

Personal Cooling System Control Algorithm Development and System Optimization

Final Report
Phase I SBIR
for the performance period
9/01/2007 – 9/30/2008

Grant Funded by NIOSH
Grant Number: 1R43OH009191-01

Work Performed
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A. List of Terms and Abbreviations

NC: no cooling

CC: continuous control, continuous water flow to vest

AC: alternating flow control, changes flow direction every two (2) minutes

PC: pulsed control, cooling systems cycles on and off every two (2) minutes

PPE: personal protective equipment

MSC: microclimate cooling system

VC: vapor-compression

KSU: Kansas State University

USARIEM: U.S. Army Research Institute of Environmental Medicine

SOA: State-of-the-Art

POC: proof-of-concept

Eta: efficiency = output/input

Garment eta: manikin cooling rate / vest cooling rate

COP: Coefficient of Performance = output / input for systems involving cycles (i.e. refrigeration cycles)

Chiller COP: chiller cooling rate / chiller input power

System COP: garment eta * Chiller COP = manikin cooling rate/chiller power

B. Abstract

Wearing level A or B protective suits, the HAZMAT worker is particularly vulnerable to heat stress which results in reduced worker productivity and increased injuries, illnesses, and even death. The program's overall goal is to develop a high-performance personal cooling system, optimized to safely protect workers from heat stress, fatigue, and injury. Presently, existing systems are too large, heavy, and inefficient which precludes wide user acceptance. Existing control systems limit the efficiency of these systems because delivery of cooling to the user is suboptimal, resulting in overcooling or undercooling the user.

This Phase I effort demonstrated the feasibility and benefits of using several new control approaches with a mobile personal cooling system based upon miniature vapor-compression (VC) refrigeration technology. Benefits include delivery of cooling that is more effective for removing heat from the user's body and increases the overall efficiency of the system – enabling longer mission durations and a smaller, more lightweight unit.

Different control approaches were tested using a mobile cooling system which delivered cooling to a thermal manikin by means of a liquid-cooled tubesuit vest. Continuous control (CC) approach was used as a baseline – delivering constant water flow at a fixed supply temperature of 55°F to the vest and maintaining a manikin 'skin' temperature of 82°F. The manikin temperature of 82°F is consistent with previous physiological tests by other researchers using the original CC approach and mobile cooling system. 82°F represents an actual skin temperature at which the skin is overcooled, resulting in severe vasoconstriction which causes significantly increased thermal resistance within the body and a reduction in actual body heat removal by the cooling garment. Tests were conducted for increasing manikin skin temperatures of 82°F (baseline) and 92 and 95°F to imitate gradual reductions in overcooling, skin vasoconstriction, and body thermal resistance. Corresponding to increases in manikin temperature, water delivery temperature setpoints were 55 (baseline), 65, and 68°F, respectively, to result in a constant manikin heat rejection.

The results demonstrate that, by avoiding overcooling of the user along with a new control approach called alternating flow control (AC), up to 54 percent increase in system efficiency can be achieved. The AC control approach changes the direction of water flow through the vest cooling system every 2 minutes. The increased efficiency reduces power draw by 35 percent; thus, for a given battery energy capacity, mission duration increases by 54 percent. Additionally, compressor speed dropped by 39 percent. Similar gains, but to a lesser degree, can also be achieved using the continuous control approach (CC) for the higher manikin skin temperatures. Results from a third approach, pulsed control (PC) -- which turns the cooler on and off every 2 minutes -- were inconclusive.

Designers can use these findings to optimize the system and improve its acceptability to workers. The findings improve performance of the system while, at the same time, reduce system requirements so that smaller, more lightweight and efficient systems may be developed. To achieve these gains over a range of operating conditions, a greater level of control resolution (i.e. besides one or two water delivery setpoints) and better feedback from user (i.e. manual or automatic from physiology) is needed so that overcooling (resulting in low temperatures) can be reduced or eliminated.

In Phase II of this program, the control approaches will be further developed through physiological testing of HAZMAT workers, and a smaller, more lightweight cooling system will be developed, optimized, and integrated within the HAZMAT PPE. It is anticipated that the

NIOSH National Personal Protective Technology Laboratory (NPPTL) will be involved in much of this effort, since increasing human performance and safety and developing fully-integrated, intelligent ensembles for workers is one of the laboratory's strategic objectives [1, 2].

C. Highlights/Significant Findings

This Phase I effort demonstrated the feasibility and benefits of using several new control approaches with a mobile personal cooling system based upon miniature vapor-compression (VC) refrigeration technology. Benefits include delivery of cooling that is more effective for removing heat from the user's body and increases the overall efficiency of the system – enabling longer mission durations and a smaller, more lightweight unit.

The different control approaches were tested using a mobile cooling system which delivered cooling to a thermal manikin by means of a liquid-cooled tubesuit vest. The control approaches included continuous control (CC), alternating flow control (AC), and pulsed control (PC). A baseline was established with continuous control (CC) approach and consisted of delivering a constant continuous flow of water supply at a temperature setpoint of 55°F to the vest and a 82°F manikin 'skin' temperature – representing an actual skin temperature which resulted from previous physiological tests using the original CC approach with the mobile cooling system. Tests were conducted for increasing manikin temperatures from 82°F (baseline) to 92 and 95°F to imitate a reduction in overcooling, skin vasoconstriction, and body thermal resistance. Corresponding to increases in manikin temperature, water delivery temperature setpoints of the cooling unit were also increased from 55 (baseline), 65, and 68°F, respectively, to result in a constant manikin heat rejection. Key results are as follows:

- For CC at 92°F compared to 82°F (baseline), garment efficiency ($\eta = \text{manikin cooling rate} / \text{vest cooling rate}$) rose from 65 to 75 percent, while chiller COP (Coefficient of Performance = $\text{chiller cooling rate} / \text{chiller power}$) increased from 1.30 to 1.48. These garment and chiller efficiency gains result in an overall system COP (= $\text{manikin cooling rate} / \text{chiller power}$) of 1.11 – a 32 percent increase from 0.84 at baseline. This efficiency gain is equivalent to a 24 percent reduction in power draw for a given manikin cooling rate.
- The AC approach changes the direction of water flow every 2 minutes and results in increased overall efficiency by increasing garment efficiency to 85 percent at 95°F manikin temperature. AC approach achieves a system COP of 1.29 – a 54 percent increase compared to baseline. Therefore, for a given manikin cooling rate, chiller power and current draw drop by 35 percent. Additionally, compressor speed has dropped 39 percent -- from 4838 to 2955 rpm. Due to the alternating flow and resulting thermal dynamics within the tubesuit vest, the skin temperature approaches more uniformity under the vest tubing from inlet to outlet compared to the CC approach.
- PC testing was inconclusive. However, analysis and calculations indicate that, when compared to CC approach, some efficiency gains may be possible but unlikely due to off-cycle losses.
- To achieve these gains over a range of operating conditions, a greater level of control resolution (i.e. besides one or two water delivery setpoints) and better feedback from user (i.e. manual or automatic from physiology) are needed so that overcooling (resulting in low temperatures) can be reduced.

In this Phase I effort, the CC and AC approaches have been demonstrated to be feasible. By increasing manikin 'skin' temperature and water delivery temperature setpoints by just 10°F, significant increases in overall system efficiency are achieved due to a cascade of favorable effects for heat transfer between the garment and human body, and for chiller subsystems.

D. Translation of Findings

The Phase I effort proved the feasibility of several control approaches to improve mobile personal cooling systems for workers. These systems need to be as small, lightweight, and efficient (i.e. long mission durations) as possible so that workers will use them. The findings can be used by designers to optimize and improve acceptability of these systems.

Both the continuous control (CC) and alternating flow control (AC) approaches resulted in significantly higher system energy efficiency compared to the original control approach. Furthermore, compressor speed and pressure rise also significantly decreased. These benefits improve performance of the system while, at the same time, reduce system requirements. Specifically, the AC approach achieved the following:

- A system COP of 1.29 – a 54 percent increase compared to baseline. Therefore, for a given manikin cooling rate, chiller power and current draw drop by 35 percent. *Translation:* The mobile system uses a battery. So, for a given battery energy capacity, mission duration would increase by 54 percent. Or, a smaller, more lightweight battery may be used to deliver the mission duration that was achieved with baseline. Or, heat exchangers and flow devices could be made smaller to reduce system size and weight while achieving less of an efficiency gain.
- Additionally, compressor speed has dropped 39 percent -- from 4838 to 2955 rpm. *Translation:* Top speed of the existing compressor is 6500 rpm, and the maximum efficiency is at 4500 rpm. Due to AC approach, the speed is now so low that the existing compressor is oversized. A smaller, more lightweight compressor could be used and significantly reduce the overall system size and weight, since the compressor is the largest component in the system.
- Due to the alternating flow and resulting thermal dynamics within the tubesuit vest, the skin temperature approaches more uniformity under the vest tubing from inlet to outlet compared to the CC approach. *Translation:* This effect may enable a more reliable measurement from a skin temperature sensor for providing automatic feedback to chiller controls during use.
- To achieve these gains over a range of operating conditions, a greater level of control resolution (i.e. besides one or two water delivery setpoints) and better feedback from user (i.e. manual or automatic from physiology) is needed so that overcooling (resulting in low temperatures) can be reduced or eliminated. *Translation:* Technical means of achieving these issues need to be developed.

These same benefits are also applicable for the CC approach but with less of a gain. (However, bullet point #3 is not applicable for CC approach.)

E. Outcomes/Relevance/Impact

Wearing level A or B protective suits, the HAZMAT worker is particularly vulnerable to heat stress which results in reduced worker productivity and increased injuries, illnesses, and even death. The program's overall goal is to develop a high-performance personal cooling system, optimized to safely protect workers from heat stress, fatigue, and injury. Presently, existing systems are too large, heavy, and inefficient which precludes wide user acceptance. Existing control systems limit the efficiency of these systems because delivery of cooling to the user is suboptimal, resulting in overcooling or undercooling the user.

This Phase I effort d the feasibility and demonstrated the benefits of several control approaches to improve mobile personal cooling systems for workers. These systems need to be as small, lightweight, and efficient (i.e. long mission durations) as possible so that workers will use them. Existing control systems limit the efficiency of these systems because delivery of cooling to the user is suboptimal resulting in overcooling or undercooling the user.

The Phase I findings demonstrate that, by reducing or eliminating overcooling to the user, up to 54 percent increase in system efficiency can be achieved with a new control approach called alternating flow control (AC). This control approach changes the direction of water flow through the system every 2 minutes. The increased efficiency reduces power draw by 35 percent. Additionally, compressor speed dropped by 39 percent. Such benefits can also be achieved by the continuous control approach (CC) but with less improvement.

These findings, classified as 'intermediate outcomes', can be used by designers to optimize and improve worker acceptability of these systems. The findings improve performance of the system while, at the same time, reduce system requirements so that smaller, more lightweight and efficient systems may be developed, improving the system's acceptability to the worker. To achieve these gains over a range of operating conditions, a greater level of control resolution (i.e. besides one or two water delivery setpoints) and better feedback from user (i.e. manual or automatic from physiology) is needed so that overcooling (resulting in low temperatures) can be reduced or eliminated.

In Phase II of this program, the control approaches will be further developed through physiological testing of HAZMAT workers, and a smaller, more lightweight cooling system will be developed, optimized, and integrated within the HAZMAT PPE. It is anticipated that the NIOSH National Personal Protective Technology Laboratory (NPPTL) will be involved in much of this effort, since increasing human performance and safety, and developing fully-integrated, intelligent ensembles for workers is one of the laboratory's strategic objectives [1, 2].

F. Scientific Report

F.1 Background

Aspen System's overall goal is to develop and commercialize a high-performance personal cooling system, specifically designed to safely protect commercial and industrial workers from heat stress, fatigue, and injury. Aspen has years of experience in developing man-mountable personal cooling systems for advanced military applications, such as for military Explosive Ordnance Disposal (EOD) as shown in Figure 1. Through this NIOSH SBIR program, Aspen endeavors to leverage this experience towards developing a system suitable for the common worker, like that shown in Figure 2.



