A PHYSIOLOGICAL STUDY OF

THE EFFECTIVENESS OF TWO PROTOTYPE

PORTABLE COOLING VESTS

by

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CHAPTER I

INTRODUCTION

1.1 BACKGROUND

First responders are highly trained state and local fire, law enforcement, and medical workers who are called upon to assist victims and provide public safety when any kind of emergency or disaster strikes, whether it is an explosive, biological or chemical attack or some other kind of major disaster. First responders play a critical role in the initial investigation of disaster sites for hazardous substances including containing and neutralizing the substances thereby rendering the site safe for the public. First responders are specially trained to recognize various hazards and to use appropriate personal protective equipment (PPE).

First responders' mission areas range from survey of the hot zone to crowd control, emergency medical services, hazardous material spill clean up and decontamination of tools, materials and people. The nature of the hazard dictates the type of PPE needed by the first responder. All hazardous materials responses are considered high risk initially, until assessed and confirmed safe (Ruhl, 2002; Anderson, 2002; Stoockey, 2002, and Hohl, 2001). For example, an incident of an unknown substance in the hot zone requires the highest possible protection for the first responder. Thus, fully encapsulated special garments are used to inhibit or prevent both liquid and gas

substances to come into contact with the first responder's body. Sometimes the nature of the hazard is identified at the time of the response. In this case, liquid splash protection might be adequate; therefore a simpler, waterproof overall garment with rubber boots and gloves might be sufficient.

Today, first responders have a wider choice of PPE than a decade ago (Torvi and Hadjisophocleous, 1999; Williamson, 2000; and Tiron, 2001). PPE is commercially available in partially or fully encapsulating suits with varying protection levels and degrees of permeability in order to prevent hazardous liquid and/or vapor contact with the wearer's skin (Hohl, 2001; NIOSH, 2002; Willingham, 2000). The Environmental Protection Agency (EPA) levels of protection are summarized in Table 1 (EPA Levels, 2003).

Level D suits are recommended when the air contains no known hazard and no direct contact with chemicals is expected. Level D suits are composed of coveralls, safety boots or shoes, safety glasses or chemical splash goggles and provide minimal skin protection with no respiratory protection.

Level C suits include chemical resistant gloves, safety boots, two-way communication system, hard hat, full-facepiece, and an air-purifying respirator. They protect the skin from liquid splashes but not from chemical gases. Additionally, they provide some respiratory protection. Level C suits are recommended when air contaminants have been identified and the site and its hazards have been completely characterized. Level C and Level D suits are not acceptable for chemical emergency response.

Table 1. Chemical Protection Levels as Suggested by EPA.

(Adapted from OSHA Technical Manual, Section VIII: Chapter 1 Chemical Protective Clothing, 2003).

Description	Protection Provided	Used When	Limitations
LEVEL A: Vapor protective suit (meets NFPA 1991) Pressure-demand, full-face SCBA Inner chemical-resistant gloves, chemical-resistant safety boots, two-way radio communication Optional Cooling system, outer gloves, hard hat	Highest available level of respiratory, skin, and eye protection from solid, liquid and gaseous chemicals.	The chemical(s) have been identified and have high level of hazards to respiratory system, skin and eyes. Substances are present with known or suspected skin toxicity or carcinogenity. Operations must be conducted in confined or poorly ventilated areas	Protective clothing must resist permeation by the chemical or mixtures present. Ensemble items must allow integration without loss of performance.
LEVEL B: Liquid splash-protective suit (meets NFPA 1992) Pressure-demand, full-facepiece SCBA Inner chemical-resistant gloves, chemical-resistant safety boots, two-way radio communications Hard hat. Optional Cooling system, outer gloves	Same level of respiratory protection as Level A, but less skin protection. Liquid splash protection, but no protection against chemical vapors or gases.	The chemical(s) have been identified but do not require a high level of skin protection. Initial site surveys are required until higher levels of hazards are identified. The primary hazards associated with site entry are from liquid and not vapor contact	Protective clothing items must resist penetration by the chemicals or mixtures present. Ensemble items must allow integration without loss of performance.
LEVEL C: Support Function Protective Garment (meets NFPA 1993) Full-facepiece, air-purifying, canister-equipped respirator Chemical resistant gloves and safety boots, two-way communications system, hard hat Optional Faceshield, escape SCBA **Not Acceptable for Chemical Emergency Response**	Same level of skin protection as Level B, but a lower level of respiratory protection. Liquid splash protection but no protection to chemical vapors or gases	Contact with site chemical(s) will not affect the skin. Air contaminants have been identified and concentrations measured. A canister is available which can remove the contaminant. The site and its hazards have been completely characterized.	Protective clothing items must resist penetration by the chemical present. Chemical airborne concentration must be less than IDLH levels. The atmosphere must contain at least 19.5% oxygen.
LEVEL D: Coveralls, safety boots/shoes, safety glasses or chemical splash goggles OPTIONAL: Gloves, escape SCBA, face-shield **Not Acceptable for Chemical Emergency Response**	No respiratory protection, minimal skin protection.	The atmosphere contains no known hazard. Work functions preclude splashes, immersion, potential for inhalation, or direct contact with hazard chemicals.	This level should not be worn in the Hot Zone. The atmosphere must contain at least 19.5% oxygen.

Level A and B suits are used by first responders to perform site surveys, rescue, oil and chemical spills and decontamination procedures. Level B suits protect the wearer from liquid hazardous materials. Level A suits are also vapor impermeable and are fully encapsulated (Figure 1)

Figure 1. A typical Level A Suit. Always Fully Encapsulated, Vapor Resistant.

On the other hand, Level B suits (Figure 2) can come in different shapes and styles. They may be two pieces, composed of a bib and a jacket, with or without a hood or may look exactly like a Level A suit. A HazMat worker also has to carry instruments, tools, and a radio. All encapsulating ensembles require a respirator system unless the air is supplied through an umbilical hose (air-supply hose). Respiratory and other equipment plus the layered hand and footwear make the protective gear even heavier and hotter. Duggan (1988) found that increasing weight by 3 or 5 kg through the addition of protective clothing raised the energy costs of bench-stepping by 5 and 9% respectively, compared to normal clothing. Therefore, more metabolic heat is generated to accommodate working with additional weight. When the body builds up too much internal heat, it triggers the body's built-in cooling mechanism. Researchers agree that work tolerance was found to decrease in all encapsulating work even in cool (18'C) environments and that liquid, air and ice cooling were found to provide beneficial effects (McClure, McClure, and Melton, 1991; Bishop, Ray, and Reneau, 1995).

Figure 2. Types of Level B Suits: Fully encapsulated, Two Piece, Bib Style Overall, and Hooded Style. (Taken from Lakeland Industries website)

Evaporation of sweat is one major way of providing heat relief. However, when the perspiration is unable to evaporate and provide sufficient cooling, the strain on the body can cause heat stress (Zeigler, 2002; Torvi and Hadjisophocleous, 1999). The outer layers of Level A and Level B garments are impervious, often treated with chemicals so that the hazardous liquids and/or vapors cannot penetrate the suit material which makes it difficult for body sweat to evaporate and provide cooling. When the core body temperature reaches unsafe limits, the PPE wearer might experience cramps, skin rash, exhaustion, reduced mental capacity, confusion, impaired vision; impaired mobility and difficulty in communication, collapse, heat stroke, heart attack or even death. The effects of wearing Level A and Level B suits range from uncomfortable to dangerous. (Zeigler, 2001 and 2002). To alleviate heat stress, OSHA Technical Manual, (2003) suggests using optional cooling systems with Levels A and B protection. Due to the heat stress problem

several types of cooling garments have been designed and marketed for use with PPE to provide relief from the heat.

1.2 COOLING GARMENTS

Cooling garments have been used since the late 1950's. The earliest models, used in Gemini and Apollo space suits, were gas-cooled and not particularly effective in cooling the body (Nunneley, 1970). Water-cooling was introduced in 1962 with garments that looked like long johns with pipes running through the torso and the extremities. The water was cooled and pumped by an external unit and introduced to the garment via an "umbilical cord." They had limited applications for industry and aerospace until portable models were developed. Today, there are several different technologies used in cooling garments and there are broader applications for law enforcement, traffic control, military, fire fighters and HazMat workers to name a few. Cooling garments also have health applications in alleviating multiple sclerosis symptoms (Cooling vest improves symptoms for MS patients, 2002).

Currently, in addition to water-cooled vests which use cold water circulating inside tubing embedded in the strategic sections of the torso, there are ice packs, gel packs, evaporative, and phase change technologies that are used in assorted designs. Gel packs and ice packs are placed in deep pockets or attached by means of hook and loop tape to the front and the back of the vest and deliver cooling until they melt.Evaporative cooling vests are lightweight (Kaufman and Fatkin, 2001), however, they do not provide as much cooling as liquid/ice cooled or phase change vests. The vests are completely soaked with water and the excess water is wrung out. As the water evaporates from the absorbent special core material, it absorbs heat from the adjoining body.

Phase change materials are the newest trend in cooling garments (McCullough, 2001). They use a technology that provides constant temperature until all the crystals change from solid to liquid state, at which point the user should "recharge" the garment by soaking it in a tub filled with ice and water, or keep it in the refrigerator until firm. There is also, what is called "Feather Ice", or "ThermaLink" which feels like powdered ice and can be frozen overnight. It also keeps a constant temperature and but is not as stiff, as phase change material in its solid form.

Some vests are made entirely of evaporative or phase change material. A more common type of commercial cooling vest has several deep pockets to hold rectangular cooling units made of evaporative, phase-change or feather-ice material. One advantage of the latter is that the user can freeze smaller packets rather than the whole garment and has the option of having spare frozen units for replacement.

There is concern among industry leaders that even though the benefits of using cooling garments are well documented, workers are reluctant to wear them (Corcoran, 2002). The complaints often voiced by users should be addressed in any design improvement study. Corcoran (2002) lists user concerns, in no specific order, as: (1) too heavy, (2) can't move in it, (3) activate slowly, (4) smell bad, (5) restrict movement, and (6) don't work.

Therefore, a cooling garment design should involve most of the following properties: minimal weight; ease of use; donning and doffing; minimal activation time; durability in use and laundering; available replacement parts; no hazards associated with the technology; attractiveness; perceived comfort and cooling effectiveness.

1.3. PRIOR RESEARCH AND DEVELOPMENT OF THE PROTOTYPE GARMENTS

A prototype, battery-powered, portable personal cooling garment system for use by HazMat first responders is under development as a joint effort of two universities and three commercial partners as part of a three-year research project led by Oklahoma State University (OSU) and funded by the Oklahoma City National Memorial Institute for the Prevention of Terrorism (MIPT). This research is one component of the three year project. Two separate but interconnected research efforts contributed to the development of a portable, battery-powered, alpha prototype, personal cooling system for first responders at the conclusion of the second year. The cooler research led to development of a prototype cooling unit. Fabric and design component testing led to the development of a prototype garment. The garment research was conduced primarily at OSU with collaboration from the second university and one commercial partner. A schematic representation of the research components is shown in Figure 3.

Development of an effective cooling garment was the focus of Oklahoma State University research team. Levine L., Sawka M.N. and Gonzalez R.R. (1998) suggest a process and test methodology to be employed by the US Army's Health Hazard Assessment for material in the development and acquisition process. They propose the use of the guarded hot plate, the thermal manikin, mathematical modeling and human physiological testing in the order stated. A similar procedure has been followed in developing the OSU cooling vests. Additional refinements of the prototype for a fit analysis were completed in preparation for the physiological study. The design process used to develop and test two prototype cooling garments involved multiple components and rigorous laboratory testing as shown in Figure 4.

Figure 3. Schematic Representation of the Research Components that Resulted
in the Development of an Alpha Prototype Cooling System.
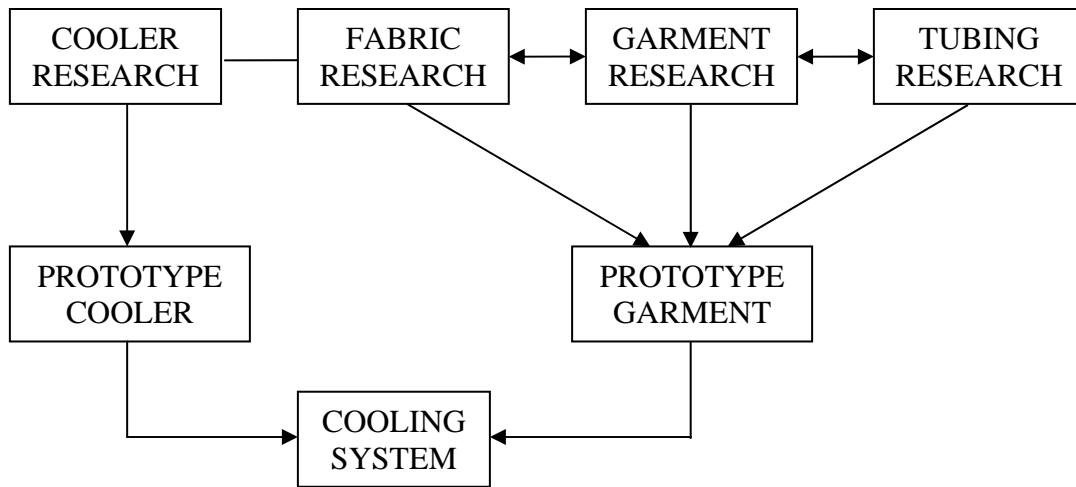
Fabric selection was accomplished after conducting various laboratory tests to
determine physical, thermal and moisture management properties of a battery of fabrics.
A market analysis of currently available cooling vests was conducted. Focus group
interviews provided user input. PVC tubing which is currently used in various available
vests was used to construct 12"x12" vest sections for evaluation of cooling effectiveness
by fabric and tubing layout. These components which are reported in detail elsewhere
were all used to develop two prototype cooling garments (Cao, Branson, Nam, Peksoz,
and Farr, 2005; Branson, Farr, Peksoz, Nam, and Cao, 2005). The garments' cooling
capabilities were assessed by a thermal manikin at the US Army Soldier Center, Natick,
Massachusetts. The positive results of these tests led to the planning of the current
component, a human subject physiological study.

Figure 4. Design Process Implemented at OSU While Developing Prototype Cooling Garments

Fabric Search

Cooling Vest Market Analysis

Focus Groups

Fabric Testing

- Thermal Resistance
- Moisture Management
- Abrasion

12"x12" Composite Test Sample

Pattern Development and Tubing Layout

Cooling Capability Testing

Prototype 1

Prototype 2

Garment Testing

- Pressure Drop testing
- Flow Constriction Testing
- Thermal Manikin Testing

Refined Prototype Cooling Garment

1.4. SIGNIFICANCE

There is need for relief from the heat and moisture that accumulate inside an impermeable HazMat suit. P. Bishop, P. Ray, P. Reneau (1995) reviewed research done prior to 1995 on personal protective clothing and found that that body cooling and microclimate cooling increased work time and lowered the core temperature significantly except for extreme environmental conditions. Speckman, Allan, Sawka, Young, Muza, and Pandolf, (1988) studied the effectiveness of liquid cooling on both a manikin and human subjects. They showed that the greater the area of the body covered the greater the cooling capacity. They also showed that cooling the arms plus the torso during upper-body exercise provided no cooling advantage, but cooling the upper leg in addition to the torso during lower-body exercise did provide a cooling advantage.

Most effective cooling relief can be provided by making use of the power available in military vehicles or laboratories. However, portable personal cooling devices are still in their developmental stage. Commercially available cooling garments were discussed in several focus groups (Branson, et al., 2005) and the need for a lightweight and portable cooling garment was emphasized. Not only HazMat workers but also soldiers, police, miners and numerous other professionals who need to be mobile while working in a hot environment, would benefit from an easy to use cooling garment. This study is another step in providing one such device by testing its effectiveness under two types of PPE within a controlled environment.

In addition to this practical significance, there is also the potential for methodological significance. In order to test the effectiveness of cooling the HazMat worker, a protocol was developed to closely simulate the typical activities of a first

responder, which has the potential to be a better indicator of assessing variables of intent. Also, inclusion of activities other than simple movements such as walking and bending permitted the subjects to judge fit, comfort and visibility inside a fully encapsulating suit and a hooded coverall garment..

1.5. RESEARCH PURPOSE AND OBJECTIVES**Error! Bookmark not defined.**

The purpose of this research was to obtain comparative human subject data for subjects wearing two prototype cooling vests under PPE in a controlled environment, in order to evaluate the cooling effectiveness of the prototypes and wearer comfort perceptions. The objectives for achieving this goal were:

1. To analyze the physical, physiological and perceptual data provided by the subjects wearing two prototype cooling vest designs as compared to a control (no cooling) over time.
2. To investigate the physiological and perceptual responses of subjects wearing the cooling vests with respect to two different types of tubing in the vests over time.
3. To determine the impact that two types of outer garments have on physiological and perceptual data over time.
4. To determine the differences, if any, between measured physiological responses and perceived comfort levels of the subjects wearing the test vests.
5. To analyze the feedback that subjects provided to evaluate the design of the prototype vests for fit and comfort.

CHAPTER 2

LITERATURE REVIEW

2.1. HEAT TRANSFER PROCESS

The human body, like any other organism, exchanges heat with its surroundings by four physical processes: conduction, convection, radiation and evaporation. *Conduction* is the direct transfer of heat between molecules of the environment and the surface of the human body, as when a person steps on a cold floor. Thermal energy moves through the floor material when atoms bounce off each other, transferring kinetic energy from the foot to the floor, since this transfer of kinetic energy goes from regions of high kinetic energy to regions of low kinetic energy; heat is also transferred from regions of high temperature to areas of low temperature. In other words, heat flow (gradient) will always be from the warmer surface to the cooler. *Convection* occurs when air or liquid is heated. Warmer liquid / air moves upward (since it is now less dense) and is replaced with cooler liquid/air, causing a circular movement of the air/liquid. When human skin warms the nearby air and the air rises, it is replaced with cooler air, which can carry more heat away from the body. A cold breeze intensifies the cooling by removing the warmer air next to the skin. *Radiation* can transfer heat by emission of electromagnetic waves between objects that are not in direct contact with each other, as in sun's rays. *Evaporation* is the loss of heat from the surface of a liquid. Since it requires energy to convert liquid water to vapor, when water evaporates on the skin's surface, heat

from the skin supplies the evaporation energy, and so the skin is cooled. Then, the blood moves the heat from the core by means of conduction to the skin surface (Watkins, 1984; Campbell, 1993).

2.2. HUMAN THERMOREGULATION SYSTEM

Homeostasis is one of the fundamental characteristics of living things. It refers to the maintenance of the internal environment within tolerable limits. Homeostasis is crucial for the health of humans. One of the largest portions of physiological homeostasis is thermoregulation of the body. There are several ways the human body regulates its temperature because it is essential to keep it within a very narrow range for the proper functioning of its components. The hypothalamus is the principal "thermostat" and it gets its input from thermoreceptors located in the skin (peripheral thermoreceptors) and within the central nervous system and abdomen (central thermoreceptors). The hypothalamus maintains a constant core body temperature. The fluctuations in skin temperature happen more frequently. Since the skin's thermoreceptors sense a change in external body temperature before the internal thermoreceptors, the hypothalamus initiates corrective homeostatic mechanisms before the core temperature even begins to change. There are four major ways that adjustment happens:

1. *Change the rate of metabolic heat production.* When the core body temperature drops, the hypothalamus increases muscular activity which increases metabolic rate and produces heat. When the environment gets colder, muscle contractions increase in frequency, causing shivering, (about 15 contractions per second). In warmer conditions, the hypothalamus lowers the basal level of muscle contractions, which explains why one

feels sluggish in hot weather. In addition to regulating muscle metabolism, the hypothalamus activates some hormone production to control body temperature.

2. *Adjust the rate of heat exchange between the body and the environment.* The amount of blood flowing to the skin is controlled by little muscles that constrict to restrict blood flow to the skin. This process is called vasoconstriction. These muscles can also cause vasodilation, an increase in the diameter of blood vessels near the skin, which greatly increases the amount of blood passing through the surface. Vasoconstriction and vasodilation are very effective in changing core temperatures; for example, if a person's core body temperature is higher than the ambient temperature, an increase in blood flow to the skin and a release of internal body heat can lead to body cooling (by conduction). If the core temperature is higher than the ambient temperature, blood flow to the skin must be restricted in order to conserve body heat.

3. *Evaporative heat loss:* Humans lose water from their respiratory tract surfaces and across their skin. The skin can change its temperature and the temperature of the blood flowing through it by evaporated sweat. A person can lose up to 4 liters of water in an hour during intense exercise, which corresponds to a loss of 2400 kcal of body heat per hour. The sweat must freely evaporate to lose that much heat. If the air is already saturated with water, such as in humid areas of the world or inside an impervious suit, the water will not move into the vapor phase as easily, and will not remove heat from the skin. This is one reason that it is important to keep the sweat rate and the degree of vapor saturation inside the suit a minimum.

4. *Behavioral responses:* Curling up into a ball to reduce the surface area from which heat may be lost, wearing light clothes to decrease heat absorption from radiation,

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wearing warm clothing to insulate against heat loss (clothing creates a layer of air next to the skin which insulates against heat loss), or to merely move to a warmer or colder environment are a few examples of how humans consciously regulate their thermal environment.

Core temperature: It is imperative that the body core maintains a steady state temperature around 37°C. During a heat stroke there is an interruption of the body's heat regulating mechanisms and the core temperature increases unchecked, and the person may suffer from nervous system malfunction (Campbell, 1993). Some people go into convulsions at just 4° C above normal temperatures. A study conducted in 2002, Sund-Levander, Forsberg and Wahren did not find the upper limit of normal oral, rectal, tympanic and axillary body temperature in adult men and women to be significantly different. The findings indicate however, that the lower limits vary by gender and age. In a study that involves human subjects who can attain higher core temperatures it is important to measure and monitor these threshold temperatures. The body's core temperature is usually measured by a rectal thermometer which is considered the most reliable (Shapiro, Pandolf, Sawka, Toner and Goldman, 1982; Faerevik and Reinertsen, 2003; Levine, Johnson, Teal, Merullo, Cadarette, Staab, Blanchard, Kolka, and Sawka, 2001; Muir, Bishop, and Kozusko, 2001).

Muir, Bishop, Lomax and Green (2001) found that core temperatures can be approximated from ear canal temperature measurements for worker safety predictions. When deep core temperatures cannot be measured via rectal probes, tympanic temperatures have been used in heat stress studies (Foued, Duflot, Nicol, and Grealot,

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2001; Vasmatzidis, Schlegel, and Hancock, 2002; Cheuvront, Kolka, Cadarette, Montain, and Sawka, 2003).

2.3. THERMAL COMFORT

Among the widely accepted definitions of comfort is the sensation of contented well being and the absence of unpleasant feelings (Goldman, 1977). Fanger (1970) defined thermal comfort as the condition of thermal neutrality in which a person would prefer neither warmer nor cooler surroundings. Such comfort is important for one's well being, human performance and productivity. According to the theory described by Fanger (1970), thermal comfort depends on the following conditions:

- Activity of the person (heat production in the body),
- Thermal resistance of the clothing of the person
- Environmental variables: - Air temperature - Air velocity - Humidity, - Mean radiant temperature of the surrounding area.

Fanger's basic assumption here is that thermal comfort is defined in terms of the physical state of the body. What a human body actually senses is skin temperature and not air temperature. For thermal balance, rate of heat loss should equal rate of heat production and mean skin temperature and sweating should be at appropriate levels dependent on activity and metabolic rate. He collected data from environmental chamber experiments, in which sweat rate and skin temperature were measured on people who considered themselves comfortable at various metabolic rates. He concluded that the condition for thermal comfort is that the skin temperature and sweat secretion should lie within narrow limits (comfort zone).

