The convection heat transfer coefficient, h , is dependent on numerous variables, including flow conditions next to the solid boundary and a number of thermodynamic and transport properties of the fluid (45). Radiant energy absorption is dependent on a material surface property called absorptivity, α . Ignoring radiative heat transfer for simplicity, the conduction heat flux (W m^{-2}) is expressed as

$$q''_{\text{conduction}} = -k \frac{dT}{dx} \quad (3)$$

where $\frac{dT}{dx}$ is the derivative of the temperature distribution from one side of the solid to the other. The convection heat flux (W m^{-2}) is expressed as

$$q''_{\text{convection}} = h(T_s - T_\infty) \quad (4)$$

where T_s is the temperature of the solid surface and T_∞ is the temperature of the fluid. To obtain heat transfer rates in watts for both of these equations, multiply by the cross-sectional area through which the heat transfer is occurring. To increase the heat transfer rates, surface area can be increased, h or k can be increased, and temperature differences can be higher. In the case of conduction, material thickness can be reduced. To decrease the rates, the inverse of these rules applies.

With these heat transfer fundamentals in mind, it is possible to approach improvement of combat vehicle engine compartment and crew cabin thermal environment from a number of different perspectives. Starting from the outside of a combat vehicle and working inwards, it would be conceivable to try to change the vehicle's surface characteristics to enhance convection or reduce solar loading; modify the armor material properties to enhance conduction or reduce specific heat capacity; or reduce heat generation from various mechanical and electrical internal components of the vehicle.

Approaching the problem from one perspective, TARDEC thermal engineers have innovative plans to enhance convection in engine compartments by focusing on the advancement of cooling system fan blade design coupled with a variable speed motor (9). This will enhance the efficiency and compactness of engine cooling systems, and decrease the power draw from the engine. Advancing heat exchanger design will require material and geometry improvements, as well as innovative designs that take greater advantage of the high convective heat transfer coefficients that occur during two-phase cooling. Traditional condensers have the entire mass

flow of refrigerant following a single path back and forth in an S-pattern through heat transfer enhancing fins. A design that could potentially be incorporated into cooling system condensers and evaporators is one that allows some of the superheated vapor initially entering the condenser to be redirected and injected back into the mainstream flow further downstream. This concept is displayed in figure 9. Ye et al. (46) experimented with this type of design using mini-channels of hydraulic diameter 1.3 mm. Their results showed up to a 9.6% improvement in heat transfer for the condenser using the re-injection scheme relative to a baseline test without re-injection.

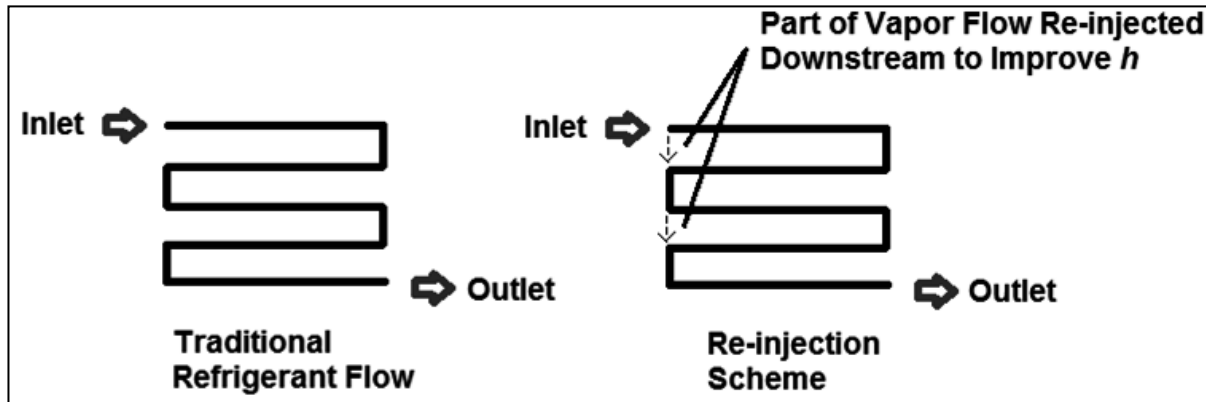


Figure 9. Potential condenser redesign scheme from (46).

