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EVALUATION OF COMMERCIAL OFF-THE-SHELF AND GOVERNMENT OFF-THE-SHELF MICROCLIMATE COOLING SYSTEMS

by

Brad Laprise
Walter Teal
Leah Zuckerman
and
Jason Cardinal

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U.S. Army Research, Development and Engineering Command
Natick Soldier Center
Natick, Massachusetts 01760-2642

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14. ABSTRACT
Professionals in dire need of body cooling, namely the First Responder community, can currently choose from an extensive variety of commercially available microclimate cooling products incorporating a wide range of technologies. Since not all products will meet the requirements of all users, it is important to understand the characteristics of the systems that are available, prior to making a selection. Currently, no standards exist for validating microclimate cooling systems, so users are forced to rely on vendor claims when purchasing equipment. The goals of this project include searching the commercial market for all current Microclimate Cooling products, and evaluating a representative cross-section of products for their thermal performance. The information gathered was compiled in a database and a report, and can be provided to Emergency Responders to aid in their equipment-purchasing process.

15. SUBJECT TERMS
COMMERCIAL EQUIPMENT, COOLING, COTS(COMMERCIAL OFF THE SHELF), COMMERCIAL-OFF-THE-SHELF, MICROCLIMATE COOLING, GOTS(GOVERNMENT OFF THE SHELF), COOLING AND VENTILATING EQUIPMENT, TEST AND EVALUATION, OFF THE SHELF EQUIPMENT

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Preface

This report details the results and findings of data collection efforts on commercially available Microclimate Cooling Systems (Project #NPC05-001). This work was conducted during the period of January 2004 – January 2005 for the U.S. Department of Homeland Security – Office of State and Local Government Coordination and Preparedness.

EVALUATION OF COMMERCIAL OFF-THE-SHELF AND GOVERNMENT OFF-THE-SHELF MICROCLIMATE COOLING SYSTEMS

1.0 Introduction

Homeland Security Operations incorporate numerous user groups operating in a wide range of conditions and scenarios. In order to fulfill their goals, Homeland Security Operations impose significant demands on every professional group executing their mission, even under extreme environmental and emotional conditions. Therefore, those users operating in high temperature or stressful environments, compounded with the need for protective clothing and equipment, become very susceptible to the effects of heat stress. Heat stress results from a combination of factors, such as: environmental load (temperature, humidity, radiant load, wind speed, terrain, geographical location, etc.), clothing and equipment used, task or mission performed (i.e. work rate), physical condition of the user, and so on. When these elements combine to produce highly elevated body temperatures, mission performance can be inhibited, and operator health is placed in danger. In many cases, the environmental conditions cannot be avoided, thus, alternative methods of reducing core body temperature rise must be examined. Providing auxiliary microclimate cooling has been shown to positively affect the physiological state and operational performance of many user groups. In general, this approach involves applying cooling within the microclimate created under the protective clothing. For users who need to operate independently, Microclimate Cooling Systems (MCS) must provide sufficient cooling to sustain the user for his/her mission, be small, lightweight, require minimal logistics support, and consume minimal electrical power.

2.0 Background

Professionals in dire need of body cooling, namely the First Responder community, can currently choose from an extensive variety of commercially available microclimate cooling products, incorporating a wide range of technologies. Since not all MCSs will meet the requirements of all users, it important to understand the characteristics of the systems that are available, prior to making a selection. Unfortunately, some manufacturers and vendors make ambiguous and unsubstantiated claims with regards to the performance of their MCS products. Since, there are presently no performance standards that microclimate cooling products must meet, Emergency Responders often rely solely on these claims when they select a product. As a result, the procured system(s) often do not meet their technical, physiological and operational needs, nor are they logistically supportable.

3.0 Approach

The goals of this project include searching the commercial market for all current MCS products, and evaluating a representative cross-section of products for their thermal performance (see Section 3.2). The information gathered was compiled in a database (see Section 3.3) and can be provided to Emergency Responders to aid in their equipment purchasing process.

3.1 Product Survey

The first stage of the project included a thorough product survey to evaluate the available Commercial-off-the-Shelf (COTS) and Government-off-the-Shelf (GOTS) MCS products. The intent of this effort was *not* to survey technology or system developmental efforts, rather to evaluate the current market place. Further, this survey does not include sources that customize microclimate cooling products for specific customers. Products identified in this survey, primarily focus on "man-portable" single user systems; that is, multi-person coolers are generally not included. If an item was developed by the Government, the following two requirements had to be met for it to be included in this survey:

- The system had to be available for purchase (existing production contract, or in stock)
- The system had to have a National Stock Number (NSN) assigned.

To conduct the product survey, several sources were used, including:

3.1.1 Internet Searches

The Internet was a powerful tool and was used extensively to assess the market for commercial microclimate cooling products. Since the product survey was largely completed within the first several months of the program, the content of some websites have changed, as vendors have modified their product line. Periodic updates to this survey should be conducted so that the information in the database remains current.

3.1.2 Request for Information (RFI) on FedBizOpps.gov website

A RFI was advertised for approximately five months to provide suppliers of commercial microclimate cooling products an opportunity to submit information to the Natick Soldier Center. A copy of the RFI is provided in Appendix A.

3.1.3 Professional Contacts

Professional contacts were used to identify known sources of microclimate cooling products.

3.1.4 International Market Investigation

A formal memorandum was prepared by the Natick Soldier Center's International Office, seeking product literature on international commercial microclimate cooling products. A copy of this memorandum is provided in Appendix B.

3.2 Testing

In addition to the primary task of conducting a market survey of commercially available microclimate cooling systems, the Natick Soldier Center also tested a representative cross-section of products on a sweating Thermal Manikin at the Navy Clothing Textile Research Facility (NCTRF) in a climatically controlled chamber. The Thermal Manikin (TM) is a tool that provides objective feedback on the thermal performance of cooling systems. The Thermal Manikin Test System consists of a heated manikin and ancillary equipment used to track and maintain the TM's surface temperature. The TM is divided into 16 thermally isolated regions (head, upper torso, middle torso, lower torso, right upper arm, right forearm, right hand, left upper arm, left forearm, left hand, right thigh, right calf, right foot, left thigh, left calf, and left foot), which contain embedded heaters and thermistors. The computerized control system collects temperature data on each TM region from the thermistors at one-minute intervals and resets the power to the heaters to maintain the desired TM temperature set point.

The TM testing was conducted in accordance with the draft ASTM Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin. Accordingly, the TM surface temperature was set to 95°F (note: this value is representative of the human skin temperature when working in the heat while wearing protective clothing) and was fully wetted, using the integrated sweating mechanism. The chamber was also maintained at 95°F, therefore, the only means by which the TM can lose heat is due to the cooling provided by a cooling system and through the evaporation of "sweat". The TM responds to heat loss by applying power to the heaters in the region(s) that need it, resulting in an accurate measurement of the total heat removed from the TM. However, to get a true measurement of the amount of heat removed from the TM *by* the cooling system, the evaporative potential, or baseline, must be subtracted from the total value. To obtain this baseline value, a test is conducted with the cooling system turned off. The TM is allowed to come to thermal equilibrium and after approximately 30 minutes of stable data, the cooling system is activated. The test method requires that one baseline and three cooling tests be conducted per cooling system, however, due to cost and schedule constraints, only two cooling tests were conducted per cooling system. Each cooling test was terminated when the heat gained by the cooling source dropped to less than 50 watts, above the baseline, in accordance with the draft test method.

The performance of a microclimate cooling system can be significantly influenced by the outer protective clothing layers and equipment worn by users. In particular, a uniform's insulation and water vapor permeability characteristics will affect the amount of environmental heat gained by the cooling garment, and the amount of sweat and water evaporation that can occur. Thus, each microclimate cooling system was tested on the TM in conjunction with two outer clothing garment configurations, representing the extremes in Emergency Responder uniforms: a standard police uniform, representing a low insulation/high water vapor permeable ensemble; and a Level A chemical protective uniform, representing a high insulation/low water vapor permeable ensemble (see Figure 1).

Figure 1. Police Uniform and Level A Uniform on the Thermal Manikin

The documentation accompanying each purchased cooling system was reviewed prior to use to understand its operation and support requirements, including instructions on battery and phase change material charging, polymer activation duration, etc. These manufacturer's instructions were followed in the preparation of each system for testing.

3.3 Database

To organize the information garnered from the microclimate cooling product survey, a database was created in Microsoft Access. It is organized into two tables, one providing specific information on each product, and the other providing information on the company that manufactures, sells, or distributes that product. The tables are linked together by the product field. Tables 1 and 2 describe the fields contained in the Product and Company Table, respectively.

Table 1. Product Table

Field Name	Description
Product	Name of Microclimate Cooling System (MCS) Product
Product Description	Description of the MCS
Technology	Type of technology used in MCS (i.e. Evaporative, Passive Phase Change, Vapor Compression, Thermoelectric, Compressed Air, Ice Based)
System Weight (lbs)[1]	Weight of a fully functional MCS required to achieve the Heat Removal Rates/Durations
Replenishment Part	Consumables; component of the MCS that is replaced, excluding batteries, for continued operation (e.g. water, phase change packs, etc.)
Replenishment Part Weight (lb)	Weight of the consumable(s) required for continued operation of the MCS
System Dimensions (LxWxH)(in) [1]	Approximate size of the MCS; does not apply to cooling garments
Other Required Support	General equipment required to support the operation of the MCS (e.g. freezer)
Specific Support Equipment	Specific equipment identified by the manufacturer/distributor required to support the operation of the MCS (e.g. battery charger)
Battery Description	Battery chemistry, cell type, primary/rechargeable, etc.
Battery Weight (lbs) [1]	Weight of batteries to operate the MCS during the Heat Removal Duration
Integration	Specific issues that may affect the functionality of the MCS with other clothing/equipment
Sizing	Cooling garment sizes available
Heat Removal Rate-Level A (watts) [1]	Cooling performance of MCS with a Level A Uniform as measured on a Thermal Manikin IAW Draft ASTM
Heat Removal Rate-Uniform (watts) [1]	Cooling performance of MCS with a Police Uniform as measured on a Thermal Manikin IAW Draft ASTM
Heat Removal Duration-Level A (min) [1]	Duration of cooling of MCS with a Level A Uniform as measured on a Thermal Manikin IAW Draft ASTM
Heat Removal Duration-Uniform (min) [1]	Duration of cooling of MCS with a Police Uniform as measured on a Thermal Manikin IAW Draft ASTM
Comments	Additional details on MCS not reported elsewhere
NSN	National Stock Number

[1]These fields only filled on products purchased and tested by the Natick Soldier Center

Table 2. Company Table

Field Name	Description
Company	Company Name
Manufacturer/Distributor	Identifies company as a manufacturer and/or distributor
Address 1	Manufacturer/Distributor address
Address 2	Second Address
City	Manufacturer/Distributor City
State	Manufacturer/Distributor State
Zip Code	Manufacturer/Distributor Zip Code
Country	Manufacturer/Distributor Country
Telephone 1	Manufacturer/Distributor Primary Telephone Number
Telephone 2	Manufacturer/Distributor Alternate Telephone Number
Fax Number	Manufacturer/Distributor Fax Number
Email Contact	Manufacturer/Distributor E-mail Address
Website	Manufacturer/Distributor Website Address
Point of Contact	Name of person at Manufacturer/Distributor
Product	Microclimate Cooling System (MCS) Product Name
Sold By This Company As:	MCS Product Identifier
Price	Manufacturer/Distributor's Price
GSA Price	Manufacturer/Distributor's General Services Administration price
Price Replenishment Part	Cost of Replenishment Part
Price Battery	Cost of Battery
Price Specific Support Equipment	Cost of Specific Support Equipment
Date of Information	Date when material/price was received
Primary Source of Information	Where information was obtained (e.g. web, phonecon, RFI, etc.)
GSA Contract #	Contract number assigned by the General Services Administration

Two forms were created to ease the product data entry in Microsoft Access. The Product Data Entry Form and the Company Information Form are shown in Figure 2.

