Thermal Conditions for Portable Military Electronic Equipment

Ross Wilcoxon
Rockwell Collins
400 Collins Road
Cedar Rapids, IA USA
rkwilcox@rockwellcollins.com

Abstract

Soldiers and Marines rely on electronics for communication, navigation and situational awareness. Increasing these capabilities, such as with longer range and higher bandwidth communication, generally comes at a price of greater power consumption and a corresponding increase in system power dissipation/thermal load. This increased power dissipation can limit the functional capabilities of systems when used in thermally challenging environments. One of these thermally challenging environments is inside the packs used by dismounted troops. This paper presents the results of testing to quantify the thermal resistance associated with operating electronics within packs that are typical of those that may be used by soldiers and Marines. Thermal mock-up systems were tested in two types of backpacks under various conditions. Steady state and transient temperature test results are compared to predictions generated with a spreadsheet-based analysis.

Keywords

Portable Electronics, Transient Thermal Testing

Nomenclature

Parameter	Units	Description
A	m^2	Heat transfer area
c_p	J/kg K	Specific heat
h	W/m^2K	Convection coefficient
k	W/mK	Thermal conductivity
Δl	cm	Thickness of conduction path
L	m	Vertical distance (for convection)
m	kg	Mass
Q	W	Heat Dissipation
R	°C/W	System thermal resistance
T	°C	Temperature
t	s	Time
ε	-	Emissivity

1. Introduction

The miniaturization of electronics has led to a significant increase in the amount of electronics carried by personnel in military operations. These electronic systems may be used for functions such as Global Positioning System (GPS), night vision and voice/data communications capabilities. New systems will continue to increase the electronic capabilities of soldiers and Marines [1,2]. One critical factor that inhibits the greater use of electronics by individuals on the battlefield is the ability to effectively provide sufficient power for an operation. It is common that soldiers embarking on a three day patrol to carry more than 7 kg of batteries to power their equipment [3]. In response to this, military organizations are actively developing alternative methods for providing electrical power to dismounted troops [3,4].

Increases in the electrical energy available to individuals through technologies such as improved batteries, fuel cells and energy harvesting are beneficial from weight and logistics perspectives. However this greater availability of stored energy will inevitably increase the system power dissipation and add to the thermal management challenges of portable electronics.

Previous investigators have shown that the transient operational time of portable electronics can be extended with technologies such as phase change materials [5.6]. However, there is relatively little published data regarding the thermal conditions for portable electronics when they are placed within devices such as backpacks. The thermal resistance of transport equipment will impact system-level capabilities such as maximum transmit power and allowable operating time, as well as operational procedures such as whether electronics need to be removed from a backpack during use.

2. Objective

In this study, power dissipating test modules were placed within military-style packs and their temperatures were monitored. The objective was to quantify these thermal conditions so that system temperatures could be predicted for a variety of operational scenarios. To address this objective, test data were incorporated into a spreadsheet-based analysis tool to simulate various transient operational scenarios.

While this work was targeted at military electronics applications, the results may also be applicable to other fields, such as consumer products and public safety, in which electronics devices may be operated while stored in a backpack or similar transportations.

3. Testing

Testing was conducted with four combinations of test articles. Test articles included two different transport equipment styles as well as two different thermal dissipation mockup systems that were instrumented for temperature measurements.

3.1. Test Articles

Two transportation equipment, i.e. pack, styles were used in the testing. The first of these was a 5.11 RUSH 24 Backpack [7], which is shown in Figure 1. This pack is a relatively rugged day pack that is used by outdoorsmen as well as military personnel. The pack has multiple pockets that can be closed with zippers. Small holes are located on the bottom of the pack, presumably to allow for the drainage of any spilled liquids. With a diameter of ~2-3mm, these holes were not large enough to provide significant ventilation. This pack is referred to as a 'Backpack' in this paper.