Solar loading of an armored vehicle is tremendous given its large mass and thus large energy storage capacity. The solar load must be overcome by both the engine cooling system and cabin air conditioning. In one approach, TARDEC engineers are considering development of an active insulation for vehicles that responds to temperatures and solar radiation (9). The insulation would actively increase R-values (R is a measure of thermal resistance that is a ratio of the driving temperature difference to the corresponding heat transfer rate) on portions of a combat vehicle exposed to higher temperatures and solar loading while decreasing R-values in areas that could reject heat to a lower ambient temperature.

To improve the conductivity through composite missile shells, AMRDEC engineers have experimented with incorporation of metal pins in their composite construction. Heat spreading techniques have also been used to reduce the intensity of hotspots at the missile shell wall.

For tents, solar barriers are cost effective at reducing energy consumption in summer months while insulating liners reduce the heating required in winter months (47). The insulating liners tend to be heavy and expensive, so NSRDEC has called upon industry to improve immature technology alternatives such as aerogel, phase change, and collapsible cellular types of insulation.

2.4 Application Area Summary

As shown earlier, thermal management challenges are prevalent across numerous organizations and applications within RDECOM. The technical obstacles faced have an immediate and definite impact on the performance and capability of resulting Army systems, thus finding an effective and efficient way of addressing these research areas is of paramount importance.

2.4.1 Path Forward

As a result of our roadmapping efforts, we suggest a new taxonomy (figure 10) to be used by RDECOM and the PE TFT that reflects the three common research areas identified in section 2.3. Inside each major category, we note the sub-focus areas and primary projects/programs in that area while noting the organizations most invested in each.