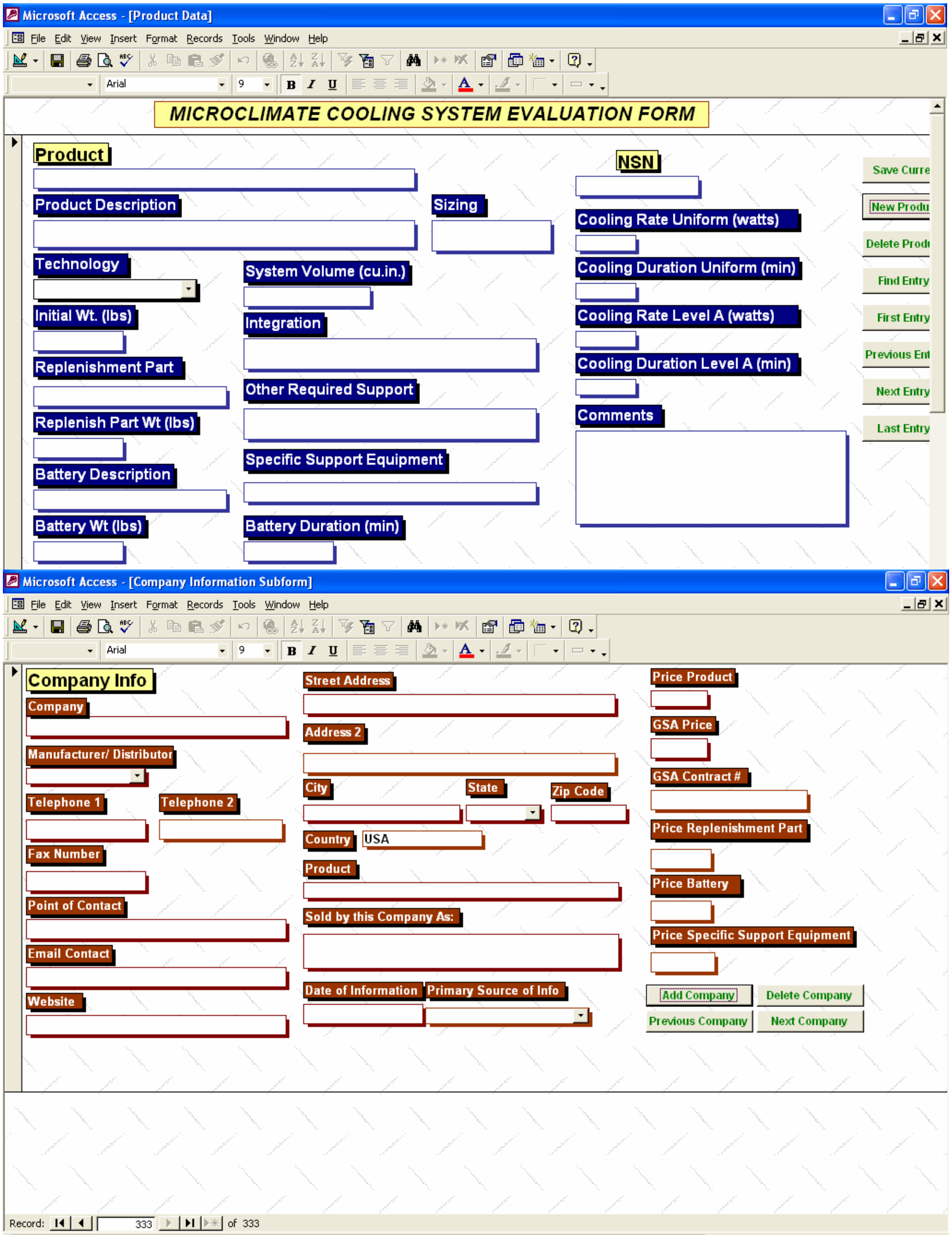

Figure 2. Product and Company Data Entry Forms

4.0 Results

4.1 Product Survey

The product survey was conducted between 1 January and 31 May 2004 and includes only Commercial-off-the-Shelf (COTS) and Government-off-the-Shelf (GOTS) personal cooling products (note: product updates were conducted if systems not previously identified came to our attention). This survey does not include developmental systems nor technology developments. Products introduced or discontinued after this period may not be included (see Section 4.3).

The results of the product survey indicate that there are approximately 330 Commercial-off-the-Shelf (COTS) and Government-Off-the-Shelf (GOTS) personal cooling products available. However, only 256 of these are unique; that is, an item may be manufactured by one company, but sold by several distributors under different brand names or labels. Often, it cannot be determined if a product is a "duplicate" of another unless a side-by-side comparison is made. Due to funding and schedule limitations, all available products could not be purchased, thus, an assessment of the number of distinct products could not be made with certainty.

Based on the results of the survey, all of the products can be categorized into one (or more) of the following six groups:

Evaporative Products
Passive Phase Change Material Products
Vapor Compression Liquid Circulating Products
Thermoelectric Liquid Circulating Products
Compressed Air Products
Active Phase Change Material Products
Other

Each group is defined in the following sections including a brief description of the technology/products, assessment of the range of cooling rates and durations, logistics issues, weight ranges, and cost ranges.

4.1.1 Evaporative Products

Description. Evaporative products rely upon the evaporation of water to provide a cooling effect to users. These products are simple, inexpensive, and require no external power to operate. They account for approximately 56% of the commercial personal cooling market, and while many of the products sold in this category are vests, other configurations such as neck wraps, caps, etc. are also available (see Figure 3).

Figure 3. Evaporative Cooling Products

In general, the items in this category consist of a hydrophilic material (i.e. materials that absorb water) captured in a fabric liner. While the instructions for each product may vary slightly, all must be soaked in water for several minutes, where the encapsulated polymer absorbs several times its weight in water; the adsorption of water also causes the product to swell to several times its initial volume.

These products should usually be worn close to the skin to maximize the transfer of body heat. However, if the evaporative vest, for example, becomes dry and ineffective, the user must doff his/her external personal protective clothing to recharge (i.e. re-soak) the item. This may be unacceptable in many operational scenarios in which personal protection cannot be compromised.

Cooling. Sweat evaporation is, of course, the primary mechanism by which the human body cools itself. Thus, water evaporation is an extremely effective method for removing heat from the body; theoretically, the evaporation of water can result in the transfer of approximately 540 calories/gram of heat, if evaporation can be supported.

The ability of evaporative products to provide beneficial cooling is influenced by many factors, including the ambient environment (temperature, humidity, wind speed, etc.) and clothing layers worn by the user. Elevated relative humidity, the absence of air movement, and/or the need to wear protective clothing will all significantly reduce the ability of water to evaporate, and, thus, the effectiveness of evaporative cooling products to cool users. In fact, even protective clothing ensembles with low insulation and high moisture vapor permeability values can provide a significant barrier to water evaporation, limiting the performance of these systems. Based on Thermal Manikin testing, this category of products is the least effective of the six listed in section 4.1. The cooling durations and rates are shown in Table 3 below.

Table 3. Cooling Rate and Duration for Evaporative Cooling Products

Clothing Outer Ensemble	Cooling			
	Rate (Watts)		Duration (hours)	
	Range	Median	Range	Median
Police Uniform	0-69.4	0	0-2.45	0
Level A Uniform	0	0	0	0

Logistics. The only consumable in evaporative cooling products is water. Therefore, a supply of water is required to recharge these items when they have dried out. The amount of water required will vary with each product. Periodic cleaning of the systems would also likely be necessary.

Weight. Since there are several different configurations of evaporative cooling products available, there is also a wide range of system weights. While the effectiveness of these products is highly dependent on the criteria cited above, performance is also related to the amount of water absorbed by the product (in environments that will support water evaporation), to a certain extent. Of course, the trade-off is weight. For vests, the weight range is between 2.4 and 6.13 pounds. Other products, such as cooling hats weigh approximately 0.59 pounds. It should be noted that since this category of products is only effective when soaked with water, the weight range reported here is the "wet weight".

Cost. Table 4 below shows the cost ranges for the various configurations of evaporative cooling products.

Table 4. Cost Ranges for Evaporative Cooling Products

Configuration	Cost Range
Vest	\$20-\$260
Neck Wrap/Cap	\$2-\$20

4.1.2 Passive Phase Change Material Products

Description: Passive phase change material (PCM) products rely upon the change of phase of a material from a solid to a liquid (i.e. melting) to provide a cooling effect to users. These products are labeled as "passive" because they have no moving parts. Thus, they are simple, relatively inexpensive, and require no external power to operate. Based on the survey results, nearly 30% of the products on the commercial market can be classified as passive PCM products. Like the evaporative products, the majority of these products are vests (see Figure 4), however, other configurations, such as neck wraps and hats are also available. In general, vests consist of several pockets or sleeves into which packets of encapsulated phase change material can be inserted. The size of the sleeves and configuration of the PCM packets vary between products. With some products, however, the PCM is contained within the structure of the vest.

There are several PCMs that are commonly used in commercial cooling products today. In general, the most effective for personal cooling, in terms of heat exchange, is ice. However, ice based systems can be very cold when they are initially donned, thus, many products use alternative materials called paraffins (i.e. hexadecane, tetradecane, octadecane, etc.) that melt at higher temperatures. These tend to be

Figure 4. Passive Phase Change Product

more comfortable, but they also have less cooling capacity compared to ice (see *Cooling* section below). The temperature required to refreeze a paraffin material is generally greater than that required for ice, therefore, only a refrigerator may be required (see *Logistics* section below) for recharging. It should also be noted that paraffin based materials are flammable and can cause skin irritation. The Material Safety Data Sheets (MSDS) should always be consulted to understand the characteristics of the materials used in the product being considered.
In general, most personal cooling products should be worn next to, or close to, the skin to maximize heat transfer efficiency. Passive PCM products are no different. However, when the PCM completely melts and no longer provides beneficial cooling, the product can become a *barrier* to the body's natural cooling mechanism, and potentially contribute to the user's heat stress burden. Thus, the PCM must be periodically replaced with recharged materials so that the user continues to receive cooling. To do this, however, the user must doff his/her external clothing to replace the PCM, potentially compromising the protection that it provides.

Cooling. In order to determine a PCM's ability to provide beneficial cooling to MCC, it is worth comparing their melting points and heats of fusion. To effectively cool people, the melting point should be sufficiently below skin temperature to allow significant heat transfer to occur. The heat of fusion is a measure of the quantity of heat required to melt a unit mass of a solid, expressed in energy per unit mass; thus, it is desired to use PCMs with high heats of fusion. Three paraffin PCMs commonly used in microclimate cooling applications are listed in Table 5 with their associated melting temperatures and heats of fusion. As a point of comparison, the characteristics of ice are shown as well.

Table 5. Melting Temperatures and Heats of Fusion of Commonly Used Phase Change Materials*

PCM	Melt Temperature (°F)	Heat of Fusion (cal/g)
n-Tetradecane ($C_{14}H_{30}$)	41.9	54.3
n-Hexadecane ($C_{16}H_{34}$)	64.8	56.8
n-Octadecane ($C_{18}H_{38}$)	82.8	58.8
Ice (H_20)	32	79.7

*Note: Some companies may combine PCMs to customize a product with desired melt temperatures and/or heats of fusion.

This information can be useful when comparing the amount of material required to provide a specific amount of cooling. For example, if 200 watt-hours of heat removal are desired, then the following mass of each material would be required:

Table 6. Mass of PCMs for a 200 Watt-hr System

PCM	Mass (lb_m) required for 200 watt-hr system
n-Tetradecane ($C_{14}H_{30}$)	7.0
n-Hexadecane ($C_{16}H_{34}$)	6.7
n-Octadecane ($C_{18}H_{38}$)	6.4
Ice (H_20)	4.8

This calculation assumes that 100% of the heat absorbed by the PCM is from the user's body (i.e. no losses to the environment). Since this is an ideal situation, additional PCM will be needed to account for system heat gains. However, as a relative comparison, it is clear that the amount of cooling provided is directly related to the type and mass of material used in each product. Based on Thermal Manikin testing, systems that use ice as the phase change material fare better than those that use paraffin based materials. Table 7 shows the cooling rate and duration for passive phase change material products.

Table 7. Cooling Rate and Duration for Passive Phase Change Material Cooling Products

Clothing Outer Ensemble	Cooling			
	Rate (Watts)		Duration (hours)	
	Range	Median	Range	Median
Police Uniform*	5.6-131.9	89	0-2.64	1.5
Level A Uniform	67.9-157.2	105.7	0-2.43	1.3

*Includes testing on a neck wrap product

Logistics. To support the use of passive PCM cooling products, refrigerators/freezers, insulated containers (e.g. coolers), and sufficient quantities of replacement PCM packets (or products) to sustain the required mission duration will be needed. In general, products that are ice based will require a freezer to recharge; those that are paraffin based may only require a refrigerator. The product manufacturer/distributor should be consulted for recommended recharging methods. Finally, periodic cleaning of the systems would likely be necessary.

