Document Title: Improved Thermal Control Body Armor

Author(s): Paul J. Biermann

Document No.: 209607

Date Received: May 2005

Award Number: 2000-RD-CX-K004

Grantee: Johns Hopkins University – Applied Physics Laboratory
Agency Grant Number: 2001-RD-CX-K004
Report No.: ?
Implementing Subgrantee: ?
Reporting Period: 1/1/2002 – 6/30/2003
Short Title of Project: Improved Thermal Control Body Armor
Grant Amount: $199,560
Type of Report: Regular
Name and Title of Project Director: Paul J. Biermann, Senior Member Professional Staff

Signature: ______________________
Date: 7/30/03
As of June 27th, we have expended $185.4K out of $199.5K or approx. 93% of the funding.

Background

The background information relevant to this program is contained in Appendix 1.

Program Task Summary

The following task descriptions are taken from the original proposal. Changes, if any, are noted in the progress section for each task.

Design Development, Analysis and Trade-Off Study (Task 1)

A current review of thermal mitigation technology will be conducted to avoid duplication of effort and to integrate the latest results into this program (Task 2). During the initial design portion of the program, mechanical requirements, thermal design, and prototype fabrication of a modular thermal control system will be investigated (Task 3). A simplified thermal model will be used along with actual thermal test data from multiple volunteers wearing a soft body armor equipped with a thermocouple data logger to provide a performance baseline (Task 5). The model as modified by the initial thermal testing will provide a baseline standard against which material combinations should be tested (Task 4).

Physical specimens for material characterization will be designed (Task 6) based on the initial data collected and the initial list of candidate materials will be reduced during a down selection process (Task 7).

Fabrication and Testing of Representative Material (Task 8)

Test coupons representative of the critical thermal interfaces will be fabricated and tested. At least six samples will be tested for each configuration to show statistical variations in materials and fabrication (Task 9, 10). These tests will model the system to determine thermal transfer capability under different boundary conditions. Boundary condition variables include heat flux from the test subject's body, volume of moisture or sweat produced by the officer over the sample area, and external air temperature and humidity.

Fabrication and Testing of Initial Prototype

The best candidates (Task 11) will be fabricated into a full-scale prototype and tested on volunteers with the data logger for comparison with the baseline data collected previously (Task 12). If required, the sequence of subscale and/or full-scale prototype fabrication will be performed iteratively to improve and optimize the results (Task 13, 14).

Progress

Task 1 – Heat and Moisture Mitigation

Due to unforeseen delays associated with receiving approval from the JCCI (Joint Committee on Clinical Investigation (The Institutional Review Board for the Johns Hopkins University School of Medicine (JHUSOM)) to conduct tests involving human subjects, the entire program effort did not actively start until mid February, a delay of 20 weeks beyond award of contract funding. We adjusted our schedule to show beginning of work at February 15, 2002.

Task 2 – Technology Assessment

This task is completed, although we are continuing to update our files and look for other applicable technology that can be adapted or inserted into this program.

A literature/patent search was performed that resulted in 43 articles being obtained on heat transfer, moisture wicking and mass transport of water in fabrics (Appendix 2). These articles also include the experimental and analytical/numerical modeling as well as current fabrics used.

Task 3 – Initial Design and Materials Selection

This task was completed with the exception of the carbon fiber / conductive materials selection. This delay in choosing those materials has had limited negative effects on other program tasks as of this time.

Moisture wicking materials have been researched and vendors were contacted to obtain test materials. Not all of the fiber manufacturers produce finished woven or knitted products, so contacts had to be established with fabric suppliers to obtain materials. We have obtained the following materials for testing:

Table 1 - Fabrics to be tested

Manufacturer	Material	Description
Intera Corporation	Intera	Fabric style I-301
Rockywoods Fabrics	Dupont Coolmax®	Open Mesh #8526
Rockywoods Fabrics	Dupont Coolmax®	Grid Knit #49241
Rockywoods Fabrics	Fabrictex Wickaway®	Jersey #46970
Rockywoods Fabrics	Hydrolon®	Performance Knit #8294
Faytex		Drilex®
Faytex		Aero Spacer Drilex®
Aquatex	Hydroweave®	2 fabric combination types

This gives us a current total of nine fabric samples. Carbon fiber was to be selected once preliminary data had been run through the thermal model.

Task 4 - Thermal Model Construction:

This task was scheduled to be completed in early February 2003 at the completion of year 1 funding. It required output data from Tasks 10 and 11. Due to laboratory material testing apparatus difficulties, these tasks were delayed and that resulted in the postponement of the thermal modeling task until further funding is received. The thermal modeling task is detailed below, but has not been executed. The subcontract was closed out without any activities being conducted by UC Berkeley. It can be reinstated after the necessary data is generated to provide the input for the thermal model.

Several models have been proposed to study human thermoregulation from one-dimensional to three-dimensional. However, the two models most often used by other investigators are the 21-Node Man and the Wissler models. These are one-dimensional finite difference models that include as input: weight, mean skin fold thickness, dry bulb temperature, dew point, wet bulb temperature or relative humidity, black globe temperature, wind speed, pressure, gas or liquid, (if gas other than air, give the composition,) metabolic rate, kind of work, such as walking, standing, sitting, bicycling and kind of clothing worn on each element of the body. In the Wissler model, the water absorption and thermal conductivity must be experimentally measured and inserted in the model. However in either of these models only moisture wicking through the thickness of the fabric is considered, there is no path provided for water transport in the vertical direction (direction of gravity). In our vest, once the moisture has wicked through the fabric, this would be the primary path for mass transport. Therefore, we considered a simple two or three-dimensional model using a finite difference code. The model would consider conduction, convection, and radiation of heat as well as mass flow between parts of the model such as inside to outside of soft body armor. Experimental data would be used to verify the model.

After reviewing our modeling ideas with Richard R. Gonzalez, Ph.D., Chief of Biophysics & Biomedical Modeling Division at USARIEM, Natick, we accepted his suggestion that we contact Dr. Charlie Huizenga at University of California at Berkeley (UCB) to see if we could use a model they have already developed. This resulted in a subcontract to UCB to cover the following:

The Center for Environmental Design Research at UCB has developed an advanced model of the human thermal regulatory system that is capable of predicting the thermal state of the body based on clothing, metabolic activity, and environmental conditions. The objective of this subcontract is to use the Berkeley Comfort Model to estimate the effect of the JHU/APL overvest under a range of environmental and metabolic conditions.

Subcontract Task 1. Establish the effects of a traditional soft armor vest on thermal stress. Simulations will be performed with the Berkeley Comfort model under four environmental conditions (cool, warm, hot/humid, hot/dry), three metabolic rates (standing, walking, running/highly active), and two sets of clothing (with and without a standard soft armor vest). Results will include core and skin temperatures for each condition. JHU/APL will provide data on standard clothing worn with the soft body armor and an estimation of the thermal insulation of the soft body armor.

Subcontract Task 2. Develop a modeling method for the JHU/APL vest. UCB will work with JHU/APL to develop an equivalent thermal conductance and moisture conductance for the JHU/APL vest. JHU/APL will provide laboratory measurements made on the vest as well as physiological measurements made from a human subject. If possible, core and skin temperature data will be provided for the human subject wearing the JHU/APL vest and wearing a standard soft body armor.

Subcontract Task 3. Repeat the simulations of Task 1 using the model developed in Subcontract Task 2.

Subcontract Task 4. Prepare a short report that describes the results of the model predictions, estimates the effectiveness of the JHU/APL vest, and identifies potential areas to improve the performance of the vest.

Again, this subcontract was closed out without execution of any activities until the necessary input data can be generated.

Task 5 – Baseline Thermal Data Collection:

This task is completed. In late August, 2002, TSM began testing on human volunteers for the Improved Thermal Control Soft Body Armor Program (DMK01XXX). The approach was taken to have a series of instrumented volunteers undergo an exercise regime without soft body armor (control), with soft body armor, and with soft body armor modified with the thermal/moisture wicking material. Human testing issues were discussed and the decision was made to conduct the initial tests using volunteers from outside law enforcement to increase availability and minimize scheduling difficulties. Several volunteers were selected that provide a wide range of health ranges but were screened to insure they were healthy enough for the exercise. Law enforcement volunteers will be sought for the next stage when the initial prototype solutions have been selected and input from end users will have more immediate value.

Test Methodology

SUBJECTS

Three healthy males, all amateur cyclists, volunteered for the study. The subjects were informed of the purpose, procedures, and risks of the study and affirmed their understanding of the study by signing a statement of informed consent as approved by the JHUSOM IRB.

The three subjects were assigned the appellations A, C, and D to conceal their identities. Subject A was 44 years old, weighed 172 pounds and taught stationary bicycling classes three times a week. Subject C was 56 years old, weighed 235 pounds, and participated in weekly rides as well as long-distance events. Subject D was 37 years old, weighed 190 pounds, and also took weekly medium distance rides. The researchers requested that the subjects not make any lifestyle or exercise changes for the duration of the testing series.

TEST CONDITIONS

For this study, the subjects were asked to ride a stationary bike (Cateye® Ergociser EC-1600) for a 34 minute period. This included an initial four minute "warm-up" period immediately followed by the 30 minute test. An exercise bicycle was chosen to provide a highly regulated method of exercising the participants. Initially, the volunteers were required to pedal under constant power, but due to variations seen as a function of each volunteer's physical conditioning it was decided to change the fixed variable to constant heart rate. To further remove variables, we conducted the baseline testing under controlled exertion conditions by having the test subjects ride an exercise bike in a room where we could control the temperature and humidity.

Test conditions consisted of a constant pedal rate with varying pedal resistance influenced by the subject's heart (or pulse) rate. The riders were asked to maintain a pedal rate of 80 rpm during the entire test. As the subjects exercised, the bike monitored their pulse rate. If their pulse rate was lower than the target rate determined prior to testing, the pedal resistance would increase in an effort to increase the subject's work output. Conversely, the Ergociser adjusted to a rider with a heart rate that was higher than the specified target rate by reducing the tension on the pedals, thus lowering the work output and reducing heart rate.

The calculated target heart rate (HR_T) was based on 70% of the subject-specific maximum estimated heart rate (HR_M) during safe exercise. This value was calculated using the formula

$$HR_T = HR_M \times 0.70 = (220 - \text{age}) \times 0.70 \ \text{[bpm]}$$

The target heart rate is calculated for each subject and displayed in Table 2.

Table 2 - Subject target heart rate (HR_T).

SUBJECT	AGE (yrs)	HR_T (bpm)
A	44	123
C	56	115
D	37	128

Subjects participated in a cycling test usually twice a week and always in the morning hours. The subjects were asked to cycle under three different testing conditions: no body armor, body armor, and body armor lined with moisture wicking material. During these tests, temperature and humidity data was collected from sensors attached to a shirt at various locations on the torso. Pulse rate was measured by a sensor attached to the earlobe and core body temperature readings (Braun® Thermoscan) were calculated based on temperature taken from the ear canal. Headphones were worn during the test to isolate the ear canal from the external environment. Body weight measurements were taken before and after each test.

Instrumentation

The exercise bike, data collection equipment, and sensors were specified, ordered, and tested for correct operation (Figure 1 and Figure 2). The sensors were mounted to jerseys and testing started in August, 2002.

Figure 1 - Ergocizer Bicycle

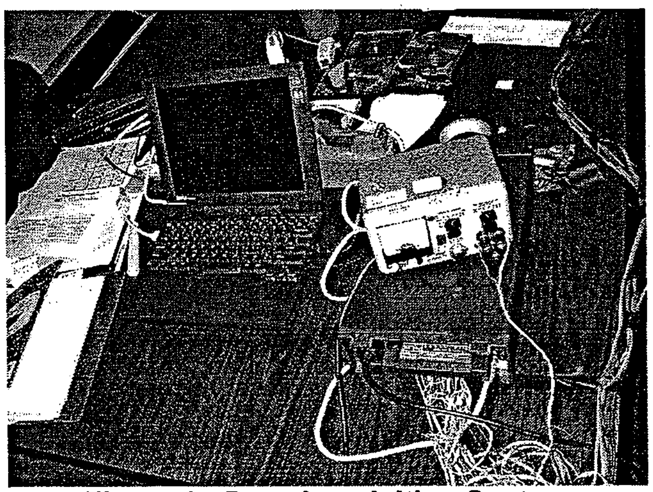


Figure 2 - Data Acquisition System
Computer, NetDAQ, and Relative humidity Power Supply

Since comfort of the subject while wearing soft body armor (vest) was the objective of the program, it was decided to monitor temperature and humidity between the vest and the subject. Both measurements were inexpensive, yet quick and simple to collect. Stranded 26 gauge T-type thermocouples were used to monitor temperature since they provided the most accuracy over the required range yet were flexible enough to not constrict the wearer. Humidity was monitored with Honeywell model HIH-3610-004 sensors. Several were purchased with NIST calibration and the remainder used standard humidity equations. All humidity sensors were temperature and power supply compensated via equations.

Table 3 - Thermal Vest Instrumentation

Measure	Sensor	Range	Resolution	Accuracy	Power Requirements
Humidity	Honeywell HIH-3610-004	0-100% RH	±0.2% RH	±2% RH	200 μA at 5 V_{dc}
Temperature	26 Gauge Stranded T-Type	-270 to 400 °C	±0.03 °C	±0.4 °C	
Body Temperature	Tympanic Temperature	0-100 °C	±1.0 °C		200 μA at 5 V_{dc}
Power Output	Ergociser Fitness Cycle	kCal	kCal		n/a
Heat Rate		BPM	BPM		
Cycling Rate					

A Fluke NetDAQ® 2640A was used to capture the data from the thermocouples, humidity sensors, and power supply (Appendix 4). The resolution of the NetDAQ® sets the limits of the thermocouples, but the resolution of the humidity sensors is well below the resolution of the NetDAQ®. Data was collected every 10 seconds from all sensors. The environment of the room was controlled by normal air handling, a dedicated humidifier, and a dedicated dehumidifier.

Ambient temperature and relative humidity sensors were positioned on the front of the Ergociser, but away from the participant's movement or induced air flow.

Sensor Placement

The sensors were placed in locations on the body suspected of having high humidity and temperature gradients, particularly in the arm pits (TC_{pr}, TC_{pl}, RH_{pr}, and RH_{pl}). NIST calibrated humidity sensors were located at RH_{pr}, RH_{pl}, and in the ambient environment (RH_{amb}). A temperature sensor was also used in the ambient environment (TC_{amb}) as was a spare thermocouple (TC_{spare}). The humidity sensor power supply was also monitored to provide calibration data relative humidity calculations.

Table 1 - Sensor Placement

Label	Location
TC_{pr}	Right Arm Pit Temperature
TC_{fl}	Lower Front Temperature
TC_{pl}	Left Arm Pit Temperature
TC_{su}	Upper Side Temperature
TC_{sl}	Lower Side Temperature
TC_{bl}	Lower Back Temperature
TC_{bu}	Upper Back Temperature
TC_{bm}	Middle Back Temperature
TC_{fm}	Middle Front Temperature
TC_{fu}	Front Upper Temperature
TC_{skin}	Skin Temperature on Left Hand
TC_{amb}	Ambient Temperature
TC_{spare}	Spare Ambient Temperature
RH_{fm}	Front Middle Relative Humidity
RH_{pr}	Right Arm Pit Relative Humidity
RH_{bl}	Lower Back Relative Humidity
RH_{pl}	Lower Arm Pit Relative Humidity
RH_{sl}	Lower Side Relative Humidity
RH_{amb}	Ambient Relative Humidty

The subjects wore standard nylon/spandex biking shorts and jerseys. Velcro was sewn onto the jerseys so that sensors could be affixed to the outside of the garments. There were ten thermocouples (type T) and five humidity sensors attached to the body (Figure 3). The T_{skin} thermocouple was attached to the back of the hand with either tape or a band-aid. The other sensors were sewn to Velcro™ patches to mate with Velcro™ patches sewn to the jersey. Thermocouples were placed in the Velcro™ patches so that the bead was not exposed. Relative humidity sensors were also positioned so that they faced away from the participant to minimize of the possibility of contact with liquid. The participant would don the sensor jersey and the sensors were attached at the appropriate locations. Next, a cotton tee shirt was worn over the sensor jersey, and finally, the soft body armor was put on (Figure 5). Thus, when needed, the jersey and shirt can be laundered. The jerseys were selected to be tight on the participant. All data channels were recorded using a NetDAQ data acquisition system. The sampling rate was set at 0.1 Hz.

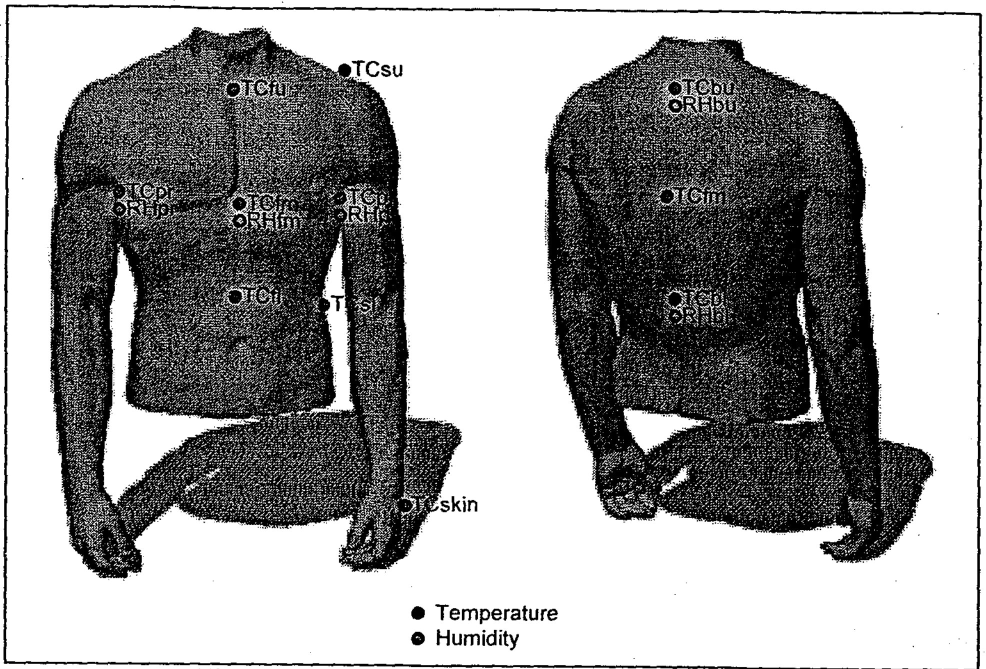


Figure 3 - Thermal Vest Sensor Placement

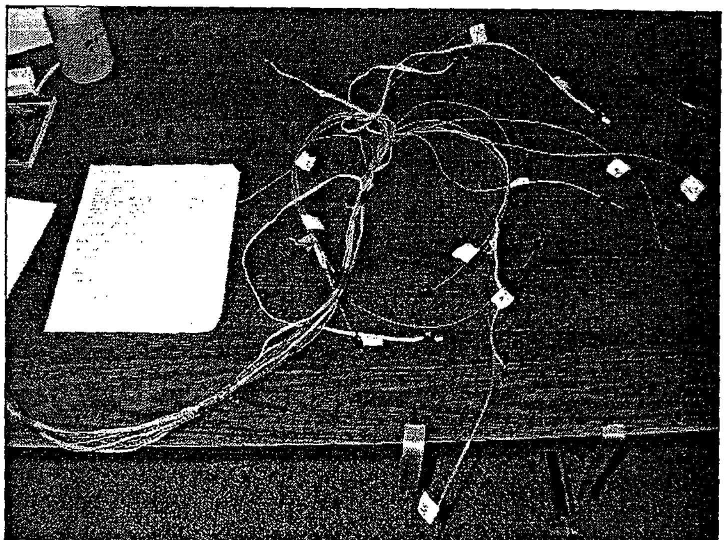


Figure 4 - Sensor Chain

A T-shirt was worn over the cycling jersey for all tests. This test condition (cycling jersey plus T-shirt) was the control test condition (Figure 5). During tests involving soft body armor, both the cycling jersey and T-shirt were still worn and the armor was placed over them and fastened at the shoulders and waist. The final test condition introduces a moisture wicking material. This material has been sewn together in the shape of the soft body armor and is Velcroed on to both the front and back.

Several initial tests were performed to flush problems with the test set up which were corrected, such as: misplacement of ambient instrumentation, participant movement during the test, sensor slippage and disconnect, dehumidifier misplacement, controlled cadence, constant power, constant heart rate, etc.

- 12 tests run at a controlled work level of 100 W (some with controlled cadence and others without); we found this did not require much effort from the subjects
- 14 tests run at a controlled heart rate (70% of maximum determined by age and weight of subject)

The temperature and humidity of the surrounding environment were controlled. The nominal values for temperature and relative humidity were 70°F and 40%, respectively. These values were measured by sensors placed in the vicinity of the bike. Once testing began, the temperature (Carrier) and humidity (Whirlpool Dehumidifier; Emerson HD13030 Humidifier) sources were shut off and an initial ambient temperature and humidity value were recorded.

Figure 5 - Control test conditions showing sensors attached to jersey (left) and the T-shirt placed over the sensors (right).

Subjects were permitted to consume water during the testing in an effort to avoid dehydration. Although drinking times were not controlled, the subjects were encouraged to suspend drinking until their core body temperature measurements were taken, which was every five minutes.

TEST METHODS

Control

Prior to cycling, the subjects recorded their nude weight and then proceeded to dress in cycling shorts and shirt. Upon entering the testing room, they seated themselves on the bike and adjusted the seat position to a level of their choice while the test operator began data acquisition for all sensors. The thermocouples were attached to the cycling shirt followed by the attachment of the humidity sensors. Then, the subject put on a T-shirt to cover the sensors. The final thermocouple for sensing skin temperature was taped to the left forearm. After all sensors were attached, the environmental controllers were shut off and the values for ambient start conditions (temperature and humidity) for the room were recorded. The initial core temperature was taken, the subjects placed on headphones and the testing began.

The first four minutes were used as a warm-up so that the subjects did not strain themselves too quickly. During this time they were asked to pedal at 80 rpm as their heart rate rose towards the target value. At the end of the four minutes, their core temperature was again recorded and they often took a drink. Core temperature was measured again after five minutes at which time the subject was again permitted to drink. This sequence was repeated until the total 34 minutes of cycling time was complete. At the end of the test, the ambient room conditions were recorded and the subject was asked to record a post-test nude weight.

Armor

Tests involving the addition of soft body armor follow the procedure used for the control tests with on exception. After the sensors have been attached and the T-shirt has been placed over the jersey, the soft body armor is placed on the subject and secured at both shoulders and the waist. All remaining steps are unchanged from those used in the control tests.

Armor with Wicking Material

The test procedures are again similar to those used for the control and armor tests. However, in these tests the soft body armor is outfitted with a layer of moisture wicking material (either Faytex Aero Spacer Drilex® or Coolmax® Grid Knit) (Figure 6). The material is secured to the soft body armor with Velcro strips. The soft body armor with the moisture wicking material is placed over the T-shirt and jersey as done with the previous armor tests. All other steps are unchanged.

Figure 6 - Tests involving soft body armor with a layer of moisture wicking material. Subject C (left) shown wearing Faytex Aero Spacer Drilex® wicking material and Subject D (right) shown wearing Coolmax® Grid Knit material.

Table 2 - Tests Performed

Test Method	Subject	A	B	C	D
Controlled Work, 100W	Without Armor	5	3	2	0
	With Armor	0	1	1	0
Controlled HR, 70% of maximum	Without Armor	3	0	3	2
	With Armor	2	1	3	2

Analysis

Although relative humidity was calculated using the NetDAQ, the values were recalculated in Excel during data analysis (Table 3).

Table 3 - Relative Humidity Calculations

Equation	NIST Calibration
$RH_{fm} = (H_1 / V_{dd} - 0.16)/(0.0067766 - 0.00000744^* TC_{fm})$	No
$RH_{pr} = (H_2 / V_{dd} - 0.1598)/(0.00692197 - 0.0000075996^* TC_{pr})$	Yes
$RH_{bl} = (H_3 / V_{dd} - 0.16)/(0.0067766 - 0.00000744^* TC_{bl})$	No
$RH_{pl} = (H_4 / V_{dd}\ m - 0.1694)/(0.00691935 - 0.00000759672^* TC_{pl})$	Yes
$RH_{bu} = (H_5 / V_{dd} - 0.16)/(0.0067766 - 0.00000744^* TC_{bu})$	No
$RH_{amb} = (H_6 / V_{dd} - 0.1682)/(0.00697553 - 0.0000076584^* TC_{amb})$	Yes

Vital Statistics Data

Data was captured on the vital health statistics (RPMs, Pulse, T_{core}, and Power) of each participant and monitored closely during testing. All of these data points except T_{core} are captured by the exercise bicycle. The T_{core} is estimated from tympanic temperature taken at fixed intervals during the test. There seems to be no immediately obvious correlation with the vital statistics and the discomfort of the soft armor at the work levels we have the volunteers performing.

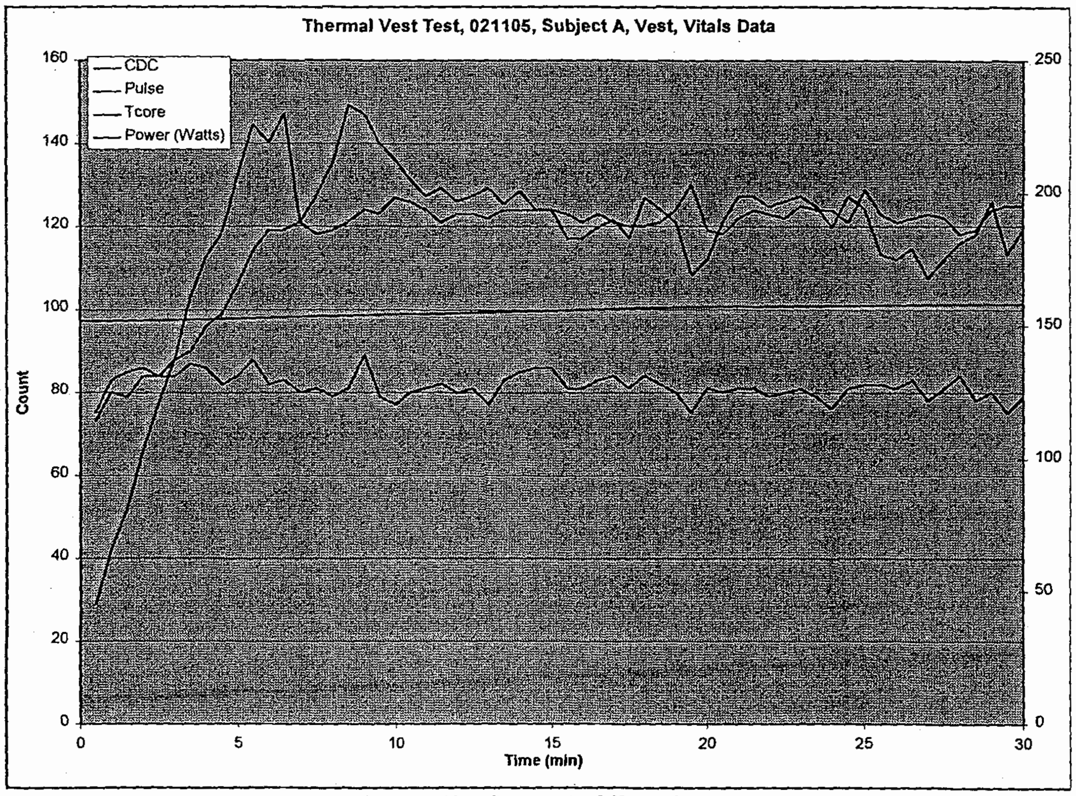


Figure 7 - Sample Vital Data

Instrumentation Data

Raw data was captured for all tests (example in Figure 8). The test data was extracted from the pre-test and warm-up data. The measurement at the start of the test was used as the offset of the sensor and subtracted from the subsequent measurements. Samples of temperature and relative humidity are provided (Figure 4 and Figure 5, respectively). This example is characteristics of most of the tests. RH_{amb} varies less than +8/-3%RH with and minor relative humidity increase of less than 1.1%RH during the test. T_{amb} varies less than ±0.6°C with and minor temperature increase of less than 0.05°C during the test. T_{spare} shows a more significant rise, but it was note located in any particular orientation to the test. There seems to be no obvious correlation with most of the temperature measurements and the discomfort of the soft armor. However, TC_{bm} seems to provide the most consistent measure between the participant wearing or not wearing soft body armor.

Preliminary analysis of the data suggests that the TC_{bm} is the only consistent measure of discomfort of the subject using a soft armor vest (Figure 23, Figure 43, and Figure 61). Additional analysis will be conducted including the warm-up cycle and using mathematical cross-correlation.

