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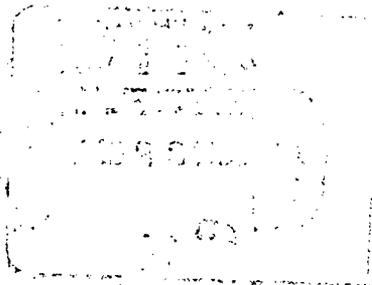
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THE ROLE OF THE  
HOST CELL/VIRION CARRIER  
IN THE ESTABLISHMENT OF  
A NEW INFECTION DURING  
REINOCULATION



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October 1988

DCIEM No. 88-RR-40

THE ROLE OF THE  
MOISTURE/VAPOUR BARRIER  
IN THE RETENTION OF  
METABOLIC HEAT DURING  
FIRE FIGHTING

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DEPARTMENT OF NATIONAL DEFENCE - CANADA

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### Abstract

The relationship between metabolic heat build-up and the vapour permeability of the barrier layer in fire fighter turnout clothing was examined under a variety of conditions. Laboratory exercise tasks were used to simulate the work of fire fighters performing under three different environmental conditions, cold, hot and extended very hot conditions. The laboratory studies were followed by a field trial in which true fire fighting activities were performed. The clothing elements examined included three outer shells, five moisture/vapour barrier configurations, and two thermal liners. Ten parameters indicative of thermal physiological strain were monitored in eight professional fire fighters to assess the role of the barrier in the retention of metabolic heat.

The results showed that the moisture/vapour barrier material/configuration was the dominant factor in determining thermal physiological strain, with the shell and liner playing very minor roles. Differences in strain as a function of barrier were discernible even under low to moderate stress, but became more pronounced with higher ambient temperatures and longer work periods. The laboratory results were clearly substantiated during the field trial.

It is concluded that a full vapour barrier of a material such as neoprene leads to significantly higher thermal physiological strain than a vapour permeable water barrier of a material such as Gore-tex. Partial coverage barriers of either material provide even greater reduction in strain, and omission of the barrier entirely is best from a physiological perspective. The best fire fighter turnout clothing will be a compromise between the requirement to protect against external hazards and the need to dissipate metabolically generated heat. *Canada (AW)*

### Foreword

The Canadian Forces Fire Marshal (CFFM) has recognized that metabolic heat strain may be a problem for fire fighters wearing bunker clothing containing an integral impermeable barrier material such as neoprene. In the interests of developing a Canadian standard for fire fighter clothing that would provide sufficient hazard protection without imposing an exorbitant thermal load on the wearer, the Defence and Civil Institute of Environmental Medicine (DCIEM) was tasked by CFFM via the Directorate of Clothing and General Engineering Maintenance (DCGEM) to study the physiological impact of including a moisture/vapour barrier in fire fighter turnout clothing. In particular, DCIEM was asked to examine the relationship between metabolic heat build-up and the vapour permeability of the barrier by comparing physiological responses to wearing neoprene versus Gore-tex® as the barrier material.

DCIEM responded to this task with a three-phase project. Phase I was a field study to document the extent of the metabolic heat build-up problem as it exists with current CF bunker clothing. It provided a baseline upon which the subsequent research activities could be based. Phase II, the main portion of the project, consisted of an extensive laboratory study in which the physiological impact of wearing the vapour barrier was carefully examined under tightly controlled conditions of temperature, humidity, and work activity. This phase involved extensive physiological monitoring of the test subjects, and included studies under cold, hot, and extended very hot environmental conditions. Finally, Phase III was again a field study, this time carried out under more controlled conditions than Phase I, with repeated identical activities for each subject. Phase III used the same clothing and test subjects as in Phase II, and was conducted to validate in the field those conclusions arrived at in the laboratory work. This report summarizes the results of the study in three parts corresponding to the three phases of the work.

## FIRE FIGHTER METABOLIC HEAT STRESS STUDY

### Introduction

Fire fighting is unquestionably a hazardous occupation for which highly specialized protective clothing is required. One of the more recent developments in fire fighter turnout gear is "bunker clothing" consisting of high cut trousers and an overcoat. Compared with the standard "petch coat" and rubber hip boots, the bunker clothing provides higher levels of hazard protection for the fire fighter, but it also impedes the dissipation of metabolic heat generated within the body.

Much of this impediment comes directly from the insulative nature of the clothing in its capacity to reduce conductive, convective, and radiant heat transfer [1, 2]. A portion of it may, however, arise from the vapour barrier, commonly neoprene rubber, that is called for in fire fighter clothing by NFPA 1971, *Standard on Protective Clothing for Structural Fire Fighting*, as adopted by the National Fire Protection Association, Inc. (USA) and issued by the Standards Council (USA) in 1981. This barrier is included to shield the fire fighter from steam and hazardous chemical vapours, and to help keep him/her dry (a vapour barrier is also a liquid barrier). It interferes, however, with metabolic heat dissipation by preventing evaporation of sweat from the body. With conduction, convection, and radiation often being sources of heat gain for the body during fire fighting, evaporation remains the only natural mechanism for passively cooling the body.

A recent development in barrier materials was the introduction of expanded polytetrafluoroethylene (PTFE) in the form of a membrane laminated to a fabric base. The most common trade name for such a product is "Gore-tex<sup>®</sup>" [registered trade mark of W.L. Gore and Associates, Elkton, Maryland]. The Gore-tex<sup>®</sup> membrane is claimed to be vapour permeable while still providing a barrier to air and liquid. These properties would seem to identify Gore-tex<sup>®</sup> as an ideal material for a moisture barrier in turnout clothing. (Note: although Gore-tex<sup>®</sup> was one of the first vapour permeable water barrier fabrics on the market, several competitive products of different composition but with similar properties are now

available.)

While laboratory tests have confirmed that Gore-tex® does indeed have "breathability" as claimed by the manufacturer [3, 4, 5], the real question is whether this enhanced vapour permeability provides a significant physiological benefit to the fire fighter performing his duties. Research comparing permeable and impermeable barriers in fire fighter clothing has been done, but the results have not been consistent [6, 7, 8]. The Defence and Civil Institute of Environmental Medicine (DCIEM) was, therefore, tasked by the Canadian Forces Fire Marshal (CFFM) through the Directorate of Clothing and General Engineering Maintenance (DCGEM) to examine the role of the vapour barrier in the build-up of metabolic heat in fire fighters wearing both breathable and nonbreathable turnout gear.

The initial concept of the study was a straightforward laboratory comparison of the two barriers, neoprene and Gore-tex®, in "standard bunker turnout clothing". However, it rapidly became clear that there was no "standard" for turnout clothing, since garments made from a variety of fabrics are available on the market. Although the turnout clothing used by CF fire fighters is standardized throughout the Forces, this study was also intended to provide information to civilian fire departments and other interested agencies including the Ontario Ministry of Labour, the Canadian General Standards Board, and the National Research Council of Canada. The study was, therefore, extended to include three different outer shells and two different thermal liners.

In addition, the feasibility of partial-coverage barriers of both neoprene and Gore-tex® was raised, since these may provide a sufficient level of hazard protection while minimizing the overall thermal stress imposed by a complete barrier. The proposed partial barriers would cover the shoulders, upper arms, and buttocks areas only.

The scope of the study was finally set to include three outer shells (wool, Nomex® [registered trade mark of Dupont Chemicals], and cotton), two thermal liners (wool and Nomex®), and five barriers (neoprene and Gore-tex®, in both full and partial configurations, and a no-barrier condition as a control). This represented 30 distinct clothing combinations that needed testing. Since the

degree of interaction among these clothing elements was not known, a  $3 \times 2 \times 5$  factorial experimental design was proposed. Studies would be conducted in the laboratory under carefully controlled environmental conditions, with subjects performing defined tasks representative of fire fighting duties.

Clearly, it was not possible to simulate all aspects of fire fighting in the climatic chamber of the laboratory. For this study, it was decided to use physiological strain, measured primarily by deep body temperature and heart rate, as the criterion for establishing that the work rates and environmental conditions under which the clothing was being tested were realistic. Stated simply, we wanted to elevate core temperatures and heart rates in the test subjects to levels comparable to those experienced by fire fighters performing their duties in the field.

Since the literature contains limited data on body temperatures and heart rates data during actual fire fighting [9], a field trial was conducted prior to the laboratory work to document the level of physiological strain reached by fire fighters performing typical fire fighting duties while wearing their present issue of turnout clothing. This portion of the study was labeled Phase I and, in addition to providing the physiological data base, it provided DCIEM researchers with a first-hand look at the activities and physiological stresses associated with fire fighting. This information assisted in the selection of laboratory work tasks and intensity that simulated many aspects of the upper and lower body movements seen in the field.