Figure 1: 'Backpack' Pack used in Testing

The second pack style used in this study was the Yote Modular Assault Pack [8] shown in Figure 2. This equipment is better suited for transporting power dissipating systems since it allows much of the system to be exposed to ambient air. In addition, the primary pocket used to hold the electronics is made of a mesh material that improves ventilation on the sides and bottom. In this paper, this pack is referred to as a 'Rucksack' to differentiate it from the more conventional Backpack.

Figure 2: 'Rucksack' Pack used in Testing

The test modules were instrumented with Type T thermocouples and power was dissipated from sets of load resistors attached to the inside of the module covers. Two test modules were fabricated. The 'Small' test module, shown in Figure 3, consisted of an anodized aluminum heat sink with a sheet metal cover that was attached to the edges of the heat sink to cover the heat dissipating load resistors. Figure 4 shows the 'Large' test module, which consisted of a machined aluminum chassis and machined aluminum cover to which load resistors had been attached on the inside surface.

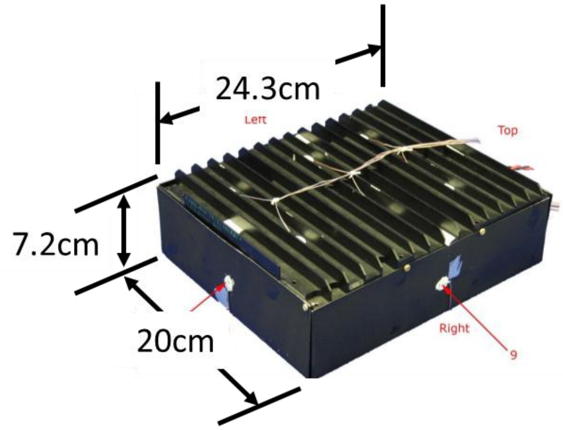

Figure 3: Small Thermal Mockup

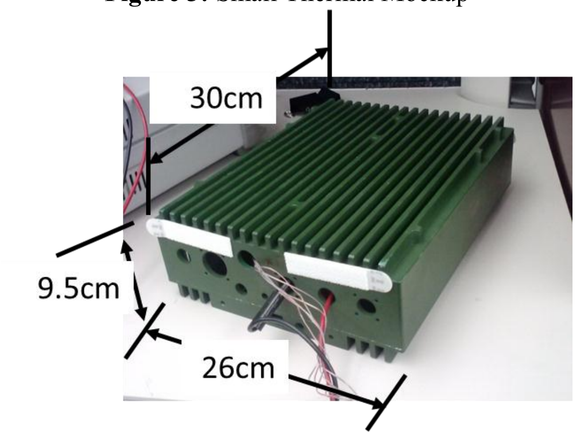

Figure 4: Large Thermal Mockup

3.2. Testing Approach

To simulate ambient conditions for a pack worn by an individual, testing was conducted with packs attached to the back of a conventional chair. This configuration ignored the thermal impact of conduction to the wearer, which could potentially add to or remove heat from the contents within the pack. However, given that each thermal test was conducted for at least two hours to allow the system to stabilize, this approach was logistically more reasonable than using a human test subject. A single test at one power level was conducted with a pack on a volunteer and the measured thermal resistance did not measurably change relative to the standard test.

Testing was conducted by applying a voltage from a DC power supply to the load resistors in the test module. Total power dissipation was monitored with a digital power analyzer. Thermocouple temperatures were recorded using a National Instruments cDAQ-9174 with a 9213 data acquisition module controlled with Labview. Configurations were tested at with power dissipations ranging from 20-65W. Modules were allowed to stabilize such that the temperature variation was less than 0.1°C/min.

While thermocouples were used for monitoring internal temperatures of the test modules, an infrared (IR) camera was also used in early testing to better understand the test results.

Figure 3 shows an IR image of the Backpack during a typical test in which the ambient temperature was 24°C and the power dissipation in the pack was 40W.