Weight. Since there are several different configurations of passive PCM cooling products available, there is also a wide range of system weights. Of course, the cooling rate and duration is directly related to the type and amount of PCM in the product. That is, a lighter weight product will provide less cooling and/or shorter duration than a heavier product using the same material. For vests, the weight range is between 2.24 and 11.8 pounds. Other products, such as neck wraps weigh approximately 1.1 pounds.

Cost. Table 8 below shows the cost ranges for the various configurations of passive PCM cooling products.

Table 8. Cost Ranges for Passive Phase Change Material Cooling Products

Configuration	Cost Range
Vest	$46-$348
Neck Wrap/Cap	$9-$35

4.1.3 Vapor Compression Liquid Circulating Products

Description: Vapor Compression refrigeration is a very mature and well understood technology; in fact, it is has been used for many years in household refrigerators and air conditioners. In general, this technology absorbs heat from the source to be cooled and rejects it to a warmer environment. When used in a microclimate cooling application, these systems tend to be arranged in closed loop, liquid-circulating configurations. Users generally wear an undergarment lined with small diameter tubing (Figure 5) through which a chilled fluid is pumped, absorbing body heat. This heat is transferred to a refrigerant in the liquid/liquid evaporator within the vapor compression system, where it vaporizes. The refrigerant gas is compressed by a mechanical compressor and then pumped into the condenser, where heat is rejected to the ambient environment, assisted by a fan. As it cools, the refrigerant condenses into a liquid and is metered by a capillary tube or thermostatic expansion valve to control its flow back into the evaporator.

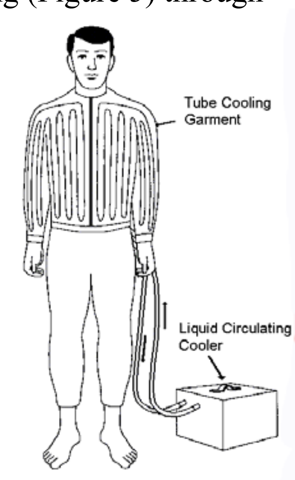

Figure 5. Liquid Circulating Microclimate Cooling System

Very few vapor compression personal cooling systems exist commercially. While several systems have been developed by the Government, only one system met the criteria for this report (see Section 3.1). The Air Warrior Microclimate Cooling System is currently in production for installation on several U.S. Army rotary wing aircraft and one armored ground vehicle.

Vapor compression systems require electrical power to operate, which is typically provided by a vehicle for mounted applications, or by batteries in portable modes. They are expensive compared with other simpler technologies. However, they provide significant, efficient, and consistent cooling as long as power is available. The cooling unit must be located external to the user's uniform since heat from the condenser must be rejected to the ambient environment. As a result, the liquid supply/return lines must pass through the uniform layers to interface with the cooling garment worn next to the skin.

Cooling. The Air Warrior Microclimate Cooling System was tested on the Thermal Manikin. Since this unit is not a portable system, it was operated from a dc power supply. Therefore, the cooling duration parameter is not applicable. The average cooling rates were 174.4 watts and 226 watts under the Police Uniform and Level A Uniform, respectively.

Logistics. The vapor compression system identified here is a non-portable system; that is, it requires electrical service from an existing dc power source. Thus, re-supply of batteries is not a logistical concern for this system. Periodic maintenance is required, in particular periodic filling/purging of the coolant fluid within the system. In addition, maintenance of the refrigeration system may also be required, potentially requiring a technician knowledgeable in HVAC systems. In addition, frequent laundry/cleaning of the cooling garment would be necessary.

Weight. The weight of the Air Warrior system is approximately 13 pounds.

Cost. Cost of the Air Warrior system is approximately $8000.

4.1.4 Thermoelectric Liquid Circulating Products

Description: Thermoelectric cooling is based on the Peltier Effect, which was discovered in 1834. Jean Peltier observed that when a dc current was applied across two dissimilar materials, heat was transferred from one side to the other, resulting in a temperature gradient. Thermoelectric coolers are solid-state heat pumps which can be used to heat and cool, depending on the direction of the current.

While much research is ongoing with respect to thermoelectric cooling, there are very few microclimate cooling products available as personal cooling devices. Generally, they tend to be closed loop, liquid circulating systems, which interface with a cooling garment lined with small diameter tubing (see Figure 5 above).

In several respects, thermoelectric liquid circulating coolers are similar to the vapor compression systems:

- A thermoelectric system chills and pumps a fluid through the cooling garment, where body heat is transferred.
- Heat is rejected to the ambient environment via a heat exchanger within the thermoelectric system.
- Thermoelectric systems require electrical power to operate, which is typically provided by a vehicle for mounted applications. However, this technology tends to be very inefficient compared with vapor compression technology, thus, portable systems operating on batteries tend to be heavy or don't provide significant beneficial cooling.
- Thermoelectric systems can provide significant, consistent cooling as long as power is available.
- The cooling unit must be located external to the user's uniform since heat from the hot side heat exchanger must be rejected to the ambient environment. As a result, the liquid supply/return lines must pass through the uniform layers to interface with the cooling garment worn next to the skin.

Thermoelectric systems also tend to be robust, due to few moving parts; they are also quiet, with the only noise generated by a fan and one or two circulating pumps.

Cooling. One thermoelectric system was purchased as part of this effort. However, efforts to test this item were not successful, as the system failed to operate on several occasions. Thus, no data is available. It should be noted that this is not indicative of the performance of thermoelectric systems. In general, the thermal performance of a thermoelectric system is similar to that of a vapor compression system; that is, the system will provide consistent cooling as long as electrical power is available.

Logistics. Re-supply of batteries would likely be the most significant logistical issue associated with thermoelectric systems; systems operating on secondary batteries would, of course, also require a batter charger. Cleaning of the cooling garment would also be necessary.

Weight. The weight of the purchased thermoelectric system is approximately 10.8 pounds.

Cost. Cost of thermoelectric systems range from approximately $50-$714.

4.1.5 Compressed Air Products

Description: Personal cooling products using the expansion of compressed air as the cooling source account for approximately 4% of the products available. In general these systems consist of an air distribution garment and associated hoses and fittings (Figure 6) to interface with an existing air supply infrastructure.

Thus, these systems are non-portable and usually are used in factory or industrial settings where compressed air is available. Some systems utilize a vortex tube to further chill the temperature of the air entering the distribution garment. A vortex tube is a device, which separates high energy molecules from those of low energy (Figure 7); the cooler air stream is directed into the distribution garment, while the warmer flow is rejected to the ambient environment. Generally, a small valve is provided for user adjustment of the volume and temperature of air released from the cold end.

These air systems tend to be inexpensive, robust, and lightweight, however, their performance is solely dependent on the source of compressed air and the user is always tethered. If a compressed air cooling device is worn in conjunction with protective clothing, then an integrated pass-through fitting allowing the supply hose to penetrate the clothing layers will likely be required.

Figure 6. Compressed Air Cooling Product

Figure 7. Vortex Tube

Cooling. Two compressed air products were purchased for testing. Laboratory compressed air was used as the source and its pressure was adjusted in accordance with the manufacturer's instructions (note: air flow rate was not specified in the instructions, and, therefore, was not measured). Cooling rates are noted in Table 9 (note: duration is not applicable as long as the source of compressed air is constant).

Table 9. Cooling Rate for Compressed Air Cooling Products

Clothing Outer Ensemble	Cooling Rate Range (Watts)*
Police Uniform	189.6-288.3
Level A Uniform	209.8-353.5

*Note: Median cooling rates are not reported here since two systems were tested.

Logistics. There is a minimal logistics burden associated with these products. Periodic cleaning of the distribution garment is necessary. While not part of these systems, maintenance of the compressed air source is also likely required.

Weight. The weight of the compressed air systems (exclusive of compressed air source) ranges from 1.8 to 2 pounds. This includes the distribution garment and associated person-borne hardware. Note: If the weight of the compressor is included, the system would likely be too heavy to be man-portable.

Cost. Cost of compressed air cooling products range from $100 to $256.

4.1.6 Active Phase Change Material Products

Description: Based on the results of the market survey, there are approximately 18 Active Phase Change Material Products available commercially. All of the products identified in this category are ice based liquid circulating products. Like the thermoelectric and vapor compression liquid circulating products, active PCM systems circulate a chilled fluid through a cooling garment worn by the user (see Figure 5). However, in this case, ice is used as the cooling source. In general a battery powered pump draws the chilled ice water from a reservoir and circulates it through the cooling garment (Figure 8). Some systems use an intermediate heat exchanger placed in the reservoir, requiring the need for a freeze suppression additive to the coolant (e.g. salt water, propylene glycol, etc.).

Figure 8. Active Phase Change Material Products (Ice-Based Liquid Circulating Products)

To maximize heat transfer efficiency, the cooling garment should be worn as close to the skin as possible. Depending on the product, the cooling source may be worn external or internal to the protective clothing. If it is worn (or placed) outside of the clothing, a pass-through device would likely be required for the supply/return tubing to penetrate the clothing layers. In this configuration, it is relatively easy to replenish the ice, once it has melted. However, if the cooling system is worn inside of the protective clothing, then a pass-through fitting is not required, but the clothing may have to be doffed or opened to replace the expired ice, exposing the user to potential health and safety hazards.

Cooling. As discussed in the Passive Phase Change Material Products section above, the cooling rate and thermal capacity is directly related to the amount of ice in the system. Thus, the thermal performance of portable versus non-portable Active Phase Change Material Products can be significantly different, due to the differences in their capacity for holding the ice. Table 10 reflects this variance in the wide range of cooling rates and system durations.

Table 10. Cooling Rate and Duration for Active Phase Change Material Products (Ice-Based Liquid Circulating Products)

Clothing Outer Ensemble	Cooling			
	Rate (watts)		Duration (hours)	
	Range	Median	Range	Median
Police Uniform	60.8-180.6	135.3	0.9-3.7	1.3
Level A Uniform	72.2-234.7	169.1	0.9-2.8	1.3

Logistics. The use of Active Phase Change Material Products requires significant logistical support, both in the re-supply of ice and batteries (if the system is portable). Like the passive phase change material products, freezers and insulated containers (e.g. coolers) will be needed to support ice based systems. Some products use custom containers to freeze the water, so sufficient quantities of these components would probably be needed to support the mission duration of the user. Periodic cleaning of the garments would also likely be necessary. Product literature should be consulted for specific maintenance activities.

Weight. The weight of Active Phase Change Material Products ranges from 9.7-17.1 pounds.

Cost. The cost of Active Phase Change Material Products ranges from $350 to $1854.

4.1.7 Other
This category captures systems that don't necessarily fit the definitions of the technologies described in the previous sections.

4.2 Testing
As stated in section 3.2, thermal performance testing was conducted on a Thermal Manikin at NCTRF. Figure 9 shows an idealized plot of cooling power versus time for a non-steady state cooling system.

