THE INTERNATIONAL FIRE FIGHTER PROTECTIVE CLOTHING BREATHABILITY RESEARCH PROJECT

Mild Environment Protocol

by

Dr. Roger L. Barker
Dr. Barbara J. Scruggs
Ms. Chureerat Prahsarn
College of Textiles
North Carolina State University

Warm Environment Protocol

by

Dr. Loren G. Myrhe
Ms. Melanie Teer
Ms. Tonya Miszko
Alamo Physiological Research Institute

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FOREWORD

The International Fire Fighter Protective Clothing Breathability Project was conducted in 1998 with the aim of documenting the heat stress and comfort of several NFPA 1971-compliant turnout systems with a range of heat loss values. Objective and subjective measures of human physiological and psychological responses were applied to quantify turnout performance in several categories. The report also documents the use of a device, the guarded sweating hot plate, used for independent measurement and comparison with human subject results.

The data developed in this independent project was initially for consideration by the NFPA Technical Committee responsible for NFPA 1971, *Protective Ensemble for Structural Fire Fighting.* It is hoped that this report will also be valuable to fire departments, brigades and related organizations who are considering the breathabiltiy of protective clothing ensembles.

The Research Foundation expresses its gratitude to Dr. Roger Barker of North Carolina State University's College of Textiles, and to Dr. Loren Myrhe of Alamo Physiological Research Institute for their technical guidance and the preparation of this report. The Foundation and authors thank the project's Technical Advisory Committee listed on the following page for their contributions of expertise, financial resources and in-kind donations. Thanks also to other contributors named on the following page for their in-kind contributions. And special thanks to the fire fighters from the City of Raleigh, NC Fire Department who participated as subjects in the study.

Of course, participation on the Technical Advisory Committee does not necessarily constitute a participant's endorsement of every statement in this report.

THE INTERNATIONAL FIRE FIGHTER PROTECTIVE CLOTHING BREATHABILITY RESEARCH PROJECT

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International Firefighter Protective Clothing Breathability Research Project

Final Report
to

National Fire Protection Research Foundation

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by

Dr. Roger L. Barker
Dr. Barbara J. Scruggs
Ms. Chureerat Prahsarn

Textile Protection and Comfort Center (T-PACC)
College of Textiles
North Carolina State University
Raleigh, NC 27695-8301

Warm Environment Protocol

by

Dr. Loren G. Myrhe
Ms. Melanie Teer
Ms. Tonya Miszko

Alamo Physiological Research Institute
San Antonio, TX 78218-1107

August, 1998

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Synopsis

The NCSU state-of-the-art climate chamber was used to conduct wear trials to evaluate the heat stress and comfort of six NFPA 1971 compliant turnout systems with measured sweating hot plate heat loss values ranging from 97 to 251 watts/m^2. Seven professional firefighters from the City of Raleigh Fire Department participated in these studies.

Two different wear tests were performed to simulate different climate conditions, levels of work activity and clothing and equipment variables. One protocol featured light to moderate work activity in a mild climate (21°C, 65% RH) with the firefighter wearing a turnout coat and pants over a station uniform and underwear. A separate study was conducted to determine the heat stress experienced by firefighters performing moderate work activities in a warm environment (39°C, 35% RH). For this protocol, firefighters wore the total turnout ensemble as well as a helmet, hood, gloves, and SCBA. Objective and subjective measures of human psychological and physiological response were applied to quantify and to rate turnout performance in several categories. The following observations can be made:

Mild Environment Protocol (21°C, 65% RH)

- Physiological heat stress limits are not approached, regardless of the "breathability" of the turnout composite. At low work loads, in a mild environment, core temperatures increase less than 0.6°C. No significant differences are seen in measured core temperature or heart rates that can be correlated with differences in turnout breathability.

- For mild conditions, differences in turnout breathability surface at the comfort level: sweating plate heat loss values correlate with measured indexes that associate with turnout comfort performance (higher sweating plate scores correlate with lower skin temperatures and less indicated buildup of moisture vapor in the turnout microclimate). However, firefighters can decisively perceive and differentiate among composites on the basis of comfort sensations only in the case of the composite having the lowest total heat loss (Qt - 97 watts/m^2). Statistically significant differences in comfort performance can be related to feelings of warmth and skin wettness that occur in wearing turnout #4.

- System #4 produced the highest accumulation of sweat and lowest level of sweat evaporation through the clothing to the ambient environment. This factor undoubtedly contributed to the heightened sensation of skin wetness experienced when wearing this garment.

Warm Environment Protocol (39°C, 35% RH)

- For moderate work in heat there is no statistical significance to the slight differences observed in either core temperature or exercise heart rate and garment breathability.

- Mean skin temperatures did not differ during the first 15 minutes of work, but thereafter, garment #4 exhibited significantly higher skin temperatures (but limited to 0.3 to 0.9°C) than any of the other garments. There was no correlation between mean skin temperature and sweating plate scores for any of the other garments.

- Work tolerance time for garment #4 was significantly less than for any of the other garments studied. The actual difference was about 6 minutes or about 13% less than the average for the other garments. (Note: Work tolerance time in these experiments was predominately subjective, but correlates well with mean skin temperature).

- There is no significant difference, relative to sweating plate scores, in any of the objective physiological indices of heat stress during the first 30 minutes of work under these environmental conditions. Thereafter, only mean skin temperature is higher for garment #4, and all other garments exhibit the same skin temperature - regardless of sweating plate values.

- Several statistically significant subjectively perceived comfort disadvantages were associated with wearing system #4. Subjective response data show that turnout #4 was perceived by wearers to be hotter and to produce significantly greater sensations of skin wettedness, than other turnouts.

- As in the mild protocol, system #4 produced the highest accumulation of sweat and lowest level of sweat evaporation through the clothing. This finding correlates with the subjective perception of higher skin wettedness in this garment. However, the total grams of sweat that evaporated through the most "breathable" turnouts averaged less than 10% of the total sweat secreted during the warm climate experiments. Although measurable and statistically significant, even if this volume of sweat evaporated in a manner efficient enough to provide some cooling, it would be insignificant with respect to protecting the body from cumulative heat stress.

Conclusions

This study shows that the guarded sweating hot plate test can be used to predict a minimum level of total heat loss that correlates with diminished turnout performance in some categories of heat stress and subjective comfort performance. Sweating plate test scores differentiate at the lowest level of heat loss measured among NFPA 1971 compliant turnout systems (97 watts/m^2). Differences in the physiological heat stress performance of the 97 watts/m^2 system are not indicated by core temperature, but they are indicated by higher skin temperatures and reduced tolerance time to work in heat. Subjective ratings show that the 97 watts/m^2 system is perceived to be hotter with greater sensations of skin wettedness than the other test turnouts.

All of the "warm" experiments, regardless of the garment worn, proceeded to a point where every firefighter complained that he could go no further giving full meaning to the parameter referred to as "work tolerance time". The average 6.8 minute (13%) advantage, observed for garments ranging from 146 to 251 watts/m^2 in heat loss values was significant.

No decisively significant differences in physiological heat stress response can be found in systems having total sweating hot plate heat loss values within the range of 146 to 251 watts/m^2.

Caveat

These scientific findings strictly reflect the specific laboratory test conditions chosen for the experiments. Wear test variables, including environmental temperature and humidity, work loads, and clothing and equipment variables are known to have major effect. Conclusions regarding the contribution of the composite "breathability" to turnout heat stress or comfort performance can vary, depending on the assumptions of the test conditions.

Practical application of any laboratory observed differences related to system "breathability" must ultimately depend on firefighter use conditions, and prudent consideration of the wide range of additional factors known to contribute to or alleviate firefighter heat stress problems.

Introduction

The sweating guarded hot plate test procedure is being considered for use in determining the breathability of firefighter turnout clothing ensembles. Since the sweating hot plate test measures heat loss through flat fabrics, there is a critical need to determine the relationship between these measurements on turnout materials and the heat stress and wear comfort of a firefighter clothed in these materials. More specifically, there is a need to qualify how different levels of heat loss, as measured on a sweating plate, translate to heat stress and comfort performance in turnout ensembles.

This project conducted human subject wear trials to evaluate the heat stress and comfort of sets of turnout clothing that are constructed from materials having different levels of breathability, as measured using the sweating guarded hot plate procedure. The specific objective of this project was to determine the relationship between laboratory measurements and the impact of a breathable liner on the heat stress and comfort of firefighters.

Controlled environment wear trials were conducted using the state-of-the-art climate chamber available at the Center for Research on Textile Protection and Comfort (T-PACC) in the College of Textiles at North Carolina State University. Firefighters from the City of Raleigh Fire Department participated in these studies. Two different wear tests were performed to simulate two levels of work activity, climate conditions, and clothing and equipment variables: One protocol featured light to moderate work activity in a mild climate (21°C, 65% RH). Subjective and objective measures of human psychological and physiological response were applied to quantify and rate performance in several categories. A separate study was conducted to determine the heat stress experienced by firefighters performing moderate work activities in a warm environment (39°C, 35% RH). The body core temperature of the firefighters was measured as an index of the heat stress experienced by the firefighters.

Experimental Procedures

Test Materials

Six different turnout composites were evaluated. These materials were selected to span the range of heat loss values representative of the NFPA 1971 compliant turnout systems. Each of the six turnout composites used the same shell fabric, but incorporated moisture barriers with different moisture vapor permeability. Different thermal liners were also used to achieve the desired range of sweating hot plate values. The use of a common shell fabric and garment design eliminated the contribution of visual clues, which may have otherwise complicated the translation between composite breathability and perceived ensemble performance.

Sweating Hot Plate Test

The total heat loss through each of the six turnout composites was measured using the guarded sweating hot plate procedure. These tests were conducted at the NCSU, T-PACC laboratories, which are equipped to perform the specific sweating plate test protocol currently under consideration by NFPA 1971.

Table 1 and Figure 1 show the total heat loss measured for the test composites using the guarded sweating hot plate method. Table 1 also shows the measured thickness and weight, and the thermal and evaporative resistance (Rcf and ARef values) for the turnout systems.

These data indicate that the test turnout systems represent total heat loss values ranging from 97 to 251 w/m^2. This range of plate scores is typical of the range of total heat loss values encountered in NFPA 1971 compliant turnout systems.

Table 1. Total Heat Loss Values for Turnout Systems*

System	Weight (oz/yd^2)	Thickness (mm)	Rcf	ARef	Qt
1	19.95	4.98	0.119	0.016	251
2	19.59	5.28	0.153	0.017	222
3	19.82	5.08	0.161	0.034	146
4	27.25	4.17	0.134	0.087	97
5	19.51	4.90	0.115	0.016	247
6	20.19	4.88	0.118	0.034	158

*Turnout system used same outer shell. Three different thermal liners and two different moisture barriers were combined with this shell fabric to produce range of total heat loss values.

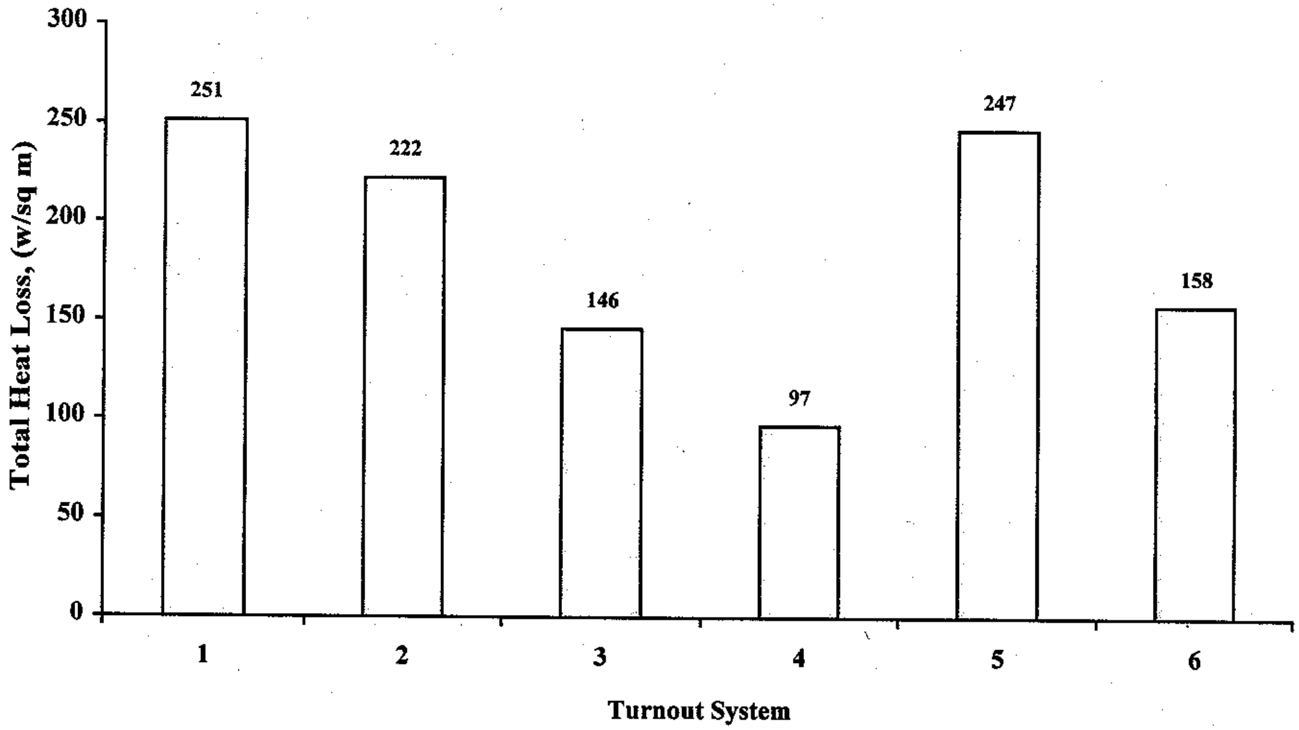


Figure 1. Total Heat Loss of Composites

Test Garments

The turnout systems tested consisted of coat and pants identical in design. The garments were custom made for each firefighter participating in the study. All of the turnouts are assumed to be compliant with NFPA 1971.