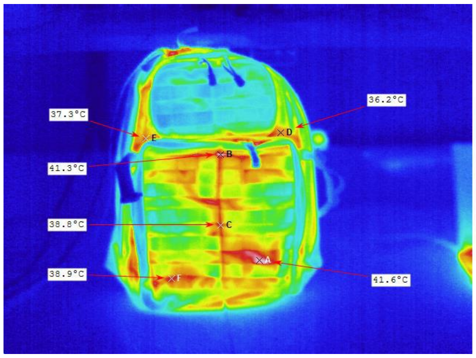

Figure 5: IR Image of Backpack under Test

Test parameters included pack style (Backpack and Rucksack) and test module size (Small and Large). The Backpack was tested both with the top zipper completely closed and with it somewhat open (such that a length of ~15cm was left open to form a gap of ~1-2cm) to improve ventilation past the test module. One set of tests was also conducted with the Backpack filled with insulating material (cloth) to better simulate worst-case use conditions.

3.3. Thermal Augmentation with Air Movers

In addition to quantifying the thermal resistance of packs, some testing was conducted to assess thermal augmentation methods for the Large module in the Backpack. These assessments were not extensive; they were intended to only identify whether adding an air mover would provide sufficient benefit to justify further investigation.

One augmentation method was an array of six Sunon GM1202PFV1-8 miniature rotating fans (shown in Figure 6). The advantages of these fans are that they can increase flow rate relative to free convection, have a low physical profile and they are reasonably quiet[1]. The primary drawback of this augmentation approach is the relative fragility of the fans that limit their suitability for military environments.

Figure 6: Miniature Rotating Fan Array

Figure 7 shows an alternative air-moving approach that used an array of two Nuventix XFlow30 Synjet piezoelectric fans. These fans have no rotating parts and are therefore expected to be more robust than conventional fans. They also generated less noise and consumed less electrical power than the miniature fan array. These fans rely on entraining air to generate flow rather than directly imparting momentum to the air as a fan blade does. Therefore, they were not expected to generate significant net flowrate within the closed Backpack, but would enhance convection through local turbulence.

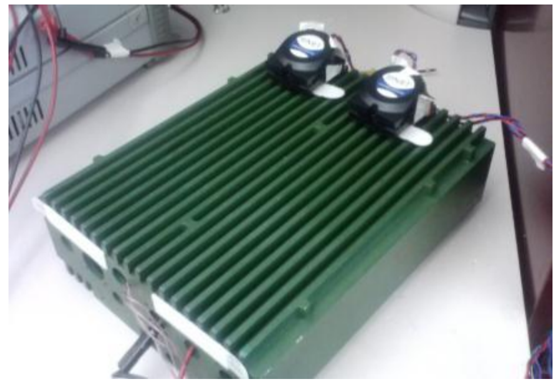

Figure 7: Piezoelectric Fans

3.4. Test Results

3.4.1. Packs Alone

Test results are reported in terms of thermal resistance, R, defines as:

$$R = (T_{max} - T_{ambient}) / Q, \qquad \{1\}$$

where T_{max} is the maximum temperature of the test module chassis, $T_{ambient}$ is the ambient air temperature and Q is the power dissipated from the test module.

Table 1 summarizes data for the two test modules when operated within each of the pack styles as well as a baseline case in which the test module was vertically oriented on a lab bench. This table shows the thermal resistance values, with the numbers in brackets indicating the increase of the increase of thermal resistance in the pack relative to the baseline condition of outside the pack.

Pack	Test Module	
	Small	Large
No Pack (baseline)	0.6-0.7	0.5 - 0.6
Rucksack	0.9 - 1.1 [53%]	0.6-0.8 [27%]
Backpack (closed)	2.0 - 2.3 [230%]	1.1 [100%]
Backpack (open)	1.5 - 1.6 [140%]	1.0 [82%]

Table 1: Measured Thermal Resistance (°C/W) [typical increase relative to baseline]

The additional test conducted with a full pack illustrates that the results shown in Table 1 should be used with some caution when predicting temperatures of fielded equipment. In that testing, the Small module was placed in the Backpack when filled with cloth rags to simulate more typical use conditions. This showed that the full pack had a thermal resistance that was ~60% higher than when the pack was empty (3.7°C/W rather than 2.3°C/W).