The laboratory portion of the study was Phase II of the overall project and comprised the major portion of the work. It involved extensive physiological monitoring of the subjects performing a series of tasks under cold, hot, and extended very hot environmental conditions.

A third and final phase was then added to the project. Phase III was again a field trial, but this time carried out with much stricter control over activities than Phase I. A battery of fire fighting tasks was defined and carried out repeatedly by each subject while wearing a subset of the 30 clothing combinations tested in Phase II. This phase was included to see if the conclusions arrived at in Phase II under simulated conditions in a climatic chamber would still hold true under the

more realistic conditions of actual fire fighting.

This report is a summary of the entire project. It is presented in three major sections corresponding to the three phases of the work. Phase II is further subdivided into three subsections representing the three environmental conditions under which the laboratory study was conducted.

## FIRE FIGHTER METABOLIC HEAT STRESS STUDY

### PHASE I: FIELD STUDY #1 -- CFB BORDEN

#### *Background:*

This portion of the study provided DCIEM researchers with a first-hand look at the activities and physiological stresses associated with fire fighting, thereby establishing a baseline for subsequent research activities.

The field exercise during which these data were collected was a regular fire fighter training session carried out at the Canadian Forces Fire Academy (CFFA) at Canadian Forces Base (CFB) Borden during September 1985. Several of the "students" on the course agreed to being monitored for body temperatures and heart rate while they went through their training exercises.

It is emphasized that DCIEM had no control over the activities of this field trial -- the subjects were simply monitored as they performed their specified tasks. The scope of the training was quite broad and involved a wide variety of fire fighter activities. Several of the scenarios to which the fire fighters had to respond during Phase I did not, in fact, involve extinguishing fires (i.e., no exposure to the heat of a fire).

#### *Methods:*

Eight healthy male fire fighters volunteered to participate in the study. The physical characteristics of the subject sample were as follows: age,  $34.3 \pm 3.2$  yr; height,  $178.5 \pm 3.5$  cm; and weight,  $84.3 \pm 4.0$  kg; (mean  $\pm$  SD). The men were active CF fire fighters and were accustomed to the work conditions encountered. Each subject wore standard CF fire fighting clothing which included cotton underwear, Nomex<sup>®</sup> coveralls, cotton canvas bunker coat and pants, rubber boots, leather gloves, and helmet; for those entering the buildings, a cotton flash hood, mask, and self-contained breathing apparatus (SCBA) were also worn.

Training was carried out over a two day period during which time the outside environmental temperature averaged 16° C. Six separate training scenarios were presented, with two on the first day and four on the second. Each scenario required a group of five fire fighters with a pumper truck to respond to an alarm, approach the building, evaluate the situation, search for and evacuate victims, and extinguish any fires. All the activities were timed and recorded by observers, and the subjects were classified into one of four activity categories as follows:

- a) Crew Captain (CC) -- the individual who directed the activities;
- b) Lead Hand (LH) -- the first individual(s) who entered the building, evacuated victims, and/or engaged in fire fighting;
- c) Secondary Help (SH) -- the individuals who entered the building at a later time and either helped extinguish fires or assisted in secondary searches of the building; and
- d) Exterior Fire Fighting (EF) -- the individuals who operated water hoses outside the building or who drove and operated the pumper truck.

Skin temperatures were measured with thermistors placed on the chest and rear thigh. Rectal temperature was measured with a thermistor probe inserted 15 cm beyond the anus. All temperatures were recorded with YSI Series 400 thermistors (Yellow Springs Instrument Company, Yellow Springs, Ohio), and heart rate (HR) was recorded from a standard single lead ECG.

Data were collected continuously by a portable data acquisition system, the Vitalog PMS-8 (Vitalog Corp., Palo Alto, California). The PMS-8 was programmed through its accompanying Apple IIe computer to record the three temperatures and IIR every 10 seconds for the duration of the day's activity. At the end of each day, the data were transferred back to the computer for permanent storage and later analyses.

Temperature data were analyzed by extracting initial and final values for each site for each man-run. Mean skin temperature was estimated by averaging the chest and rear thigh temperatures. Changes in site temperature over the duration of the run, as well as rate of change of rectal temperature were calculated. Raw HR data were reduced by computing mean HR over the duration of the work period for each man-run.

The individual subject data for temperature and mean HR were then averaged over all subjects participating in a given scenario, or were averaged over those subjects performing similar tasks to view the physiological responses in relation to the various activity categories. Group means were analyzed by a one-way analysis of variance (AOV) with post hoc multiple-comparisons performed according to Bancroft [10].

*Results and Discussion:*

Data were successfully collected for 23 man-runs during the six fire fighting scenarios (subjects with incomplete data were not included in the analyses). Figure 1 shows as an example the HR and three temperatures recorded for one subject who worked as the Crew Captain during the morning scenario, and as the Lead Hand during the afternoon. From the figure it can be seen that the HR and body temperatures reflect the differing levels of physiological strain for the two activities being performed by this subject. The maximum HRs measured in this study are consistent with the values of 175 - 195 beats/min recorded in the field by other investigators [9].

Table I-1 summarizes the average HR and temperature changes recorded for each group of subjects performing each scenario. The highest average HR for a scenario was 151 beats/min, while average rises in rectal and skin temperatures exceeded 1 and 4 °C, respectively. In general terms, Run 2 of Day 1 was the most stressful of the six training sessions, but all training sessions elicited HRs that were near maximal for many of the subjects. Clearly, the training sessions were hard work.

Table I-2 presents the data according to activity. Total rise and rate of rise in rectal temperature, final mean skin temperature, and HR were significantly higher ( $p < 0.05$ ) for the LH group when compared with any other activity. There were no significant differences between HRs or temperatures for the SH group as compared to the EF group, and CC showed the smallest changes of all groups. These data show that physiological strain during fire fighting depends heavily on the work load.

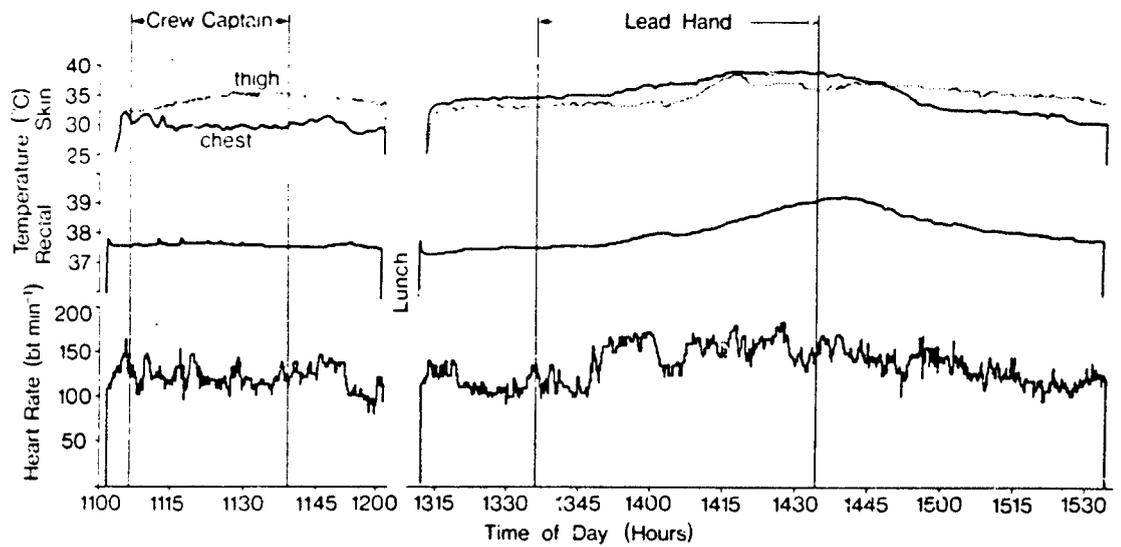


Figure I-1

Heart rate, rectal temperature, and two skin temperatures of one subject during Day 1 of the Phase I field study. Two fire fighting scenarios are shown.