Test garments were worn in combination with a station uniform (55% FFR/ 45% cotton shirt and pants), 100% cotton knit underwear, cotton socks and sneaker type shoes. To assure uniformity, station uniforms, underwear and socks were provided to the firefighters. The turnout pant legs were taped at the ankles to prevent any greater circulation of air to the lower extremities than that which would occur when wearing boots.

Each firefighter wore each of the six test turnouts during the wear test protocols called for by this study. The order in which an individual test garment was worn was determined by a randomized process of selection.

Evaluators

Seven professional firefighters from the City of Raleigh Fire Department, Raleigh, North Carolina participated as evaluators. Through pre-screening, they were determined to be healthy, nonsmoking individuals between the age of twenty-nine and thirty-six.

The firefighters arrived at the laboratory following a normal night's sleep or before engaging in any other physically strenuous activity. Fluid intake prior to arrival was prescribed to assure a state of euhydration, and an additional 500 ml (measured) was ingested during the dressing and preparation period (approximately 30 minutes) prior to beginning work in the test environment.

An EKG apparatus for transmitting the heart rate signal to a wireless receiver was attached to the chest via an elastic belt. Yellow Springs skin thermistors were attached via sweat resistant clinical tape to specific sites on the upper arm, chest, back, and thigh for calculating mean skin temperature. A sterile, flexible rectal probe was inserted by the firefighter 12 cm beyond the anal sphincter and anchored in place with a harness of 2-inch roll gauze. A hygrometer probe, position at the center back, between the station uniform and liner of the turnout coat, was used to record humidity buildup in the clothing microclimate.

Results of Wear Tests

The two wear trials conducted for this study will be discussed in separate sections of this report.

Part I. MILD ENVIRONMENT WEAR TRIAL PROTOCOL

Method and Procedures

Test Conditions

- Mild Climate (21°C, 65% RH)
- Light to moderate work activity
  - Treadmill walk at 2.5 mph, 2% grade

Subjects

- Seven male professional firefighters from City of Raleigh Fire Department
  - Healthy and physically fit
  - 29 to 36 years old
  - Aerobic capacity precisely measured by cycle ergometry

Clothing Configuration

- Turnout coat and pants
- Station uniform and underwear (issued)
- Socks and walking/jogging shoes

Test Sessions

- Firefighters arrived rested (no prior physical activity) and euhydrated.
- Time of day for individual session kept constant to minimize circadian variations in physiological responses.
- Firefighters wore each of six different turnouts over course of wear trial. Sequence of wearing was determined by a randomized assignment process.

Data Generated

- Core (rectal) temperatures
- Skin temperature
  - back
  - chest
  - upper arm
  - thigh
- EKG heart rate
- Microclimate humidity
- Moisture loss in subject
- Moisture gain in clothing
- Subjective ratings

Protocol

For this protocol, firefighters wore turnout test clothing over a station uniform and underwear. They did not wear gloves, hood, helmet or don a SCBA. At least a 24 hour period separated a subject's participation in test sessions.

The wear trial requirement (Table 2) included a 15-minute rest, or sitting period, followed by two 20-minute exercise periods that consisted of walking on a treadmill at 2.5 mph at a 2% grade. The treadmill speed and grade were kept constant to impose an energy expenditure of approximately 450 kal/hr (i.e. an oxygen requirement of approximately 18 ml/kg/min). The actual energy requirement for each subject was determined precisely by indirect calorimetry.

Heart rate, skin temperatures and rectal temperature were measured at 5 minute intervals during the two exercise periods and the final rest period. The physiological measurements were taken only at the start and end of the initial rest period and the rest period after the first exercise when the changes were negligible. Microclimate relative humidity was continuously monitored. Subjective ratings of the firefighters perception of the heaviness, humidity sensation, heat sensation and the overall wear comfort of the turnout were recorded at the end of each of the test periods (Table 2). The detailed protocol is in Appendix D and the rating form used is found in Appendix B.

The evaluator and clothing were weighed before and after the test session to assess the amount of weight loss (assumed water loss) and to identify where moisture is held in the clothing and how much moisture evaporated into the atmosphere.

Table 2. Mild Climate Protocol (21°C, 65% RH)

Test Period	Time (min.)	Cumulative Time (min.)	Activity	Physiological Measurements*	Subjective Ratings
Pretest Baseline			Prior to donning turnout	Initial T_s, T_{re}, HR	
1	15	1 - 15	Rest	T_s, T_{re}, % RH, HR @ 5 & 15 min.	End of period
2	20	15 - 35	Walk 2% grade treadmill @ 2.5 mph	T_s, T_{re}, % RH, HR @ 5 min. intervals	End of period
3	30	35 - 65	Rest	T_s, T_{re}, % RH, HR @ 5 & 25 min.	End of period
4	20	65 - 85	Walk 2% grade treadmill @ 2.5 mph	T_s, T_{re}, % RH, HR @ 5 min. intervals	End of period
5	30	85 - 115	Rest & cool down	T_s, T_{re}, % RH, HR @ 5 min. intervals	End of period

*T_s = Skin temperature of chest, back, arm and thigh
T_{re} = Rectal temperature
% RH = percent relative humidity in the clothing microclimate
HR = Heart rate

Results (Mild Climate Protocol)

This section contains summarized test data and discussion of the results of the turnout evaluation in the mild climate test protocol.

Physiological Measurements

Core Temperature: The rate of rise in core temperature (Tre) experienced by the firefighters while wearing each of the six turnout systems is shown in Figure 2. Table 3 compares the maximum average core temperature experienced in wearing the turnouts.

These data clearly demonstrate that, regardless of the turnout that is worn, light work in a moderate environment (21°C, 65% RH) does not result in a significant increase in core temperature. The maximum rise in core temperature is less that 0.6°C for all the test systems. Statistical tests reveal no statistically significant difference among the test garment (see Appendix F).

The relationship between the increase in Tre and elapsed time in this protocol, is generally identical for all test garments (Figure 2).

Heart Rate: Figure 3 shows the relationship between subject heart rate and time in the mild test protocol. These data indicate the expected correlation between physical activity and heart rate. They indicate no significant differences in heart rate response that can be associated with wearing any of the turnout systems studied.

Skin Temperature: Mean skin temperature (T_{sk}) was estimated from weighted surface areas as follows $T_{sk} = 0.32\ T_{chest} + 0.12\ T_{arm} + 0.32\ T_{back} + 0.24\ T_{leg}$. Figure 4 shows mean skin temperature as a function of time. Table 4 shows mean temperature averaged over the 35 - 115 minute duration of the wear test. Figure 4 indicates a rise in skin temperature, occurring in the initial resting period of the protocol, that continues through the first exercise period. The skin temperature drops when the evaluators rest after the exercise sessions of the protocol. Mean skin temperature peaks for all turnout systems studied, in the range of 35.5°C to 36°C. Although the differences are relatively small, differences in mean skin temperature appear to be associated with wearing different turnout garments. Data in Table 4 and Figure 4 indicate that Turnout 4 generates the highest skin temperature.

Microclimate Humidity: The relative humidity (% RH) in each type of test garment, measured by a sensor probe positioned between the station uniform and liner of the turnout coat , is shown in Figure 5. The general tracking pattern for each garment is similar. Major changes in the humidity are highly associated with changes in physical activities, far more so than with differences in the garment material components.

During the initial period, the humidity in all the clothing systems was similar to the ambient environment (65% RH) with some drop-off in % RH observed during this sitting/resting period (Period 1). This is shown in the 0 to 15 minute segment of the

Table 3. Comparison of Maximum Core Temperature Rise

Composite ID	Maximum Core Temperature Rise (°C)
1	0.49
2	0.42
3	0.41
4	0.54
5	0.47
6	0.35

Table 4. Averaged Mean Skin Temperature Over the Range of 35 - 115 Minutes.

Composite ID	Averaged Mean Skin Temperature (°C)
1	34.97
2	35.08
3	35.36
4	35.64
5	35.05
6	35.22

Figure 2. Effect of Garment Selection on Core Temperature in Mild Environment (21C, 65% R.H.)

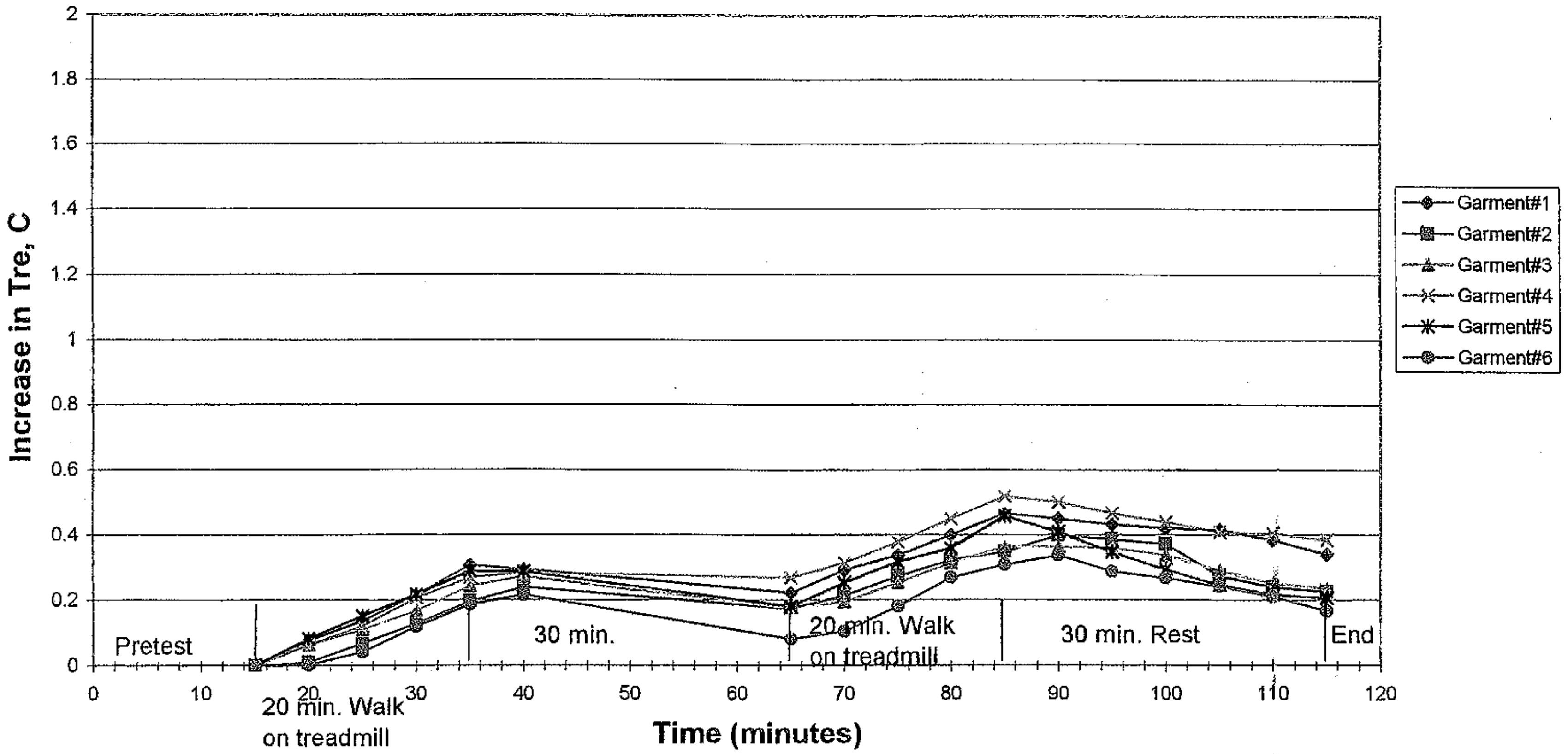


Figure 3. Effect of Garment Selection on Average Heart Rate in Mild Environment (21 C, 65% R.H.)