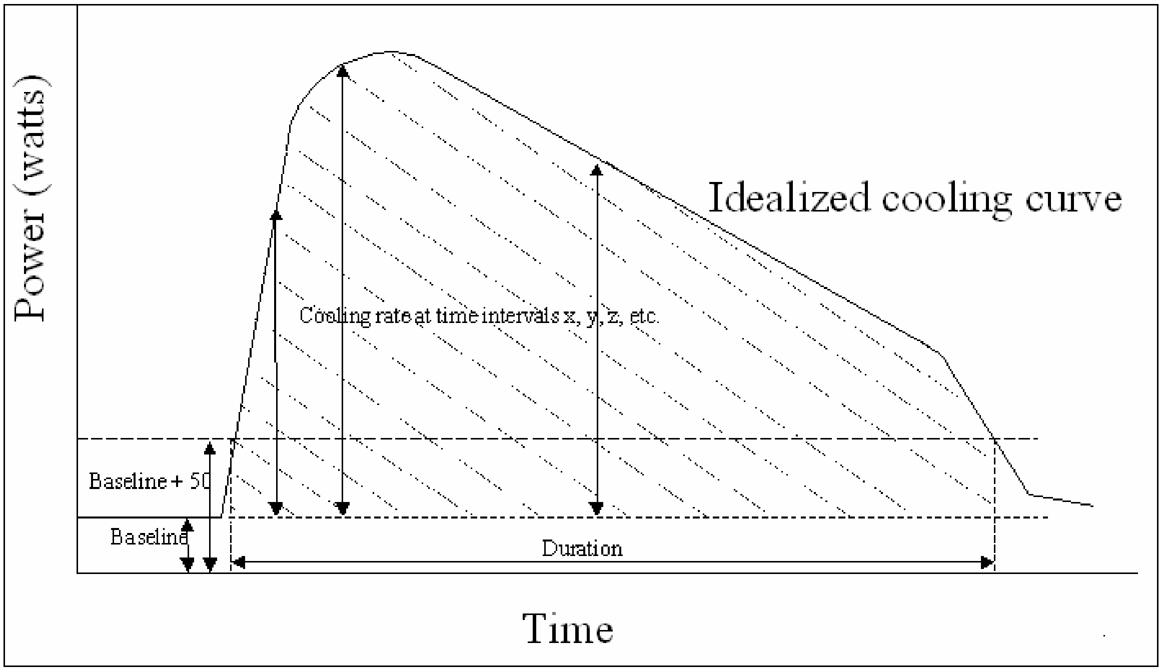

Figure 9. Idealized Thermal Manikin Cooling Power Curve

In accordance with the draft ASTM Standard Test Method for Measuring the Heat Removal Rate of Personal Cooling Systems Using a Sweating Heated Manikin, a test begins with the cooling system inactive. Electrical power is applied to the heaters in response to the evaporation of sweat until the TM reaches a steady state condition for approximately 30 minutes; this defines the baseline, or evaporative value, of the ensemble. Temperature and power level measurements are recorded at one-minute intervals throughout the test. When the cooling system is turned on, the TM responds by applying additional power to the heaters to maintain its surface temperature at 95°F. As the source of cooling degrades over time, the TM responds by applying less power, which accounts for the downward sloping curve in the plot.

As defined by the ASTM test method, a cooling system is only considered effective when the cooling power is at least 50 watts *greater* than the baseline cooling power. When the cooling power is less than the baseline plus 50 watts, then the test is terminated. System duration is defined as the period of time where the cooling power is above this line. The duration for steady state systems (e.g. vapor compression and compressed air products) is infinite for as long as electrical power or compressed air is constantly available. Average cooling power is determined by calculating the mean value of the individual one-minute cooling power values measured during the test. Cooling capacity is calculated as the product of the duration and average cooling power (note: cooling capacity cannot be calculated for steady state systems).

While Figure 9 shows a well defined transition from the baseline cooling power to the TM's response to the activation of a cooling system, there are actually some initial cooling power spikes, which are not shown. The relevance of these overshoots is dependent on the type of cooling system being tested. That is, those systems that require the full or partial removal of the outer uniform clothing layers to activate the cooling, tend to cause the TM to react with significant power spikes. This is caused by the sudden increase in "sweat" evaporation due to the decrease in thermal resistance when the outer clothing layers are removed. The TM responds by applying significant electrical power to the heaters to compensate for this increased evaporation. In general, this phenomenon is seen in the data from Evaporative and Passive Phase Change Material microclimate cooling products. Evaporative vests need to be periodically re-soaked and phase change packs need to be exchanged after they melt. In both cases, the outer clothing must be removed to accommodate this process. The other technologies, however, do not require the disturbance of the clothing layers to activate the cooling process, thus the cooling spikes are not significant. The draft ASTM recognizes this issue and states that the clothing should not be open for more than five minutes to minimize this effect. However, there is currently no guidance that addresses how this data should be analyzed. Since these large spikes may not be indicative of the performance of a cooling system, and can artificially dominate the cooling power data, an alternate approach to analyze the performance of these systems was developed as follows: the net cooling rate of a system must be above 50 watts for at least *30 minutes* for it to be considered beneficial. This will prevent the situation in which the data from a cooling system shows a “false” high cooling rate for a short duration, when, in fact, the cooling spikes are primarily due to an artifact of the test method (i.e. opening the outer garments to don the cooling vest) and not due to the performance of the cooling system. Thus, if a system's duration (as defined in the prior paragraph) was less than 30 minutes, it was reported in this document to provide 0 watts of cooling for a duration of 0 minutes.

Figure 10 shows sample net cooling power versus time curves for specific systems representing the various technologies (except thermoelectric products), tested on the TM under the Police Uniform.

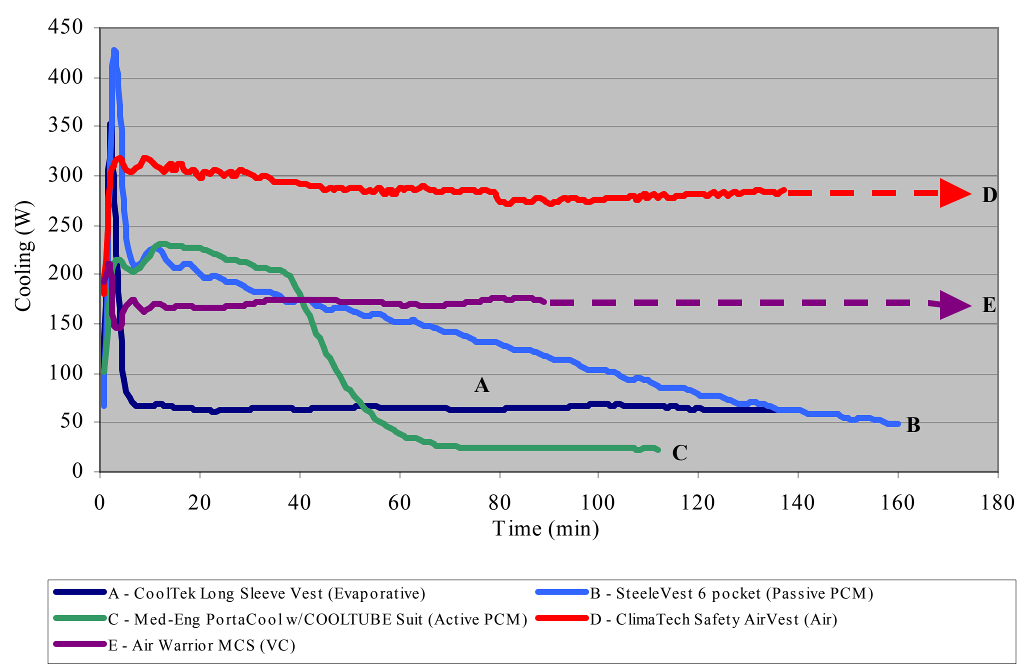

Figure 10. Net Cooling Power vs. Time for Systems Under Police Uniform

Appendix C contains cooling power plots for each of the systems tested.

4.3 Database

The MCS product survey database is provided as an attachment to this report. There is an extensive amount of information in the database, thus, it is recommended that the user take advantage of the functions within MS Access to obtain the information needed. In particular, the Reports capability is very useful. For example, if a summary of all the products that weigh less than 5 pounds is desired, then the following report could be run, including the product name, company, and technology:

Table 11. Example of MS Access Report (Systems < 5 Pounds)

Product	System Weight (lbs)	Technology	Company
Colin Vest PC-EC-VEST	4.64	Phase Chg. Passive	Cool Draft Scientific, LLC
Cool Jacket CJ-65	4.31	Phase Chg. Passive	Glacier Tek, Inc.
Allegro Safety Evaporative Cooling Vest	3.86	Evaporative	ProBuy.net
#56 HF Climate Control Vest	3.82	Phase Chg. Passive	Heat Factory
Classic Vest	3.06	Evaporative	Silver Eagle Outfitters
CoolTek Zip-Front Vest 100-3M	2.89	Evaporative	Heat Relief Products Int'l, Inc
VE-01 Full Vest	2.83	Evaporative	Akemi Body Cooler
Maximum Activity Cooling Vest VE-08	2.71	Phase Chg. Passive	Akemi Body Cooler
SteeleVest SF 100	2.43	Evaporative	Industrial Supplies and Services
ClimaTech Safety HeatShield	2.24	Phase Chg. Passive	ClimaTech Safety Inc.
DC70 Dual-Cool Cooling Vest	2.03	Compressed Air	Bullard
ClimaTech Safety AirVest	1.79	Compressed Air	ClimaTech Safety Inc.
ClimaTech Safety CoolCollar	1.11	Phase Chg. Passive	ClimaTech Safety Inc.
CoolTek Foreign Legion Cap 500-FL	0.59	Evaporative	Heat Relief Products Int'l, Inc

5.0 Conclusions/Recommendations

Based on the results of this survey, it is clear that there are many Microclimate Cooling products on the commercial market today. It is also clear that there is not one product that will meet the needs of all users; that is, there are trade-offs associated with all of the items identified in this survey. Users considering the purchase of a cooling product should consider the implications of using that product, including the system's size and weight, cost, clothing/equipment integration/compatibility issues, logistics burden, support equipment required, level of cooling provided, etc.

Evaporative cooling products account for the majority of the products available on the commercial market. Figure 11 shows the percent of each type of cooling products as a fraction of the total market.

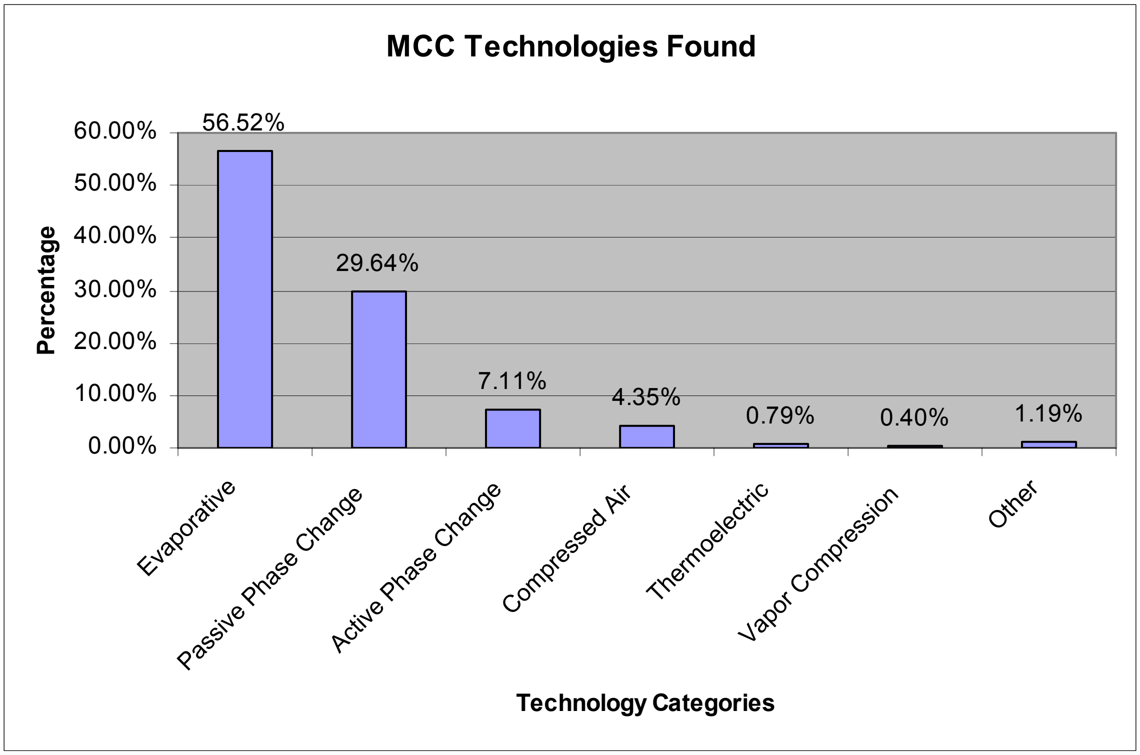

Figure 11. Percentage of Products for Each Technology

Based on the Thermal Manikin testing, Evaporative products tend to be less effective than all of the other technologies with respect to thermal performance, when worn under protective clothing. The testing also confirmed that ice based passive PCM products provide more cooling per unit mass than paraffin based products.

Based on the results of this survey, there are many products available that will help to mitigate the effects of heat stress. It is hoped that this report and accompanying survey will help users to more clearly understand the trade-offs and implications of the different types of Microclimate Cooling products. It is ultimately the user who best understands their unique mission scenarios and requirements, therefore, it is not the intent of, nor is it appropriate for, this report to recommend specific products or identify the "best" system.