Table I-1

**Body Temperatures and Heart Rates  
During Six Fire Fighting Scenarios**

Scenario	Day 1		Day 2			
	Run 1	Run 2	Run 1	Run 2	Run 3	Run 4
<b>No. of Subjects</b>	3	4	5	4	4	3
<b>Duration (min)</b>	32	48	25	20	27	20
<b>Rectal (° C)</b>						
Initial	37.7	37.7	37.5	37.8	37.6	37.8
Final	38.3	38.8	38.1	38.1	38.0	38.2
Δ	0.6	1.1	0.6	0.3	0.4	0.4
<b>Chest (° C)</b>						
Initial	32.5	33.0	31.1	31.9	31.5	33.4
Final	32.5	37.3	33.6	33.5	33.9	33.7
Δ	0.0	4.3	2.5	1.7	2.4	0.3
<b>Thigh (° C)</b>						
Initial	34.0	33.8	32.7	33.5	33.2	33.5
Final	36.9	38.0	36.6	35.4	35.8	35.7
Δ	2.9	4.2	3.9	1.9	2.6	2.2
<b>HR (beats/min)</b>						
Mean	143	151	127	123	123	122
Range	92-193	79-183	77-162	77-162	88-178	88-182

Data are averages over those subjects participating in a scenario.

Table I-2

Comparison of Body Temperatures and Heart Rates  
Between Different Fire Fighting Activities

Group	LH	SH	EF	CC
No. of Subjects	5	7	7	4
Duration* (min)	24.2	19.8	23.3	28.7
<b>Rectal Temperature (°C)</b>				
Initial	37.7 ± 0.2	37.7 ± 0.2	37.6 ± 0.2	37.6 ± 0.2
Final	39.0 ± 0.7	38.4 ± 0.5	38.0 ± 0.4	37.9 ± 0.5
Rate of Rise (°C/min)	.032 ± .008	.022 ± .009	.016 ± .006	.009 ± .000
<b>Mean Skin Temperature (°C)</b>				
Initial	34.5 ± 0.6	33.0 ± 0.4	33.1 ± 0.4	32.4 ± 0.5
Final	37.4 ± 0.4	35.3 ± 0.5	34.9 ± 0.6	33.9 ± 0.5
<b>Heart Rate (beats/min)</b>				
Mean	153 ± 12	130 ± 16	123 ± 16	112 ± 8
Range	148 - 162	118 - 149	110 - 132	102 - 122

\* The average time the subjects performed the activity.

Data are presented as mean ± SD.

LH = Lead Hand; SH = Secondary Help;

EF = Exterior Fire Fighting; CC = Crew Captain.

Note: the Lead Hand and Secondary Help may have entered the building more than once during a scenario.

Figure I-2 summarizes graphically the changes in body temperatures as a function of activity observed in this study. The strong influence of work load on body temperatures is clearly demonstrated. Note especially the large difference in rectal temperature change between the LH and CC groups.

The HR data were further analyzed by calculating the percent time during any scenario spent in each of three IHR zones: less than 120 beats/min; between 120 and 160 beats/min; and greater than 160 beats/min, representing light, moderate and heavy work. These results, again grouped according to activity, are shown in Figure I-3 and demonstrate unequivocally that the physiological strain of fire fighting varies with the quantity and nature of the work being performed.

Rectal temperature continued to rise at the end of each exercise in 14 cases. The average post exercise rise in temperature, and post exercise time required for the temperature to reach its maximum, were  $0.2 \pm 0.01^{\circ}\text{C}$  and  $7.7 \pm 3.0$  min, respectively. The average rate of decline in temperature from its maximum was  $0.02^{\circ}\text{C}/\text{min}$ . The data for the second fire fighting scenario in Figure I-1 where the subject played the role of LH typifies this response.

#### *Conclusions:*

Phase I showed that fire fighting can be strenuous work. Core temperature changes exceeding  $1.5^{\circ}\text{C}$  were observed in several individuals, and HRs were frequently near maximum levels. The physiological responses did, however, vary with both the physical and environmental stresses to which the fire fighters were exposed. In general, those tasks involving building entry, fire extinguishing, and casualty rescue were most stressful, while outside duties were less demanding.

The levels of physiological strain observed in this study, which generally approached but did not exceed levels considered dangerous to young healthy fit individuals (also see Figures II-4 and II-5), were reached in less than 30 min. Considering that deep body temperature continued to rise after the most strenuous work was terminated, and that the subsequent decline in temperature was very slow, a fire fighter returning to hard work without sufficient time to cool could be at high risk of succumbing to heat stress.

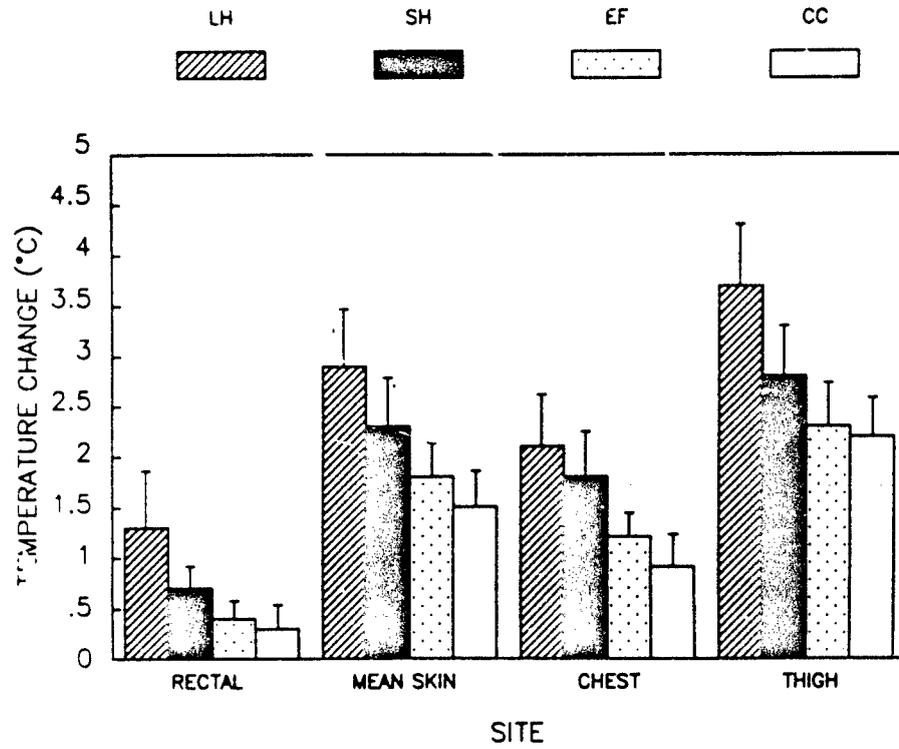
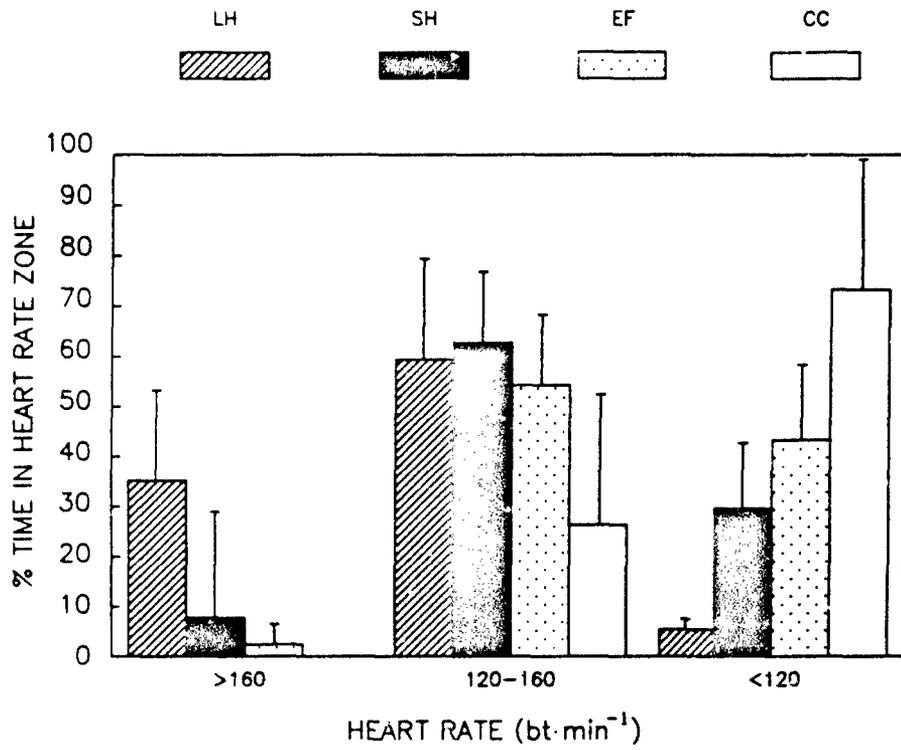


Figure I-2

Comparisons of the relative changes in body temperatures between subjects in different activity classifications. LH -- lead hand; SH -- secondary help; EF -- exterior fire fighting; CC -- crew captain.