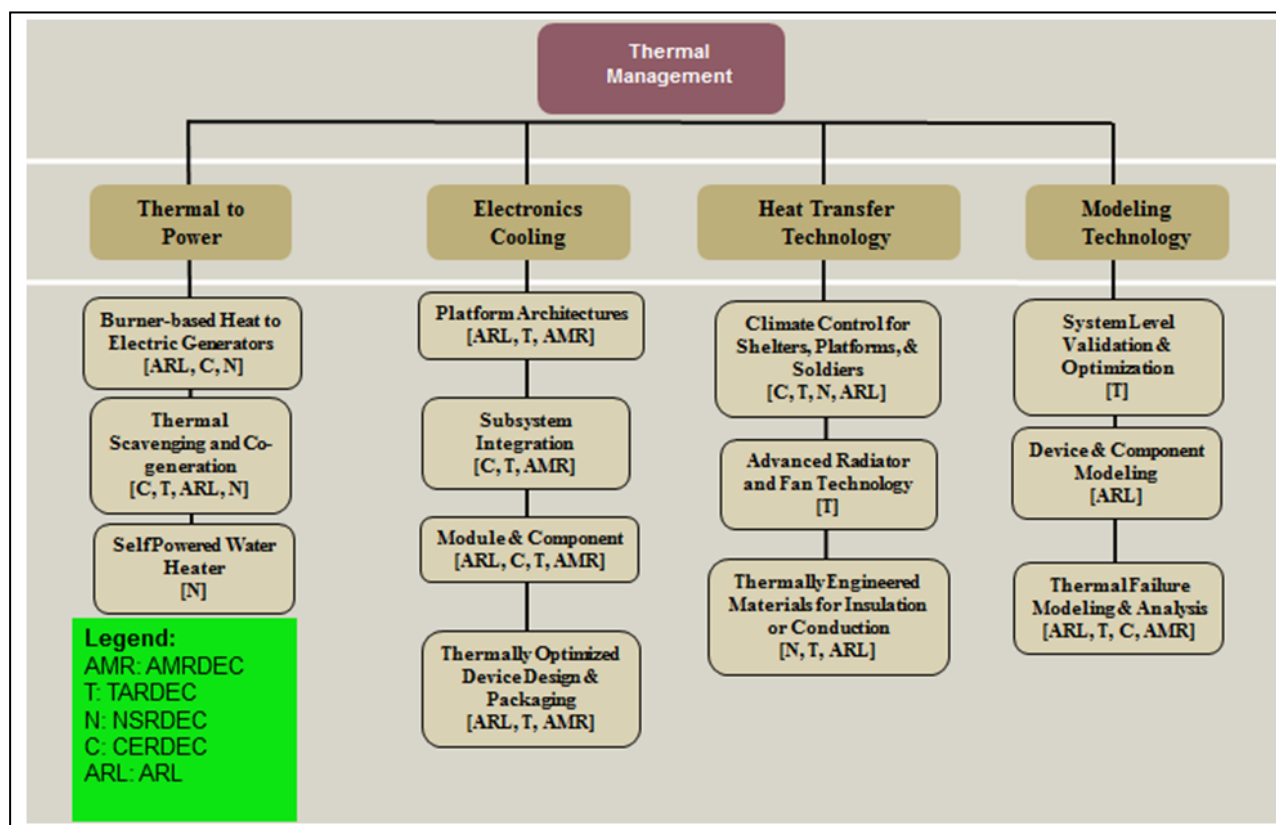


Figure 10. RDECOM thermal management taxonomy chart.

One will notice that a fourth major category is included in this taxonomy called Modeling Technology. The Army Material Systems Analysis Activity (AMSAA) provides extensive thermal and stress analysis capabilities for the RDECs, but their work is mostly focused on analysis of existing systems rather than systems that “could be.” In contrast, each thermal research and development target is implicitly evaluated using various modeling tools across ARL and the RDECs. These tools range from multi-physics-based models to system-level software for evaluating fundamental constraints, identifying technical bottlenecks, and prioritizing

investments. Modeling, therefore, cuts across all application areas and thus deserves to be called out separately as a major category of thermal management activity. It should also be noted that modeling at or across these various technology development levels requires specific and dedicated expertise to perform accurately and to be able to extract meaningful conclusions.

To support this taxonomy, we recommend that the RDECs stay aligned by application area, but that ARL align its basic and applied research into three research areas: materials, fluidic heat transfer, and modeling. These research areas will most effectively cover the applications and technology relevant to the RDECs and have been identified as having high potential payoff for Army investment. Furthermore, it is expected that each area will be an Army priority for many years, such that small teams of 4–5 subject matter experts in each could be fostered as stable entities for the RDECs and other DoD groups to leverage as their application needs wax and wane. The approximate focus and benefits of each of these areas is suggested below:

- *Materials:* Achieving extremely high or low thermal conductivity in constitutive materials can have immediate impact in numerous spaces, like shelter temperature regulation or heat spreading within electronic components. For energy conversion, such as thermoelectric or thermophotovoltaics, the exchange between energy domains requires careful control of both electronic and thermal material properties to achieve desired efficiencies. Unique combinations of material properties may also be important—for example, high thermal conductivity in a lightweight material could reduce the bulk of air-side radiators, or matching rare-earth-based thermoelectric cooling performance with earth-abundant materials could decrease cost and secure supplies. Therefore, a group with a pure materials research focus, and the ability to characterize the primary thermal properties of interest, has a rich pool of applications, materials systems, and opportunities for impact.
- *Fluidic Heat Transfer:* The limited cooling density of air heat exchangers, also a top concern for the Department of Energy (48), adds a significant SWaP penalty to a given system and is incompatible with many of the Army's small high flux thermal sources. Moderate thermal flux applications could benefit from further development of passive spreaders like heat pipes, which offer effective thermal conductivities higher than diamond by leveraging latent heat effects and capillary pumping to spread the generated heat over a local area. Applications with extreme heat flux likely need direct fluidic cooling in a pumped loop; however, the performance of such a loop is highly dependent on fluid and surface parameters, as well as geometric/manufacturing constraints on the proximity to the heat source with which fluid can be brought. As a result, understanding and optimizing the transfer of heat to/from air and other fluids across size scales and surfaces is a critical and ongoing challenge that the Army should be addressing for its own unique applications.
- *Modeling:* To articulate potential component performance improvements or extrapolate component performance into capabilities in higher level systems, a concerted effort in thermal modeling is essential. This capability should span from analytical models of basic

physical phenomenon, to finite element models of small subsystems, up through simplified system-of-system models. Not only is the software required to do this expensive, making coalescence around a centralized team ideal, but significant experience and training is required to use it properly (mundane issues like improper mesh convergence can render all output meaningless). In particular, modeling of this sort requires experience and expertise to ensure internal assumptions and boundary conditions are, in fact, representative of the physical system, while also defining a tractable solution space from which meaningful conclusions can be drawn. Therefore, this team in particular must be a collaborative venture with the application and component developers and would serve as resource across the technical readiness level (TRL) spectrum.