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Fanger (1970) proposed that an expression for optimal thermal comfort could be deduced from the metabolic rate, clothing insulation and environmental conditions. Fanger derived his comfort equation from extensive survey of literature on experiments. He presented the solution of his equation in the form of various charts from which thermal comfort conditions could be obtained if the metabolic rate and clothing insulation are measured or fairly well established.

Clothing protects people from humidity, heat, and cold, and helps them feel physically comfortable. Characteristics of fabric that affect physical comfort include flexibility, bulkiness, weight, and texture. Garment construction also affects physical comfort. Clothing gives the wearer a sense of well being. It tells something about the person. Clothing also affects the way others see, think of, and react to the person (psychological comfort). A person can be comfortable or uncomfortable wearing a certain garment or type of clothing in a social situation. Social comfort may be involved when a person wishes to "make an impression" through the clothing he or she wears. Taking into consideration these three factors, clothing comfort is often conceptualized in terms of balance or equilibrium between the body and the environment (Fourt and Hollies, 1970; Goldman, 1977). Fourt and Hollies introduced the triad - the person, his environment and his clothing- and units and quantities for describing clothing comfort. Some authors have proposed that social factors often go together with physical factors in everyday life circumstances. Pontrelli (1977) identified three groups of variables: (1) physical, (2) psyco-physiological, and (3) stored modifiers. Branson and Sweeney (1991) proposed a model in which each element of the triad has physical as well as non- physical dimensions. They included the interaction among attributes within each dimension and

across dimensions. The filtering component of the model takes into account past experiences, expectations, and memory that may influence a comfort judgment.

2.4. THERMAL COMFORT STUDIES

Comfort studies are often a part of functional garment design evaluation studies. Laboratory testing is conducted in an environmentally controlled chamber with instrumented human subjects wearing test garments of interest and performing a specified work protocol. Studies comparing different ensembles typically keep the metabolic rate/work load constant during testing (Duggan, 1988; Karlsson and Rosenblad, 1998; Ashley, Preston, Bernard, and Bennett, 2002; Fernandes, Richards, and Bernard, 2002; Bishop, Jung, and Church, 2003; Caravello, Preston, Ashley, and Bernard, 2003). Other studies compare garment systems under different metabolic rates by increasing the work load (McLellan, Frim, and Bell, 1999) Bernard, Ashley, and Preston, (2003) explored the physiological strain associated with the upper limit of sustained exposure to heat stress. Thirteen subjects walked at different metabolic rates in five different clothing ensembles. Once the participant reached physiological steady state at a lower level of heat stress, ambient temperature was increased incrementally at 50% relative humidity until the participant could no longer maintain thermal equilibrium. Bishop, et al. (2003) reported that some subjects wearing encapsulating particle-barrier suits performing simulated generic work tasks were unable to complete a full 90 minute test due to high rectal temperatures when the testing was performed in moderate and hot environments. Karlsson and Rosenblad (1998) designed a chamber experiment to simulate the conditions on board a fishing boat. The subjects alternated between two work stations

simulating tasks of `pulling nets' and moving baskets or crates of fish when landing the catch.

La Tourette, Peterson and Bartis (2003) conducted extensive interviews and surveys to compile data concerning emergency responders. Many participants noted that HazMat gear is not designed for extended or repeated use, which would likely be the case with weapons of mass destruction (WMD) event. Chemical protective suits tear easily, and protective equipment degrades with repeated decontamination. Especially with level A suits the wearer is discouraged to kneel on the floor in order not to jeopardize the integrity of the suit. Response time to simulated emergencies varied between 25 to 65 min in a study conducted by the Department of Transportation (Mathur, 1997), however the time spent inside a HazMat suit in the hot zone is limited by the size of the SCBA air bottle. Most emergency responders have only 30-45 min of time due to the air bottle (Branson, Farr, Peksoz, Nam, and Cao, 2005).

Schneider (1999) found that depending on the work intensity and state of heat acclimization, sweat rates can rise as high as 2-3 liters per hour. Caravello, et al. (2003) established that with regard to heat stress, the limiting factor inherent in clothing ensembles is the total evaporative resistance such that he greater the evaporative resistance of the clothing, the lower the ability to cool by sweat evaporation.

A sizeable amount of research has been done to evaluate different personal cooling garments (Shapiro, Pandolf, Sawka, Toner, Winsman, and Goldman, 1982; Bishop, Nunneley, Garza, and Constable, 1988: Bishop, Nunneley, and Constable, 1991; Ashley, Preston, Bernard, and Bennett, 2002; Fernandes, et al., 2002; Cheuvront, Kolka,

Cadarette, Montain, and Sawka, 2003). The general conclusion is that cooling garments could alleviate the physiological strain experienced when working in hot environments.

Bumberger (2000) reports that Dr. David Pascoe found that refrigerated vests reduced skin temperature for a short time but caused vasoconstriction. This retained the warmer core temperatures. The vest which is made of a 3-layer evaporative cooling fabric increased work time by 16.4 %. Bernard, Hart and Richards (1992) compared the performance of six different commercially available cooling systems including ice and ice cooled water circulation and air cooled systems. They concluded all of the cooling garments tested increased exposure time as compared with the control (no cooling) condition. An extensive study on microclimate cooling was compiled by army, navy and air force research laboratories in a report by Pandolf, Gonzalez, Sawka, Teal, Pimental, and Constable (1995). Thermal manikin testing of both long and short cooling undergarments, caps, and vest combinations revealed that cooling can be increased by a increasing the amount of body surface area covered by a liquid cooled garment. When air flow and dry conditions are available, air cooled vests were effective. Pandolf et al. (1995) conducted human laboratory testing on liquid cooled garments and showed that lower the inlet temperature the more cooling the garments provided. However, a severe environmental heat load (over 35 ° C) negates the thermal advantage from these cooling garments. A comfortable 20 ° C inlet temperature provided 264 W and 387 W for short and long undergarments respectively. Nag, Pradhan, Nag, Ashtekar, and Desai, H. (1998) reached a similar conclusion in their study with water cooled garments. Pandolf et al. (1995) also confirmed that cooling increased with increasing skin to water temperature gradient and with increasing flow rate. They noted that the heat gain from the

environment reduces the cooling capability and suggested using insulation over cooling systems. Kaufman and Fatkin (2001) tested four different cooling garments, each with a different method of cooling, with a level A as control overgarment and two types of supplied air systems. They reported that the phase change and evaporative vests did not differ significantly from the control and lighter and more permeable garments did not noticeably improve heat stress. The liquid cooled vest and SuperCritical Air Mobility Pack (SCAMP) reduced the skin temperature but not the core temperature in the climatic conditions of 37 ° C and 75 % relative humidity. Heart rate and sweat loss did not vary.

Testing methods vary among researchers. Nag, Pradhan, Nag, Ashtekar, and Desai, H. (1998) measured the inlet and outlet temperatures to evaluate water cooled jackets. Subject in this experiment remained seated in a climatic chamber under three different environmental conditions. However, the most common form of exercise employed in environmental chambers for evaluating personal protective garments is walking on a treadmill with different speeds and slopes. Some studies incorporate other forms of exercise such as carrying or lifting weights, (Kaufman and Fatkin, 2001; Muir, Bishop, and Ray, 1999), or work-rest cycles (Cheuvront, Kolka, Cadarette, Montain, and Sawka, 2003; Ondo and Lippy, 2002). Field testing of prototype garments is the next stage in evaluation and development as in the studies conducted by Carroll, Vencill, Graves, and Darnell (2000) where they measured and compared microclimate temperatures and studied the thermal effects of the reflectiveness and color of level A garments.

At the time this study was planned, no standard protocol for testing cooling garments in a human subject physiological test was approved. ASTM published its first

standard testing protocol for personal cooling systems in June 2004 in which

environmental conditions, testing protocol and subject testing were addressed (ASTM F

2300-04a).

2.5. DEVELOPMENT OF COOLING GARMENTS AT OSU

A battery-powered, portable personal cooling garment system for use by HazMat

first responders to terrorist threats was developed as part of an Oklahoma City National

Memorial Institute for the Prevention of Terrorism (MIPT) funded project. Thermal and

moisture transport and other physical properties of potential textiles were measured and

used to select textiles for prototype garments. Levine et al. (1998) propose using a

guarded hot plate, the thermal manikin, mathematical modeling and human physiological

testing in the order stated. A similar procedure was followed in developing the cooling

vest prototypes at OSU (Figure 5). During the first year of the MIPT project, the design

process addressed fabric selection through various laboratory tests to determine physical,

thermal and moisture properties of candidate fabrics. In year 2, based on laboratory test

results, one fabric was selected for use as both the inner and outer fabric with tubing

sandwiched between these fabrics. Multiple 12"x12" samples that simulated the layered

system anticipated for the vest were constructed and tested for their cooling capability

using a sweating guarded hot plate (Cao, Branson, Nam, Peksoz, and Farr, 2005). Two

tubing layout patterns were developed into two prototypes in March 2003 (Figure 5).

Thermal manikin, testing of the prototypes was conducted at Natick Soldier Center. This

successful test resulted in vest modification and the conduct of a fit study using a 3D

body scanner (Nam, Branson, Ashdown, Cao, Jin, Peksoz, and Farr, 2005).The successful

fit study led to the physiological study, the subject of this dissertation.

Figure 5. Testing Sequence

Fabric Testing:
•Water Distribution
•Thermal conductivity
•Evaporative thermal onductivity
•Wicking
•Abrasion

12"x12"
Composite Sample
Cooling Capability
Testing

Prototype Vest Testing
Thermal Manikin Study

Vest Fit Testing

Human Subject
Physiological Study of
Cooling System
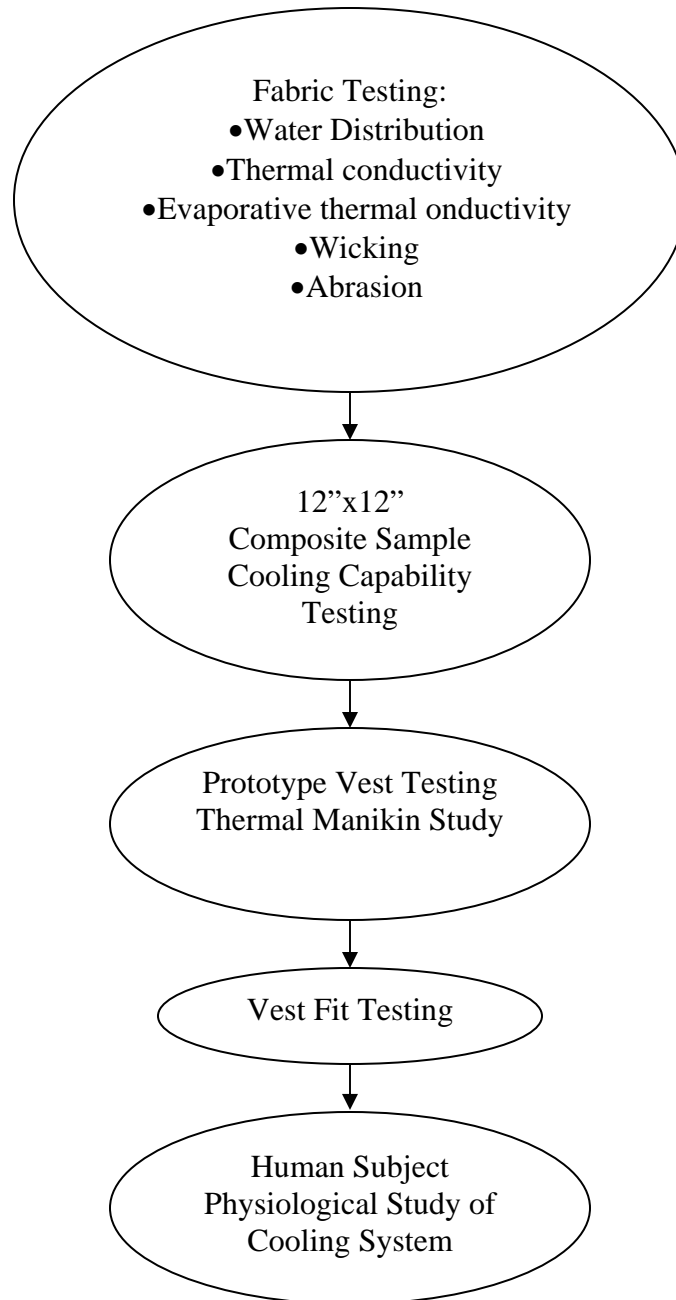
CHAPTER III

METHODS

The purpose of this investigation was to determine subjects' selected

physiological and subjective responses while wearing no cooling garment and two

prototype cooling garments under personal protective equipment while performing a

typical workload under controlled environmental conditions. As required by Oklahoma

State University for all experiments involving human subjects an approval (Appendix A)

was obtained from OSU's Institutional Review Board (IRB).

3.1. VARIABLES

An overview of variables is presented in this section. Independent variables are

described in detail followed by dependent variables. Measurement methods for physical

and physiological variables and coding for the perception variables are given next.

Controlled variables are briefly discussed at the end.

3.1.1. INDEPENDENT VARIABLES

Chemical protective suit with two levels, level A suit and level B suit; cooling

treatments with three levels, control, prototype 1 and prototype 2; and time were the

independent variables in this study.

3.1.1.1 SUIT VARIABLE

Level A and level B protective garments made up the two levels for this variable.

The garment on the left in Figure 6 is a level A, Kappler Responder, System CPF 2, Style 41551, a fully encapsulating, front entry training suit with attached inner boots and butyl gloves. The Level B suit used is shown on the right. This suit is a front entry, coverall style, with hood and booties. Both suits were used with the same respirator system. The bottle was mounted on the outside of the Level B suit, whereas it was encapsulated inside the level A garment.

Figure 6. Level A and Level B Protective
Overgarments Used in This Study

3.1.1.2 COOLING VARIABLE

The three levels of the cooling variable were: a control level in which subjects did not wear a cooling garment and the two prototype cooling vests which were of the same design except for the tubing. The vest, shown in Figure 7, was constructed of black 100% polyester knit fabric (manufactured by Milliken Mills). Tubing was embedded

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Figure 7. Prototype Water Cooled Cooling Vest Used in This Study

between two layers of this fabric and bonded by means of a fusible web (Steam-A-Seam2 by The Warm Company).

The vest dimensions were based on the U.S. army's anthropometric data as explained in Nam, et al., (2005) and the large size was chosen for this study. The design allowed for torso shape variations in both length and girth. Extensible fabric inserts were placed at the side seams and center back as shown in the sketch in Figure 7 for a tight fit without being uncomfortable. Length adjustment was achieved by the shoulder flaps with hook-and-loop closure that allowed the user to vary the angle of the shoulder as well as making the length adjustments. These adjustments would be made the first time the vest was worn by a first responder. A vislon plastic separating zipper placed at the center front provided ease of donning and doffing.

A sample of each type of tubing used in the prototype vests is shown in Figure 8. The pair of tubes at the top of Figure 8 were 3/8 " PVC tubing, which is widely used in

Figure 8. Two Kinds of Tubing Used in the Prototype Cooling Vests

most commercial cooling vests . The second type of tubing was a prototype tubing (PE-Al) with aluminum additive for better thermal conductivity developed as part of the MIPT project (pair of tubes at the bottom in Figure 8). Ten independent circuits of tubing, five on each left and right side of the torso entered and exited the vest at the back neck and inlet and outlet water was directed by means of a manifold that was connected to the pump. Tubing was distributed relatively evenly over the surface of the vest except for the extensible panels and under the zipper.

3.1.1.3. TIME VARIABLE

Physical and physiological data was measured at 30 or 60 second intervals depending on the dependent variable over the experiment. The perceptional data were collected at two points in time, the middle of the testing exercise and the end of testing. Fit and comfort issues did not depend on time therefore these data were collected only once at the end of the testing.

3.1.2. DEPENDENT VARIABLES

The dependent variables for the physical and physiological measurement section included microclimate temperature and humidity, subjects' core temperature, skin temperature at three locations, sweat rate at two locations, and heart rate. Temperature and humidity at eight upper body locations, face, head, front neck, back neck, chest, upper back, abdomen and lower back were the dependent variables for the perception component of the study. Perception of visibility was another dependent variable. Fit and tactile perceptions of the cooling garment were assessed for the neck, armhole, chest, abdomen, and shoulder areas. Perception of garment length adjustment, garment stiffness, overall garment cooling effectiveness, overall cooling system practicality, overall garment attractiveness, and convenience of the garment closure system were also assessed.

Physical and Physiological Variables

Microclimate temperature and subjects' skin temperatures at three locations on subjects' torso were measured using CS500 (Campbell Scientific, Inc.) thermocouples every 60 seconds. Microclimate humidity and sweat rate at two locations were measured and recorded by dew point capsules every 30 seconds. Both temperature and humidity sensors were interfaced with a personal computer and Campbell Scientific Inc. data logger system. Polar Interface Plus heart rate monitor recorded subjects' heart rate every 60 seconds and transferred to electronic files using Polar Training Advisor Software. A hand held Braun Thermoscan tympanic thermometer was used to measure subjects' core temperature every 3 to 4 minutes and recorded manually.

Perceptional Variables

Temperature and humidity perceptions at eight upper body locations, face, head, front neck, back neck, chest, upper back, abdomen, and lower back were assessed using a six-point response scale with 1 representing cold or dry, 2 cool or somewhat dry, 3 neutral, 4 warm or slightly wet, 5 hot or wet and 6 very hot or very wet. The visibility perception ballot was designed with a scale from 1 to 9, 1 representing very good to 9 representing very poor. The ballots were then coded and evaluated.

Fit and Comfort Variables

Subjects' perceived fit and tactile sensations of the vest were evaluated at the neck, armhole, chest, abdomen, and shoulder. Subjects' fit perception was assessed on a scale of 1 to 9, with 1 indicating loose and 9 indicating tight and tactile sensations were assessed on two nine-point scale with 1 indicating smooth and 9 indicating rough and 1 indicating wet and 9 indicating dry. Subjects evaluated their perception of general comfort parameters using a nine-point scale, with one indicating a relevant adjective and 9 indicating the opposing adjective. Ease of donning and doffing, length adjustment, perceived stiffness of the vest, vest closure, practicality, overall effectiveness, and attractiveness constituted the fit and comfort variables. The variables and related adjectives used to evaluate these features are discussed in detail in Chapter 4.

3.1.3. CONTROLLED VARIABLES

For the purpose of this study, the following variables were controlled: subjects' age range, gender, physical condition, physical activity (the same protocol/test/obstacle course was used), garment size, and environmental conditions of ambient temperature,

relative humidity and air movement (wind speed). Subjects demographics are discussed

in section 3.3. Environmental conditions were set at 80±2 °C and 50±5% relative

humidity with minimal air movement. Each subject wore a pair of denim trousers under

the protective clothing. Subjects were provided with a 100% white cotton short-sleeved t-

shirt and white cotton socks. They used the same breathing apparatus, a Scott 4.5 Air-Pak

Fifty 60 minute carbon cylinder air bottle, air mask and harness system (Figure 9).

Ongard Industries Hazmax 2000 edition rubber boots were worn over the protective

booties and Guardian Hazmat Gloves over powdered nitrile disposable gloves. For the

testing conditions that required wearing a cooling vest, the subjects wore their t-shirts

over the cooling vest. The same cooler unit was contained in its own carrier vest which

was worn over the level B suit as shown in Figure 9, or within the level A encapsulated

Figure 9. Standard Clothing, Equipment a Close-up of the Air Bottle

suit. All non-disposable equipment was sterilized and t-shirts and socks were laundered at the laboratory.

3.2. EXPERIMENTAL DESIGN

The experimental design for this study was a 3x2 factorial design of treatments with repeated measures over time for the physical, physiological and perception data. This design was chosen in an effort to prevent a garment presentation bias. To minimize a practice effect for negotiating the obstacle course, subjects practiced maneuvering the course and individual tasks multiple times prior to the initiation of the test sessions. Each subject completed six test sessions and each subject wore both prototype garments under both Level A and Level B protective suits.

3.3. SAMPLE

In the field of functional design evaluation by human subject testing it is not unusual to have a small sample size. An earlier study by Young, Sawka, Epstein and Pandolf, (1987) had 6 subjects. Among the studies Pandolf, et al. (1995) compiled, majority had 5 or six subjects, one used 8, and another study used 9 subjects. Kaufman and Fatkin (2001) used only four subjects to assess various cooling systems under PPEs. A new standard, ASTM F 2300-04a, suggests using five human subjects for evaluating the performance of personal cooling systems. Therefore a convenience volunteer sample of six fire fighters was recruited for this study: three fire fighters from the Stillwater Fire Department, two HazMat technicians from the Oklahoma State University Environmental Health and Safety Organization, and one student from the School of Fire Protection and Safety Technology at Oklahoma State University. Subjects were all male with a mean age

of 28.66 ±7.42 , mean height of 69.13±2.40 inches, and mean weight of 187.83 ± 7.57 lb. Subjects' fitness level was determined at the prescreening stage and the mean score of the chosen subjects was of 47.9 ± 6.97 ml/kg oxygen/min. Despite the large age range, 21 to 41, all subjects individually rated "good" as defined by the ACSM's Resource Manual For Guidelines for Exercise Testing and Prescription (1993). All subjects had experience with PPE, passed a physical screening procedure, and passed a prescreening for fit of the test garments. Small sample size is not unusual in this kind of study

3.4. HUMAN SUBJECT TESTING

All procedures for the study were reviewed and approved by the OSU Institutional Review Board (IRB) (Appendix A). Screening for potential subjects began by determining age and size requirements of male volunteers who had Hazmat training or experience. The nature of the experiment was explained to potential subjects so that they understood what the study required of them. The candidates then went thorough pre testing to assess their fitness level. The candidates who fit the size criteria, passed the screening tests and agreed to participate in the research study were selected as subjects and provided with the schedule of the test sessions. Finally, the testing protocol was explained and demonstrated to all selected subjects.

3.4.1. PRE-TESTING PROCEDURES

Human subject candidates signed an Informed Consent form (Appendix B) that outlined the physical screening procedure. First, candidates filled out a Personal Medical History Survey as administered by the A.B. Harrison Human Performance Laboratory at

OSU (Appendix C). The Graded Exercise Test (GXT) was administered afterwards to all subjects.

Maximal oxygen consumption (VO_{2max}) is widely regarded as the criterion measure, or best objective laboratory measure of aerobic fitness. Measuring VO_{2max} using indirect calorimetry requires that the subject exercise to a maximal load to achieve a maximal heart rate and VO_2. Such tests are usually done following a predetermined protocol with several ascending "grades" of exercise – thus the term, Graded eXercise Test or GXT. A VO_{2max} test evaluates a variety of physiological responses such as oxygen consumption (VO_2), carbon dioxide production (VCO_2) heart rate (HR), blood pressure (BP), respiratory exchange ratio (RER or RQ), rate of perceived exertion (RPE) and pulmonary ventilation (VE). The test requires duration in excess of 5-6 minutes.

Risks associated with a maximal GXT include sweating, heavy physical exertion, and a remote risk of fainting and myocardial infarction. Subjects were informed that risks were minimized by following the Guidelines for Exercise Testing of the American College of Sports Medicine (ACSM). ASCM states that apparently healthy male subjects below the age of 45 years are low risk individuals and do not necessitate physician supervision during an exercise test. Subjects with no more than one of the following risk factors are considered "apparently healthy": myocardial infarction in an immediate family member younger than 55 years, cigarette smoking, hypertension, diagnosed hypercholesterolemia, impaired fasting glucose, obesity, sedentary lifestyle. Subjects were also informed that in case of emergency, the Stillwater Medical Center Emergency room would be notified. Subjects were monitored by technicians certified in cardiopulmonary resuscitation during active and resting recovery.