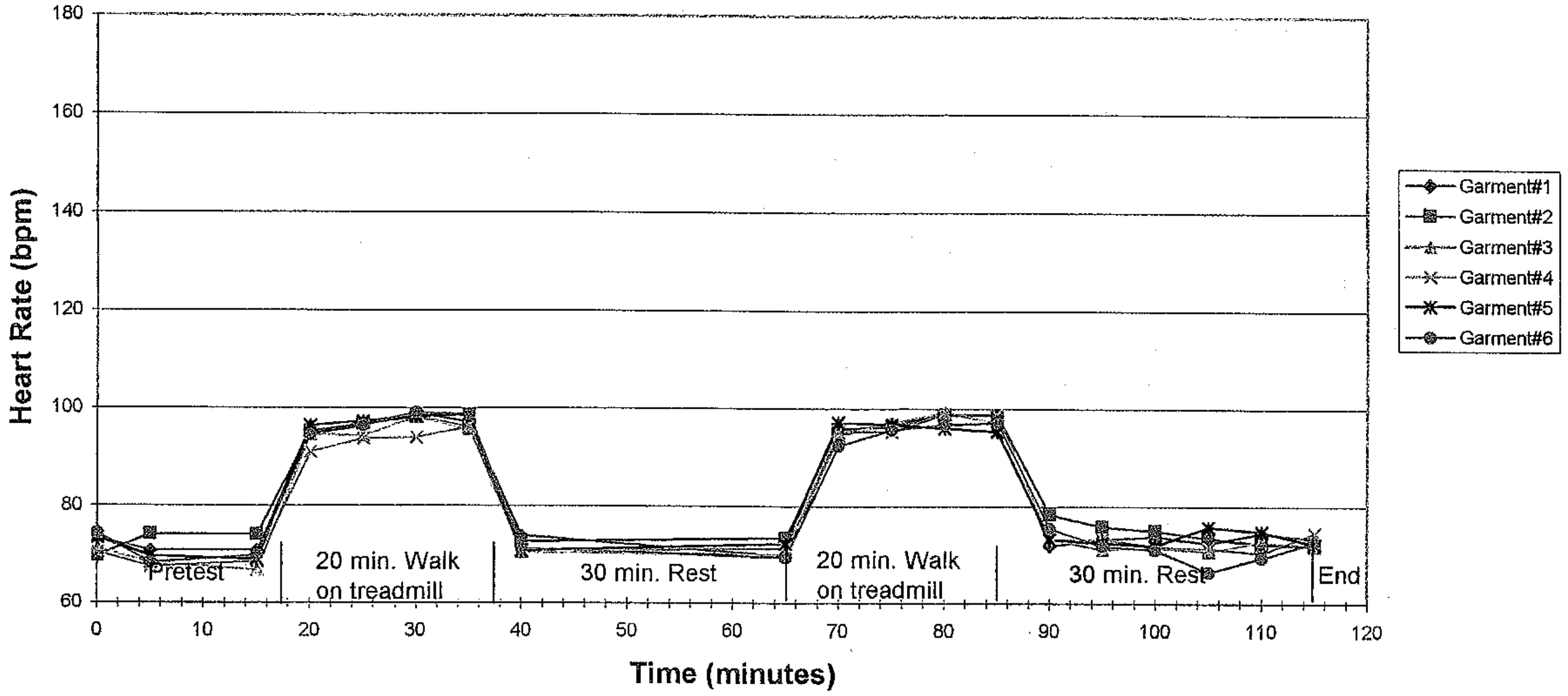
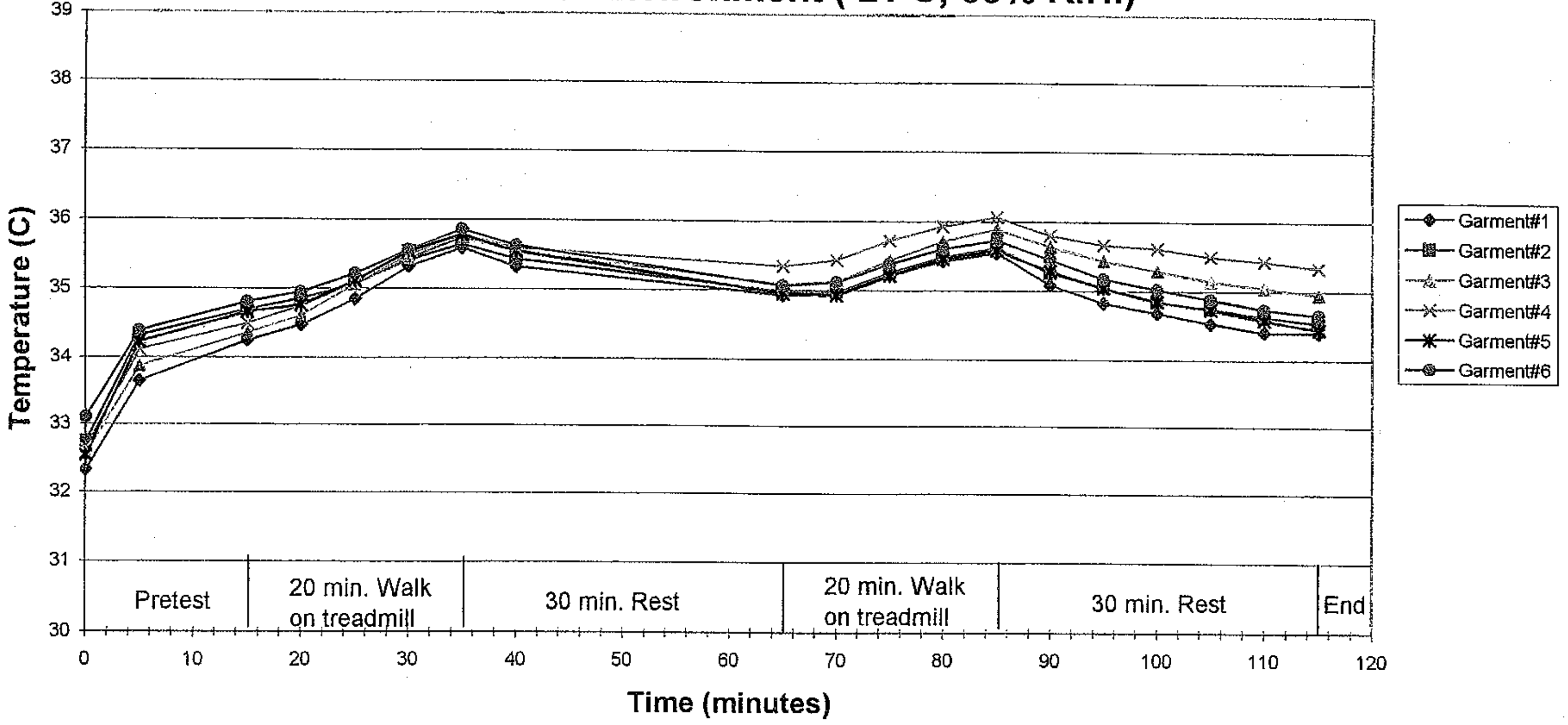


Figure 4. Effect of Garment Selection on Mean Skin Temperature in Mild Environment (21 C, 65% R.H.)



humidity versus time plot (Figure 5). This is due to the higher than ambient temperature in the clothing microclimate which lowers the % RH as long as no new moisture generation occurs.

Because of clothing "pumping effects" associated with body movements, there is a measurable drop in % RH when evaluators start to walk on the treadmill (Period 2). Then there is a continued build-up of humidity in all the turnout systems which causes the microclimate RH to reach nearly peak levels by the end of the first 20 minute exercise period. These humidity levels are maintained through the rest period following the first exercise session. Again, there is a noticeable reduction in humidity levels, in most systems, that coincides with the onset of the second exercise period. The microclimate humidity increases through the second exercise and cooling down period, achieving peak level by the end of the testing session.

Correlation is evident between the clothing microclimate humidity and garment "breathability": Microclimate humidity buildup increases as the composite sweating plate total heat loss value decreases (Figure 6).

Detailed instrument data is included in Appendix E.

Subjective ratings

Subjective ratings were based on multiple wear evaluations of each type of test garment using specially chosen descriptor terms for rating of comfort feelings and certain garment properties. Participants rated subjective qualities of the turnout clothing after each of five rating periods, including wear comfort, heat sensation (warm/cool feeling), skin moistness (wetness), heaviness (weight), and flexibility of materials (bendability). After completion of all test periods, the participant rated the additional items (fatigue, fit, protection and general preference) only once at the end of the test period.

Analysis of subjective data (Appendix G) indicates that these firefighters can decisively perceive and differentiate among composites on the basis of comfort sensations only in the case of the composite having the lowest total heat loss (Qt = 97 watts/m^{2}.) Statistically significant differences in comfort performance are most strongly related to feelings of warmth (Figure 7) and skin wettedness (Figure 8) that occur in wearing turnout #4.

A summary of the results of a statistical analysis (T-Tests) showing the significance of the various subjective parameters is given in Appendix H to this report.

Clothing Weight Gains

The subjects and the test garments were weighed before and after each wear trial so that moisture loss from the sweating skin could be determined. Figures 9-12 show the evaluator weight loss and garment weight gains measured for each turnout tested. These graphic presentations show that there was significantly greater weight gain in clothing items when wearing turnout #4. The weight gain in the clothing items confirms responses in the subjective evaluation which rated system #4 as generating the greatest feeling of skin wettedness. Detailed information on the weights can be found in Appendix J.

Figure 5. Effect of Garment Selection on Microclimate Humidity change in Mild Environment (21 C, 65% R.H.)