NIOSH SBIR Development for Industrial and Commercial Workers

**Figure 1 High Capacity 'Heavy-duty'
Personal Cooler for Military EOD
Applications**

(DEVELOPED)

**Figure 2 Miniature Personal Cooler for
Industrial And Commercial Applications**

(PROPOSED CONCEPT)

In this background section, the importance of such a microclimate cooling system (MCS) is reviewed by considering the causes and severity of heat stress for a variety of worker occupations. To meet this need, a variety of products have been developed with little success and are briefly described. In contrast, Aspen's state-of-the-art (SOA) in chiller technology has great potential to meet this need and is described in detail. Finally, an introduction is given to the importance of the cooling control system and its development in order to deliver efficient cooling to the user – a primary focus of this NIOSH program. Advancing the control system will enable a more energy-efficient system, longer mission durations, and reductions in chiller hardware size and weight. This applied research is critical for advancing personal cooling technology, increasing human performance and safety, and developing fully-integrated, intelligent ensembles for workers -- a strategic objective of the NIOSH National Personal Protective Technology Laboratory (NPPTL) [1, 2].

Heat Stress: A Critical Problem for Workers

Heat stress as a critical problem for workers. Heat stress and fatigue and heat-related injuries, illnesses, and even death are a significant concern for many military, government, industrial, commercial, and medical occupations. Some of these occupations are listed below.

Government

Law Enforcement, SWAT
Explosive Ordinance Disposal
RadWaste Storage Sites
Firefighters

Commercial

Ranchers & Agricultural Workers
Dry Cleaners & Bakeries
Chemical Pesticide Applicators
Landscapers
Kitchen Workers

Medical

Emergency Medical Tech (EMTs)

Industrial

HazMat Workers
Mine Rescue and Safety
Miners in Deep Mines
Nuclear Power Plants
Utility Workers
Construction Workers
Tank Inspection/Repair
Welders, Painters, Sandblasters
Steel Mills, Foundries, oil, gas
Boiler Room Operators
Roofers

Certain occupations expose workers to extreme or hot environments and require them to perform well while enduring physically demanding work tasks and wearing protective gear and clothing. Wearing level A or B protective suits, the HAZMAT worker is particularly vulnerable to heat stress which results in reduced worker productivity and increased injuries, illnesses, and even death. For example, from 1997 to mid-2001, 113 incidents of heat stroke were reported among workers at U.S. government facilities while wearing chemical protective clothing. If left unprotected against heat, workers may jeopardize the safety of themselves or others and also compromise their productivity.

Microclimate Cooling Technologies and Products

Personal cooling systems reduce heat buildup and storage and enhance work performance. Such a cooling system is considered to be a countermeasure for protective clothing such as for EOD and HAZMAT ensembles. Commercially-available cooling products range from simple bandanas filled with water absorbing beads, to ice packs or phase-change vests, to chilled air or liquid systems. One of the most effective portable cooling systems commercially-available is the Personal Ice Cooling System (PICS). This system chills and pumps water from an ice cooler to a tubesuit garment worn by the user.

Although various types of personal cooling systems have been developed and are available commercially, none of these products provide an effective solution to meet the cooling needs of workers, particularly those wearing any type of protective ensemble. Available systems which deliver adequate amounts of body cooling to maintain a safe core body temperature are simply too large and heavy to provide a well-integrated, mobile solution. Furthermore, these systems have simplistic, unintelligent control systems -- limiting cooling effectiveness to the user and resulting in poor overall system energy efficiency and, thus, short mission durations.

Although the existing personal cooling products and technologies fall short of providing adequate cooling, independent studies confirm that vapor-compression refrigeration systems offer the greatest potential to succeed and offer the best combination of advantages. One study was presented at the Microclimate Cooling Conference in 2004 [3]. This study evaluated over 15 different technologies such as vapor-compression, magnetic, evaporative air systems, absorption, ice, chemical reaction, etc. The evaluation used a “top-down” assessment based upon thermodynamics and uniform metrics among the different technologies. Weighted criteria included parameters such as size, weight, logistics, reliability, safety, mission duration, noise, orientation independence, etc. The study concluded that vapor-compression (VC) refrigeration technology is the most-attractive, largely due to its small size, low weight, and high efficiency.

Another study was conducted by Kansas State University (KSU) and used “bottom-up” assessment of available personal cooling products for soldiers [4]. The cooling products included liquid-circulating VC refrigeration systems, liquid-circulating ice-based systems, and forced-air evaporative cooling systems. The study evaluated and tested these cooling systems on sweating manikins and also on human subjects while collecting physiological data. The study concluded that Aspen’s VC refrigeration system performed thermally superior to the other systems but is still too bulky and heavy for soldier applications.

Aspen has developed several different types of wearable mobile personal cooling systems for military applications, all based upon mini-VC technology. These mobile systems comprise 3 subsystems: a chiller, battery, and liquid-cooled vest. Closed-loop liquid cooling (as opposed to closed- or open-loop air cooling) inherently enables designs of chiller unit and garment which are compact, lightweight, highly-controllable, and versatile and is used conveniently within nuclear, chemical, or biological (NCB) environments by naturally and easily integrating with encapsulated body suits without any additional equipment (i.e. inlet air filtration). Additionally, the tubesuit vests (as shown in Figure 3) which are used with the chillers are permeable to perspiration-generated moisture.



Figure 3 Tubesuit Vest

Over the last three years, Aspen developed a high-capacity ‘medium’-sized chiller as shown in Figure 4. Targeted for Explosive Ordnance Disposal (EOD) applications, the chiller unit can be mounted on the thigh (as seen in Figure 1), measures about 3.4” x 6.7” x 8.2” (~188 in³), and weighs about 6.5 lbs. This high-capacity unit achieves superior cooling performance of over 250 W, even for high ambient temperatures of 120°F, often typical for these applications. On the top of the chiller unit is a user interface to power on the system and adjust the cooling temperature setpoint, quick-disconnect fittings to the liquid coolant garment/vest, and an electrical connector for power input from the battery or other power source. The custom-designed rechargeable lithium ion battery may be worn anywhere on the user and provides 124 W-hr of electrical energy, weighs about 1.8 lbs, and measures 30 in³.

Continuing development efforts primarily focus on a reduction of system size and weight, while maintaining substantial cooling capacity and mission duration. As a result of these efforts Aspen recently developed the ‘small’ chiller in Figure 4. This unit is almost half (~ 96 in³ ~ 7.0x5.5x2.5”) the size of the ‘medium’ chiller (mentioned above), weighs about 4.5 lbs (or ~ 6.3 lbs with battery), and produces significantly less noise and vibration. The unit supplies 150 W at 120°F ambient for about 1 hour using one battery and more capacity and duration for lower ambient temperatures.



Figure 4 Progression of Chiller Development Cycles

The small chiller is a scaled-down version and redesign of the medium chiller with some impact to cooling capacity and efficiency. In order to develop an ultra-small, efficient chiller capable of the adequate cooling capacity as the small chiller requires significant technological advances and system optimization.

The control system interfaces with system hardware as shown in the schematic, Figure 5. Worker body heat is transferred to a coolant (i.e. a water-based solution) which is circulated through the garment and chiller by the small pump. An evaporator heat exchanger absorbs heat from the circulating water loop, thus cooling the water. The body heat is ultimately rejected to ambient air which is pulled through the air-cooled condenser by a fan. At the heart of the refrigerant loop/circuit is the compressor which ‘pumps’ or compresses the refrigerant fluid to the condenser for heat rejection and through the rest of the VC system components. The refrigerant working fluid is R-134a which is non-toxic and has zero ozone depletion potential.

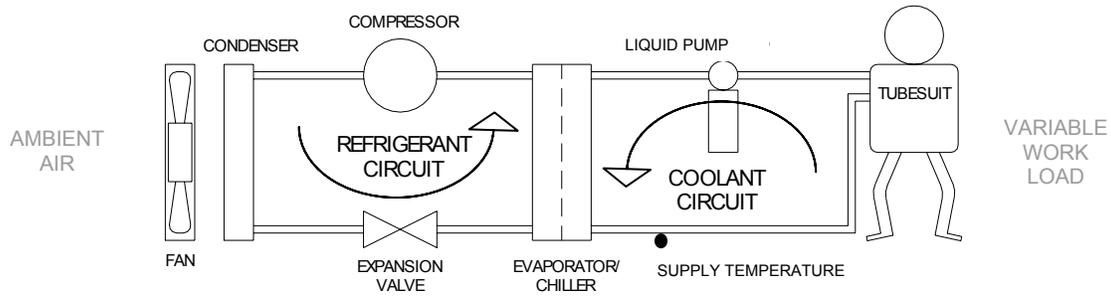


Figure 5 Vapor Compression (VC) Personal Cooling Schematic

The existing control system automatically adjusts the speed of the miniature compressor to maintain the liquid supply delivery temperature at the desired set point (selected by the user). Therefore, while delivering a fixed setpoint, the chiller can respond to changes in cooling load as worker activity changes. Also, the expansion valve meters and controls the liquid refrigerant into the evaporator to achieve efficient performance over a wide range of cooling loads and conditions.

Figure 6 shows the miniature hermetic rotary compressor which stands 3" tall and just over 2" in diameter while weighing about 1 lb. In addition to the compressor, Aspen also developed a new high-performance microchannel evaporator in order to reduce system size and weight and improve manufacturability, durability, reliability, and ease of integration into the small chiller. The new evaporator consists of stacked stainless steel laminates (see Figure 7) which are diffusion-bonded together, resulting in a strong, compact design which weighs about 0.2 lbs. The etched laminates provide thin minichannels (0.018") and microwalls (0.013") which bring the water coolant and refrigerant flows close together, resulting in very high heat transfer rates. These as well as the other component technologies in the system have proven to physically integrate well into low profile packages, as in the small chiller which is Aspen's state-of-the-art.

Although further advances and optimization could be made to the hardware, control system development has received little attention -- particularly as it relates to how effectively cooling is delivered to the user. Heat is removed from the user's body at the interface of cooling vest and user's skin; a liquid water temperature that is too cold may cause vasoconstriction of skin, reduce skin surface temperature, increase body thermal insulation, and, in effect, result in inefficient transfer and removal

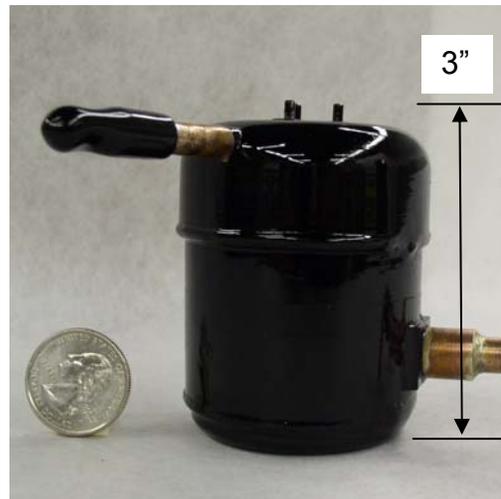


Figure 6 Miniature Hermetic Rotary Compressor

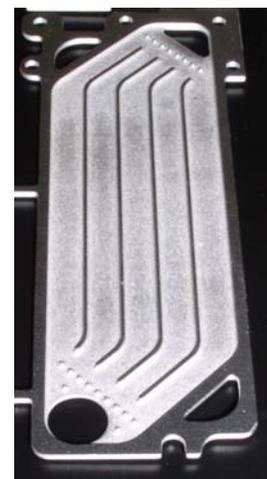


Figure 7 Photochemically-Etched Laminate

of heat from the body to liquid-cooled vest. Furthermore, how much of an adverse impact this has to overall cooling system performance -- particularly to the chiller efficiency and mission duration -- is largely unknown. This subject is the focus of the next section entitled "Cooling Control System: Critical for Effective Cooling Performance".

In retrospect, in order to develop an ultra-small, efficient chiller capable of adequate cooling capacity for the worker requires significant technological advances and system optimization. These technological advancements can be made under this NIOSH SBIR program, starting with improving the control system which is the focus of Phase I. Control system improvements offer the promise of significant system-level payoffs including reductions in size, weight, power draw, and audible noise while increasing efficiency and mission duration.

Cooling Control System: Critical for Effective Cooling Performance

Portable liquid-circulating personal cooling systems consist of three main pieces of hardware: a cooling unit, a tube suit garment, and a portable battery source. Aspen's cooling unit contains a mobile miniature vapor-compression (VC) refrigeration chiller. This chiller delivers cold water through the tube suit worn by the worker. The tube suit garment is typically worn underneath personal protective gear to be in close proximity to skin to remove body heat, providing microclimate cooling for the worker.