**Figure I-3**

Percent time spent in each of three heart rate zones by subjects in each activity classification. LH -- lead hand; SH -- secondary help; EF -- exterior fire fighting; CC -- crew captain.

Since the SCBA typically provides breathing air for 15 to 30 min of hard work, a recovery period following air bottle depletion may be desirable. In fact, using the air bottle as a timing device to signal rotation of duties from hard physical labour to less strenuous tasks may be a practical approach to reducing the risk of heat illness in fire fighting.

## FIRE FIGHTER METABOLIC HEAT STRESS STUDY

### PHASE II: LABORATORY STUDY

#### *Background:*

Phase II was the major portion of the overall study and involved the most extensive as well as intensive evaluation of the contribution of the barrier to the retention of metabolic heat in fire fighters. The scope of the study included 30 different clothing combinations, and the  $3 \times 2 \times 5$  factorial experimental design shown in Table II-1 was used for the evaluations.

Phase II was conducted as three smaller studies corresponding to three different test conditions. Condition HOT ( $30^{\circ}\text{C}$ ) was conducted under ambient conditions simulating a hot summer day and involved 30 min of work. Eight subjects were used in this portion of the study, and each subject wore each of the 30 clothing combinations.

The following two experimental conditions were carried out with a reduced number of subjects and clothing combinations. This was a result of first, the prohibitive cost of manpower and facility time to run all eight subjects in each of the 30 clothing combinations, and secondly, the initial HOT condition trials indicated there was little additional information to be gained by including the partial barrier ensembles in the remaining conditions.

Condition COLD ( $-18^{\circ}\text{C}$ ) was carried out to see if the various clothing ensembles would provide enough warmth, or possibly even impede heat dissipation, under ambient conditions simulating a cold winter day. Four of the eight subjects were used, and only 18 clothing combinations were evaluated. Work duration was again 30 min.

Condition VERY HOT ( $35^{\circ}\text{C}$ ), with the work period extended to 70 min, was selected to simulate the ambient conditions of a very hot summer day with a repeated entry into a building. Only three of the eight subjects were available for this study, and again only 18 clothing combinations were evaluated.

Table II-1

Phase II Experimental Design: 3-Way Factorial

SHELL	LINER	BARRIER				
		FULL NEOPRENE	FULL GORETEX	PARTIAL NEOPRENE	PARTIAL GORETEX	NONE
WOOL	WOOL					
	NOMEX					
NOMEX	WOOL					
	NOMEX					
COTTON	WOOL					
	NOMEX					

Since these three studies differed considerably in test conditions and data analysis techniques, they are presented in three separate subsections. The physiological monitoring procedures were virtually identical in all three studies and are outlined only once. However, the data analysis technique was varied and will be described for each experimental condition. Condition HOT is presented first since it was the largest study and contains most of the statistical information about the clothing element effects.

## CONDITION: HOT

### *Methods:*

Eight CF fire fighters gave their informed consent to participate as subjects in this study. Age, height and weight are listed in Table II-2. A fairly broad range of subject age was deliberately used since it was felt that this would improve the applicability of the results to the population of fire fighters at large.

Since this portion of the study was carried out during the late winter through early spring months (February - April 1986), subjects were assumed to be unacclimated to heat. Furthermore, since subjects would be exposed to exercise in the heat twice per day for 15 days, it was anticipated that there might be some degree of progressive heat acclimation throughout the period of investigation that could confound the interpretation of the study results. To help counter such effects, the order in which subjects wore the various clothing combinations was counterbalanced. As a further precaution, subjects were partially acclimated to the environmental and working conditions of the experiment by having them exercise several hours per day in the hot chamber on cycle ergometers, treadmills, etc. for one week prior to the actual experiments [11, 12]. This period of time was also used to accustom the subjects to the physiological monitoring and experimental protocol procedures by carrying out full dress rehearsals on the last two days of the acclimation week.

The experiments were carried out in the Tropical Chamber at DCIEM under the following environmental conditions: dry bulb temperature ( $T_{db}$ ) = 30 °C; wet

Table II-2

Physical Characteristics of the Subjects

Subject	Age (yr)	Height (cm)	Weight (kg)
RN	43	171.0	71.8
MH	40	173.0	67.0
JG	31	175.0	82.0
DM	25	175.0	75.1
SH	28	173.0	91.0
GV	25	173.5	66.7
JL	28	192.0	72.7
WS	30	183.0	81.0
Mean $\pm$ SD	31.25 $\pm$ 6.71	176.88 $\pm$ 7.10	75.91 $\pm$ 8.30

bulb temperature ( $T_{wb}$ ) = 22 ° C; relative humidity = 50%.

Subjects rotated between three work stations: treadmill walking at 4.5 km/h; bench stepping on two standard 8-in steps at 60 steps/min; and carrying 20 kg boxes a distance of 2 m across the room at a frequency of six box transports/min. This latter activity involved transferring a stack of four medical supply cases from one location to the other by moving one box at a time, therefore requiring lifting from, and placing boxes at, various heights above floor level. These tasks were selected to simulate the work of fire fighting by including elements of upper and lower body work in walking, stair climbing, bending, lifting, and load carrying. Each task lasted 9.5 min with 0.5 min between activities for station rotation. Total time in the chamber was 30 min.

Rectal temperature was measured with a thermistor probe inserted 15 cm into the rectum, and mean skin temperature was measured with 12 thermistors taped to the skin at standard locations (head, chest, abdomen, forearm, hand, front thigh, shin, foot, calf, rear thigh, lower back, and upper back). Heart rate was measured with a standard single lead ECG connected to a Quinton Model 611 Cardiometer (Quinton Instruments, Seattle, Washington). Subjects were weighed both nude and fully dressed to within  $\pm 10$  g with a load platform connected to an ElectroScale 925 Counting Scale (ElectroScale Corporation, Santa Rosa, California). Body weights were taken before and after each test exposure to calculate sweat production and sweat evaporation during the test.

After being instrumented for physiological monitoring, subjects were dressed in a long sleeved cotton turtle-necked undershirt, cotton long-johns, wool socks, Nomex<sup>®</sup> coveralls, and the appropriate set of turnout clothing. The turnout clothing used in this study was produced by Safety Supply Canada and was one of their standard products modified so that the shells, barriers, and liners were interchangeable. Apart from being able to distinguish different clothing ensembles by the color of the outer shell, subjects were not aware of the barrier or thermal liner they were wearing. Leather gloves, rubber boots, a helmet, and SCBA completed the attire.

Immediately upon entering the climatic chamber, the subjects' physiological monitoring cables were connected to a computerized data acquisition system (HP

9836CS Computer, HP 3497A Data Acquisition/Control Unit; Hewlett-Packard Company, Palo Alto, California) and the work activity was begun. The computer system scanned all physiological parameters continuously, displayed their current status on a graphic display, and printed and recorded mean values for the parameters every 30 seconds. It also signaled subjects when to stop work, rotate to the next station, and resume working. High body temperature and heart rate alarms were included in the program to signal observers that physiological safety limits were being approached.

Since a full SCBA bottle of air rarely lasted for the 30 min duration of the exposures, and since bottle changes had not been explicitly incorporated into the protocol timing, the procedure adopted was to close the valve on the bottle and disconnect the mask air supply hose from the regulator upon hearing the low air supply alarm bell. Subjects then completed their chamber activities by simply breathing ambient air through the respirator.

The contributions to thermal stress of the various clothing elements/ensembles were assessed by examining 10 parameters indicative of thermal physiological strain in the body. These parameters are described briefly below.

Final Mean Skin Temperature (FMST) was the area-weighted body surface mean skin temperature recorded at the end of the test exposure from the 12 thermistors.

Delta Mean Skin Temperature (DMST) was the change in mean skin temperature from beginning to end of the exposure. This calculation corrects individual subject responses for variations in initial skin temperatures at the start of the tests.

Final Rectal Temperature (FTRE) was the rectal temperature recorded at the end of the test exposure.

Delta Rectal Temperature (DTRE) was the change in rectal temperature from beginning to end of the exposure. Again, this value

accounts for variations in initial temperature data between subjects, and between tests.

Heart Rate (HR) was the average heart rate recorded over the final 3 min of the exposure.

Fluid Loss (FLOSS) was the change in nude body weight over the 30 min of exposure. This is a physiological parameter used to calculate the extent of dehydration during the exposure.