Measurement of Maximal Oxygen Consumption:

At the time of scheduling, subjects were given proper instructions for the preparation of GXT testing. They were provided with a written instruction sheet (Appendix E) to remind them to follow certain rules, starting a day before the testing. Figure 10 shows a subject on the treadmill and the equipment used for fitness testing.

Equipment: Cycle ergometer, treadmill, metabolic cart, heart rate monitor, nose clip, non-rebreathing mouthpiece, flexible hoses.

Preparation:

1. Calibrate metabolic cart. Record room and barometric pressure

2. Assemble mouthpieces, nose clips and hoses for the subjects.

3. Check each subject's completed medical history form.

4. Determine subject's age predicted maximal HR.

5. Show subjects the location of the red "STOP" button in the case the test must be stopped immediately.

Figure10. Subject Fitness Testing at the A.B. Harrison Human Performance Laboratory at OSU.

6. Weigh the subject without shoes.

7. Record subject's weight and age.

8. Attach heart rate monitor to the subject and prepare him to exercise.

<u>Testing Protocol</u>

1. Expired gases were collected at rest (prior to exercise while subject sat quietly and relaxed, without movement, in a chair next to a treadmill) for 10 minutes. Values were recorded at the end of the 5th & 10th minutes.

2. Workload was increased every 3 minutes as shown in Table 2.

3. Speed and grade was recorded at each stage of the treadmill test (Appendix C).

4. HR, VE, RPE, RER, VO2, and VCO_2 were recorded at the end of each minute throughout the test.

Conditions for the early termination of the test were one or more of the following:

1. Signs of poor blood perfusion: light-headedness, confusion, nausea, ataxia, cyanosis, pallor, cold or clammy skin**.** Signs of significant chest pain, EKG change consistent with ischemia and/or significant rhythm changes.

2. Failure of heart rate to increase with increased intensity.

3. Failure of VO2 to increase following an increase in workload.

4. Age-predicted maximal HR is reached.

5. RER was above 1.

6. Physical or verbal manifestations of severe fatigue.

7. Subject requests to stop.

Table 2. Bruce Treadmill Test

Stage	Speed (mph)	Grade (%)
1	3.4	2
2	3.4	8
3	3.4	14
4	5.0	14
5	5.0	18
6	5.5	20

Increase speed and grade at 3-minute stages

3.4.2. TESTING

Subjects testing for the evaluation of the two prototype cooling vests were conducted in an environmentally controlled chamber. Prior to testing, the exercise protocol and the ballots were fully explained to the subjects. Each subject was tested six times wearing each cooling-PPE combination. After the subject was instrumented, he wore the vest and PPE, entered the chamber and performed the protocol. Ballots were filled out and measurements were taken during and after the exercise. Following a brief recovery period, the subjects were allowed to change back to their own clothing and filled out the final ballot.

3.4.2.1 ENVIRONMENTAL CHAMBER

The environmental chamber was equipped with an obstacle course as shown in Figure 11, designed to simulate the potential tasks and work load that a first responder might encounter in responding to an incident. The treadmill was used to simulate the walk from the vehicle to the hot zone. A two-step device and a 4-rung ladder represent the terrain and any structure that a first responder might need to climb during work. Valves and pipes that were mounted on a bookcase were used to simulate cognitive tasks that might be encountered.

The chamber was kept at a constant temperature of 80±2 degrees Fahrenheit, 50%±5 relative humidity (rh), with minimal air movement (wind speed). Equipment that the subjects used during the exercise was clearly labeled to minimize confusion. The exercise protocol was broken into simple components. Small posters featuring written

and graphic instructions were prepared and placed at specific stations so that the subjects could easily see them.

Figure 11. The environmental chamber and equipment
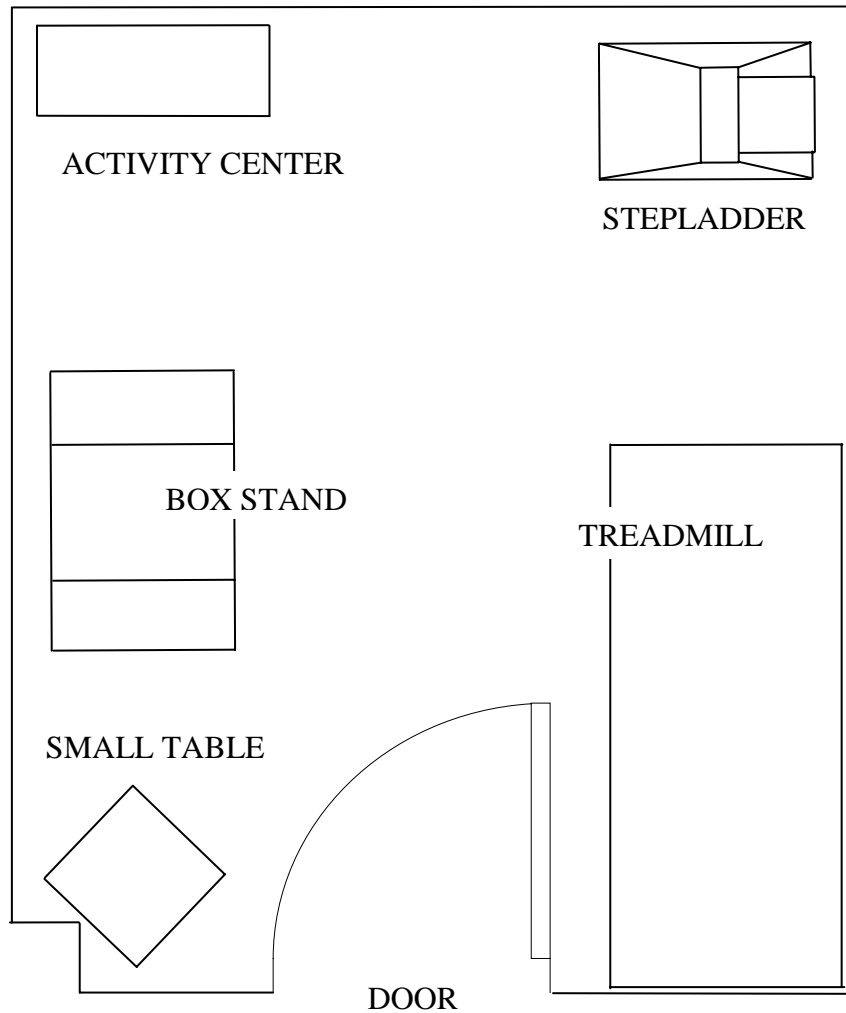
3.4.2.2. PRETEST

The complete protocol was explained and demonstrated for the subjects before the onset of actual testing. All necessary explanations about the instrumentation were given at this time. Ballots were read and explained and a sample ballot was provided for the subject to complete (Appendix F).

3.4.2.3. PREPARATION

Subjects were instrumented as seen in Figure 12. First, the heart rate monitor was placed in the middle of subject's chest. After the subject rested for ten minutes to allow his heart rate to become stable, he was instrumented with skin temperature thermocouples and sweat rate capsules. Initially, only two skin temperature sensors were used, one in the middle of the chest and another at the left back shoulder. A third sensor was added at lower right abdomen after completing a few testing sessions. One sweat rate capsule was placed at the middle of the chest and the second one at the upper left arm.

Skin temperature and microclimate data were collected every 60 seconds. Sweat rate and heart rate data were collected every 30 seconds and core temperature data at 3-

Figure 12. Sensor placement on subject's torso

Microclimate sensor
on the air bottle harness for level A,
on t-shirt for level B suit.

Skin
temperature
sensor placed
3-4" down
from the mid-
shoulder.

Skin
temperature and
sweat rate
sensors placed
in the middle of
chest, under arm
level.

Sweat rate
monitor placed on
the outside of the
left arm at armpit
level

Skin temperature sensor
placed on the abdomen halfway
between armpit level and waist
below right breast.

Heart rate monitor
strapped around chest,
sensor at the middle.

minute intervals, throughout the test session. After instrumentation, the subject put on the specified vest treatment (PVC tubed vest, PE- Al tubed vest or no vest), a t-shirt, SCBA, facemask, and the specified chemical protective suit.

3.4.2.4. EXERCISE PROTOCOL

The exercise protocol was designed before the ASTM standard F2300-04a was published. The protocol described below was designed using personal experiences as an observer to HazMat training courses, and focus group transcripts. ASTM F1154-99a, Standard Practices for Qualitatively Evaluating the Comfort, Fit, Function, and Integrity of Chemical-Protective Suit Ensembles, was used as a guide for the activities included during the exercise.

As soon as the subjects activated their air supply and cooling, data collection started. The protocol was designed to be completed in two rounds with each round lasting 14-15 minutes. The researcher was present in the chamber at all times to monitor the time needed to complete each activity. For example, if a subject moved slightly faster to complete one exercise than the allotted time, he was told to slow down or he would wait several seconds to start the next section. Likewise if a subject was too slow the researcher pointed out that he was to complete the activity faster.

The exercise consisted of the following steps:

1. Walk on a treadmill at 1.8 mph and 0% grade for 3 minutes (Figure 13).
2. Stop. Walk to box stand.
3. Pick up box #2 (wood grain, 10 lbs.); place on floor left of box stand.
4. Pick up box #3 (white, 15 lbs.); stack it on top of box #2.
5. Pick up box #1 (red, 7 lbs.), "the box".
6. Step over the box stand while carrying box; walk to bookcase (Figure 13).

Figure 13. A Subject in Level B Suit During Testing.

a. First treadmill exercise.   b. Arranging boxes,   c.Walking over box stand

Activity Center (Figure 14):

   (I): Middle shelf:
   - Place red box on shelf.

   (II) Upper shelf:

   - Pick up one pipe.
   - Turn red knob to close pipe.
   - Disassemble; leave pieces on shelf.
   - Turn red knob to open pipe.
   - Repeat with second pipe.

   (III) Lower shelf:

Figure 14. A Subject Performing Left and Right Hand Manipulations at
the Activity Center

- Screw in wooden rods on walls of shelf.

 (IV) Bottom shelf:
- Screw appropriate size pieces in holes. Some pieces will not be used.

(V) Upper shelf:
- Pick up one pipe.
- Turn red knob to close pipe.
- Assemble by screwing in ALL pieces on shelf.
- Turn red knob to open pipe.
- Repeat with second pipe.

(VI) Lower shelf:
- Remove wooden rods from walls of shelf.
- Leave on shelf.

(VII) Bottom shelf:
- Remove plugs/caps; place on shelf.

(VIII) Middle shelf:
 - Pick up red box and walk to stepladder.

7. Stepladder activity (Figure 15):
   - Place red box on shelf.
   - Stand in front of ladder.
   - Step up to first rung with right foot.

Figure 15. A subject in Level A Suit at the Stepladder and

Graphic Representation of the Exercise
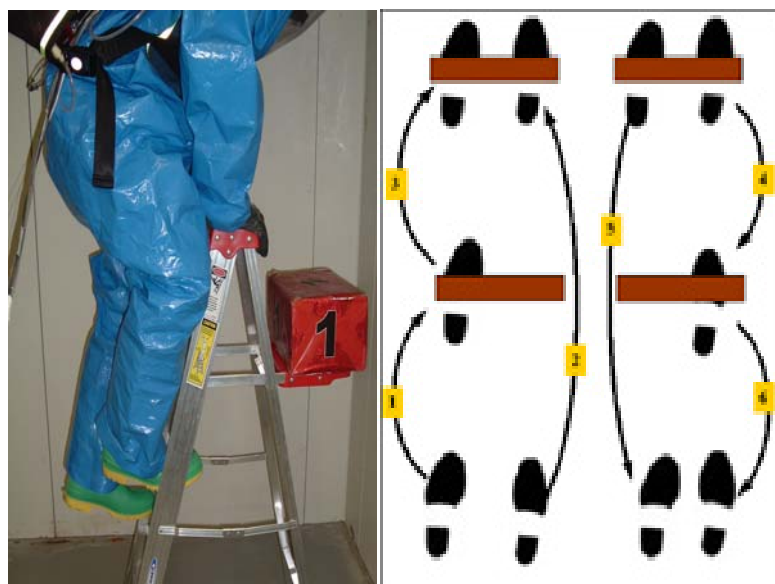
Figure 16. Subjects in Level A and Level B suits:

	b. Filling out the
a. Second Treadmill Exercise	Temperature and Humidity
Carrying a Box	Ballot

- Step up to second rung with left foot.
- Step up to second rung with right foot.
- Step down to first rung with left foot.
- Step down to floor with right foot.
- Step down to floor with left foot.
- Step up to first rung with left foot.

- Step up to second rung with right foot.
- Step up to second rung with left foot.
- Step down to first rung with right foot.
- Step down to floor with left foot.
- Step down to floor with right foot.
- Pick up red box and carry it to treadmill.

8. Repeat "step 7" three times

9. Walk on treadmill at 2.2 mph and 0% grade for 3 minutes, while holding box (Figure 16 a.)

10. Stop. Walk to box stand.

11. Put box on top shelf of the stand.

Administer temperature and humidity ballots, (Figure 16 b) for the round one.

12. Repeat steps 1 through 11.

Administer temperature and humidity ballots for round two.

3.4.2.5. PASSIVE RECOVERY

During the recovery, the subject was allowed to unzip his suit and remove his facemask and stop the airflow from his air bottle. Then he removed his air tank and other equipment with the help of the researcher. The heart rate monitor remained on the subject until his heart rate reached below 100 beats per minute while the subject rested sitting in the chair. At the end of the recovery stage, all thermocouples, heart rate monitor, and sweat capsules were removed and data collection stopped. The subject was then allowed to change into his own clothing, offered a liquid replacement drink and asked to fill out the comfort and fit ballot.

3.4.2.6. TERMINATION OF TESTING

Testing was terminated either when the test protocol was completed or if any of the following conditions occurred:

1. the subjects' core body temperature reached above 38°C,

2. 90 % of maximum heart rate (=220-age) was attained,

3. the subject's air was low,

4. subject experienced serious fatigue, or

5. subject wanted to stop.

3.5. DATA COLLECTION AND ANALYSIS

Microclimate temperature and humidity, skin temperatures, sweat rates and heart rate data were recorded electronically. Core temperature data were recorded by the researcher at approximately every three minutes. This measurement was taken with certain caution not to disturb the flow of the exercise, therefore when the subject was between activities, he was asked to stop and his temperature was taken. Perception of temperature, humidity, ballots were completed twice and fit and comfort ballots were completed once at the end of the testing. Three-factor repeated-measures ANOVA, with appropriate post hoc analyses, were performed on each of measurement and perception response dependent variables described earlier. Analyses were performed using SPSS release 11. A significance level of .05 was used unless otherwise specified.

CHAPTER IV

RESULTS

4.1. INTRODUCTION

The purpose of this study was to assess the cooling effectiveness of two prototype cooling vests under two personal protective ensembles (PPE), compared to no cooling by collecting measurement and perceptual data during testing. The subjects were instrumented with three temperature sensors, two sweat rate sensors, and one heart rate monitor. The core temperature data were logged manually by means of a tympanic thermometer. In addition, one temperature and one humidity sensor were placed between the cooling vest and the PPE to measure the climatic conditions inside the PPE.

The subjects were asked to fill out two questionnaires twice during the testing protocol to assess their thermal and sweating perceptions for both cooling and no cooling (control) conditions. The questions were designed to evaluate the subjects' perceptions of cooling effectiveness of the prototype vests on the torso and the head only. The rest of the body and the extremities were not considered.

The last part of the data collection involved the subjects' perception of design and fit of the prototype vests and achieved by the subjects filling out another questionnaire after each test in which they wore a cooling vest. The questions were arranged so that the subjects not only evaluated the fit but also the comfort, attractiveness, practicality, and ease of use of the prototypes. Both ballots included open-ended questions.

4.2. MEASUREMENT DATA

Measurement data consisted of physical conditions of the microclimate inside the PPE and six subject physiological measurements. Data were first reduced in time dimension and missing data was filled. Subsequently, all nine dependent variables data were analyzed separately and presented in five sections: microclimate, skin temperature, core temperature, sweat rate and heart rate.

4.2.1. PRELIMINARY MEASUREMENT DATA ANALYSIS

Reduction of time dimension:

Nine dependent variables were recorded separately using different data loggers that either recorded data every 30 seconds or 60 seconds. The microclimate temperature and humidity and all skin temperatures were logged every 30 seconds, and sweat rates and heart rate were logged every 60 seconds. Given that the testing lasted 30 minutes, each set of measurement generated 30 or 60 values, therefore the time dimension of the data had 29 or 59 degrees of freedom. Analyzing these data using three way repeated measures ANOVA proved to be quite cumbersome and difficult to interpret. Successively, time degree of freedom was reduced down to 8 by averaging data at 9 equal time intervals. This reduction was achieved by calculating the mean of the first three minutes and assigning this value to the third minute, then calculating the next three minutes and assigning it to the sixth minute and so forth. This would normally yield 10 data points, however, some tests lasted a little less than 30 minutes and it was found that 27 minutes was the longest time period all measurement had in common, therefore those test measurements were truncated to achieve 9 data points all three minutes apart.

Missing data analysis:

Primarily due to equipment failure some measurements were not collected. When faulty measurements could be observed on the computer monitor (all but core temperature and heart rate) the testing would be terminated and rescheduled at a later time. However, core temperature and heart rate could not be seen before subjects removed their protective clothing, the vest and the sensors. Those tests that had more than one faulty or missing measurement data set were repeated at the subjects' convenience. Despite these efforts, some missing data occurred. As such, application of repeated measures of analysis of variance could result in large amount of deleted data, because cases with any missing values at any trial must be dropped from the analysis. SPSS automatically deleted the entire observation in the presence of any missing data (listwise deletion), which reduced the analytic sample size, lowering the power of any test carried out. Information on missing data is given in Table 3. Codes followed by an (*) indicates the tests for which reliable data were missing due to equipment failure. Other cases had only a few measurements missing.

One subject's microclimate temperature and humidity data were missing when he was tested wearing the PVC tubed vest with the level B ensemble. The microclimate data, both temperature and humidity, on another subject wearing PE-Al tubed vest with the level B ensemble were missing data between 12 and 27 minutes. In this case, without data filling, the subject degree of freedom would have been only 3 while the data were analyzed with repeated measures ANOVA analysis.

Table 3. Missing Data for Each Dependent Variable and Cooling/PPE Combinations

	Level A			Level B		
	No Cooling	PVC	PE-Al	No Cooling	PVC	PE-Al
Microclimate temperature		S #4[*]				S#2 6 time points
Microclimate humidity		S #4[*]				S#2 6 time points
Chest skin temperature		S#3[*]	S#6 3 time points			
Back skin temperature		S#3[*]	S#6 2 time points			
Abdomen skin temperature		S#4[*]		S#3[*]		
Core temperature	S#4[*]	S#2 [*] S#4[*]				S#3[*]
Chest sweat rate		S#2 2 time points	S#3[*]	S#2[*]		S#4[*]
Arm sweat rate			S#2[*]			
Heart rate						S#6 1 time point

S# denotes "subject number code"
[*] No reliable data on this dependent variable were recorded during this testing

Chest skin temperature data also had missing values. Two subjects while wearing the PE-Al tubed vest and level A ensemble and another subject while wearing the no cooling treatment under level B ensemble had data missing at 12, 15, and, 21 minutes respectively. In this case SPSS would have disregarded three subjects' data, reducing the subject degree of freedom to 2.

One subject while wearing the PVC tubed vest and level A suit and another subject wearing the PE-Al vest and level A suit at 9 and 12 min had no reliable recorded back skin temperature. Abdomen temperature data were also missing for one subject wearing the PVC vest and level A suit and for another subject wearing the level B suit with no cooling vest. In these skin temperature cases, SPSS would have used only four out of six subjects' data without data filling.

The first three subjects' core temperatures were measured using a sensor that had to be placed in subjects' ear. The data were transferred via a cord to a recording box that was attached to subjects' belt. This device turned out to be not suited for the ensembles worn and the type of testing performed because the ear module slipped out of subjects' ear when they started sweating. Additionally, the cord slipped out of the socket and the box interfered with other sensors and resulted in faulty data which in turn was discarded. For the remaining tests, core temperatures were measured every 3 minutes by means of a tympanic thermometer. Therefore, the core temperature data were missing for one subject's level A-no cooling and PVC tubed vest cases, second subject's level A- PVC tubed vest case and a third subject's level B no cooling case data resulting in four sets of missing data reducing the usable subject number to only three without the missing data filling.

One subject had no chest sweat rate data while wearing no cooling under level B ensemble. The same subject had missing chest sweat rate measurements at 13 and 16 minutes while wearing level A ensemble with a PVC tubed vest. Also, a second subject had no chest sweat rate data while wearing PE-Al tubed vest under level B and a third subject's chest sweat rates were missing with level A- PE-Al tubed ensemble. This dependent variable would have had 2- subject degree of freedom without data filling. Arm sweat rate had the least number of missing cases; one subject while wearing level A suit and PVC tubed vest this would have reduced the effective number of subjects by one, from 6 to 5.

Problems with the heart rate monitor during most of the level B tests resulted in exclusion of these data in the statistical analysis. Therefore, the data with level A

ensembles were considered in the analysis. Only one subject while wearing the PE-Al

tubed vest with a level A suit had no heart rate measurement.

As discussed earlier, in this study, only six subjects were used, which is

commonly done in this type of research. Therefore, ignoring the missing data would have

reduced the power of the tests performed by reducing the subject degree of freedom from

5 to, in some extreme cases 2. Thus, filling the missing values was performed using the

"Mean of nearby points" option which automatically replaces missing values with the

mean of valid surrounding values. The span of nearby points is the number of valid

values above and below the missing value used to compute the mean.

4.2.2. MEASUREMENT DATA ANALYSIS

Repeated measures analyses of variance were employed for all dependent

variables. For all variables except two, the three-way interaction was not statistically

significant. Non-significant three-way interaction suggests that temperature differences

between the vests across time did not wary between the two levels of suits. Given this

finding, to enhance the interpretation of the focal vest-by-time effect with greater power,

the data was collapsed across the two suits. Re-running the pooled data increased the

power of the test by increasing the apparent number of subjects. The physical and

physiological data are presented in four sections: microclimate temperature and humidity;

skin temperature and sweat rate; core temperature and heart rate.

4.2.2.1. MICROCLIMATE

The level A garments used in this study were liquid and gas impervious and the

level B garments were liquid impermeable. This property of impermeability of PPE

seriously limits the potential for moisture created by a subject's perspiration and respiration to escape thereby increasing the moisture levels within the microenvironment, that is, the environment created between the t- shirt and the outer protective garment. A similar phenomenon exists for the microclimate temperature. In this study, the temperature and the humidity between the impervious layer of the PPE and the t-shirt were measured to evaluate if the cooling treatment affected microenvironment temperature and humidity.