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Appendix A

Request for Information (RFI)

Appendix A
Request for Information (RFI)

The U.S. Army Research, Development, and Engineering Command/ Natick Soldier Center (NSC) is conducting a Request For Information (RFI) to collect information pertaining to commercial Microclimate Cooling Systems. The purpose of this RFI is to establish a database of commercially available personal cooling products that could be used by the military, emergency response community, and others in high heat stress occupations. The NSC is interested in all types of personal cooling systems, including evaporative products, ice and phase change vests, liquid circulating garments, air systems, etc. All interested firms, regardless of size, are encouraged to respond to this RFI by submitting product literature, technical specifications (size, weight, cooling performance), pertinent test data, cost, material safety data sheets (if applicable), and product availability. Please only submit information on products that are currently commercially available, not items that are under development. This is not a Request for Proposal, solicitation, or an indication that the Government will contract for this equipment. The Government will not pay for information received in response to this RFI and is in no way obligated by the information received. Inclusion in this RFI or the resulting database does not constitute Department of the Army approval for any product. Responses may be sent to via email or by regular mail to: Dennis Magnifico, Natick Soldier Center/ RDECOM, ATTN: AMSRD-NSC-TP-N, 15 Kansas St. Natick, MA. 01760; Tel (508) 233-4432; Fax (508) 233-6447; Email: dennis.magnifico@natick.army.mil

Appendix B

Memorandum from Natick Soldier Center's International Office

Appendix B
Memorandum from Natick Soldier Center's International Office

DEPARTMENT OF THE ARMY
U.S. ARMY SOLDIER AND BIOLOGICAL CHEMICAL COMMAND
SOLDIER SYSTEMS CENTER
KANSAS STREET
NATICK, MA 01760- 5019

REPLY TO
ATTENTION OF

International Office 16 September 2003

MEMORANDUM FOR SEE DISTRIUTION

SUBJECT: Market Investigation for Microclimate Cooling Systems

1. The U.S. Army Natick Soldier Center (NSC) is conducting a world-wide market research investigation for Microclimate Cooling Systems. The NSC is interested in all types of personal cooling systems, including evaporative products, ice and phase change vests, liquid circulating garments, and air systems.

2. Interested individuals must submit within sixty (60) days from the date of this request, information on their system. This information should include product literature, specifications (size, weight, cooling performance), illustrations and pertinent test data, cost, material safety data sheets (if applicable), product availability, and any other information that they believe best describes their system. Please submit only information on products that are currently commercially available, not items that are under development. THIS IS NOT A REQUEST FOR PROPOSAL. No solicitation document is available at this time.

3. Point of contact is Ms. Anne McLaughlin, commercial 508-233-4446, DSN 256-4446, FAX 508-233-4120 or via electronic mail at anne.mclaughlin@natick.army.mil.

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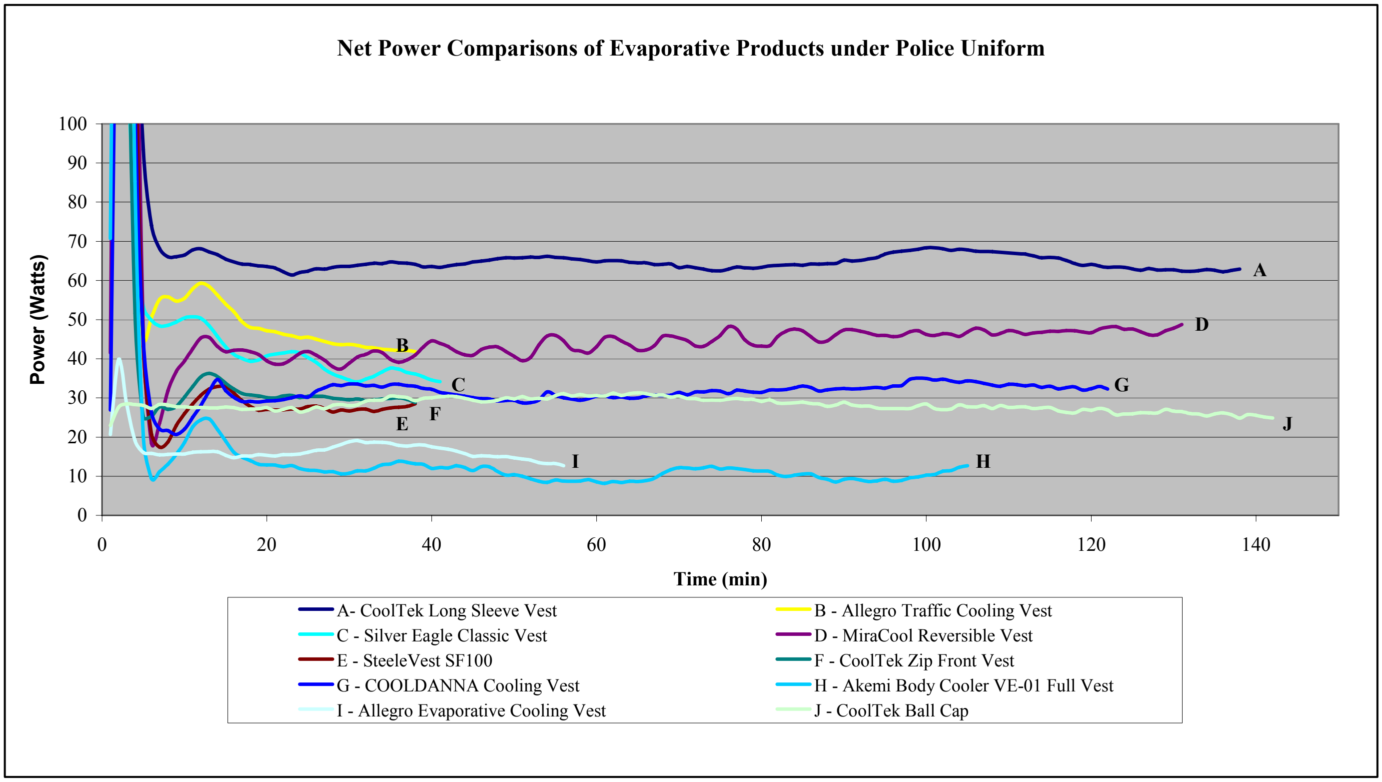
JAN LANZA
International Office