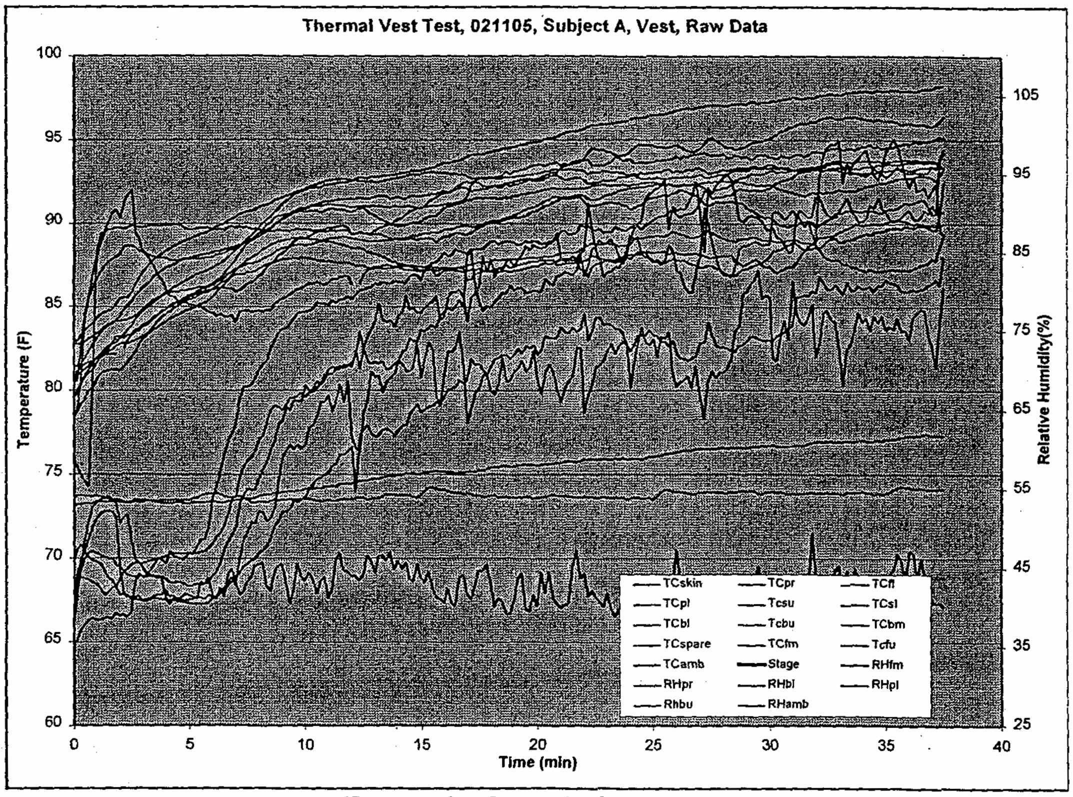


Figure 8 - Sample Raw Data

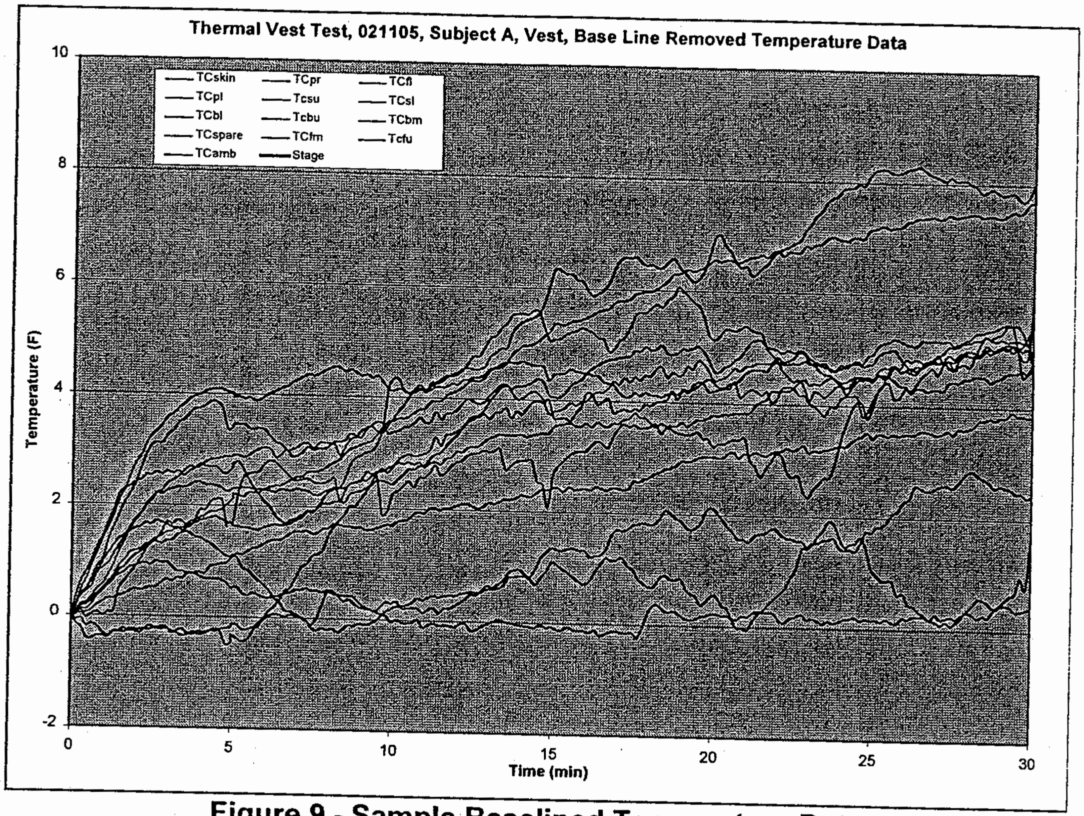


Figure 9 - Sample Baselined Temperature Data

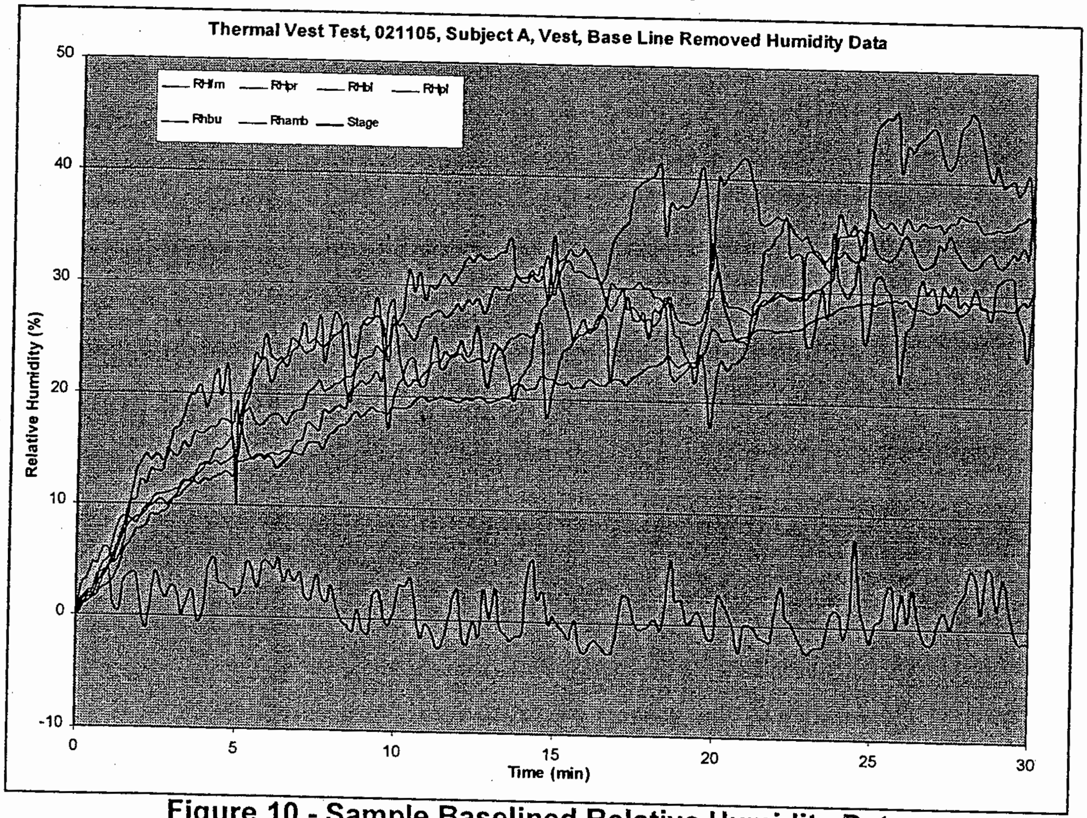


Figure 10 - Sample Baselined Relative Humidity Data

Task 6 – Physical Specimen Design

This task was started ahead of schedule to allow us to construct our own test fixtures and calibrate the data collection system. This task is completed after revisions to the testing apparatus were completed.

The current technology for moisture and thermal transport testing can be found in ASTM F1868-98 "Standard Test Method for Thermal and Evaporative Resistance of Clothing Materials Using a Sweating Hot Plate" and a series of manikins described by Fan and Chen in their paper on a novel perspiring fabric thermal manikin[1]. We compared the various test methods and determined that none of the existing tests actually provides a true representation of our desired test conditions. These systems were designed to test the through thickness transfer of thermal energy and moisture vapor. In our design we are forced to go around the body armor edges to move the moisture and heat from the body surface to an external surface where evaporation can occur. Therefore we have fabricated our own test stations that will duplicate most of the capabilities of the sweating hot plate, but also provide for the orientation of the test samples to mirror that of the materials when worn by a test subject. In addition, the device will provide for a controlled distribution of a liquid to simulate high volume sweat at the "skin" surface, to supplement the vapor transpiration.

A commercially produced "Sweating Guarded Hotplate" with controls and sensors is available for approximately $50K and it would have to be modified to meet our test requirements as described above, which places it outside the scope of this project. We have assembled two test devices designed to achieve the same overall function as the commercial test apparatus, which are being used to do comparative testing of our materials and to measure the effect of external conditions on the performance of the materials.

Initial "dry" testing showed the requirement for controlling the temperature and humidity of the air that is blown over the "skin" of the test apparatus. Fluctuations in room conditions can cause the test conditions to exceed the required boundary conditions and result in changes that are greater in magnitude than the expected data values. Therefore we have revised the test method to place our sweating hot plates into a controlled temperature/ humidity chamber. This allowed us to complete the "dry" testing. We are now trying to get the conditions to stay inside the required boundaries for the "wet" testing.

Task 7 – Initial Materials Down Selection

This task is completed. The two Hydroweave® materials have high thermal insulation values and are very bulky. While they are useful for validating the fabric test apparatus over a range of materials and conditions, they are not appropriate for the test conditions of this program. In addition the Dupont Coolmax® Open Mesh has too little material cross section to transport the moisture as intended for our design. These three materials have been eliminated from the prototype fabrication tests. The remaining 6 materials will be considered for prototype fabrication.

Task 8 – Specimen Fabrication and Testing

This task is a summary task that encompasses the following three tasks.

Task 9 – Fabricate Thermal Evaluation Specimens

This task is completed. All of the moisture wicking materials were fabricated into test samples for the testing apparatus described in Task 6 above. These specimens will be modified with the addition of the thermally conductive fibers after test data is collected without the fibers.

Task 10 – Conduct Thermal / Moisture Tests

This task has been started and is scheduled to be completed in 2 weeks. Testing of the samples in wet and dry conditions will indicate the relative performance of the material candidates. This test has been the source of the delay in the program. Please refer to the Task 6 description for details on the testing apparatus and associated issues.

Humidity and temperatures sensor performed nominally during chamber tests. The environmental chamber performed nominally in dry ambient testing, however, moisture testing requires purging of the humid environment otherwise wick moisture swamps the system. Intera I-301 shows consistent reduction in thermal resistance in ambient humidity (60% RH).

Table 4 - Chamber Test Results

$R_{tc} = (T_{plate} - T_{ambient})$*Area/Power		R_{tc} Measured			R_{tc}(Measured-GoreTex)				
clo = 0.155		Km²/W			Km²/W			Avg	StDev
GoreTEx	a	0.1094	0.12	0.15				0.12	0.02
GoreTEx	b	0.1778	0.17	0.19				0.18	0.01
Aquatex Hydroweave with Bdr.	1	0.2414			0.12			0.12	
Aquatex Hydroweave	2	0.3118			0.14			0.14	
Fabrictex WickAway Jersey #46970	3	0.1295	0.13		0.00	0.01		0.00	0.00
Aero-Spacer Dri-Lex 622	4	0.2098	0.23		0.03	0.05		0.04	0.01
Hydrolon Performance Knit #8294	5	0.1353	0.14		0.01	0.02		0.01	0.01
Drilex	6	0.1655	0.19		-0.01	0.01		0.00	0.02
Dupont CoolMax Mesh #8526	7	0.1258	0.13	0.13	0.00	0.01	0.00	0.00	0.00
Intera I-301	8	0.1601	0.17	0.17	-0.02	-0.01	-0.01	-0.01	0.01
Dupont CoolMax Grid Knit #49241	9								

Task 11 – Final Materials Selection

This task has not started. It will occur with the completion of Task 10.

Task 12 – Prototype Fabrication and Testing

This task is a summary task that encompasses the following three tasks.

Task 13 – Fabricate Complete Prototype (Overvest)

This task was started using the most promising materials based on tests to date.

Task 14 – Thermal Data Collection

This task was started with two wicking materials (Faytex Aero Spacer Drilex® and Coolmax® Grid Knit). We will collect as much data as possible depending on the remaining funding and time. Humidity and temperatures sensor performed nominally during early human tests. However, inconsistencies in sensor readings were exhibited in later testing presumable due to salt contamination on the thermal sensors.

Results show that human testing provides poor empirical data. However, subjective human data is necessary for evaluation. Sensors near soft body armor openings show little change. Consistent differences were found between control and soft body armor tests with thermocouples placed on all subjects' lower backs. Humidity sensors were not consistent, but most changes were noted in areas similar to the consistent thermocouple data. The confirmed thermal rise over control when wearing soft body armor and the rise in relative humidity on front middle and back lower over control when wearing soft body armor are seen below:

Table 5 - Difference from Control to Soft Body Armor

Subject	Temperature Difference	Relative Humidity Difference
A:	+10°F	+5% RH
C:	+7°F	+20% RH
D:	+6°F	+35% RH

There appears to be an inverse correlation between subjects' temperature and relative humidity dependent on subject's health. This is difficult to determine from the small sample size of subjects and tests.

Initial test results show that the wicking material increases the insulative value of the soft body armor. This is believed to be due to the lack of air flow between the subject and the soft body armor. As confirmation, it can be seen from the test data that the relative humidity drops substantially when the subject sits upright for tympanic temperature readings which allow air to circulate in soft body armor/subject interface area.

Table 6 - Wicking Soft Body Armor Initial Results

	Soft Armor		Soft Armor w/ Wicking Material	
Subject	Temp. Peak (F)	RH Peak (%RH)	Temp. Peak (F)	RH Peak (%RH)
A	11	45	19	68
C	7	45	18	50
D	11	42	25	47

***Summary*:**

Tasks 1, 2, 5, 6, 7, 9, and 12 are completed. Task 3 is completed except for conductive fiber final selection. Task 4 was placed on hold until data from task 10 could be generated. Tasks 8, 9 and 10 are all started and most are substantially completed. Tasks 11 cannot be completed on current funding. Tasks 13 and 14 are partially completed. This program was the first year of a proposed two year effort. Our goal was to fabricate and begin testing of at least one prototype over-vest with body armor by the completion of the first year of funding. Based on the current progress we will reach that goal. If the second year of funding becomes available we will continue that testing in laboratory and field under conditions, adding law enforcement officer volunteers to the program. The rest of the proposed tasks will be executed and a refined prototype will be provided with the test data and thermal model. We will also explore commercial body armor manufacturer's interest in producing an integrated version of this technology, construct, and test a prototype of that device.

APPENDIX 1 - Background

The Office of Technology Assessment report clearly shows the effectiveness of body armor in saving lives[2]. This experience gives body armor wide acceptance by law enforcement groups to mitigate and prevent firearm injury. These groups include a wide range of State and local police forces, corrections officers and federal agencies such as the Drug Enforcement Agency, Federal Bureau of Investigation, and Secret Service. However, each group has different sets of specific needs based on tactical needs. These needs dictate which features are given the most important in selecting body armor. These needs recognize factors such as the duration of wear, expected firearm threat, need for body armor concealment and cost. When looking at the duration of wearing body armor, the requirements can range from short, incident driven periods lasting minutes to hours, to patrol shifts lasting 8 or more hours.

The longer the duration, the more critical that the officer finds body armor comfortable to wear. As one body armor company states:

> *When selecting armor for full-time routine use by an officer, comfort is a major factor. Armor that is set aside or relegated to the trunk of a cruiser is of no benefit. The NIJ development effort recognized this "real world" problem and therefore emphasized comfort in the design of lightweight body armor for police use. Two fundamental factors were considered: fit - from the standpoint of mobility and the weight distribution of the armor - and heat discomfort.*[3] (Emphasis added)

When law enforcement personnel who own body armor are asked why they decide not to wear it, they generally point out that the discomfort of wearing the armor outweighs the perceived risk of getting shot. The officers, who decide not wear body armor, comment that the armor is hot, heavy, stiff, and chafs[2]. While some of these complaints may be related to overall weight and fit, the other complaints expose an unavoidable consequence of wearing armor. The basic issue is that body armor, particularly the ballistic insert, is both a thermal insulation that interferes with heat conduction and convection, and blocks the evaporation of sweat. The body armor covers about 50% of the torso or 20% of the body's total skin area[4]. The combined effect of the shell, waterproofed insert and the layers of ballistic cloth significantly inhibit vapor transport and heat conduction through the thickness of the vest. For areas covered by the body armor, most of the cooling occurs by heat and moisture exchange through the arm, neck and torso openings. To prevent discomfort and heat strain, the decrease in heat loss from the covered areas of the torso needs to be compensated for by an increased heat loss from the remainder of the body or a decrease in activity.

In discussions with a bike patrol officer from Howard County, Maryland, the officer commented that body armor forced him to change clothing more than once a shift to maintain a professional appearance because of moisture accumulation[5]. When worn cycling, the vest became wet, took extended periods of time to dry, and when a wet vest was worn over dry clothes, quickly caused the dry clothes to become sweat soaked. Wearing polypropylene or silk shirts under the vest did not help because once the shirt was saturated with sweat, its cooling effectiveness disappeared.

Similar results were documented in testing conducted at the FBI Academy where untreated Kevlar® armor was worn by an instructor performing prolonged strenuous activity on a hot, humid day[6]. After the activity, the armor retained 22% of the vest's weight in perspiration. This added weight not only places an extra load on the officer, but the moisture may also degrade the ballistic properties of the body armor.

Heat generated by the body needs to be dissipated into the environment in order to maintain a balance of the core body temperature. On one side of the balance is heat loss through respiration, radiation, convection, conduction, and evaporation. The body generates heat from the basal metabolism and muscle activity and gains heat from the environment through radiation, conduction, and convection.[4]

Previous work has estimated that wearing body armor is equivalent to a 10°F increase in the ambient Wet Bulb Globe Temperature Index.[7]

In order to develop new solutions to reducing the discomfort of body armor it is important to understand:

◊ How body armor usage is affected by the climate.
◊ How much heat the body generates.
◊ Mechanisms by which the body dissipates heat.
◊ The relationship between core body temperature and heat dissipation mechanisms.
◊ How body armor affects heat dissipation.
◊ The implications of heat build-up on comfort, health, and activity.

Effect of ambient conditions on body armor usage

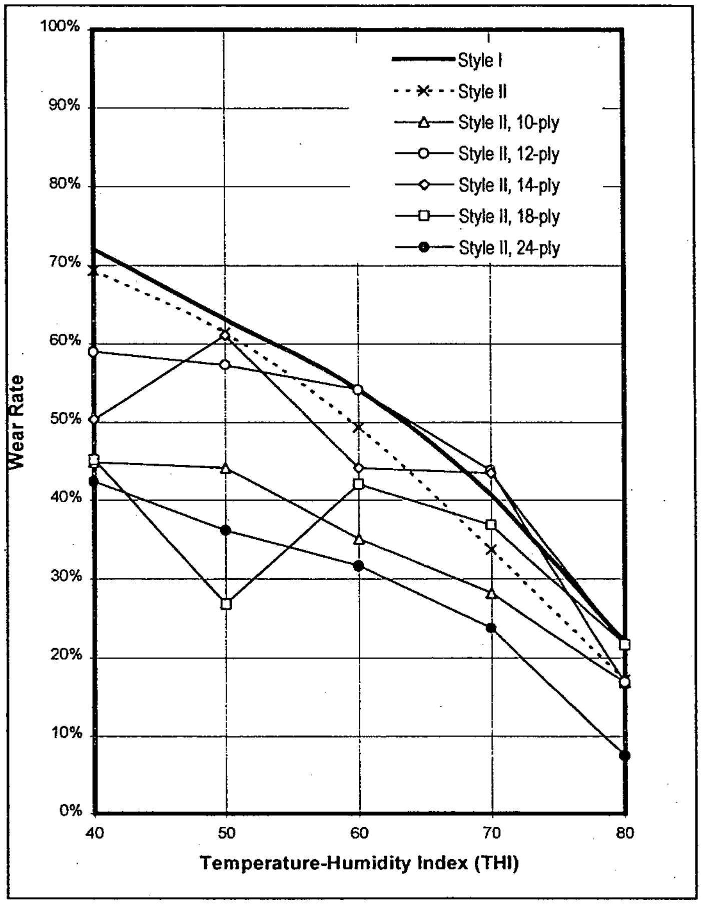


**Figure A11 - Wear rate versus Temperature Humidity Index (THI) 6.
The temperature-humidity index is defined as THI = 15 + 0.4 x (T + Tw),
where T = dry-bulb temperature (°F), and Tw = wet-bulb temperature (°F).**

In a large, year-long survey conducted for the NILECJ, the Aerospace Corporation [8,9] found that the strongest influence on wear rate was the temperature-humidity index, a measure of how hot the environment feels to the officer. Not surprisingly, reported wear rates are higher on cooler days; i.e. days with lower THI (Figure A1). Similarly, the body armor wear rates are higher in the winter months than in the summer (Figure A2).

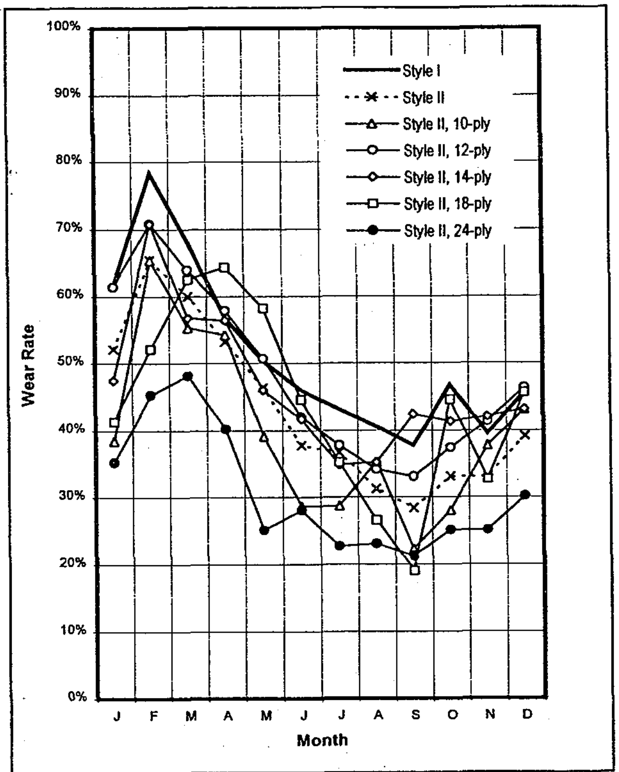


Figure A2 - Wear rate versus month[7]

Although the NILECJ report did not address the effect of sunlight, it is expected that the addition of heat from sunlight would decrease body armor wear rate.[7, 8] During the night, there is radiation heat loss to the sky. During daylight, the heat gain from the sun will contribute to the apparent environmental temperature. Additionally, there may be net heat loss or gain from the surrounding terrestrial environment depending on ambient temperatures. The sun may contribute as much as 140W of heat or more depending on the sun's intensity and body position relative to the sun[10]. The heat gain from the sun can easily exceed the heat generated by the basal and muscular metabolism during periods of inactivity. This apparent temperature increase is expected to a further decrease body armor usage.

Heat Generation

The body's heat may be generated by basal metabolism or by muscular activity. The basal metabolic activity generates approximately 75 watts of heat[11]. Strenuous exercise my increase this rate of heat generation to over 1000 Watts. Table A1 lists the calorie expenditure for a number of activities. Unless this heat is dissipated at the rate it is generated, the core body temperature increases and a number of physiological changes occur. These changes include increased heat rate, vasodilatation of the blood vessels near the skin (particularly in the extremities) and sweating. The increase in core body temperature also decreases the anaerobic exercise threshold, potentially making a formerly aerobic exercise level very difficult. When the core body temperature becomes excessive, heat exhaustion, heat stroke and even death can result. Although rare, death is possible when a person ignores the physiological distress associated with elevated core body temperature and dehydration.

Table A1 - Energy expenditure for 70 kg male for different activities.

Activity	Calories/Hour
Sleeping	65
Sitting	100
Walking slowly	200
Active exercise	290
Severe exercise	450
Swimming	500
Running (5.3 MPH)	570
Walking (5.3 MPH)	650
Walking up stairs	1100

Heat Dissipation

The body dissipates the majority of heat through four mechanisms.[9] They are:

Respiration – The inhaled air is heated or cooled to a temperature near that of the core body temperature. Additionally, evaporative heat loss occurs as the inhaled air is humidified by the body. This is relatively constant, unaffected by the wearing of body armor.

Radiation - Radiation is the heat loss or gain to the environment. With equal emissivities, when the environment is hotter than the body temperature, heat flows into the body. When the surrounding temperatures are lower than the body temperature, heat is lost to the environment. The heat gained from sunlight varies considerably depending on the sun angle and posture of the body to the sun. At night, heat is lost to the sky. During the day, heat gained from sunlight on the body can be more than twice the heat from the basal metabolism. Clothing (including body armor) slows the heat exchange between the skin and the atmosphere.

Conduction and Convection - Heat transferred from a warmer object to a cooler object by contact is termed conduction. When one of the objects is a moving fluid such as air or water, the component of heat transfer associated with the fluid flow is termed convection. Convection accelerates normal conduction heat flow by increasing the temperature gradient. Compared with water, air is relatively poor at removing heat from the body. It has about 5% of the thermal conductivity of water and about 1/1000th of the specific heat.[12] Relative to measuring human physiology in air or water, it is difficult to separate the effects of conduction and convection hence they are usually discussed together. At cool ambient air temperatures, a significant portion of the body's heat can be dissipated through these mechanisms. As the temperature approaches the body's core temperature, the heat dissipation through these mechanisms shrinks and disappears. At temperatures above the core body temperature (about 98°F), the ambient air heats the body, increasing the amount of heat that needs to be dissipated to maintain thermal homeostasis. Wearing body armor increases the thermal resistance between the skin and the ambient air by limiting air movement under the armor.

Evaporation – At elevated temperatures, evaporation is the body's principle method to dissipated heat. Evaporation of a gram of water at 30°C from the body removes 2.43 kJ of heat.[13] In more practical terms, evaporation of 1 L of water dissipates the heat from approximately 580 Calories of exercise (about an hour of running).

The rate and onset of perspiration varies with fitness level, heat acclimatization and between individuals. The physiological differences due to acclimatization and a high fitness level include earlier onset perspiration, greater perspiration rate, and greater plasma volume[14, 15]. The rate of sweating for a fit individual may be 2-3 times that of a sedentary individual. The limited moisture transport of the carrier and the lack of moisture transport through the ballistic layer combine to significantly reduce evaporation under body armor.

The interaction of relative humidity and ambient temperature on heat dissipation is seen in Figure A3.[16] As the relative humidity increases, the rate of evaporation and cooling decreases. At an ambient temperature of 37°C and 100% relative humidity, there is no evaporative cooling. If the relative humidity decreases at this temperature, evaporative cooling can occur. This has important consequences under body armor where the air is trapped and can become saturated with moisture. Evaporative cooling ceases once the trapped air is saturated and reaches body temperature.

The role of air circulation is very important in evaporative cooling. In a static atmosphere, air near the body becomes saturated with moisture that needs to diffuse away from the body for further cooling to occur. With air circulation, the moist air is carried away allowing drier air to increase the rate of evaporation. Likewise moist air trapped under clothing loses its evaporative cooling effect. The effect of air circulation on evaporative cooling is one of the principle reasons fans are effective in cooling.