[1] Per the manufacturer's data sheet, the expected flow for one of these fans in parallel with a pressure head of 16 Pa (25% of the maximum static pressure) would be ~ 1 L/s and the noise would be 23 dBA.

3.4.2. Thermal Conditions with Small Air Movers

The two air mover configurations assessed in this study did provide some thermal enhancement, however it was not extremely significant. Figure 8 shows a plot of some results of testing conducted with the Large test module in the Backpack. During this testing, the piezoelectric fans drew a total electrical power of 1-1.5 W (power consumption decreased at higher temperatures) while the six miniature rotating fans had a total power consumption of 4.4±0.1 W.

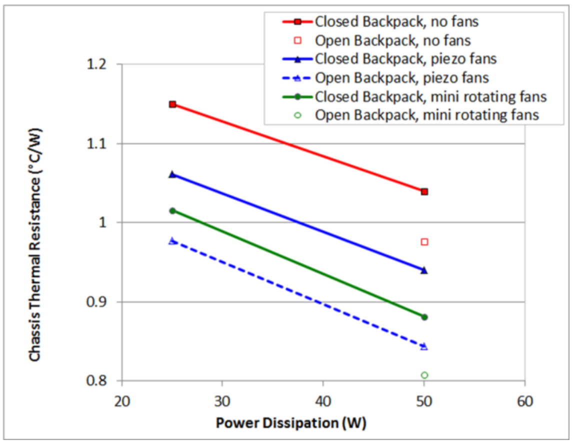

Figure 8: Impact of Air Movers on Thermal Resistance

Overall, the piezoelectric fans reduced the overall thermal resistance by ~10% while the miniature rotating fans reduced thermal resistance by ~15%. In a practical application, the benefit of the rotating fans would likely be reduced by the additional pressure drop associated with shrouding needed to protect their rotating blades.

While the measured benefits achieved with these small air movers were not huge, it should be noted that, in this study, the implementation of these devices was a far from optimized design. With improved ducting and airflow management, as well as a modified chassis fins, these technologies would be good candidates for enhancing the thermal management of portable equipment in the appropriate applications.

4. Predicting System Thermal Characteristics

A spreadsheet-based analysis tool was developed to allow other chassis geometries, power dissipations and thermal enhancements to be assessed. The spreadsheet implemented a hybrid approach that combined empirical test data with analytical thermal resistances to estimate chassis temperatures as a function of time during transient operation.

4.1. Analysis Approach

The spreadsheet analysis was based on the simple resistance network shown in Figure 9. Power dissipated from the chassis traveled through thermal resistances either directly to the surrounding air or first through the pack and then into the air.

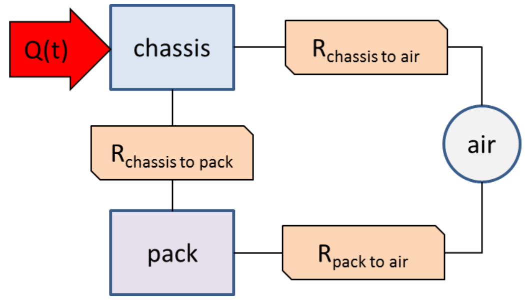

Figure 9: Thermal Resistance Network

The temperature of the chassis was determined using the energy balance equation, shown in Equation {2} for both masses in the system. In this energy balance, the change in the stored energy (E) of a mass is proportional to its rate of change of temperature and equal to power dissipation minus heat losses.

$$\sum \dot{E}_x = Q_x - \sum_{i=1}^{n} \frac{T_x - T_i}{R_{x-i}} = m_x c_{p,x} \frac{dT_x}{dt} \qquad \{2\}$$