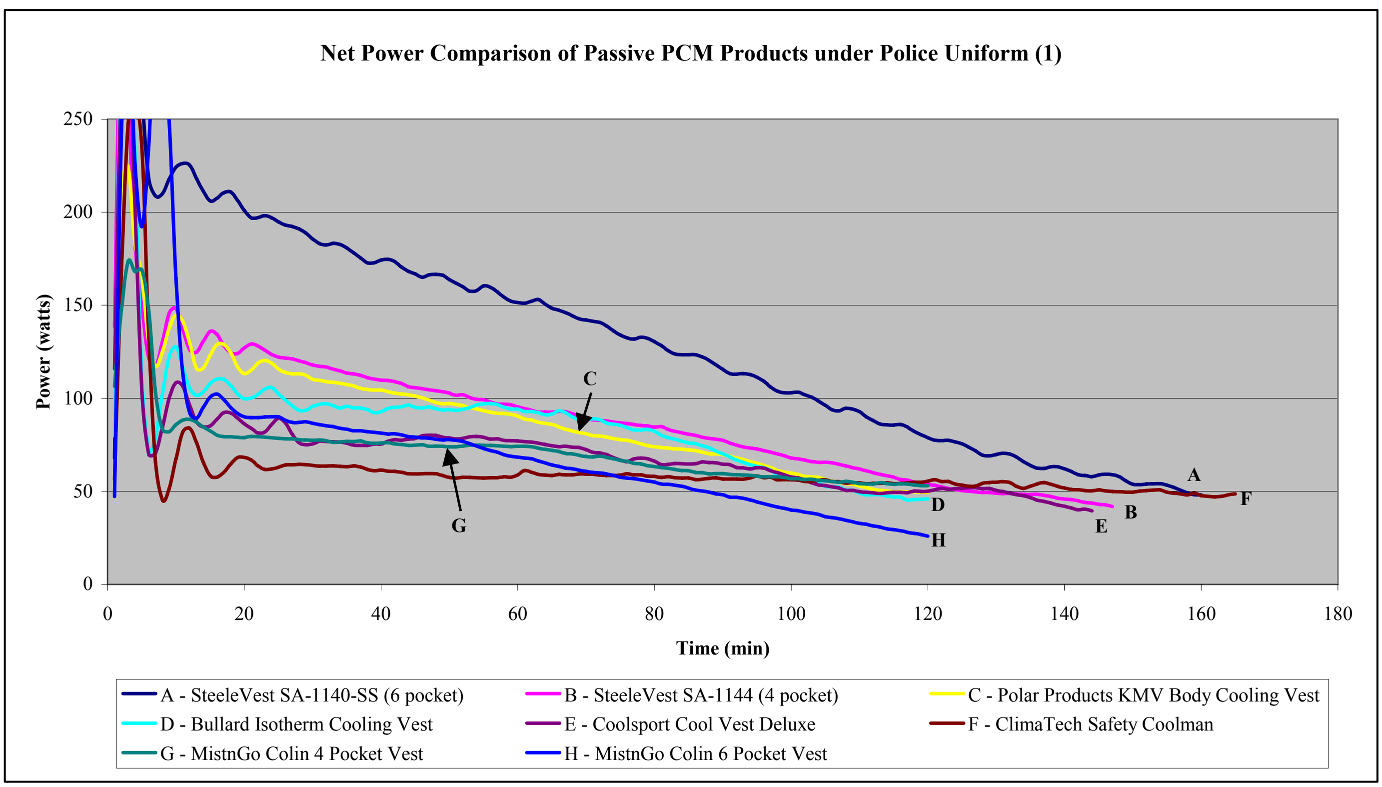
Distribution:
RTC Commanders

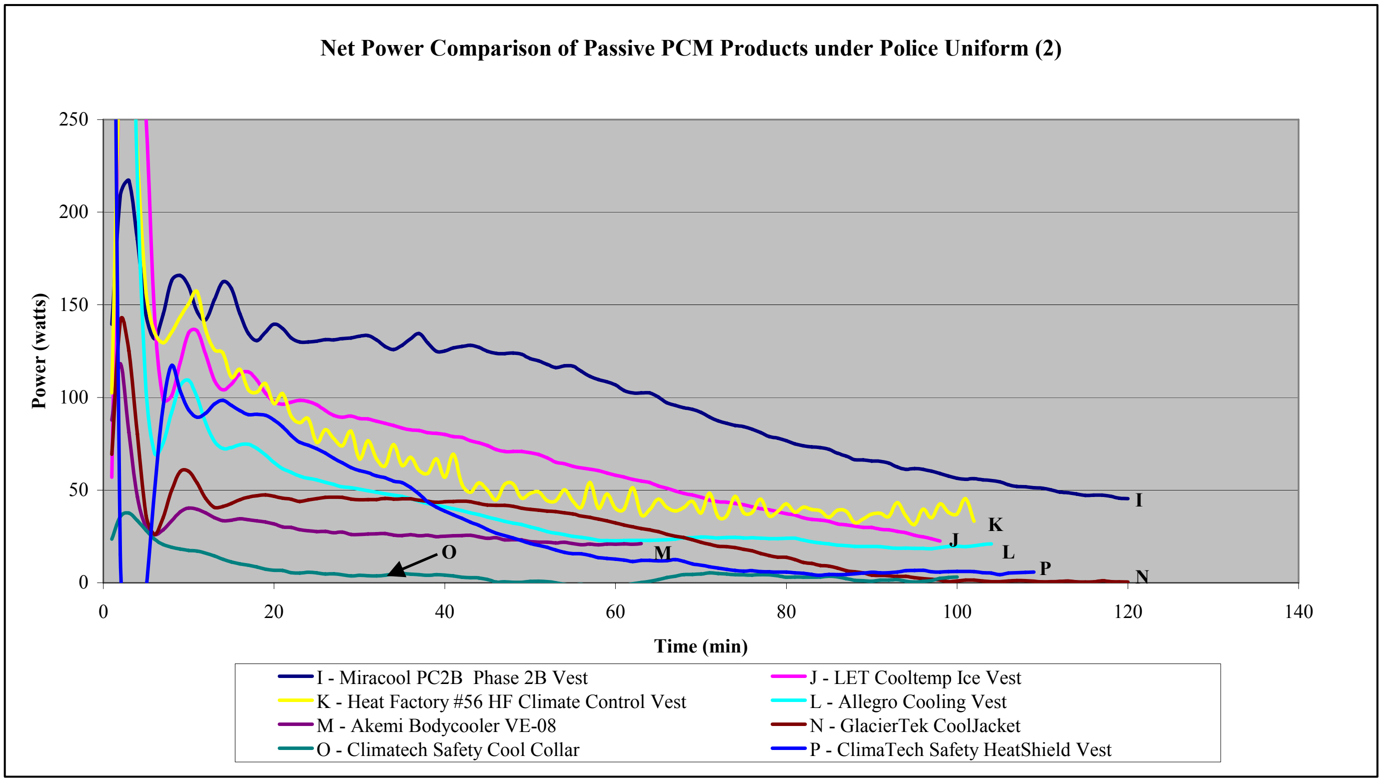
Appendix C

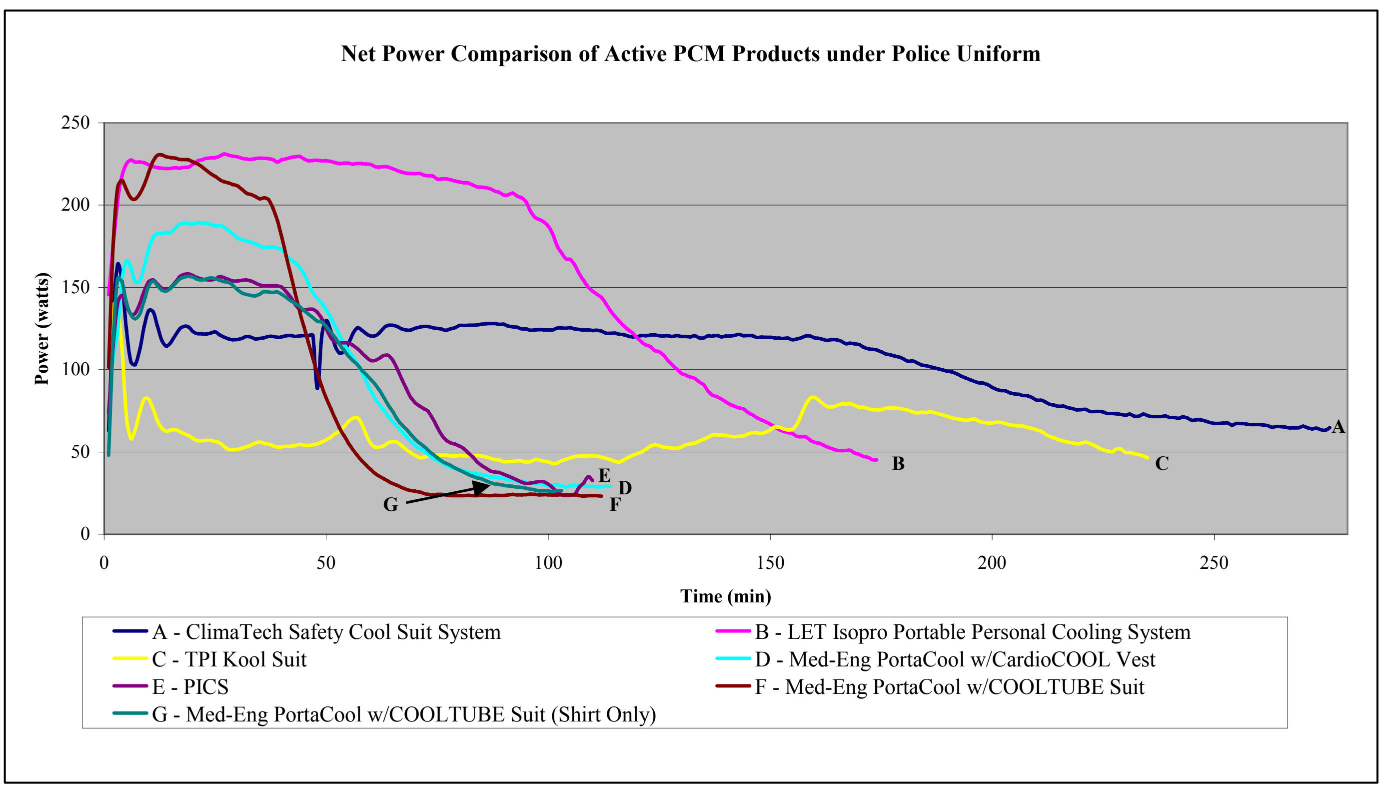
Cooling Power Plots

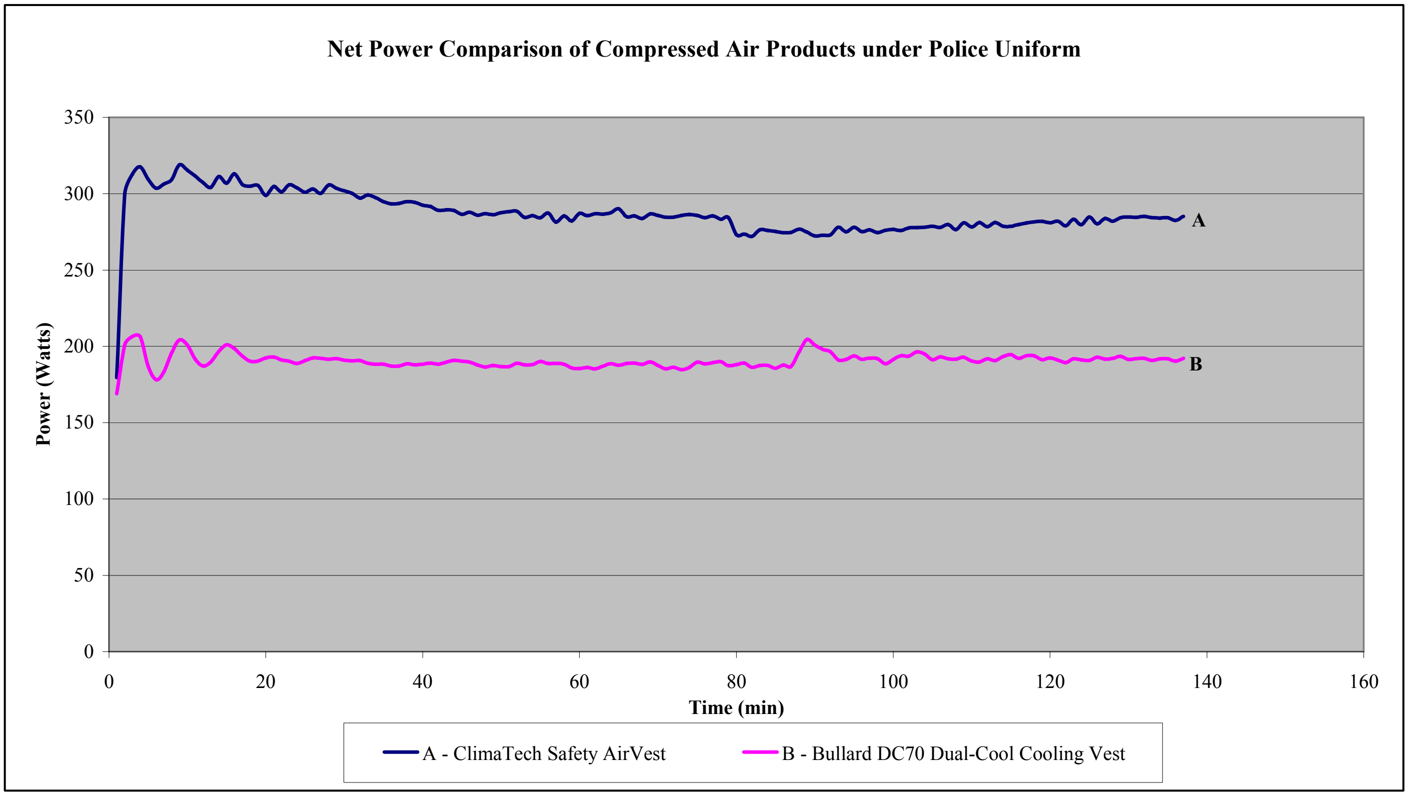
Appendix C
Cooling Power Plots



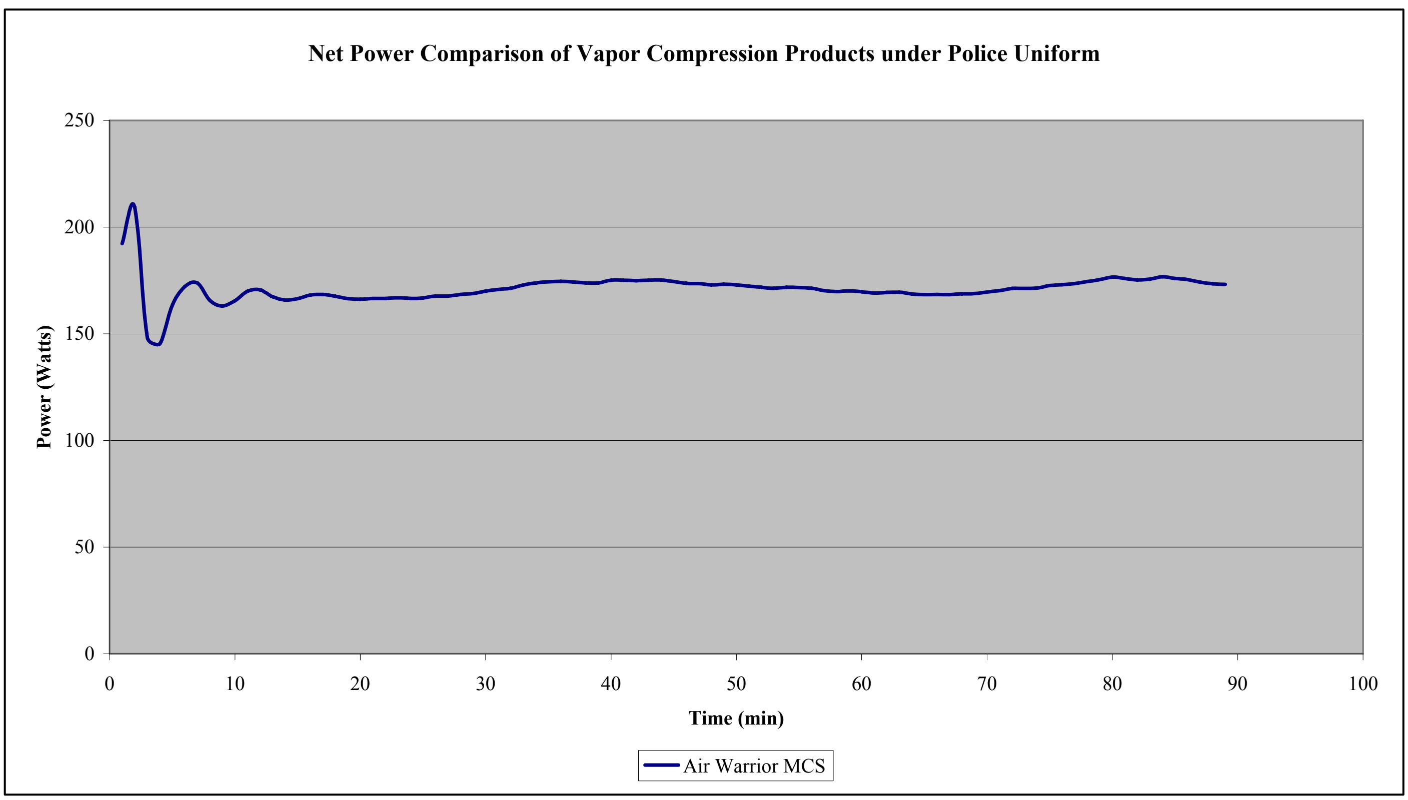



Net Power Comparison of Passive PCM Products under Police Uniform (2)
Power (watts)
Time (min)
I - Miracool PC2B Phase 2B Vest
J - LET Cooltemp Ice Vest
K - Heat Factory #56 HF Climate Control Vest
L - Allegro Cooling Vest
M - Akemi Bodycooler VE-08
N - GlacierTek CoolJacket
O - Climatech Safety Cool Collar
P - ClimaTech Safety HeatShield Vest