This centralized thermal management structure at ARL will provide easy access to thermal expertise and consulting assistance for the RDECs to ensure sound consideration of heat transfer or thermal bottlenecks in various stages of the technology development cycle.

3. Conclusion

The cross-engineering discipline, widespread nature, and constant change of RDECOM's (and the Army's) thermal management capability needs call for a periodic review of its status that aids in a general aligning of all the different moving pieces into a cohesive effort. This technical report, based on the P&E TFT's 2011 early efforts at roadmapping for thermal management technologies, has reviewed the current thermal management application portfolio in RDECOM and summarized the candidate technologies being developed to address these applications. A new taxonomy was then introduced to reflect the current RDECOM focus and a re-alignment/increased investment of ARL thermal management efforts was recommended to provide a stronger supporting fundamental research capability that aligns with the areas poised for highest potential impact.

4. References

1. United States Department of Defense, Office of the Assistant Secretary of defense for Operational Energy, Plans, and Programs. *Energy for the warfighter: Operational energy strategy*; Technical Report, May 2011, <http://www.dtic.mil/docs/citations/ADA544100.ADA481011>.
2. United States Department of the Army, Research, Development and Engineering Command, Army Capabilities Integration Center. *Power and Energy Strategy White Paper*; Technical Report; April 2010, <http://www.arcic.army.mil/Docs/PE%20Strategy%20Apr%202010.pdf>.
3. Power and Energy Architecture for Army Advanced Energy Initiative, Nov 1 2006. 2006 Army Science Conference. <http://www.dtic.mil/docs/citations/ADA481011>.
4. Chau, K.; Chan, C. Emerging Energy-Efficient Technologies for Hybrid Electric Vehicles. *Proceedings of the IEEE* **2007**, 95 (4), 821–835. doi:10.1109/JPROC.2006.890114.
5. Yang, J. Potential Application of Waste Heat Recovery in the Automotive Industry. *Proc. of 2005 IEEE International Conference on Thermoelectrics*, 2005, 155–159.
6. Smith, K.; Thornton, M. *Feasibility of Thermoelectrics for Waste Heat Recovery in Conventional Vehicles*; NREL/TP-540-44247; National Renewable Energy Laboratory Department of Energy: Golden, CO, 2009.
7. Hendricks, T. J.; Lustbader, J. A. Advanced Thermoelectric Power System Investigations for Light-duty and Heavy Duty applications. *I International Conference on Thermoelectrics* 2002, 381–386. doi:10.1109/ICT.2002.1190343.
8. Fairbanks, J. Vehicular Thermoelectrics: A New Green Technology. *2011 Directions in Engine-Efficiency and Emissions Research (DEER) Conference*, Detroit, MI, Oct 3–6, 2011.
9. Crane, D. T.; LaGrandeur, J. Progress Report on BSST-Led U.S. Department of Energy Automotive Waste Heat Recovery Program. *J. of Electronic Materials* **2010**, 39 (9).
10. Crane, D. T.; LaGrandeur, J. Progress Report on BSST-Led U.S. Department of Energy Automotive Waste Heat Recovery Program. *J. of Electronic Materials* **2010**, 39 (9).
11. Cardine, Christopher. Scientist for Tank Technologies, Engineering, Development and Technology, General Dynamics Land Systems, personal communication, 3 February 2012.
12. Army AL&T Magazine, April–June 2012, p10.
13. Waits, C. M. *Thermophotovoltaic Energy Conversion for Personal Power Sources*; ARL-TR-5942; U.S. Army Research Laboratory: Adelphi, MD, Feb 2012.