Microclimate temperature: The two graphs in Figure 17 show the marginal means of microclimate temperature by three cooling treatments and two levels of PPE over time. As shown in Figure 17, for subjects wearing level A ensembles, the microclimate

Figure 17. Microclimate Temperature Marginal Means by Cooling Treatment Over Time
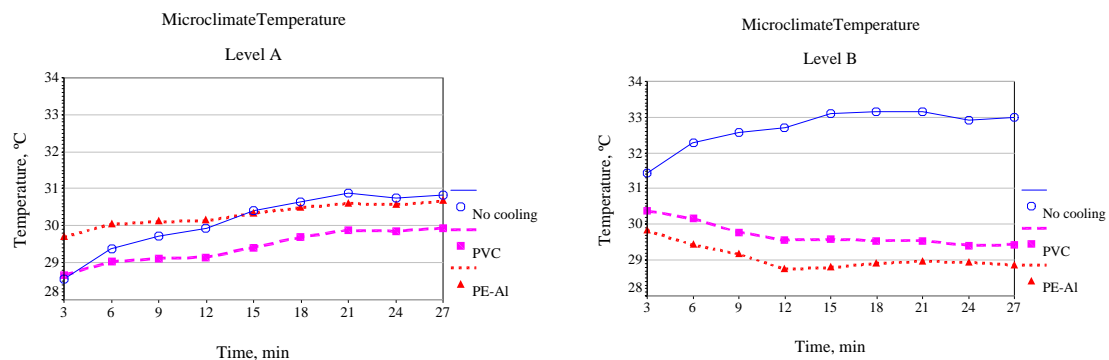
temperature steadily increased without cooling, whereas the presence of the cooling treatments tended to keep the rate of temperature increase low. With level B ensembles, the difference is more pronounced. The no-cooling treatment resulted in a steady increase in microclimate temperature, but both cooling treatments reduced the temperature steadily. It is interesting that the PVC tubed vest resulted in lower temperatures than the

PE-Al tubed vest when the subjects wore the cooling vests with level A ensembles but the condition was reversed when they wore a level B ensemble.

Repeated measures ANOVA was performed to find out if there were significant differences in treatment levels. There was no significant three-way vest-by-suit-by- time interaction for microclimate temperature (F=1.223 at 16, 80 d.f; p=.0.269) which means that the two way interactions were not affected by the levels of the third variable. Further the non-significant main effect of suit suggests that, overall, the temperature did not vary between the protective outer garment, level A or level B. Therefore, to examine the focal vest-by-time effect, with greater power the data were collapsed on "suit" variable.

The graph (Figure 18) of the marginal means of microclimate temperature over time using the collapsed data shows the differences between the control treatment and the cooling treatments. When the subjects did not wear a cooling vest, the temperature

Figure 18.   Microclimate Temperature Marginal Means Over Time for Level A and B Ensembles (Collapsed Data).

MicroclimateTemperature

Collapsed Data
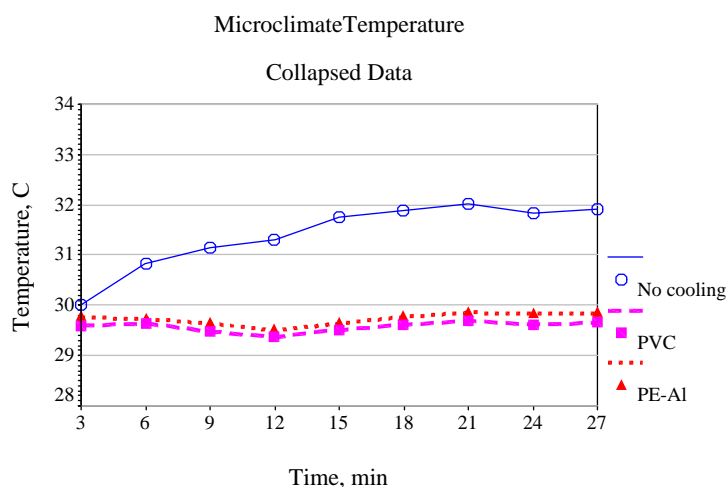
increase from the beginning to the end of the protocol was 1.55ºC. However, when the subjects wore the cooling treatments, the increase was only a fraction of one degree. Essentially, the microclimate

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temperature did not increase when the subjects wore either of the prototype cooling treatments.

ANOVA analysis (Table 4) indicates a significant vest-by-time interaction effect, and vest and time main effects. As can be seen in Figure 18, the interaction is ordinal as far as the control and cooling treatments are concerned. The graph also suggests that time interaction on the cooling treatments is negligible since they follow a parallel pattern over

Table 4. ANOVA Table for Microclimate Temperature Data Collapsed on Suit Treatment

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
VEST	224.089	2, 22	112.045	4.870	**0.018**
TIME	17.875	8, 88	2.234	5.359	**0.000**
VEST * TIME	27.203	16, 176	1.700	9.137	**0.000**

time. Interaction contrasts showed significant differences between cooling and no cooling (F=5.995 at 1, 11 d.f; p=.0.032), but no difference between the cooling vests (F=0.144 at 1, 11 d.f; p=0.711) was detected. In conclusion, the cooling vest treatments improved microclimate temperature compared to wearing PPE without cooling.

Microclimate humidity: Figure 19 shows the marginal means of microclimate humidity by the cooling treatments for level A and level B ensembles over time. Clearly microclimate humidity increased over time. For both ensembles, the microclimate relative humidity is generally less for subjects wearing the cooling treatments compared to the no-cooling treatment. The graphs also indicate that both cooling treatments followed a similar pattern and consistently increased without leveling off. It should be noted that the microclimate humidity exceeded 90% without cooling for subjects wearing

Figure 19. Microclimate Humidity Marginal Means by Cooling Treatment Over Time
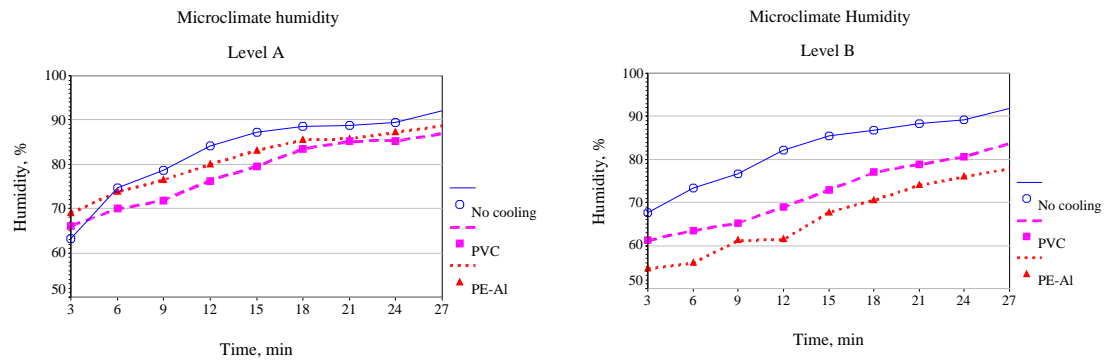
both level A and level B ensembles. While cooling provided an improvement, subjects wearing level A appeared to achieve higher microclimate humidity than when subjects wore level B ensembles.

Repeated measures ANOVA analysis indicated that there was no significant three-way vest-by-suit-by-time interaction for microclimate humidity (F=0.538 at 16, 80 d.f; p=0.919). As with the microclimate temperature, the protective outer garment, level A or level B did not influence the time and cooling treatment interaction. Therefore to examine the vest-by-time effect, the data were collapsed on the "suit" variable.

Figure 20 shows the plot for the combined data. When no cooling vest was worn, relative humidity inside the protective ensembles increased from 66% to 92%. When the subjects wore either prototype vest, the relative humidity increase in the microclimate was slightly smaller.

Figure 20. Microclimate Humidity Marginal Means Over Time for Level A and B Ensembles (Collapsed Data)
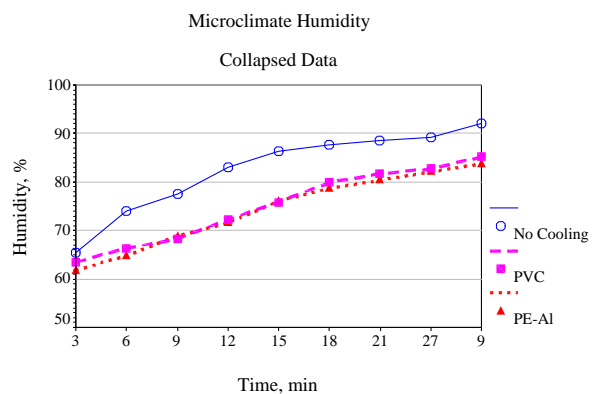
Analysis of data collapsed on "suit" indicates significant vest and time main effects and vest-by-time interaction effect (Table 5). Figure 20 displays the interaction as disordinal among all cooling treatments. Interaction contrasts showed significant differences between cooling and no cooling (F=13.997 at 1, 11 d.f; p=0.003) but no difference between the vests (F=0.126 at 1, 11 d.f; p=0.729). The significant differences between control and cooling treatments depended on time: this difference was not significant at the beginning and towards the end but became significant around the middle of testing. On the other hand, the difference of cooling effectiveness of the two prototype vests never reached significance.

Table 5. ANOVA Table for Microclimate Humidity Data Collapsed on Suit Treatment

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
VEST	4661.68	2, 22	2334.85	7.078	**.004**
TIME	18650.968	8, 88	2331.371	80.821	**.000**
VEST * TIME	392.964	16, 176	24.560	2.112	**.010**

In summary, microclimate humidity was lowered by the cooling garments however, there were no statistically significant differences between the Pe-Al and PVC tubed vests.

4.2.2.2. SKIN TEMPERATURE.

Skin temperatures were recorded at three torso locations: middle of the chest, upper right shoulder, and the abdomen.

Chest skin temperature: The graphs of chest skin temperature marginal means by cooling treatments for level A and level B over time are shown in Figure 21. Both graphs seem in agreement that subjects wearing no cooling treatment experienced steady temperature increase without leveling off. Cooling treatments appear to have slowed

Figure 21. Chest Skin Temperature Marginal Means by Cooling Treatment Over Time
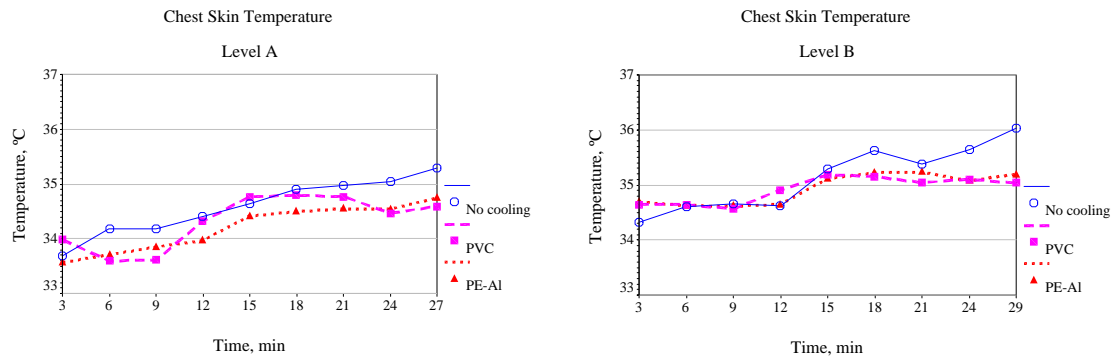
down subjects' chest temperature increase as the slopes of the graphs level off around the middle of the testing period. Without cooling, the average chest temperature raised approximately 2ºC and 1.5 ºC under level A and level B ensembles respectively. The cooling vests resulted in cooler chest temperatures under level A suits with less than 1 ºC increase. When the subjects wore a cooling vest under level B ensembles, their chest skin temperature stayed close to the conditions without cooling at first, however the total temperature increase was only about 0.5 ºC at the end of the testing.

ANOVA results showed that there was no significant three way vest-by-suit-by-time interaction effect (F=0.478 at 16, 80 d.f; p=0.951). As with the microclimate dependent variables, the protective outer garment, (level A or level B) did not influence the time and cooling treatment interaction. Therefore to examine the vest-by-time effect, the data were collapsed on the "suit" variable.

Figure 22 shows the chest skin temperature over time, of the combined data. The graph indicates that all three cooling conditions started out with comparable chest skin temperatures, however with cooling, the subjects' chest skin temperatures leveled off around the middle of the test protocol and chest skin temperature continued for subjects with no cooling.

Figure 22. Chest Skin Temperatures Marginal Means Over Time for Level A and B Ensembles (Collapsed Data)

Analysis of the collapsed chest skin temperature data on "suit", (Table 6), shows a significant time main effect, no significant vest main effect and no vest-by-time interaction effect. Therefore no interaction contrasts were performed.

Table 6. ANOVA Table for Chest Skin Temperature Data Collapsed on Suit Treatment

Source	Sum of Squares	df,df$_{error}$	Mean Square	F	Sig.
VEST	4.451	2,22	2.225	0.232	.795
TIME	44.837	8,88	5.605	18.474	**.000**
VEST * TIME	6.843	16,176	0.405	1.629	.065

Back skin temperature: Back skin temperature by cooling treatments for level A and B ensembles over time graphs (Figure 23) indicate that the back skin temperatures stayed somewhat constant with no-cooling. Back skin temperatures were considerably

Figure 23. Back Skin Temperature Marginal Means by Cooling Treatment Over Time.
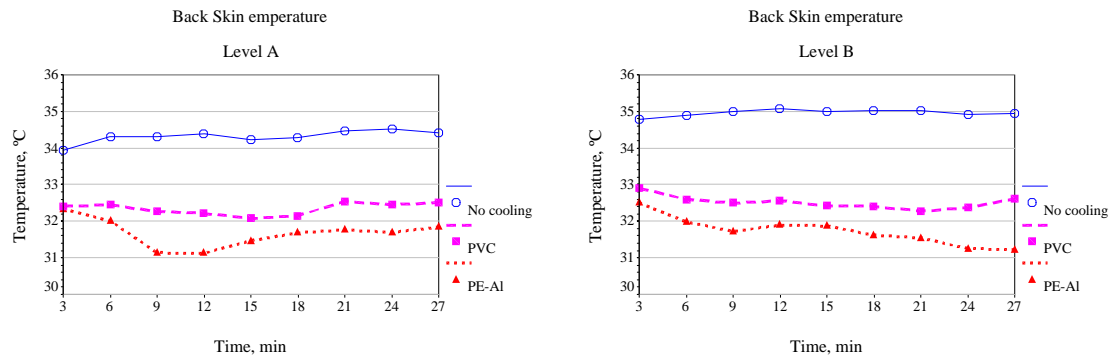
lower when subjects wore either cooling vests. For both level A and level B ensembles,

the PE-AL tubed vest produced the lowest back skin temperatures.

Statistical analysis of back skin temperature data indicated no significant three-

way vest-by-suit-by-time interaction effect (F=0.728 at 16, 80 d.f; p=0.758) , therefore

further analysis was conducted, similar to the previously discussed dependent variables,

by collapsing the data on the "suit" variable. Figure 24 shows the plot of back skin

temperature data (collapsed on suit) over time for both cooling treatments and the control

treatment. Clearly, the subjects wearing no cooling showed higher overall temperatures than when they wore the prototype vests. While the back skin temperatures somewhat increased with no cooling,

Figure 24. Back Skin Temperatures Marginal Means Over
Time for Level A and B Ensembles (Collapsed Data)

the PVC tubed vest and the Pe-Al tubed vest generated enough cooling to lower the back skin temperatures slightly. In Figure 24, the PE-Al tubed vest looks favorable to the PVC tubed vest in cooling this part of the body.

The statistical analysis carried out on the collapsed data (Table 7) showed a significant vest-by- time interaction and vest main effect. Interaction contrasts detected significant differences between cooling and no cooling (F=48.710 at 1, 11 d.f; p=0.000) but no difference between the vests (F=1.992 at 1, 11 d.f; p=0.186).

Table 7. ANOVA Table for Back Skin Temperature Data Collapsed on Suit Treatment

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
VEST	501.251	2,22	250.625	20.901	**0.000**
TIME	3.098	8,88	0.387	1.116	0.361
VEST * TIME	9.125	16,176	0.271	2.108	**0.010**

In conclusion, the data analyses indicated that subjects experienced cooling relief at their back when they wore cooling vests. Both prototype cooling vests generated similar cooling effectiveness regardless of whether level A or B ensembles were worn.

Abdomen skin temperature: Originally, two temperature sensors were placed on the back of the subjects. After the first two subjects were tested without abdomen skin temperature measurements, one of the sensors at the back was moved to the middle of the lower abdomen area in order to evaluate a wider area of the torso. The abdomen skin temperature data, based on only four subjects were plotted over time as shown in Figure 25. Noticeably, the cooling vests lowered abdomen skin temperature regardless of which protective ensemble was used.

Figure 25. Abdomen Skin Temperature Marginal Means by Cooling Treatment Over Time
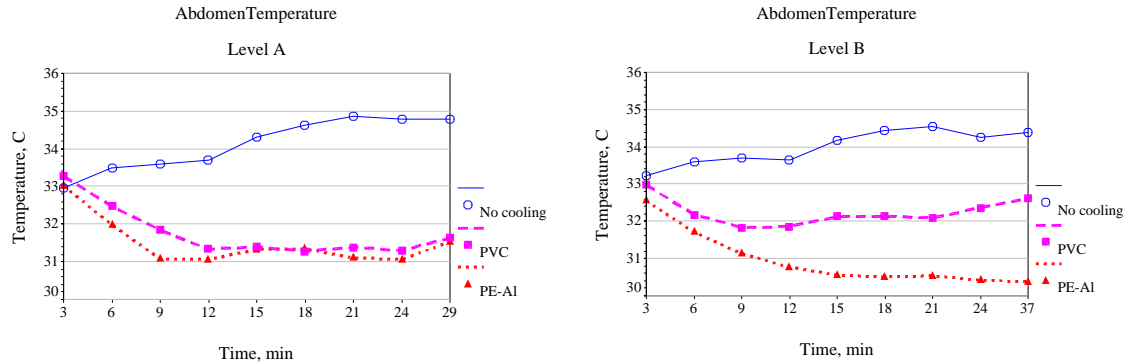
As can be read from the graph, abdomen skin temperature increased as much as 1.8ºC under level A and 1.1ºC under level B ensembles when subjects did not wear a cooling vest. Conversely, when they wore the PVC tubed vest, the temperature drop was 1.6 ºC with level A, and 0.3 ºC with the level B overgarment. The PE-Al tubed vest reduced the skin temperature 1.5 ºC when worn under the level A suit and as much as 2.2 ºC with the level B suit.

To understand the interaction among the variables more clearly, an ANOVA test was carried out (F=2.103 at 16, 48 d.f; p=0.187). Since there was no three-way suit-by-vest-by-time interaction effect, the data were collapsed on the "suit" variable. The graph (Figure 26) of these data leads to the same conclusion as before, namely that the cooling treatment resulted in cooler abdomen temperatures for the subjects when they wore either prototype cooling vest. Abdomen skin temperatures for the subjects were about the same at the beginning (33 ºC) for the control treatment and both cooling treatments. At the end of the testing protocol, while the control group experienced a 1.6 º C increase in temperature, PVC tubed and PE-Al tubed prototype vests reduced the abdomen skin temperature by 0.9-1.8 º C.

Figure 26. Abdomen Skin Temperatures Marginal Means Over Time for Level A and B Ensembles (Collapsed Data)

Abdomen SkinTemperature
Collapsed
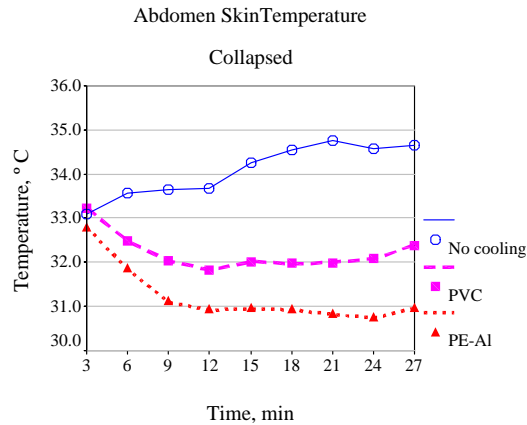
ANOVA analysis of the collapsed data showed a significant vest-by-time (Table 8) interaction effect as well as vest and time main effects. The interaction contrasts showed that the difference between the control and treatment effects was significant (F= 25.802, at 1, 7 d.f.; p=0.001), though there were no significant differences between the two prototypes (F= 2.382 at 1, 5 d.f.; p=0.0167). Similar to the back skin temperature results, this section of the torso was affected positively by the cooling treatments because the well-fitting vest moved with the body when the subjects performed the protocol.

Table 8. ANOVA Table for Abdomen Skin Temperature Data Collapsed on Suit Treatment

Source	Sum of Squares	df	Mean Square	F	Sig.
VEST	303.211	2,14	151.605	11.900	**0.001**
TIME	12.829	8,56	1.604	5.196	**0.000**
VEST * TIME	50.722	16,112	3.170	13.863	**0.000**

4.2.2.3. CORE TEMPERATURE

Overall marginal means of the subjects' core temperatures while wearing the control and treatment ensembles were plotted over time in Figure 27. The graph on the left shows that the core temperatures increased from 36.60ºC to 37.15ºC (0.55 ºC) with no-cooling and from 36.73 ºC to 36.80 ºC (0.11 ºC) when the PE-AL tubed vest was worn under level A ensembles. The PVC tubed vest decreased the core temperature a

Figure 27. Core Temperature Marginal Means by Cooling Treatment Over Time
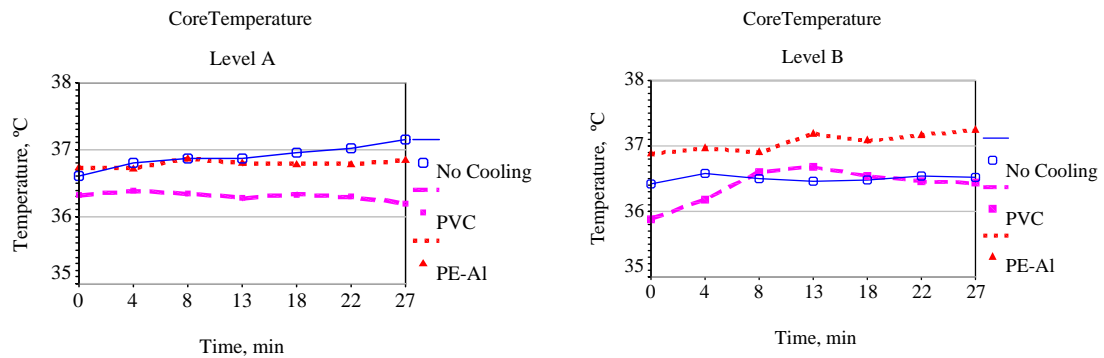
total of 0.13 ºC (from 36.33 to 36.20). The graph on the right (Figure 27) suggests regardless of the cooling treatment subjects' core temperatures increased between 0.10 to 0.55 ºC with level B ensemble.

ANOVA analysis indicated no statistically significant three way suit-by-vest-by-time interaction effect for core temperature (F=0.970 at 12, 60 d.f; p=0.487. Data were again collapsed on the "suit" variable to further evaluate the treatment effects. Temporal changes in the core temperature were plotted in Figure 28. The effect of prototype cooling garments on the core temperature is not conclusive. The marginal means of subjects' core temperature show a slight increase regardless of the cooling treatment.

Figure 28 Core Temperatures Marginal Means Over Time for Level A and B Ensembles (Collapsed Data)
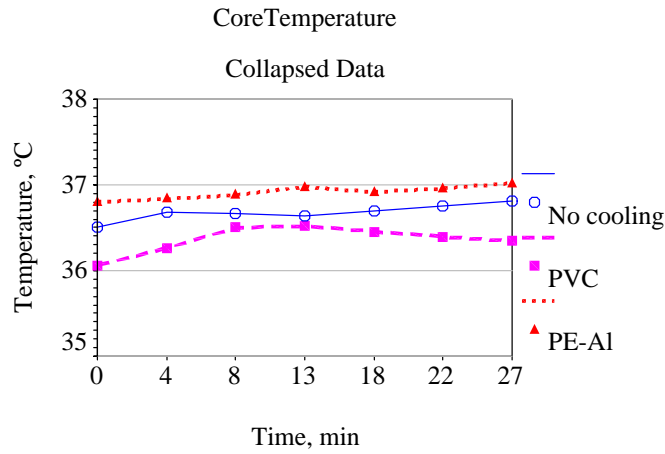
Collapsed data ANOVA analysis (Table 9) shows no significant interaction effect and no main effects of time and vest at the 0.05 level.