Equation {2} can be rearranged into the form shown in Equation {3} and then used to calculate temperatures as a function of time using a finite time step, Δt. This can be accomplished in a spreadsheet by setting the temperatures of the masses (the chassis and the pack) as ambient temperature at time = 0 in the first row of the calculation and then each following row corresponds to one time step later and uses temperatures and power dissipations in the previous row to calculate the new temperature.

$$T_{x,new} = T_{x,old} + \frac{\Delta t}{m_x c_{p,x}} * \left[Q_x - \sum_{i=1}^{n} \frac{T_{x,old} - T_{i,old}}{R_{x-i}} \right] \qquad \{3\}$$

The analysis initially included time dependent power dissipation to account for repeated high power transmit operations followed by lower power receive/standby modes. Figure 10 shows an example of the type of transient thermal responses predicted with the spreadsheet model. To emphasize the 'sawtooth' temperature spikes visible in Figure 10, the analysis used to generate the plot had a very long transmit/receive cycle (multiple minutes). With the shorter cycle times that are more typical of communications systems, the magnitudes of the temperature spikes on the module chassis were much smaller. Therefore, the majority of the subsequent analyses used the less complex boundary condition of constant time-averaged power dissipation.

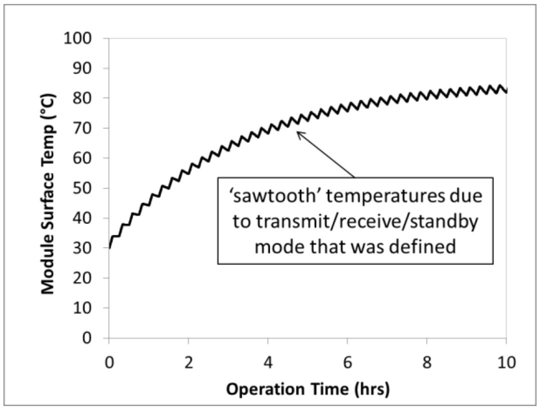

Figure 10: Example of Transient Temperature Prediction

The resistances between nodes in the thermal resistance network were initially defined as fixed values calculated with one dimensional heat transfer equations. The resistance between the chassis and the pack was $R_{chassis\ to\ pack} = \Delta l/kA$, where Δl was the thickness of the pack material, k was the pack material thermal conductivity, and A, was the area of the chassis in contact with pack. The convective resistances, $R_{chassis\ to\ air}$ and $R_{pack\ to\ air}$, were defined as 1/hA, where h was the convection coefficient (assumed to be in the 5-10W/m^{2}K range) and A was the surface area exposed to cooling air. These initial estimates for the individual contributors to the thermal resistances allowed the overall system temperatures to be roughly predicted to provide a better understanding of which parameters had the greatest effect on temperature.

As testing demonstrated that the thermal resistance decreased ~10% when the power dissipation increased, the model was modified to account for temperature dependent convection coefficients. Rather than assuming that the heat transfer coefficients were fixed, the external convection was estimated using the semi-empirical correlation for laminar natural air convection on a vertical plate adapted from [9]:

$$h_{convection}(W/m^2K) \approx 1.42 * \left[\frac{(T_{surface} - T_{air})(°C)}{L(m)}\right]^{1/4} \qquad \{4\}$$

where L is the vertical length of the convecting surface. Radiation was also accounted for by calculating an effective heat transfer coefficient defined as [10][2]:

$$h_{radiation} = \varepsilon\sigma(T_{surface} + T_{air})(T_{surface}^2 + T_{air}^2) \qquad \{5\}$$

where ε is the emissivity of the radiating surface, σ is the Stefan-Boltzmann constant and it is assumed that the temperature of the surroundings is equal to the air temperature. In the analysis, the emissivity of the pack surfaces was assumed to be 0.8. Note that Equation {5} requires the use of absolute temperatures.

For the chassis to air resistance, the 'air' temperature used in Equations {4} and {5} was assumed to be equal to the pack temperature.