14. Guazzoni, G.; Matthews, S. A Retrospective of Four Decades of Military Interest in Thermophotovoltaics. In *AIP Conference Proceedings* **2004**, 738, 3–12.
15. Bermel, P.; Ghebrehbrhan, M.; Chan, W.; Yeng, Y.; Araghchini, M.; Hamam, R.; Marton, C.; Jensen, K.; Soljagic, M.; Joannopoulos, J.; Johnson, S.; Celanovic, I. Design and Global Optimization of High Efficiency Thermophotovoltaic Systems. *Optics Express* **13 September 2012**, 18, A314–A334.
16. Wernsman, B.; Siergeij, R. R.; Link, S. D.; Mahorter, R. G.; Palmisiano, M. N.; Wehrer, R. J.; Schultz, R. W.; Schmuck, G. P.; Messham, R. L.; Murray, S.; Murray, C. S.; Newman, F.; Taylor, D.; Depoy, D. M.; Rahmlow, T. Greater than 20% Radiant Heat Conversion Efficiency of a Thermophotovoltaic Radiator/Module System Using Reflective Spectral Control. *IEEE Transactions on Electron Devices* **March 2004**, 51, 512–515.
17. Tuley, R. S.; Nicholas, R. J. Band Gap Dependent Thermophotovoltaic Device Performance using the InGaAs and InGaAsP Material System. *J. of Applied Physics* **15 Oct 2012**, 108.
18. Tritt, T. M. Thermoelectric Phenomena, Materials, and Applications. *Annual Review of Materials Research* **2011**, 1, 433–448.
19. Miller, E.; Hendricks, T.; Peterson, R. Modeling Energy Recovery Using Thermoelectric Conversion Integrated with an Organic Rankine Bottoming Cycle. *J. of Electronic Materials* **2009**, 38 (7), 1206–1213.
20. Weerasinghe, W.M.S.R.; Stobart, R. K.; Hounsham, S. M. Thermal Efficiency Improvement in High Output Diesel Engines a Comparison of a Rankine Cycle with Turbo-compounding. *Applied Thermal Engineering* **2010**, 30 (14–15), 2253–2256.
doi:10.1016/j.applthermaleng.2010.04.028.
21. Johnson, R. W.; Evans, J. L.; Jacobsen, P.; Thompson, J. R.; Christopher, M. The Changing Automotive Environment: High-temperature Electronics. *IEEE Trans Electron Packag. Manuf.* **July 2004**, 27 (3), 164–176. doi:10.1109/TEPM.2004.843109.
22. McCluskey, F. P.; Grzybowski, R.; Podlesak, T. *High Temperature Electronics. The Electronic Packaging Series*; New York, NY: CRC Press; 1997.
23. Urciuoli, D.; Green, R.; Lelis, A.; Ibitayo, D. Performance of a Dual, 1200 V, 400 A, Silicon-carbide Power MOSFET Module. In: *Proc. IEEE Energy Conversion Congress and Exposition*, 2010 Sep 12–16; Atlanta, GA. p. 3303–3310. doi: 10.1109/ECCE.2010.5618324.
24. Mishra, U. K.; Parikh, P.; Wu, Y.-F. AlGa_N/Ga_N HEMTs-An Overview of Device Operation and Applications. *Proceedings of the IEEE* **2002**, 90 (6), 1059–1064.
25. Janice Rock of AMRDEC, phone interview, July 2011.