It is not surprising that the cooling treatments did not significantly lower core temperature because the testing environment was not severe in terms of temperature and humidity and the protocol was only 30 minutes.

Table 9. ANOVA Table for Core Temperature Data Collapsed on Suit Treatment.

Source	Sum of Squares	df, df_{error}	Mean Square	F	Sig.
VEST	12.808	2, 22	6.404	2.662	0.092
TIME	2.048	6, 66	0.341	1.966	0.083
VEST * TIME	0.937	12, 132	7.807E-02	0.501	0.911

4.2.2.4. SWEAT RATE

Sweating is one of the body's cooling mechanisms and is effective as long as the sweat is allowed to evaporate. If the air is already saturated with humidity as inside an impervious suit, converting liquid sweat to vapor is difficult, thus rendering heat remova

by evaporation nearly impossible. It is important to keep sweat rate low and the degree

of vapor saturation inside the suit to a minimum. It was hoped that the prototype cooling

vests would decrease subjects' sweat rate. The fabric selected for the vest has good

moisture transfer properties and if sweat rate is not too high, the fabric has the potential

to reduce the discomfort of feeling wet. Secondly, fogging of the face shield because of

moisture built-up in the microclimate, affects workers' ability to perform required tasks.

Therefore, in order to monitor and study sweat rate in those areas of the body covered by

the vest as well as not covered by the vests, two sweat rate sensors were used to record

data on subjects' left upper arm and the center of their chests.

     Chest sweat rate: Reduction of sweat at the chest by cooling the upper torso can

be seen by comparing the graphs (Figure 29) on sweat rate with and without the

prototype cooling vests. The graphs suggest that the subjects wearing level A ensembles

experienced higher sweat rates than when they were wearing level B ensembles. Under

level A ensembles, without a cooling vest, subjects' sweat rate increased from the

beginning of the test to the end a total of 0.27 mg/min, whereas with cooling vests the

Figure 29. Chest Sweat Rate Marginal Means by Cooling Treatment Over Time
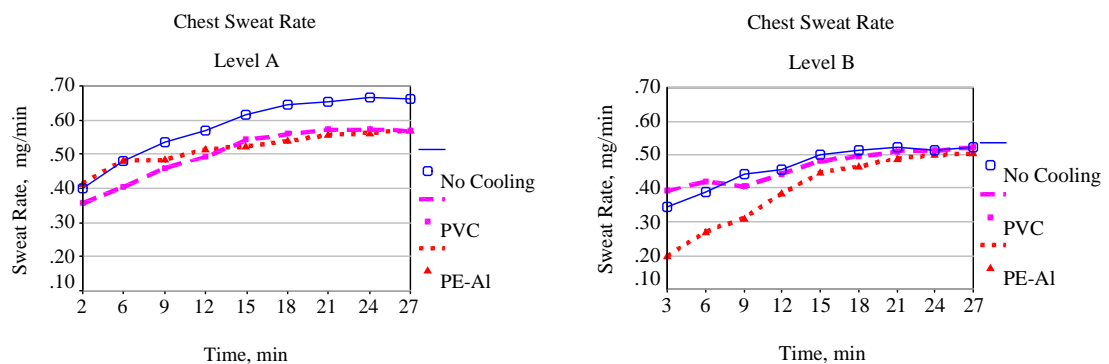
increase was 0.15-0.20 mg/min. Under level B suits, the sweat rate increase was smaller

with a total of 0.15 mg/min with no cooling treatment, and with the PVC tubed vest but

seems to have increased when the subjects wore a cooling vest with PE-Al tubed vest.

For this vest, the total increase was 0.30 mg/min from the beginning of the test to the end.

One possible explanation for this effect is that the semi-impermeable and partially

open level B suit allowed sweat to escape and evaporate thereby causing some degree of

cooling relief regardless of whether the subjects wore a cooling vest. However, when

they wore a cooling vest, the cooling provided by the unit was not enough to offset the

workload imposed on the subjects by the additional weight of the cooling unit.

ANOVA table shows (Table 10) that the chest sweat rate data has significant

suit-by-vest-by-time interaction effect and suit, vest and time main effects. Two-way

interactions are not significant. Chest sweat rate marginal means of level A and level B

were plotted (Figure 30), separately at three levels of the cooling treatments over time to

have a better understanding of the three way interaction. With no cooling treatment and

with PE-Al tubed vest, sweat rate at each time level was higher for subjects wearing a

level A suit than subjects wearing a level B suit. The interaction was ordinal. When the

subjects wore   PVC tubed vests, the sweat rate was higher with level B suit at the

Table 10. ANOVA Table for Chest Sweat Rate

Source	Sum of Squares	df, df_{error}	Mean Square	F	Sig.
SUIT	0.669	1, 5	0.669	15.821	0.011
VEST	0.247	2, 10	0.123	4.089	0.050
TIME	1.581	8, 40	0.198	10.589	0.000
SUIT * VEST	0.110	2, 10	0.005	1.242	0.330
SUIT * TIME	0.005	8, 40	0.0007	0.421	0.901
VEST * TIME	0.025	16, 80	0.001	0.526	0.926
SUIT * VEST * TIME	0.148	16, 80	0.009	15.790	**0.000**

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beginning of testing but the situation reversed after 6 minutes where subjects wearing level B experienced sweat rates that remained lower than subjects in level A.

To further explore the differences in cooling treatments a second version of an interaction graph is presented in Figure 31 where the marginal means of chest sweat rate data were plotted separately at nine levels of time variable over the two levels of suit treatments. The interaction appears to be disordinal at the beginning of testing. The sweat rates were differentially affected by the vest and suit combination worn over time. The

Figure 30. Chest Sweat Rate Marginal Means at Three Cooling Treatments Over Time
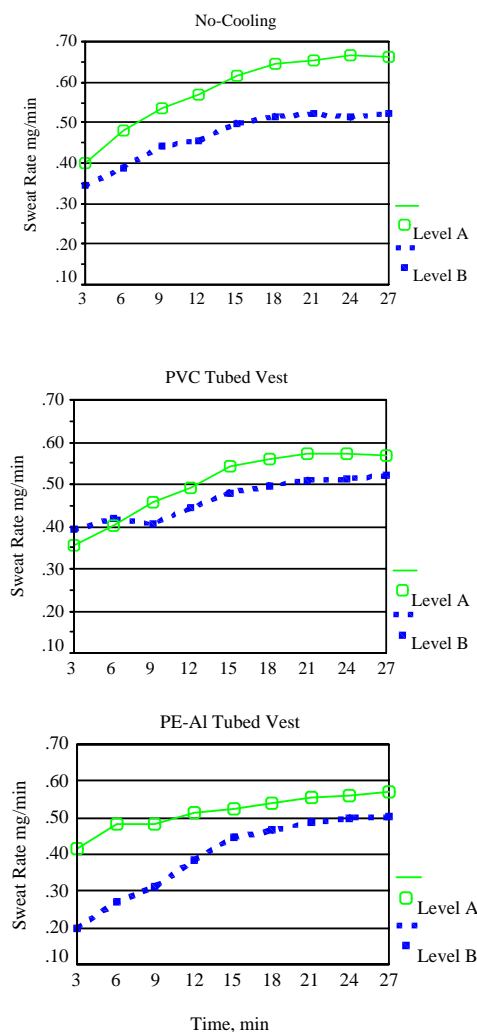
second half of the testing appears to be more consistent. Subjects wearing level A and level B, no cooling condition had higher sweat rate values. Regardless of which vest was used the subjects' sweat rates with level A suits are always higher than subjects wearing level B ensembles.

Interaction contrast analysis indicated significant differences between control and cooling treatments (F=6.384 at 1, 5 d.f.; p=0.05) but not between the two prototypes F=1.450 at 1, 5 d.f ; p=0.282). Other interaction contrasts revealed no significant differences. Studying the graphs (Figures 30 and 31), the cooling vests appeared to have decreased sweating at the

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Figure 31. Chest Sweat Rate Marginal Means at Nine Time Levels Over Suit Treatments
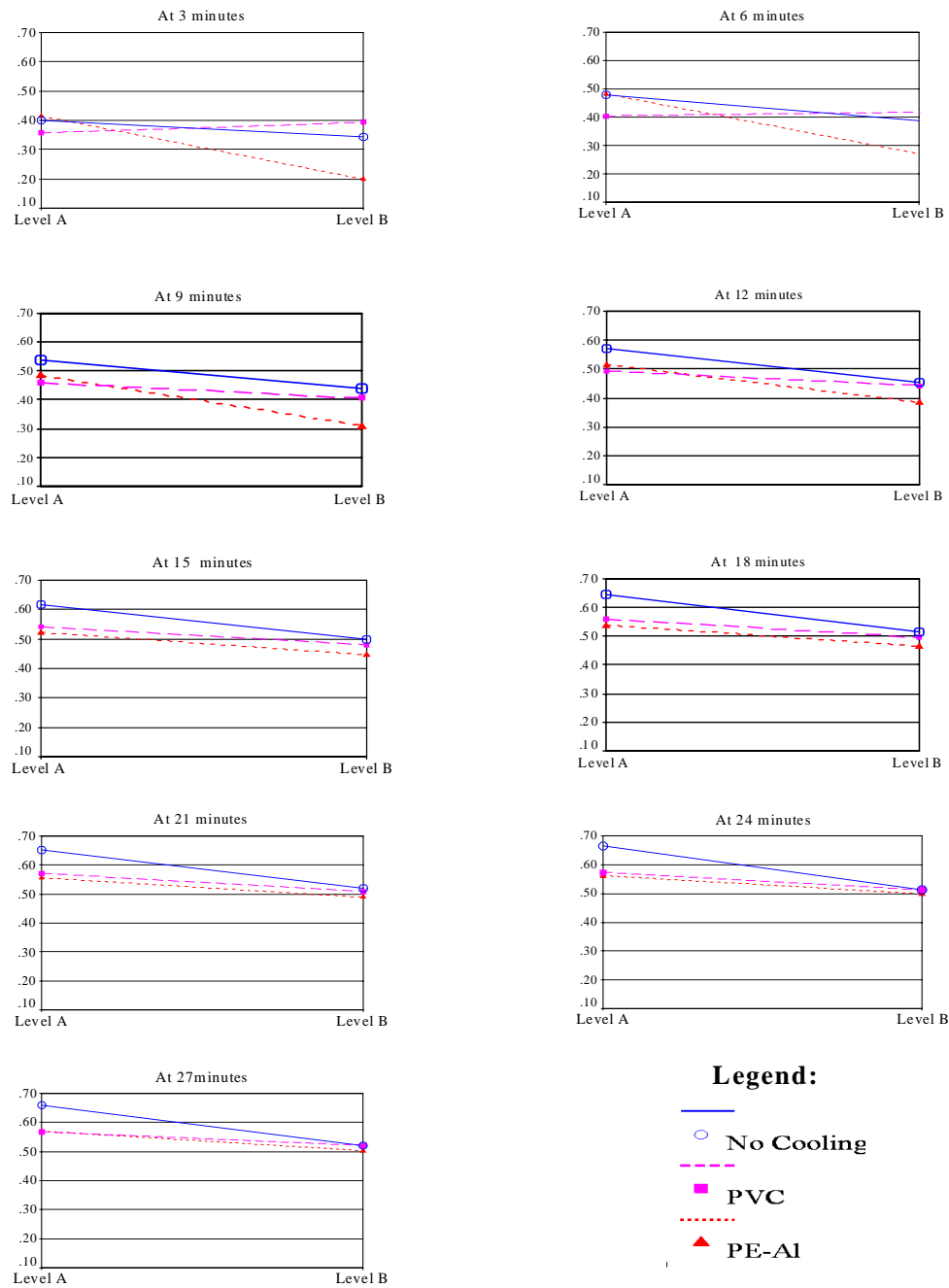
chest compared to no cooling. The PE-Al tubing was more effective throughout testing

for both level A and Level B, whereas PVC tubing was more effective in the beginning

for Level A but after 15 minutes into the testing PE-Al tubing showed better performance.

The statistical analysis indicated significant differences in subjects chest sweat rate when they wore a level A or a level B suit. Cooling treatments had a significant effect on the chest sweat rate of the subjects but the differences in cooling were not significant between the two prototypes.

Arm sweat rate: The prototype cooling vests do not have sleeves, therefore this area of the body, that is the upper arm, was not in contact with the chilled tubing and no significant improvement in sweat rate was expected at this location. Monitoring the sweat rate at this location allowed researchers to explore whether cooling the torso might affect other areas of the body as well. However, the results shown in Figure 32 suggest that the

Figure 32. Arm Sweat Rate Marginal Means by Cooling Treatment Over Time
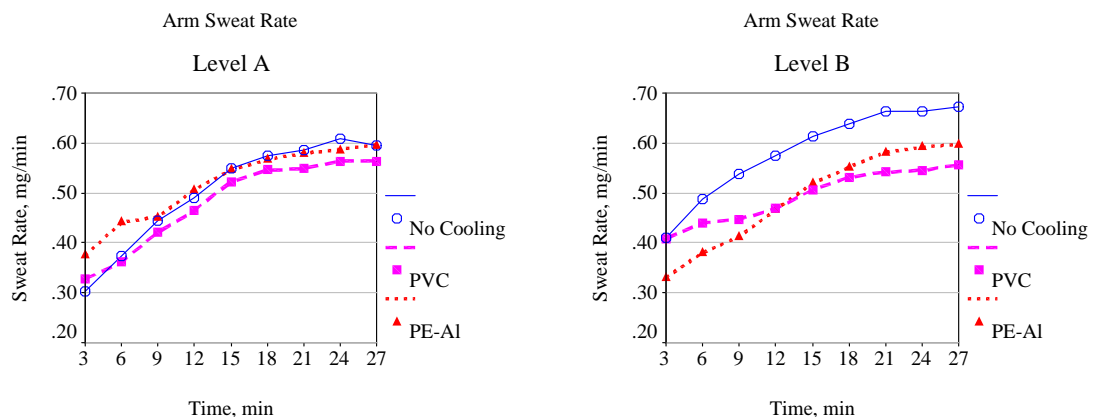
cooling treatments might have influenced arm sweat rate for subjects in level B ensembles only.

ANOVA analysis of these data shows significant suit-by-vest-by-time and vest-by-time interaction effect and time main effects (Table 11). Suit and vest main effects are not significant. The differences in arm sweat rate between the two protective ensembles depend on which cooling condition is applied. This two-way pattern changes across nine

Table 11. ANOVA Table for Arm Sweat Rate

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
SUIT	0.046	1, 5	0.046	0.554	0.490
VEST	0.181	2, 10	0.091	1.603	0.249
TIME	2.152	8, 40	0.269	22.486	**0.000**
SUIT * VEST	0.155	2, 10	0.078	2.355	0.145
SUIT * TIME	0.015	8, 40	0.002	1.244	0.300
VEST * TIME	0.048	16, 80	0.003	1.839	**0.040**
SUIT * VEST * TIME	0.047	16, 80	0.003	2.653	**0.002**

Figure 33. Arm Sweat Rate Marginal Means at Three Cooling Treatments Over Time
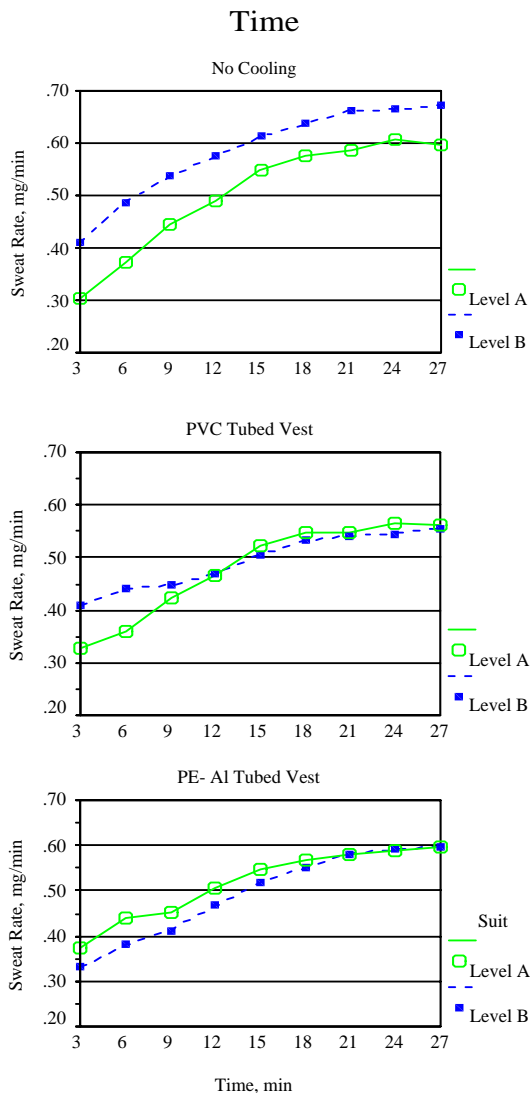
time points. Figures 33 and 34 show two different plots of marginal means of arm sweat rate to illustrate the interaction effects.

The arm sweat rate pattern is definitely different for different cooling treatments over time, as seen in Figure 33. With no cooling, it appears that there is almost no interaction at all. The graphs for level A and level B are parallel at all time intervals, although the difference between level A and level B is clear. This graph indicates that when no cooling vest was used, the subjects' arm sweat rate was less in a level A overgarment compared to a level B garment. On the other hand, because sweat rate amounts were higher at

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the beginning of testing with level B ensembles, this assessment is misleading. The overall increase in arm sweat rates with both ensembles from the beginning to the end of the testing are similar. With a PVC tubed vest, sweat rate increase was more pronounced in a level A suit than in a level B suit, which is in agreement with the fact that the level A suit is vapor impermeable and retains humidity more. Notice that the at the beginning of testing, subjects' arm sweat rates are higher when they wore a PVC tubed vest under level B suits than under level A ensembles. Figure 33 indicates that the arm sweat rate did not differ between level A and level B suits while using the PE-Al tubed cooling vest.

Figure 34 shows how the cooling treatments affected the arm sweat rate under two different protective suits (suit-by-vest interaction) at each time level. During the first 12 minutes, the effect of cooling treatments on subjects' arm sweat rate depended on the protective level of garment they wore. During the second half of the testing, cooling treatments appear to have reduced the arm sweat rate under either protective garment, although the effect was more noticeable when they wore level B suits.

Interaction comparisons indicated that the interaction occurred only at time dimension. No significant suit or vest differences were observed. The difference between the control and the cooling treatments depended on the time factor.

In summary, statistical analysis revealed that the cooling treatments did not alter the sweat rate at the arm. A significant increase in subjects' sweat rate was observed from the beginning to the end of the testing regardless of cooling treatment.

Figure 34. Arm Sweat Rate Marginal Means at Nine Time Levels Over Suit Treatments

Legend:

No Cooling

PVC

PE-Al
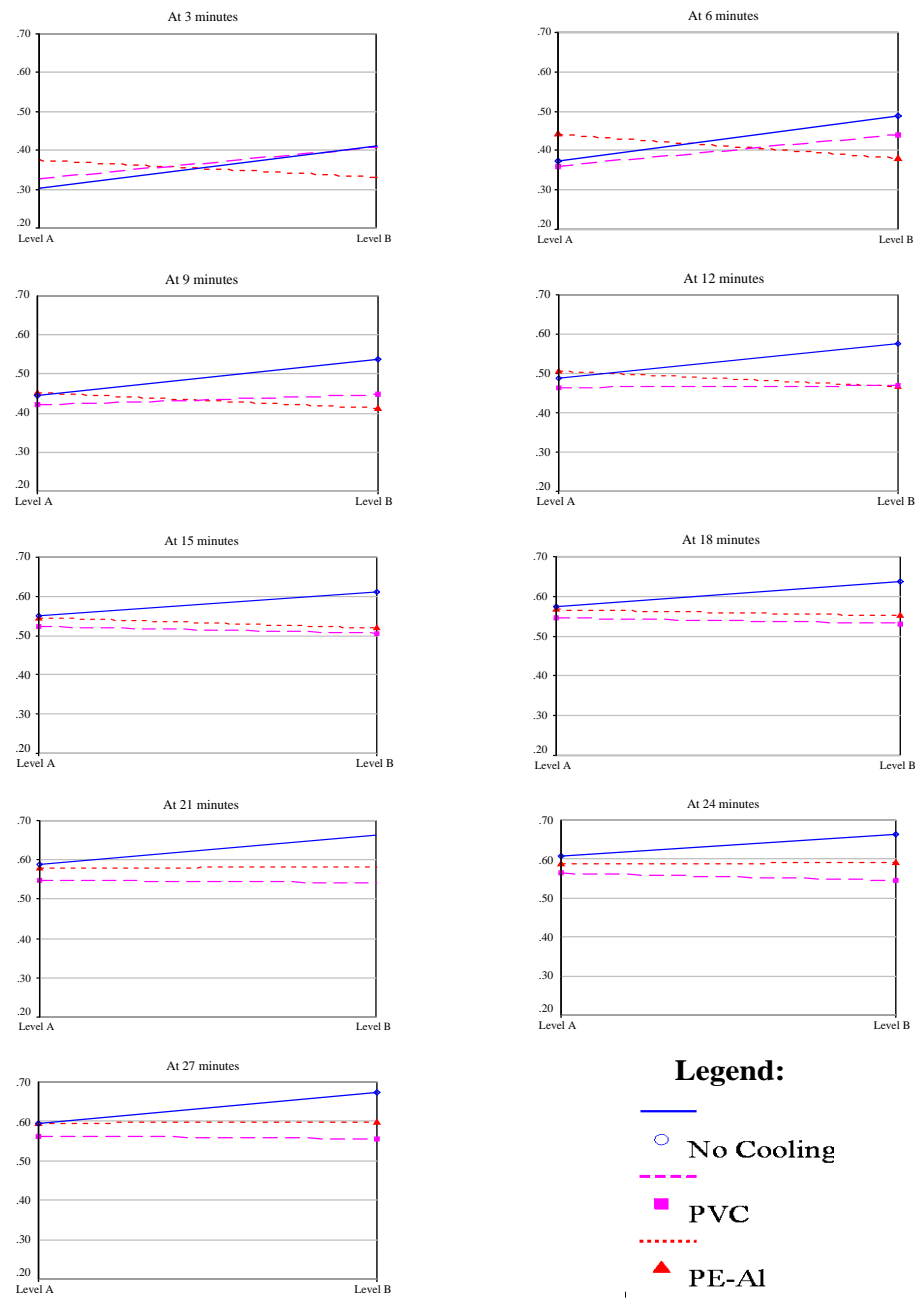
4.2.2.5. HEART RATE

Marginal means of subjects' heart rate during Level A testing were plotted over time in Figure 35. This graph shows a consistent heart rate increase with several fluctuations regardless of the cooling conditions. For the control condition and both treatment conditions, heart rate increased from about 95-99 beats per minute (50% predicted maximum heart rate) for the average of the first three minutes to 111-117 beats per minute (60% predicted maximum heart rate) which would be considered light physical activity.

Figure 35. Heart Rate Marginal Means by Cooling Treatment Over Time.