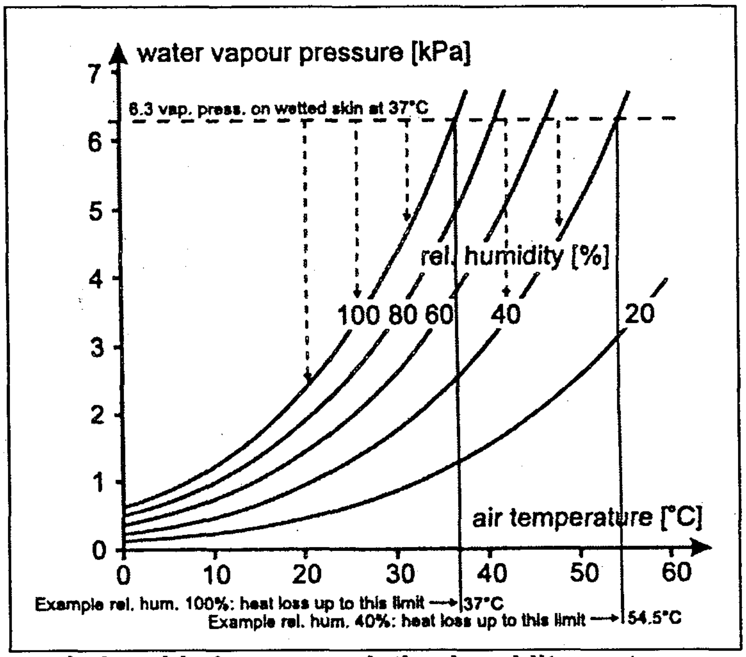


Figure A3 - Interrelationship between relative humidity, water vapor pressure, air temperature and heat loss.[15]

For example, the difference in vapor pressure between 100% RH ambient air at 20 C and the vapor pressure on wet skin (100% RH at 37°C) is about 4 kPa. With an ambient temperature of 37°C and 40%RH, there remains about a 4 kPa difference in pressure. This difference in vapor pressure results in evaporative cooling of the body. If a warm, moist layer of air remains trapped against the skin, no evaporative cooling may occur.

Effect of core temperature on heat dissipation

If the core body temperature cools slightly below the body's set-point, the body responds in a number of ways.[9] In the short-term, these responses include vasoconstriction reduces skin's blood supply, allowing the skin temperature to drop (Figure A4). Vasoconstriction also occurs in the distal limbs to further reduce heat loss. If the core temperature increases above the body's set-point, the short-term responses include vasodilatation at the skin along with increased blood flow to the extremities. It can be thought of as a thermal core (consisting of the brain, thoracic and abdominal organs) that maintains a relatively constant temperature, surrounded by a thermal shell whose temperature varies over a much greater range to maintain the proper temperature of the core.

At low temperatures, a nude body loses most of its heat by radiation.[12] (Clothing reduces this radiation heat loss.) As the surrounding temperature increases and radiation losses decrease, there is an increase in the fraction of heat loss due to convection and conduction. As the core body temperature increases, this conductive and convective heat loss increases as the skin temperature increases. Then, to accommodate further core body temperature increases, the rate of perspiration increases. Figure 4 shows how the skin temperature varies in different locations as the core body temperature increases.[4] Figure 5 shows this transition - how the evaporation of perspiration is the dominant heat loss mechanism for a jogger at 30°C ambient temperature. Figure 6 shows a slightly different portioning of heat loss mechanisms as a function of temperature. Note that the level of activity, clothing, and air movement variables in Figures 5 and 6 differ.

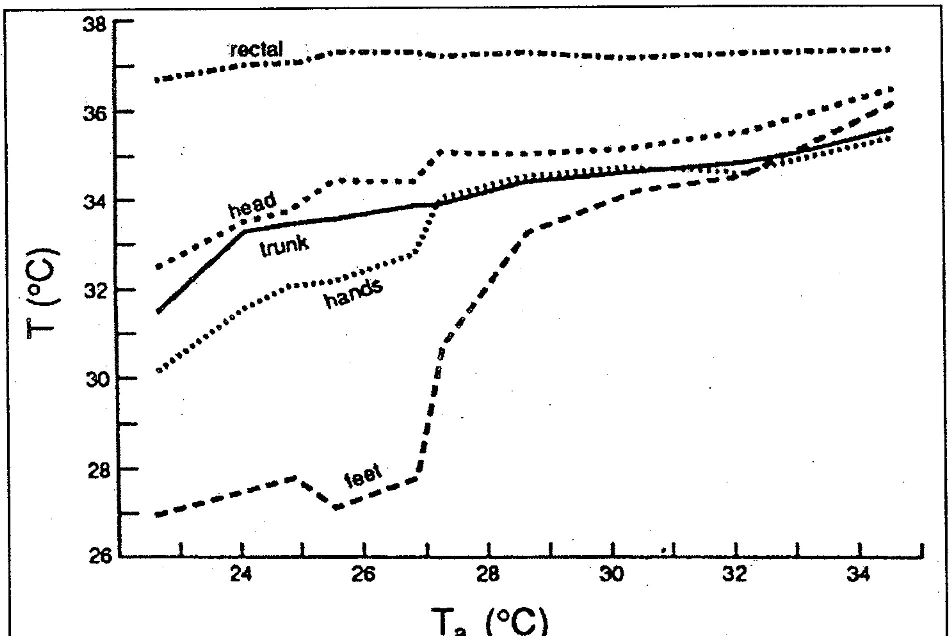


Figure A12 - Effect of ambient temperature (Ta) on skin and core temperature.[4]

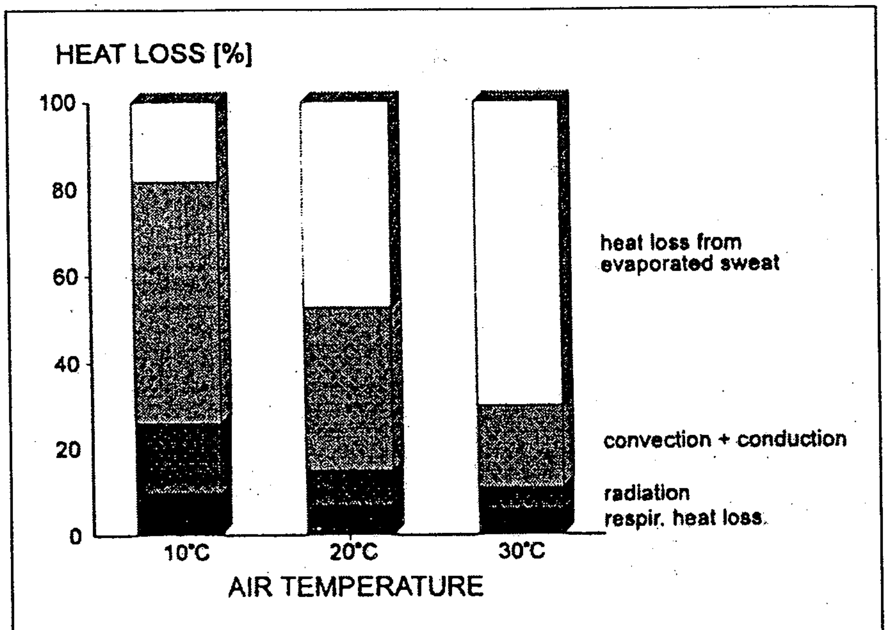


Figure A13 - Partitioning of heat loss for a runner (3.3 m/s) wearing shorts in the sun with 980 W metabolic heat and 140W of solar radiation, 60% RH.[9]

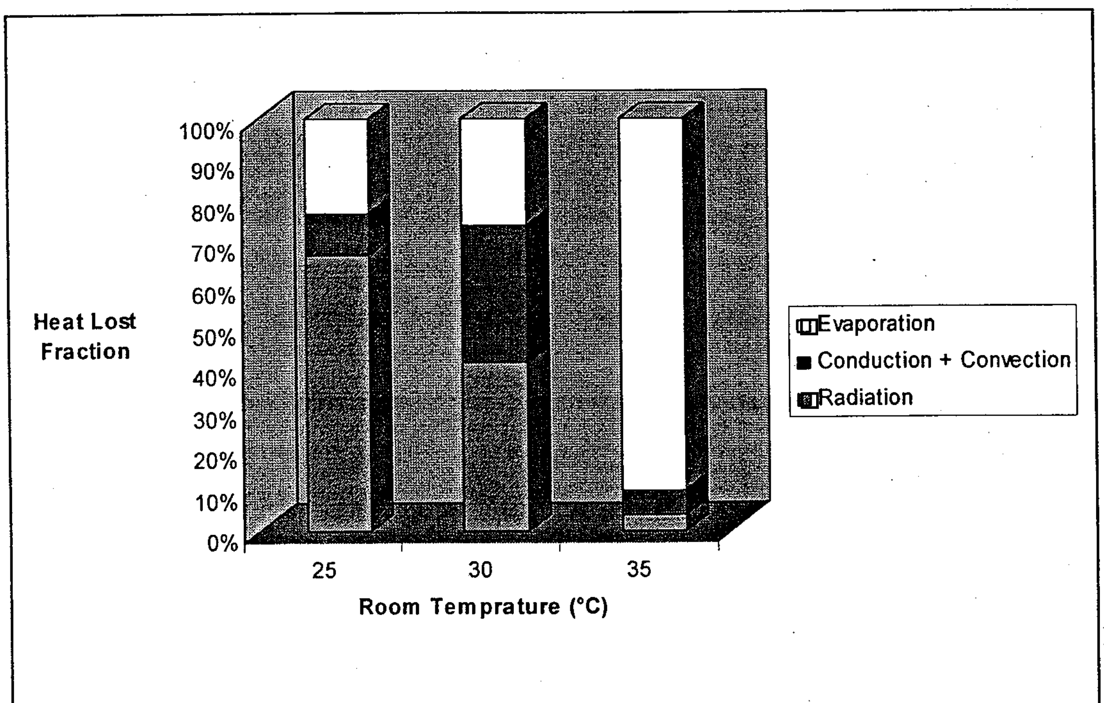


Figure A14 - Heat lost partitioning for nude human subject in a room with a constant, low air movement.[12]

Effect of body armor on heat dissipation

Body armor affects heat dissipation in several ways. Body armor is a thermally insulating and relatively moisture impermeable layer that covers more than 50% of the torso. With the torso having 36% of the body's surface area, body armor affects heat dissipation over approximately 20% of the body's surface area.[3] Although there is no effect on respiration heat loss and little effect on radiation heat loss (assuming that the law enforcement officer would normally be wearing a shirt), conduction, convection and evaporation are affected in the areas covered by body armor. In covering the torso, it reduces the body's heat dissipation mechanisms by insulating it from conduction and convection (when the ambient temperature is below the body's temperature) and slowing evaporation by reducing local air flow. (However, when the ambient temperature is above the body's temperature, such as in the desert, the insulation provided by body armor would slow the heat gains from conduction and convection.)

The effect of body armor on cooling mechanisms of the body is complex; however, it can be estimated from the literature. Early work used a "sweating", copper man to measure the effect that body armor has on decreasing the evaporative, radiant, and convective heat loss. The evaporative effects were measured in i_m and the radiant and convective effects were measured in *clo*. I_m is the ratio of the measured evaporative cooling to the maximum potential evaporative cooling (measured by a slung wet-bulb thermometer); therefore as i_m increases, the better the evaporative cooling. A *clo* is a derived unit having the property of combined radiant and convective thermal resistance of 0.18°C/m^2·hr·kcal; therefore as *clo* increases, the thermal resistance increases. Table A2 shows the effect that body armor has on both *clo* and i_m values

Table A7 - Effect of body armor and equipment on radiant, convection and evaporation heat loss from soldiers. Larger the i_m/clo ratio, the cooler the ensemble[7]

Ensemble	clo	i_m/clo
Combat, tropical	1.43	.34
+Helmet	1.51	.32
+Helmet and Pack	1.55	.29
+Body Armor	1.66	.24
+Body armor, Helmet and Pack	1.77	.20

The effect of body armor on evaporation is complex. As sweat moves away from the surface of the skin its potential for cooling the body decreases. The evaporative cooling effect occurs at the site of evaporation. When sweat evaporates from the skin surface, the body supplies most of the heat lost. When sweat evaporates from sweat saturated clothes, the cooling occurs on the surface of the clothing. The heat lost may be supplied by the body and ambient air depending on the thermal resistance of the two paths. The further from the body that the evaporation occurs i.e. the greater the thermal resistance path, the less the evaporation contributes to cooling the body. When sweat drips off the body, its potential for evaporation is lost and the sweat's contribution to cooling is limited to its specific heat.

Another study looked at different armor configurations to determine the extent that they improved comfort.[17] This study looked at the effect of changing the collar, shoulder and side armor on the physiological response of soldiers. The test environment was desert-like, with a temperature of 40°C, 20% RH, and a wind speed of 1 and 2.5 m/s. The soldiers walked on a treadmill at a workload of about 425 W. The testing showed that the different armor configurations had no significant effect on the soldier physiology or on dissipating heat. However, these results may not be applicable to either a humid environment or high workload intensities.

Effect of body armor on comfort and health

Wearing body armor in warm environments poses both comfort and health concerns. As discussed earlier the frequency of wearing body armor is closely tied to comfort and the primary variables in comfort are armor fit, ambient environment, and activity level. The issue of thermal comfort is subjective and highly variable. Those acclimatized to hot and humid weather are less sensitive to heat and humidity than those not accustomed to these conditions. Some people find any sweating is uncomfortable while others can sweat considerably without discomfort. Some people sweat more easily than others.

If the core body temperature becomes excessive, health may be compromised. Excessive core body temperature (105-108°F) may result in heat stroke or death. A person's sensitivity to heat stroke is also highly variable. Not only is there individual variability, there is also variability due to acclimatization. During acclimatization there are a number of physiological changes that improve the body's ability to adapt to the heat. These changes include about a twofold increase in the maximum rate of sweating, and increase in blood plasma to allow for vasodilatation. Acclimatization may be accomplished by slowly increasing the exposure to work in a hot, humid environment.

There are a number of heat stress indices such as physiological strain index (PSI), cumulative heat strain index (CHSI) and predicted 4-h sweat rate index (P4SR) to measure heat strain. The most recent of these indices, PSI, was developed as an easily measured index between 0 and 10 that would measure heat strain.[18] It is based on changes of two measurements, core body temperature, and heart rate. The measurement is not based on an integration of strain, but a simple difference between resting and stressed state. Mathematically, PSI is calculated as:[18]

$$PSI = 5(T_{ret} - T_{re0}) * (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) * (180 - HR_0)^{-1} \quad (1)$$

Where:

T_{ret}	Rectum temperature at time, *t*
T_{re0}	Rectum temperature at rest
HR_t	Heart rate at time, *t*
HR_0	Heart rate at rest

The PSI index was developed initially for young male adults; however, its method has been extended to men and women of all ages.[18, 19, 20] The scale is sensitive to both acclimatization and fitness, both of which allow an individual to exercise at PSI levels. The advantage of PSI is it reflects a real-time measure of heat strain. Table A3 shows typical results of testing using the PSI scale.

Table A8 - Calculated PSI from measured heart rate and temperature (rectum) obtained from 100 subjects exposed to 120 min. heat stress.[18]

Strain	PSI	Beats/min	T_{re} (°C)	n
	0	71±1.0	37.12±0.03	100
No/little	1	90±1.1	37.15±0.04	47
	2	103±1.1	37.35±0.03	81
Low	3	115±1.3	37.61±0.03	80
	4	125±1.4	37.77±0.04	61
Moderate	5	140±1.9	37.99±0.05	28
	6	145±5.3	38.27±0.07	13
High	7	159±1.3	38.60±0.04	5
	8	175	38.7	1
Very high	9			0
	10			0

Values are means ± SD (n is no. of subjects). Heat stress, 40°C, 40% relative humidity, 1.34 m/s at 2% grade; PSI, physiological stress index. No data available for very high strain.

Appendix 2 - List of Documents from Literature/Patent Search

1. Author(s) unknown, "Space Station and advanced EVA; Proceedings of the 21st International Conference on Environmental Systems," presented in *San Francisco, CA*, Jul. 15-18, 1991.Hanrahan, J. R.; Levine, R. G., "Unites States Patent 4,193,134: Protective Device with Integrally Molded Pad," *United States Patent Office*, Mar. 1980.
2. Honeywell, Inc., "Selection and Application Guide to Personal Body Armor," in *National Institute of Justice*, Nov. 2001.
3. Iyoho, A.; Thornton, S.; Nair, S., "Further Studies Quantifying Human Thermal Modeling Uncertainties"
4. Koscheyev, V. S.; Leon, G. R.; Hubel, A.; Nelson, E. D.; Tranchida, D., "Thermoregulation and Heat Exchange in a Nonuniform Thermal Environment During Simulated Extended EVA," in *Aviation Space and Environmental Medicine, vol. 71 (no. 6): p. 579-585,* Jun. 2000.
5. Mays, D. C.; Campbell, A. B.; Nair, S. S.; Miles, J. B.; Thomas, G. A., "Thermal Technologies for Space Suits," in *ASHRAE Journal, vol. 43 (no. 1): p. 25-+,* Jan. 2001.
6. Nyberg, K. L.; Diller, K. R.; Wissler, E. H., "Model of Human/Liquid Cooling Garment Interaction for Space Suit Automatic Thermal Control," in *Journal of Biomechanical Engineering, vol. 123 (no. 1): p. 114-120,* Feb. 2001.
7. Osczevski, R. J., "Design and Evaluation of a Three-Zone Thermal Manikin Head," *Defense and Civil Institute for Environmental Medicine, Ontario, Canada,* Oct. 1996.
8. Smith, L. F; Miles, J. B; Nair, S. S; French, J. D; Webbon, Bruce W., "Evaluation of Human Thermal Models for EVA Applications," presented at *SAE, International Conference on Environmental Systems, 26th, Monterey, CA*, Jul. 8-11, 1996.
9. Suga, M.; Matsuda, T.; Okamato, J.; Takizawa, O.; Oshiro, O.; Minato, K.; Tsutsumi, S.; Nagata, I.; Sakai, N.; Takahashi, T., "Sensible Human Projects: Haptic Modeling and Surgical Simulation Based on Measurements of Practical Patients with MR Elastography – Measurement of Elastic Modulus," *Nara Institute of Science and Technology.*
10. Sun, G.; Yoo, H. S.; Zhang, X. S.; Pan, N., "Radiant Protective and Transport Properties of Fabrics Used by Wildland Firefighters," in *Textile Research Journal, vol. 70 (no. 7): p. 567-573,* Jul. 2000.
11. Truong, Q. T.; Wilsuz, E.; Rivin, E., "Development of Selectively Permeable Membranes for Chemical and Biological Agent Protective Clothing," presented at *International Conference on Safety and Protective Fabrics: A Technical Focus on Textile and material Development for Personal Protection,* Apr. 29-May 1, 1998.
12. Wilsuz, E.; Truong, Q. T.; Rivin, D.; Kendrick, C. E., "Development of Selectively Permeable Membrane for Chemical Protective Clothing," in *Polymeric Materials Science and Engineering, vol. 77 (no. 365),* Sept. 1997.
13. Wissler, E. H., "Comments on the New Bioheat Equation Proposed by Weinbaum and Jiji," in *Journal Of Biomechanical Research, vol. 109: p. 226-233,* Aug. 1987.
14. Wissler, E. H., "Comments on Weinbaum and Jiji's Discussion of Their Proposed Bioheat Equation," in *Journal of Biomechanical Engineering, vol. 109: p. 355-356,* Nov. 1987
Woo, S. S.; Shalev, I.; Barker, R. L., "Heat and Moisture Transfer Through Nonwoven Fabrics, Part I: Heat Transfer," in *Textile Research Journal, vol. 64 (no. 3): p. 149-162,* March 1994.
15. Woo, S. S.; Shalev, I.; Barker, R. L., "Heat and Moisture Transfer Through Nonwoven Fabrics, Part II: Moisture Diffusivity," in *Textile Research Journal, vol. 64 (no. 4): p. 190-197,* April 1994.
16. Yigit, A., "The Computer-Based Human Thermal Model," in *International Communications in Heat and Mass Transfer, vol. 25 (no. 7): p. 969-977,* Oct. 1998.

17. Yoo, H. S.; Sun, G.; Pan, N., "Thermal Protective Performance and Comfort of Wildland Firefighter Clothing: The Transport Properties of Multilayer Fabric Systems," in *Performance of Protective Clothing: Issues and Priorities for the 21st Century, vol. 7: p. 504-518,* 2000.
Zeigler, J. P.; Bryner, M. A.; Carroll, N. L.; Stein, P. S., "Thermal Comfort Performance of Limited-Use, Protective Apparel Fabrics," presented at *International Conference on Safety and Protective Fabrics: A Technical Focus on Textile and material Development for Personal Protection,* Apr. 29-May 1, 1998.
18. Zhang, H.; Huizenga, C.; Arens, E.; Yu, T. F., "Considering Individual Physiological Differences in a Human Thermal Model," in *Journal of Thermal Biology, vol. 26 (no. 4-5): p. 401-408,* Sept. 2001.
19. Gregor, E., "New & Immerging Fiber Technologies," proceedings from EVA Technology Forum '99.
20. Stein J., "Thermal Challenges for Planetary Suit Materials," proceedings from EVA Technology Forum '99.
21. Trevino, L., "Materials Research Plans and Future Needs," proceedings from EVA Technology Forum '99.
22. Koscheyev, V. S.; Leon, G. R.; Hubel, A.; Nelson, E. D.; Tranchida, D., "Thermoregulation and Heat Exchange in a Nonuniform Thermal Environment During Simulated Extended EVA," in *Aviation Space and Environmental Medicine, vol. 71 (no. 6): p. 579-585,* Jun. 2000.
23. Mays, D. C.; Campbell, A. B.; Nair, S. S.; Miles, J. B.; Thomas, G. A., "Thermal Technologies for Space Suits," in *ASHRAE Journal, vol. 43 (no. 1): p. 25-+,* Jan. 2001.
24. Nyberg, K. L.; Diller, K. R.; Wissler, E. H., "Model of Human/Liquid Cooling Garment Interaction for Space Suit Automatic Thermal Control," in *Journal of Biomechanical Engineering, vol. 123 (no. 1): p. 114-120,* Feb. 2001.
25. Osczevski, R. J., "Design and Evaluation of a Three-Zone Thermal Manikin Head," *Defense and Civil Institute for Environmental Medicine, Ontario, Canada,* Oct. 1996.
26. Smith, L. F; Miles, J. B; Nair, S. S; French, J. D; Webbon, Bruce W., "Evaluation of Human Thermal Models for EVA Applications," presented at *SAE, International Conference on Environmental Systems, 26th, Monterey, CA*, Jul. 8-11, 1996.
27. Suga, M.; Matsuda, T.; Okamato, J.; Takizawa, O.; Oshiro, O.; Minato, K.; Tsutsumi, S.; Nagata, I.; Sakai, N.; Takahashi, T., "Sensible Human Projects: Haptic Modeling and Surgical Simulation Based on Measurements of Practical Patients with MR Elastography – Measurement of Elastic Modulus," *Nara Institute of Science and Technology.*
28. Sun, G.; Yoo, H. S.; Zhang, X. S.; Pan, N., "Radiant Protective and Transport Properties of Fabrics Used by Wildland Firefighters," in *Textile Research Journal, vol. 70 (no. 7): p. 567-573,* Jul. 2000.
29. Truong, Q. T.; Wilsuz, E.; Rivin, E., "Development of Selectively Permeable Membranes for Chemical and Biological Agent Protective Clothing," presented at *International Conference on Safety and Protective Fabrics: A Technical Focus on Textile and material Development for Personal Protection,* Apr. 29-May 1, 1998.
30. Wilsuz, E.; Truong, Q. T.; Rivin, D.; Kendrick, C. E., "Development of Selectively Permeable Membrane for Chemical Protective Clothing," in *Polymeric Materials Science and Engineering, vol. 77 (no. 365),* Sept. 1997.
31. Wissler, E. H., "Comments on the New Bioheat Equation Proposed by Weinbaum and Jiji," in *Journal Of Biomechanical Research, vol. 109: p. 226-233,* Aug. 1987.
32. Wissler, E. H., "Comments on Weinbaum and Jiji's Discussion of Their Proposed Bioheat Equation," in *Journal of Biomechanical Engineering, vol. 109: p. 355-356,* Nov. 1987

33. Woo, S. S.; Shalev, I.; Barker, R. L., "Heat and Moisture Transfer Through Nonwoven Fabrics, Part I: Heat Transfer," in *Textile Research Journal, vol. 64 (no. 3): p. 149-162,* March 1994.
34. Woo, S. S.; Shalev, I.; Barker, R. L., "Heat and Moisture Transfer Through Nonwoven Fabrics, Part II: Moisture Diffusivity," in *Textile Research Journal, vol. 64 (no. 4): p. 190-197,* April 1994.
35. Yigit, A., "The Computer-Based Human Thermal Model," in *International Communications in Heat and Mass Transfer, vol. 25 (no. 7): p. 969-977,* Oct. 1998.
36. Yoo, H. S.; Sun, G.; Pan, N., "Thermal Protective Performance and Comfort of Wildland Firefighter Clothing: The Transport Properties of Multilayer Fabric Systems," in *Performance of Protective Clothing: Issues and Priorities for the 21st Century, vol. 7: p. 504-518,* 2000.
37. Zeigler, J. P.; Bryner, M. A.; Carroll, N. L.; Stein, P. S., "Thermal Comfort Performance of Limited-Use, Protective Apparel Fabrics," presented at *International Conference on Safety and Protective Fabrics: A Technical Focus on Textile and material Development for Personal Protection,* Apr. 29-May 1, 1998.
38. Zhang, H.; Huizenga, C.; Arens, E.; Yu, T. F., "Considering Individual Physiological Differences in a Human Thermal Model," in *Journal of Thermal Biology, vol. 26 (no. 4-5): p. 401-408,* Sept. 2001.
39. Gregor, E., "New & Immerging Fiber Technologies," proceedings from EVA Technology Forum '99.

Appendix 3 - Test Procedure for Thermal Vest Tests

1) Operator: ______________________
2) Date: ______________________
3) Time: ______________________

4) Weight of Subject Naked: __________ lbs.
5) Weight of Water: __________ lbs.
6) Weight of Vest: __________ lbs. (if vest test)
7) Pedal Rate: __________ W (generally 100 W)

8) Save previous data file (C:\My Documents\Thermal Vest Test\thermal vest test.csv) and delete original
9) Turn off Dehumidifier and AC
10) Start RH Power Supply
11) Turn on NetDAQ
12) Confirm Data File location and sampling rate (6 sec)
13) Check NetDAQ Operation

14) Attach Body Thermocouples to Inner Shirt with Velcro
15) Attach Body Humidity Sensors to Inner Shirt with Velcro
16) Attach Test Cable Bundle to Shirt and Strain Relief to Table with Kapton
17) Attach Skin Thermocouple under watch to Left Hand with Band-Aid
18) Attach Ambient Thermocouple to Front of Bike with Kapton
19) Attach Ambient Thermocouple to Top of NetDAQ with Kapton
20) Attach Ambient Humidity Sensor to Front of Bike with Kapton
21) Place headphones on subject to insulate ears
22) Check NetDAQ Data with Spy

23) Start Data Recording
24) Check NetDAQ Data with Quickplot
25) Start Music CD
26) Record Start Ear Core Temperature Value: __________ F
27) Begin Cycling Warm-up for 4 min.
28) Begin Cycling Test for 30 min
29) Record Ear Core Temperature Values from Start of Cycling Test (after Warm-up)
    0 min: __________ F Actual time: __________
    5 min: __________ F Actual time: __________
    10 min: __________ F Actual time: __________
    15 min: __________ F Actual time: __________
    20 min: __________ F Actual time: __________
    25 min: __________ F Actual time: __________
    30 min: __________ F Actual time: __________
30) Note times subject drinks and/or sits up.
31) At subject's discretion, perform a burst cycling.
32) Take final ear core temp if burst cycling occurs
    ___ min: __________ F Actual time: __________
33) At subject's discretion, perform cycling cool down.
34) Stop recording data
35) Remove outer shirt

36) Weigh shirt and vest
37) Remove sensors
38) Send subject to weigh themselves after removing clothing and to shower
39) Turn on Dehumidifier and AC
40) Change data name from C:\My Documents\Thermal Vest Test\thermal vest test.csv to C:\My Documents\Thermal Vest Test\MMDDYY Thermal Vest Test "Type" Subj "?".csv where "Type" is either Control or Vest and "?" is subject identifier.