26. Kemerley, R. T.; Wallace, H. B.; Yoder, M. N. Impact Wide Bandgap Microwave Devices on DoD Systems. *Proceedings of the IEEE* **2002**, 90 (6), 1022–1031.
27. Roberts, K. Integrated Thermal Management Solutions in Composite Missile Skins. *Presented at the 18th Annual International Conference on Composites/Nano Engineering*, Anchorage, AK. July 4–10, 2010.
28. Conover, J.; Husted, H.; MacBain, J.; McKee, H. Logistics and Capability Implications of a Bradley Fighting Vehicle with a Fuel Cell Auxiliary Power Unit. In: *Proc. 2004 SAE World Congress*, 2004 Mar 8–11; Detroit, MI. doi: 10.4271/2004-01-1586.
29. Finn, J.; Ewing, D. J.; Ma, L.; Wagner, J. Thermal Protection of Vehicle Payloads using Phase Change Materials and Liquid Cooling. In: *Proc. 2010 American Control Conference*, Jun 30–Jul 2, 2010, Baltimore, MD, 1204–1210.
30. Rodriguez, Rogie I.; Ibitayo, Dimeji; Quintero, Pedro O. High Temperature Die Attach by Low Temperature Solid-Liquid Interdiffusion. In *Proc. Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems (InterPACK2011)*, July 6–8, 2011, Portland, Oregon, 9–17. doi:10.1115/ipack2011-52049.
31. Ibitayo, D.; Everhart, L.; Morgenstern, M.; Geil, B. R.; Mitchell, J. W. Reliability Assessment of Lead-free Universal Solder for Direct Bonding in Power Electronics Packaging. in *proc. 10th Electronics Packaging Technology Conference*, Singapore, 9–12 Dec 2008, 1364–1368.
32. Urciuoli, D.; Green, R.; Lelis, A.; Ibitayo, D. Performance of a Dual, 1200 V, 400 A, Silicon-carbide Power MOSFET Module. In: *Proc. IEEE Energy Conversion Congress and Exposition*, 2010 Sep 12–16; Atlanta, GA, 3303–3310. doi: 10.1109/ECCE.2010.5618324.
33. Jankowski, N. R.; Everhart, L.; Geil, B. R.; Tipton, C. W.; Chaney, J.; Heil, T. et al. Stereolithographically Fabricated Aluminum Nitride Microchannel Substrates for Integrated Power Electronics Cooling. In: *Proc. 11th Intersociety Thermal and Thermomechanical Phenomena in Electronic Systems Conference*, 2008 May 28–31; Orlando, FL, 180–188. doi: 10.1109/ITHERM.2008.4544269.
34. Sharar, D. J.; Jankowski, N. R.; Morgan, B. Thermal Performance of a Direct-Bond-Copper Aluminum Nitride Manifold-microchannel Xooler. In: *Proc. Semiconductor Thermal Measurement and Management Symposium*, 2010 Feb 21–25; Santa Clara, CA, 68–73. doi: 10.1016/j.rser.2007.10.005.

35. Boteler, L.; Jankowski, N.; Geil, B.; McCluskey, P. A Micromachined Manifold Microchannel Cooler. In: *Proc. International Mechanical Engineering Congress and Exposition, 2009*, 2009 Nov 13–19; Lake Buena Vista, FL, 61–68. doi: 10.1115/IMECE2009-11780.
36. Akishin, G. P.; Turnaev, S. K.; Ya, V.; Vaispapir, M. A.; Gorbunova, Yu.; Makurin, N. Kiiko, V. S.; Ivanovskii A. L. Thermal Conductivity of Beryllium Oxide Ceramic. *Refractories and Industrial Ceramics* **2009**, 50 (6), 465–468. DOI: 10.1007/s11148-010-9239-z.
37. Mallik, Sabuj; Ekere, Ndy; Best, Chris; Bhatti, Raj. Investigation of Thermal Management Materials for Automotive Electronic Control Units. *Applied Thermal Engineering* **2010**, 31 (2–3), 355–362. doi:10.1016/j.applthermaleng.2010.09.023.
38. Jiang, N.; Novak, J.; Fink, R. Fabrication and Characterization of Carbon-Aluminum Thermal Management Composites. in *Proc. IEEE SEMI-Therm 2010*, Austin, TX, 2010, 87–92.
39. Sienski, K.; Eden, R.; Schaefer, D. 3-D Electronic Interconnect Packaging. *Proc of the IEEE Aerospace Applications Conference*, vol.1, Aspen, CO, 3–10 Feb 1996, pp. 363–373. doi:10.1109/AERO.1996.495896.
40. Mudawar, I. Assessment of High-heat-flux Thermal Management Schemes. *IEEE Transactions on Components and Packaging Technologies* **June 2001**, 24 (2), 122–141.
41. Sharar, D.; Morgan, B.; Jankowski, N. R.; Bar-Cohen, A. Two-phase Minichannel Cold Plate for Army Vehicle Power Electronics. in *Proc ASME Pacific Rim Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Systems*, July 6–8, 2011, Portland, Oregon, pp. 133–142. doi:10.1115/IPACK2011-52079.
42. Jankowski, N. R.; McCluskey, F. P. Modeling Transient Thermal Response of Pulsed Power Electronic Packages. In: *Proc. IEEE Pulsed Power Conference*, 2009 Jun 28–Jul 2; Washington, DC. p. 820–825. doi: 10.1109/PPC.2009.5386368.
43. Jankowski, N. R.; McCluskey, F. P. Numerical Study on the Thermal Performance of a Substrate Integrated Thermal Buffer Heat Sink. In: *Proc. International Mechanical Engineering Congress and Exposition*, Denver, CO, Nov. 11–17, 2011.
44. David Carrier of AMSAA, Phone Interview, 12 Mar 2012.
45. Incropera, F. P.; DeWitt, D. P. *Introduction to Heat Transfer*, Chap 1; John Wiley & Sons, New York, 1996, pp. 4–9.
46. Ye, Liang; Tong, Ming Wei; Zeng, Xin Design and Analysis of Multiple Parallel-pass Condensers. *International Journal of Refrigeration* **2009**, 32, 1153–1161.