Most applied research, at Aspen and elsewhere, has focused on development or improvement of one or more of these three pieces of hardware (or subsystems). However, very little work has been done to advance controls technology of cooling systems – particularly related to the interaction between the subsystems which, most notably, affect the cooling efficiency at the worker (i.e. worker microclimate and physiology) and cooling performance of the chiller.

The factors which affect cooling performance – both for the worker and the chiller -- are multiple: personal protective equipment (PPE), work load/metabolic rate, environmental conditions, design of chiller and garment, and the control system. The control system determines *how and how much* cooling is delivered to the worker and, thus, affects how effective cooling is delivered to the body. Heat is removed from the user's body at the interface of cooling vest and user's skin – affected by controlled variables such as to water coolant temperature and flow rate. The manner in which chilled water is controlled (both its temperature and flow) and delivered to the garment affects worker physiology which, in turn, affects physical productivity, mental clarity and alertness, and safety.

In addition to affecting the quality of worker microclimate, the degree of cooling efficiency at the body also affects the performance of the chiller. Due to the interdependence between chiller design and performance, more efficient cooling extends battery mission duration for the worker to complete his/her task and reduces design requirements (i.e. size, weight, power draw, etc) which can result in a chiller and battery that is less physically burdensome for the worker.

Despite the importance of the system controls, they have received little attention in the industry. The current state-of-the-art (SOA) is continuous control (CC) which delivers a continuous, steady cold water supply at a fixed constant temperature setpoint. For some systems, this setpoint is set at the factory to deliver water at one fixed temperature and cannot be altered. Other systems provide the user with the option of manually-selecting between two or three temperature setpoints, either by some toggle switch or knob. In any case, the worker has very limited control over the cooling they receive, if any, which can cause the worker to make frequent manual adjustments to changing the setpoint, if available, or adjusting his/her clothing (or, worse yet, protective gear) to adjust the microclimate. Thus, worker performance and safety is compromised. This situation is exacerbated for a worker who has a variable work load and will frequently find themselves “overcooled” or “undercooled” and having to manually adjust the system.

“Overcooling” or “undercooling” occurs because there is a suboptimal mismatch between how cooling is being delivered to the garment and what the body physiologically needs for efficient heat rejection from the skin. During overcooling, water delivery temperatures are too cold which causes reduced skin surface temperature, vasoconstriction of blood vessels and

reduction of blood flow, increased body thermal insulation, and, in effect, inefficient transfer and removal of heat from the body core, through the skin, and to the liquid-cooled vest.

In addition to compromising worker productivity and safety, this inefficiency at the garment-skin interface adversely impacts chiller performance and efficiency, affecting mission duration. How much of an adverse impact this has to overall cooling system performance -- particularly to the chiller efficiency and mission duration -- is not well understood. Therefore, this subject is central to this NIOSH program and is of growing interest as people are becoming more aware of its importance.

Some basic research has been conducted on the subject in recent years and has been reported in the literature. The most prominent findings come out of the U.S. Army Research Institute of Environmental Medicine (USARIEM). Reported in a recent paper [5], Caderette *et al.* (2006) studied the physiological response of an exercising worker wearing a cooling garment which used a new control approach called pulsed cooling (PC) (i.e. 2-minutes ‘on’, 2-minutes ‘off’) compared to the traditional continuous cooling (CC) and no cooling (NC). Although there was no significant difference in heat strain between PC and CC approaches, PC approach resulted in maintaining “peripheral cutaneous vasodilation compared to cutaneous vasoconstriction which occurs if the skin is overcooled”. Avoiding skin overcooling and achieving vasodilation results in less body insulation for more efficient heat rejection from the body core to the cooling vest. Unfortunately, the chiller performance was not monitored in this study.

In a subsequent study conducted at USARIEM [6], the chiller performance was measured simultaneously with the physiologic response under similar conditions. This study concluded that the PC approach can lead to significantly more efficient cooling at both the worker and chiller unit without increasing thermal strain to the worker. The PC approach avoids ‘overcooling’ the skin (i.e. vasoconstriction) resulting in inefficient heat rejection from body core to the cooling suit. This study and key results are summarized in the section below.

Additionally, researchers at Kansas State University (KSU) conducted a study [4] which evaluated different cooling systems and tested them on sweating manikins and human subjects while physiologically-monitored. Aspen’s personal cooling system was tested and, although it delivered better cooling performance relative to other systems, the chiller ‘overcools’ the skin, resulting in inefficient cooling delivery and chiller performance. The amount of efficiency that could be gained was not measured, however.

Both Stephenson’s latest work and the KSU report provided the groundwork which led to this NIOSH program. These studies and their results are summarized below.

Study Conducted at U.S. Army Research Institute of Environmental Medicine (USARIEM)

One recent study conducted at USARIEM evaluated the effects of a new control approach on worker physiology and cooling hardware performance [6]. In this study, a pulsed control approach (PC) was compared to a constant cooling approach (CC) using a large stationary cooling system. Physiologic testing was performed with eight men and consisted of the following:

- PPE consisting of HAZMAT chemical protective clothing
- Underneath the PPE, three-piece tubesuit garment covers 72% of body surface area: torso(22%), legs(44%), and head(6%)
- Treadmill Exercise at 1.36 m/s, 2% grade = 225 W-m²; equivalent to 425 W metabolic rate; 80 min
- Ambient temperature = 30°C (86°F)
- Cooling was delivered by a large stationary chiller

Real-time measurements were acquired including core temperature (T_c), local skin temperatures, heart rate, inlet and outlet tubesuit temps, flow, electrical power, metabolic rate.

The new control approach, called pulsed control (PC), pulses the cooled water supply on and off, inducing a thermal dynamic at the garment-body interface. One version of PC control is based on fixed time intervals, turning the system on for 2 minutes and off for 2 minutes. Another version, called PCskin, uses skin temperature feedback to turn on the cooled water supply when the worker's skin temperature exceeded 94.1 °F and off when lower than 92.3 °F. The effects of the pulsed-control approaches (PC and PCskin) were compared to continuous control (CC) and a summary of the results are given below.

The overall 'system' is comprised of both the worker and the chiller. Table 1 presents data related to the worker. Physiological heat strain as measured by core body temperature and heat rate did not statistically differ but remained the same from test to test. The PC approach resulted in the following:

- Higher skin temperatures
- Lower body insulation (or resistance to heat rejection from core to skin surface)
- Lower tubesuit cooling averaged over a cycle

These effects were even higher for PCskin. Although the cycle-averaged tubesuit cooling is lower for the PC approaches, the real-time average cooling rate ('Cooling per minute') when the cooling system is activated ('on-cycle') is higher. This effect is due to the fact that during the off-cycle, the garment is continuing to absorbing heat (although passively) from the body. Then, when the chiller is turned on, the extra heat gain from the off-cycle plus the active heat gain of circulating chilled water during the on-cycle results in high 'Cooling per minute'.

Table 1 Test Results Related to Worker

Control Approaches	Skin Temp (degF)	Body Insulation, R (T_c-T_{skin})/M	Tubesuit cooling, Q (W avg)	Duty Cycle (%)	Cooling per min (W/min)	Inlet Temp* (degF)	Outlet Temp* (degF)	Tubesuit Temp, avg (degF)
CC	89	0.024	253	100	253	70.7	75.9	73.3
PC	91	0.020	196	50	392	72.3	78.8	75.6
PCskin	93	0.016	146	41	356	75.6	80.4	78.0

* temperatures are averaged

Table 2 presents data related to the chiller. For the PC approaches, the less ‘tubesuit cooling’ (cycle-averaged) resulted in less chiller power draw – 25 and 46 percent for PC and PCskin, respectively. Furthermore, the Coefficient of Performance of the chiller (chiller COP = chiller cooling rate / chiller input power) also increased a few points. By applying a heat balance, it can be shown that there is substantial heat loss from the worker to the environment (the difference between the metabolic rate and tubesuit cooling) which increases for the PC approaches.

Table 2 Test Results Related to Chiller

Control Approaches	Metabolic Rate, M (W)	Loss to Environ (W)	Tubesuit cooling, Q (W)	Power, Chiller (W)	Power Reduction (%)	COP, Chiller (-)	COP Increase (%)
CC	425	172	253	224	-	1.13	-
PC	425	229	196	169	25	1.16	3
PCskin	425	279	146	122	46	1.20	6

NOTES: 86 degF ambient

A key factor that contributes to these benefits is the cutaneous vasomotor response due to skin temperature. This topic has been well-studied in humans which shows that skin temperatures below thermoneutral (~91°F) activates vasoconstriction of the cutaneous vasculature, leading to greater body insulation and, thus, resistance to heat rejection from the body to the skin. For skin temperatures slightly above this level, vasoconstriction is inhibited. For even warmer skin, vasodilation occurs leading to increased heat rejection. Therefore, by inducing a thermal dynamic at the garment by pulsing the cooling rate, the skin temperature increased above thermoneutral and garment-body effectiveness was enhanced, thereby, significantly reducing power draw and increasing system hardware efficiency. The higher skin temperatures relative to ambient (86°F) also drove greater heat losses directly from the worker, bypassing the need to be absorbed in the tubesuit. Furthermore, the higher average tubesuit temperatures (76 – 78°F) absorbed less heat from the ambient (86°F) and contributed also to less tubesuit cooling.

Another factor contributing to the large reduction in cooling unit power draw is the thermal dynamics/transients at the cooling unit, although it was not studied in this research since the focus was on the physiological effects. It is important to note that this study did not use a man-mountable cooling unit but one that was larger and stationary with umbilical lines to the garment worn by the worker on a stationary treadmill. If the unit would have been powered by a battery, the battery mission duration would have increased by 33 percent with PC and 85 percent with PCskin resulting from the reduction in power draw! Or, for the same CC power draw, the unit could be made smaller and lighter -- which would be a critical improvement for a portable system.

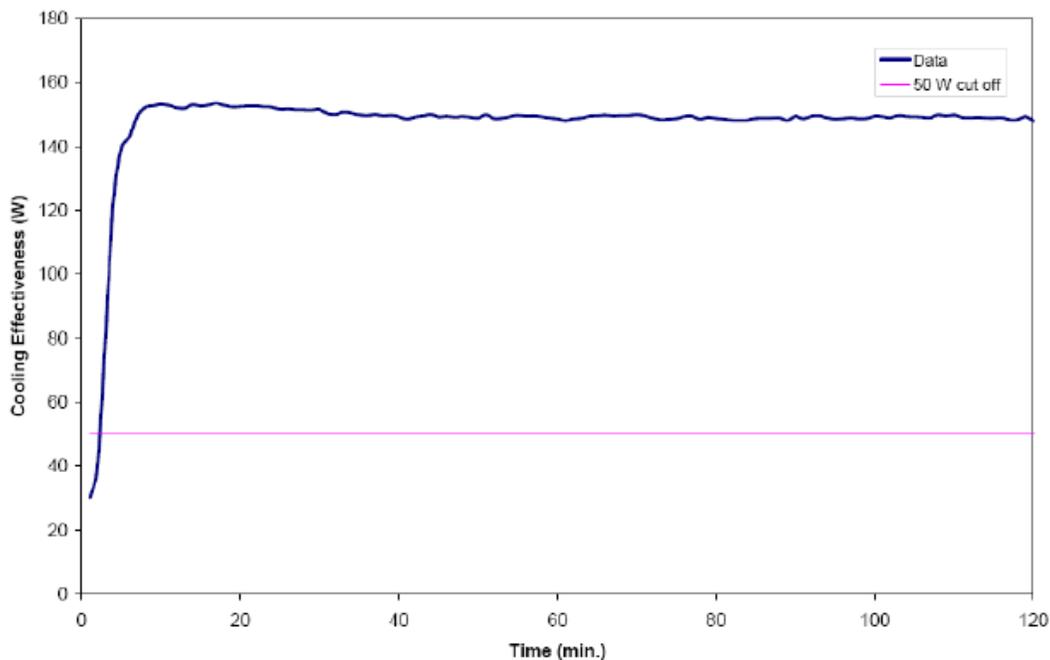
Study Conducted at Kansas State University (KSU)

Another recent study conducted at KSU [4] evaluated the effectiveness of different cooling systems worn on a sweating manikin and on soldiers during exercise. Aspen's cooling system was tested, and results are summarized here.