Percent Dehydration (%DEHY) was calculated as the percentage change in nude body weight due to water loss. This calculation accounts for the greater physiological impact of a given water loss from a smaller individual.

Fluid Evaporated (FEVAP) was the change in dressed weight over the 30 min of exposure. This is a physical parameter that describes in a crude manner the vapour permeability of the clothing ensemble. It also gives some indication of the body heat dissipation capability of the clothing ensemble.

Air Consumption (AIRCONSUM) was calculated from pre- and post-exposure SCBA air bottle weights and was expressed as kg of air utilized per minute.

Subjective Thermal Comfort (COMFORT) was assessed from a numerical scale running from 1 (So cold I am helpless), through 7 (Comfortable), to 13 (So hot I am sick and nauseated). Subjects rated their perceived level of thermal comfort at the end of each test exposure.

Photographs of a subject at various stages throughout the experimental procedures are shown in Appendix A. The placement of thermistors and ECG

electrodes, the weighing procedures, and the work activities are clearly indicated. Appendix B shows the various elements of the turnout clothing used in this study.

*Data Analyses:*

Although the collection of data by computer can greatly simplify the subsequent analyses, it is generally required that all data files be complete, with no missing values in any parameter. However, during a study as large as this, some data will inevitably be lost or recorded incorrectly. Therefore, prior to any analyses by computer, all files were carefully checked for omissions or seemingly incorrect values, and 36 "problems" in 2400 parameter values (i.e., 8 subjects  $\times$  10 parameters  $\times$  30 tests) were identified. A variety of data recovery techniques such as interpolation, extrapolation, averaging, entry of manually recorded values, etc., were then employed to maximize the integrity of the data, but in spite of these efforts, 14 "bad" data values remained.

The ideal statistical analysis technique to be followed would be a 3-way factorial design using Analysis of Variance (AOV) with Repeated Measures. However, this technique requires that every subject used in the analyses have complete data for every parameter under every test condition. Using this approach, only 4 subjects remained in the data set due to the 14 lost data values and this would discard too much valuable information.

Therefore, each of the 10 physiological parameters was treated as an independent study, making the data appear as 10 separate experiments with a varying number of subjects in each experiment. Using this technique, the data were balanced so that any subject included in the analyses did have complete data for all 30 exposures. In the worst case, parameter FEVAP was reduced to an N of 5 subjects, while most parameters included 7 of the 8 subjects.

In actual fact, both types of AOV were performed and the results were compared. It is interesting to note that analyses performed using the two techniques showed only small differences between the two, and the AOV tables led to virtually the same conclusions. Main effects were considered significant at a level  $p \leq 0.05$ , and the Least Significant Difference (LSD) post hoc test was used to

determine which conditions differed significantly from one another.

*Results and Discussion:*

Table II-3 is a sample printout of the raw data as collected by the computer over the first 10 min of one test during condition HOT. Figure II-1 shows the data for the entire 30 min of this test in graphic form. Again, it is included as a sample only, and no attempt has been made to separate and identify the specific skin temperatures. Rectal temperature is the dot-dash line. It is interesting to note the different IIR responses (shown by the dashed line and referred to right ordinate) from these two subjects. This is explained by the fact that the subjects worked in the chamber in pairs, rotating sequentially among the three work activities. Subject JL (upper panel) followed the sequence steps, treadmill, and boxes, while subject SH (lower panel) followed the sequence treadmill, boxes, and steps. Stepping had the strongest effect of increasing the heart rate, and once elevated, it was difficult to lower even during less strenuous work (see subject JL). By comparison, the subject who began with a less strenuous task (subject SH) did not show the large increase in HR until he reached the stepping task at 20 min. In spite of these different temporal responses, final HR was quite comparable between the two subjects, and this pattern was fairly consistent throughout all Phase II laboratory studies.

An abbreviated summary of the AOV results for each parameter is shown in Table II-4. There are several features in these results that deserve comment. First, BARRIER was the most significant main effect in the study, with 8 of the 10 physiological parameters examined showing a statistically significant effect ( $p \leq 0.05$ ). In addition, parameter FEVAP was marginally affected by SHELL, and COMFORT was surprisingly influenced by LINER. However, it should be noted COMFORT is a subjective parameter with a large degree of scatter in the data, and the importance of the relationship remains unclear. Although not indicated in the table, only parameter DMST exhibited an interaction between factors, with a marginally significant ( $p = 0.05$ ) interaction between SHELL and BARRIER. This implies that the rise in skin temperature may depend upon the specific combination of shell and barrier used.