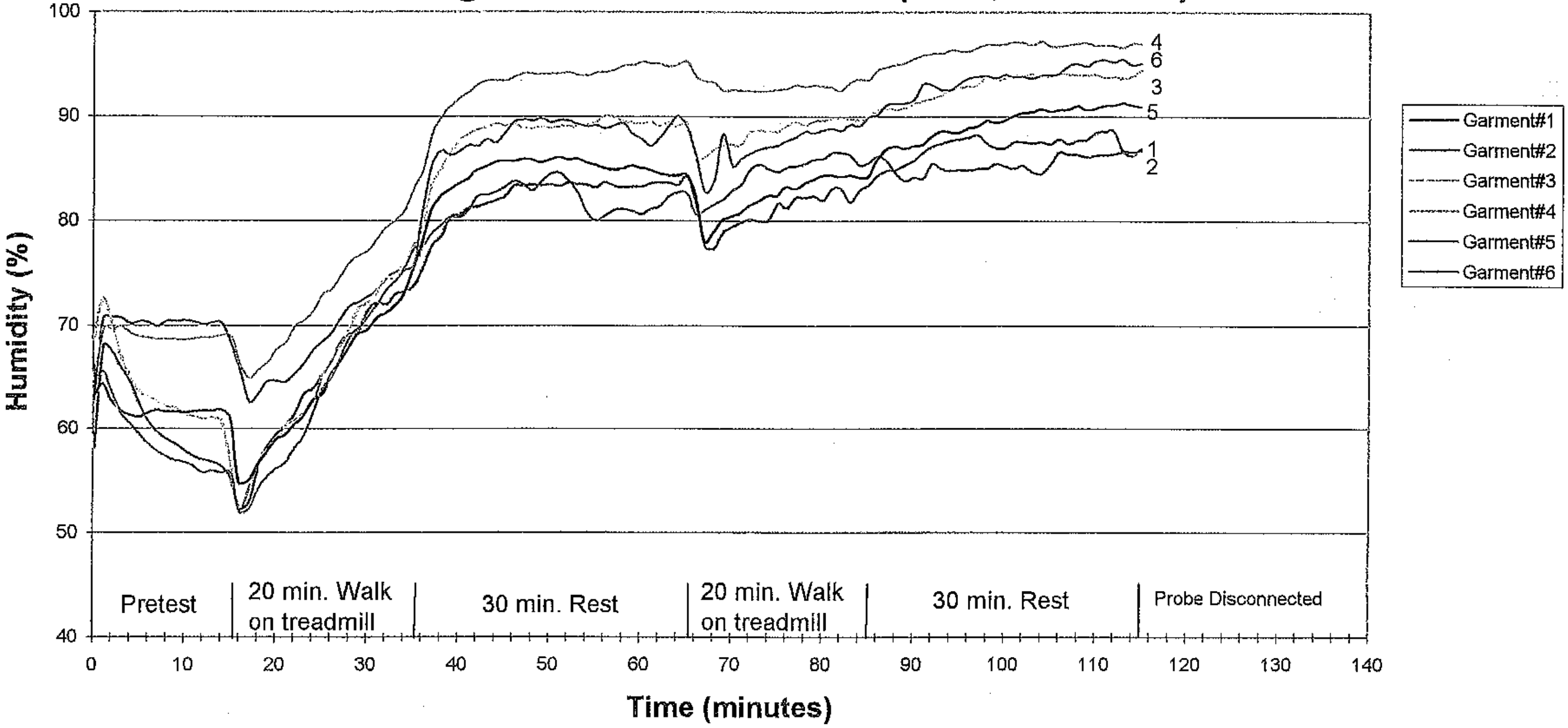
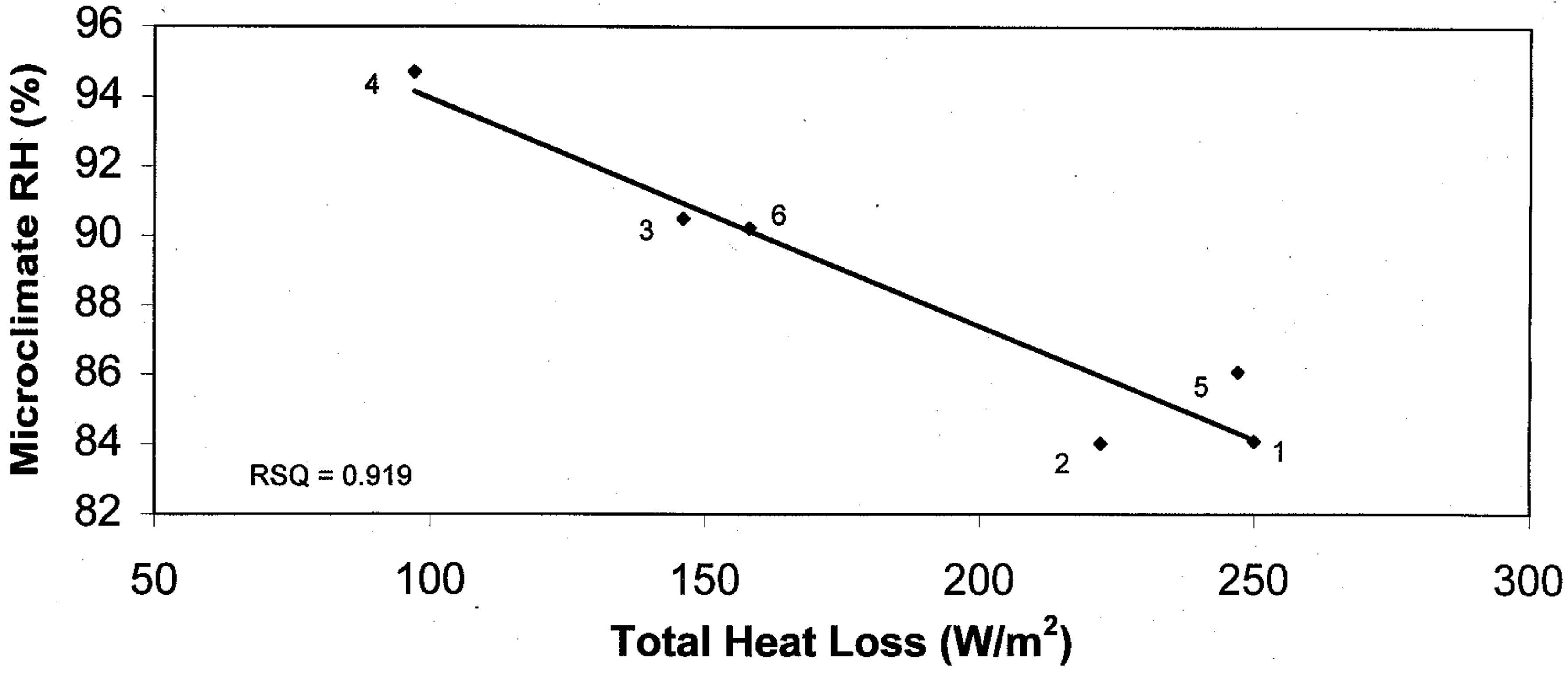


Figure 6. Correlation between Garment Breathability and Microclimate Humidity



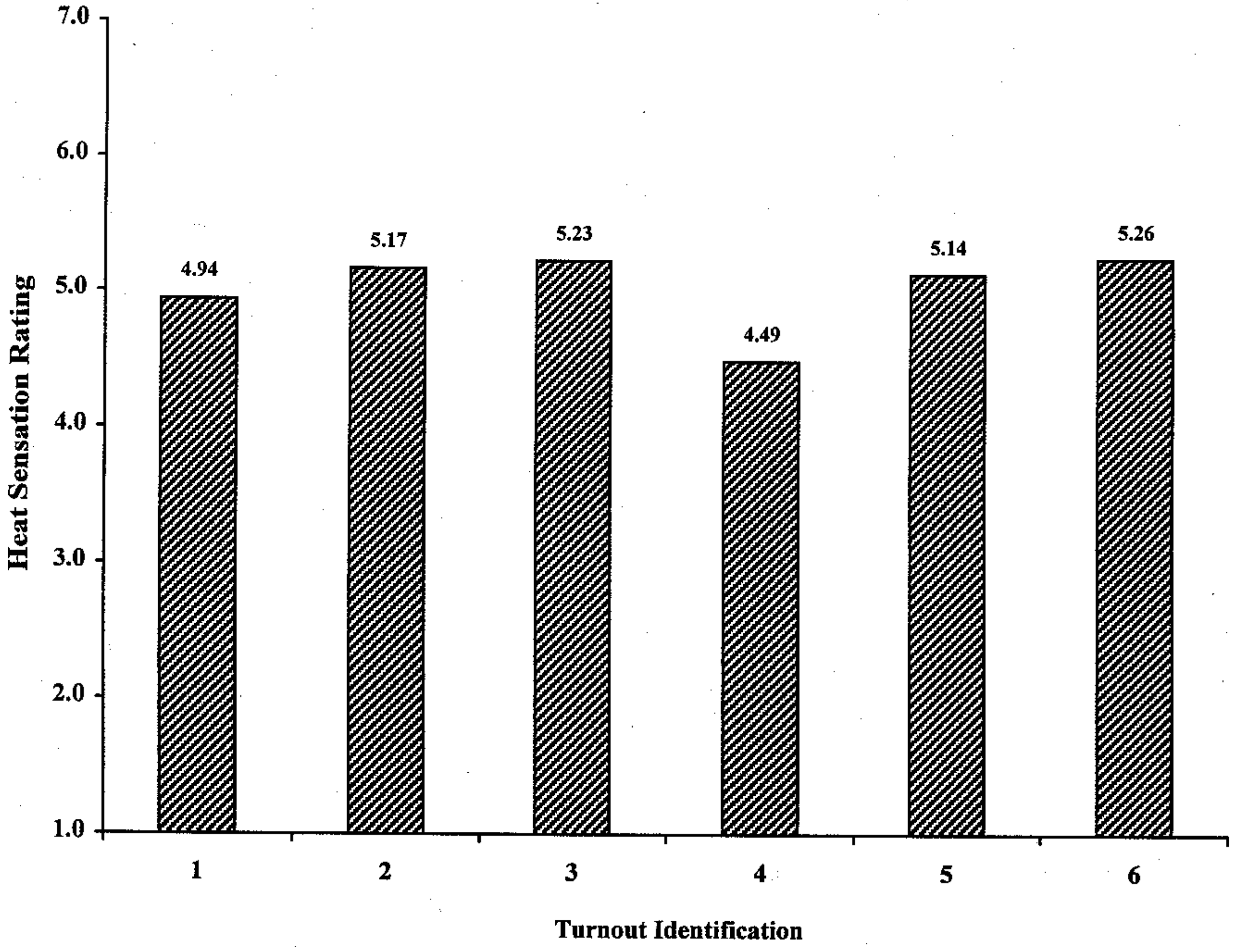


Figure 7. Mean Heat Sensation Rating of Ensemble; All Periods Combined (Mild Protocol: 21 deg C, 65% RH)

Scale:	**7**	**Cool**
	6	**Neither Cool nor Warm**
	5	**Slightly Warm**
	4	**Warm**
	3	**Very Warm**
	2	**Hot**
	1	**Intolerable**

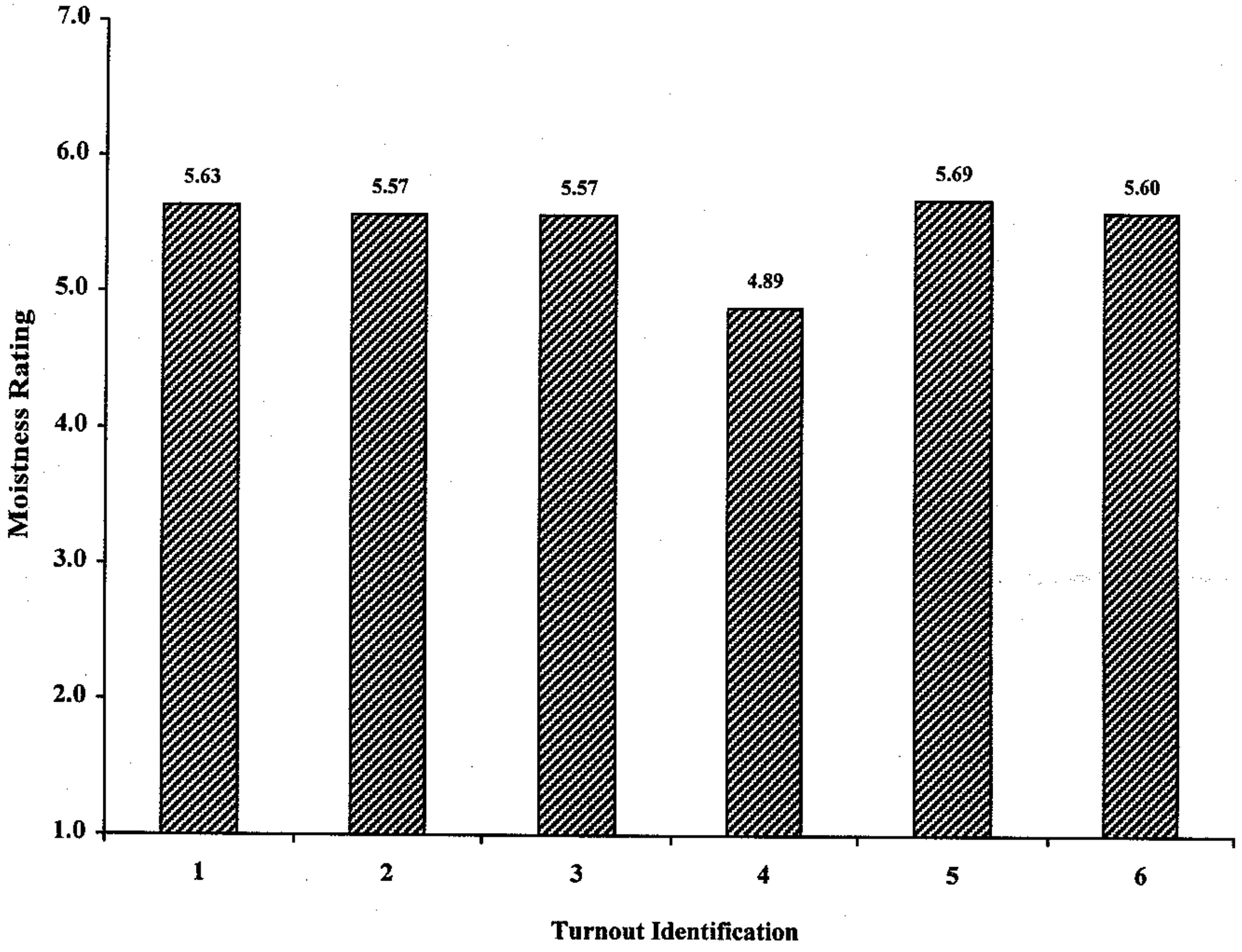


Figure 8. Mean Moistness Rating of Ensemble; All Periods Combined (Mild Protocol: 21 deg C, 65% RH)

Scale:	**7**	**Totally Dry**
	6	**Slight Feeling of Moistness on Back/ Chest Area**
	5	**Breaking a Sweat**
	4	**Most of the Back and Chest Feel Wet**
	3	**Some Dripping**
	2	**Heavy Dripping**
	1	**Sweat Running Off the Back**