41) Stop RH Power Supply
42) Turn off NetDAQ and shut down application
43) Shutdown computer
44) Retrieve Cycle printout
45) Wipe down the cycle

46) Final Weight of Subject Naked: ______________ lbs.
47) Final Weight of Water: ______________ lbs.
48) Final Weight of Vest: ______________ lbs. (if vest test)

Appendix 4 - NetDAQ Configuration

INSTRUMENT CONFIGURATION - 01

Description: Thermal Vest Tests
Model: 2645A
Trigger Type: Interval
Interval 1: 10.000 sec
Interval 2: NA
Reading Rate: Slow (High Res.)
Drift Correction: Yes
Duration: NA
Temp Units: Fahrenheit
Monitor Chan: 0101
Total Debounce: Yes
Data File: c:\my documents\thermal vest tests\thermal vest test.csv
File Mode: Append
File Format: ASCII (CSV)

Chan	Function	Range	Alarm 1	Alarm 2	Trg	Mx+B	Units	Label
0101	TC	T	OFF	OFF	NA	OFF	TCskin °F	TCskin
0102	TC	T	OFF	OFF	NA	OFF	TC#1 °F	TC#1
0103	TC	T	OFF	OFF	NA	OFF	TC#2 °F	TC#2
0104	TC	T	OFF	OFF	NA	OFF	TC#3 °F	TC#3
0105	TC	T	OFF	OFF	NA	OFF	TC#4 °F	TC#4
0106	TC	T	OFF	OFF	NA	OFF	TC#5 °F	TC#5
0107	TC	T	OFF	OFF	NA	OFF	TC#6 °F	TC#6
0108	TC	T	OFF	OFF	NA	OFF	TC#7 °F	TC#7
0109	TC	T	OFF	OFF	NA	OFF	TC#8 °F	TC#8
0110	TC	T	OFF	OFF	NA	OFF	TCspare°F	TCspare
0111	TC	T	OFF	OFF	NA	OFF	TC#9 °F	TC#9
0112	TC	T	OFF	OFF	NA	OFF	TC#10 °F	TC#10
0113	VDC	30 V	OFF	OFF	NA	OFF	H#1 VDC	H#1 - 481
0114	VDC	30 V	OFF	OFF	NA	OFF	H#2 VDC	H#2 - 470
0115	VDC	30 V	OFF	OFF	NA	OFF	H#3 VDC	H#3 - 492
0116	VDC	30 V	OFF	OFF	NA	OFF	H#4 VDC	H#4 - 415
0117	VDC	30 V	OFF	OFF	NA	OFF	H#5 VDC	H#5 - 490
0118	VDC	30 V	OFF	OFF	NA	OFF	Vsup VDC	Vsupply
0119	TC	T	OFF	OFF	NA	OFF	TCamb °F	TCambient - 405
0120	VDC	30 V	OFF	OFF	NA	OFF	Hamb VDC	Hambient
0121	Equation	OFF	OFF	NA	OFF	RH#1	%RH	RH#1
0122	Equation	OFF	OFF	NA	OFF	RH#2	%RH	RH#2
0123	Equation	OFF	OFF	NA	OFF	RH#3	%RH	RH#3
0124	Equation	OFF	OFF	NA	OFF	RH#4	%RH	RH#4
0125	Equation	OFF	OFF	NA	OFF	RH#5	%RH	RH#5
0126	Equation	OFF	OFF	NA	OFF	RHamb	%RH	RHambient

Appendix 5 - Thermal Data Collection Plots

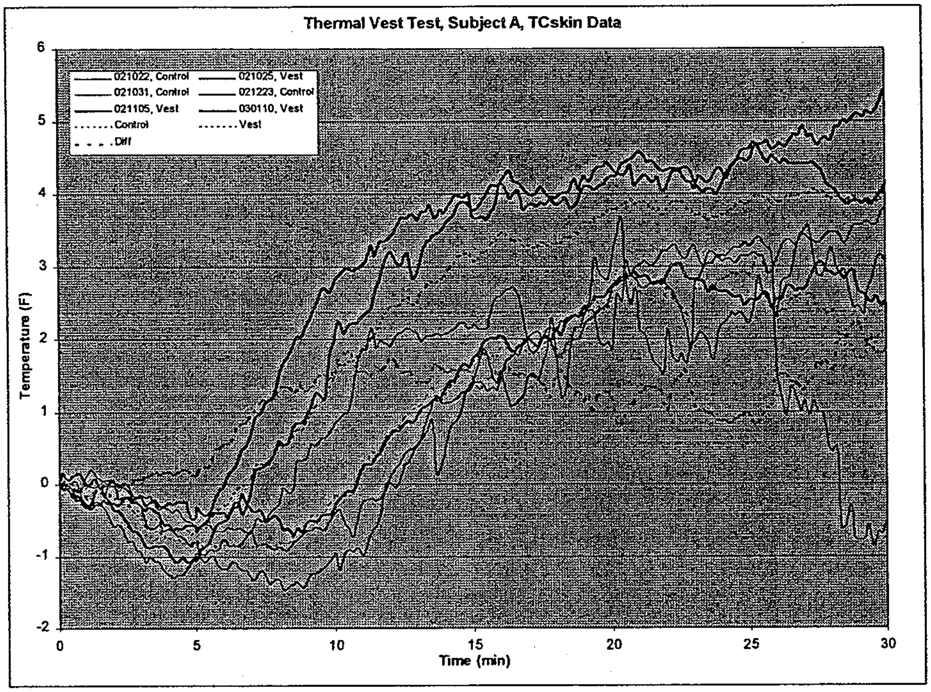


Figure 15: Thermal Vest Test, Subject A, TCskin Data

Some correlation detected, however Vest and Control tests coincide.

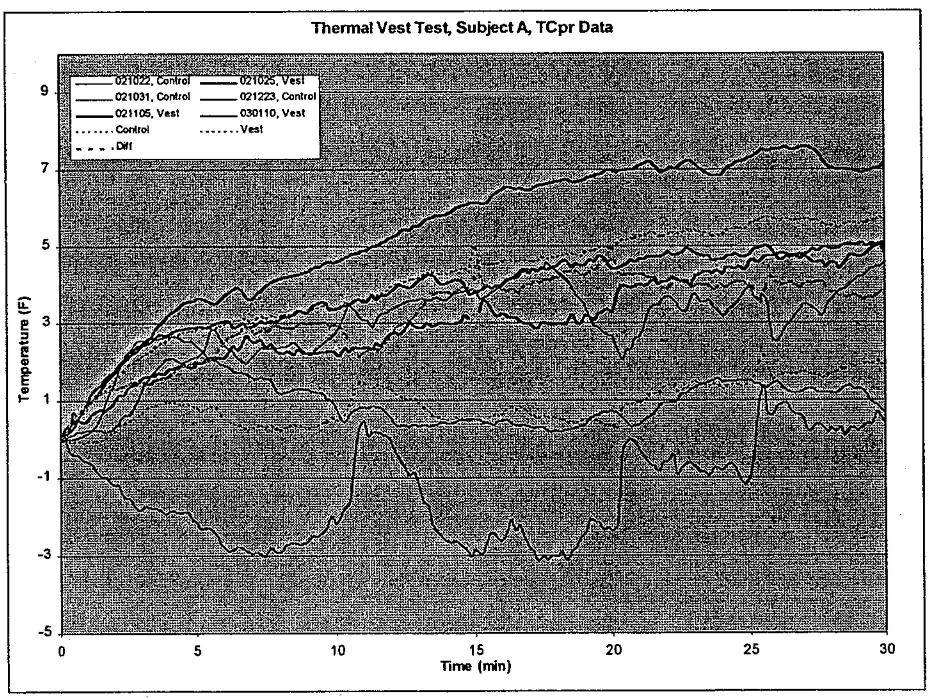


Figure 16: Thermal Vest Test, Subject A, TCpr Data

Some correlation detected, however Vest and Control tests coincide.

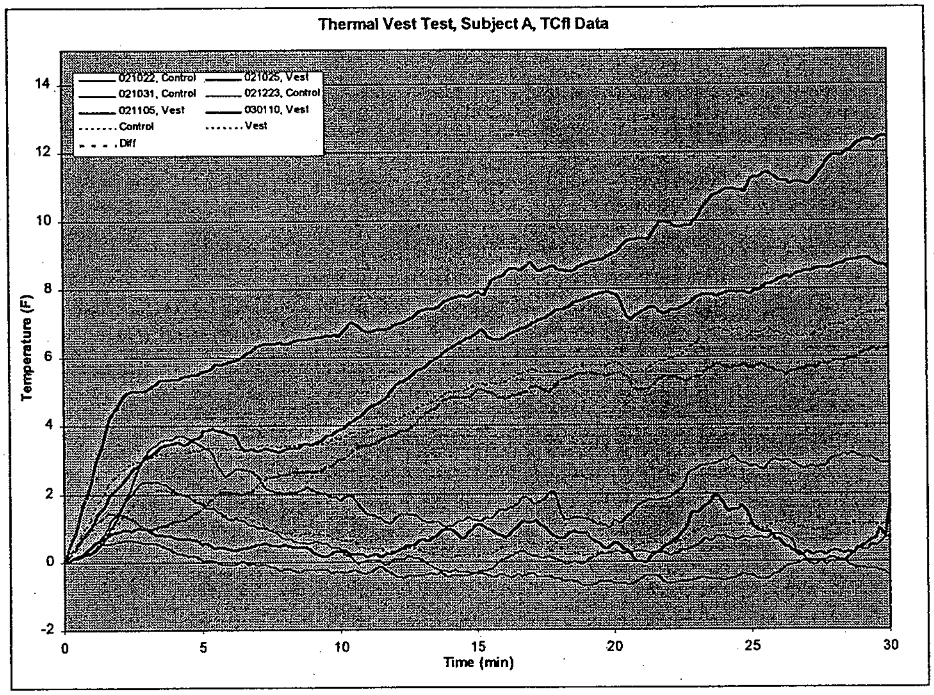


Figure 17: Thermal Vest Test, Subject A, TCfl Data

Some correlation detected, however Vest and Control tests coincide.

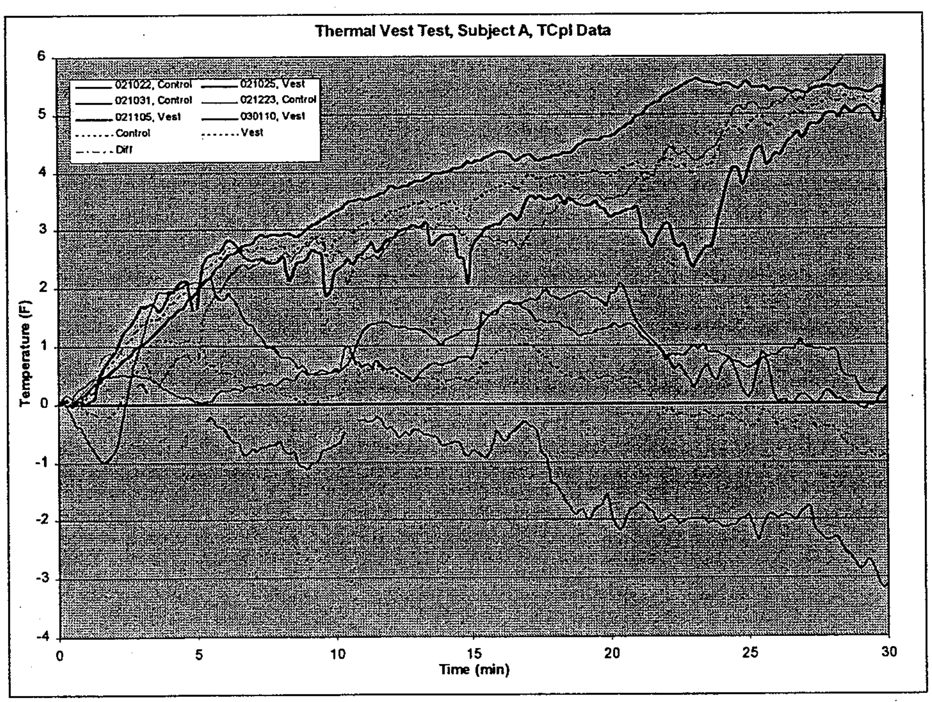


Figure 18: Thermal Vest Test, Subject A, TCpl Data

Some correlation detected, however Vest and Control tests coincide.

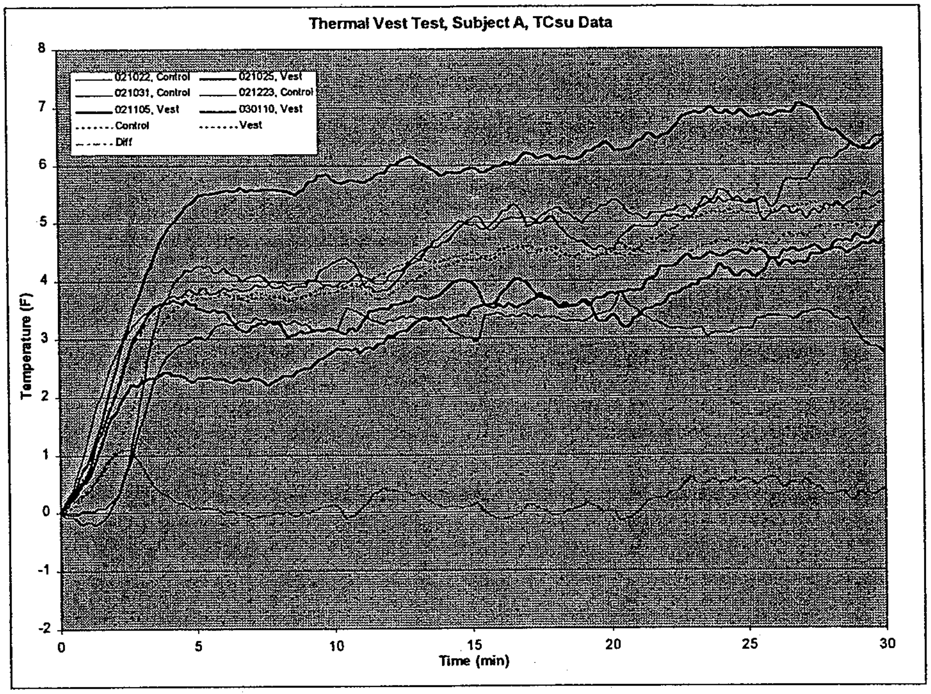


Figure 19: Thermal Vest Test, Subject A, TCsu Data

No correlation detected, Vest and Control tests coincide.

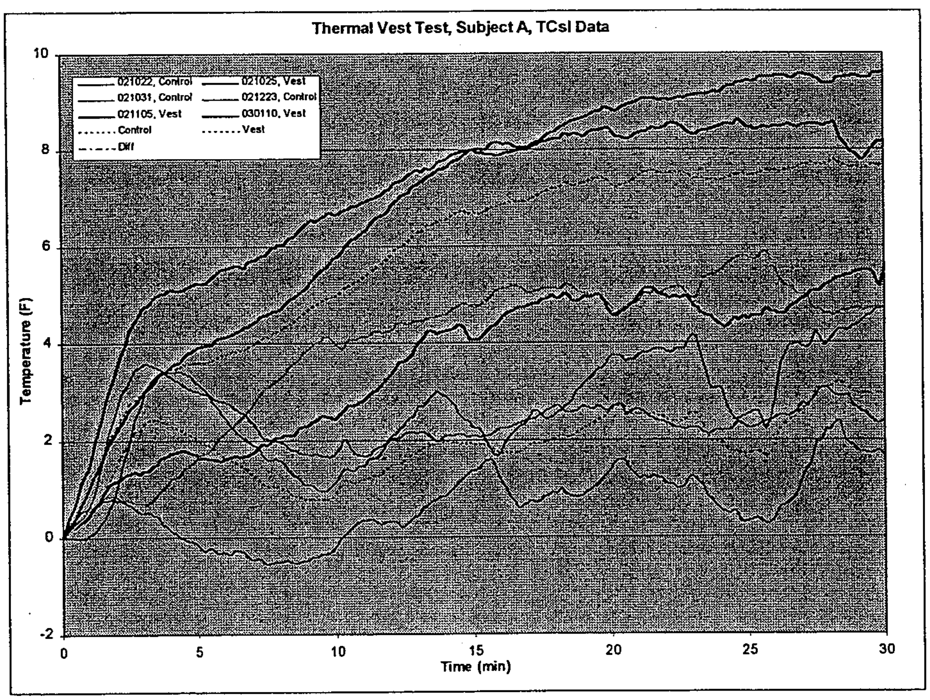


Figure 20: Thermal Vest Test, Subject A, TCsl Data

Some correlation, most Vest data exceeds Control data.

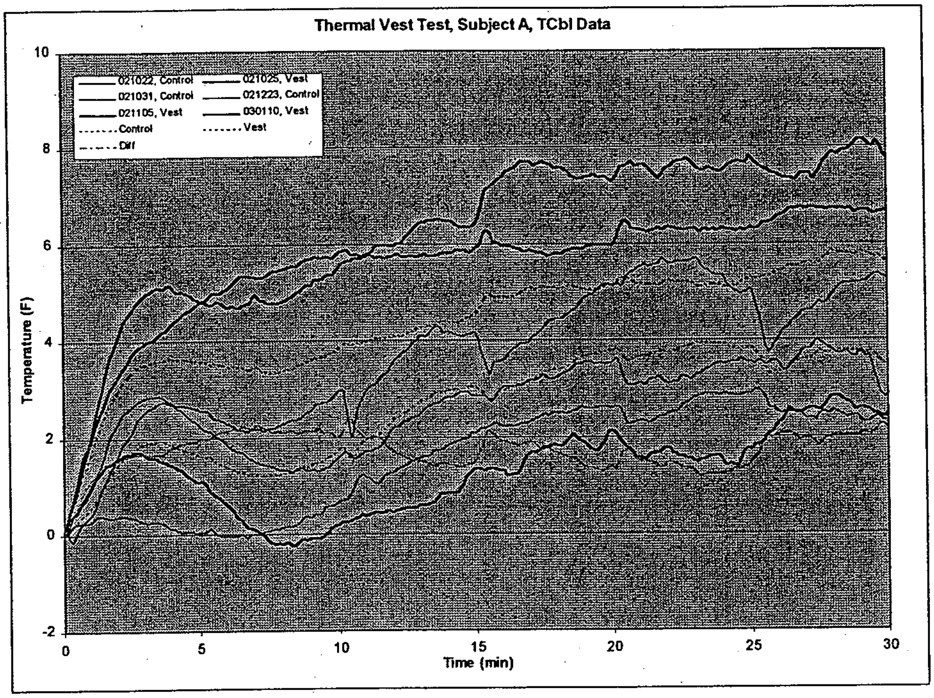


Figure 21: Thermal Vest Test, Subject A, TCbl Data

Some correlation detected, however Vest and Control tests coincide.

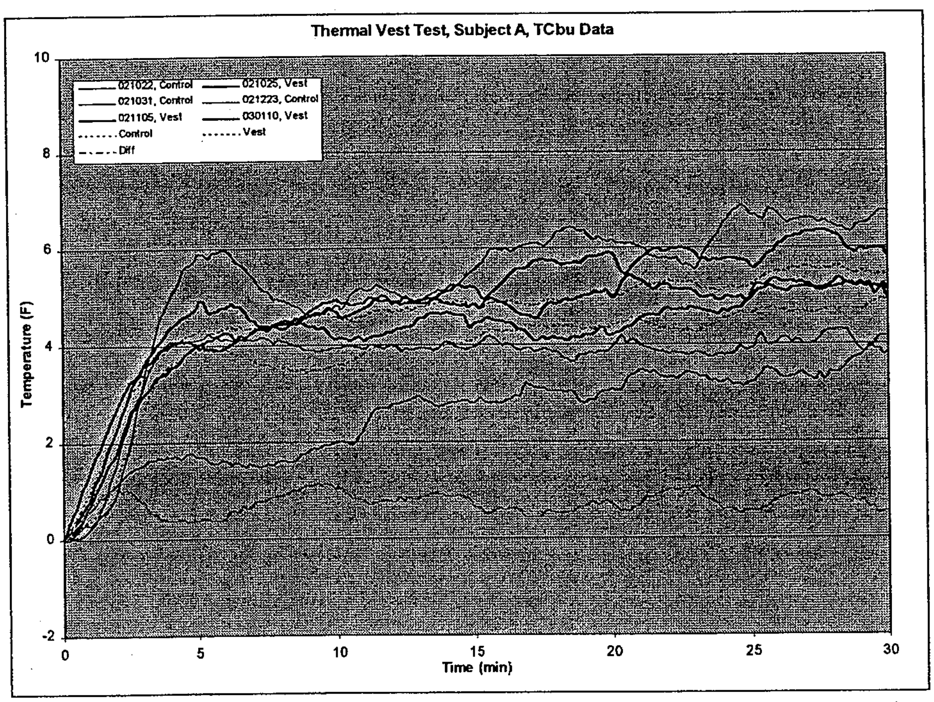


Figure 22: Thermal Vest Test, Subject A, TCbu Data

No correlation detected, Vest and Control tests coincide.

PRELIMINARY

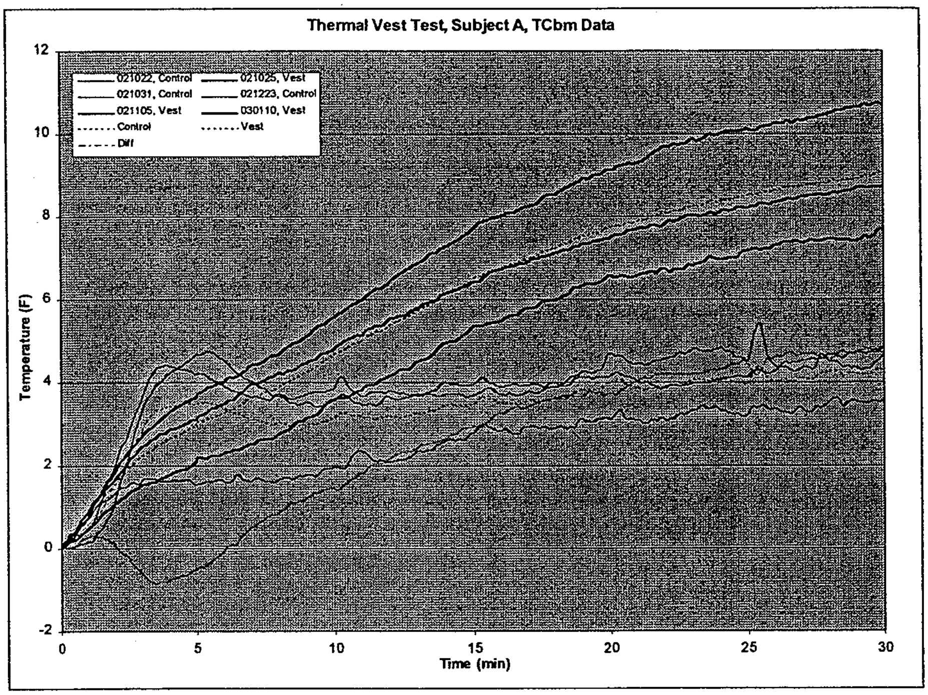


Figure 23: Thermal Vest Test, Subject A, TCbm Data

Good correlation, after 7 minutes, all Vest data is above Control data.

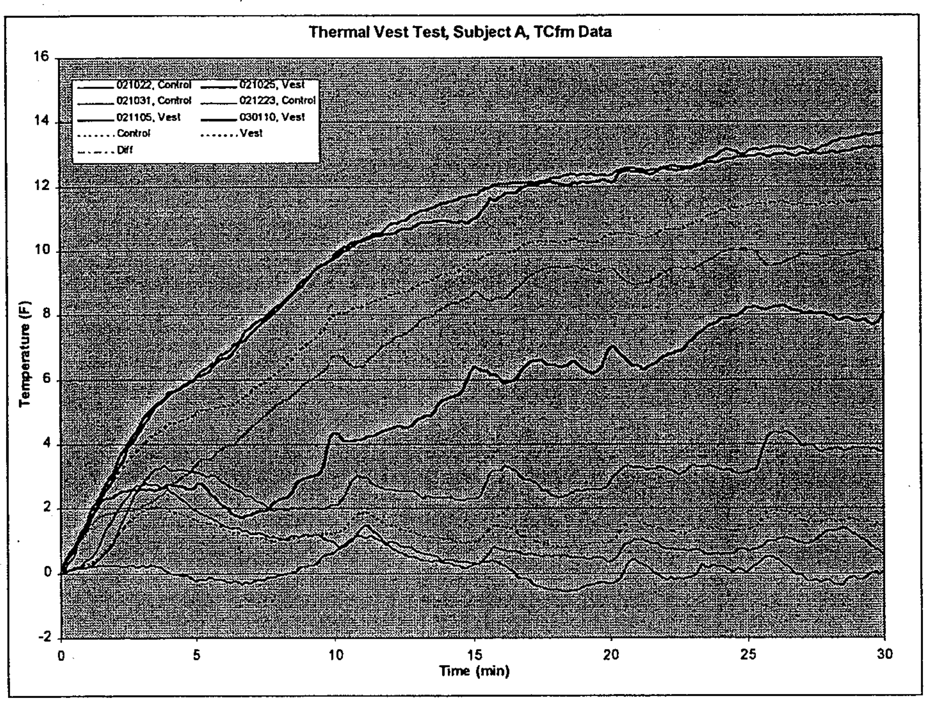


Figure 24: Thermal Vest Test, Subject A, TCfm Data

Good correlation, after 7 minutes, all Vest data is above Control data.

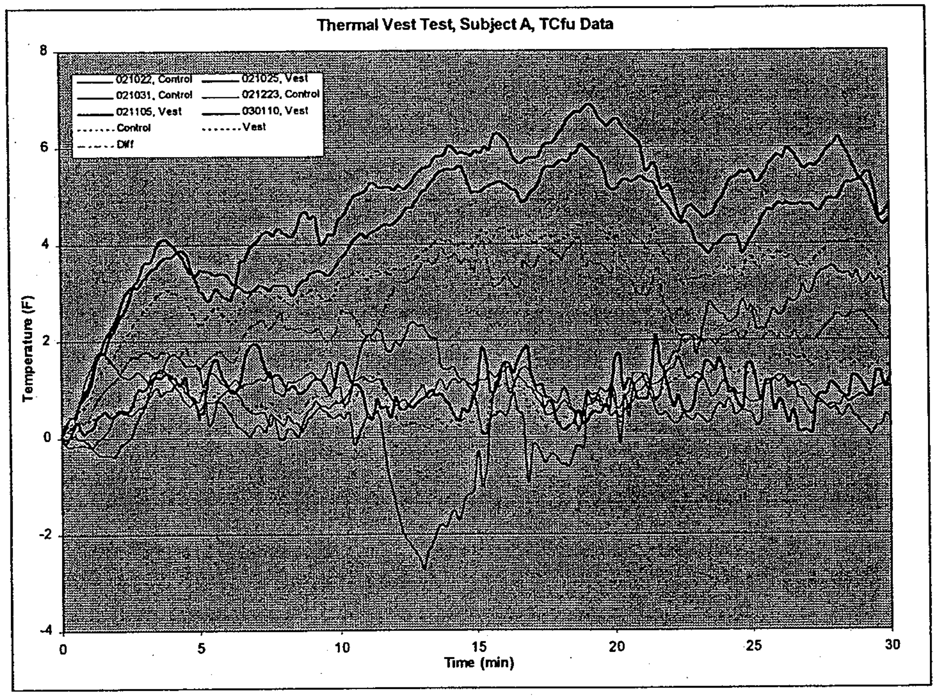


Figure 25: Thermal Vest Test, Subject A, TCfu Data

Some correlation detected, however Vest and Control tests coincide.

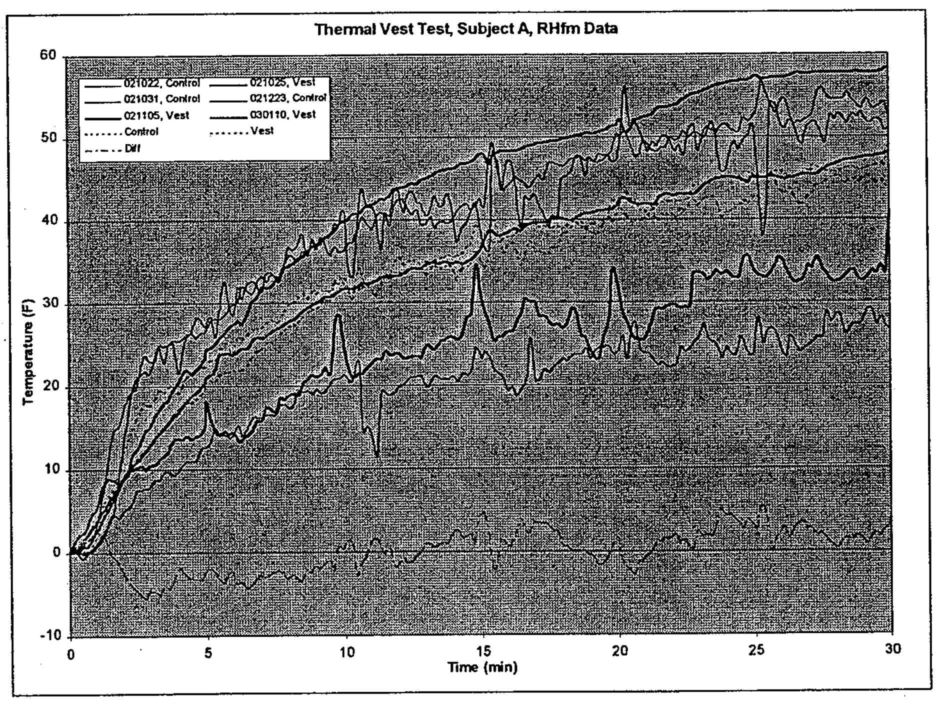


Figure 26: Thermal Vest Test, Subject A, RHfm Data

No correlation detected, Vest and Control tests coincide.