ANOVA analysis shows (Table 12) no significant interaction effect between time and cooling treatment, and vest main effect. However, time main effect was statistically

Table 12 ANOVA Table for Heart Rate

Source	Sum of Squares	df,df$_{error}$	Mean Square	F	Sig.
VEST	149.112	2, 10	74.556	0.091	0.914
TIME	6362.264	8, 40	795.283	12.337	**0.000**
VEST * TIME	694.496	16, 80	43.406	0.618	0.860

significant, which indicates that subjects' heart rate increased over time regardless of cooling treatment. Comparable to core temperatures, the subjects' heart rate was not sufficiently significantly affected by the cooling treatments because they were not physically challenged due to the testing conditions and moderate exercise protocol.

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4.2.3. SUMMARY OF PHYSICAL AND PHYSIOLOGICAL DATA FINDINGS

Measurement data analyses indicated that cooling treatments significantly affected the microenvironment temperature and humidity and subjects' physiological measures over time on all the areas of the body examined, except for chest temperature, heart rate and core temperature. In other words, the test subjects had similar chest temperature, heart rates and core temperatures whether they wore no-cooling or either of the prototype cooling vests. Skin temperatures at the abdomen and back and microclimate temperature and humidity were improved when subjects wore either prototype vest as compared to when they wore no cooling vests. Sweat rate at the chest and the left arm measurements changed differentially over the levels of cooling treatment and protective overgarment over time (a three-way significant interaction). Nevertheless the change was not statistically significant.

Table 13 shows a summary of all the findings resulting from the physical and physiological data. The last column shows that time significantly affected eight out of nine dependent variables. PPE significantly affected only sweat rate at both locations. The cooling treatment significantly affected five out of nine dependent variables. No significant differences by vests were found.

4.2.4. DISCUSSION OF MEASUREMENT DATA FINDINGS

It is reasonable that the subjects' physiological data indicated that on several levels the cooling treatment made a difference and the data showed no differences between the two prototype cooling vests.

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Table 13. Summary Table for the Nine Dependent Variables

Dependent Variable	Cooling vs. no-cooling	PVC vs. PE-Al	Level A vs. Level B	Time Effect
Microclimate				
Temperature	Significant	Not significant	Not significant	Significant
Humidity	Significant	Not significant	Not significant	Significant
Skin Temperature				
Chest	Not significant		Not significant	Significant
Back	Significant	Not significant	Not significant	Significant
Abdomen	Significant	Not significant	Not significant	Significant
Core Temperature	Not significant		Not significant	Not significant
Sweat Rate				
Chest	Significant	Not significant	Significant	
Arm	Not significant		Significant	Significant
Heart rate	Not significant		Not significant	Significant

One critical issue that arose with the physical and physiological data was the different initial temperature, humidity and sweat rate values. One would expect that all data corresponding to one variable should start at a similar value, but this was not the case. This unexpected issue may be due to the donning process. For level A ensembles, subjects dressed in pants, underwear, and socks, donned the cooling vest (when appropriate), then the SCBA respiratory system, including the mask, level A suit and the cooler unit. This required that the level A ensemble was completely zipped before attaching the cooler unit and carrier. Thus, the subject became warm during the donning process before data collection was even initiated. In contrast, subjects donned the level B ensemble over pants, underwear, socks, and the cooling vest (when appropriate). The level B ensemble neck area could remain open while attaching the SCBA respiratory system, the cooling unit and the carrier. The mask was donned immediately before the onset of testing. This allowed the subjects to stay cooler during the donning process for level B ensembles.

Similarly, when a defective cooler cartridge replacement was needed it took proportionally longer for this task for a level A ensemble than for a level B ensemble. When subjects wore a level A ensemble, the cartridge replacement procedure involved un-latching the tubes from the cooler and removing the cooler from the carrier. After the carrier was detached completely, the level A suit could be unzipped and the mask removed to allow the subject to breathe on his own and ventilate the microclimate. While the new cartridge was installed, the subject kept his level A suit open down to the waist and was allowed to sit down and drink some liquid. This process lasted approximately five to ten minutes. Occasionally, another replacement would be necessary. In that case the testing was aborted and rescheduled because the lengthy procedure would have likely resulted in misleadingly high readings. In contrast, when subjects wore the level B suit, they could immediately remove their mask and unzip the neck area to cool down if a cooling cartridge replacement was necessary.

Logically one would expect the chest skin temperature data to be similar to the abdomen and upper back skin temperature data which exhibited strong cooling relief when a cooling garment was worn. However, chest skin temperature was not significantly affected by the use of the cooling vests. The placement of the temperature sensor likely contributed to the unexpected results. The temperature sensor and the heart rate monitor shared the same spot on the chest with the sweat rate monitor. The sweat rate sensor was placed on top of the temperature sensor in the middle of the chest. The heart rate monitor was strapped around the chest as well, with the sensor section next to the other two sensors. The heart rate monitor was housed in a 1-inch wide hard plastic strip with elastic extensions at both sides, strapped around the chest. The sweat rate sensor was shaped like a cylinder that was about 1 inch thick and 2 inches in diameter. Thus, the thickness of the

sweat rate sensor and the heart rate monitor strap prevented the cooling vest from having proper contact with the skin around it, thus impeding cooling transfer. Second, fit of the cooling vests at the upper chest area was influenced by the type of activity being performed. Thus, sometimes the vest did not directly touch the subjects' skin, thereby reducing the cooling effectiveness of both vests. The air bottle harness system played a role as well. Weight of the harness system pushed against the vest toward the skin, expanding the contact between the vest and the skin at the back.

Core temperature and heart rate measurements were not altered by the cooling treatments therefore the effect of cooling vests on these variables is inconclusive. In order to asses this effect, one should increase the physical effort during testing, or make the environmental testing conditions more severe or employ a combination of both.

4.3. PERCEPTION DATA ANALYSIS

The subjects were asked to complete two kinds of ballots. The first ballot was geared towards assessing subjects' perception of temperature and humidity at six torso locations: front and back neck, chest, upper and lower back, and abdomen, plus the head and face. Temperature was assessed using a six-point response scale with 1 representing cold, 2 cool, 3 neutral, 4 warm, 5 hot and 6 very hot and humidity was assessed using a similar six point response scale with 1 representing dry 2 somewhat dry, 3 neutral, 4 slightly wet 5 wet and 6 very wet. This ballot was administered at the middle of the testing protocol, after subjects had completed their first set of exercises around the chamber and again at the end of the protocol. Since the subjects wore full protective ensembles including double layers of gloves, it was difficult for them to write. Therefore, the researcher filled out the questionnaire by asking the subjects to indicate by displaying

the number of fingers that corresponded with their perception of temperature and humidity for the eight locations. The second ballot assessed the perception of visibility using a scale from 1 representing very good to 9 representing very poor. All questionnaires were coded and analyzed in order to detect any differences by different garment combinations.

4.3.1. TEMPERATURE PERCEPTION

Subjects' facial temperature perception marginal means indicates that subjects perceived their faces to be hottest at the end of testing in the level A ensemble worn without a cooling vest (Table 14). They reported their coolest score after the first round when they wore a Pe-Al tubed vest under a level B ensemble with a score of 3.667, slightly above the "neutral" score. At the end of the first round while wearing the PVC tubed vest, subjects reported a comparable score of 3.833 for both level A and level B ensembles. In general, regardless of treatment, subjects' perception of facial temperature increased with the second ballot.

Table 14. Marginal Means of Subjects' Face Temperature Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	5.167	3.833	4.667	4.167	4.5
Level B	4	4.667	3.833	4.333	3.667	4.5

ANOVA analysis indicated no significant interaction; and the time main effect was significant (f=48.077 at 1,5, p=0.001), the subjects felt warmer at the end of the testing protocol than the middle of the testing however cooling the torso was not a significant influence on subjects' perception of facial temperature.

At the back of their heads, subjects reported a score of 5.167 (hot) at the end of the exercise while wearing a level B ensemble without a cooling vest. The coolest they perceived was when they wore a level B ensemble with a PVC tubed cooling vest. For all other protective garment-cooling vest arrangements they reported feeling warm to hot (Table 15). Again, regardless of treatment, subjects' perception of their head temperature increased with the second ballot.

Statistical analysis showed that there were significant time and vest main effects (F= 49.000 at d.f. 1,5 ;p=0.001 and F= 10.750 at d.f. 2,10 ;p=0.003 respectively). Two- and three-way interaction effects were non-significant. Test of within subjects contrasts showed a significant difference between cooling and no cooling (F= 42.250 at d.f.

Table 15. Marginal Means of Subjects' Head Temperature Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	5	4	4.667	4.1667	4.5
Level B	4.333	5.167	3.833	4.333	3.667	4.167

1,5 ;p=0.001) and no difference between the two prototype vests (F= 0.250 at d.f. 1,5;p=0.0638). Subjects perceived that they were cooler when they wore a cooling vest and they felt warmer at the end of testing.

The marginal means of subjects' temperature perception at their front neck is shown in Table 16. They perceived their neck to be hottest at the end of testing when they did not wear a cooling vest. Nevertheless, the perception of temperature at this location did not reach the "hot" level. Again, regardless of treatment, subjects' perception of neck temperature increased with the second ballot.

Table 16. Marginal Means of Subjects' Front Neck Temperature Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	4.883	3.667	4.167	4.167	4
Level B	4.333	4.833	3.5	4	3.167	4.167

ANOVA analysis indicated a significant three-way interaction effect, together with significant vest and time main effects as seen in Table 17. Figure 36 shows the interaction. When the subjects wore the no cooling treatment, they perceived their front neck to be warmer then when they wore one of the cooling treatments, with one exception, round one for the PE-Al tubed vest regardless of level A or B ensembles. Within subject contrasts indicated a significant difference between the control and cooing treatments (F= 21.600 at 1, 5 dof; p=0.006) and no significant differences between the two prototype cooling vests (F= 0.0357 at 1, 5 dof; p=0.576).

Table 17. ANOVA Table for Front Neck Temperature Perception.

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
SUIT	0.681	1, 5	0.681	5.976	0.058
VEST	11.861	2, 10	5.931	19.953	**0.000**
TIME	8.681	1, 5	8.681	48.077	**0.001**
SUIT * VEST	1.028	2, 10	0.514	1.480	0.274
SUIT * TIME	0.681	1, 5	0.681	5.976	0.058
VEST * TIME	0.861	2, 10	0.431	1.303	0.314
SUIT * VEST * TIME	2.028	2, 10	1.014	21.471	**0.000**

Figure 36. Interaction Graphs for Front Neck Temperature Perception

Front Neck Temperature Perception at Round 1

Front Neck Temperature Perception at Round 2
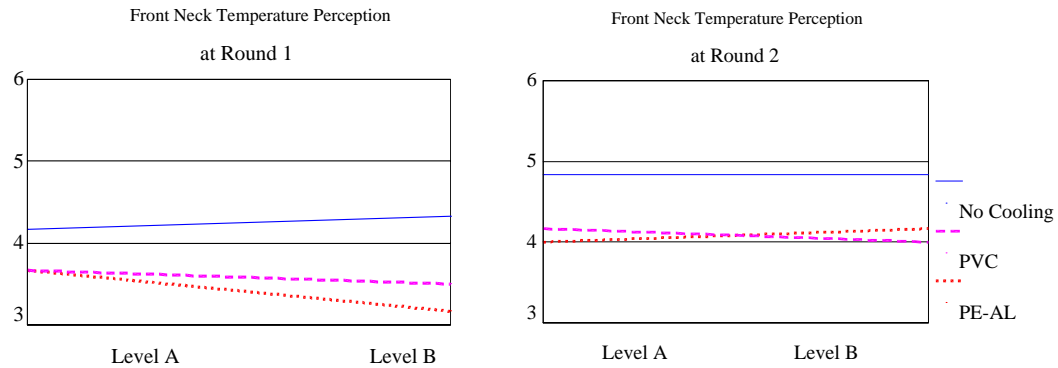
No Cooling
PVC
PE-AL

Table 18 shows that the subjects' perceptions of temperature at their back neck were similar to their front neck temperature perceptions. They felt the hottest without cooling at the end of testing under both level A and B suits. Note that the subjects rated the temperature at their back neck between "neutral" and "cool" before the second round of their exercise when they wore a PE-Al tubed vest under level B suits. The statistical analysis indicated that the time and vest main effects were significant ($F=31.154$ at d.f. 1, 5; $p=0.003$ and $F=19.407$ at d.f. 2, 10; $p=0.003$ respectively). Within subjects contrasts revealed that the cooling treatment significantly affected the subjects' temperature perception for the back neck ($F=29.490$ at d.f. 1, 5; $p=0.003$) but the prototype vests were not significantly different ($P=2.753$ at d.f. 1, 5; $p=0.158$).

Table 18. Marginal Means of Subjects' Back Neck Temperature Perception.

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	5	3	4	3.333	3.667
Level B	3.833	4.667	3.167	3.833	2.5	3.333

Marginal means of subjects' temperature perception (Table 19) at their chest shows a similar trend to that of the neck area. It is interesting to note the similarity in perception of cooling with the cooling vests regardless of level A or B or time.

Table 19. Marginal Means of Subjects' Chest Temperature Perception.

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	4.833	2.833	3.667	3.333	3.667
Level B	4.167	4.667	3.167	3.667	2.333	3.5

ANOVA analysis resulted in similar significant time and vest main effects (F=40.000 at d.f. 1, 5; p=0.001 and F=10.920 at d.f. 2, 10; p=0.003 respectively). Contrasts indicated that there was significant perception of temperature differences between cooling and no-cooling (F=18.867 at d.f. 1, 5; p=0.007) but no differences between the two prototype cooling vests (F=0.211 at d.f. 1,5; p=0.665).

Upper back temperatures were perceived cooler than the other seven locations studied. Table 20 shows that the temperature perception at the end of the protocol was close to "hot" without cooling and very close to "cool" with the PE-Al tubed vest under level B ensembles halfway through the protocol. It is interesting that the physiological data and the perception data correspond so well.

Table 20. Marginal Means of Subjects' Upper Back Temperature Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	4.667	2.333	3.333	2.833	3.167
Level B	4.167	4.667	2.833	3.333	2.167	3.167

Statistical analysis indicated significant time and vest main effects (F=43.214 at d.f. 1, 5; p=0.001 and F=16.942 at d.f. 2, 10; p=0.001 respectively). The cooling perception at subjects' upper back while wearing a cooling vest was significant (F= 25.545 at d.f. 1, 5; p=0.004) but no difference between the cooling vests was detected (F= 0.238 at d.f. 1, 5; p=0.646).

Abdomen temperature perception was similar when subjects did not wear a cooling vest. Subjects felt between "neutral" and "cool" under level A ensembles when worn with a PVC tubed vest as well as under B ensembles together with a PE-Al tubed vest (Table 21). Analysis of variance resulted in a significant 3- way suit-by-vest-by-time interaction effect and suit and time main effects (Table 22).

Table 21. Marginal Means of Subjects' Abdomen Temperature Perception.

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	4.667	2.5	3.667	3.333	3.333
Level B	4.167	4.5	3	3.5	2.167	3.333

Interaction graphs (Figure 37) show that subjects' temperature perception at the abdomen area depended on the time of testing (halfway versus end of testing) and the cooling treatment they received. While they felt warmer when no cooling vest was worn

Table 22. ANOVA Table for Abdomen Temperature Perception

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
SUIT	0.681	1, 5	0.681	14.412	**0.013**
VEST	27.750	2, 10	13.875	7.400	**0.011**
TIME	6.125	1, 5	6.125	66.818	**0.000**
SUIT * VEST	1.694	2, 10	0.847	2.699	0.116
SUIT * TIME	0.125	1, 5	0.125	0.349	0.580
VEST * TIME	0.750	2, 10	0.375	1.552	0.259
SUIT * VEST * TIME	2.583	2, 10	1.292	5.741	**0.022**

Figure 37. Abdomen Temperature Perception Interaction Graphs
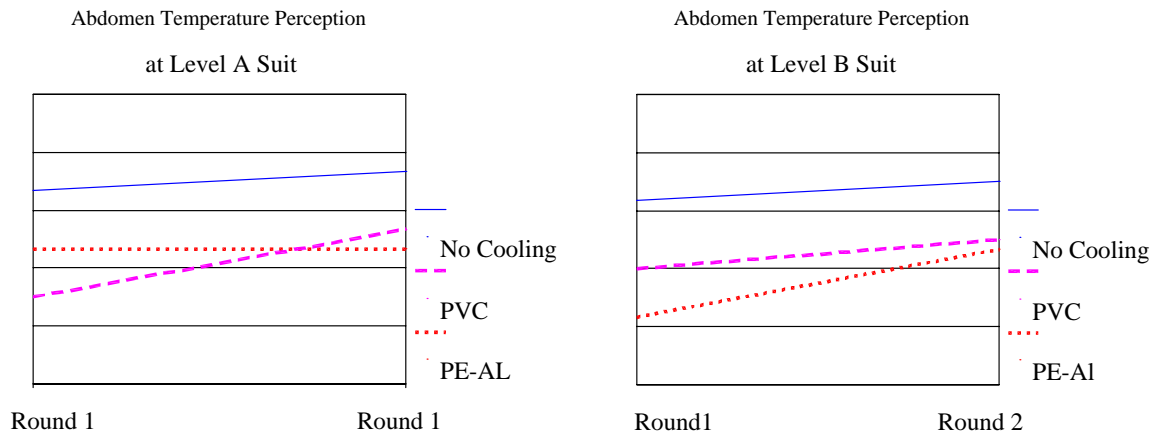
than with a cooling vest, under a level A suit, the abdomen was perceived warmer with
the PVC tubed vest than with the PE-AL tubed vest at the halfway point but perception
was reversed at the end of testing. Under level B ensembles, the perceived abdomen
temperature differences between the two prototype vests were larger at the halfway point
than the end of the protocol. Subjects perceived abdomen temperatures to be warmer with
the control condition than either cooling treatment conditions throughout the test session.

Interaction contrasts showed that cooling was significant (F= 9.4645 at d.f. 1, 5;
p=0.028) but the perception of abdomen temperature differences between the prototypes
was not significant (F=0.224 at d.f. 1, 5; p=0.656).

Subjects' perception of temperature at the lower back location was similar to the
other seven locations as shown in Table 23, where the lowest temperature perception
score was reported at the halfway point during the testing protocol while wearing a level
A suit with a PVC tubed cooling vest. Warmest reported case was again under the level A
suit when no cooling was worn. Again, subjects wearing the no cooling treatment clearly
perceived their lower back to be warmest regardless of level A or B suits over time.

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Table 23. Marginal Means of Subjects' Lower Back Temperature Perception.

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	4.667	2.167	3.333	3.167	3
Level B	4	4.5	2.667	3.167	2.167	3.167

Statistical analyses indicate significant vest and time main effects ($F=12.365$ at d.f. 2, 10; $p=0.002$ and $F=100.00$ at d.f. 1, 5; $p=0.000$ respectively). The test of within subject contrasts revealed a significant cooling effect ($F= 17.847$ at d.f. 1, 5; $p=0.008$) and no significant differences between the two prototypes ($F=0.023$ at d.f. 1, 5; $p=0.886$).

4.3.1.1. TEMPERATURE PERCEPTION RESULTS SUMMARY

At all eight body locations, subjects' temperature perceptions were similar. They reported feeling the warmest while wearing no cooling particularly with level A ensembles. All analyses indicated significant time and cooling effects but the differences between the two prototypes were not significant.

4.3.2. HUMIDITY PERCEPTION

The subjects perceived humidity around their faces to be highest when they did not wear a cooling vest under either level A or level B suits at the end of the protocol (Table 24). Statistical analysis showed a significant time main effect only ($F=34.091$ at 1, 5, $p=0.002$).

Table 24. Marginal Means of Subjects' Face Humidity Perception.

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.5	5.333	3.833	5.167	4.5	5
Level B	4.333	5.167	4	4.333	3.5	4.667

The subjects' humidity perceptions at their head were higher when the subjects did not wear cooling (Table 25). Statistical analysis showed a significant three-way suit-by-vest-by-time interaction effect (Table 26). The interaction graphs shown in Figure 38

Table 25. Marginal Means of Subjects' Head Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	5	4	4.667	4.167	4.5
Level B	4.333	5.167	3.833	4.333	3.667	4.167

show that they felt more humid without cooling than with cooling and regardless of what combination of garments they used at all times. When subjects wore level B ensembles and PE-Al tubed vests they tended to perceive their heads to be dryer than when they

Table 26. ANOVA Table for Head Humidity Perception

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
SUIT	3.556	1, 5	3.556	16.000	**0.010**
VEST	1.778	2, 10	0.889	2.105	0.173
TIME	9.389	1, 5	9.389	13.000	**0.015**
SUIT * VEST	1.444	2, 10	0.722	3.824	0.058
SUIT * TIME	0.055	1, 5	0.056	0.294	0.611
VEST * TIME	0.111	2, 10	0.056	0.625	0.555
SUIT * VEST * TIME	1.444	2, 10	0.722	4.643	**0.037**

wore the PVC tubed vest. The interaction appears to be when they wore level A ensembles, since at round one and two they felt differently with different cooling vests. At round one, they felt dryer when they wore the PVC tubed vest, but this perception was reversed at round two. The interaction contrasts indicated significant differences in perception of wetness at subjects' head between the two protective suits and between round one and two.

Figure 38. Head Humidity Perception Interaction Graphs
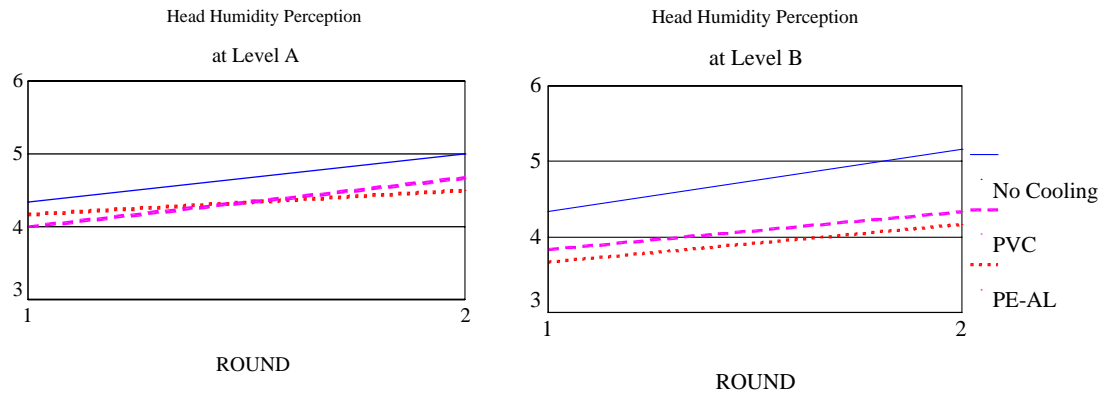
Subjects' front neck humidity perception marginal means are shown in Table 27.

It is apparent that subjects felt dryer when they wore a cooling vest and at round one. The

Table 27. Marginal Means of Subjects' Front Neck Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	5	3.667	5	4.333	4.833
Level B	4.167	5	3.667	4.333	3.833	4.333

ANOVA table indicates that there was a significant vest-by-time interaction and a time

main effect (Table 28).

Table 28. ANOVA Table for Front Neck Humidity Perception

Source	Sum of Squares	df, df$_{error}$	Mean Square	F	Sig.
SUIT	1.389	1, 5	1.389	4.808	0.080
VEST	2.111	2, 10	1.056	1.532	0.263
TIME	10.889	1, 5	10.889	28.000	**0.003**
SUIT * VEST	0.778	2, 10	0.389	2.059	0.178
SUIT * TIME	0.222	1, 5	0.222	1.818	0.235
VEST * TIME	0.778	2, 10	0.389	4.375	**0.043**
SUIT * VEST * TIME	0.444	2, 10	0.222	1.000	0.402

The two graphs in Figure 39 show this interaction. Subjects perceived neck humidity differently when wearing level A and level B ensembles. Under the level A suit, at round one, the subjects' front neck felt driest when they wore a PVC tubed vest and wettest when they wore a PE-Al vest. However by the end of the test session, subjects reported neck humidity perception similarly although they reported feeling slightly dryer when wearing level B ensembles.