Table II-3

Sample Computer Printout of Raw Data for  
Two Subjects During Condition HOT

	DATE (G-M-Y) 19-3-68												TIME (HH-MM-SS) 9-7-42							
TIME	1	2	3	4	5	6	7	8	9	10	11	12	IST	OMST	COPE	DCOR	HR	DB	MB	SUEJ
3.0	33.3 32.4	35.4 34.6	35.0 34.0	34.6 33.0	34.6 34.6	32.5 32.8	33.0 32.4	33.2 33.8	33.2 32.5	34.7 34.8	34.8 32.4	33.8 33.4	34.1 33.5	0.0 0.0	37.2 37.0	0.0 0.0	99 78	29.9 29.9	21.6 21.6	CTZZMLHTJL MLPGMLHTSH
3.5	33.3 32.3	35.4 34.7	35.1 34.1	34.6 33.1	34.7 34.7	32.6 32.9	33.1 32.4	33.2 33.8	33.2 32.5	34.8 34.8	34.8 32.5	33.8 33.4	34.2 33.5	0.0 0.0	37.2 37.0	0.0 0.0	105 95	30.0 30.0	21.6 21.6	CTZZMLHTJL MLPGMLHTSH
4.0	33.2 32.1	35.5 34.9	35.1 34.1	34.7 33.4	34.8 34.8	32.6 33.1	33.2 32.6	33.2 33.7	33.3 32.6	34.8 34.9	34.9 32.6	34.8 33.4	34.2 33.6	.1 .1	37.2 37.0	0.0 0.0	112 106	30.3 30.3	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
4.5	33.2 32.0	35.5 35.0	35.2 34.2	34.8 33.6	34.8 35.0	32.6 33.1	33.4 33.8	33.3 33.8	33.4 32.7	34.9 35.0	35.0 32.8	34.1 33.4	34.3 33.7	.2 .2	37.2 37.0	-0.0 0.0	112 101	30.4 30.4	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
5.0	33.3 31.9	35.6 35.2	35.3 34.3	34.9 33.8	34.9 35.1	32.5 33.1	33.5 33.0	33.5 33.9	33.6 32.8	35.0 35.1	35.1 32.9	34.2 33.9	34.4 33.8	.3 .4	37.2 37.0	-0.0 0.0	110 102	30.2 30.2	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
5.5	33.4 31.9	35.7 35.3	35.3 34.4	35.0 34.0	34.9 35.2	32.5 33.2	33.6 33.1	33.4 34.0	33.7 32.9	35.1 35.2	35.3 33.1	34.3 33.6	34.5 34.8	.4 .5	37.2 37.0	-0.0 0.0	111 101	30.0 30.0	21.6 21.6	CTZZMLHTJL MLPGMLHTSH
6.0	33.5 31.7	35.8 35.4	35.4 34.5	35.1 34.2	34.9 35.3	32.5 33.4	33.7 33.3	33.5 34.2	33.9 33.1	35.2 35.3	35.4 33.3	34.4 33.8	34.6 34.1	.4 .6	37.2 37.0	-0.0 0.0	113 98	29.8 29.8	21.5 21.5	CTZZMLHTJL MLPGMLHTSH
6.5	33.6 31.6	35.9 35.5	35.5 34.6	35.1 34.4	34.9 35.4	32.5 33.5	33.8 33.5	33.6 34.3	34.0 33.2	35.3 35.4	35.6 33.5	34.5 33.9	34.6 34.2	.5 .7	37.2 37.0	-0.0 0.0	116 100	29.4 29.4	21.5 21.5	CTZZMLHTJL MLPGMLHTSH
7.0	33.7 31.7	36.0 35.6	35.6 34.6	35.2 34.6	35.0 35.4	32.5 33.7	33.9 33.7	33.7 34.6	34.1 33.3	35.4 35.5	35.8 34.1	34.5 34.1	34.7 34.3	.6 .8	37.2 37.0	-0.0 0.0	115 100	29.4 29.4	21.5 21.5	CTZZMLHTJL MLPGMLHTSH
7.5	33.8 31.7	36.1 35.7	35.7 34.7	35.3 34.7	35.0 35.4	32.6 33.3	34.1 33.8	34.3 34.5	35.5 33.4	35.9 35.6	35.9 33.8	34.6 34.1	34.8 34.4	.7 .9	37.2 37.0	-0.0 0.0	117 101	29.5 29.5	21.5 21.5	CTZZMLHTJL MLPGMLHTSH
8.0	33.8 31.7	36.1 35.7	35.7 34.7	35.4 34.8	35.0 35.5	32.8 33.8	34.2 33.9	34.4 34.5	35.6 33.5	36.0 35.6	34.7 34.0	34.9 34.2	34.9 34.5	.8 1.0	37.2 37.0	-0.0 0.0	119 101	29.6 29.6	21.5 21.5	CTZZMLHTJL MLPGMLHTSH
8.5	33.8 31.5	36.2 35.8	35.8 34.7	35.4 34.9	35.0 35.5	33.1 33.9	34.4 34.0	34.1 34.6	34.5 33.5	35.6 35.6	36.1 34.1	34.7 34.2	35.0 34.5	.9 1.0	37.2 37.0	-0.0 0.0	122 99	29.9 29.9	21.6 21.6	CTZZMLHTJL MLPGMLHTSH
9.0	33.9 31.4	36.2 35.8	35.8 34.8	35.5 35.0	35.1 35.4	33.3 33.9	34.6 34.0	34.2 34.7	34.7 33.6	35.7 35.7	36.2 34.4	34.8 34.3	35.1 34.5	1.0 1.0	37.2 37.0	-0.0 -0.0	121 100	30.1 30.1	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
9.5	34.0 31.3	36.2 35.9	35.9 34.8	35.5 35.1	35.1 35.4	33.6 34.8	34.8 34.1	34.3 34.8	34.8 33.7	35.8 35.7	36.2 34.4	34.8 34.3	35.2 34.6	1.1 1.1	37.2 37.0	-0.0 -0.0	122 99	30.3 30.3	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
10.0	34.0 31.3	36.3 35.9	35.9 34.8	35.6 35.1	35.2 35.4	33.9 34.8	34.9 34.1	34.4 34.9	34.9 33.8	35.8 35.8	36.3 34.5	34.9 34.4	35.2 34.6	1.1 1.1	37.2 37.0	-0.0 -0.0	123 101	30.4 30.4	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
10.5	34.1 31.2	36.3 35.9	35.9 34.9	35.6 35.3	35.2 35.4	34.1 34.1	35.1 34.3	34.5 34.9	35.0 33.8	35.9 35.8	36.4 34.6	35.8 34.4	35.3 34.7	1.2 1.2	37.2 37.0	-0.0 -0.0	124 100	30.2 30.2	21.7 21.7	CTZZMLHTJL MLPGMLHTSH
11.0	34.1 31.2	36.3 35.9	36.0 34.9	35.7 35.3	35.2 35.4	34.3 34.2	34.6 34.2	35.1 35.0	35.1 33.9	35.9 35.8	36.5 34.7	35.8 34.5	35.4 34.7	1.3 1.2	37.2 37.0	-0.0 -0.0	122 98	30.2 30.2	21.6 21.6	CTZZMLHTJL MLPGMLHTSH
11.5	34.1 31.1	36.3 36.0	36.0 34.9	35.7 35.4	35.3 35.4	34.5 34.3	35.3 35.0	34.6 34.8	35.1 35.8	36.0 35.8	36.6 34.8	35.1 34.5	35.4 34.7	1.3 1.3	37.2 37.0	0.0 -0.0	124 105	29.9 29.9	21.6 21.6	CTZZMLHTJL MLPGMLHTSH
12.0	34.1 30.9	36.3 36.0	36.0 34.9	35.8 35.5	35.3 35.4	34.6 34.3	35.4 34.5	34.7 34.5	35.2 35.8	36.0 35.9	36.7 35.8	35.2 34.5	35.5 34.8	1.4 1.3	37.2 37.0	0.0 -0.0	125 100	29.8 29.6	21.6 21.5	CTZZMLHTJL MLPGMLHTSH
12.5	34.1 32.0	36.4 36.0	36.0 34.9	35.8 35.5	35.4 35.4	34.9 34.3	35.8 34.5	34.8 34.5	35.4 35.1	36.2 35.9	36.7 35.1	35.3 34.7	35.6 34.8	1.5 1.4	37.3 37.0	0.0 -0.0	125 92	29.5 29.5	21.5 21.5	CTZZMLHTJL MLPGMLHTSH

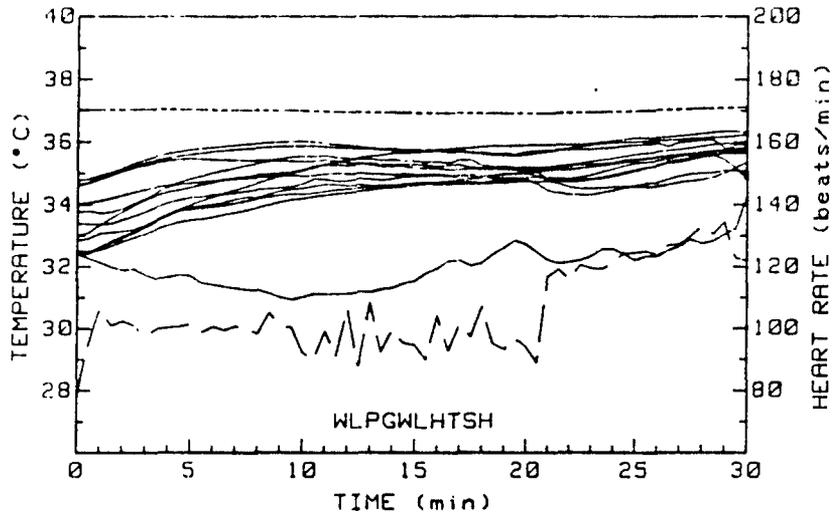
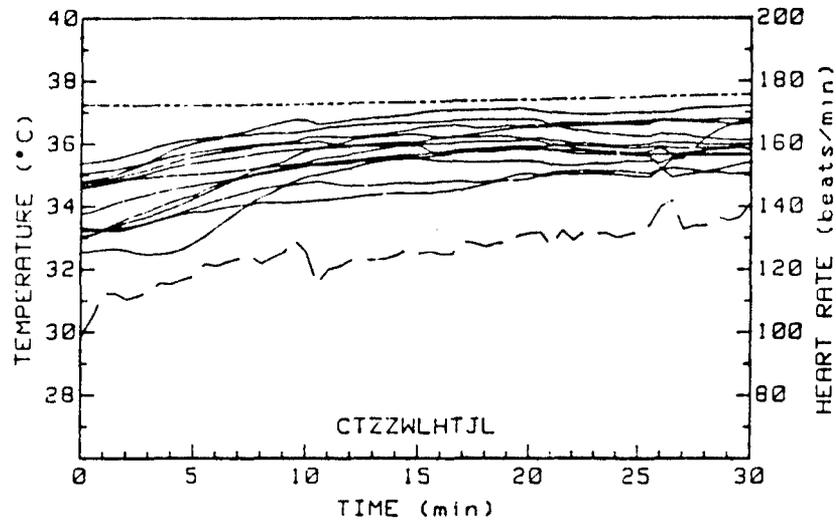


Figure II-1

Sample of raw data for two subjects during condition HOT. The solid lines are temperatures at the 12 skin sites while the dot-dash line is rectal temperature; the dashed line represents heart rate.

Table II-4

Summary of Physiological Results

Probability from AOV with Repeated Measures

Phase II Condition HOT Varying "N"

Parameter	Factor			N
	SHELL	BARRIER	LINER	
FMST	.6989	0.0000 *	.2237	8
DMST	.9016	0.0000 *	.3791	7
FTRE	.9625	.2094	.5893	6
DTRE	.7327	.0076 *	.9367	6
HR	.8784	.0370 *	.2497	7
FLOSS	.3498	.0287 *	.0638	7
%DEHY	.3447	.0281 *	.0594	7
FEVAP	.0373 *	0.0000	.5037	5
AIRCONSUM	.3490	.2190	.1886	8
COMFORT	.4265	.0044 *	.0076 *	7

\*  $p \leq 0.05$

Also note that BARRIER had an extremely significant effect on parameter FEVAP. This shows that the composition and/or extent of the barrier used in the clothing profoundly affects moisture evaporation from the clothed body. Theoretically, an increase in the vapour permeability of the barrier should allow for greater evaporation of moisture and, hence, heat removal from the body. Since evaporative cooling is essentially a surface phenomenon, it should have its most profound cooling effect at the skin. The fact that the two parameters associated with skin temperature also showed a comparable extremely significant effect of BARRIER suggests that this was indeed the case. However, the fact that parameters FTRE and DTRE associated with deep body temperature were not influenced by the increased evaporation suggests that there may simply not have been sufficient time for the surface cooling effect to penetrate to the body core.