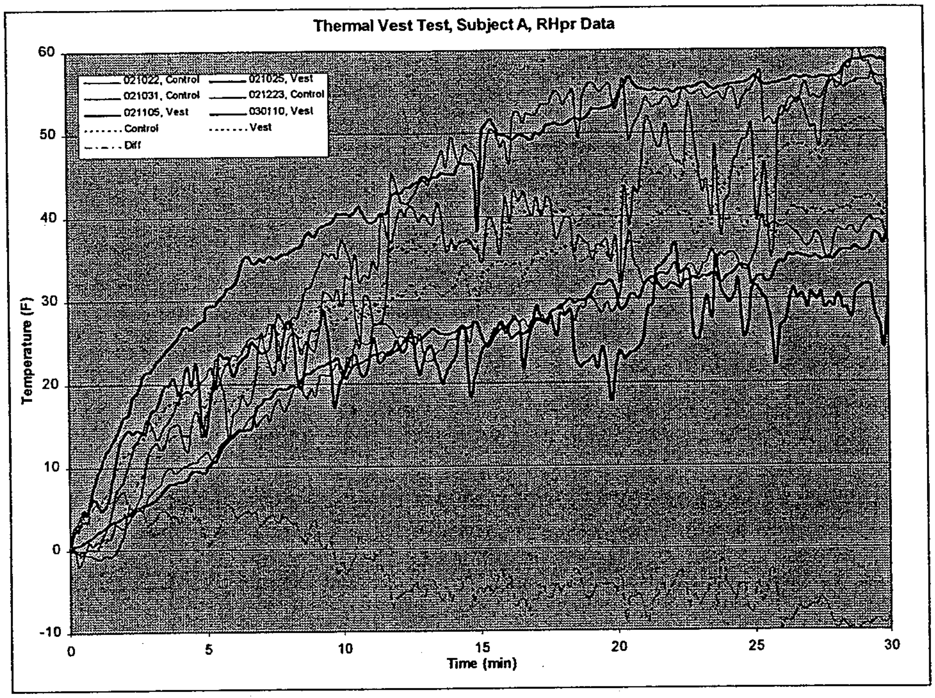


Figure 27: Thermal Vest Test, Subject A, RHpr Data

No correlation detected, Vest and Control tests coincide.

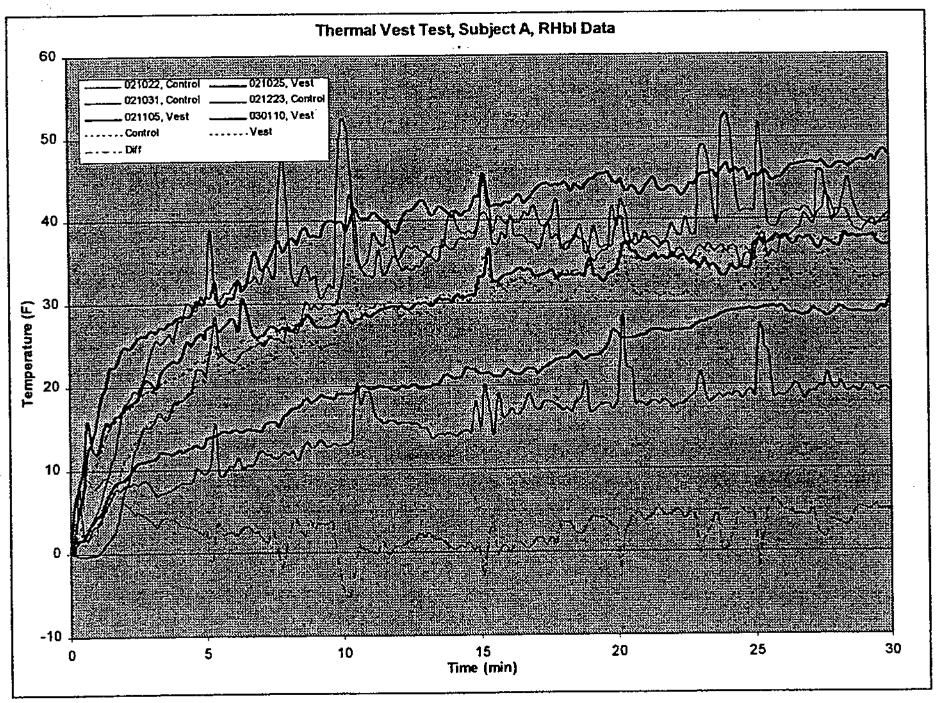


Figure 28: Thermal Vest Test, Subject A, RHbl Data

No correlation detected, Vest and Control tests coincide.

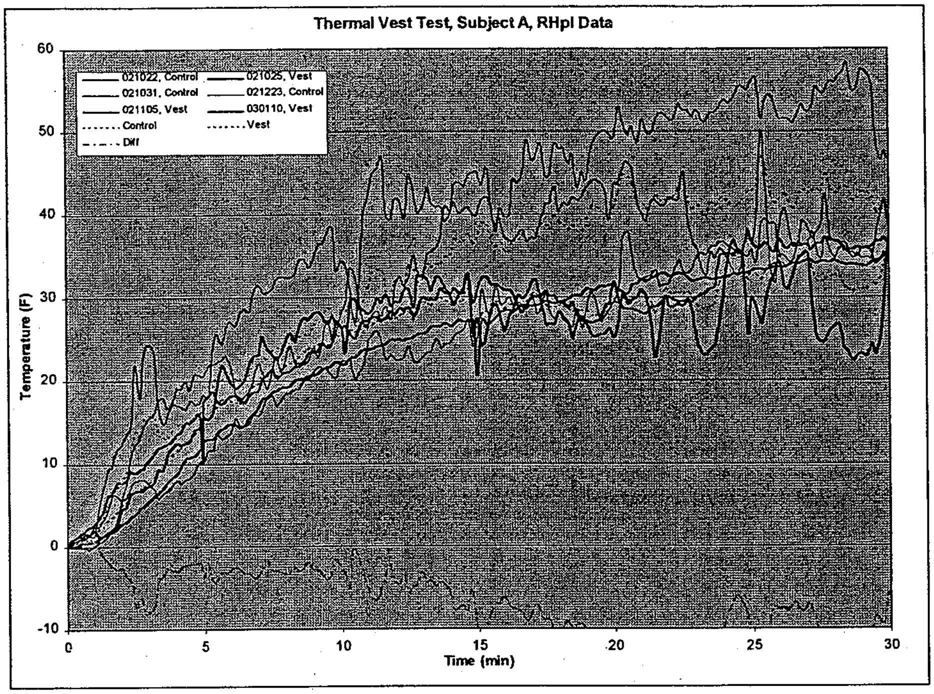


Figure 29: Thermal Vest Test, Subject A, RHpl Data

No correlation detected, Vest and Control tests coincide.

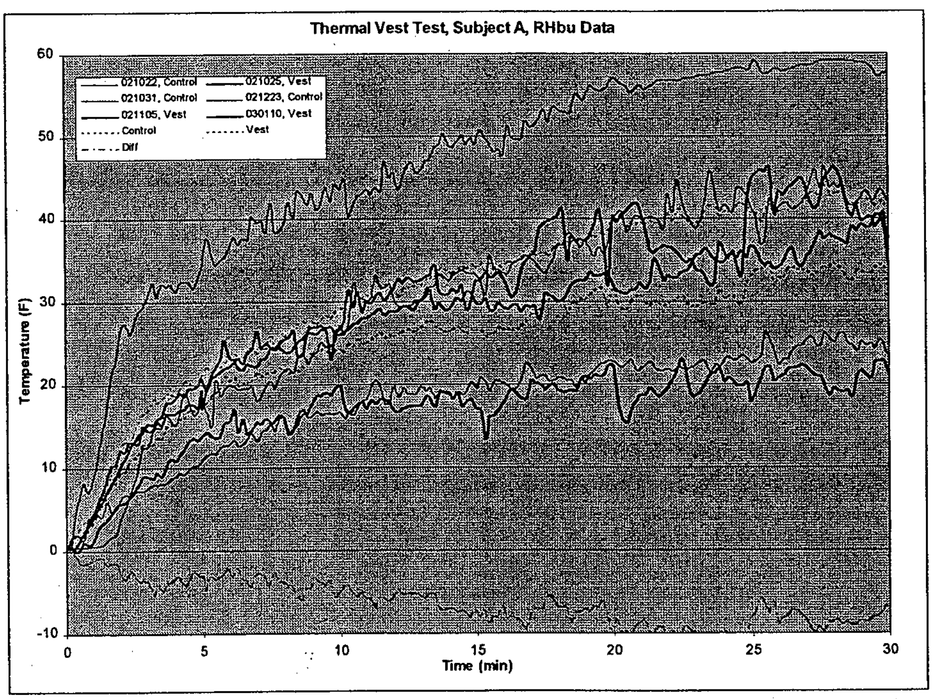


Figure 30: Thermal Vest Test, Subject A, RHbu Data

No correlation detected, Vest and Control tests coincide.

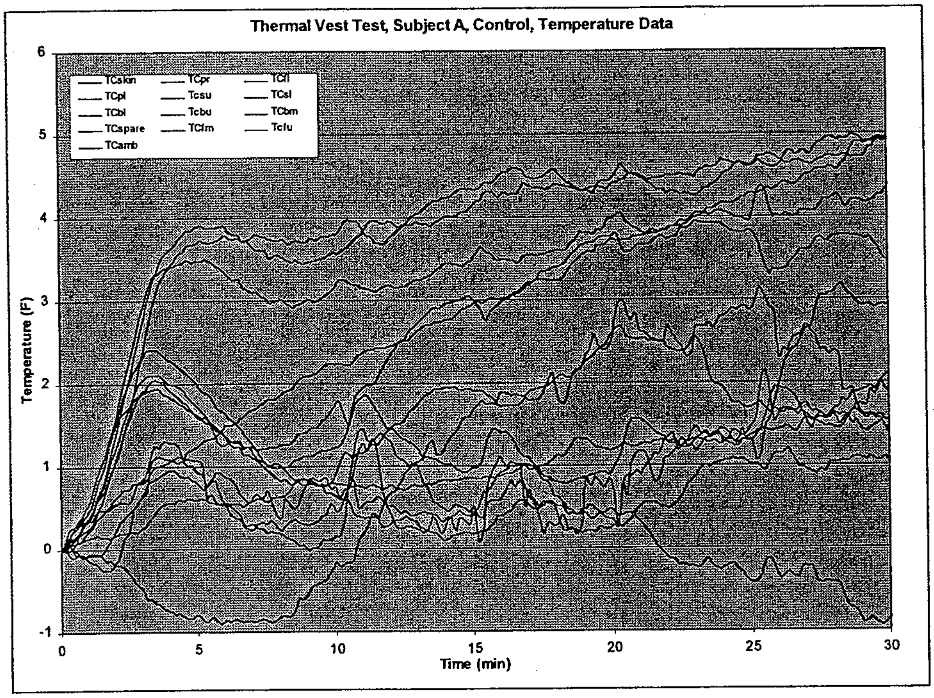


Figure 31: Thermal Vest Test, Subject A, Averaged Control Temperature Data

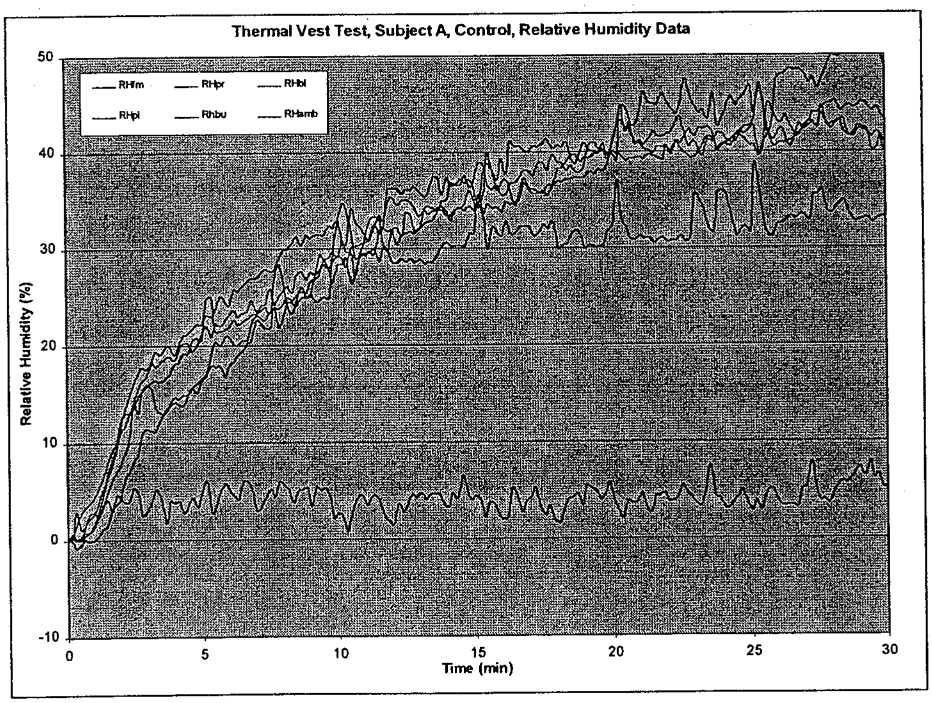


Figure 32: Thermal Vest Test, Subject A, Averaged Control Relative Humidity Data

No correlation detected, Vest and Control tests coincide.

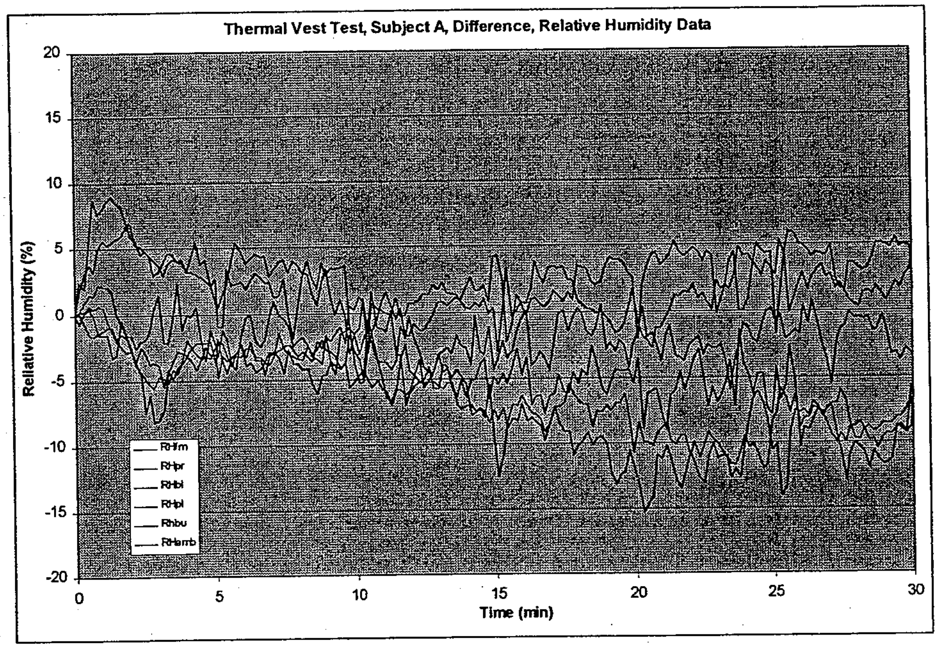


Figure 33: Thermal Vest Test, Subject A, Averaged Difference Relative Humidity Data

No correlation detected, Vest and Control tests coincide.

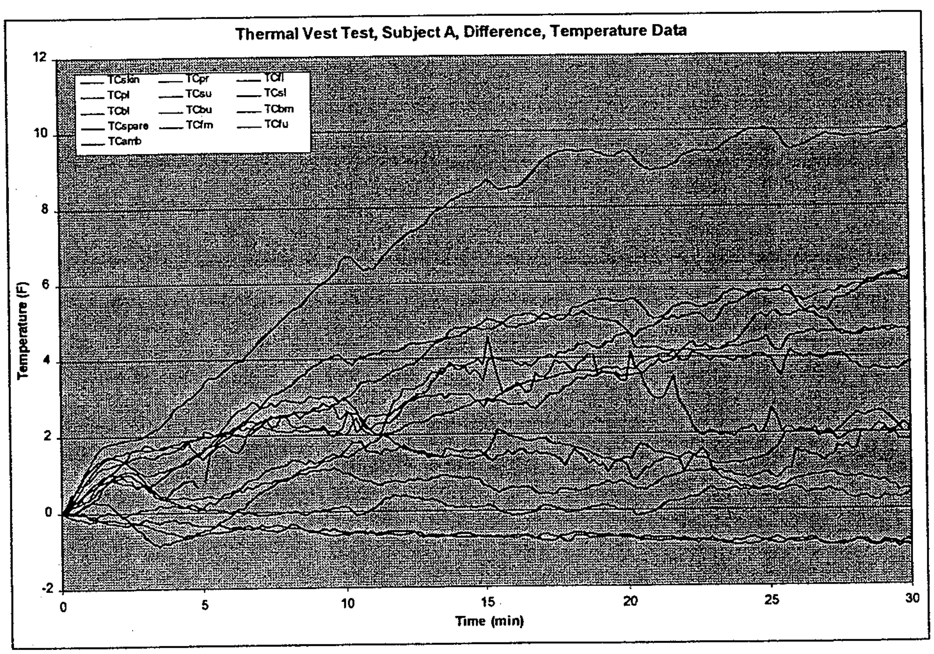


Figure 34: Thermal Vest Test, Subject A, Averaged Difference Temperature Data

PRELIMINARY

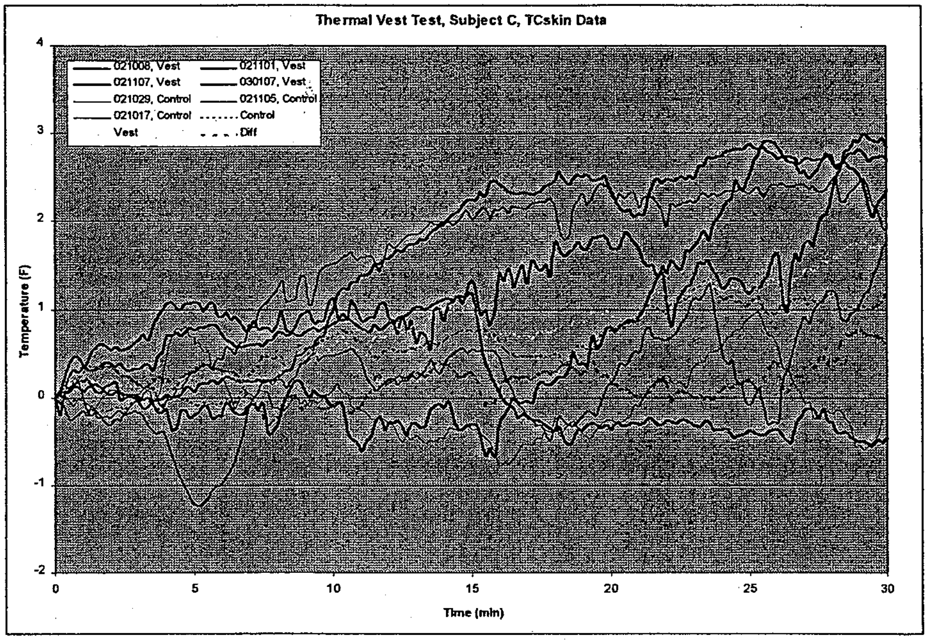


Figure 35: Thermal Vest Test, Subject C, TCskin Data

No correlation detected, Vest and Control tests coincide.

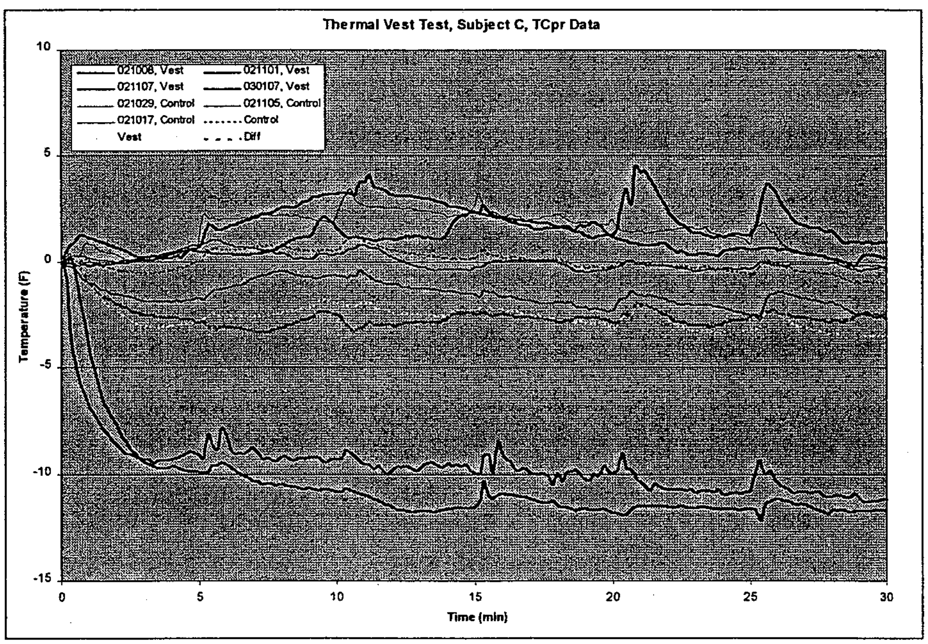


Figure 36: Thermal Vest Test, Subject C, TCpr Data

Some correlation detected, however Vest and Control tests coincide.

PRELIMINARY

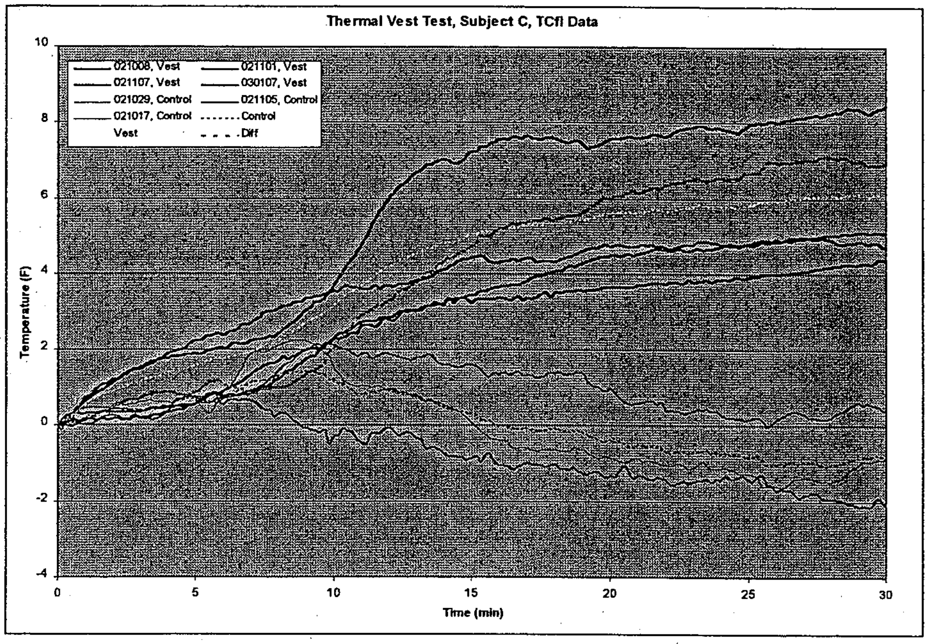


Figure 37: Thermal Vest Test, Subject C, TCfl Data

Some correlation, most Vest data is above Control data.

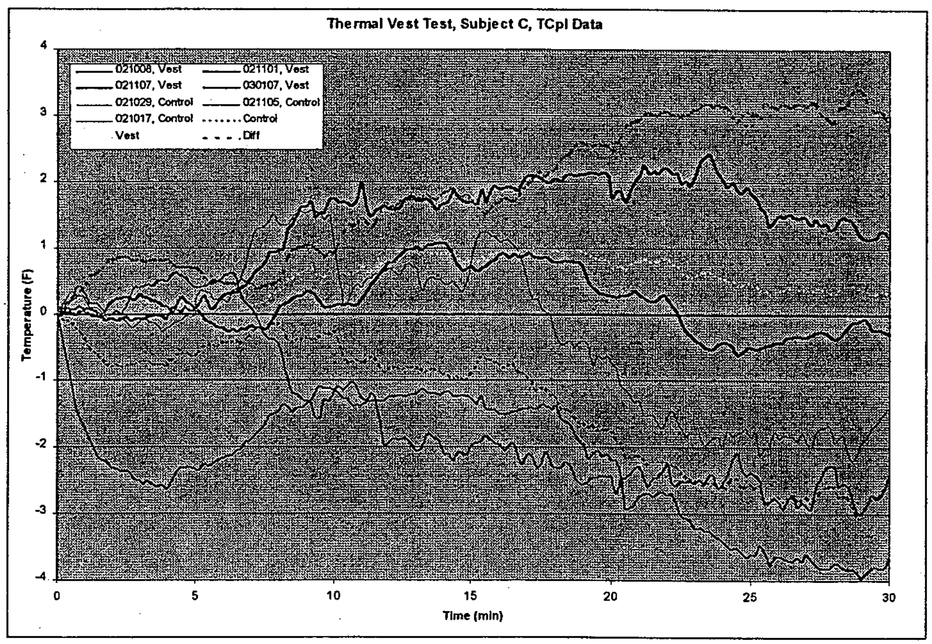


Figure 38: Thermal Vest Test, Subject C, TCpl Data

Some correlation detected, however Vest and Control tests coincide.
TCpl was non-functional.

PRELIMINARY

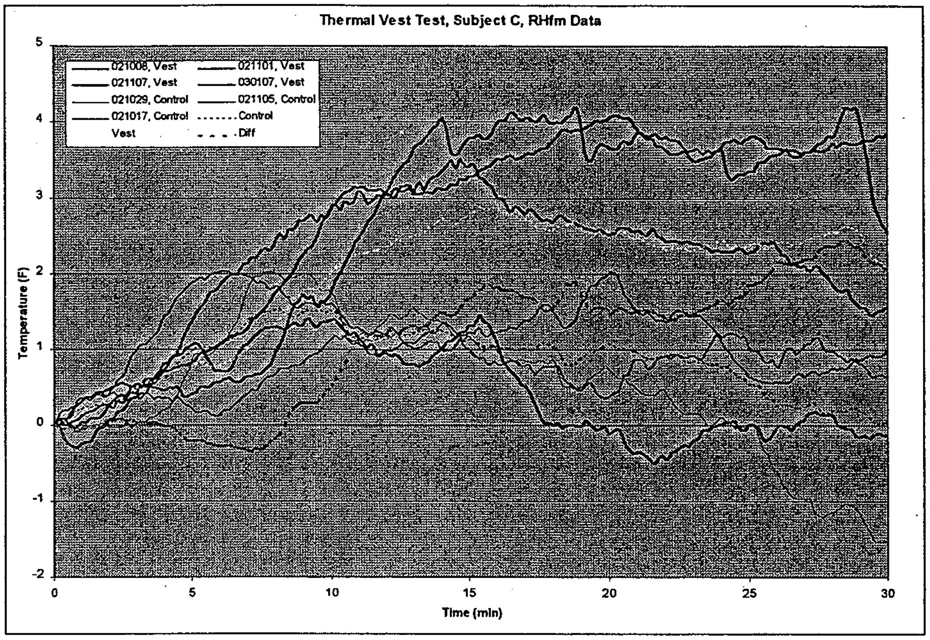


Figure 39: Thermal Vest Test, Subject C, TCskin Data

Some correlation detected, however Vest and Control tests coincide.