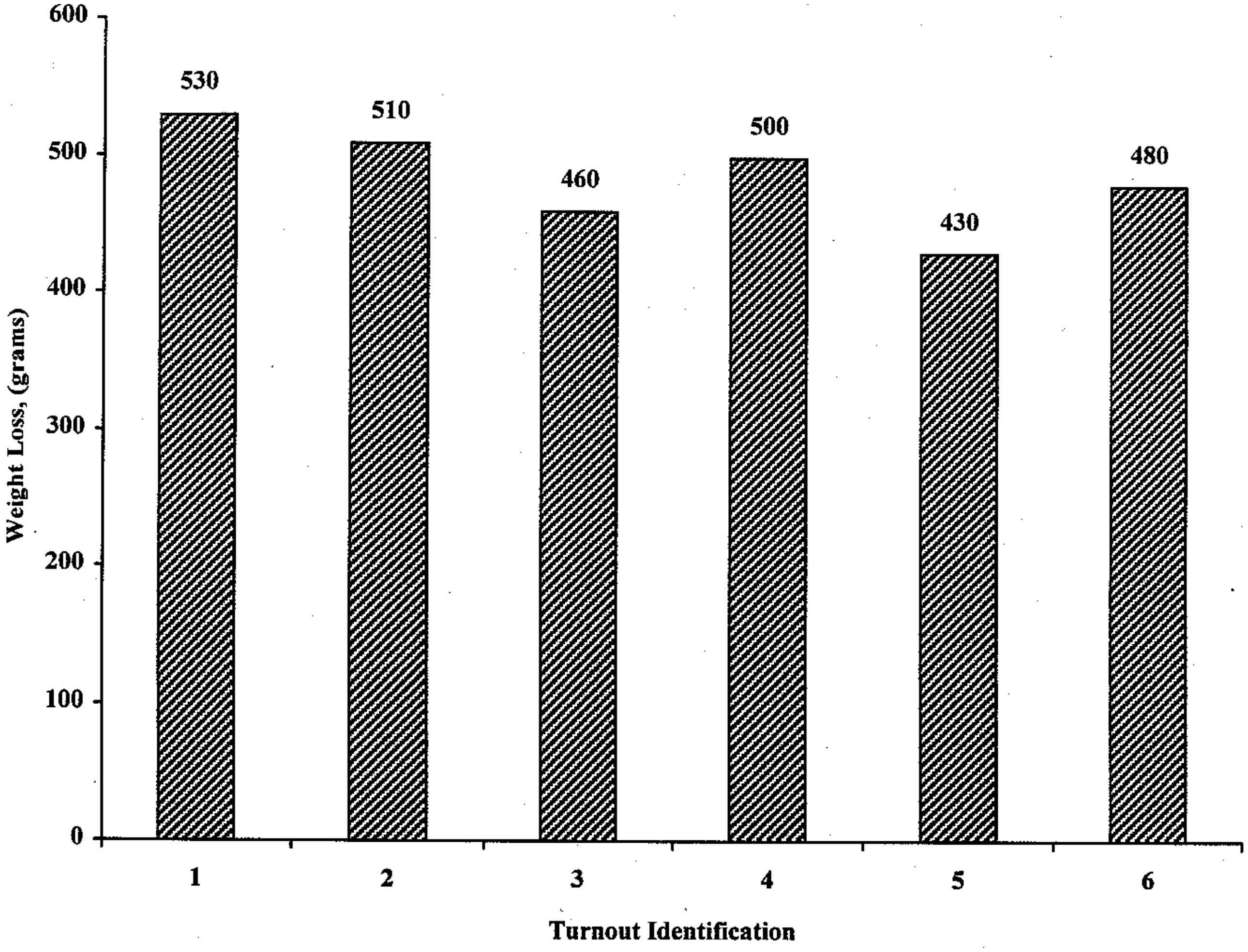


Figure 9. Average Evaluator Weight Loss

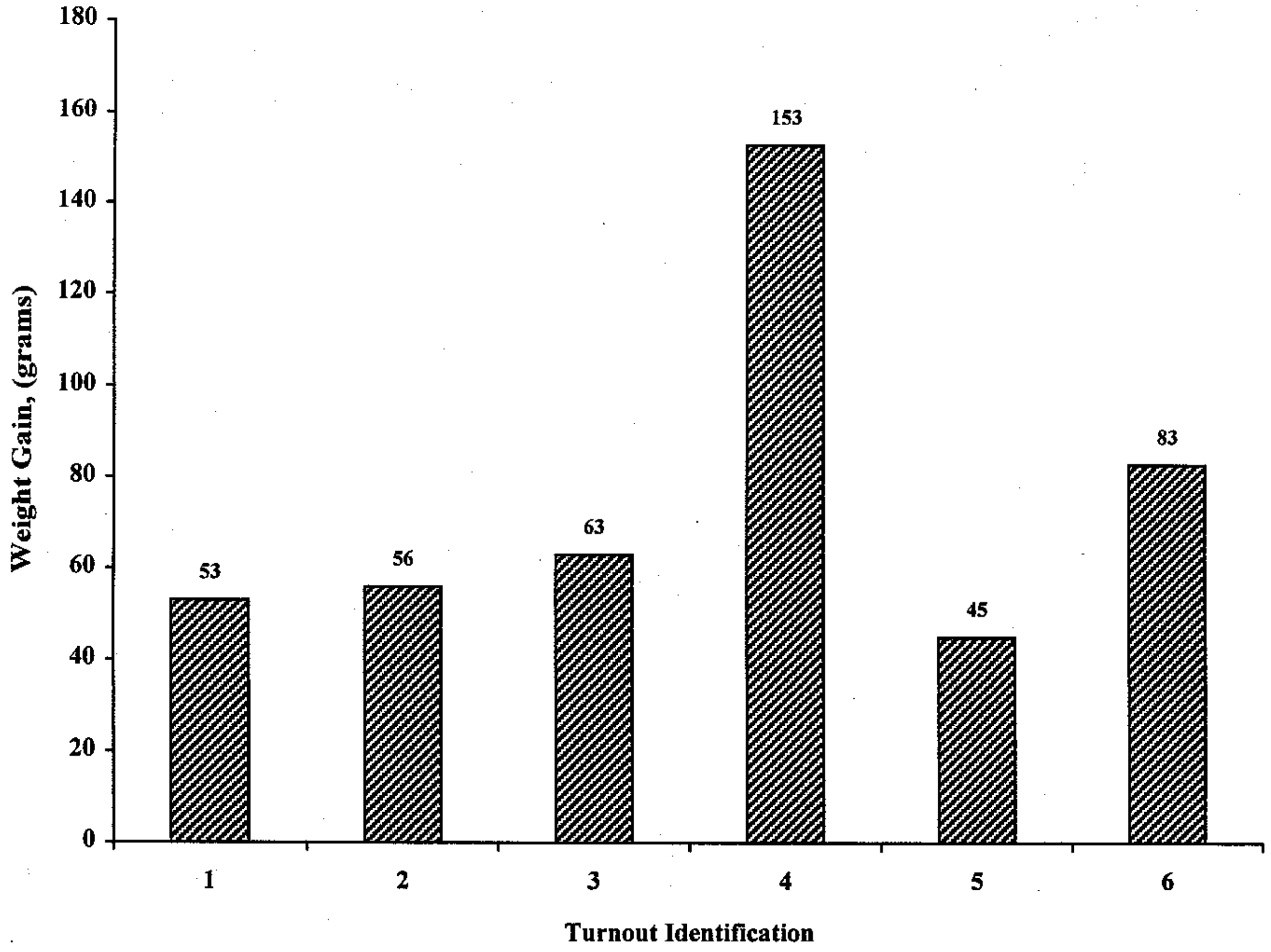


Figure 10. Average Weight Gain of Turnout Coat & Pants

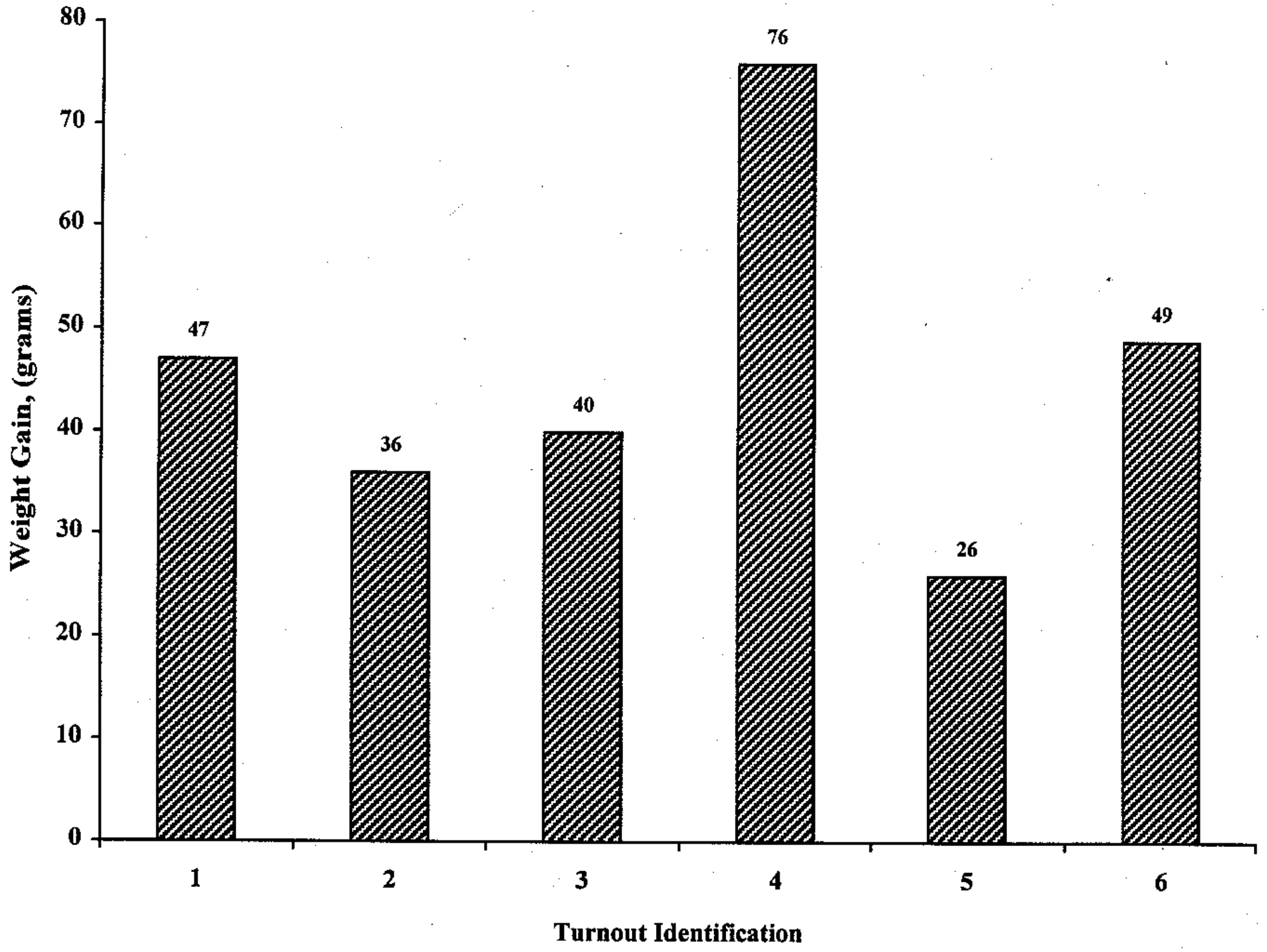


Figure 11. Average Weight Gain of Underwear

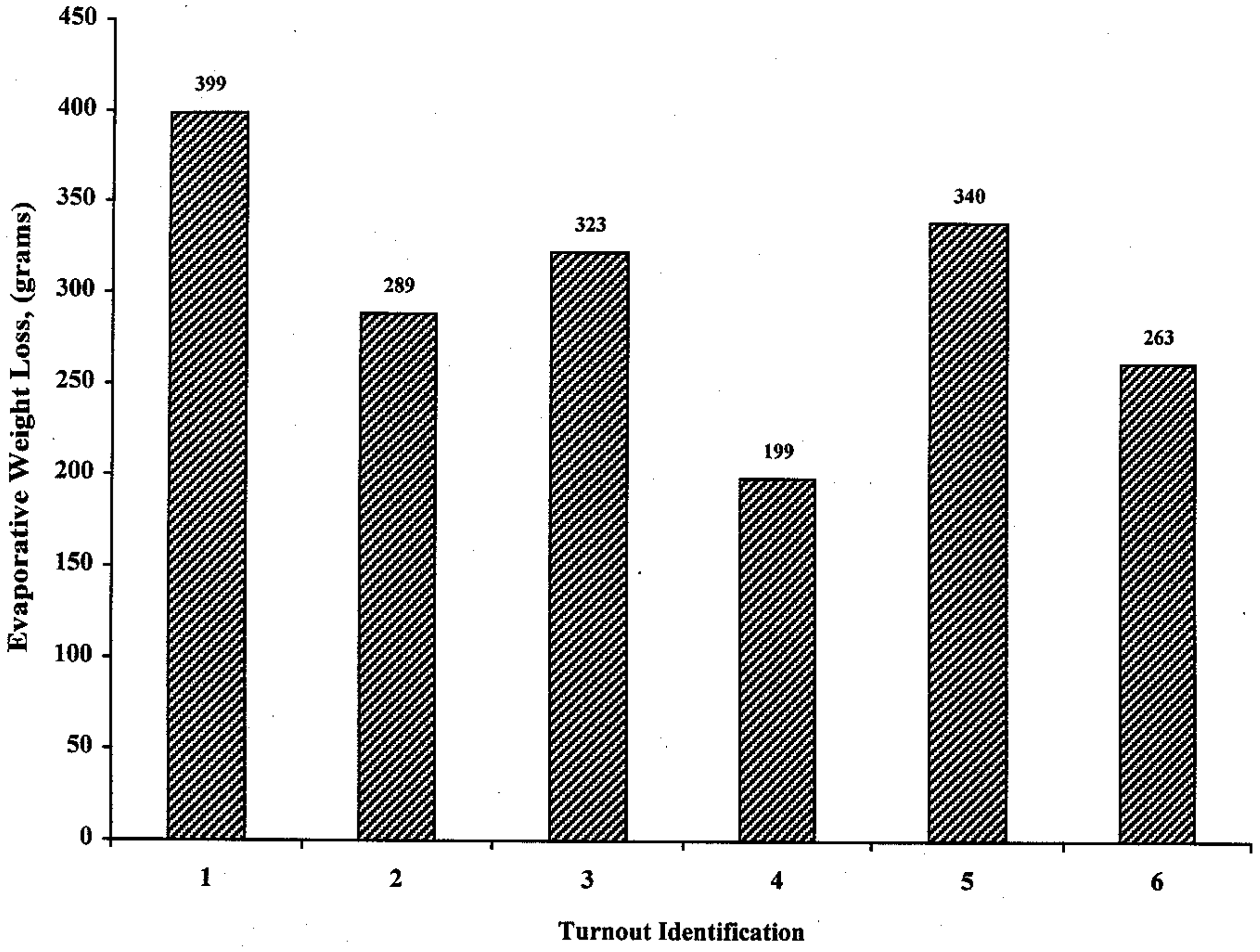


Figure 12. Average Evaporative Weight Loss*
*Evaporative Weight Loss = Evaluator Weight Loss - Ensemble Weight Gain

Summary

The relationship between system "breathability", as measured in the guarded sweating hot plate test, and wear response in the mild climate protocol can be summarized as follows:

Physiological Data	**Correlation** (Garment breathability vs. response)
Core Temperature	Less than 0.5°C increase for any turnout system. No statistically significant difference related to breathability.
Heart Rate	No significant difference.
Mean Skin Temperature	Correlates with breathability. Statistically significant differences among some garments indicated.
Clothing Data	
Microclimate Humidity	Correlates with breathability. Statistically significant differences indicated for garment #4 (Qt = 97 watts/m^2).
Subjective Data	
Moisture Sensation	Primary statistically significant differences indicated for moisture, heat sensations.
Heat Sensation	Perceived disadvantages associate only with garment #4 (Qt = 97 watts/m^2).

Conclusions From the Mild Environment Protocol

For low work loads, in a mild environment, physiological heat stress limits are not approached, regardless of the "breathability" of the turnout composite. At low work loads, in a mild environment, core temperatures increase less than 0.6°C. No significant differences are seen in measured core temperature or heart rates that can be correlated with differences in turnout breathability.

For mild wear conditions, differences in turnout breathability surface at the comfort level: sweating plate heat loss values correlate with measured indexes that associate with turnout comfort performance (higher sweating plate scores correlate with lower skin temperatures and less indicated buildup of moisture vapor in the turnout microclimate). However, firefighters can decisively perceive and differentiate among composites on the basis of comfort sensations only in the case of the composite having the lowest total heat loss ($Qt = 97$ watts/m^2). Statistically significant differences in comfort performance can be related to feelings of warmth and skin wettedness that occur in wearing turnout #4.

System # 4 produced the highest accumulation of sweat and lowest level of sweat evaporation through the clothing to the ambient environment, with less than 40% of the generated sweat evaporating. This factor undoubtedly contributed to the heightened sensation of skin wetness experienced wearing this garment.

Part II. WARM ENVIRONMENT WEAR TRIAL PROTOCOL

Method and Procedures

The same group of seven professional firefighters participated in the warm environment study. Since the experiments were conducted during the summer in a southern city, all of these full-time firefighters would have been expected to be partially if not fully acclimated to work in the heat. Physical characteristics of these subjects are presented below.

	Age (years)	Height (inches)	Weight (pounds)	VO2 max (nk/ kg/ min)	S.A. (m^2)
	34	69	186.8	45.5	2.02
	36	72	196.0	44.2	2.12
	35	75	202.3	46.6	2.22
	35	72	179.5	46.3	2.03
	29	73	200.0	43.2	2.15
	33	76.5	261.6	41.7	2.50
	34	69	258.6	30.2	2.28
Mean	33.7	72.4	212.1	42.5	2.19
S.D.	± 2.3	± 2.8	± 33.7	± 5.2	± 0.17

Aerobic capacity (VO_2 max) was estimated by computer-guided submaximal cycle ergometry (Biomedical Computer Systems, San Antonio, Texas). This method was validated against the criterion method and agrees within ± 1.4 ml/kg/min with those determined by indirect calorimetry during maximal treadmill exercise (Myhre, L.G., In Press). Body surface area (S.A.) was according to Dubois and Dubois (Dubois, D., and E.F. Dubois. A formula to estimate the approximate surface area if height and weight are known. Arch. Intern. Med. 17:863-871, 1916.)

Test Work Load

Subjects wearing the complete fire fighter protective ensemble walked on motor-driven treadmill set at 2.5 mph and up a grade of 2%. The energy cost of this activity was determined by indirect calorimetry; expired air collected in Douglas bags following 6 minutes of steady walking at this pace was measured in a dry gas meter and analyzed for oxygen and carbon dioxide on a Haldane apparatus. Ventilation and oxygen uptake during these experiments averaged 28.8 ± 8.3 liters/min and 15.6 ± 2.7 ml/kg/min respectively; energy expenditure during work averaged 225 ± 39 watts/m^2.

Ambient Conditions

All experiments were conducted in a thermally controlled environmental chamber. Air and globe temperatures were 39 + 0.1°C and relative humidity was maintained at 35%. Wet bulb globe temperature was 29.9°C (85.8°F)

Experimental Procedures