The environmental conditions for the isothermal sweating manikin tests were controlled as follows

- Manikin surface temperature = 95°F
- Ambient air temperature = 95°F
- Air velocity = 0.3 m/s
- Relative humidity = 40%

Figure 8 presents the real-time cooling rate experienced by the sweating manikin using Aspen's cooling system. At a manikin surface temperature of 95°F, 150W of manikin cooling is achieved for the cooling system at a water supply delivery temperature of 65°F setpoint. Presently, the military believes 150 W of personal cooling for soldiers is adequate [7].



**Figure 8 Manikin Cooling from Aspen's Cooling System
(high cooling setpoint)**

Also, physiologic human subject testing was conducted with soldiers, and adequate cooling was delivered from Aspen's cooling system. Physiologic testing conditions included the following:

- Soldiers fitted with DCU ensemble and helmet
- Underneath the DCU ensemble, a tubesuit cooling vest
- Treadmill Exercise resulting in 350 W metabolic rate; 80 min
- Ambient temperature = 40°F (104°F), relative humidity = 20%, air velocity = 2 m/s
- Cooling was delivered by a Aspen's cooling system worn by the soldiers

Real-time measurements were acquired including core temperature (T_c), local skin temperatures, heart rate, and metabolic rate. Although no chiller parameters were measured, results are still insightful.

Figure 9 shows chest skin temperatures underneath the cooling garment for no cooling system and Aspen's cooling system at two test runs: a 'low cooling' setpoint (a 65°F water delivery temp) and a 'high cooling' setpoint (a 60°F water delivery temp). With Aspen's system, a lower skin temperature of 80°F results from the 'high cooling' setpoint than the 85°F from the 'low cooling' setpoint. These skin temperatures fall well below the thermoneutral skin temperature of 91°F which suggests that the soldier is being 'overcooled' -- vasoconstriction is occurring and leading to more body insulation (i.e. body resistance to rejection of heat) and inefficient delivery of cooling to the body.

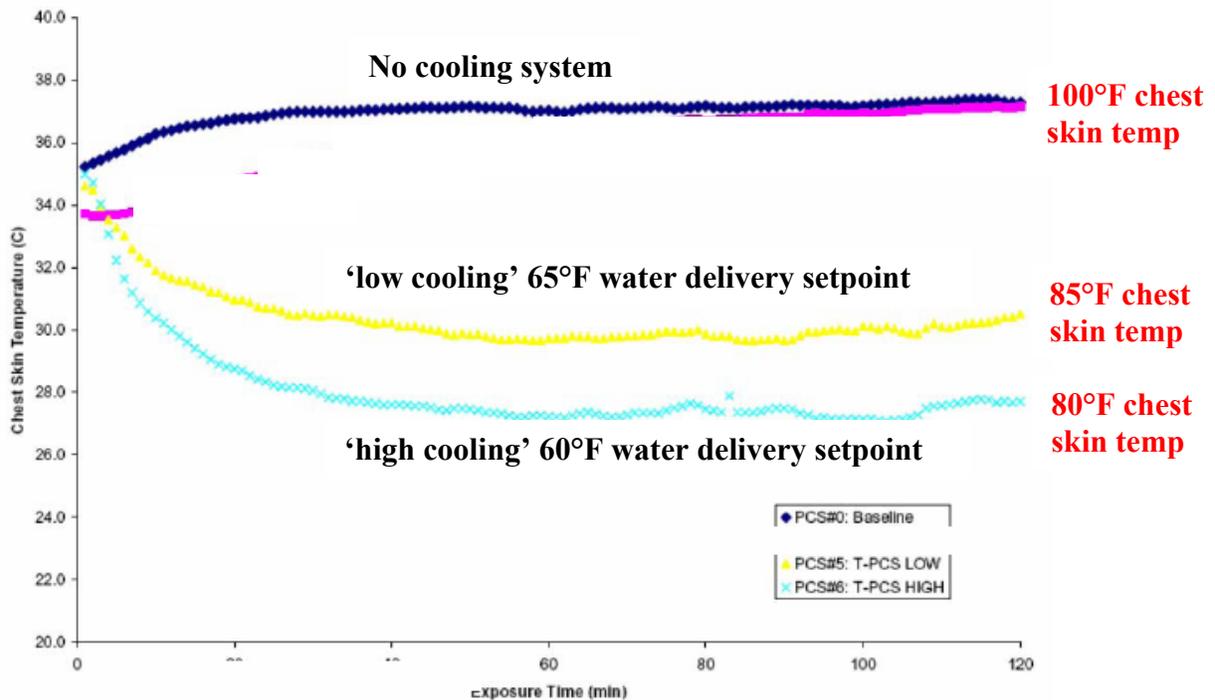


Figure 9 Chest Skin Temperature: No cooling versus Aspen's Cooling System ('high cooling' 60°F and 'low cooling' 65°F water delivery setpoints)

Despite lower skin temperatures and vasoconstriction, adequate cooling is still achieved by Aspen's system and was reported by the researchers as 'superior' in comparison to the other cooling systems. Final core temperatures are not rising for either setpoint and are at a safe level (~100°F) as shown in Figure 10. Nevertheless, it is important to note that the final core temperature is the same between 'high cooling' and 'low cooling' settings for water supply delivery temperature to the garment, despite the fact that at the 'high cooling' setpoint (a 60°F water delivery temp) resulted in a lower skin temperature and more vasoconstriction as compared to the 'low cooling' setpoint (a 65°F water delivery temp).

Achieving the same core temperature at different cooling settings indicates that the 'high cooling' setting is not delivering any more cooling to the body than the 'low cooling' setting. Greater body insulation at the 'high cooling' setpoint resists more heat rejection and results from vasoconstriction due to this overcooling. The extra work performed by the chiller to achieve the 'high cooling' setting (a low 60°F water delivery temp) is wasted energy resulting in system inefficiency. This extra work results from both a lower evaporator temperature (to achieve the low 60°F water delivery temp) and heat losses from the chiller and lines to the 104°F ambient. Unfortunately, the researchers at KSU did not take power measurements from the chiller, so the increased power at the 'high cooling' setpoint was not quantified.

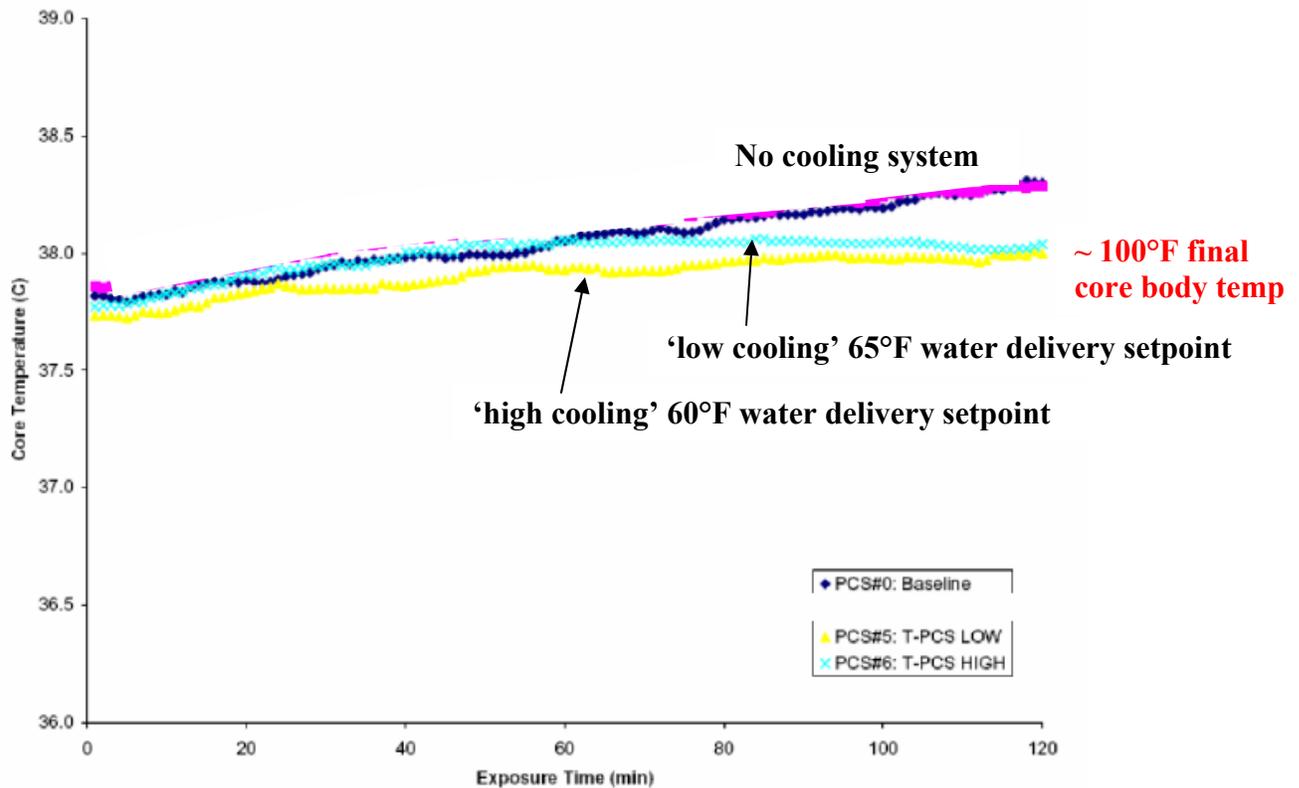


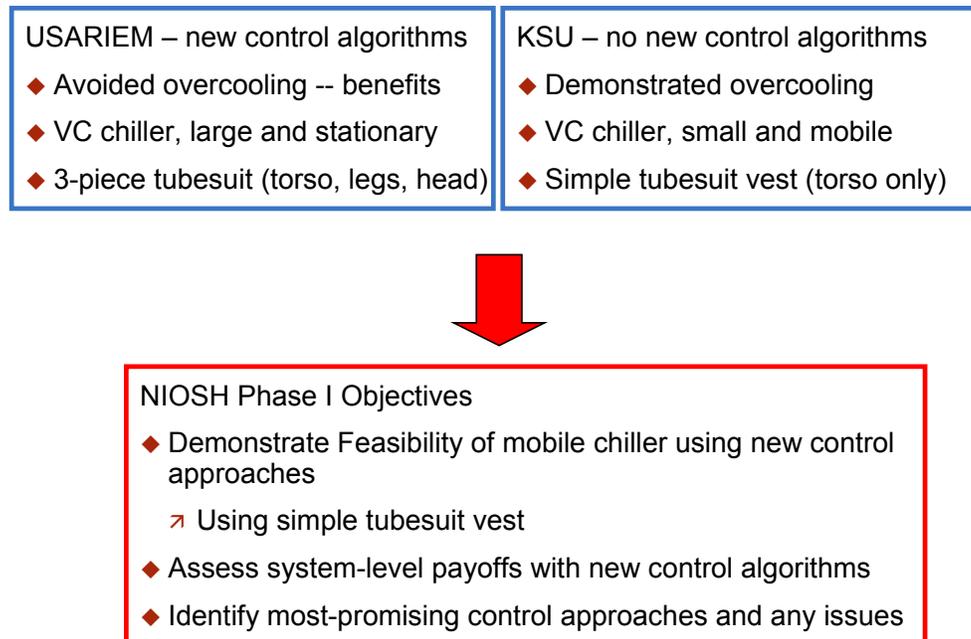
Figure 10 Body Core Temperature: No cooling versus Aspen's Cooling System ('high cooling' 60°F and 'low cooling' 70°F water delivery setpoints)

Summary

Controls development is important because previous studies (summarized on previous pages) show that some control approaches are better than others for delivering cooling efficiently to the user. The KSU study showed that Aspen's small and portable cooling system delivers adequate cooling with the traditional CC controls approach but overcools the skin resulting in low skin temperatures and vasoconstriction and leads to inefficiency. Although two different setpoints delivering different water supply temperatures were tested, each resulted in skin temperatures well below thermoneutral skin temperatures (91°F) but delivered the same final core body temperature. The second setpoint which delivered higher water supply temperatures resulted in higher skin temperatures. These results suggest that more efficient cooling can be delivered to the skin by avoiding overcooling, and, in turn, higher efficiency can result from cooling unit due to higher water delivery temperatures – although the exact amount of inefficiency was not measured for Aspen's mobile VC cooling system and tubesuit vest.