47. Kostka, F. E. Primer on the Development of Military Shelters. *Military Medical/CBRN Technology* **2011**, 15 (6).
48. Energy Recovery and Thermal Management Breakout Group Notes, Advanced Vehicle and Power Technology Workshop, July 18, 2011, Detroit, MI.

Appendix. Informal Survey Results

Table A-1 shows the results of ARL's informal survey of major thermoelectric manufacturers and researchers. Responses were restricted to experimental data for power generation modules. No attempt was made to verify or validate the data reported by each individual, nor were the methods of testing consistent from one to the next; bottom line, take the data with a grain of salt. Nonetheless, the cumulative data do provide an aggregate snapshot of thermoelectric technology when implemented at the device level. (POC: Brian Morgan, brian.c.morgan25.civ@mail.mil).

Table A-1. Results of ARL's informal survey of major thermoelectric manufacturers and researchers.

Maturity	Manufacturer	POC	Type or Designator	T _{hot} (C)	T _{cold} (C)	Power (W)	Efficiency (%)	Extracted ZT
R&D	ARL	Patrick Taylor	PbTe – Gen 1 / 2010	415	125	0.066	2.5	0.21
R&D	ARL	Patrick Taylor	PbTe – Gen 2 / 2010	379	73	0.125	4.4	0.34
R&D	RTI	Rama Venkatasubramanian	Thin Film Bi ₂ Te ₃ – ICM 2679	230	17	0.036	4.2	0.38
R&D	RTI	Rama Venkatasubramanian	Nano bulk Bi ₂ Te ₃ alloy – BCA 878	250	30	0.015	6.2	0.62
R&D	RTI	Rama Venkatasubramanian	Nano bulk Bi ₂ Te ₃ alloy – BCA 878	280	31	0.019	6.6	0.6
R&D	RTI	Rama Venkatasubramanian	BSST bulk Bi ₂ Te ₃ alloy – BCA 681	228	39	0.028	4.8	0.53
R&D	RTI	Rama Venkatasubramanian	Ames Lab TAGS/PbTe – BCA 794	377	43	0.074	8.5	0.68
R&D	RTI	Rama Venkatasubramanian	Ames Lab TAGS/PbTe BCA 914	375	31	0.188	7	0.5
R&D	RTI	Rama Venkatasubramanian	Ames Lab TAGS/PbTe – BCA 425	364	80	5.1	6	0.54
R&D	RTI	Rama Venkatasubramanian	UVa/Clemson half-Heusler – BCA 907	751	58	0.454	8.9	0.44
R&D	RTI	Les Lee (AFOSR)	Thin Film Bi ₂ Te ₃ (ICM-2994 4x4 bars)	179.7	32.3	0.67	2.6	0.31
R&D	BSST	Doug Crane	TAGS/BiTe & PbTe/BiTe segmented	550	20	5.3	10	0.56
R&D	NASA JPL	Jean-Pierre Fleurial	Skutterudites	590	90	1.27	9.8	0.66
R&D	NASA JPL	Jean-Pierre Fleurial	Skutterudites	700	90	1.05	11.5	0.71
R&D	NASA JPL	Jean-Pierre Fleurial	Bi ₂ Te ₃ / Skutterudites	700	27	1.2	13.8	0.76
R&D	NASA JPL	Jean-Pierre Fleurial	Skutterudites	455	206	1.01	4.7	0.6

Note: AFOSR=Air Force Office of Scientific Research, BiTe=bismuth telluride, Bi₂Te₃=bismuth telluride, JPL=Jet Propulsion Laboratory, NASA= National Aeronautics and Space Administration, PbTe=lead telluride, TAGS= tellurium, antimony, germanium and silver, and UVa=University of Virginia,

Table A-1. Results of ARL's informal survey of major thermoelectric manufacturers and researchers (continued).