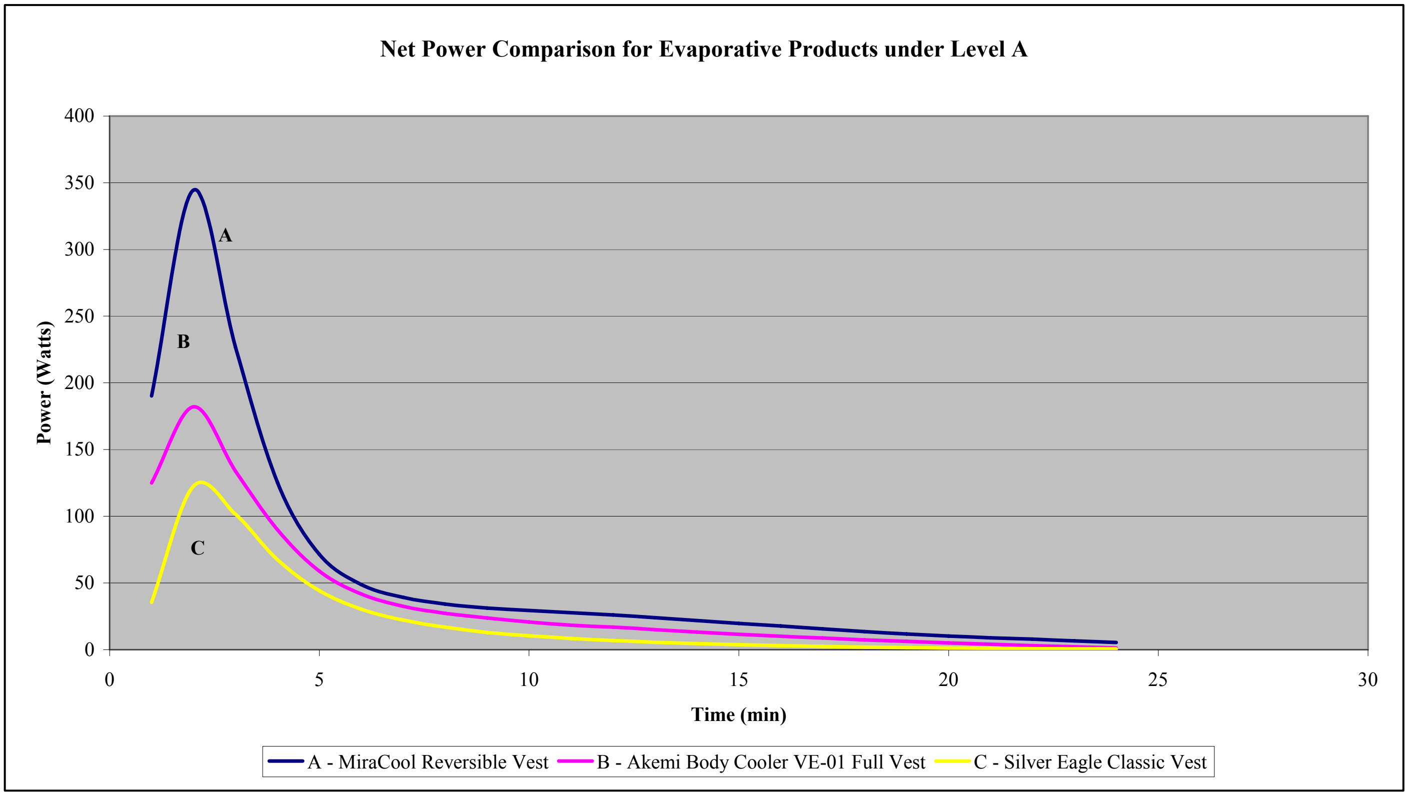

Net Power Comparison of Active PCM Products under Police Uniform
Power (watts)
Time (min)
A - ClimaTech Safety Cool Suit System
B - LET Isopro Portable Personal Cooling System
C - TPI Kool Suit
D - Med-Eng PortaCool w/CardioCOOL Vest
E - PICS
F - Med-Eng PortaCool w/COOLTUBE Suit
G - Med-Eng PortaCool w/COOLTUBE Suit (Shirt Only)

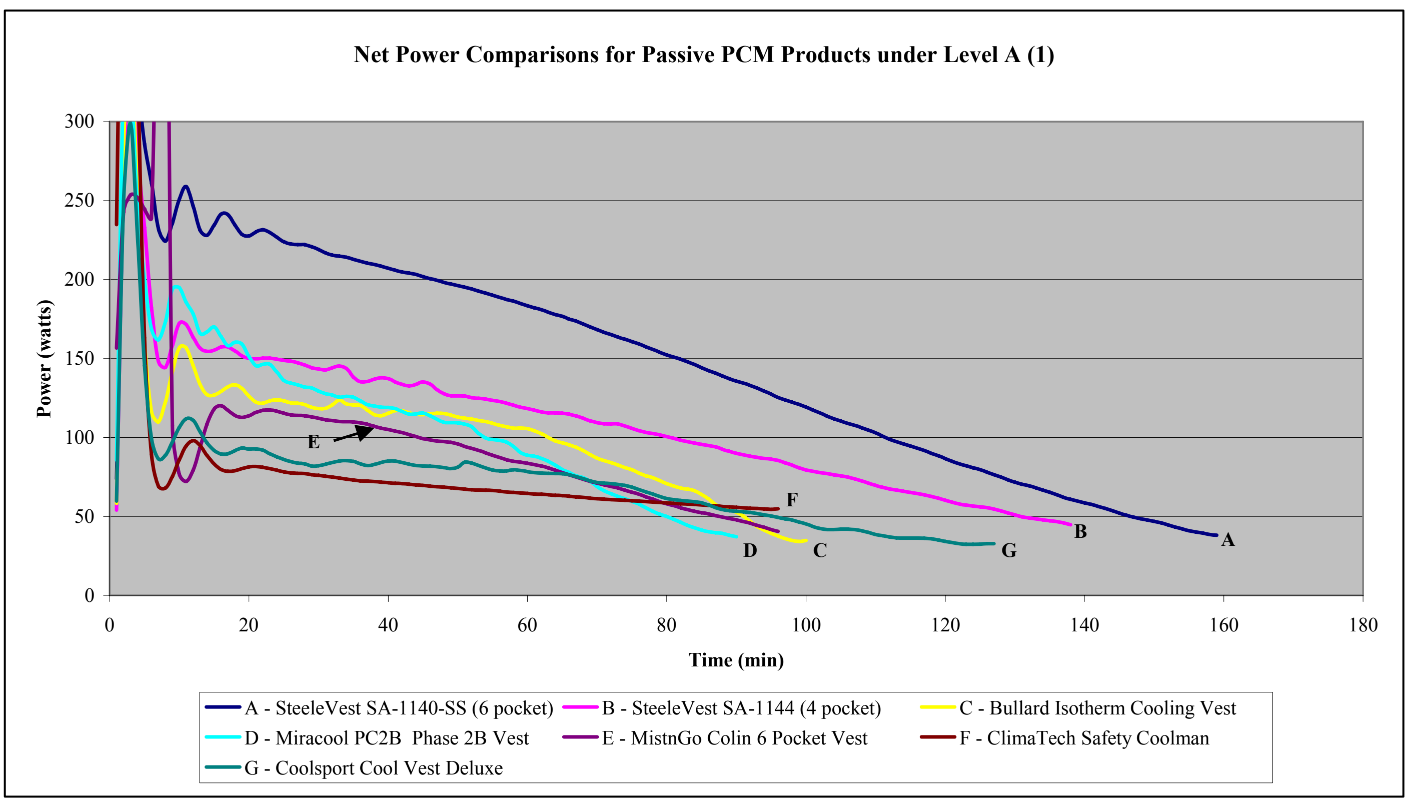


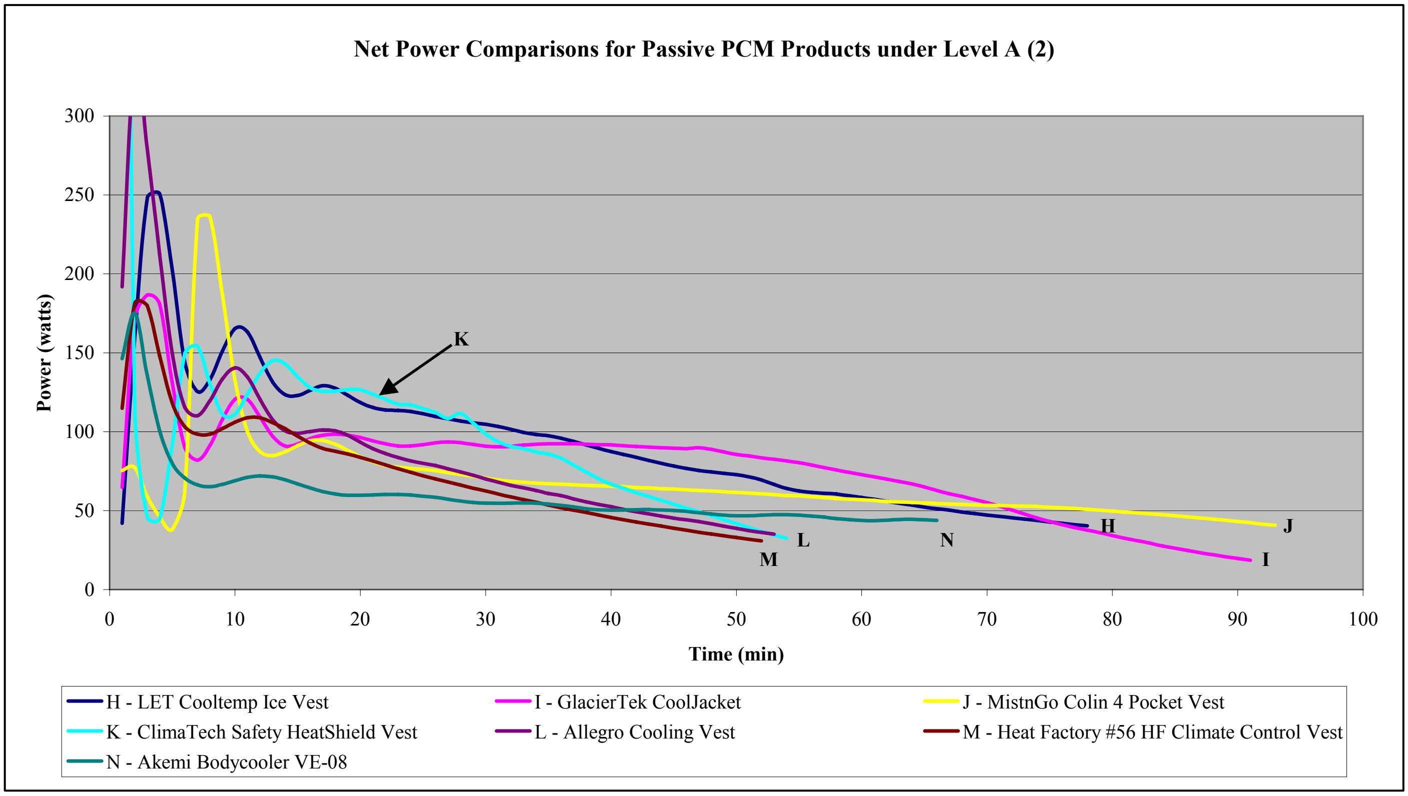
Net Power Comparison of Compressed Air Products under Police Uniform
350
300
250
200
150
100
50
0
0
20
40
60
80
100
120
140
160
Power (Watts)
Time (min)
A
B
A - ClimaTech Safety AirVest
B - Bullard DC70 Dual-Cool Cooling Vest