The USARIEM study, using a large stationary VC cooling system and testing users with full-body tubesuits, measured the amount of efficiency gain if overcooling was avoided by using new cooling approaches. The PCskin approach resulted in 46 percent reduction in power draw. If the unit would have been powered by a battery, the battery mission duration would have increased by 85 percent resulting from the reduction in power draw.

As depicted in Figure 11, by leveraging the understanding gained by these previous studies, Aspen demonstrates the feasibility of new control approaches with Aspen's mobile cooling system in this NIOSH SBIR Phase I and quantifies system-level benefits such as efficiency gains. The most-promising control approaches are identified as well as any potential issues.



**Figure 11 Previous Studies Provide Basis for Present Project
(NIOSH SBIR Phase I)**

F.2 Specific Aims

Aspen System's overall goal is to develop, optimize, and commercialize a high-performance wearable personal cooling system, specifically designed to protect commercial and industrial workers from heat stress, fatigue, and injury (as shown in Figure 2). This NIOSH SBIR program provides an opportunity to achieve this goal. To do so, we propose a systems-level development and optimization effort for a cooling system based upon mobile miniature vapor-compression (VC) chiller technology, a battery power source, and a liquid-cooling garment.

A critical area for development and optimization is the control system, which controls how cooling is delivered to the worker. The control system affects overall system performance and operability – the interaction between different components of hardware as well as between the hardware and worker. Control approaches which overcool the worker result in reduced system efficiency and, thus, longer mission duration. Thus, developing control approaches which avoid overcooling the worker and result in efficient system performance is a main goal of the program.

Phase I focuses on the feasibility and development of new control approaches to improve cooling and system performance. Specifically, the aims of the Phase I program were met and include the following:

- The feasibility of several different control approaches were demonstrated through design, analysis, and system breadboard testing of a wearable, mobile cooling system and a thermal manikin.
- System-level payoffs were evaluated using the results from feasibility demonstration.
- The most-promising control approach(es) and any potential issues were identified.

The primary focus in Phase I was the control approaches and their effects using an *actual wearable cooling system* and physically-simulating the thermal interaction between a *garment* and a *human body* by means of a simple thermal manikin wearing a cooling garment in Aspen's Laboratory.

Building on the results of Phase I, Phase II will employ worker physiological testing with human subjects using the new control approaches. We plan to conduct this testing at the NIOSH National Personal Protective Technology Laboratory (NPPTL), while collaborating with Dr. Jon Williams, the senior physiological expert at the laboratory. Furthermore, additional improvements to the whole system, including the hardware design, will be made to develop a fully-optimized personal cooling system in Phase II.

The final outcome of this NIOSH SBIR program will be a personal cooling system which will be small, lightweight, mobile, self-contained, and versatile to accommodate a wide range of worker anthropometrics, activities, and environments. The optimal system design may require a wide range of cooling levels, controllability, and operating time durations. The system will deliver high cooling performance and convenient operability with a user working under a dynamic work load. The system will be well-integrated ergonomically into the worker's protective gear and clothing.

F.3 Procedure

In order to fulfill the aims (in Section F.2 Specific Aims), the Phase I effort was conducted in a series of well-defined tasks. These tasks are itemized and described below. The results led to flushing out methodology detail (section F.4) and in Section F.5 Results and Discussion.

Task 1 Define Requirements

The first task is to define the key requirements for the cooling system to be developed in the program. To do so, worker needs must be understood and then translated into product requirements. This task ensures that the efforts of this program will result in a cooling system that will significantly benefit workers. The following steps were taken:

- 1) Identify the target worker type(s). Worker types were identified that had a high level of cooling need and high number of workers. Another consideration was the ability of the worker (or employer) to pay for a cooling unit.
- 2) Determine functional requirements of the cooling system for the target worker(s). These requirements include worker cooling loads, mission duration, range of environmental conditions, preferred setpoint temperatures, controllability, etc.
- 3) Determine form requirements (size, shape, weight) of the cooling system for the target worker(s). These requirements include anthropometric and integration constraints (in consideration of protective equipment or clothing), any user interface and sensing/controls, lifetime, etc.

Although preliminary, these requirements will be used throughout the program to help guide development efforts and provide performance and design targets for the Phase I effort. These requirements will be refined and completed in Phase II as more information becomes available through further research and worker feedback/interviews.

These requirements are determined by conducting cursory literature research. Additionally, further input is provided by staff from the NIOSH National Personal Protective Technology Laboratory (NPPTL): Dr. John Williams (an experienced physiologist who has run tests with personal cooling systems) and Mr. Bill Haskell (who is experienced with workers and their need for personal cooling).

Task 2 Determine Control Approaches to be Evaluated

The best control/sensing approach is needed to meet user requirements for performance, operability, and other design considerations (i.e. size, weight, etc). In this task, new control/sensing concepts and approaches were considered. Many control/sensing approaches were generated by conducting a brainstorming meeting and exploring other approaches, including those used in other types of systems and applications. The most promising control approaches to be evaluated were downselected and include the following:

- continuous supply-temp control (CC)
- alternating flow control (AF)
- pulsed cooling control (PC)

Detailed descriptions and results of these control approaches are reported in Section F.5 Results and Discussion.

Task 3 Design and Fabricate Laboratory Setup

A system breadboard was designed and built in Aspen's Thermal Laboratory. The system breadboard will consist of the following subsystems: chiller unit, garment-body subsystem (simplified), and control system. The chiller unit is an *actual wearable cooling system*. While the garment-body subsystem physically simulates or approximates the thermal interaction between a *garment* and a *human body* by means of a simple thermal manikin wearing a cooling garment. This hardware setup is detailed further in Section F.4 Methodology.

The chiller unit is an existing unit but modified to be run by the DAQ sensing and control program. The modified chiller was tested in a controlled environmental enclosure (operated to 'ambient' spec) and well instrumented to measure and characterize performance. For example, self-adhesive thermocouples placed on heat exchangers can diagnose quality of two-phase distribution. Real-time pressure and temperature measurements can improve understanding of the sensing/control dynamics and level of effectiveness. The system can then be run and tested with different control/sensing approaches while subjected to different cooling loads and conditions.

This system test stand, although crude for representing garment-body subsystem, is sufficient to achieve our aims for Phase I with primary focus on the control/sensing approach effects on chiller performance and operability while reducing overcooling of the worker. This level of testing provides results to assess and analyze system-level feasibility, payoffs, and drawbacks of the different control/sensing approaches.

Task 4 Test Control/Sensor Approaches

The breadboard system was used to measure the effects of using different control/sensing approaches to avoid overcooling. The chiller operates in the environmental chamber (at 'ambient' spec) while attempting to deliver adequate cooling to the garment which is heated based upon prototypical worker cooling load. Different control/sensing approaches from Task 2 were tested. A baseline was first established using continuous supply temperature (ST) approach while overcooling. Relative to this baseline, the different control approaches and their effects were tested. A detailed test matrix and description is shown in Section F.4 Methodology.

Data from instrumentation, sensors, and controls was saved to a data file for analysis and diagnosis of the system. By running tests back-to-back, we were able to easily compare data from one control approach to another. We want to understand how different control/sensing approaches affect the chiller performance and operability (such as cooling capacity, cooling effectiveness and efficiency, power consumption controllability, and any non-optimal behavior) and if specific approaches easily meet worker requirements. Results will be mapped accordingly and may be attained over a range of conditions. The findings are presented in detail in Section F.5 Results and Discussion.

Task 5 Evaluate System-Level Benefits and Drawbacks

Test results and implications to system-level design and optimization were synthesized in order to evaluate system-level feasibility, benefits, and any drawbacks against the worker requirements. Further design analysis and modeling were conducted to assist in the assessment of feasibility and down-selection of the most-promising control/sensing approaches. The best control approach(es) are to be further developed in Phase II. The findings are presented in detail in Section F.5 Results and Discussion.

F.4 Methodology

The primary focus in Phase I is to evaluate new control approaches and their effects using Aspen's mobile cooling system and physically-simulating the thermal interaction between the tubesuit vest and a human body by means of a simple thermal manikin. Early in the program, the target worker group was determined (HAZMAT workers), and requirements of a cooling system for such an application was established. This provided the context to design the details of the test matrix and fabricate the test setup.

In this section, the test matrix and rationale for its design is introduced. In view of the test matrix, the control approaches and their application are also described in more detail. Then, the fabricated test setup is described along with the simple thermal manikin.

Requirements

Workers in industrial and commercial occupations have unique tasks, conditions, and constraints which must be met for any cooling solution to be acceptable. Furthermore, the diversity of worker anthropometrics and applications requires a versatile system. In order to keep design requirements manageable, this Phase I focused on one worker group which has significant cooling need, market size, and ability to afford purchasing a cooling system.

Hazardous materials (HAZMAT) workers wearing level A and B HAZMAT suits were selected as our target worker group – including first responders and commercial/industrial removal workers – totaling well over 60,000 workers in the U.S. Removal workers held about 38,000 jobs in 2004 [8]. About 8 in 10 were employed in waste management and remediation services. About 1 in 20 were employed in construction, primarily in asbestos abatement and lead abatement. A small number worked at nuclear and electric plants as decommissioning and decontamination workers and radiation safety and decontamination technicians. Firefighters also comprise a large number of HAZMAT response teams – about 24,000 [9] – responding to over 375,000 HAZMAT incidents each year [10].

Initial list of cooling system requirements:

- Cooling rate = 150 – 200 W (for light-to-moderate work activity for HAZMAT)
- Weight = 5 lbs*
- Size = small, low profile to maintain high maneuverability, ability for user to get into tight, narrow spaces *
- Mission duration = 30 min for level A, >>30 minutes for level B*
- Durability = very high, if outside the HAZMAT suit, must be able to withstand acids, corrosives, chemicals, flash fire, soap and water, and dust*
- Integration = ideally integrate with suit, must have an approved PPE pass-through*

* These specifics were determined from focus groups from the following source [11].

To start to develop and optimize a personal cooling system for workers, these initial target requirements will help guide the effort.

Test Matrix and Control Approaches

Results from the test matrix (as shown in Table 3) should indicate what control approaches are feasible and how much benefit can be achieved if overcooling is reduced or eliminated.

Table 3 Test Matrix

Water Delivery Temperature (degF)	Manikin 'Skin' Temperature (degF)		
	82 overcooling	92 overcooling reduced	95 overcooling eliminated
55	CC (baseline)		PC
65		CC	
68			CC, AC

NOTE: Ambient Temperature = 86°F

For each test, two variables will be controlled: the water supply delivery temperature from the chiller and the manikin 'skin' surface temperature. Each manikin temperature was selected purposefully and represents an average of actual human skin temperature under the garment:

- 82°F represents typical overcooling of actual skin for Aspen cooling system (refer to Figure 9 showing physiological overcooled skin measurements of 85 and 80°F)
- 92°F represents reduced overcooling and is just above the physiologic thermoneutral temperature (~ 91°F) below which vasoconstriction occurs. It is rationalized that in actual physiologic tests, some skin temperatures will be higher than this temperature close to the outlet of the garment where water is warmer than at the inlet. Towards the inlet, skin temperatures are most likely lower than 92°F where local overcooling/vasoconstriction is taking place. (more on this topic is described later with Figures 12 and 13).
- 95°F represents no overcooling where in actual physiologic tests no skin temperatures will be below the physiologic thermoneutral temperature (~ 91°F) below which vasoconstriction occurs due to the thermal dynamic caused by the PC and AC approaches (more on this topic is described later with Figures 12 and 13).

Notice that for each test in the matrix the difference between the manikin temperature and the water delivery temperature is a consistent 27°F (except for PC). This should result in same (approximately) heat removal from the manikin for each test. Therefore, the only parameters that are changing substantially are the two independent variables (manikin temperature and water delivery temperature from chiller) – which represent a reduction in overcooling as these temperatures increase -- and the dependent chiller variables (i.e. cooling delivered to vest, power draw, compressor RPM, etc). Therefore, as overcooling is reduced, chiller response can be measured and characterized as control approaches are tested. The ambient temperature of 86°F was chosen to be consistent with the USARIEM study which tested HAZMAT workers, our target worker group.

The five (5) tests in the test matrix represents the minimal number of tests that were actually conducted. In actuality, over 25 tests were conducted. Some of these tests were with the cooling system. The other tests were simply with cold water in order to characterize the manikin after it was first built and conduct pre-tests to understand how the manikin behaved under CC, AC, and PC approaches.