A second major point to consider is that not every result, that is statistically significant, has physiological significance. This is best demonstrated by looking at parameters HR and DTRE. Although BARRIER had a statistically significant effect on HR, the mean values ranged only from 141 to 149 beats/min over the 5 barrier conditions (means calculated from all clothing combinations involving a given barrier). Physiologically, this difference is rather small and would be of little consequence for healthy young fit individuals. It could, however, be highly significant for older or unfit persons with maximum heart rates near 170 beats/min (maximum HR is often predicted as 220 minus age) [13, 14, 15]. Fire fighter death due to heart attack is, in fact, a major concern in the profession [16, 17, 18, 19, 20]. In the case of deep body temperature changes, parameter DTRE ranged from 0.18 to 0.57 °C, a spread of only 0.09 °C. Again, this spread in DTRE is physiologically unimportant in healthy young fit individuals, considering that the highest mean FTRE for a barrier was only 37.78 °C.

Since BARRIER was the predominant factor in the physiological responses seen in this study, means collapsed on BARRIER for the 10 parameters were calculated by combining the data of the three shells and two liners for a given barrier. These data are presented as five-bar histograms with standard errors in Figures II-2 through II-11. They are presented as a function of the a priori assumed order of increasing vapour permeability of the barriers. Note that the trend seen in most of the graphs shows that this assumed order was correct.

Note also that the ordinate for each graph has been selected to represent a physiologically relevant range, rather than an optimum display window for the range of the data. Failure to do this tends to visually magnify the differences between means and, although it indicates the statistically significant effects well, it can lead to erroneous deductions regarding physiological significance (as discussed above regarding HR and DTRE). The ordinates for parameters FTRE and DTRE, for example, were chosen to cover the 2° C rise above a normal deep body temperature of 37° C generally considered to be indicative of unacceptable thermal stress on the body. The figure legends contain comments on the physiological relevance of several ordinal thresholds.

In the Figures II-2 through 11, the horizontal lines spanning one or more histogram bars show the subgroups of BARRIER as identified by the LSD post hoc test. Those barriers linked by a common horizontal line are not significantly different with respect to the parameter in question. The post hoc tests showed that the full neoprene barrier was subgrouped by itself for 5 of the 10 parameters and grouped with the full Gore-tex® or partial neoprene on three other occasions. This clearly shows that of the five barriers tested, the F-NEOPRENE barrier imposed the greatest stress on the body while the remaining four barriers were much more alike in their effects.

As a final general comment, the levels of physiological strain reached at the ends of the exposures in this series of tests were not overly severe, even with a full neoprene barrier (a somewhat surprising result considering how the subjects looked and seemed to feel upon exiting from the chamber). This was particularly true in the case of deep body temperature. As pointed out above, parameter FTRE differed by only 0.09° C (the range of parameter DTRE) between the F-NEOPRENE and NONE conditions. Understandably then, there was no statistically significant effect of BARRIER on FTRE, and the highest mean deep body temperature attained, 37.78° C, is not indicative of severe thermal strain.

It must be remembered, however, that the HOT exposures were of fairly short duration. Once again, time may have been an important factor, and 30 min may simply have been insufficient time for deep body temperature to rise appreciably. In this regard, other measures of physiological strain such as FMST,

**General Legend and Notes  
for Figures II-2 through II-11**

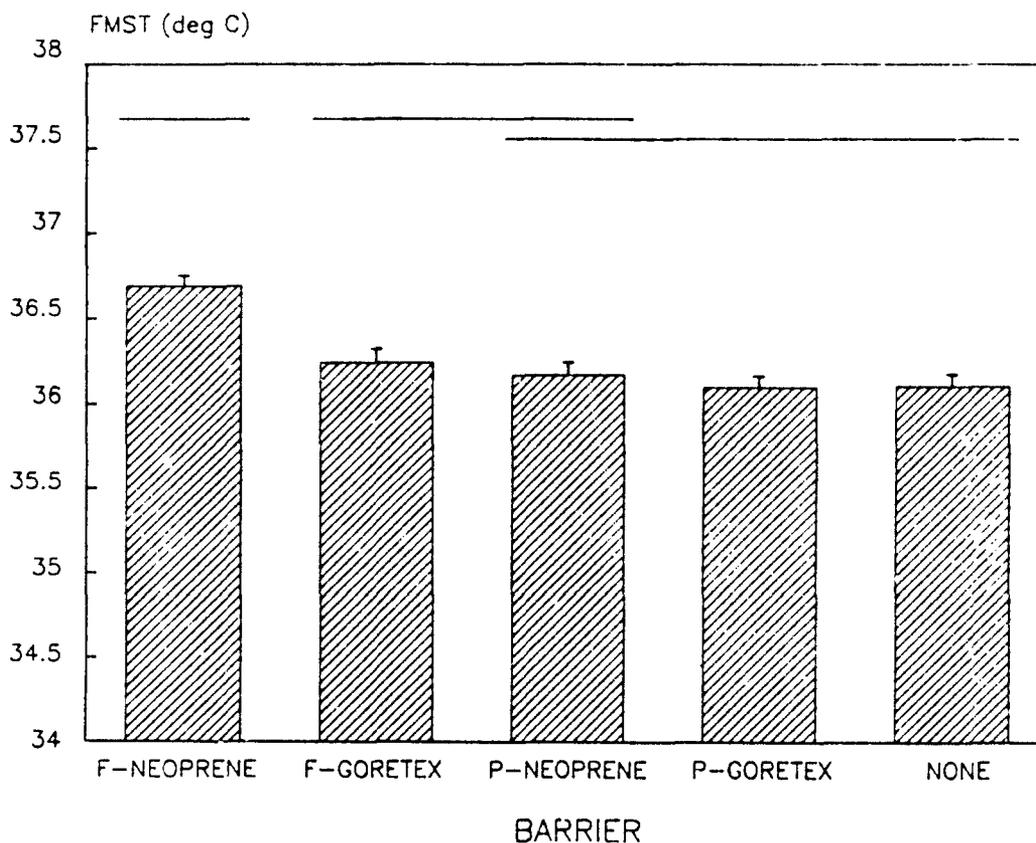
Figures II-2 through II-11 are histogram plots of the Phase II condition HOT results for the 10 parameters used in this study to evaluate the physiological impact of the various clothing configurations.

Each histogram bar represents the collapsed mean for the particular barrier configuration, computed by disregarding the effects of the shell and liner, as suggested by the AOV results. The small vertical bars represent the standard error of the mean for each barrier, based upon an N of  $6 \times$  the indicated number of subjects (i.e.,  $3 \text{ shells} \times 2 \text{ liners} \times \text{no. of subjects}$ ).

The horizontal lines indicate the subgroups identified by the LSD (solid lines) post hoc tests. Those barriers lying under a common line show no statistically significant differences in the specified parameter.

The ordinate for each graph has been selected to present the data in relation to a physiologically relevant range. The individual figure legends provide comments on the significance of the ordinal values of each parameter.