The subjects refrained from any strenuous physical activity or heat exposure overnight and prior to driving to the experimental laboratory in air-conditioned vehicles. They were instructed to drink 500 ml (measured) of water before commencing travel to the laboratory, and drank an additional 500 ml during a rest period of 20 - 30 minutes after arrival; laboratory and dressing room temperatures were maintained at 22 ± 1°C. They were then fitted with a chest strap equipped with EKG electrodes; skin thermistors (Yellow Springs Instruments series 400) were positioned on the upper arm (T_{arm}), chest (T_{ch}), back (T_b), and thigh (T_{leg}) and a rectal thermistor (Yellow Springs Instruments series 400 disposable probe) was inserted to a depth of 12 cm past the anal sphincter (T_{re}). They voided urine and "nude" weight was recorded (Ohaus platform balance, accuracy ± 10 grams) with subjects wearing only cotton briefs and the EKG and temperature sensors. Immediately after recording the nude weight and recording baseline temperatures (YSI Precision 4000 A Thermometer) and heart rate (Polar telemetry) the subjects dressed in their normal summer work uniform which consisted of 100% cotton socks, short-sleeved shirt, and trousers. They then donned the complete protective garment assigned to them for that day. (Note: Initial garment temperatures were the same as the laboratory (i.e., 22 ± 1°C) where they had had been stored for 20+ hours prior to each experiment.) Standard accessories included a 2-ply balaclava hood, gloves (meeting NFPA 1973 standard), jogging shoes (in lieu of the standard fire fighter boot), and helmet. Trouser cuffs were sealed at shoe level with duct tape and fully-clothed weight, heart rate, and body temperatures were recorded. They walked approximately 40 feet to the environmental chamber where they donned a Scott 4.5 SCBA equipped with an integrated PASS device (total weight including a light-weight fully charged cylinder was 21.5 lbs.). The SCBA regulator was not affixed to the face piece, thus allowing the subject to breathe fresh ambient air during the course of the experiment. A humidity sensor was fixed to a position at the center of the back between the station shirt and the garment's insulative liner and they commenced the first of a series of 15-minute bouts of exercise followed by 2 minutes of rest (seated) until core temperature reached 39.0 °C or, for any reason, they were either unwilling or felt that they were unable to continue.

Garments

The garments tested were identical to the garments tested in the mild conditions study. Each subject was assigned to wear each of the six experimental garments in random order and on different days. The time of day for each subject's experiment was held constant throughout the study.

Observations

Heart rate, skin and rectal temperatures were recorded at 5 minute intervals during exercise and following each 2-minute rest period until the experiment was terminated for the reasons given above. Comfort questionnaires were given during each rest period and immediately following the termination experiment. After doffing the SCBA and the humidity sensor they left the environmental chamber and returned to the dressing room. Body weight while wearing all of the protective gear was again obtained and followed by a recording of "nude" weight. Each item of clothing was weighed to determine the sweat content. Then the subjects rested in the cool dressing room while drinking either cold water or fruit juice ad lib. until the principal investigator had determined that they had recovered sufficiently to be permitted to shower and dress.

Mean skin temperature (T_{sk}) was estimated from weighted surface areas represented by the arm, chest, back, and leg sensors. Total sweat loss (TSL) was calculated from the difference between initial and final nude weight. The difference between initial and final clothed weight was assumed to represent evaporative sweat loss (ESL).

Data Generated

- Core (rectal) temperatures
- Skin temperature
  - back
  - chest
  - upper arm
  - thigh
- EKG heart rate
- Microclimate humidity
- Moisture loss in subject
- Moisture gain in clothing
- Subjective ratings

Subjective Comfort Parameters Studied

Same as in the mild study. The detailed test protocol is found in Appendix L.

Results (Warm Climate Protocol)

Results for the warm climate test protocol are discussed in this section and the detailed data from instrument measures of core and skin temperature and heart rate are in Appendix M.

Work Tolerance Time: A summary of work tolerance times (WTT) observed under the conditions described here are presented below.

	Composite Identification					
	1	**2**	**3**	**4**	**5**	**6**
Minutes (mean)	54.3	54.0	52.9	46.3*	53.3	51.0
S.D.	± 9.6	± 11.7	± 9.9	± 7.3	± 10.4	± 10.5

* $P<0.05$

The average WTTs when wearing garments # 1, 2, 3, 5, and 6 were not significantly different, but all were significantly greater than that for garment #4.

Core Temperature: Initial core temperatures observed for the fully clothed subjects while at rest in the laboratory (air conditioned facility), immediately after donning a variety of protective garments, and immediately prior to entering the environmental chamber (warm environment) for the treadmill exercise, are presented below.

	Composite Identification					
	1	**2**	**3**	**4**	**5**	**6**
Core Temperature (mean)	36.78	36.85	36.87	36.98	36.99	36.82
S.D.	0.34	0.23	0.24	0.34	0.27	0.20

Core temperatures at the start of work in the heat were essentially the same regardless of the garment worn. Mean differences were less than 0.3° C and they were not significantly different. For the most accurate comparison of garment effect on core temperature during work in the heat, the initial or baseline temperatures, summarized in the table above, were plotted as "zero" in the graphic illustrations that follow. The cumulative rise in core temperature during work when wearing each of the six garments studied and are presented in Figure 13.