4.2. Analysis Results

The spreadsheet inputs included the geometry, mass and time-averaged power dissipation from the module within the pack. The dimensions of the module were used to calculate surface areas for estimating the convective thermal resistance as well as conduction through the pack material. Using a combination of engineering judgment and some fitting of the spreadsheet to the measured data, the thermal conductivity of the pack material was fixed at 1W/mK while its thickness, t, was set to 4mm for the backpack and 2mm for the thinner rucksack. The conduction heat transfer area between the module and the pack, A, was set as total chassis surface area.

For the transient analysis, temperatures were assumed to initially be at the ambient temperature. A time step of 1.5 seconds was used in the analysis and temperatures of the pack and the chassis at the previous time step were used to calculate convection coefficients (with initial values of 5W/m^{2}K). As the transient calculations progressed and the temperatures of the chassis and pack increased over time, the total convection coefficients (including both natural convection and radiation) increased to values in the range of 10-16W/m^{2}K, depending on the power dissipation and resulting surface temperatures.

While the thermal resistances between the chassis and the pack and the pack and ambient air could be estimated reasonably well with simple one-dimensional heat transfer equations, this was not the case when accounting for heat transfer directly between the chassis and ambient air. This heat transfer mode was dependent not only on the thermal conditions in the pack but also factors related to the pack such as whether it was vented. To account for this resistance, it was assumed that $R_{chassis\ to\ air}$ was proportional to $R_{chassis\ to\ pack}$, with the constant of proportionality dependent on the pack configuration. This assumption was based on the expectation that these thermal resistances are both similar functions of surface temperatures. Assessments of test data obtained for both packs and test modules showed that reasonable thermal predictions could be achieved by setting this ratio to the values shown in Table 2. These values are approximate in nature and may change for significantly different pack styles and usages. For example, the 'Backpack (full)' result is based on the test in which the backpack was filled with cloth. In this case, the effective thickness of the backpack used in the spreadsheet was increased to 3cm to account for the thickness of the additional material in the backpack and direct heat transfer from the chassis to ambient was essentially turned off by setting the ratio shown in Table 2 to a value of 100.

Configuration	$R_{chassis\ to\ air}/R_{chassis\ to\ pack}$
Backpack (closed)	4
Backpack (open)	3
Backpack (full)	100
Rucksack	1.1

Table 2: Thermal Resistance Ratios (empirical)

Figure 11 compares results from testing with the transient temperatures predicted with the spreadsheet. The relatively good correlation between the predicted and measured steady

[2] A 'back of the envelope' approximation of this value is $h_{radiation} \approx \varepsilon(4+(T_{surface}+T_{air})/25)$, where T's are in °C [11].

state temperatures in this plot is somewhat biased by the fact that the chassis-to-air thermal resistances (shown in Table 2) were adjusted using test data.

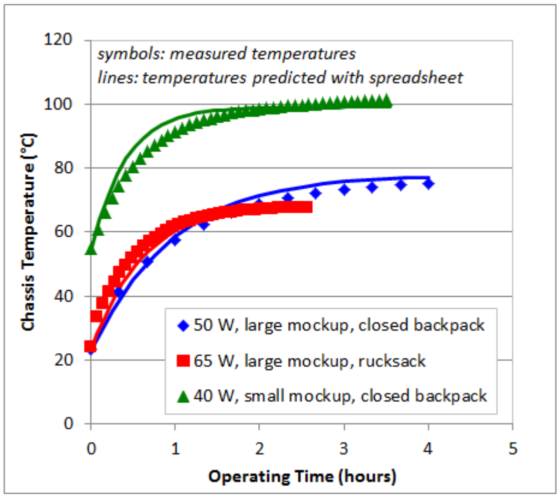

Figure 11: Comparison between Test Data and Analysis

Once the hybrid experimental/analytical spreadsheet analysis had been shown to provide adequate predictions for the experimental data, the spreadsheet was then used to assess design options for man-portable systems under development. This allowed the designers to account for the different geometries, power dissipations, and temperature limits of the proposed designs to estimate transient operational time limits for this equipment. This also provided a basis for evaluating the potential system benefits of including thermal augmentation methods, such as the air movers included in the testing, add-on fin configurations and the use of phase change materials to extend the operating times for the equipment.