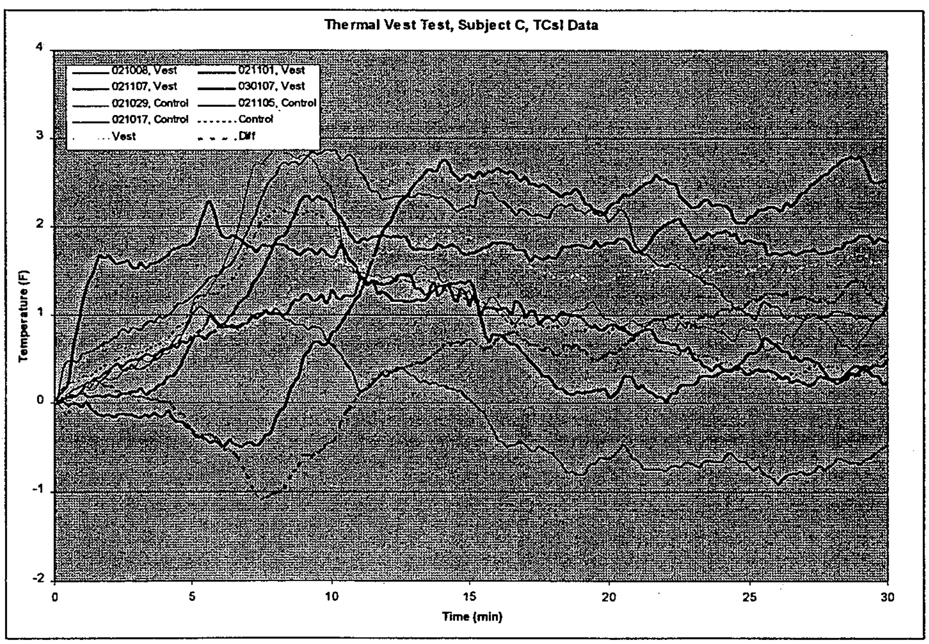


Figure 40: Thermal Vest Test, Subject C, TCsl Data

Slight correlation detected, Vest and Control tests coincide.

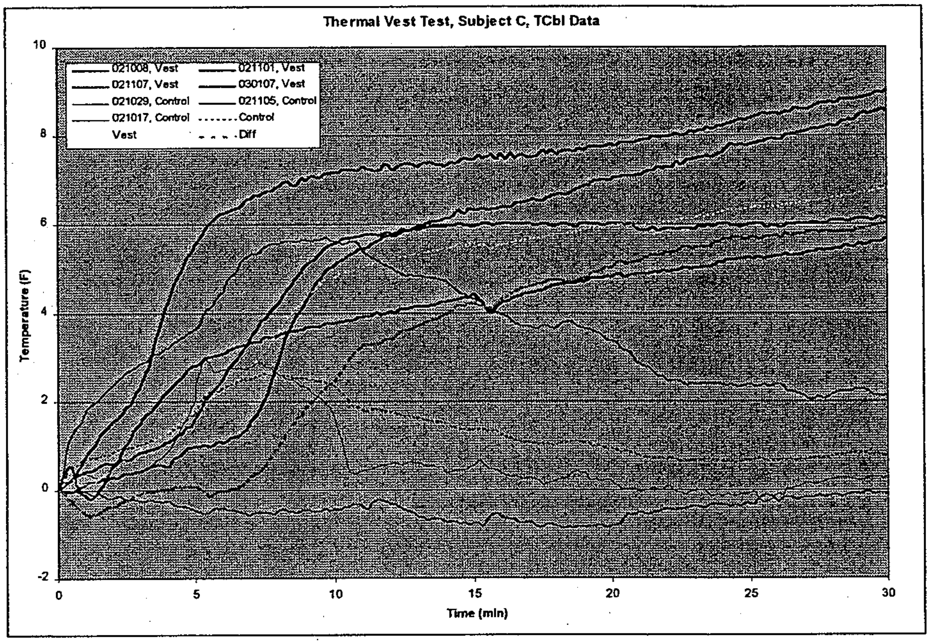


Figure 41: Thermal Vest Test, Subject C, TCbl Data

Good correlation, most Vest data is above Control data.

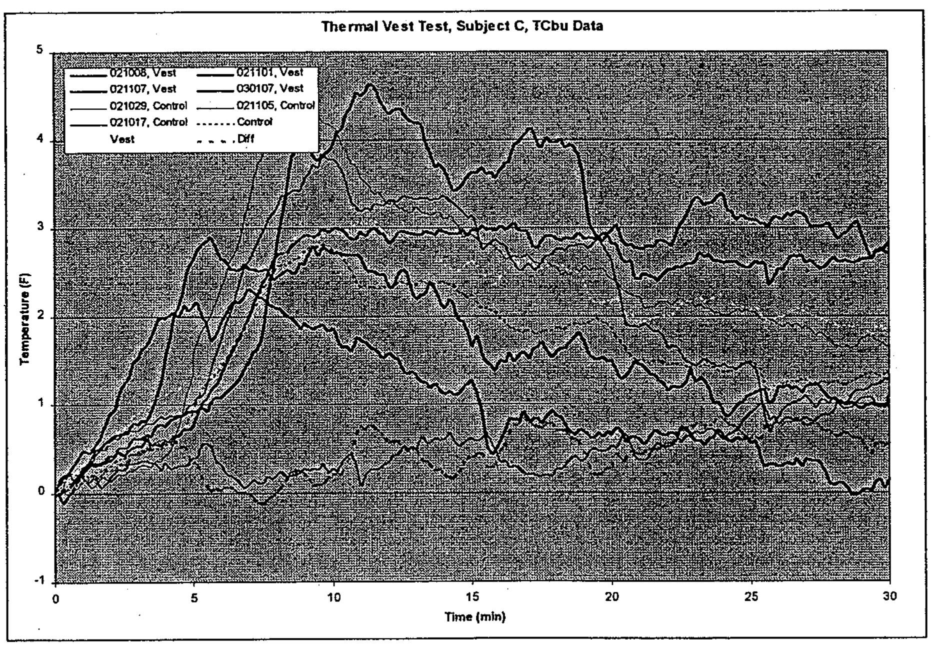


Figure 42: Thermal Vest Test, Subject C, TCbu Data

Slight correlation detected, Vest and Control tests coincide.

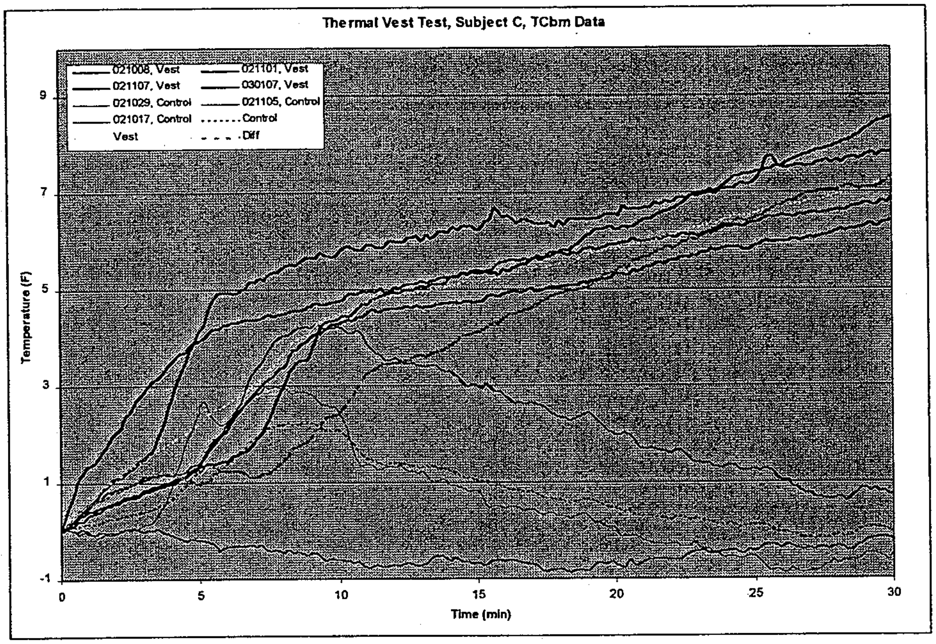


Figure 43: Thermal Vest Test, Subject C, TCbm Data

Good correlation, most Vest data is exceeds Control data.

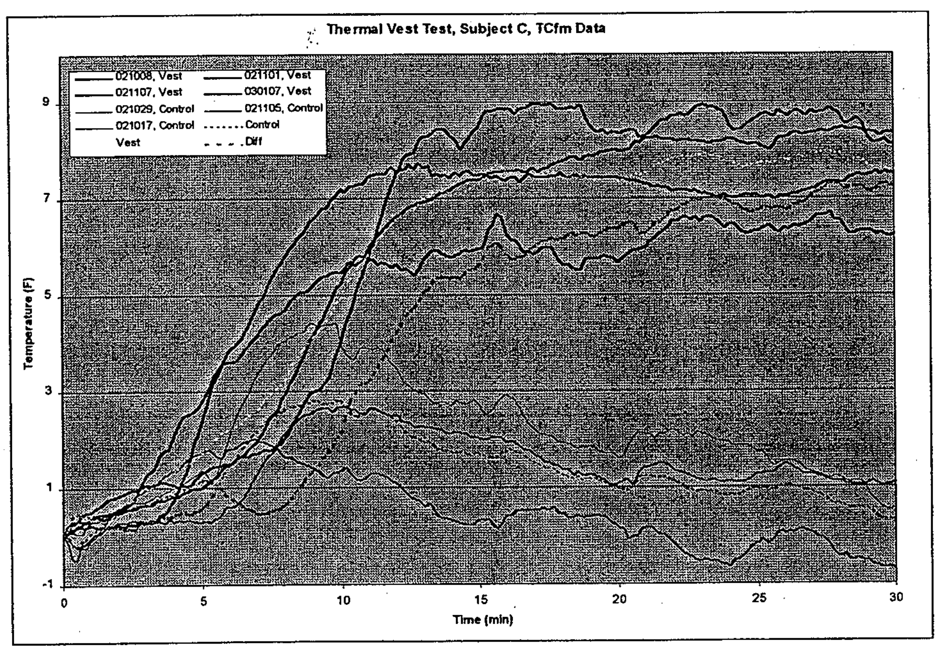


Figure 44: Thermal Vest Test, Subject C, TCfm Data

Good correlation, most Vest data exceeds Control data.

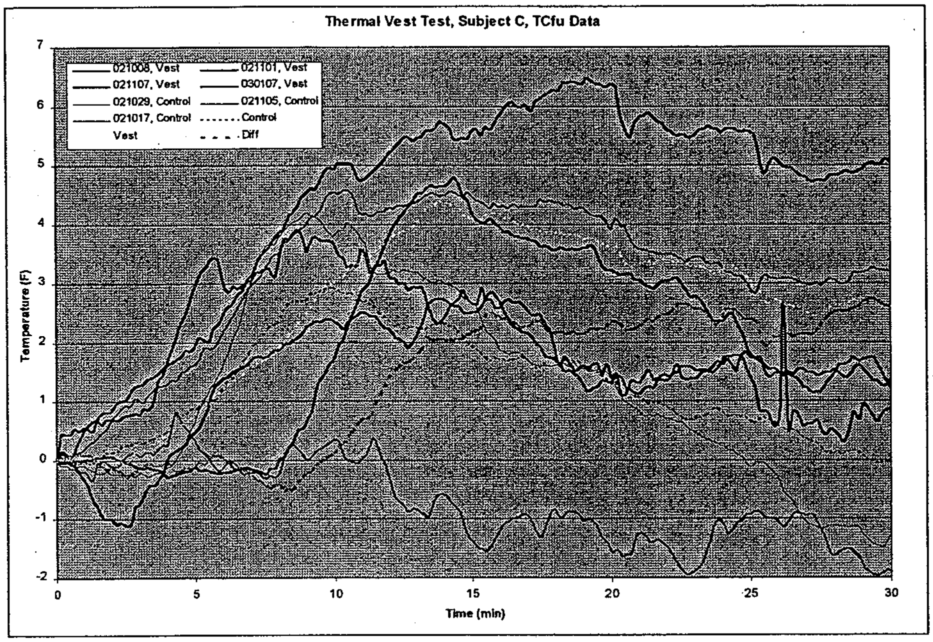


Figure 45: Thermal Vest Test, Subject C, TCfu Data

Some correlation detected, however Vest and Control tests coincide.

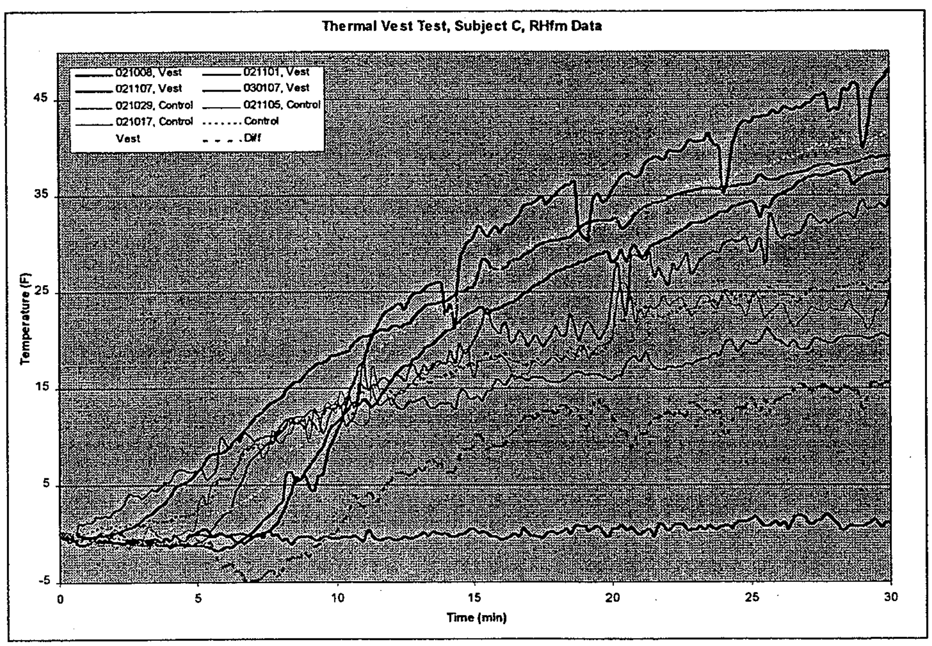


Figure 46: Thermal Vest Test, Subject C, RHfm Data

Some correlation, most Vest data exceeds Control data.
Note the data shifts every 5 minutes due to water break and the volunteer sitting up in the seat.

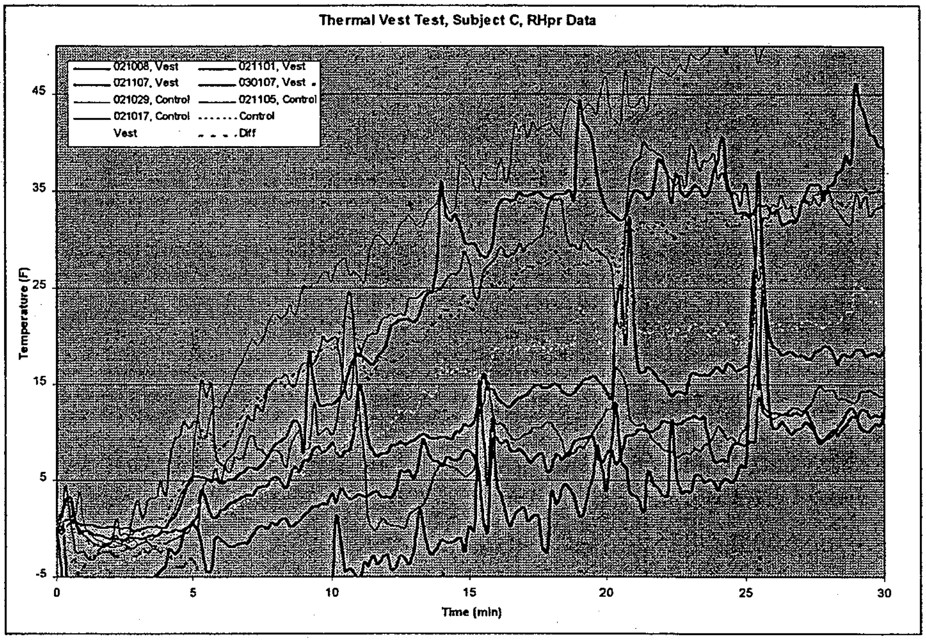


Figure 47: Thermal Vest Test, Subject C, RHpr Data

Some correlation detected, however Vest and Control tests coincide.
Note the data shifts every 5 minutes due to water break and the volunteer standing up in the seat.

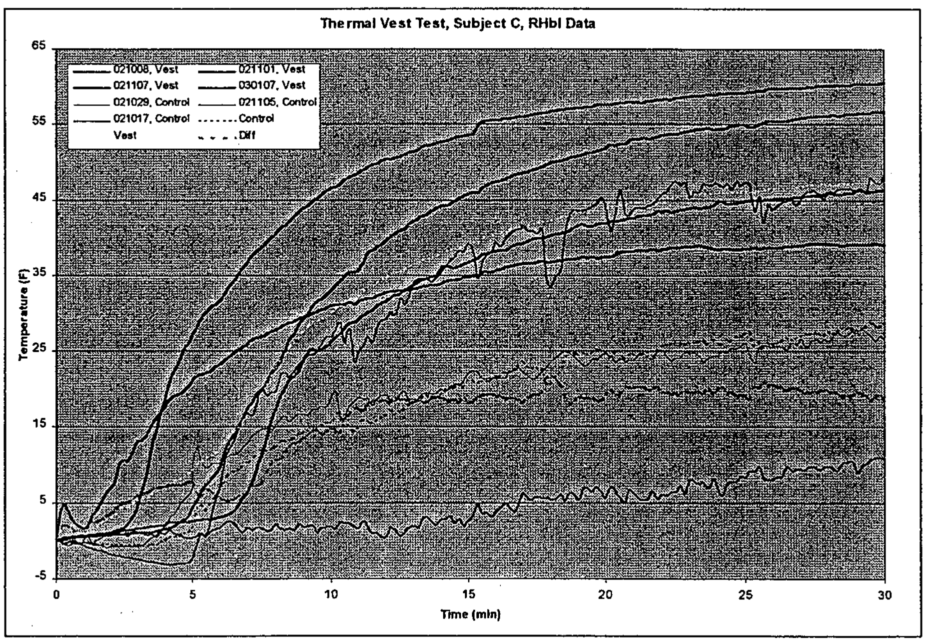


Figure 48: Thermal Vest Test, Subject C, RHbl Data

Some correlation detected, however Vest and Control tests coincide.

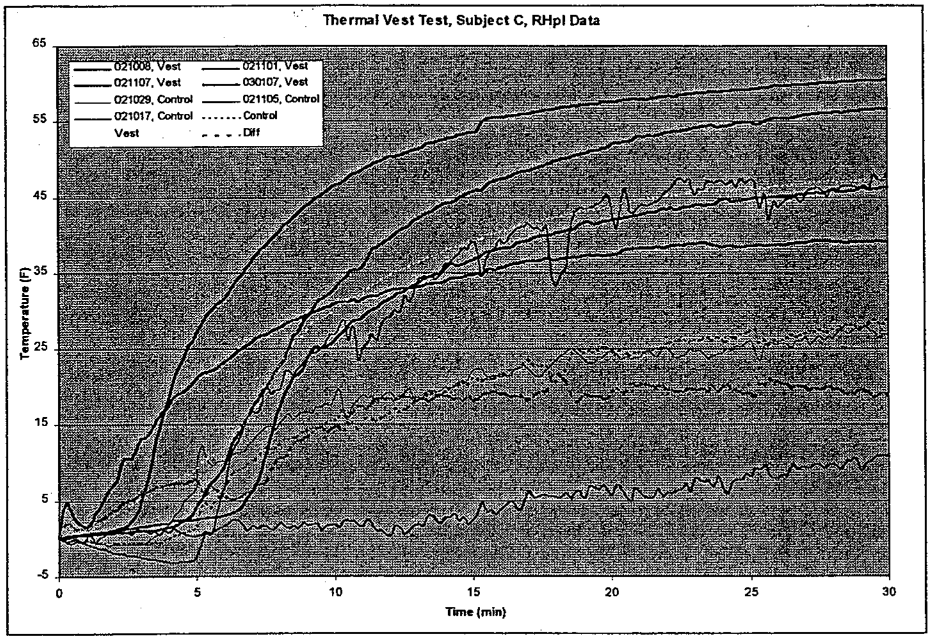


Figure 49: Thermal Vest Test, Subject C, RHpl Data

Some correlation detected, however Vest and Control tests coincide.

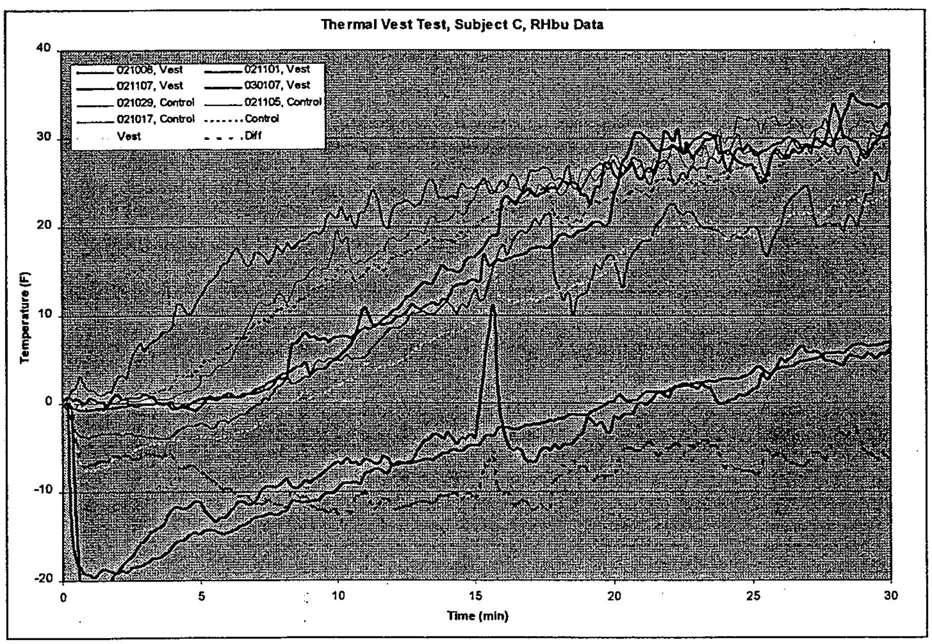


Figure 50: Thermal Vest Test, Subject C, RHbu Data

No correlation detected, Vest and Control tests coincide.

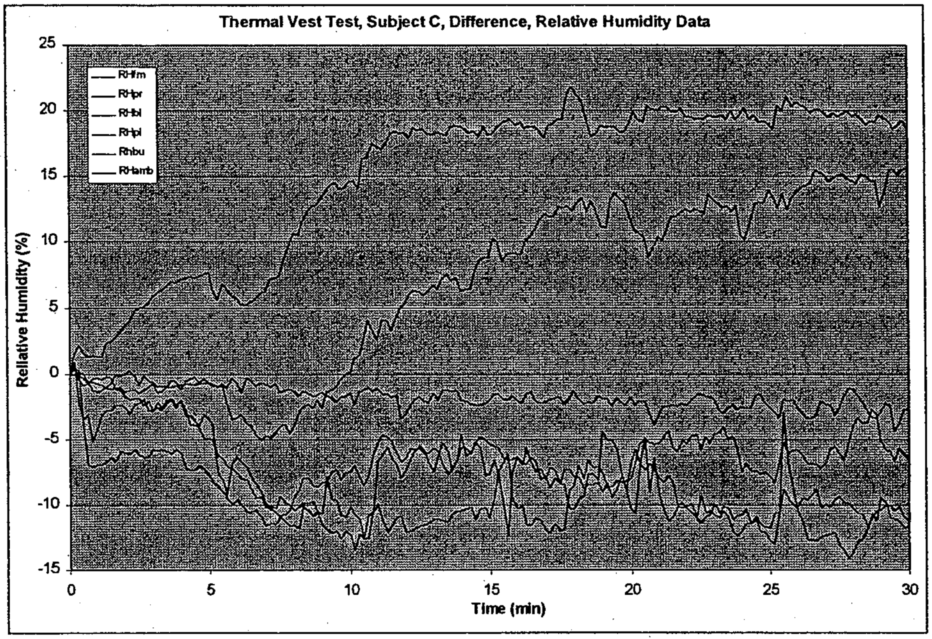


Figure 51: Thermal Vest Test, Subject C, Difference Relative Humidity Data

Some correlation detected for RHfm and RHbl.

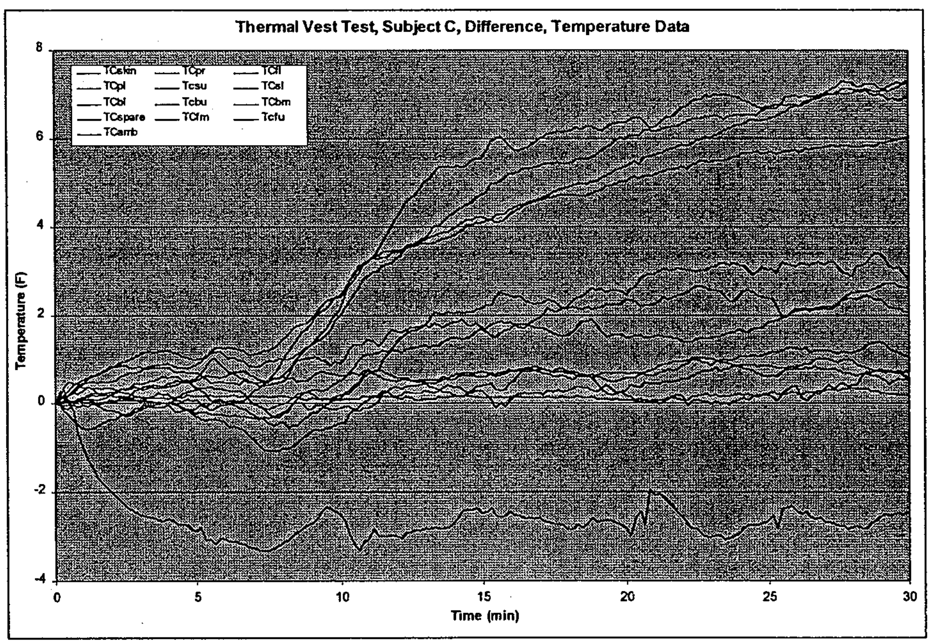


Figure 52: Thermal Vest Test, Subject C, Difference Temperature Data

PRELIMINARY

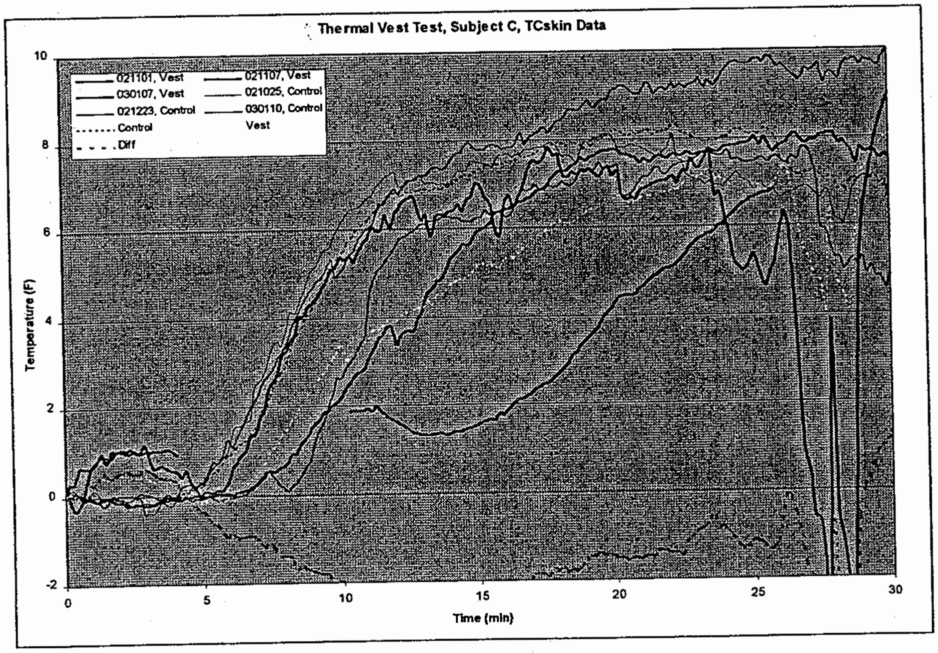


Figure 53: Thermal Vest Test, Subject D, TCskin Data

No correlation detected, Vest and Control tests coincide.