Figure 39. Front Neck Humidity Perception Interaction Graphs
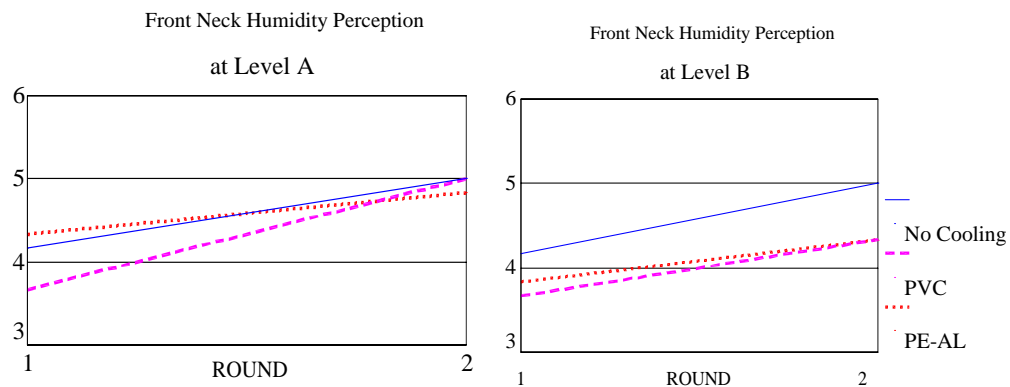
Subjects' back neck humidity perception marginal means are shown in Table 29. It is interesting to note that subjects when wearing both cooling treatments indicate dryer scores than when wearing the control treatment. All second round scores are higher (wetter) than the first round scores. The ANOVA analysis confirms this observation. There are no significant interactions but the time and vest main effects were found to be statistically significant (F=90.660 at d.f. 1, 5; p=0.000 and F=4.333 at d.f 2, 10; p=0.044 respectively). Further analysis showed the cooling vest affected the humidity perception at subjects' back neck (F=5.913 at 1, 5, p=0.049) and they did not discern any differences between the two prototype vests (F=0.044 at 1, 5, p=0.842).

Table 29. Marginal Means of Subjects' Back Neck Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	5	3.333	4.667	3.667	4.333
Level B	4.167	5.167	3.667	4.333	3.5	4.333

The marginal means of subjects' chest humidity perception (Table 30) shows the same pattern as the back neck. The scores indicate subjects perceived themselves to be wetter in level A as compared to level B, wetter in round two as compared to round one, and when wearing no cooling as compared to cooling treatments.

Statistical analysis shows that there were significant vest and time main effects (F=4.880 at d.f. 2, 10; p=0.033 and F=26.786 at d.f. 1, 5; p=0.004 respectively). Cooling

Table 30. Marginal Means of Subjects' Chest Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.333	5.167	3.333	4.167	3.666	4.333
Level B	4	4.883	2.833	3.833	3.333	4.167

treatment affected humidity perceptions at subjects' chest (F=6.447 at 1, 5 dof, p=0.042) and differences between the two prototypes were not significant (F=1.509 at 1, 5 d.f, p=0.274).

It appears that subjects' perceived their upper back to be slightly drier than the previously noted body areas (Table 31). Subjects tended to feel wetter when not wearing cooling, compared to the cooling treatments when wearing level A suit versus level B, and at round two compared to round one. However, ANOVA analysis indicated only a significant time main effect (F= 42.25 at d.f 1, 5 p= 0.01).

Table 31. Marginal Means of Subjects' Upper Back Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4	5	3.167	4	3.666	4
Level B	4.167	5	3	3.667	3.167	3.833

Abdomen humidity perception marginal means (Table 32) show a similar pattern. Subjects generally felt wetter at their abdomen with no cooling and over time. Statistical analysis shows that there were significant vest and time main effects ($F=6.850$ at d.f. 2,

Table 32. Marginal Means of Subjects' Abdomen Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	5	2.5	4	3.833	4
Level B	4.333	4.667	3	3.667	3.167	3.667

10; $p=0.013$ and $F=14.118$ at d.f. 1, 5; $p=0.013$ respectively). No statistically significant interaction effects were detected. Cooling treatment was perceived to be drier than the control treatment ($F=8.829$ at 1, 5 dof; $p=0.031$) but no significant differences were found between the two prototype cooling vests ($F=2.015$ at 1, 5 dof; $p=0.2$).

Subjects' perceived their lower back to be wetter when they did not wear cooling and over time (Table 33). Statistical analyses showed no interaction effects but significant vest and time main effects ($F=7.443$ at d.f. 2, 10; $p=0.011$ and $F=16.623$ at d.f.

Table 33. Marginal Means of Subjects' Lower Back Humidity Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4.167	5.667	3.167	4.167	3.667	4
Level B	4	5	3	3.667	3.167	4

1, 5; p=0.010 respectively). The differences in humidity perception between the two prototype vests were not statistically significant (F=0.380, at 1, 5 d.f. p=0.565) but there was a significant difference between cooling and no cooling (F=14.738 at 1,5 d.f.; p=0.012).

4.3.2.1. HUMIDITY PERCEPTION RESULTS SUMMARY

At all eight body locations, subjects rated humidity perceptions similarly. They reported feeling the most humid while wearing level A ensembles without a cooling vest. All analyses indicated significant cooling and time effects but the differences between the two prototypes were not significant.

4.3.3 VISIBILITY PERCEPTION

Since visibility under the mask and face shield of the protective ensembles was reported to be problematic by HazMat workers in the focus groups, it was important to determine whether cooling improved this problem (Branson, et al. 2005). Typical fogging of the face shield can be seen in Figure 40 which shows a subject on a treadmill during a level A exercise. Visibility perception was assessed by asking the subjects to rate their visibility at both times that they rated their temperature and humidity perceptions, using a scale from 1 representing "very good" to 9 representing "very poor". The results

Table 34. Marginal Means of Subjects' Visibility Perception

	No Cooling		PVC		PE-Al	
	Round 1	Round 2	Round 1	Round 2	Round 1	Round 2
Level A	4	6.167	2.833	5.333	2.667	5
Level B	1.667	1.167	1.167	1.167	1	1.333

Figure 40. Fogging on the Face Shield Due to Moisture in the Microclimate during a Level A Exercise.

are summarized in Table 34. It is apparent that subjects had more difficulty seeing clearly in a level A ensemble than in a level B ensemble. For the level A ensemble, cooling treatments helped alleviate the problem. Perception of visibility worsened as the subjects progressed through the testing.

Statistical analysis showed a significant two-way suit-by-time effect as seen in Table 35. Time and suit main effects were also statistically significant. Figure 41 shows the interaction graph. It appears that subjects' perception of

visibility was consistent throughout the testing while they were wearing level B

ensembles since there was a very small change between round one and round two scores.

Recalling that a score of 1 means "very good" their visibility was not affected through the

Table 35. ANOVA Table for Visibility Perception

Source	Sum of Squares	df, df_{error}	Mean Square	F	Sig.
SUIT	171.125	1, 5	171.125	23.906	**0.005**
VEST	7.750	2, 10	3.875	1.703	0.231
TIME	30.681	1, 5	30.681	39.306	**0.002**
SUIT * VEST	3.250	2, 10	1.625	0.569	0.584
SUIT * TIME	19.014	1, 5	19.014	49.964	**0.001**
VEST * TIME	0.028	2, 10	0.014	0.044	0.957
SUIT * VEST * TIME	0.528	2, 10	0.264	0.497	0.622

level B testing exercises. On the other hand, visibility was affected adversely when subjects wore level A ensembles. Half way through the testing they rated their visibility perception a little over 3 and at the end of the testing this value reached almost 6. Presence of the cooling vests did not change this perception significantly.

Figure 41. Visibility Perception Interaction Graphs.
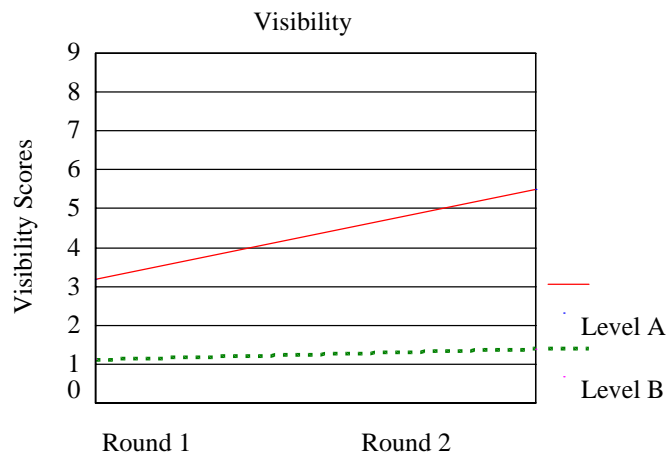
Scale: 1="very good 9="very poor"

4.3.4. SUMMARY OF PERCEPTION ANALYSIS RESULTS

The seventeen dependent perception variables, that is, eight temperature, eight humidity and one visibility perception scores, were analyzed using ANOVA. The results are summarized in Table 36. The first two columns labeled "suit" contain the marginal means of the dependent variables for the PPE independent variable level A and level B garments. Bold numbers indicate marginal means that reached statistical significance. Subjects' perception of abdomen and head temperature and humidity were significantly different when level A and level B ensembles were worn. Subjects' perception of visibility was significantly different for level A and level B ensembles.

Table 36. Summary Table of Perception Variables.

| | | Marginal Means of Subject's Perception | | | | | | |
| | | Suit | | Cooling | | | Time | |
		Level A	Level B	No cooling	PVC	Pe-Al	Round 1	Round 2
TEMPERATURE	Face	4.42	4.16	4.5	4.17	4.21	**4.42**	**4.17**
	Head	4.44	4.25	**4.71**	**4.21**	**4.12**	**4.06**	**4.64**
	Front Neck	4.08	3.89	**4.54**	**3.84**	**3.58**	**3.64**	**4.33**
	Back Neck	3.86	3.56	**4.42**	**3.50**	**3.21**	**3.33**	**4.08**
	Chest	3.75	3.58	**4.45**	**3.33**	**3.20**	**3.33**	**4.00**
	Upper Back	3.44	3.44	**4.45**	**3.04**	**2.83**	**3.11**	**3.23**
	Abdomen	**3.63**	**3.44**	**4.41**	**3.16**	**3.04**	**3.25**	**3.83**
	Lower Back	3.44	3.27	**4.37**	**2.83**	**2.87**	**3.36**	**3.63**
HUMIDITY	Face	4.72	4.33	4.83	4.33	4.42	**4.11**	**4.94**
	Head	**4.67**	**4.22**	4.67	4.33	4.33	**4.08**	**4.81**
	Front Neck	4.50	4.22	4.58	4.17	4.33	**3.97**	**4.75**
	Back Neck	4.22	4.19	**4.67**	**4.00**	**3.96**	**3.78**	**4.64**
	Chest	4.16	3.83	**4.58**	**3.54**	**3.87**	**3.58**	**4.42**
	Upper Back	3.97	3.80	4.54	3.45	3.66	**3.53**	**4.25**
	Abdomen	3.91	3.75	**4.54**	**3.29**	**3.66**	**3.50**	**4.16**
	Lower Back	4.13	3.80	**4.70**	**3.50**	**3.70**	**3.53**	**4.42**
	Visibility	**4.33**	**1.25**	3.25	2.62	2.50	**2.14**	**3.44**

Temperature: 1= cold - 9= very hot   Humidity : 1= dry - 9= very wet   Visibility : 1= very good - 9= very poor

The next three columns show the marginal means of the dependent variables for the cooling treatment, that is, no-cooling, PVC tubed vest, and PE-Al tubed vest. These values are shown in bar graphs in Figures 42 and 43 for all dependent variables except visibility. As can be seen on the charts and the table, seven out of eight temperature and four out of eight humidity dependent variables showed significant differences by cooling treatments. For all eleven, significant differences were present only between cooling treatments and the control treatment. The differences between the two prototype cooling

Figure 42. Marginal Means of Temperature Perception for the Three
Cooling Treatments at Eight Upper Body Locations

★Denotes significant cooling effect
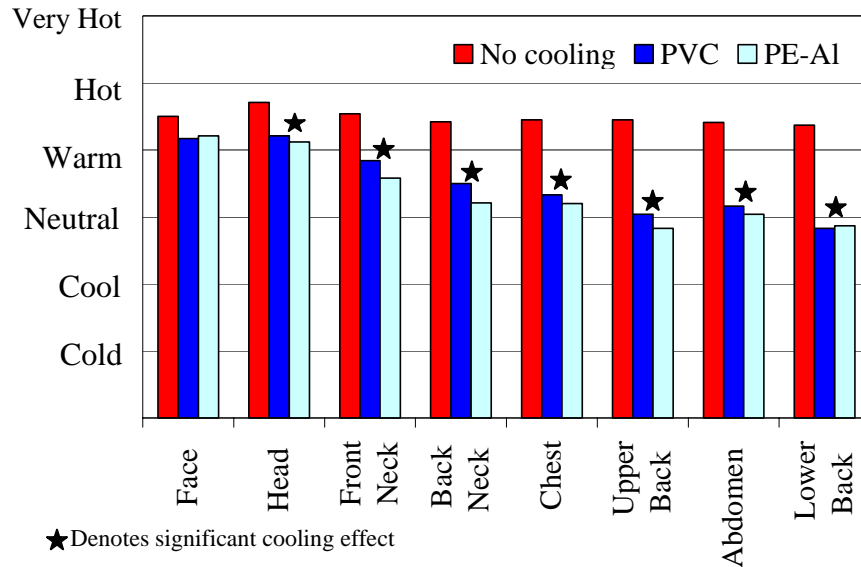
vests were not significant. The charts also reveal that the effect of cooling vests were

more noticeable to the subjects for the lower portion of the torso. This is not surprising

since the head, face, and neck were not in contact with the supplied cooling.

The last two columns of Table 36 give the marginal means of the dependent

Figure 43. Marginal Means of Humidity Perception for the Three
Cooling Treatments at Eight Upper Body Locations

★Denotes significant cooling effect
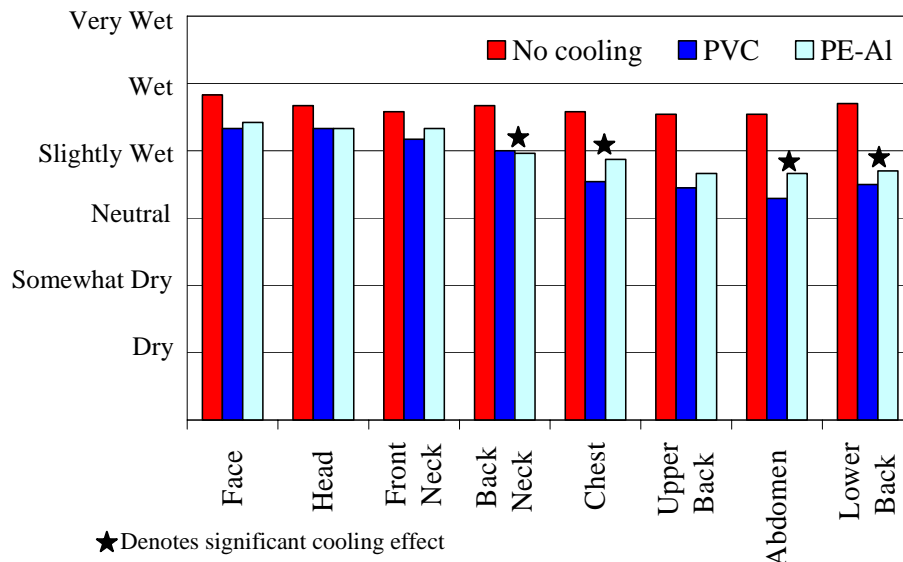
variables for the two time periods. All dependent variables showed a significant time effect. In short, subjects perceived that the cooling vests positively affected their temperature at seven out of eight locations, and their humidity at half of those locations. While the marginal means were less for 15 out of 16 temperature and humidity perception for subjects in level B versus level A, most were not significantly different. Temperature and humidity perceptions at all body areas were worsened by time.

4.4. PERCEIVED VEST FIT AND COMFORT DATA ANALYSIS AND DISCUSSION

Cooling garment fit and comfort issues were addressed in a final ballot in order to improve the design of the prototype vests. The ballots were completed by the subjects at the end of each testing in which they wore a cooling garment. The ballots were coded and averages were calculated. Since both prototype vests were identical in design except for the tubing, it was assumed that the vest fit and comfort evaluations would not vary by PPE. Therefore, the mean values were pooled for the fit and comfort evaluations.

The ballot had two sections. Section one was designed to assess subjects' perceived fit and tactile sensation of the vest. The subjects evaluated fit and tactile perceptions of the vest at (1) the neck; (2) the armhole, (3) the chest, (4) the abdomen, and (5) the shoulder. Perceived fit was assessed on a scale of 1 to 9, with 1 indicating loose and 9 indicating tight. Tactile sensations were assessed on two 9-point scales with 1 indicating smooth and 9 indicating rough and 1 indicating wet and 9 indicating dry.

The second section was designed to assess the perception of general comfort parameters. Subjects evaluated their perception of each category using a 9 point scale.

Ease of donning and doffing, length adjustment, and connecting mechanism were evaluated, with 1 indicating easy and 9 indicating difficult. Perceived stiffness of the vest was assessed with 1 indicating flexible and 9 indicating stiff; zipper closure was assessed with 1 indicating convenient and 9 indicating problematic. Perception of overall practicality, effectiveness, and attractiveness were addressed as well. Overall cooling effectiveness was evaluated using the same 9 point scale with 1 indicating effective and 9 ineffective. Aesthetic properties were assessed using a 9 point scale with 1 indicating practical and attractive and 9 indicating impractical and unattractive. The parameters and related adjectives used to evaluate these features are summarized in Table 37.

Perception of tightness at five garments sections ranged between 5 and 6, which indicates that the subjects perceived a comfortable fit. The subjects perceived the vest fabric to be smooth with ratings in the 3 to 4 range and perceived wetness was rated between 5 and 6 at all areas suggesting that the fabric's moisture transport properties were effective (Figure 44).

Table 37. Comfort Parameters and Related Adjectives Used to Assess the Vest Design

FEATURE	ADJECTIVES
Donning and doffing Length adjustment Connecting mechanism	Easy-Difficult
Stiffness	Flexible-Stiff
Overall cooling effectiveness	Effective-Ineffective
Overall practicality	Practical-Impractical
Overall attractiveness	Attractive-Unattractive
Zipper closure	Convenient-Problematic

97

Figure 44. Average Vest Fit and Comfort Evaluations at Five Body Locations
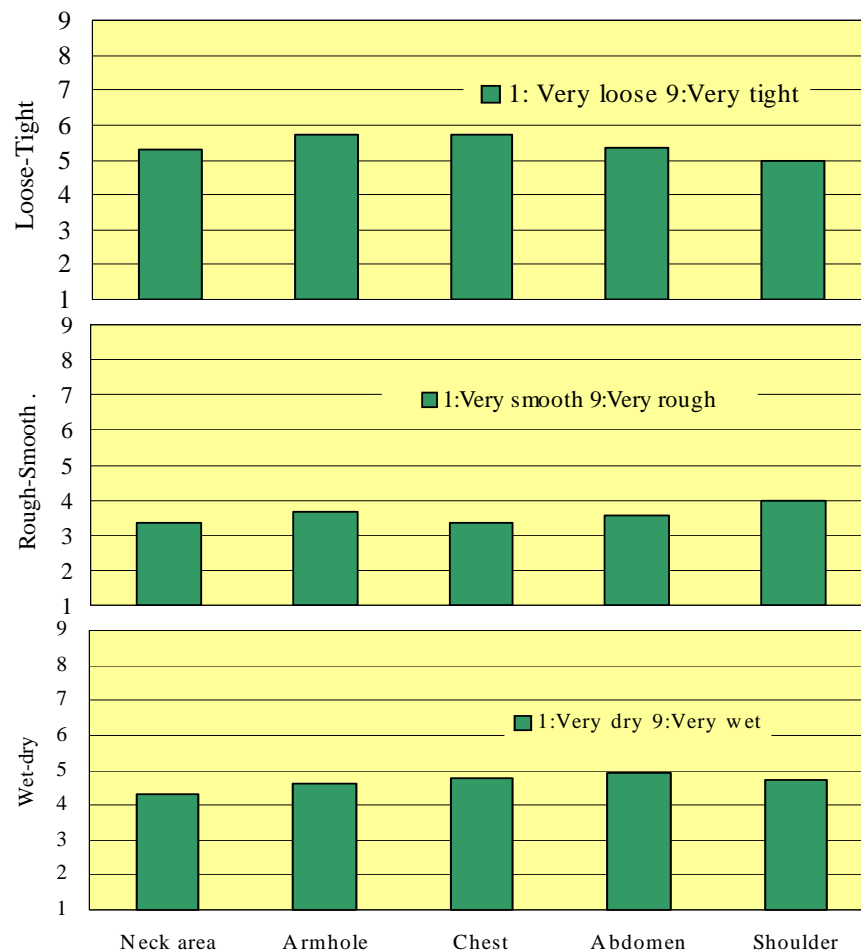
The subjects' comfort perceptions are summarized in Table 38. The subjects found the length adjustment feature and the zipper closure to be easy (rated 3.62 and 3.13 respectively). They perceived the prototype cooling vests to provide effective cooling (rated 3.33), to be attractive and practical overall, with ratings of 3.67 and 3.38 respectively, and flexible with a rating of 2.88 (Table 38). Analysis of data pertaining to cooling, fit, and aesthetic properties of the cooling garment prototypes showed that the design and cooling effectiveness were well received by the subjects. Comments on the vests were generally positive.

Table 38. Averages of Perceived Comfort Characteristics of the Prototype Cooling Vests.

Length adjustment	Easy- difficult	3.62
Zipper closure	Easy- difficult	3.13
Cooling effectiveness overall	Effective-ineffective	3.33
Overall practicality	Practical-impractical	3.38
Overall attractiveness	Attractive-unattractive	2.67
Stiffness	Flexible-stiff	2.88

All scales are from 1=positive to 9=negative (see text)

4.5. SUMMARY OF RESULTS

Human subject testing performed in a controlled environment, employing a custom made protocol, revealed valuable information regarding the cooling effectiveness and users' perception of the physical properties of the of two prototype cooling vests. Physical and physiological data showed that cooling reduced the skin temperature and the chest sweat rate significantly. Perception data indicated similar results. Subjects perceived that the use of cooling vests reduced skin temperatures and humidity especially at the lower torso. Both set of data suggested that the differences between the two prototype cooling vests were not significant.

Fit, comfort, and aesthetic perception ballot revealed that the subjects generally liked the design and the materials used to construct the vests and pleased by the cooling effectiveness, overall practicality and attractiveness.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

5.1. CONCLUSIONS

The purpose of this study was to evaluate two prototype cooling vests designed to

alleviate heat stress experienced by first responders wearing level A and level B

protective ensembles. The evaluation was carried out in an environmentally controlled

chamber using a protocol designed to simulate actual work done by first responders.

Physical, physiological and perceptual data were collected to assess the cooling

properties of each prototype cooling vest as well as to compare and contrast the results

obtained by these two sets of data.

Findings indicated that the subjects' perception of cooling relief generally agreed

with the physiological data. The two prototype cooling vests positively affected skin

temperatures at two locations, chest sweat rate, microclimate temperature and humidity

and perceived temperature and humidity. Both physiological measurement data and

perception data indicated that there were no significant and consistent differences

between the two cooling vests.