Table 4 provides descriptions of each control approach and its purpose related to the test matrix. Due to the nature of the thermal dynamic induced at the garment-body interface in actual physiologic tests, both the AC and PC approaches have potential to completely eliminate overcooling and any vasoconstriction under the garment. The next page describes this phenomena for AC in detail.

Table 4 Control Approaches

<i>Control Approach</i>	<i>Description</i>	<i>Purpose related to test matrix</i>
Continuous Control (CC)	<ul style="list-style-type: none"> - This traditional control approach delivers a fixed water supply temperature to the garment. - It may be possible that the supply temperature can be adjusted to result in reduced overcooling. 	Establishes baseline at 82°F manikin temp: overcooling
		Use at 92°F: overcooling reduced
		Use at 95°F as baseline for AC and PC
Alternating Flow Control (AC)	<ul style="list-style-type: none"> - This new control approach alternates the coolant flow direction (forward then backward) every 2 minutes without ever turning the system off. - It is likely that this approach will eliminate overcooling completely anywhere under the garment. 	Use at 95°F: overcooling eliminated
Pulsed Control (PC)	<ul style="list-style-type: none"> - This new control approach pulses the cooling rate to the garment by turning the cooling unit on for 2 minutes and off for 2 minutes. - It is likely that this approach will eliminate overcooling completely anywhere under the garment. 	Use at 95°F: overcooling eliminated

Figure 12 presents a hypothetical case of skin temperature distribution along the tubing of cooling vest. The figure depicts how vasoconstriction can impact the heat transfer and temperatures in a local region of the garment. The average skin temperature is about 92°F and the average water temperature is 68°F. The water temperature distribution is the calculated distribution for 150W of cooling for water flow of 500 ml/min. These results are predictions from a simple model that was constructed based upon classical heat exchanger analysis (NTU method) applied to vest cooling a torso where $UA \sim 10 \text{ W/K}$, consistent with actual vest-manikin test results.

These results, although hypothetical, are likely to be caused by the CC approach in actual physiological tests. Incoming water temperature to the garment (position = 0 in the figure) is about 65°F. As the water absorbs heat from the skin, the water warms and rises in temperatures until it exits at about 73°F, absorbing a total of 150W. Between the inlet and almost half-way along the tubing, the skin temperature is cooled below the thermoneutral 91°F and vasoconstriction occurs, resulting in a steep slope in skin temperature distribution along the tubing due to lack of blood flow at skin surface. Above 92°F, vasodilation occurs, resulting in a shallow slope of rising skin temperature due to plenty of blood flow. The average skin temperature over the length of the tubing is about 92°F – which is the test point for the manikin temperature for CC approach in the test matrix (Table 3) – and represents *reduced overcooling* since only a fraction of the garment has overcooling.

If the water flow in the tubes alternates back in forth, as in the AC approach, the thermal dynamic would most-likely *eliminate overcooling* altogether (as seen in Figure 13), avoid any vasoconstriction under the garment, and result in an average skin temperature of 95°F – which is the test point for the manikin temperature for AC approach in the test matrix (Table 3). For the same 150W of cooling as in the CC approach (above), the average water temperature would now increase to 72°F which would improve the cooling system efficiency. For a quick flow reversal every 1 minute or so, the thermal capacitance of the skin layer and vest tubing would dampen much of the temperature fluctuation. Since the model and predictions do not capture thermal capacitance, what is presented in the figure is, therefore, a worst case. Therefore, AC approach shows promise to improve the heat transfer and raise the water inlet temperature by 4 degF, improving chiller COP.

Lastly, the scenario in Figure 1 (CC approach) shows the difficulty of employing one skin temperature sensor to keep the average skin temperature above 92°F. Depending upon where the sensor is, it could read anywhere from 83 to 97°F. The AC approach maintains a relatively uniform skin temperature across the vest and, thus, offers a reliable means of using a single skin temperature sensor to control cooling.

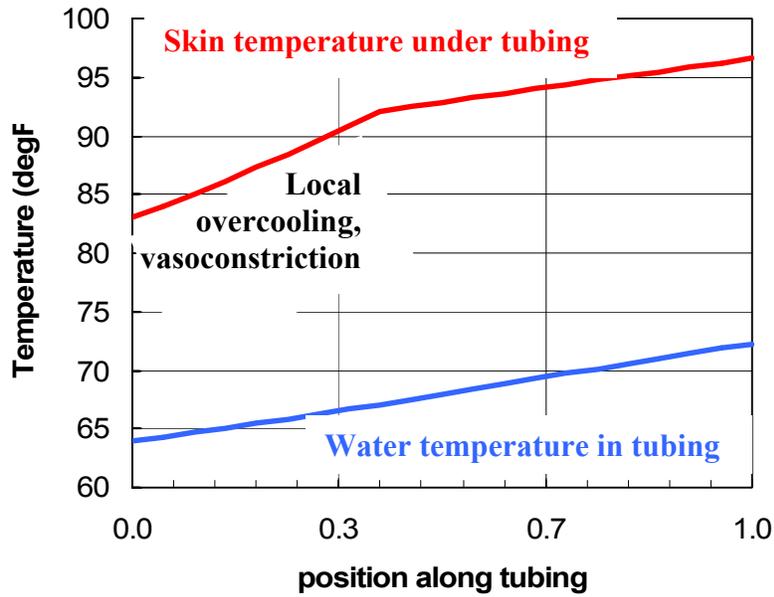


Figure 12 Temperature Distribution along Vest Tubing for CC Approach (Predictions from simple model)

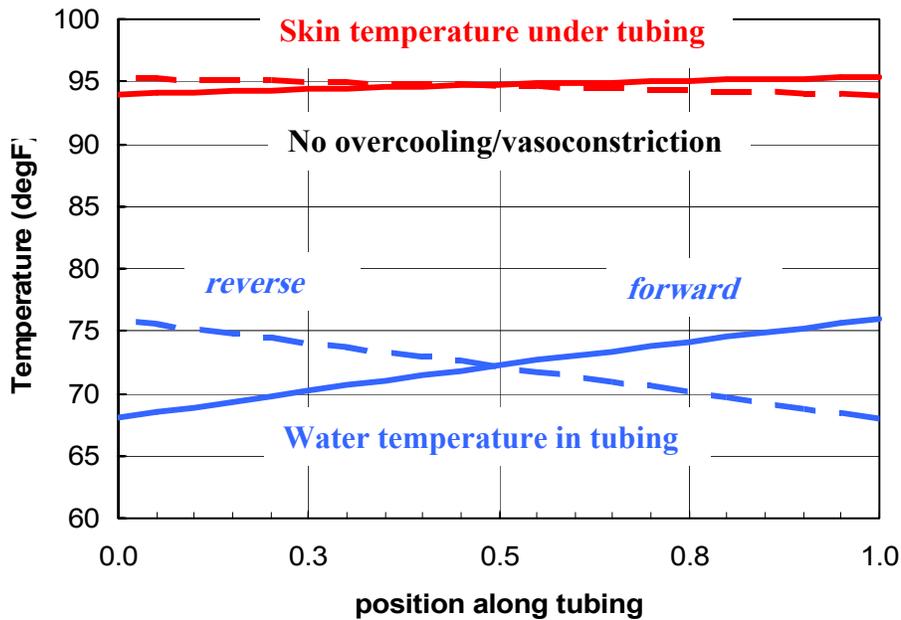


Figure 13 Temperature Distribution along Vest Tubing for AC Approach (Predictions from simple model)

Laboratory Test Setup

A laboratory test setup was designed and fabricated to test our mobile cooling system and new control algorithms. Figure 14 is a photo of the test setup and the different subsystems. The *thermal manikin* is suited with the liquid-circulating cooling vest and is instrumented with heating strips and a grid of temperature thermocouples around the manikin torso. The heaters in the manikin will be controlled to simulate the metabolic activity of the HAZMAT worker during their mission. *Aspen's portable cooling unit* was modified to run the new cooling approaches and control algorithms. The manikin and cooling system are fully instrumented to characterize performance and located within the test chamber.

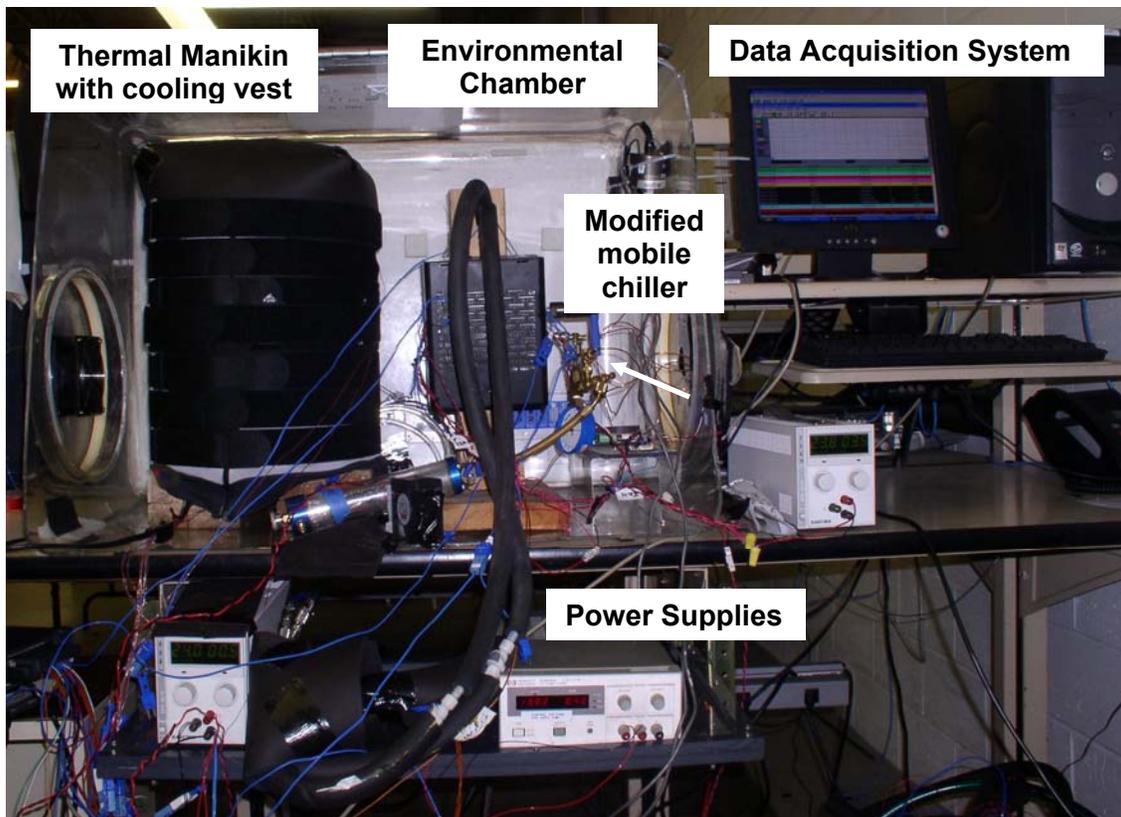
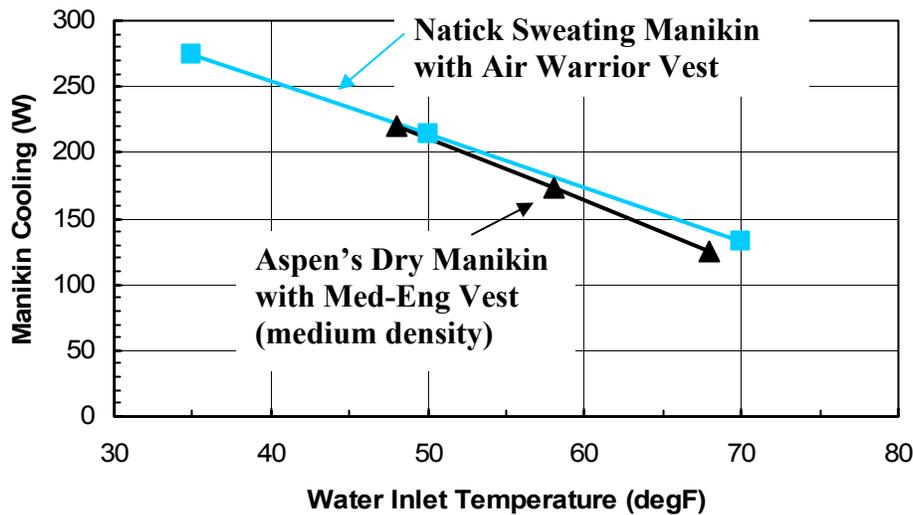


Figure 14 Test Setup

Thermal Manikin

The thermal manikin was designed, constructed, and controlled to approximate performance of a sweating manikin. Figure 15 shows the performance – vest cooling versus inlet water temperature -- of Aspen’s thermal manikin fitted with a tubesuit cooling vest (Med-Eng, medium density) as compared to a sweating manikin fitted with a similar tubesuit cooling vest (Air Warrior vest from Natick Soldier Center). This result verifies that Aspen’s simple manikin performs accurate enough for feasibility testing in Phase I.