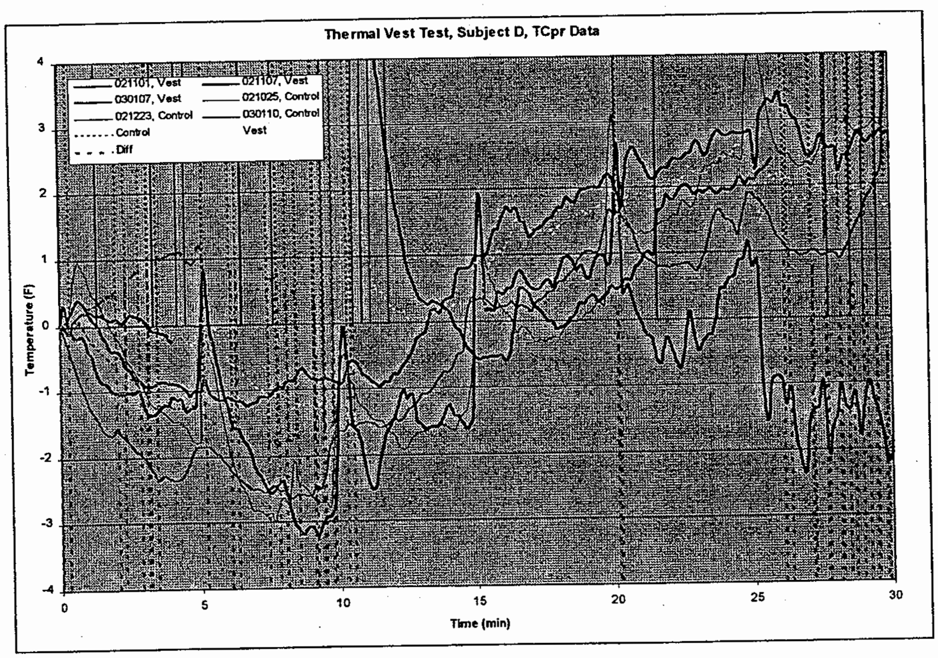


Figure 54: Thermal Vest Test, Subject D, TCpr Data

No correlation detected, Vest and Control tests coincide.
Note the data shifts every 5 minutes due to water break and the volunteer standing up in the seat.

PRELIMINARY

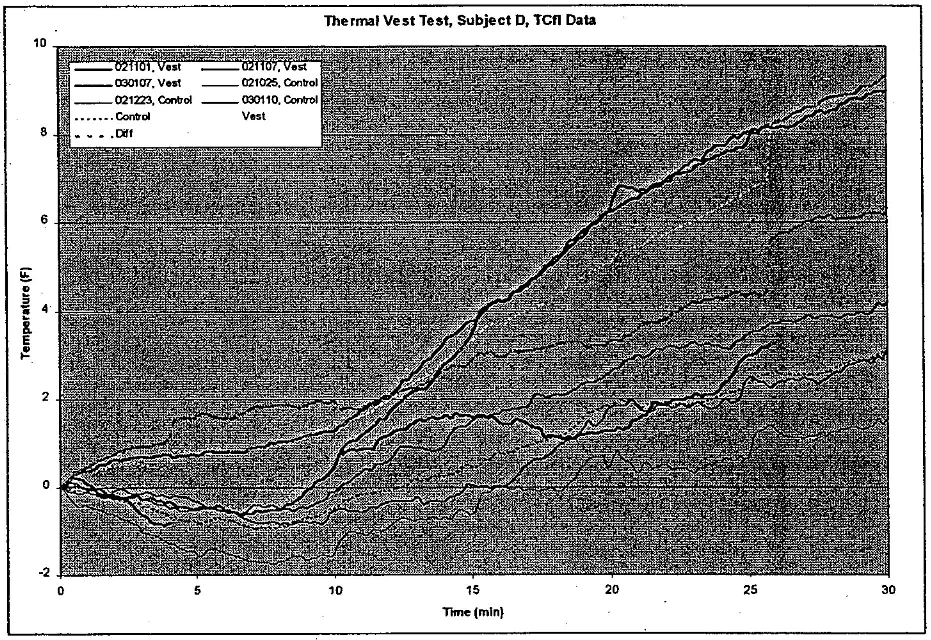


Figure 55: Thermal Vest Test, Subject D, TCfl Data

Some correlation detected, however Vest and Control tests coincide.

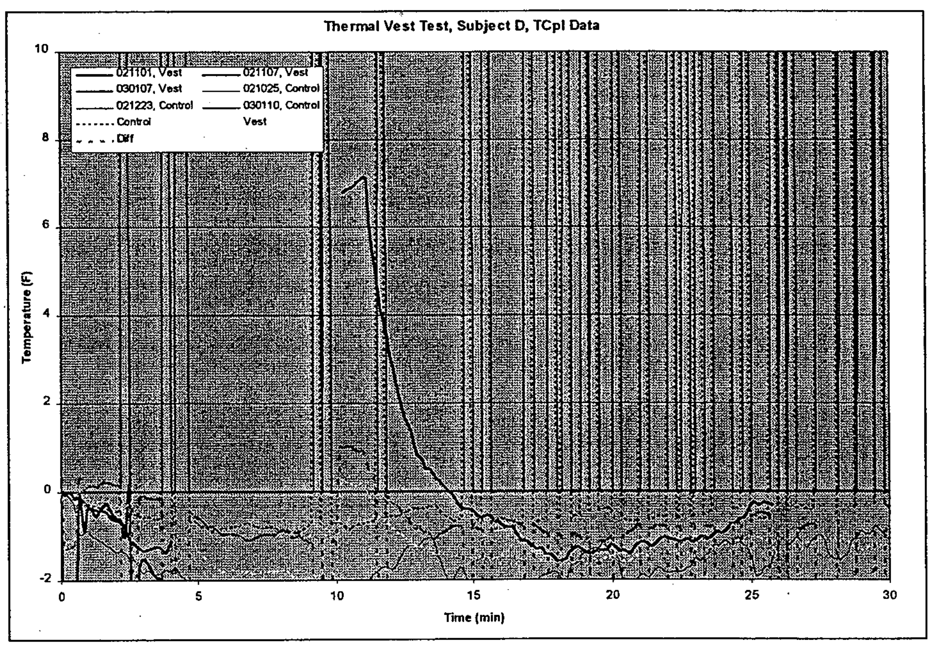


Figure 56: Thermal Vest Test, Subject D, TCpl Data

No correlation detected, Vest and Control tests coincide.
TCpl was non-functional.

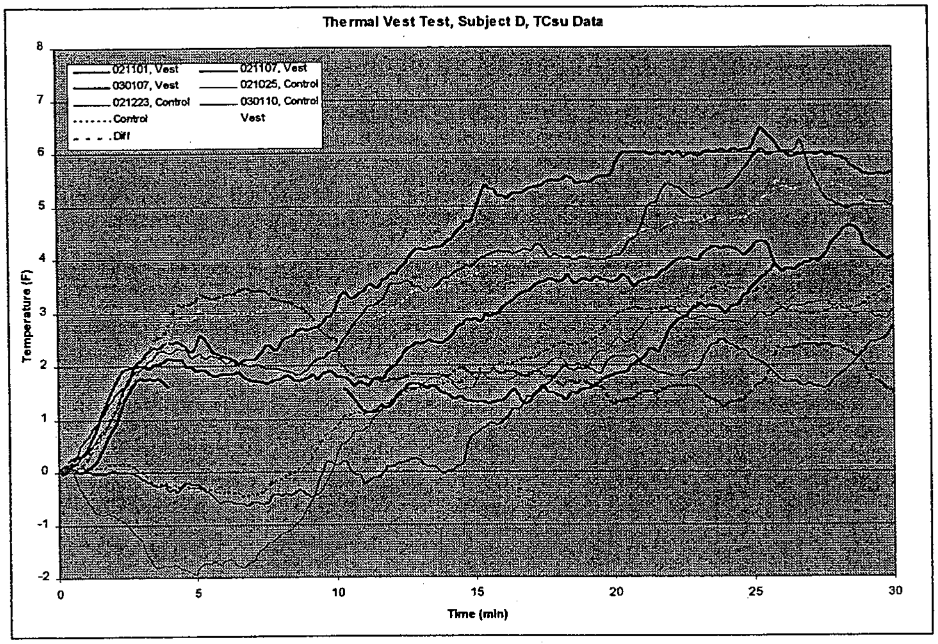


Figure 57: Thermal Vest Test, Subject D, TCsu Data

Some correlation detected, however Vest and Control tests coincide.

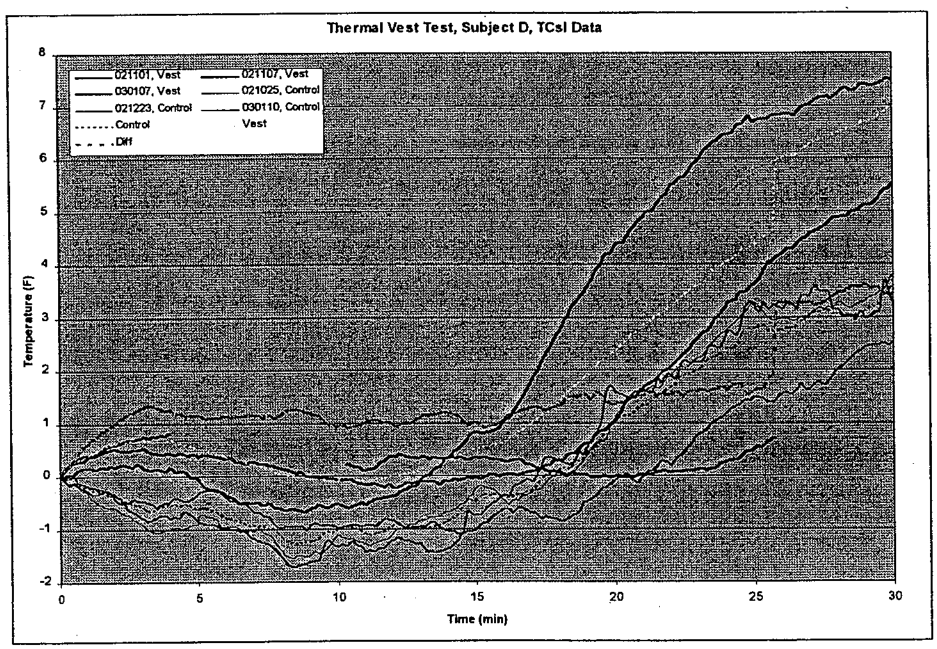


Figure 58: Thermal Vest Test, Subject D, TCl Data

Some correlation detected, Vest and Control tests coincide.

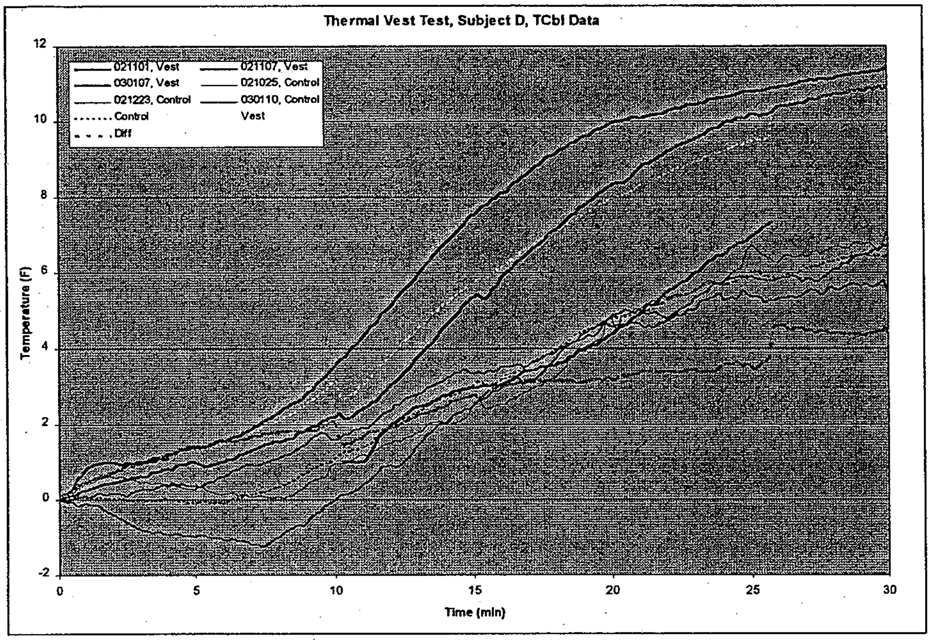


Figure 59: Thermal Vest Test, Subject D, TCbl Data

Some correlation detected, however Vest and Control tests coincide.

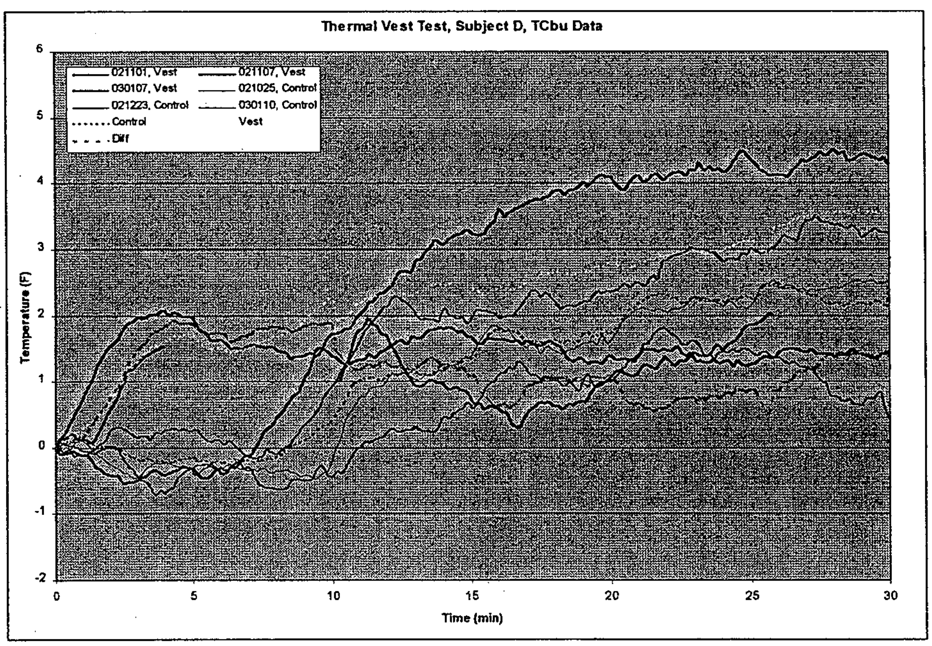


Figure 60: Thermal Vest Test, Subject D, TCbu Data

Some correlation detected, however Vest and Control tests coincide.

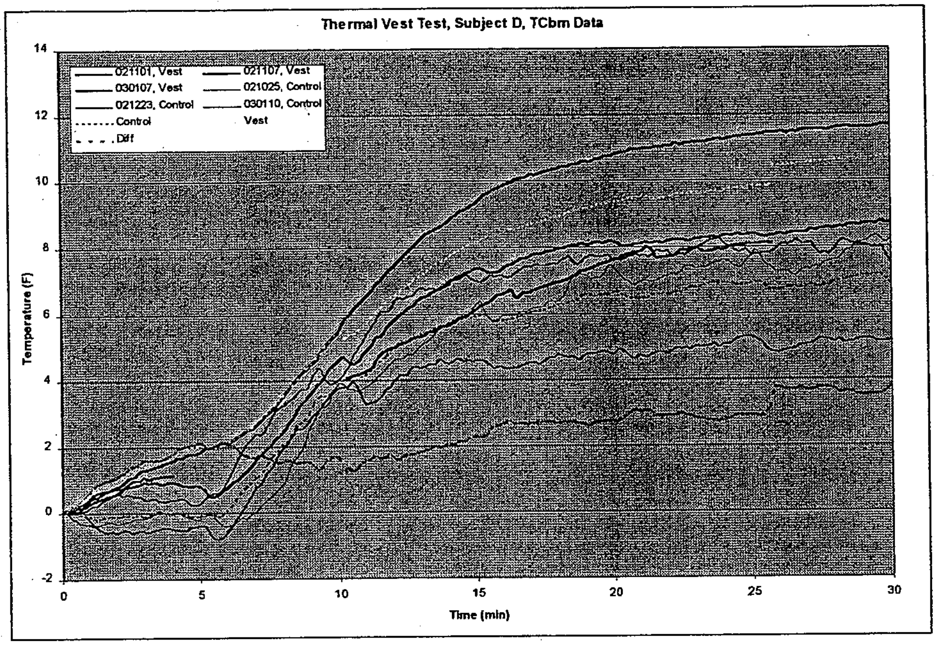


Figure 61: Thermal Vest Test, Subject D, TCbm Data

Good correlation, most Vest data exceeds Control data.

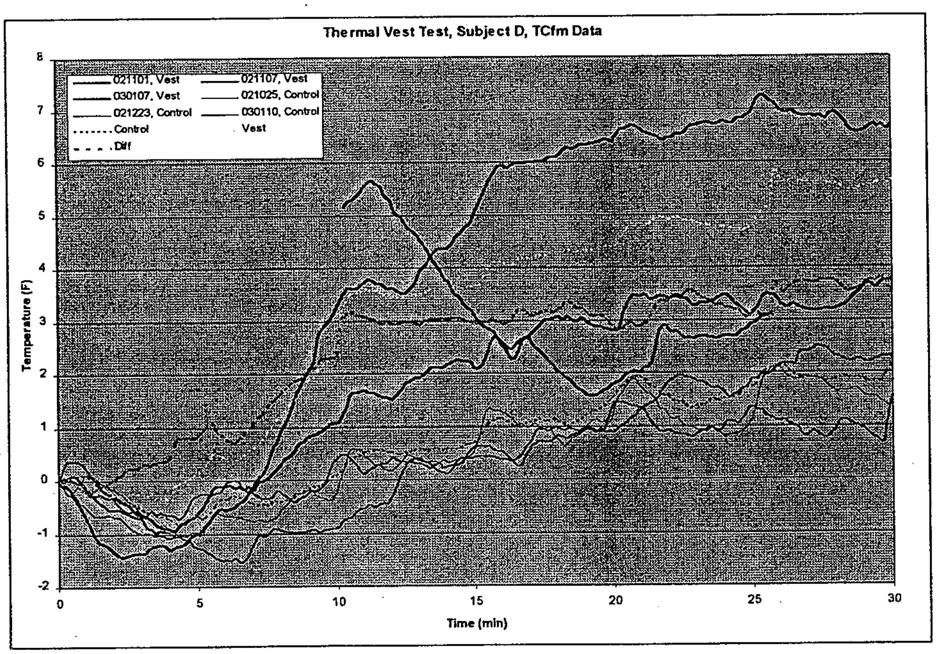


Figure 62: Thermal Vest Test, Subject D, TCfm Data

Some correlation detected, however Vest and Control tests coincide.

PRELIMINARY

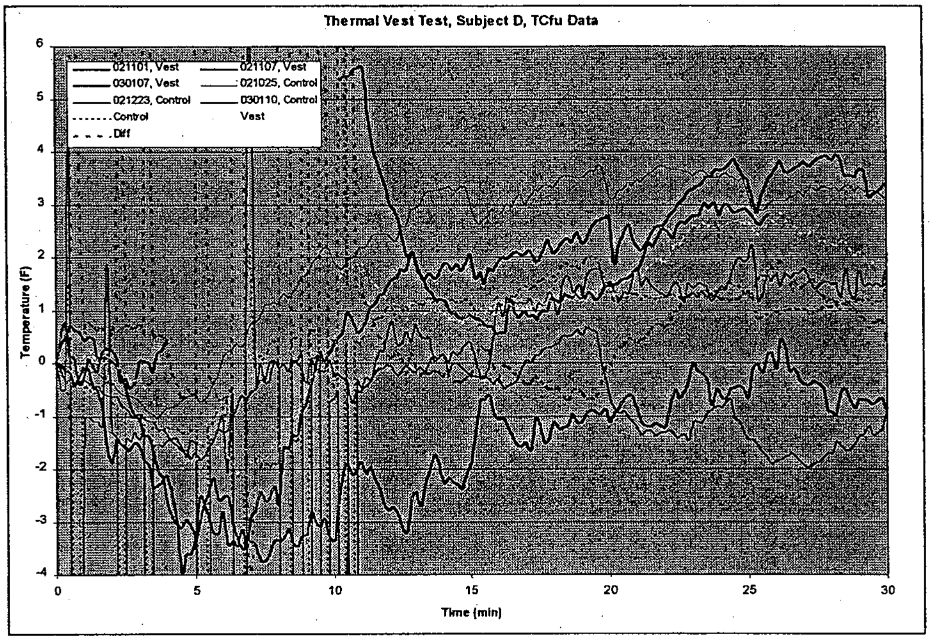


Figure 63: Thermal Vest Test, Subject D, TCfu Data

No correlation detected, Vest and Control tests coincide.

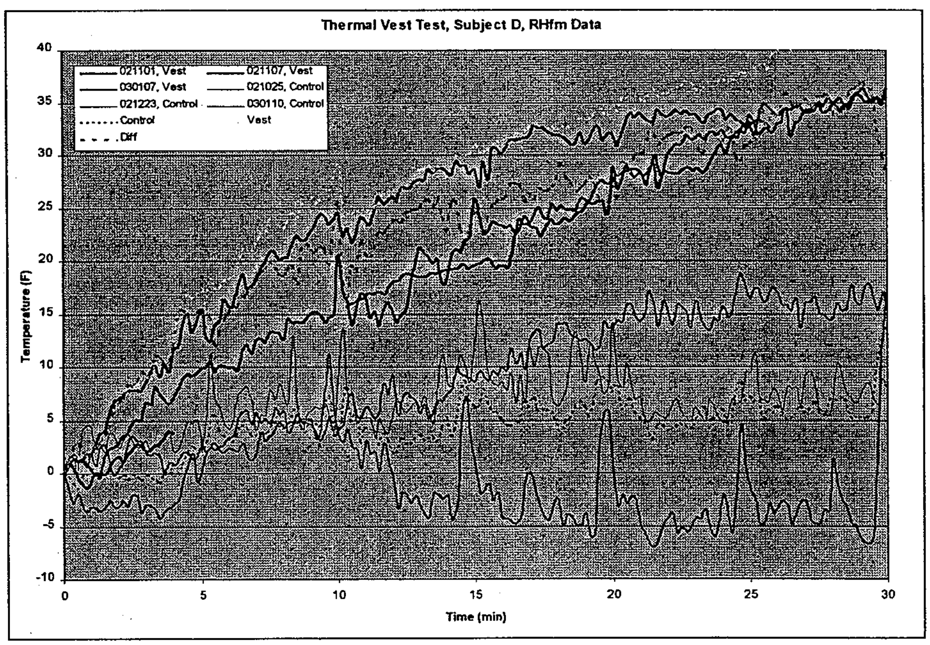


Figure 64: Thermal Vest Test, Subject D, RHfm Data

Good correlation detected, Vest data exceeds Control data. Note the data shifts every 5 minutes due to water break and the volunteer standing up in the seat.

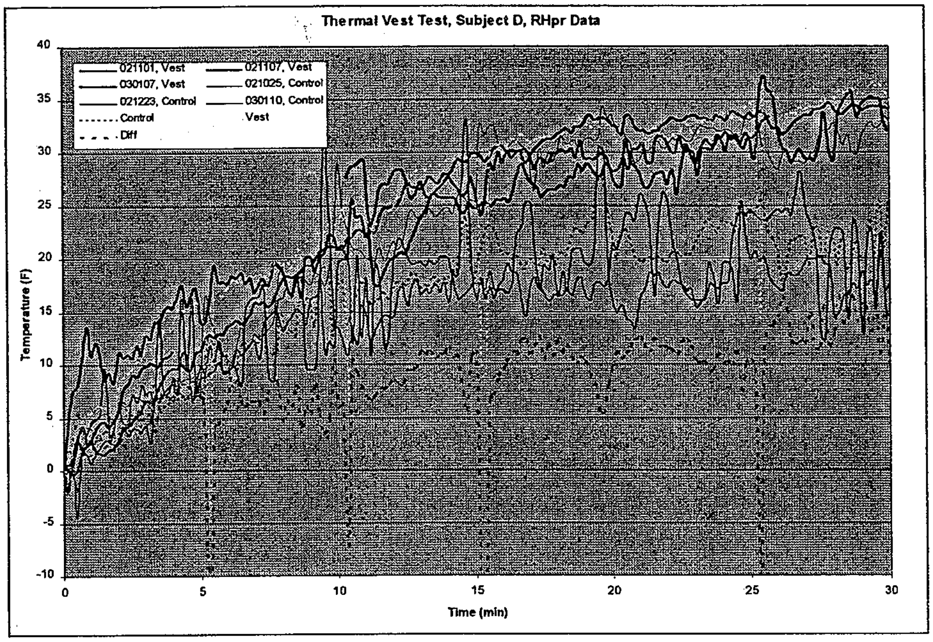


Figure 65: Thermal Vest Test, Subject D, RHpr Data

Some correlation detected, however Vest and Control tests coincide.
Note the data shifts every 5 minutes due to water break and the volunteer standing up in the seat.

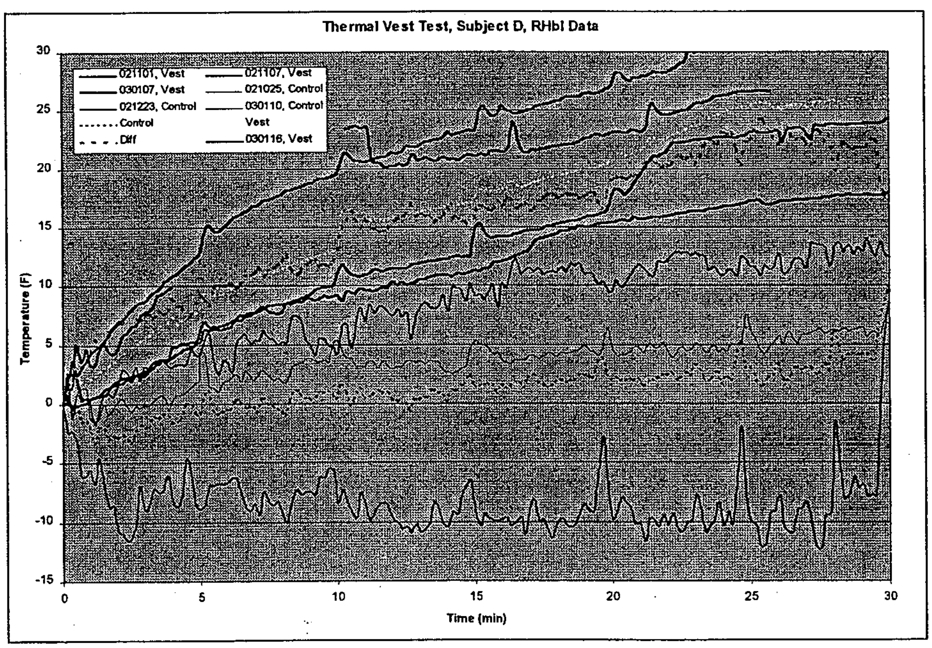


Figure 66: Thermal Vest Test, Subject D, RHbl Data

Good correlation detected, Vest data exceeds Control data.
Note the data shifts every 5 minutes due to water break and the volunteer standing up in the seat.

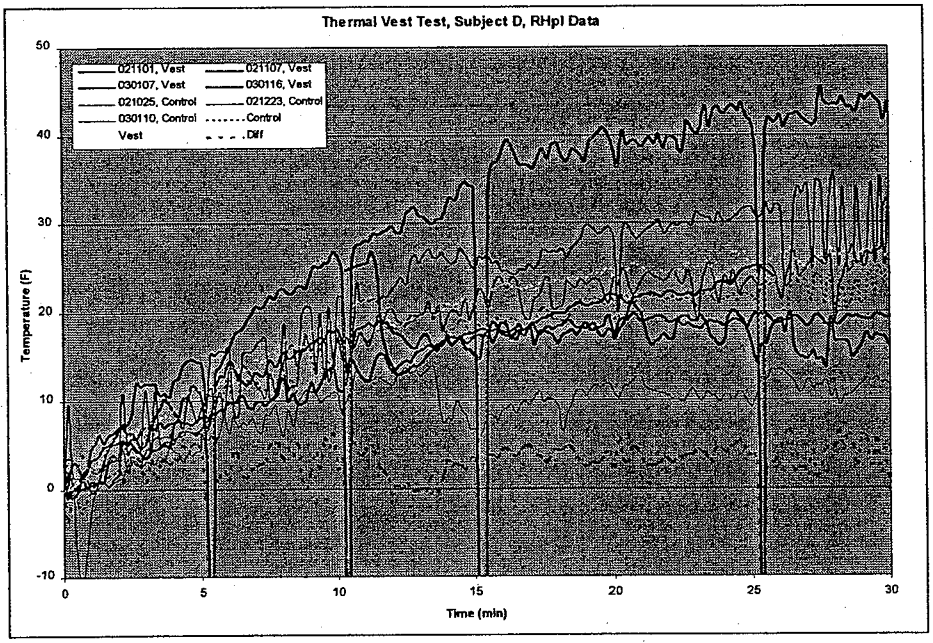


Figure 67: Thermal Vest Test, Subject D, RHpl Data

No correlation detected, Vest and Control tests coincide.
Note the data shifts every 5 minutes due to water break and the volunteer standing up in the seat.