In reviewing the data plotted in Figure 13 it should be noted that all subjects completed at least 32 minutes of the work/rest regimen before quitting with the discomfort of heat stress. The data continued to be analyzed through the 44th minute, after which only three

Effect of Garment Selection on Core Temperature During Work in the Heat

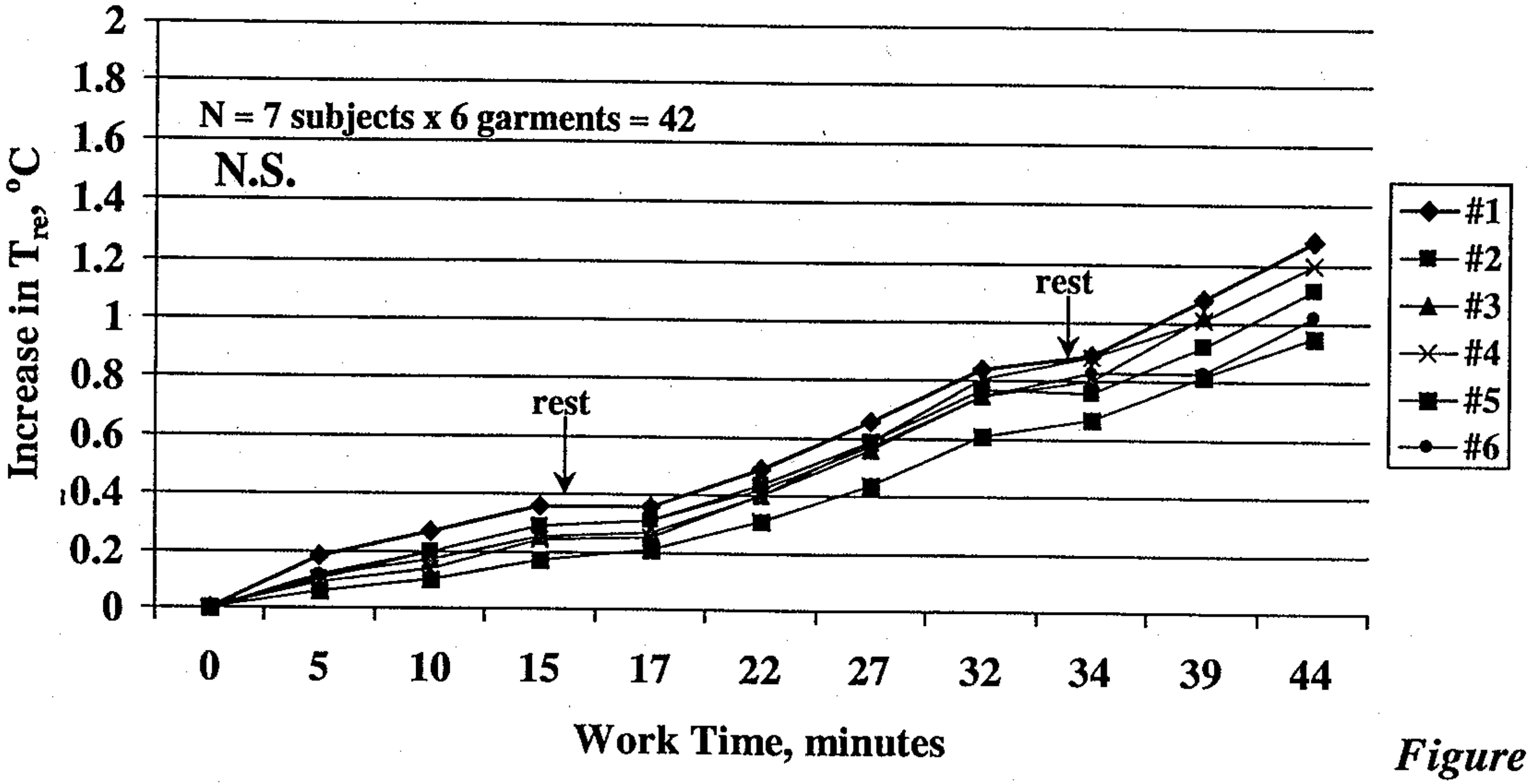


Figure 13

subjects remained which were considered inadequate for statistical analyses. It should be noted that the greatest difference in the rise in core temperature between garments was only about 0.2°C at the 27th minute and only about 0.3°C after 44 minutes of work in the heat. Although one might be tempted to suggest that the warmest garment appeared to be #1 ($\Delta = + 1.28°C$) and the coolest was #5 ($\Delta = + 0.95°C$), none of the differences observed here were significant.

Heart Rate: Heart rate responses to work in the heat wearing each of the garments studied are presented in Figure 14.

From Figure 14 it can be seen that heart rates increased progressively during work in the heat when wearing each of the garments studied. The mean heart rate observed when wearing garment #4 appeared to increase at a greater rate than that observed in any of the other garments, and this difference became significant after 32 minutes and remained significantly higher thereafter. None of the differences observed for any of the other garment conditions were significant.

Mean Skin Temperature: The weighted average for arm, chest, back, and leg skin temperatures when wearing each of the garments studied are plotted in Figure 15.

From Figure 15 it can be seen that skin temperatures at the beginning of work in the heat were essentially the same at about 32°C regardless of the garment worn. Thereafter, mean skin temperatures increased at about the same rate for all garments until the 22nd minute at which time those observed when wearing garment #4 became slightly (0.3°C), but significantly greater than any of the other garments studied. As work continued, the difference in skin temperatures between garment #4 and the others progressively increased until the 44th minute at which time those observed for garment #4 averaged 0.9°C higher than the mean of all other garments. It should be noted that mean skin temperatures for garments #1, 2, 3, 5, and 6 were essentially the same throughout the entire course of these experiments.

Sweat Rate: The rate of sweat loss observed for firefighters wearing garment #4 averaged 1721 g/hr which was significantly higher than that for all other garments which ranged from a mean of 1440 to 1498 g/hr. None of the other garments differed significantly in this response. Subtracting the weight of sweat remaining in the fire fighter's clothing at the end of the experiment from the total loss of body weight provides an estimate of the amount of sweat that evaporated during the course of these experiments. Mean values for overall sweat rate contrasted with the portion that was calculated as evaporating are plotted in Figure 16.

From Figure 16 it can be seen that only when wearing garment #4 was sweat rate significantly greater than that for any of the other garments studied. This figure also shows that most of the sweat lost was accounted for in the fire fighters' clothing at the end of the experiments. The volume of sweat not accounted for was estimated as "evaporated" and this ranged from a low of 11.5% for garment #4 to a high of 23.3% for garment #1. However, not all of the sweat which was not accounted for in the weighing