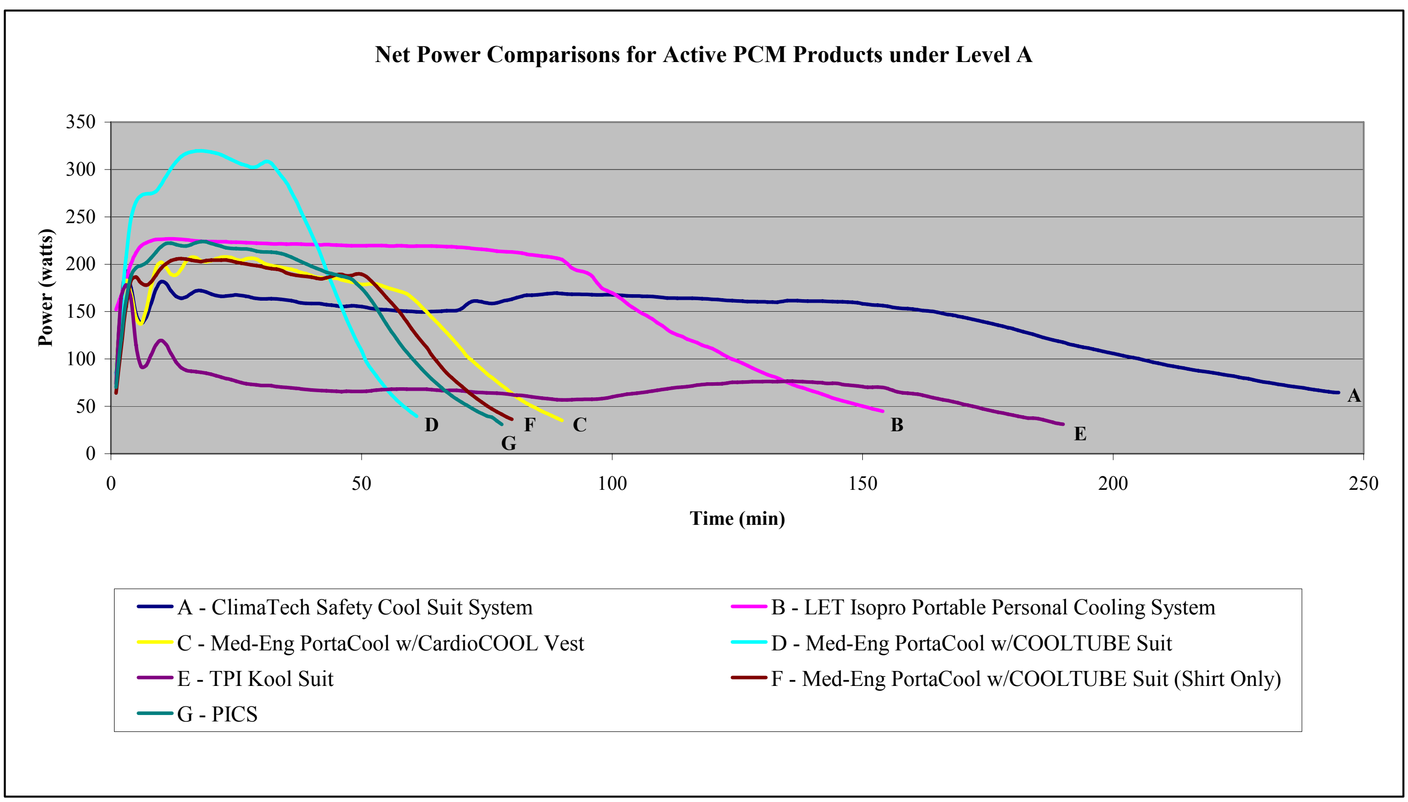


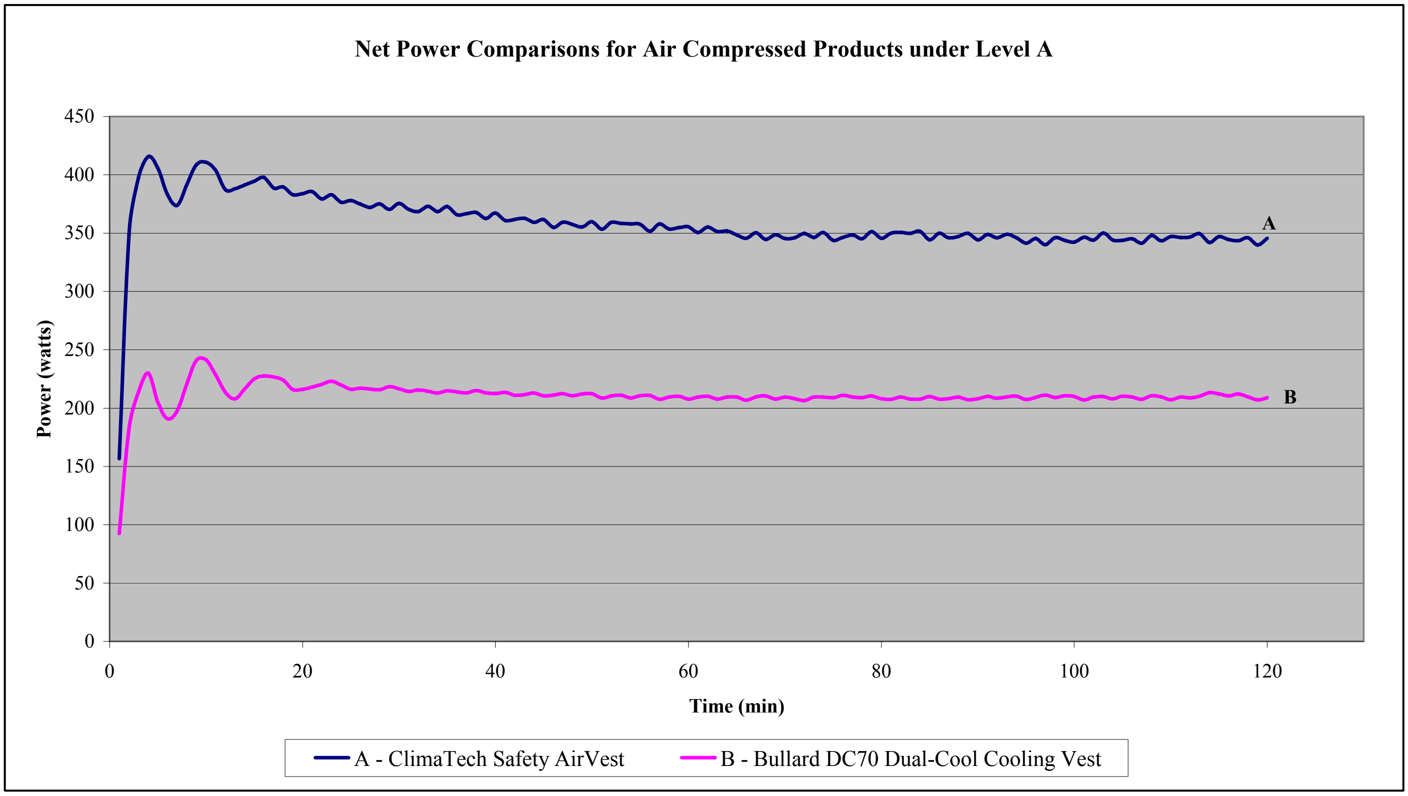
Net Power Comparison of Vapor Compression Products under Police Uniform
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Power (Watts)
Time (min)
Air Warrior MCS

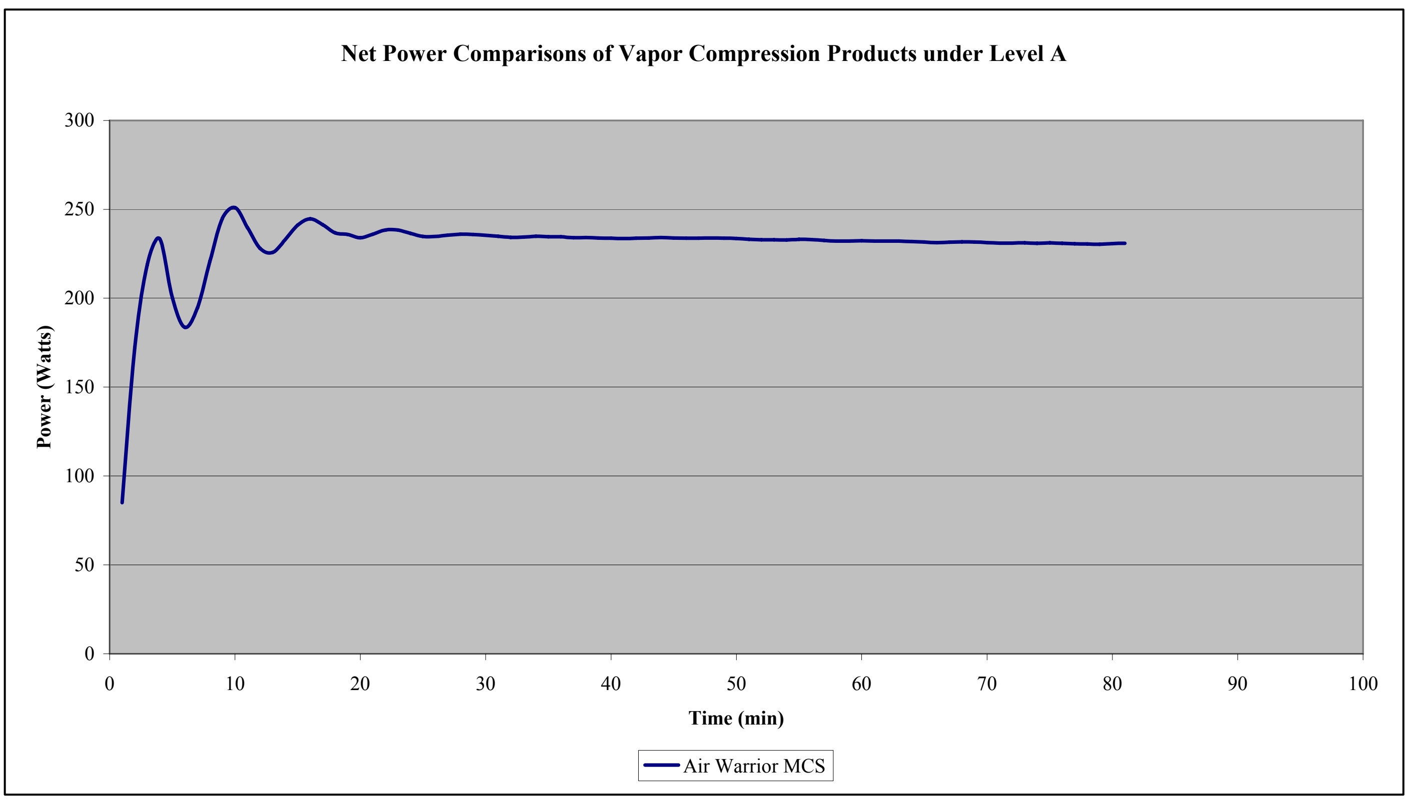

Net Power Comparison for Evaporative Products under Level A
Power (Watts)
Time (min)
A
B
C
A - MiraCool Reversible Vest
B - Akemi Body Cooler VE-01 Full Vest
C - Silver Eagle Classic Vest


Net Power Comparisons for Passive PCM Products under Level A (1)
Power (watts)
Time (min)
A
B
C
D
E
F
G
A - SteeleVest SA-1140-SS (6 pocket)
B - SteeleVest SA-1144 (4 pocket)
C - Bullard Isotherm Cooling Vest
D - Miracool PC2B Phase 2B Vest
E - MistnGo Colin 6 Pocket Vest
F - ClimaTech Safety Coolman
G - Coolsport Cool Vest Deluxe


Net Power Comparisons for Passive PCM Products under Level A (2)
Power (watts)
300
250
200
150
100
50
0
0
10
20
30
40
50
60
70
80
90
100
Time (min)
K
L
M
N
H
I
J
H - LET Cooltemp Ice Vest
I - GlacierTek CoolJacket
J - MistnGo Colin 4 Pocket Vest
K - ClimaTech Safety HeatShield Vest
L - Allegro Cooling Vest
M - Heat Factory #56 HF Climate Control Vest
N - Akemi Bodycooler VE-08


Net Power Comparisons for Active PCM Products under Level A
Power (watts)
350
300
250
200
150
100
50
0
0
50
100
150
200
250
Time (min)
D
F
G
C
B
E
A
A - ClimaTech Safety Cool Suit System
B - LET Isopro Portable Personal Cooling System
C - Med-Eng PortaCool w/CardioCOOL Vest
D - Med-Eng PortaCool w/COOLTUBE Suit
E - TPI Kool Suit
F - Med-Eng PortaCool w/COOLTUBE Suit (Shirt Only)
G - PICS


Net Power Comparisons for Air Compressed Products under Level A
450
400
350
300
250
200
150
100
50
0
Power (watts)
0
20
40
60
80
100
120
Time (min)
A
B
A - ClimaTech Safety AirVest
B - Bullard DC70 Dual-Cool Cooling Vest


Net Power Comparisons of Vapor Compression Products under Level A
300
250
200
150
100
50
0
Power (Watts)
0
10
20
30
40
50
60
70
80
90
100
Time (min)
Air Warrior MCS