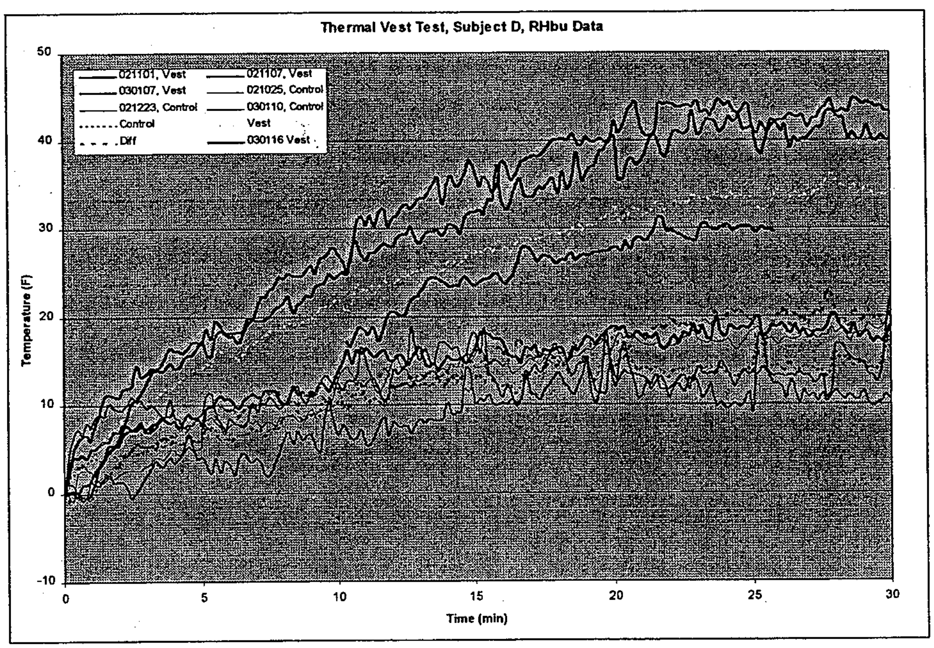


Figure 68: Thermal Vest Test, Subject D, RHbu Data

Some correlation detected, however Vest and Control tests coincide.

.

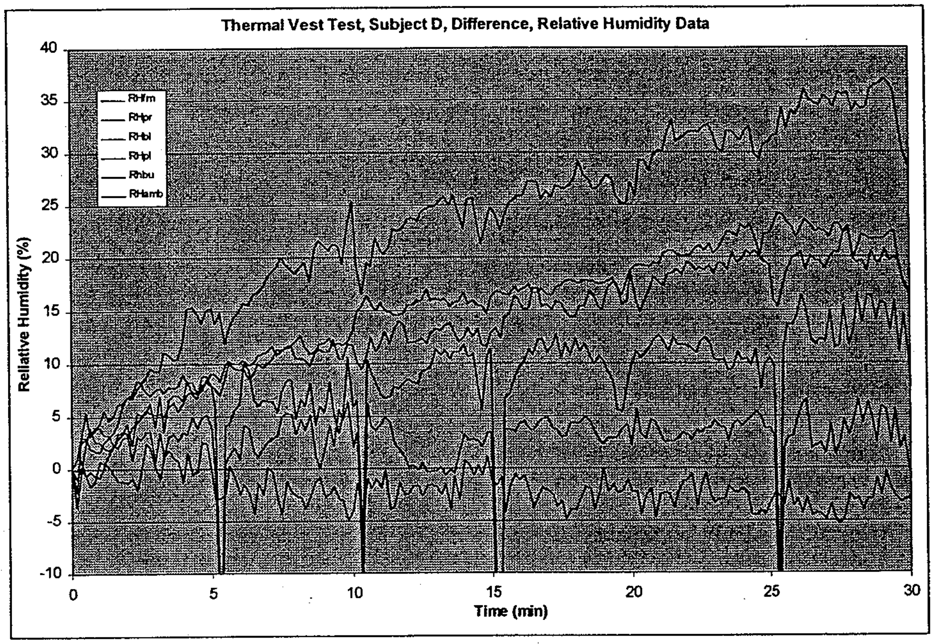


Figure 69: Thermal Vest Test, Subject D, Difference Relative Humidity Data

RHfm seems to provide the greatest difference. Note the effects of the water breaks every 5 minutes

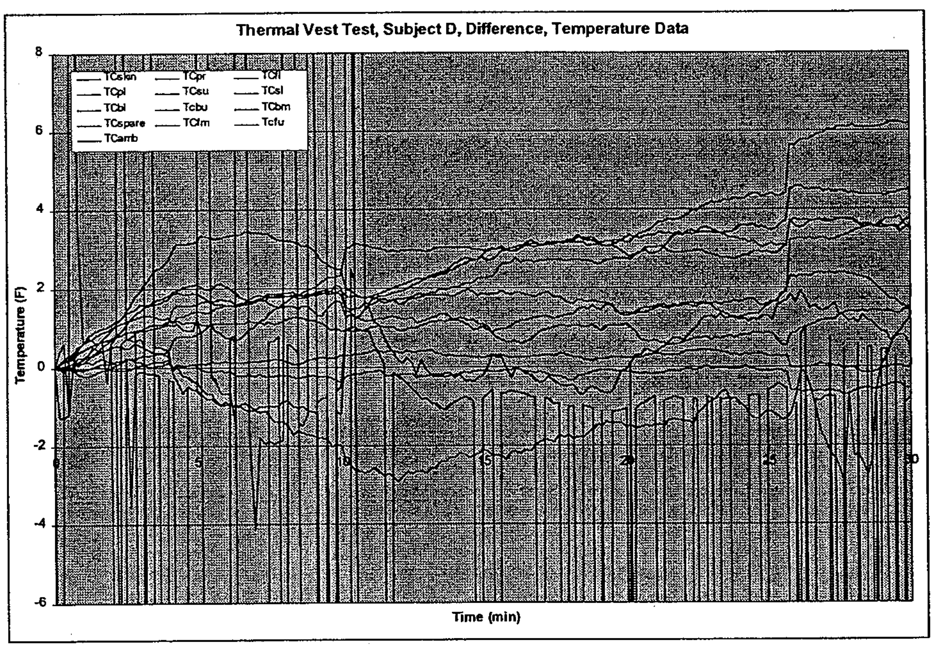


Figure 70: Thermal Vest Test, Subject D, Difference Temperature Data

TCpr, TCfl, and TCpl are intermittently failing.

Appendix 6 - Evaporative Calorimeter Controller Memo

TSE-02-047

October 22, 2002

To: Paul Bierman

From: Wolfger Schneider

Subject: Description of the Evaporative Calorimeter Controller

Reference: "i Series Temperature & Process Controller Manual, omega.com

Summary

To evaluate materials suitable for improved thermal control of body armor, an evaporative calorimeter is needed. This instrument measures the heat flow out of a constant temperature surface due to the evaporative heat loss of the material being evaluated. Two such units were built.

A 1 sq. ft. copper surface is temperature controlled with a thermocouple driven industrial temperature regulator. The average electrical heater power is computed from the DC voltage applied to the heater, the heater's electrical resistance, and the duty cycle of the switched current.

The fastest the chosen industrial controller can update the heater commands is once per second, thus the power is only computed once per second and is transmitted as a 0-5V analog signal for data collection. The data is also available as an ASCII string on an RS-232 port.

The four parallel connected heaters have a combined resistance of approx. 36 Ohms which is very stable over the temperature range of interest. Thus, for a 40 DC supply, the maximum available power to the heaters is P = 40*40/ 36= 44.4 W or cal/sec = 44.4 W/4.176 W-sec/cal = 10.6cal/sec. If more power is needed, a higher voltage power supply can be used.

Description of Operation

Referring to the attached schematic, the industrial controller from Omega, CNi3244-C24, reads the temperature of the copper plate with a Cu-Const thermocouple, displays the temperature, and generates a 10V, 1 Hz duty cycle encoded pulse for controlling the FET current switch, Q1. This 10 V pulse is divided to 5V and enters the 68HC912 microcomputer at PTØ, a timer programmed to measure the on time and off time of the 1 Hz pulse from which the duty cycle of the applied power is computed. Input ADØ receives a scaled version of the power supply voltage (60V max). PPØ is a 5V, 8 bit, pulse-width modulated output which is filtered and scaled to represent the computed power as 0.2W/bit.

The original design had 30V supplies located within the calorimeter controller box. This voltage was found to have insufficient heating margin for the tests and thus an external power supply connection was added. An external supply of up to 50VDC can be used without rescaling the software.

The attached software listing describes the configuration of the required microcomputer peripherals and the power computation performed in floating point. The software is installed in flash memory. As noted in the software, there are two parameters that need to be tailored for each unit for proper calibration.

Programming the Temperature Controller

The Omega CNi3244-C24 controller is programmed to be a PID regulator per the accompanying instruction book. The following setup instructions should help reconfigure, if necessary, using the four push button switches located under the display, whose multi function uses are detailed in the Controller Manual (Ref.1):

1. Pressing the left-most switch cycles through the four high level menus
   a) SP1, to set set point #1, which is used
   b) SP2, not used
   c) CNFG with further levels of sub menus to configure the various modes which can be temperature transmitter, alarm, or controller. We are using the unit as a PID controller with pulse-width modulated output.
   d) RUN, which is the power-on choice

2. Select SP1 using the left-most switch and enter using the right-most switch. Use the UP and DOWN switches to select the desired set point temperature. Exit with the right-most switch.
3. Select CNFG with left-most switch and enter sub menus with right-most switch. Sub menus used are:

INPT	to select the temperature sensor type
RDG	to select the display format
OUT1	to select the controller output format, polarity, and control algorithm

4. For INPT sub menu select TC for thermocouple and further select T for type T (Copper-Constantan)
5. For RDG sub menu select DEC and FFF.F for display format and TEMP and C for displaying in Deg.C
6. For OUT1 set the following sub menus as indicated:

SELF	DSBL	no manual control
CTRL	PID	for analog control
ACTN	RVRS	for loop polarity
AUTO	DSBL	do not automatically tune
ANTI	ENBL	to inhibit large error integral buildup
PROP	1.0	proportional gain - P
REST	100	integral gain - I
RATE	0.0	rate gain for loop damping - D
CYCL	1.0	output updates per second

DPNG 0.0 Sensor filtering

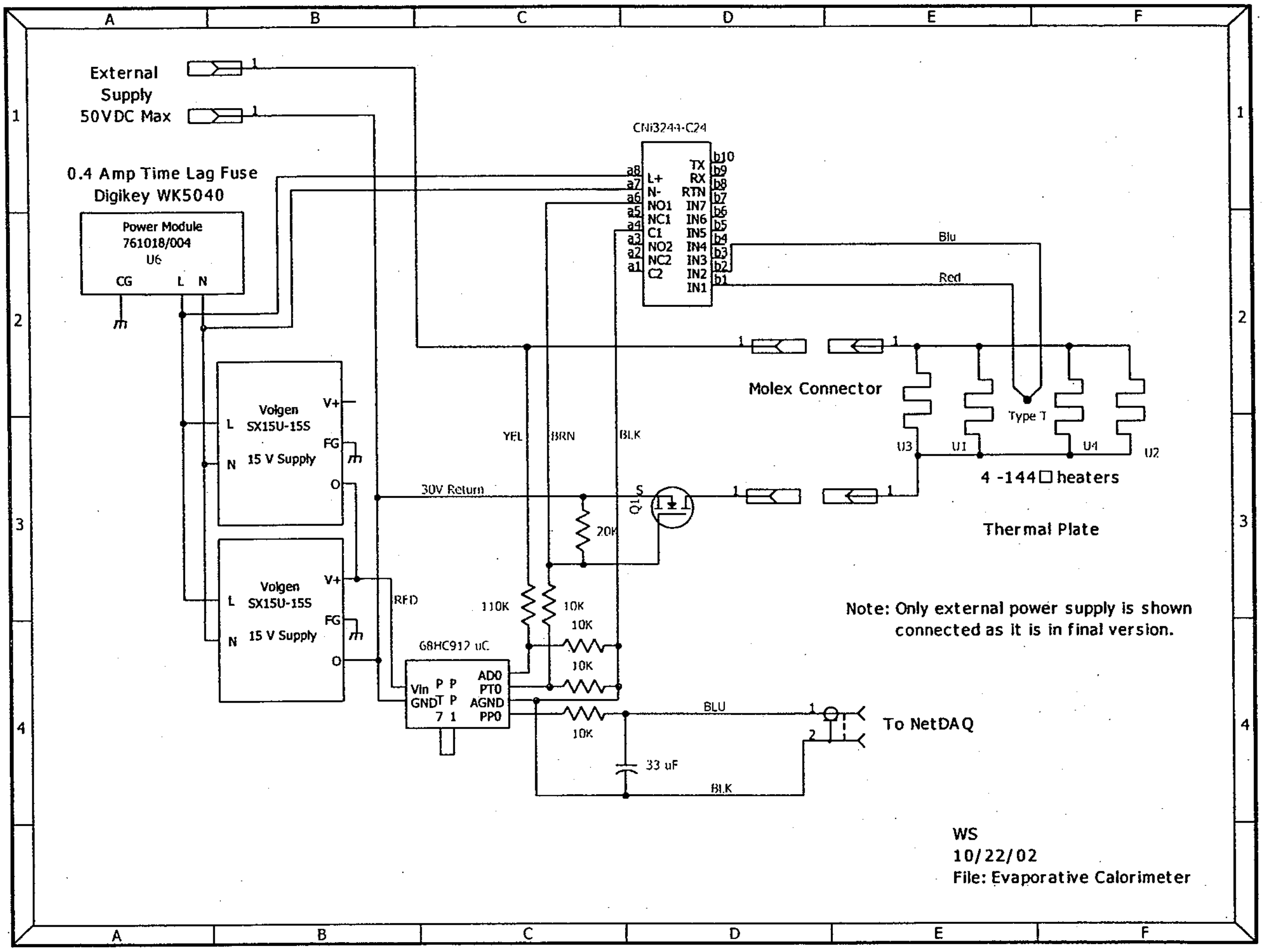
It should be mentioned that the control parameters have not been optimized. Auto tune requires a large temperature overshoot which is not possible here. The parameters shown above give reasonable response. See the attached PID tuning instructions for further help.

Thanks to Christian Williams for constructing the two units and for checking the controller configuration instructions for clarity.

Signed Original in TSE

Wolfger Schneider

Distribution:
Brian Alvarez
Paul Biermann
Jay Dettmer
Wolfger Schneider
Christian Williams



Electrical Schematic of Evaporative Calorimeter

```
( EVAPORATIVE CALORIMETER SOFTWARE, evacal2.txt,  WS - 10/22/02 )
( This version assumes the pulse width out from the controller )
( Appropriate resistance and reference voltage adjusted multipliers )
( need to be selected for the unit on which this software is installed
)
( Being Forth, downloading this code will find empty flash blocks and
)
( install all vectors.  To make it auto execute at power-on execute: )
( HEX A4 D00 EEC! )


( ** Flash Programming ** )
HEX
: FIND-FLASH-START ( - a )
  F800 F800 8000
  DO  FF I 10 OVER + SWAP
    DO  I C@  AND  LOOP  FF =
    IF  DROP  I LEAVE  THEN
    100
  +LOOP
  DUP  F800 =
  IF  CR  ." Flash is full"  CR  THEN ;

FIND-FLASH-START  FDP !

FORGET FIND-FLASH-START

( ** To FLASH complete source use the following auto-flash words ** )
  : ; [COMPILE] ; FLWORD ; IMMEDIATE FLWORD
  : CONSTANT  CONSTANT  FLWORD  ;
  : VARIABLE HERE CONSTANT  2 ALLOT ;

( ** ATOD ** )
HEX
62 CONSTANT ATDCTL2       ( enable A/D )
65 CONSTANT ATDCTL5       ( enable 4 channel sequential conversion )
66 CONSTANT ATDSTAT       ( test MSB for end of conversion )
70 CONSTANT A/D_CHAN0     ( channels are 2 bytes apart )

: A/D_INIT 80 ATDCTL2 C! ;  ( powers up in 8 bit mode )

: A/D@ ( n - c0 ) 2*
  10 ATDCTL5 C!  BEGIN ATDSTAT C@ 7F > UNTIL A/D_CHAN0 + C@ ;


( ******** PWM ******** )
HEX
0040 CONSTANT PWCLK   ( 32*16 us clock )
0041 CONSTANT PWPOL   ( PWM polarity )
0042 CONSTANT PWEN    ( PWM enable )
0050 CONSTANT PWDTY0  ( PWM0 duty )
0051 CONSTANT PWDTY1  ( PMW1 duty )
```

```
00A0 CONSTANT PACTL   ( Pulse accumulator control )

( PWM1 generates clock for timers - 64 us period )
( PWM0 controls D/A conversion for analog power )
: PWM_INIT
   8 PWCLK C!          ( PWM clock E/2 )
   3 PWPOL C!          ( Pos polarity PWM0,1 )
   0 PWDTY0 C!         ( Init to 0, PWM0,1 )
  80 PWDTY1 C!         ( init to 50% )
  44 PACTL C!          ( enable pulse accu., connect PWM clk to
timers)
   3 PWEN C!    ;      ( Enable PWM0,1 )


( ***** TIMER ****** )
DECIMAL
1562  CONSTANT 0.1SEC
   20 CONSTANT TIMEOUT

HEX
0D10 CONSTANT PT2VCT
0D13 CONSTANT PT0VCT
0080 CONSTANT TIOS    ( timer I/O select )
0084 CONSTANT TCNT    ( timer count register )
0086 CONSTANT TSCR    ( timer system control )
0089 CONSTANT TCTL2   ( timer output control )
008B CONSTANT TCTL4   ( init for +edge capture )
008C CONSTANT TMSK1   ( timer interrupt mask1 )
008D CONSTANT TMSK2   ( timer interrupt mask2 )
008E CONSTANT TFLG1   ( timer flag mask1 )
0090 CONSTANT TC0     ( duty cycle counter )
0094 CONSTANT TC2     ( output counter 1 )
00AE CONSTANT PORTT   ( timer port )

AF CONSTANT DDRT   ( TEST )

VARIABLE tick
VARIABLE timeoutflg
VARIABLE tminus
VARIABLE tplus
VARIABLE rdyflg
VARIABLE ptr
VARIABLE toff
VARIABLE ton


CODE-SUB ENINT  10EF , 3D C,  END-CODE   FLWORD
CODE-SUB INHINT 1410 , 3D C,  END-CODE   FLWORD

: PT_INIT
  80 TSCR C!                ( enable timer.. )
  05 TMSK2 C!               ( ..with :32 prescaler )
```

```
  10 TCTL2 C!                 ( toggles PT2 for tick )
  04 TIOS C!                  ( timer output compare - PT2 )
  01 TCTL4 C!                 ( trigger on +edge for PT0 )
  0  rdyflg !                 ( init variables )
  0  ptr !
  0  ton !
  0  toff !
  0  tick !
  0  timeoutflg !
  40 DDRT C!   ( TEST )
  TCNT @ DUP tminus !  tplus !
  FF TFLG1 C!   5 TMSK1 C!   ENINT  ;  ( enable interrupts )


( ***** Timer tick increment and timeout ISR ***** )
CODE-SUB PT2_SR
( LDD #0.1SEC ;   ADDD TC2 ;    STD TC2 )
  CC C, 0.1SEC ,  F3 C, TC2 ,  7C C, TC2 ,
( LDD #1 ;       ADDD tick ,    STD tick )
  CC C, 0001 ,  F3 C, tick ,  7C C, tick ,
( LDD #TIMEOUT ;   CPD tick ;   BGT DONE )
  CC C, TIMEOUT ,  BC C, tick , 2E03 ,
( INC timeoutflg )
  72 C, timeoutflg ,
( DONE  LDA #4 ;  STA TFLG1 ;   RTI )
        8604 ,   7A C, TFLG1 ,  0B C,
END-CODE   FLWORD

( ***** Duty cycle timing ISR ***** )
CODE-SUB PT0_SR   8640 , B8 C, PORTT ,  7A C, PORTT ,   ( TEST )
( TST rdyflg ;    BNE XIT ;  LDD TC0 )
  F7 C,  rdyflg ,  262F ,  FC C, TC0 ,
( TST ptr ;   BNE X1 )
  F7 C,  ptr , 2613 ,
( STD tplus ;   SUBD tminus     ;  STD toff )
  7C C,  tplus ,  B3 C, tminus ,  7C C,  toff ,
( INC ptr ;    LDA #2;   STA TCTL4 ;  BRA XIT )
  72 C,  ptr ,  8602 ,  7A C,  TCTL4 ,  2014 ,
( X1 STD tminus ;   SUBD tplus ;    STD ton )
  7C C,  tminus ,  B3 C,  tplus ,  7C C,  ton ,
( CLR ptr ;  LDA #1 ;    STA TCTL4 ;    INC rdyflg  )
  79 C,  ptr ,  8601 ,  7A C,  TCTL4 , 72 C, rdyflg ,
( XIT  LDA #01 ;  STA TFLG1   ;  RTI )
  8601 ,        7A C,  TFLG1 ,  0B C,
END-CODE   FLWORD

: INSTALL ( SR, BCT - )          ( use to link ISRs to ISR vectors )
  DUP 06 SWAP EEC!
  SWAP  4 + SWAP 1+ EE! ;
                                 ( secondary ISR vectors in flash )
 ' PT2_SR PT2VCT INSTALL         ( PT2VCT F7EA FL! )
 ' PT0_SR PT0VCT INSTALL         ( PT0VCT F7EE FL! )
```

```
( ****** Main ******* )
HEX
0E10 CONSTANT Ohm*100     ( 100 * heater resistance address in EEPROM )
DECIMAL
3695 Ohm*100 EE!        ( saved in EEPROM for changing - unit #1 )
( 3735 Ohm*100 EE! )        ( saved in EEPROM for changing - unit #2 )
VARIABLE duty_cycle       ( duty cycle for power period reported )

: DECI_SEC ( n - )  0 tick !  BEGIN  DUP  tick @  = UNTIL  DROP  ;

( input is scaled for 60 V fullscale, i.e. 6000/256 is output )
( For #2 6115 is used to compensate for Vref=5.07 )
( For #1 6000                "                5.00 )
: HTR_VOLT ( - 100V ) 0 A/D@ 6000 256 */  ;

( Duty cycle varies from 1/256 to 255/256 for 1 HZ PWM controller out
)
: DUTY_CYCLE ( - n )
  BEGIN  rdyflg C@  timeoutflg C@  OR  UNTIL
  timeoutflg C@
  IF  PORTT C@  1 AND
    IF  256 duty_cycle !  ELSE  0 duty_cycle !  THEN
  THEN
  rdyflg C@
  IF  256 ton @ DUP toff @ + */  duty_cycle !
  THEN  0 rdyflg C!  0 tick !  0 timeoutflg !  ;

( Compute power in cW - W/100 )
: POWER ( - d )  HTR_VOLT 0 D>F FDUP F*  Ohm*100 @  0 D>F F/
  duty_cycle @  S>F  F*  256 S>F  F/  F>D  ;

( Print output and PWM 0.2W/bit )
: OUTPUT
  2DUP  8 D.R DROP 10 + 20 /  DUP 8 .R  1- PWDTY0 C!  ;


DECIMAL

: INIT  A/D_INIT   PWM_INIT  PT_INIT   ;

: GO CR  DECIMAL  INIT
  BEGIN  DUTY_CYCLE  POWER  OUTPUT  ?TERMINAL UNTIL ;

( AUTOGO: places a start_up trap to GO in EEPROM @ 0D00 as expected )
( by Forth boot code.  )
HEX  ( A4 ) 4A 0D00 EE!  ' GO CFA 0D02 EE!


( *****************************************************************
)
```

This software receives a 1 Hz pulse width modulated signal (which switches the heater power on/off) from a temperature controller (CNi3244-C24) and uses it to compute the electrical power going to the heater at a voltage as read by A/D0.

Data are taken once per second and are transmitted at 9600 Baud and as a voltage (0-5V).
The RS-232 data are in mW.
The analog voltage is 0.2 W/bit as generated by PWM0.

The heater resistance value is stored in EEPROM as cOhm, xxxx at location E10. New values can be saved with

DECIMAL XXXXX HEX E10 EE!

HTR_VOLT measures the heater voltage and is scaled for 60 v full scale.
DUTY_CYCLE computes the PWM control signal from the temperature controller command to the power switching FET. It uses PT0_SR which measures the FET on and off times which occur at a nominal 1 sec rate. Since this controller output commands a steady off (0V) and a steady on (10V) at the extremes of command, PT0_SR is not called. For these cases a timer times out after 2 seconds and reads the FET command line for hi or lo.

References

1 Fan, J. and Chen, Y. S., "Measurement of clothing thermal insulation and moisture vapour resistance using a novel perspiring fabric thermal manikin," *Meas. Sci. Technol.*, **13,** pp 1115-1123, (2002)

2 U.S. Congress, Office of Technology Assessment, Police Body Armor Standards and Testing: Volume I, OTA-ISC-534 (Washington, DC: U.S. Government Printing Office, August 1992).

3 Quote taken from Point Blank Body Armor Inc., Web site: http://www.pointblankarmor.com/comfort_fit.html (Point Blank Body Armor, Inc., 1999).

4 "Physiology and Pathophysiology of Temperature Regulation," Blatteis CM, Ed. World Scientific Publishing Co, Ltd. London, England. 2001, pp 16-17.

5 Personal Communication between PJ Bierman and a Howard County, MD Police Officer, Spring of 1999.

6 Eliason, Lawrence K. (Chief, Law Enforcement Standards Laboratory), "Subject: Ballistic Limit of Kevlar (R) When Wet," Memorandum for Lester D. Shubin (Director, Science and Technology, National Institute of Justice), July 17, 1990 (unpublished).

7 Goldman, R. F.,"Physiological Costs of Body Armor," Military Medicine, Vol. 134, No. 3, March, 1969

8 Aerospace Corp., Law Enforcement and Telecommunications Division, Equipment Systems Improvement Program Final Report Body Armor Field Test and Evaluation, Volume I.--Executive Summary, Aerospace Report No. ATR-77 (7921)-2 (Washington, DC: The Aerospace Corp., September 1977).

9 Aerospace Corp., Law Enforcement and Telecommunications Division, Equipment Systems Improvement Program Final Report Body Armor Field Test and Evaluation, Volume 11. Test And Evaluation, Aerospace Report No. ATR-77(7921)-2, (Washington, DC: The Aerospace Corp., September 1977).

10 "Physiology and Pathophysiology of Temperature Regulation," pp.25-45.

11 "Textbook of Medical Physiology," Guyton, AC, and Hall, JE, W. B. Saunders Co., Phil. Pa. p 908.

12 "Physiology and Pathophysiology of Temperature Regulation," p. 133

13 "Physiology and Pathophysiology of Temperature Regulation," pp.80-90

14 MN Sawka, WA Latzka, SJ Montain, BS Cadarette, MA Kolka, KK Kraning 2nd, and RR Gonzalez, "Physiologic tolerance to uncompensable heat: intermittent exercise, field vs laboratory." Med Sci Sports Exerc, Mar 2001; 33(3): 422-30.

15 "Physiology and Pathophysiology of Temperature Regulation," pp.194-205.

16 "Physiology and Pathophysiology of Temperature Regulation," p.41

17 Cadarette BS, Blanchard L, Staab JE, Kolka MA, Sawka MN, "Heat Stress when wearing body armor," USARIEM Technical Report T-01/9. May 2001.

18 Daniel S. Moran, Avraham Shitzer, and Kent B. Pandolf, A physiological strain index to evaluate heat stress, Am J Physiol Regulatory Integrative Comp Physiol, Jul 1998; 275: 129 - 134.

19 Daniel S. Moran, Yair Shapiro, Arie Laor, Sharona Izraeli, and Kent B. Pandolf Can gender differences during exercise-heat stress be assessed by the physiological strain index? Am J Physiol Regulatory Integrative Comp Physiol, Jun 1999; 276: 1798 - 1804.

20 Daniel S. Moran, W. Larry Kenney, Jane M. Pierzga, and Kent B. Pandolf Aging and assessment of physiological strain during exercise-heat stress Am J Physiol Regulatory Integrative Comp Physiol, Apr 2002; 282: 1063 - 1069.