Core temperature and heart rate were not significantly altered by the cooling

treatments. We suspect that the moderate testing climatic conditions and exercise are the

reasons for this finding. No significant change for chest skin temperature was found when

a cooling vest was worn as compared to the perception data which showed statistically significant cooling perception at this location. No significant differences in the arm sweat rate were found whether cooling vests were used or not. This result is not surprising since this area of the body was not covered by the cooling vest.

Other body areas including face, head and neck were not provided skin contact with the cooling vests, yet they were addressed by the ballots. The subjects' perception of their facial temperature and humidity were not significantly influenced by the cooling treatments. Subjects' temperature perception of the back of their head was significantly affected by the cooling treatment, but perception of humidity was not. Subjects' neck temperature perceptions were significantly lower when cooling was worn but this was not found for humidity.

It was hoped that cooling would reduce sweating thereby reducing humidity within the microclimate and in turn reduce fogging the face shield, a serious problem associated with level A suits. Although cooling did significantly reduce microclimate humidity, nevertheless over time humidity reached 85% in the microclimate. Thus both cooling treatments generated less perceived visibility problems for the subjects than the no cooling treatment. However visibility was still poor by the end of the 30-minute test for subjects wearing level A ensembles.

Subjects' evaluation of the design of the prototype vest was generally positive. For all upper body areas subjects reported that vests were adequately tight, not binding and the adjustment capability and zipper closure were convenient features. The subjects also noted that the vest fabric stayed slightly damp. They perceived the prototype cooling vests to provide effective cooling, to be attractive and practical overall. The material used

to construct the vests was perceived to be smooth and the tubing to be flexible. This was true of both types of tubing, although the prototype PA-Al tubing was stiffer than PVC.

5.2. LIMITATIONS

This study was limited to six male fire fighters aged 20 to 42. Only two had actual HazMat experience. All had general HazMat training. The limited number of male subjects does not permit the results to be generalized to all HazMat workers.

Even though care was taken to schedule each subjects' testing at the same time of day, because of subject availability, some of the repeated tests were scheduled at subjects' convenience. Hence subjects' initial temperatures were not constant for every test. This exacerbated to the problem of individual differences.

Although subject size was controlled, yet subjects' height, weight, and body shape caused some subjects to have better contact between the skin and the cooling surface of the vest than others. This may have influenced the data.

The cooling unit used in all testing was a prototype designed as part of the MIPT project to extract, on the average, 180 watts of body heat. The cooling was achieved by a disposable cartridge connected to a water pump that circulated chilled water through the tubes. The target heat dissipation was not achieved during majority of testing and the power of cooling was not consistent from one testing to another due to the cartridge variability. This factor may have influenced the data as well. The heat dissipation during tests that the subjects wore a cooling vest is shown in Appendix G.

The environmental conditions were limited to only one humidity and temperature combination, thus the results cannot be generalized to other environmental conditions. In

fact, it is expected that had the environmental conditions been more severe, additional significant differences would have been found for the dependent variables.

Due to equipment failure some testing had to be repeated and missing data had to be managed. For those data that were severely missing casewise eliminations were performed. When there were enough data to warrant it, data was filled using the built in capabilities of SPSS.

The physical and physiological measurement data was limited by the number of sensors available for the data logging system. More sweat rate and skin temperature sensors would have been helpful in order to assess the cooling effectiveness of the prototype vests in additional body areas.

Core temperatures were measured with a tympanic instrument. Rectal probes would have been provided more complete reliable data.

Sensor placement is important. At the chest area the subjects were instrumented with temperature and sweat rate sensors and a heart rate monitor. This combination may have reduced the contact between the skin and the vest, thus affecting those three sets of data.

The liquid and vapor impermeable level A suit could not be completely closed due to the cables that had to pass through the suit. Thus the suits were not completely airtight.

Although care was taken design the exercise protocol to simulate real activities, nevertheless, the anxiety factor experienced by first responders working a real life incident, could not be duplicated Anxiety would affect the variables of interest.

Finally, subject objectivity could have been jeopardized since the subjects received monetary compensation.

5.3. RECOMMENDATIONS

Keeping in mind the limitations mentioned in the previous section, certain follow up research is recommended.

Gender Differences: The present study did not include female workers. Although the gender thermal perception differences are debatable among scholars (Cheung, McLellan, and Tenaglia, 2000; Cheuvront and Haymes, 2001; Erlandson, Cena, de Dear, Richard and Havenith, 2003) inclusion of female subjects would shed more light into the desired properties of a cooling vest for this population.

Environmental Conditions: The present study was conducted in fairly mild environmental conditions. In order to have an estimate of how different environmental conditions affect the physiological and perceptual variables, additional temperature and humidity conditions should be used and the protocol repeated. This will enable researchers to extrapolate to other temperature and humidity combinations.

PPE: The need for cooling is more crucial in a level A suit than a level B suit. Yet, at the time of testing, the cooling unit was not fully compatible with the encapsulating suit since the level A suit did not have a pass through for the cooling unit tubing. Further study using wireless technology to better test cooling with the level A suit is warranted. At the time of testing the cooling unit was not fully integrated to the encapsulating suit by way of a pass through.

System versus Component Testing: The cooling garment was tested as part of system that included a cooler unit, a cooler vest, an interface between the garment and the cooler unit, and a carrier vast to hold the cooler. A study to evaluate the cooling effectiveness of the *garment alone* would have provided helpful data. Similarly, a study to evaluate the cooler unit would have provided useful data. Both of these proposed studies could have been done on as thermal manikin studies. A manikin test would make it possible to judge the merits of the components of the system separately and to compare the laboratory results to the human subject testing results.

Data collection: Additional temperature, sweat rate and humidity sensors could be used in both in areas of the body where the vest covers the torso and in areas not covered by the vest. This could allow researchers to determine the influence of torso cooling on cooling other body areas.

Acclimization: It is recommended that the subjects be formally heat acclimated. Although all subjects lived and worked in relatively warm climate, providing acclimation is warranted.

Field Testing: Tthe ultimate test that the prototype system should be subjected to is a small scale field test to ascertain the system's usefulness while actual use condition. Feed back from actual users might indicate further design changes in the system or components to improve the system effectiveness.

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APPENDIX A

IRB APPROVAL

**Oklahoma State University
Institutional Review Board**

Protocol Expires: 11/13/2004

Date: Friday, November 14, 2003   IRB Application No   HE0432

Proposal Title: A Physiological Study of Effectiveness of Two Prototype Portable Cooling Vests

Principal
Investigator(s):

Semra Peksoz   Donna Branson
1809 N. Mansfield   431 HES
Stillwater, OK 74074   Stillwater, OK 74078

Reviewed and
Processed as: Full Board

Approval Status Recommended by Reviewer(s): Approved

Dear PI :
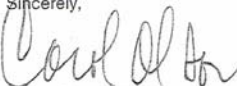
Your IRB application referenced above has been approved for one calendar year. Please make note of the expiration date indicated above. It is the judgment of the reviewers that the rights and welfare of individuals who may be asked to participate in this study will be respected, and that the research will be conducted in a manner consistent with the IRB requirements as outlined in section 45 CFR 46.

As Principal Investigator, it is your responsibility to do the following:

1. Conduct this study exactly as it has been approved. Any modifications to the research protocol must be submitted with the appropriate signatures for IRB approval.
2. Submit a request for continuation if the study extends beyond the approval period of one calendar year. This continuation must receive IRB review and approval before the research can continue.
3. Report any adverse events to the IRB Chair promptly. Adverse events are those which are unanticipated and impact the subjects during the course of this research; and
4. Notify the IRB office in writing when your research project is complete.

Please note that approved projects are subject to monitoring by the IRB. If you have questions about the IRB procedures or need any assistance from the Board, please contact me in 415 Whitehurst (phone: 405-744-5700, colson@okstate.edu).

Sincerely,

Carol Olson, Chair
Institutional Review Board

APPENDIX B

INFORMED CONSENT

I, _____, voluntarily agree to participate in this study

entitled: A <u>Physiological Study of Effectiveness of Two Prototype Cooling Vests</u> which

is sponsored by the Department of Design, Housing, and Merchandising, College of

Human Environmental Sciences through Oklahoma State University, Stillwater, OK.

I understand that the purpose of this study is to compare the physiological and perceptual

responses of subjects wearing two types of personal protective ensembles (PPE) and

prototype personal cooling device, and that testing will involve an exercise program to be

completed in the Environmental Chamber at the Department of Design, Housing, and

Merchandising at Oklahoma State University with each of these PPE and cooling

treatment ensembles.

I understand the procedures for comparing physiological and perceptual responses will

require my participation in the following ways.

    Pre-Test: You will participate in a fit test to determine if you fit the cooling

garment. After passing the fit test, a physical screening to determine you fitness level will

take place. You will be asked to complete a Personal Medical History Survey, which

helps determine the level of fitness test that is appropriate for you. Lastly, you will be

requested to perform a Graded Exercise Test (GXT) to determine your maximal oxygen

consumption (VO_{2max}), and fitness rating. You will be given instructions for preparing for

this test prior to the testing. You will be informed if you fall in the study parameters and

requested to take part in the testing. A trial run of the obstacle course and instructions for

filling out the ballots will be offered.

    Testing: The test is broken into three stages:

1. Preparation: You will be weighed and be asked to sit for ten minutes to allow your heart rate to become stable. You will then be instrumented with a tympanic ear probe, a heart rate monitor, skin temperature thermocouples and sweat rate capsules. After instrumentation you will put on the prototype vest (for the sessions where a vest is to be worn), SCBA, facemask, and the chemical protective suit. The fist temperature and humidity ballot will be administered. Upon completion of the ballot, you will be asked to enter the chamber.

2.Exercise: This stage will last 30 minutes. The complete testing protocol will be provided at the pre-test stage. Temperature and humidity ballots will be administered as soon as you enter the chamber. Afterwards you will go through an obstacle course, twice, which consists of walking on a treadmill at 0% grade, 1.8 and 2.2 mph for a few minutes at a time, manipulating two boxes (15 lb and 10 lb) and carrying one small box (7 lb), manual dexterity activities (screwing on caps and plugs, assembling and disassembling small tools, turning knobs) and climbing a few times, up and down, two steps on a stepladder.
Core temperature, skin temperature and sweat rate will be collected every minute. Temperature and humidity ballots will be administered at the completion of each run of the obstacle course. At the conclusion of the exercise, a comfort and fit ballot will be filled out.

You may terminate the test if you feel you cannot continue. The administrator will terminate the test if one or more of the following conditions occur: (1) your core temperature rises above 38 °C, (2) 90 % of maximum heart rate (=220-age) is attained, (3) your air is low, and (4) you exhibit serious fatigue.

3.Passive recovery: During the recovery, you will be instructed to unzip your suit and remove your facemask and stop the airflow from the air bottle. At a comfortable pace you will remove other equipment including the air tank. The heart rate monitor will remain on until your heart rate reaches below 100 beats per minute while you rest sitting in the chair. At the end of the recovery stage, all thermocouples, tympanic ear probe, and sweat capsules will be removed. You will leave the chamber. This entire exercise protocol will

be completed on six separate occasions while wearing two different PPEs once without and twice with two different prototype-cooling garments.

Post- Testing: You will be offered a liquid replacement drink and asked to fill out the final ballot.

I understand that participating in this study presents the following possible benefits to me: (a) Experience in a research study, (b) knowledge that your input helped develop personal cooling for use in chemical response incidents, and (c) Payment of $100. **Payment is contingent upon completion of all test sessions**.

I understand that:

- **Minimal risks are anticipated by the investigator for participants in this study. Throughout testing process you will be closely monitored for signs of poor blood perfusion (light-headedness, confusion, nausea, ataxia, cyanosis, pallor, cold or clammy skin), signs of significant chest pain, EKG change consistent with ischemia and/or significant rhythm changes and physical manifestations of severe fatigue.**
- **Records of this study will be kept confidential with respect to any written or verbal reports making it impossible to identify me individually.**
- **I can withdraw from this study at any time without negative consequences.**

I have read this informed consent document and understand its contents. I freely consent to participate in this study under the conditions described here. I understand that I will receive a copy of this signed consent form.

Date: _____   Time: _____(a.m./p.m.)

Signed: _____
Signature of Subject

Date: _____   Time: _____(a.m./p.m.)

Signed: _____

Signature of Witness

I certify that I have personally explained all elements of this form to the subject before requesting the subject to sign it.

Signed: _____

Project Director or his/her authorized representative

I may contact the principal investigator, **Semra Peksoz,** at **(405) 624-9315** or via email (semra.peksoz@okstate.edu) should I have any questions or wish further information regarding this research. I also may contact **Dr. Donna Branson** (the advisor of the principal investigator) at telephone number **(405) 744-5035.**

 The following researchers are also involved in this study:

Dr. Huantian Cao

Dr. Cheryl Farr

Dr. Melody Phillips

Dr. Bert Jacobson

Jinhee Nam

APPENDIX C

OKLAHOMA STATE UNIVERSITY
A. B. Harrison Human performance Laboratory

Personal Medical History Survey

Name:_____   Date:_____

Current Address:
Street: _____ City/State: _____ Zip:_____

Phone:_____ E-mail Address: _____

Age:_____Sex:_____ Weight:_____ Height:_____

1. Have you ever been diagnosed as having: (check all that apply)

	Never	**In the past**	**Presently**
A. Heart disease	_____	_____	_____
B. Rheumatic fever	_____	_____	_____
C. High blood pressure	_____	_____	_____
D. Other vascular disorders	_____	_____	_____
E. Diabetes	_____	_____	_____
F. Kidney disease	_____	_____	_____
G. Asthma	_____	_____	_____
H. Allergies	_____	_____	_____
I. Chronic bronchitis	_____	_____	_____
J. Other respiratory illness	_____	_____	_____
K. High serum lipids (cholesterol)	_____	_____	_____
L. Anemia	_____	_____	_____
M. Low blood sugar	_____	_____	_____
N. Neuro-musculo-skeletal disease	_____	_____	_____
O. Sores in mouth	_____	_____	_____
P. Cavities in teeth	_____	_____	_____
Q. Gum disease	_____	_____	_____
R. "Strep" throat	_____	_____	_____
S. Other oral infections	_____	_____	_____

2. Please indicate any surgery that you have undergone and the approximate date(s).

_____
_____
_____
_____
_____

3. Please indicate recent illnesses or major injuries that you have had. Also list approximate dates.

_____

_____

_____

_____

_____

4.   Do you smoke? _____ Packs per day? _____

        Do you use smokeless tobacco (chew or dip)? _____ How often?_____

5. Please list all medications or supplements (prescription and non-prescription) that you are presently taking.

        Medication   Dosage   Duration

_____

_____

_____

_____

_____

6. Describe exercise or activity program.   (Please include: the activity, amount per day, days per week, and length of time you have been exercising at this level)

        Activity   minutes/day   days/week   weeks of exercise

_____

_____

_____

_____

_____   _____
Signature   Date

APPENDIX D

Bruce Treadmill Test

Subject: _____ Age: _____ Wt: _____ (kg)

Resting HR: _____   Age-predicted max HR: _____

Stage	Time (min)	Speed (mph)	Grade (%)	HR (bpm)	RPE	RER	VE (L/min)	VCO$_2$ (L/min)	Absolute VO2 (L/min)	Relative VO2 (ml/kg/min)
Rest	5									
	10									
1	0-1									
	1-2									
	2-3									
2	3-4									
	4-5									
	5-6									
3	6-7									
	7-8									
	8-9									
4	9-10									
	10-11									
	11-12									
5	12-13									
	13-14									
	14-15									
6	15-16									
	16-17									
	17-18									
Cool-down	3 - 5 min									

APPENDIX E

Fitness Test Preparation

Dear Participants,

In order to prepare for the fitness testing and ensure a valid test, please adhere to the following guidelines. If you have any questions or concerns, please contact Dr. Melody D. Phillips at 744-9334 prior to your scheduled test day.

- Do NOT exercise the day **<u>before</u>** or the **<u>day of</u>** testing.

- Do **NOT** drink alcohol on the day **<u>before</u>** or the **<u>day of</u>** testing

- Do **NOT** drink caffeine the **<u>day of</u>** testing

- Do **NOT** eat **<u>2 hours</u>** prior to testing. If your test is in the morning, have a light breakfast (toast & juice) if you so desire.

- Drink as much water as you want.

- Please bring (or wear) clothes for exercise

APPENDIX F

Ballots

TEMPERATURE BALLOT

Please tell me the word that best describes your perception of temperature for the following specific body locations.

	COLD		COOL		NEUTRAL		WARM		HOT		VERY HOT	
FACE												
HEAD												
NECK, FRONT												
NECK, BACK												
CHEST												
UPPER BACK												
ABDOMEN												
LOWER BACK												

HUMIDITY BALLOT

Please tell me the word that best describes your perception of wetness for the following specific body locations.

	DRY		SOMEWHAT DRY		NEUTRAL		SLIGHTLY WET		WET		VERY WET	
FACE												
HEAD												
NECK, FRONT												
NECK, BACK												
CHEST												
UPPER BACK												
ABDOMEN												
LOWER BACK												

VISION AFFECTED BY HUMIDITY

Please rate your visibility through your face piece, shield and chemical protective clothing due to humidity (fogging up).

VERY GOOD	1	2	3	4	5	6	7	8	9	VERY POOR

COMFORT AND FIT BALLOT

The scale below contains adjectives opposite in meaning that describe how the prototype vest and cooling unit feel under your PPE. Please circle the number that best describes the way each item **feels.**

A) PROTOTYPE VEST

LOOSE IN NECK AREA	1	2	3	4	5	6	7	8	9	IN NECK AREA **TIGHT**
AROUND ARMHOLE	1	2	3	4	5	6	7	8	9	AROUND ARMHOLE
IN CHEST AREA	1	2	3	4	5	6	7	8	9	IN CHEST AREA
IN ABDOMEN AREA	1	2	3	4	5	6	7	8	9	IN ABDOMEN AREA
SHOULDER AREA	1	2	3	4	5	6	7	8	9	SHOULDER AREA
SMOOTH IN NECK AREA	1	2	3	4	5	6	7	8	9	IN NECK AREA **ROUGH**
AROUND ARMHOLE	1	2	3	4	5	6	7	8	9	AROUND ARMHOLE
IN CHEST AREA	1	2	3	4	5	6	7	8	9	IN CHEST AREA
IN ABDOMEN AREA	1	2	3	4	5	6	7	8	9	IN ABDOMEN AREA
SHOULDER AREA	1	2	3	4	5	6	7	8	9	SHOULDER AREA
WET IN NECK AREA	1	2	3	4	5	6	7	8	9	IN NECK AREA **DRY**
AROUND ARMHOLE	1	2	3	4	5	6	7	8	9	AROUND ARMHOLE
IN CHEST AREA	1	2	3	4	5	6	7	8	9	IN CHEST AREA
IN ABDOMEN AREA	1	2	3	4	5	6	7	8	9	IN ABDOMEN AREA
SHOULDER AREA	1	2	3	4	5	6	7	8	9	SHOULDER AREA
EASY LENGTH ADJUSTMENT	1	2	3	4	5	6	7	8	9	**DIFFICULT** LENGTH ADJUSTMENT
CONVENIENT ZIPPER CLOSURE	1	2	3	4	5	6	7	8	9	**PROBLEMATIC** ZIPPER CLOSURE
EFFECTIVE COOLING OVERALL	1	2	3	4	5	6	7	8	9	**INEFFECTIVE** COOLING OVERALL
PRACTICAL OVERALL	1	2	3	4	5	6	7	8	9	OVERALL **IMPRACTICAL**
ATTRACTIVE OVERALL	1	2	3	4	5	6	7	8	9	OVERALL **UNATTRACTIVE**
FLEXIBLE OVERALL	1	2	3	4	5	6	7	8	9	OVERALL **STIFF**
EASY DONNING/DOFFING	1	2	3	4	5	6	7	8	9	DONNING/DOFFING **DIFFICULT**
BULKY MANIFOLD	1	2	3	4	5	6	7	8	9	**COMPACT/UNOBTRUSIVE** MANIFOLD
EASY CONNECTING MECHANISM	1	2	3	4	5	6	7	8	9	**DIFFICULT** CONNECTING MECHANISM

B) COOLING UNIT

LIGHT	1	2	3	4	5	6	7	8	9	HEAVY
BALANCED	1	2	3	4	5	6	7	8	9	UNBALANCED
SECURE/ STABLE MINIMUM MOVEMENT	1	2	3	4	5	6	7	8	9	LOOSE/WOBBLY EXCESSIVE MOVEMENT
HAS SHARP EDGES	1	2	3	4	5	6	7	8	9	HAS SMOOTH EDGES

COMMENTS:_____

_____

_____

_____

_____

_____

_____

_____

_____

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_____

_____

_____

_____

_____

_____

APPENDIX G

Wattage Summary for Human Subject Tests

	PVC/ Level A	PE-Al/ Level A	PVC/ Level B	PE-Al/ Level A
Subject 1	78.02091W (9.5gph)	80.89659W (9.5gph)	78.205967W (9.5gph)	91.507W (9.5gph)
Subject 2	147.446W (9.5gph)	130.636W (9.5gph)	138.608W (9.5gph)	126.741W (9.5gph)
Subject 3	87.704W (9.5gph)	93.837W (9.5gph)	92.140W (9.5gph)	80.297W (9.5gph)
Subject 4	146.077W (7.5gph)	130.918W (7.5gph)	77.485W (9.5gph)	115.544W (9.5gph)
Subject 5	118.711W (9.5gph)	135.888W (9.5gph)	112.967W (9.5gph)	123.647W (7.5gph)
Subject 6	241.737W (7.5gph)	237.837W (7.5gph)	100.333W (9.5gph)	114.335W (7.5gph)
Average(W)	136.616	145.823	99.956	108.679

Note: the number in parentheses is the flow rate used in calculation.

V I T A

S E M R A   P E K S O Z

Phone (405) 7443035 • E-mail: semra.peksoz@okstate.edu

Education:

1975-1977 *Bachelor of Science (B.Sc.)*

Department of Civil Engineering, Middle East Technical University, Ankara, Turkey

1977-1979 Master *of Science (M.Sc.)*

Department of Engineering Sciences, Middle East Technical University, Ankara, Turkey

Thesis Title: Statistical Analyses of the Earthquake Occurrences along the North Anatolian Fault

Completed the Requirements for Doctor of Philosophy Degree at Oklahoma State University in July, 2005.

Professional Experience:

2005-present: Assistant Professor, Oklahoma State University, Department of Design Housing and Merchandising
2000- 2004:Graduate Assistant, Oklahoma State University, Department of Design Housing and Merchandising.

Professional Expertise:

AES Sun Protection Hats for Lifeguards: *Project Director: Dr. Donna Branson*
Two comparison studies of two hat designs developed at OSU and Iowa State University were conducted on human subjects and the data obtained were analyzed.
MIPT: Development of Cooling Garments for Terrorism Fighters: *Project Director: Dr. Donna Branson.* Literature review; textile testing program; vest design, pattern making and construction; fit analyses; conducting physiological and perceptual wear trials for doctoral research.
Body Armor: Development of Blast Protective Garments for Limbs: *Co investigator; Project Director: Dr. Donna Branson.* Designed, developed and manufactured three different prototype protective arm and leg coverings for blast protection. Supervised graduate and undergraduate students during production of such garments.

Funded research:

Branson, D., Farr, C. and Peksoz, S. "FSTechnology Body Armor" FSTechnology, $165,000 (2005).

Awards received:

Inventor Recognition Award, OSU, Research week, 2005.

Professional Affiliations:

Kappa Omicron Nu, International Textile and Apparel Association, Phi Kappa Phi. Merchandising and Apparel Design Association