**Figure 15 Manikin Cooling Performance:
Aspen’s Dry Manikin Versus Natick’s Sweating Manikin**

The manikin’s design and construction consisted of key design features including

- a torso diameter to snugly fit Aspen’s tubesuit vest (see Figure 16)
- isothermal surface achieved by an aluminum cylinder (see Figure 17)
- internal heating (controllable) achieved by evenly distributed heating strips on the inside of the cylinder (see Figure 18)
- ‘skin’ surface temperature measurements (8 adhesive thermocouples) around the periphery of the manikin torso

The heating power in the manikin was manually-controlled by means of a variac in order to adjust manikin ‘skin’ surface temperatures.



Figure 16 Manikin with Med-Eng Vest



Figure 17 Torso – Aluminum Tube



Figure 18 Internal Heating Strips – Provides Even Heat Distribution

F.5 Results and Discussion

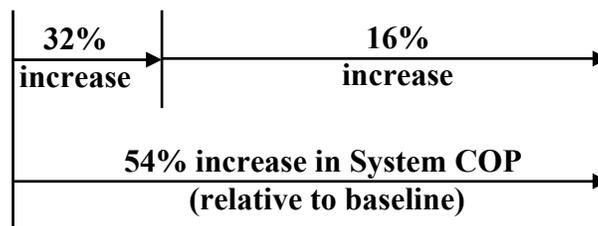
This section reports and discusses the experimental results of testing several control approaches. Some of the discussion will refer back to the previous section *F.4 Methodology* which serves as framework for the testing and the interpretation of results. Results from the *Continuous Control (CC)* and *Alternating Flow Control (AC)* approaches are presented first followed by the *Pulsed Control (PC)* results which were largely inconclusive but call to question feasibility of using PC with Aspen's cooling system.

Table 6 (below) presents test results that support key findings for *Continuous Control (CC)* and *Alternating Flow Control (AF)* approaches and follow the test matrix outlined in Table 4.

Table 6 Summary of Test Data

Test Parameters	Continuous Control (CC)			Alternating Control (AC)	
	Test 1 (baseline)	Test 2	Test 3	Test 4	Test 5
Manikin 'skin' temp (degF)	82	92	95	92	95
Water delivery temp (degF)	55	65	68	65	68
Manikin heater (W)	118	124	125	119	121
Vest Cooling (W)	182	166	162	146	142
Garment Efficiency (%)	65	75	77	82	85
Evaporator Tsat (degF)	40	53	55	55	57
Condenser Tsat (degF)	132	130	128	127	125
HX lift (degF)	92	77	73	72	68
Compressor speed (RPM)	4843	3591	3206	3300	2955
Compressor power (W)	125	97	91	85	79
Chiller power (W)	140	112	106	100	94
Chiller COP	1.30	1.48	1.53	1.46	1.51
Total System COP	0.84	1.11	1.18	1.19	1.29

NOTE: All tests were conducted at 86 degF ambient temperature



Continuous Control (CC) Approach

Test 1 represents the physiological condition where skin temperature is overcooled at 82°F (not uncommon for an Aspen cooling system, see Figure 9). At 55°F water delivery temperature and an ambient temperature of 86°F, 182W is pulled out of the vest by the chiller and is the sum of heat transferred from the manikin and that from ambient air. The amount of heat removed from the manikin is much less, contributing to a garment efficiency of 65% (=manikin heater / vest cooling). Figure 19 shows a heat flow diagram which depicts the direction of heat flows within the manikin-vest subsystem. The heat flows are governed by temperature differences between the nodes and the resistances between the nodes. Increasing temperatures is in the vertical direction. Each resistance has a different value, although they have not been quantified here (illustrative only).

To deliver the low water temperature of 55°F, a low evaporator temperature of 40°F is required, lending to a high chiller power draw and a low chiller COP of 1.3 (= vest cooling / chiller power); the chiller must pump the high 182W of cooling from low evaporator temperature to the high condenser temperature, achieving a high lift of 92°F. An overall measure of efficiency has been defined that combines the efficiency effects of both the chiller and garment -- 'System COP' (=garment efficiency * COP, chiller = manikin heat rejection/chiller power) -- resulting in 0.83. Therefore, low skin and water delivery temperatures result in low efficiencies of the garment and chiller subsystems and the overall system.

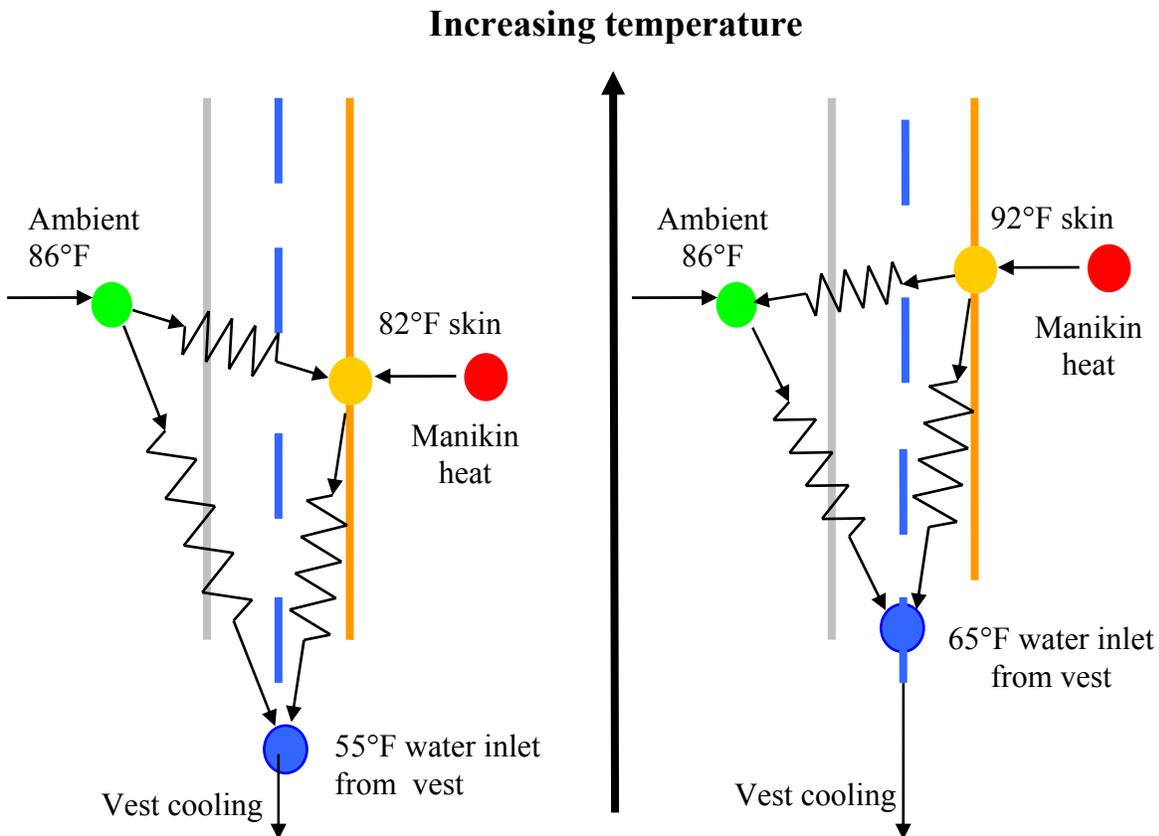


Figure 19 'Test 1' Heat Flows

Figure 20 'Test 2' Heat Flows

By increasing the water delivery setpoint temperature of the chiller from 55 to 65°F (Test 2), the manikin temperature rises to 92°F – representing a thermoneutral physiological temperature that reduces overcooling and vasoconstriction. Under such conditions, the garment and chiller efficiencies increase, resulting in an overall System COP of 1.11 – a 32 percent increase in performance. Chiller power draw is reduced by 20 percent. For a given battery energy capacity, mission duration would increase by 25 percent.

Figure 20 (Test 2) shows a heat flow diagram for this test and can facilitate understanding when contrasted with Figure 19 (Test 1). Garment efficiency has increased because the vest is absorbing less heat from the ambient due to the higher water temperatures in the vest relative to ambient. Less work from the chiller is required due to the lower lift of the heat exchangers (i.e. evaporator and condenser) over which the compressor must pump out the heat (vest cooling load). Less compressor speed is also required due to the lower vest cooling load.

In summary, increasing manikin temperature and water delivery temperature setpoint by just 10°F significantly increases overall system efficiency due to a cascade of favorable effects for garment and chiller subsystems. While increasing efficiency and, in turn, mission duration for a given battery energy capacity, chiller requirements are also reduced (such as compressor speed and capacity) enabling reductions in component sizes and weights. In considering alternative control approaches to improve system performance, the CC approach should not necessarily be abandoned; the level of control (besides one or two water delivery setpoints) and better feedback (manual or automatic) is needed so that overcooling resulting in low temperatures is reduced. Nevertheless, overcooling may not be able to be completely avoided in regions closer to the garment inlet due to inherent temperature glide of the water as it absorbs heat when traveling through the vest, as explained in F.4 Methodology. The 92°F manikin temperature represents an average of what may be experienced in actual physiological tests; due to local vasoconstriction near the inlet of the vest, the average skin temperature may not be able to go higher without incurring unsafe heat strain. The *Alternating Flow Control (AC)* promises to avoid overcooling completely, as discussed below and in F.4 Methodology.

Alternating Flow Control (AC)

By reversing the flow every 2 minutes, the *Alternating Flow Control (AC)* approach improves garment efficiency which, in turn, reduces chiller power and may avoid overcooling altogether, allowing operation at 95°F manikin temperature. Test 5 shows that manikin efficiency increases to 85 percent – a 10 point increase as compared to the CC approach in Test 2; this efficiency gain is due because of the significant reduction in vest cooling needed to maintain the manikin heat rejection. This reduction in vest cooling is reflected in the chiller data where there is a decrease in compressor speed, power draw, and heat exchanger lift. Consequently, System COP increases by 16 percent compared to Test 2. Compared to the overcooled baseline (Test 1), System COP (Test 5) increases by 54 percent – a 35 percent reduction in power draw for equivalent manikin heat rejection (say 120W). For a given battery energy capacity, mission duration increases by 54 percent.

A back-to-back comparison between CC and AC approaches is provided by a comparison between Test 3 and 5 where manikin temperature is 95°F for both tests. Similar trends are experienced but with less magnitude showing an increase of System COP from 1.18 to 1.29, respectively – a 9 percent gain.

The significant reduction in vest cooling with the AC approach is because the thermal dynamic causes less heat loss to ambient. The exact cause of this effect, however, is not well understood.

Figure 21 shows the real-time data of the thermal dynamics over several cycles. Temperature measurements are shown corresponding to the vest water 'inlet' and 'outlet' locations. The 'inlet' and 'outlet' labels correspond to the forward direction. As soon as the flow reverses, warmer water existing the vest now is measured by the 'inlet' temperature location, as seen in the figure during reverse flow (between 4 and 6 minutes).

From this figure, heat flow can also be easily understood as the heat flows from the manikin temperature at 95°F and then to vest water temperatures (between the the 'inlet' and 'outlet' water flow temperatures) and finally to the low-temperature refrigerant in the evaporator. (In this case, the evaporator pressure is roughly approximates the refrigerant temperature in the evaporator.)

In the context of these dynamics, Figure 22 presents the oscillating compressor speed for AC approach and how this compressor speed is significantly lower than that the constant speed from the CC approach. The lower compressor speed in the AC approach is delivering less mass flow due to less cooling demand from the vest, as seen in Table 6. Compared to the CC baseline, compressor speed has dropped 39 percent -- from 4838 to 2955 rpm.