5. Conclusions

Operating electronic equipment in transportation equipment such as a backpack can significantly increase the temperatures of that equipment. While this study is far from universal, it does provide some guidance for estimating the impact of the transportation equipment on the electronic temperatures:

- The thermal resistance of equipment in an empty backpack will likely be in the range of 1-2°C/W. The thermal resistance value for a specific application will depend on the size of the electronics system and the backpack construction.
- Placing equipment in a pack that exposes it directly to ambient air, such as the Rucksack in this study, will significantly improve the thermal resistance so that it is approximately half of what it would be in an empty backpack.
- Placing other materials in the backpack will increase the thermal resistance for electronics in that pack. The thermal impact will again depend on the size of the power dissipating equipment and the extent to which the bag is filled. A rough design guideline, based on this very limited data set, would be that a full backpack will have ~50% higher thermal resistance than an empty pack.
- Simple one-dimensional analysis that accounts for heat transfer from electronics to the surrounding pack and convection/radiation from the pack to the surroundings can provide a reasonable estimate of chassis temperatures for equipment used in a backpack. These estimates may be improved, at least for an empty backpack, by adding a parallel thermal resistance directly between electronics and the ambient air that accounts for airflow into the bag. Results from this study indicate that this thermal resistance will be ~3x that of the thermal resistance between the electronics and the bag.
- Small air movers did reduce the system level thermal resistance by ~10-15% with relatively little electrical power requirements; a more optimized design for implementing these air movers is expected to further increase this thermal improvement.

Acknowledgments

The author would like to thank Dave Dlouhy, Rui Zhang and Josh Beals of Rockwell Collins for assistance in conducting the testing and Ted Danhauser of Nuventix in providing Synjet samples for testing.

References

1. Cotton, S.L.; Scanlon, W.G.; Madahar, B.K., "Millimeter-wave soldier-to-soldier communications for covert battlefield operations", Communications Magazine, IEEE, Volume: 47 , Issue: 10, pp. 72-81, 2009
2. Bennett, B.; Gedney, D.; Lincoln, A.; Bush, C.; Marshall, J.; Gibbons, R., "The Rucksack Portable Receive Suite performance over WGS using the DVB-S2 Mini IRD", Military Communications Conference 2011, MILCOM 2011, pp. 1968-1973, 2011
3. K. Johnson, "Fighting Form: Military Takes On Battery Fatigue", The Wall Street Journal, June 14, 2012
4. B. Baker, "Assault on batteries – have soldier-worn power innovations stalled?", http://www.army-technology.com/features/featureassault-batteries-soldier-worn-power-innovations , (referenced 9/15/2013)
5. Vesligaj, M.J.; Amon, C.H. "Transient thermal management of temperature fluctuations during time varying workloads on portable electronics", Components and Packaging Technologies, IEEE Transactions on, On page(s): 541 - 550 Volume: 22, Issue: 4, Dec 1999
6. Alawadhi, E.M.; Amon, C.H. "Performance analysis of an enhanced PCM thermal control unit", Thermal and Thermomechanical Phenomena in Electronic Systems, 2000. ITHERM 2000. The Seventh Intersociety Conference on, Volume: 1, 2000
7. http://www.511tactical.com/ (referenced 12/26/13)
8. http://www.eagleindustries.com (referenced 12/26/13)
9. Steinberg, D. E., "Cooling Techniques for Electronic Equipment", pp. 109, John Wiley & Sons, 1980
10. Incropera, F.P. and DeWitt, D.P., "Fundamentals of Heat and Mass Transfer, 2nd edition, pp. 10, John Wiley & Sons, 1985
11. Wilcoxon, R. and Dlouhy, D., "Thermal Management of Harsh Environment Electronics", SEMI-THERM 2012 Shortcourse, San Jose, CA, March, 2012