Effect of Garment Selection on Heart Rate During Work in the Heat

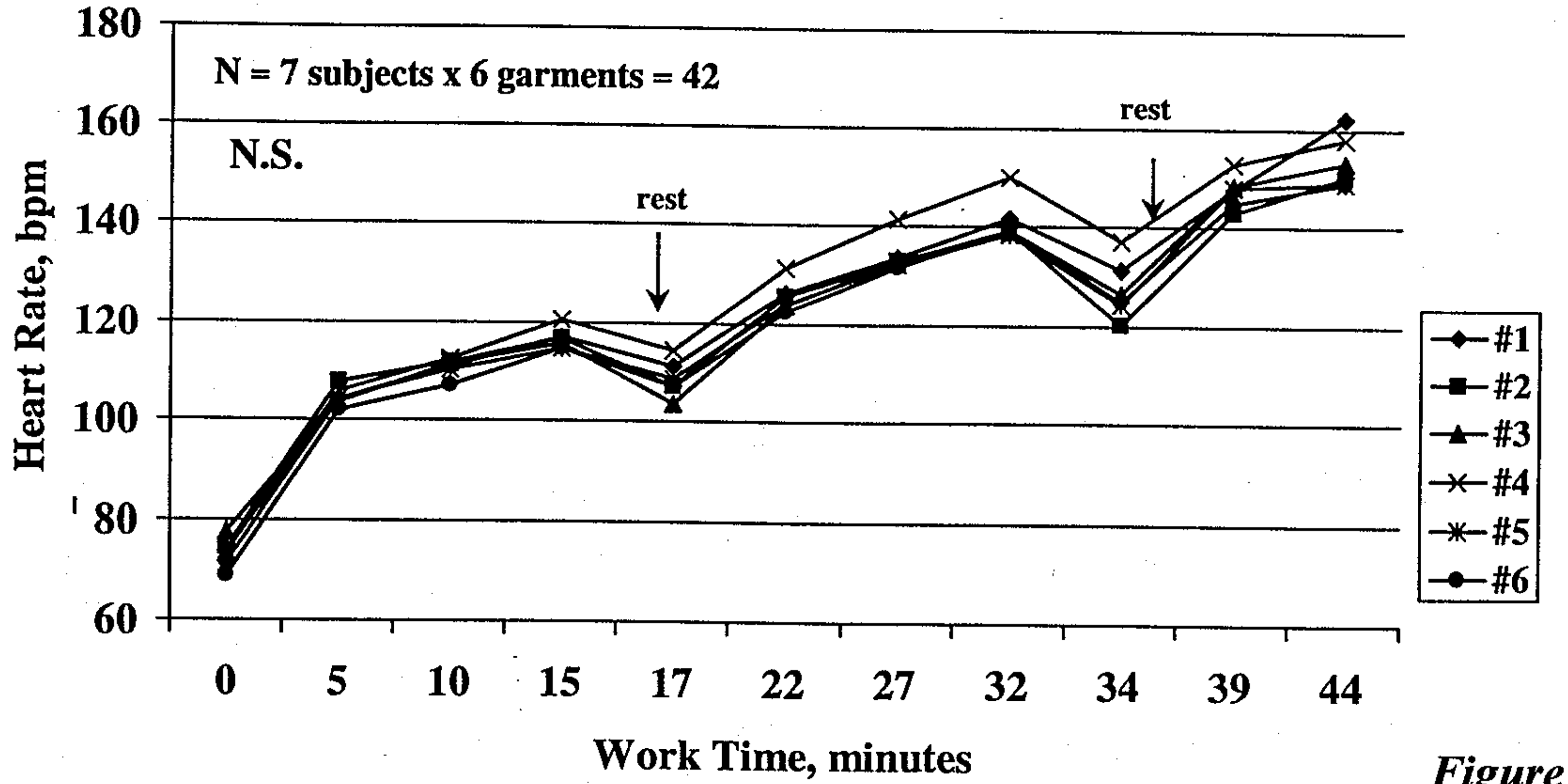


Figure 14

Effect of Garment Selection on Mean Skin Temperature During Work in the Heat

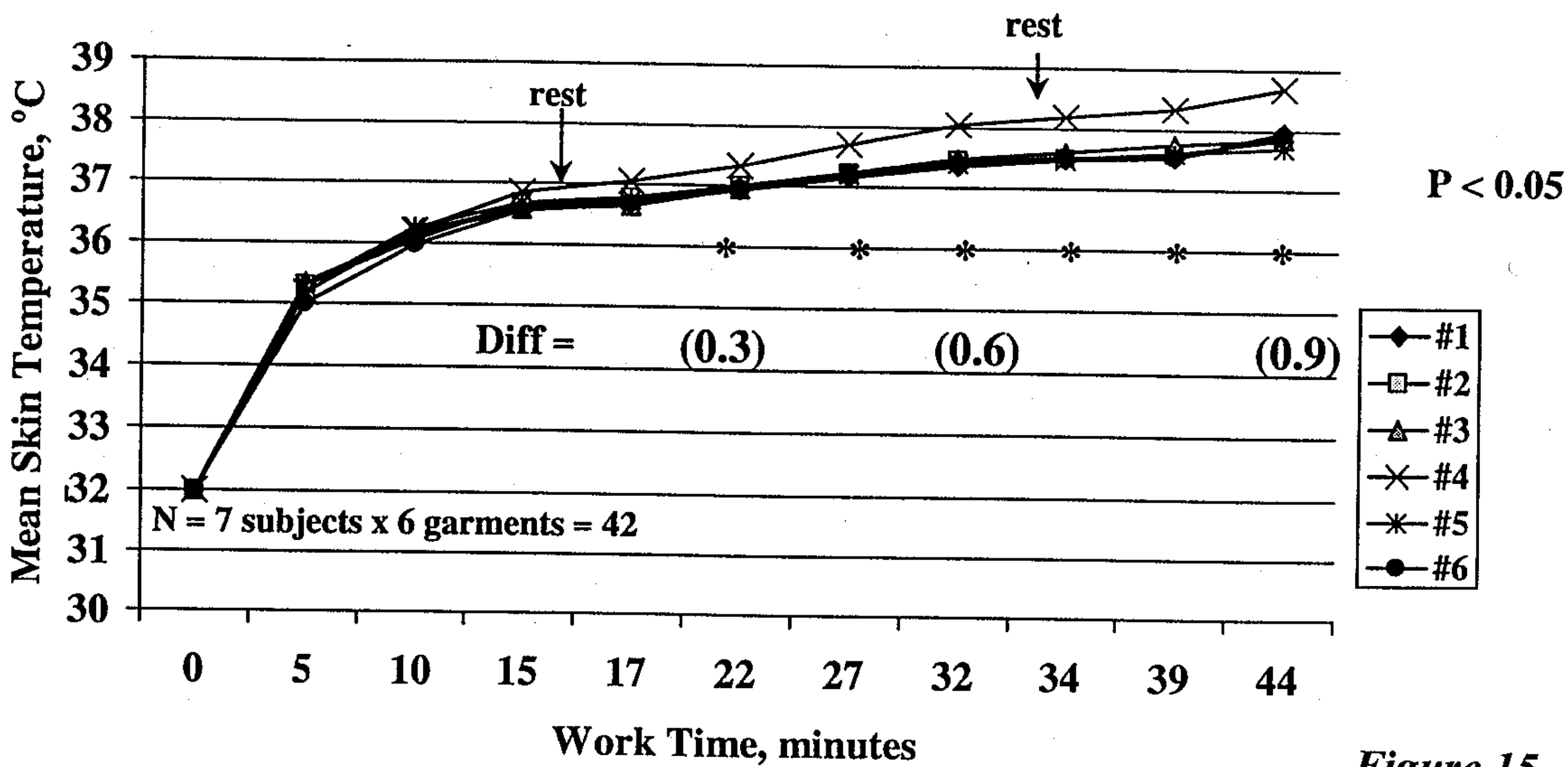


Figure 15

Effect of Garment Selection on Evaporative Sweat Rate During Work in the Heat

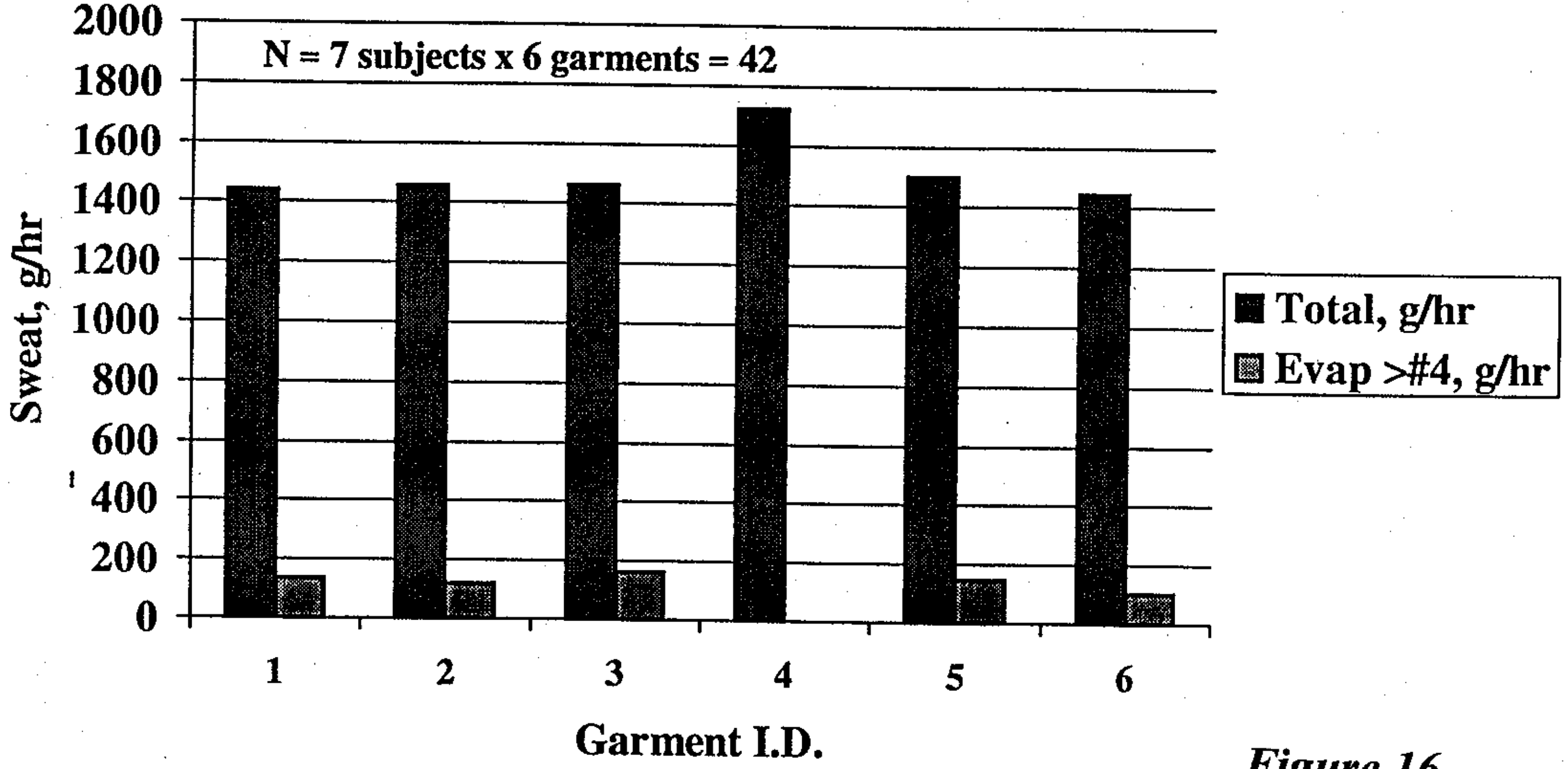


Figure 16

of the clothing evaporated through the clothing. Some of it may have dripped from the face and through the open facepiece, and some could have evaporated through the canvas shoes, around the wrist, waist, and neck areas. From Figure 16 it can seen that sweat "evaporated" at an average rate of 183 g/hr when wearing garment #4. The detailed weights data is in Appendix P and statistical analysis is in Appendix Q.

The subjective ratings showed that only system #4 was perceived by the evaluators as hotter and causing greater sensations of skin wettedness (Appendix N and O).

Evaporation rate: For further illustration, Figure 17 plots the overall sweat rates observed for each of the garments studied, and this time, the values plotted as "evaporated" are those intended to represent the volume of sweat that evaporated through the breathable moisture barriers (i.e. the 183 g/hr of sweat lost when wearing the impermeable garment #4 was considered as "0", and then 183 g/hr was subtracted from the "gross evaporation" values observed for all other garments).

From Figure 17 it can be seen that, although sweating occurred at rages exceeding 1400 g/hr, the maximum volume of sweat that could have passed through the breathable composites in garments #1, 2, 3, 5, and 6 would have been less than 200 g/hr.

Correlations: Pearson Product Moment Correlation analyses were conducted to determine the relationship between guarded sweating hot plate values for each of the garment fabrics studied and the physiological responses of the fire fighters when wearing each of these garments during a standard bout of work in a warm environment. The results of these analyses are summarized in the table below.

	-------------------- Correlation Analysis (r) -------------------- -------------------- Sweating Hot Plate Values vs.: --------------------		
Work Time	Core Temperature	Skin Temperature	Heart Rate
15th minute	- 0.19	- 0.40	- 0.53
32nd minute	- 0.31	- 0.77	- 0.61
44th minute	- 0.01	- 0.65	- 0.06

Although the fire fighters exhibited slightly, but significantly higher values for mean skin temperature, sweat rate, and heart rate during work when wearing garment #4, none of these differences were found to be correlated with values obtained from guarded sweating plate tests. Stated another way, sweat plate values for fabric samples from six of the garments studied ranged from 97 to 251 watts/m^2. However, there was no significant correlation between these measures of heat transfer and any of the physiological indices of heat stress observed when firefighters wore each of these garments during work in the heat.

Effect of Garment Selection on Evaporative Sweat Rate During Work in the Heat

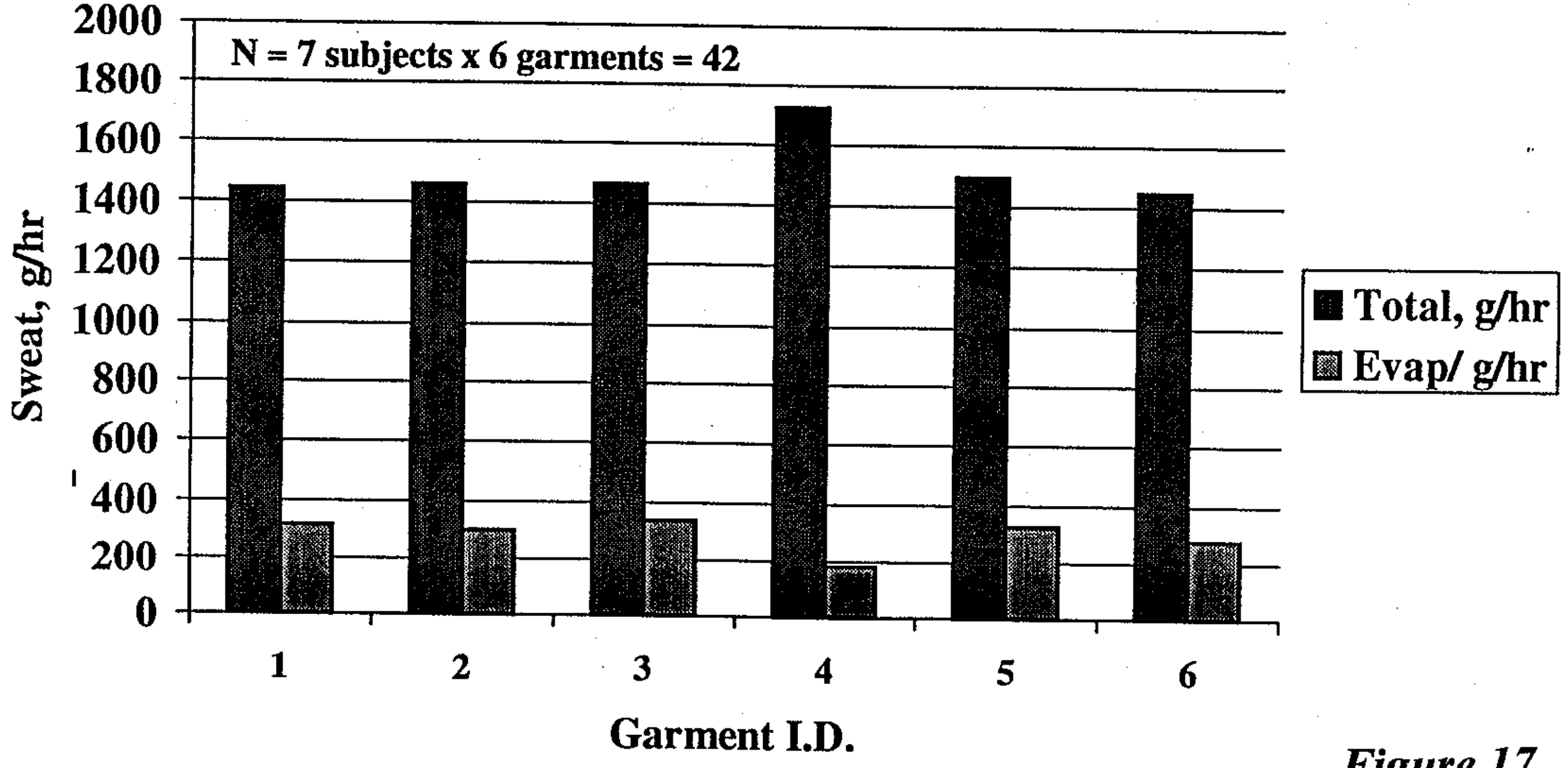


Figure 17

Summary

During the first 15 minute bout of exercise, there were no detectable differences in physiological responses to work in the heat which could be attributed to garment selection. By the end of the 32nd minute of work, body temperatures when wearing all of the garments studied had risen to levels which indicated significant heat stress, but the only significant difference observed was a slightly higher mean skin temperature (+ 0.3°C) when subjects were wearing garment #4 with the lowest heat loss value in the sweating plate test (i.e., 97 watts/m^2). Thereafter, subjects began to withdraw from the experiment as they approached their tolerance limits for work in the heat. Most of the firefighters were able to complete the 44th minute of work at which time the only significant difference in heat stress response was, again, the higher mean skin temperature (+ 0.9°C) for subjects wearing garment #4 identified by the heat loss value of 97 watts/m^2. Throughout the entire experiment, none of the other garments differed with respect to physiological responses to work in the heat.

Analyzing for the correlation between heat loss values determined by the guarded sweating hot plate and evaluator responses during 44 minutes of light to moderate work in a warm environment can be summarized as follows:

Parameter	Sweating Hot Plate Value (97 to 251 watts/ m^2)
Rate of rise in Tre	NS
Rate of rise in HR	NS
Rate of rise in Tsk	NS
Sweat rate	NS
Evaporative rate	NS

Both physiological and psychological factors influence work tolerance time (WTT), which was not significantly correlated with sweating plate values. However, WTT for garment #4 averaged 6.8 minutes less than the mean of all other garments (which were not different), and this difference was significant.

Conclusions From the Warm Environment Protocol

All subjects exhibited very similar symptoms of heat stress and fatigue following the termination of these experiments. Garments with heat loss values ranging from 146 to 251 watts/m^2 as determined by the guarded sweating hot plate were essentially equal with respect to measured physiological responses to heat stress when worn by firefighters under these conditions. None of the garments with heat loss values ranging from 97 to 251 watts/m^2 differed significantly with respect to either the rate of rise in core temperature or the exercise heart rate during 44 minutes of work in a warm environment. However, the garment with a heat loss of 97 watts/m^2 exhibited a significantly shorter WTT (13%), and significantly higher mean skin temperature (0.9°C following 44 minutes of exercise) and total sweat rate (18%) than the average for the other five garments studied.