These oscillatory dynamics of temperature in the garment and thermal capacity (from tubing and skin) will tend to even out and flatten the skin temperature distribution under the vest tubing from inlet to outlet. (A detailed description of this effect is described in F.4 Methodology.) Any local vasoconstriction that may have occurred near the cool vest inlet during CC will now be eliminated during AC as flow reverses and warmer water now flows over this region. Eliminating overcooling over all skin regions allows operation at 95°F manikin temperature. Furthermore, the evening and flattening of skin temperature distribution may also enable reliable skin temperature measurements to provide feedback to chiller controls.

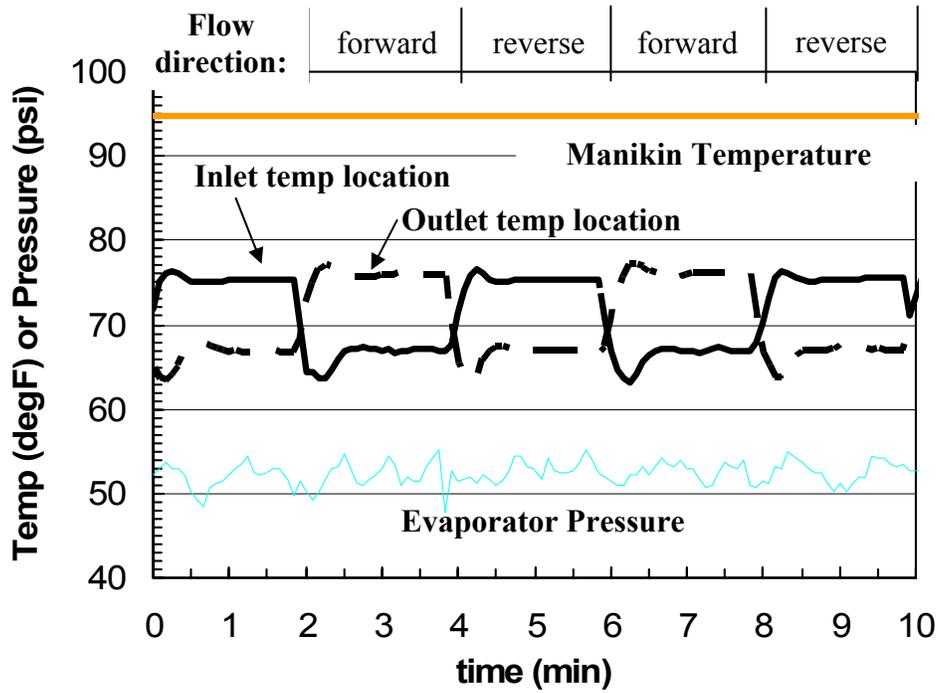


Figure 21 Thermal Dynamics of AC Approach (Test 5)

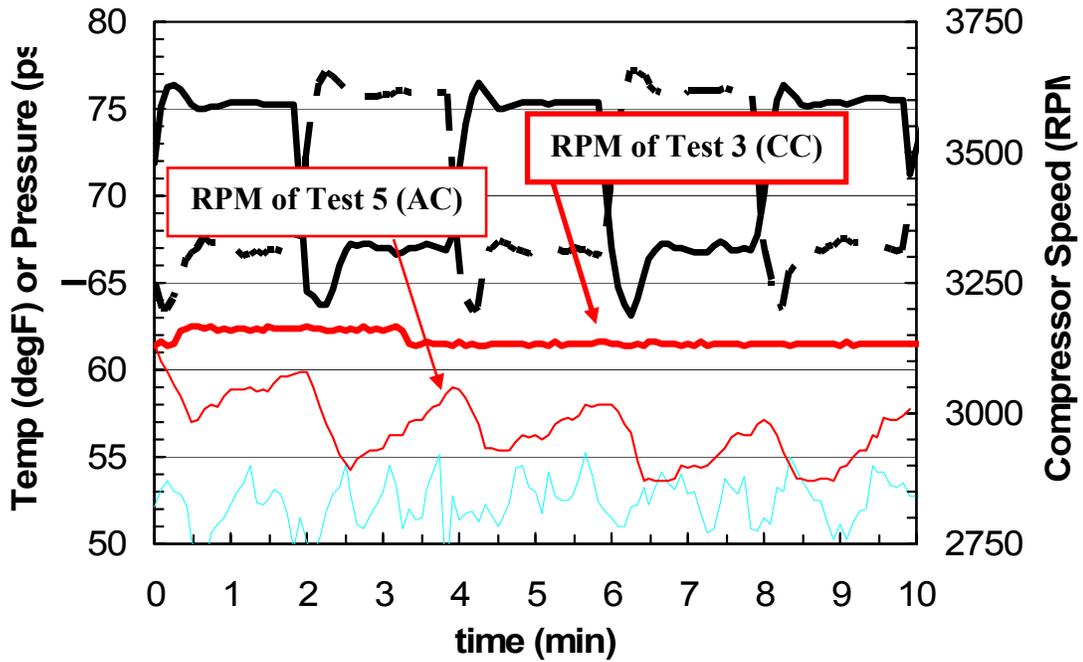


Figure 22 Compressor Speed: AC (Test 5) versus CC (Test 3)

Pulsed Control (PC) Approach

The PC approach requires the chiller to deliver cooling every 4 minutes -- 2 minutes 'on' and 2 minutes 'off'. Attempts were made to operate the chiller to deliver sufficient cooling during the 2 minutes, but these attempts were unsuccessful. The compressor cannot create the large lift (of pressures and temperatures between the condenser and evaporator) fast enough during this time period. Significant off-cycle losses prohibit a rapid pull-down. So, the experimental results were unsuccessful and inconclusive.

However, this does not mean that the Aspen chiller cannot be modified to deliver PC. It simply means that more aggressive changes must be made to the system controls and perhaps hardware. For instance, instead of having the expansion valve open during the off cycle which allows the lift to go to zero, the valve may be closed during the off-cycle to maintain a pressure lift. So when the compressor starts the on-cycle, it does not have to recreate this lift. However, the compressor may need a startup capacitor to overcome the start-up lift pressure.

Despite the unsuccessful tests, preliminary calculations were performed based upon Aspen compressor maps, fundamentals of VC refrigeration cycles, and chilled water tests with the manikin-vest only. The results showed that the PC approach may perform better than the CC approach, but any off-cycle losses may eat away the gains. The analysis also showed that the PC approach would not likely perform better than the AC approach.

Although the chiller did not operate well under the PC approach, vest and manikin testing without the chiller unit but with chilled water reservoir at 55°F was performed using PC approach to understand vest-manikin benefits. Compared to the CC approach with the same water delivery temperature of 55°F, PC increased garment efficiency from 75 to 80 percent. Figure 23 shows the thermal dynamics for this test. In addition to inlet/outlet water temperatures, outside tube temps are measured and absorb heat from manikin during the off cycle. During the 2-minute on-cycle, 267 W (avg) is removed.

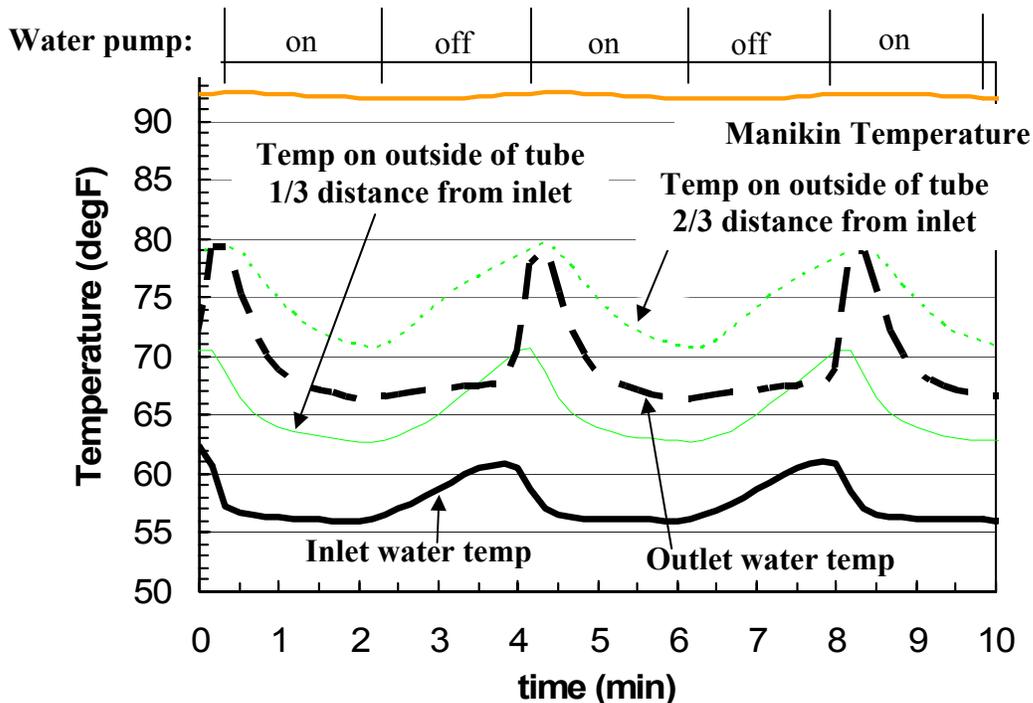


Figure 23 Thermal Dynamics of PC Approach with Chilled Water Reservoir

F.6 Conclusions

Previous studies show that some control approaches are better than others for delivering cooling efficiently to the worker – benefiting both the worker microclimate and cooling system efficiency. This Phase I effort demonstrated the feasibility and benefits of using several new control approaches with a mobile personal cooling system based upon miniature VC refrigeration technology. Benefits include delivery of cooling that is more effective for removing heat from the user's body and increases the overall efficiency of the system – enabling longer mission durations and a smaller, more lightweight cooling system.

The different control approaches were tested with a mobile cooling system delivering cooling to a thermal manikin by means of a liquid-cooled tubesuit vest. A baseline was established with continuous control (CC) approach and consisted of delivering a constant continuous flow of water supply at a temperature setpoint of 55°F to the vest and a 82°F manikin 'skin' temperature – representing an actual skin temperature which resulted from previous physiological tests using the original CC approach with the mobile cooling system. Data was taken for increasing temperatures from 82°F (baseline) to 92 and 95°F to imitate the reduction in skin vasoconstriction and body thermal resistance. Water delivery temperature setpoints were also increased to result in a constant manikin heat rejection.

For CC at 92°F compared to 82°F (baseline), garment efficiency (η = manikin cooling rate/vest cooling rate) rose from 65 to 75 percent, while chiller COP (Coefficient of Performance = chiller cooling rate/chiller power) increased from 1.30 to 1.48. These garment and chiller efficiency gains result in an overall system COP (= manikin cooling rate/chiller power) of 1.11 – a 32 percent increase from 0.84 at baseline. The AC approach which changes flow direction every 2 minutes further increases overall efficiency by increasing garment efficiency to 85 percent at 95°F manikin temperatures. AC approach achieves a system COP of 1.29 – a 54 percent increase compared to baseline. Therefore, for a given manikin cooling rate, chiller power and current draw drop by 35 percent resulting in increased mission duration of 54 percent for a given battery energy capacity.

PC testing which turns the chiller off and on every 2 minutes was inconclusive. However, analysis and calculations indicate that, when compared to CC approach, some efficiency gains may be possible but unlikely due to off-cycle losses.

In this Phase I effort, the CC and AC approaches have been demonstrated to be feasible. By increasing manikin 'skin' temperature and water delivery temperature setpoints by just 10°F, significant increases in overall system efficiency are achieved due to a cascade of favorable effects for garment and chiller subsystems. While increasing efficiency and, in turn, mission duration for a given battery energy capacity, chiller requirements are also reduced (such as compressor speed and capacity) enabling reductions in component sizes and weights. Further reductions in size and weight could be achieved with less efficiency gains.

A greater level of control resolution (i.e. besides one or two water delivery setpoints) and better feedback from user (i.e. manual or automatic from physiology) is needed so that overcooling (resulting in low temperatures) can be reduced. Although local overcooling may not be able to be completely eliminated with CC, the AC approach may avoid overcooling completely since the alternating flow tends to even out and flatten the skin temperature distribution under the vest tubing from inlet to outlet. This effect from AC approach may also enable a more reliable measurement from a skin temperature sensor for providing automatic feedback to chiller controls during use.

G. Publications

None.

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