Maturity	Manufacturer	POC	Type or Designator	T _{hot} (C)	T _{cold} (C)	Power	Efficiency	Extracted ZT
R&D	NASA JPL	Jean-Pierre Fleurial	Yb14MnSb11/La3-xTe4	1000	300	0.53	9.7	0.72
R&D	NASA JPL	Jean-Pierre Fleurial	Yb14MnSb11/La3-xTe4	900	71	0.54	9.7	0.45
R&D	NASA JPL	Jean-Pierre Fleurial	Yb14MnSb11/La3-xTe4/Skutterudites	800	232	0.86	11.1	0.93
R&D	NASA JPL	Jean-Pierre Fleurial	Yb14MnSb11/La3-xTe4/Skutterudites	1000	180	1.48	14.8	0.97
R&D	Tellurex	Chuck Cauchy	LAST / Bi2Te3; segmented	401	95	1.82	6.56	0.59
Early Production	Tellurex	Chuck Cauchy	Bi2Te3	275	35	7.45	5.61	0.51
Early Production	Tellurex	Chuck Cauchy	Bi2Te3	250	35	6.6	5.67	0.57
Product	Custom Thermoelectric	Les Lee (AFOSR)	00201-9G30-18B	218.7	23.6	0.045	5.4	0.57
Product	Ferrotec	Les Lee (AFOSR)	FTH-9500-007-018M	250.9	27.5	0.14	5.6	0.54
Product	Nextreme	Les Lee (AFOSR)	UPF40 eTEG	125.9	30	0.129	1.8	0.31
Product	Marlow Industries	Justin Thompson	TG12-6	170	50	3.38	4	0.69

List of Symbols, Abbreviations, and Acronyms

AFOSR	Air Force Office of Scientific Research
AMRDEC	Aviation-Missile RDEC
AMSAA	Army Material Systems Analysis Activity
ARL	U.S. Army Research Laboratory
BeO	beryllium oxide
BiTe	bismuth telluride
Bi ₂ Te ₃	bismuth telluride
C2	command and control
CERDEC	Communications & Electronics RDEC
DOD	U.S. Department of Defense
DRASH	Deployable Rapid Assembly Shelter
ECU	environmental control units
EW	electronic warfare
FCS	Future Combat Systems
FY12	fiscal year 2012
GaN	gallium nitride
JPL	Jet Propulsion Laboratory
MGV	manned ground vehicle
NASA	National Aeronautics and Space Administration
NSRDEC	Natick Soldier RDEC
P&E IPT	Power & Energy Integrated Product Team
PbTe	lead telluride
PCMs	phase-change materials
RDECOM	U.S. Army Research, Development, and Engineering Command

RDECs	Research, Development, and Engineering Centers
RF	radio frequency
SBIR	small business innovation research
SEDD	Sensor and Electron Devices Directorate
SiC	silicon carbide
SIGNIT	Signals Intelligence
SWaP	size, weight, and power
TAGS	tellurium, antimony, germanium and silver
TARDEC	Tank-Automotive RDEC
TFT	Technical Focus Team
TOC	tactical operations center
TPV	thermophotovoltaic
TRL	technical readiness level
UVa	University of Virginia
VCC	vapor compression cycle

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1	DIRECTOR US ARMY RESEARCH LAB RDRL CIO LL 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	DIRECTOR US ARMY RESEARCH LAB RDRL CIO LT 2800 POWDER MILL RD ADELPHI MD 20783-1197
1	COMMANDER RDECOM ATTN RDMR WDG R J BOOTH BLDG 5400 D235 REDSTONE ARSENAL AL 35898
1	SOLDIER MOBILITY &MSSN ENHANCEMENT TEAM TECHLGY, SYS & PROG DIRCTOT U.S. ARMY NATICK SOLDIER RSRCH, DEV, & ENGRG CTR ATTN RDNS TSE B LAPRISE NATICK MA 0176-5019
7	US ARMY RSRCH LAB ATTN RDRL SED E C MIGLIACCIO ATTN RDRL SED E L BOTELE ATTN RDRL SED E P BARNES ATTN RDRL SED E SHAFFER ATTN RDRL SED P A LELIS ATTN RDRL SED P B GEIL ATTN RDRL SEE I P TAYLOR ADELPHI MD 20783-1197

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