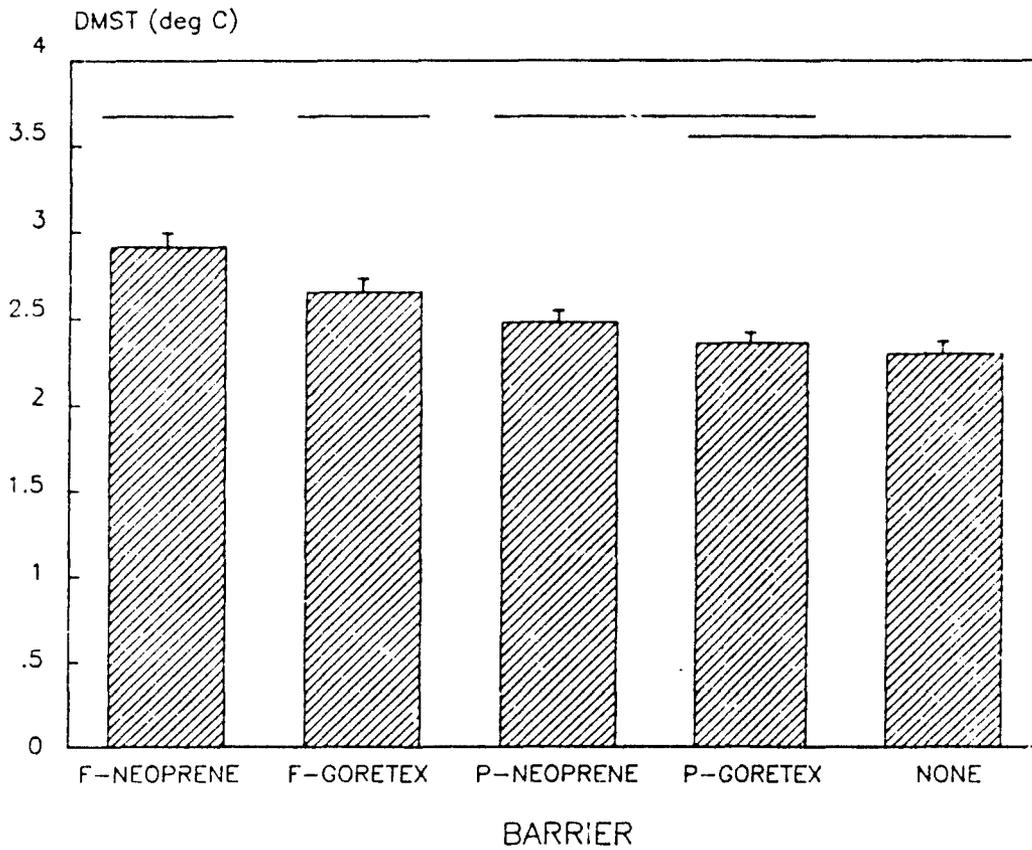
### FINAL MEAN SKIN TEMPERATURE (8 SUBJECTS)



**Figure II-2**

Mean skin temperature at thermoneutrality is  $\approx 33^{\circ}\text{C}$ , and sweating is usually observed when skin temperature exceeds  $\approx 34.5^{\circ}\text{C}$ . Imminent danger of heat stroke exists when mean skin temperature equals or exceeds a high rectal temperature, since there is no longer a gradient between the body core and surface for dissipation of heat.

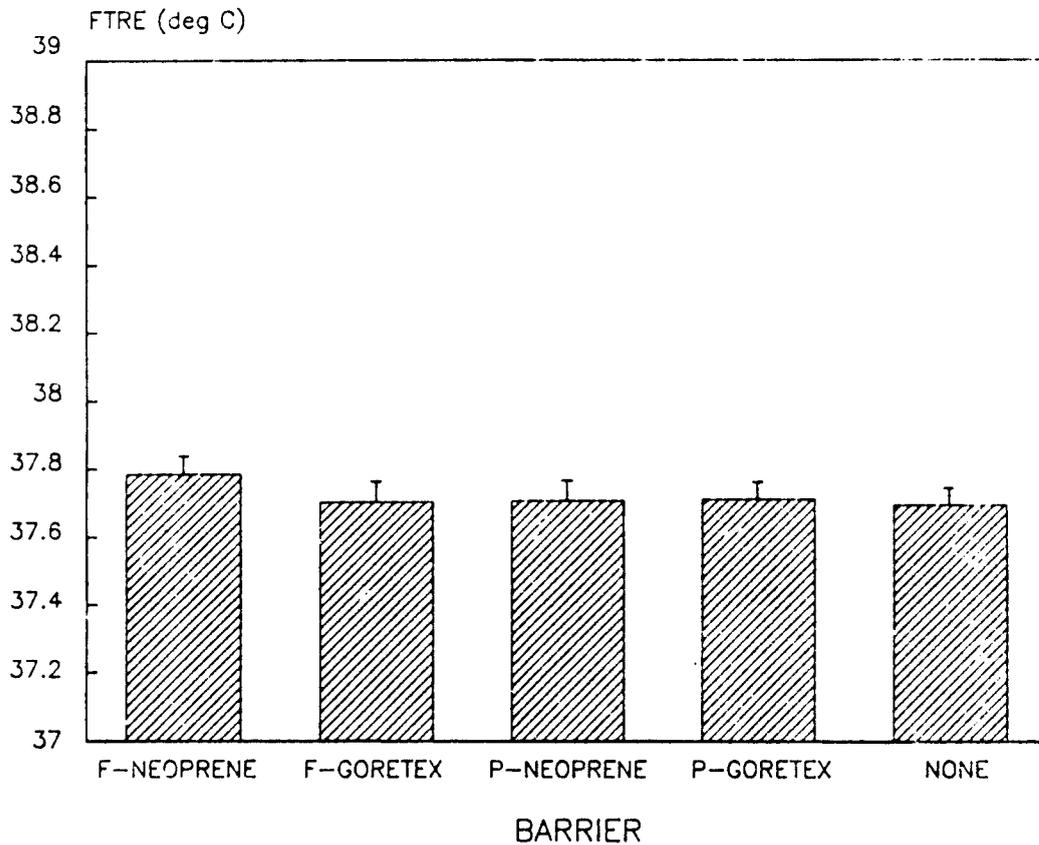
### DELTA MEAN SKIN TEMPERATURE (7 SUBJECTS)



**Figure II-3**

A rise of  $\approx 1.5^{\circ}\text{C}$  in mean skin temperature generally indicates sweating, and a rise of  $\geq 6^{\circ}\text{C}$ , concomitant with a high rectal temperature, would indicate imminent danger of heat stroke.

### FINAL RECTAL TEMPERATURE (6 SUBJECTS)



**Figure II-4**

Normal rectal temperature is  $\approx 37^{\circ}\text{C}$ . A rise in deep body temperature is normal during hard work in a hot environment, and  $39^{\circ}\text{C}$  is considered a safe termination criterion in laboratory heat stress studies. Above this temperature, various symptoms of heat strain will be evident, and  $42^{\circ}\text{C}$  is generally considered lethal.

### DELTA RECTAL TEMPERATURE (6 SUBJECTS)

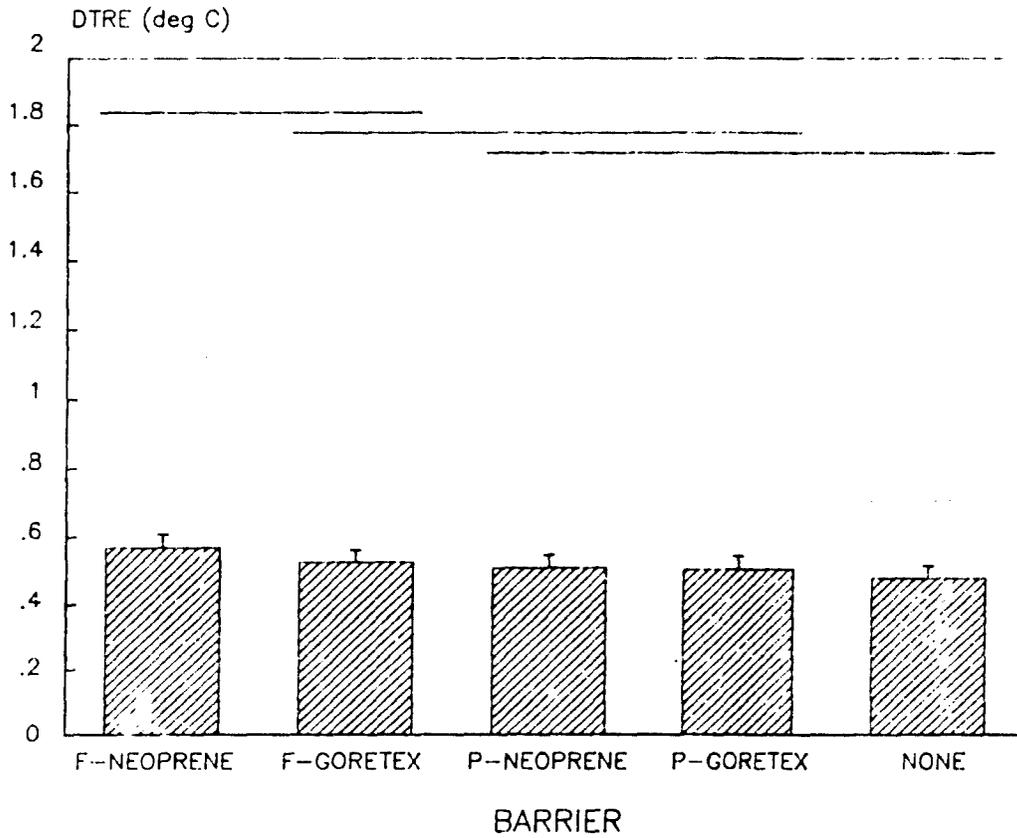
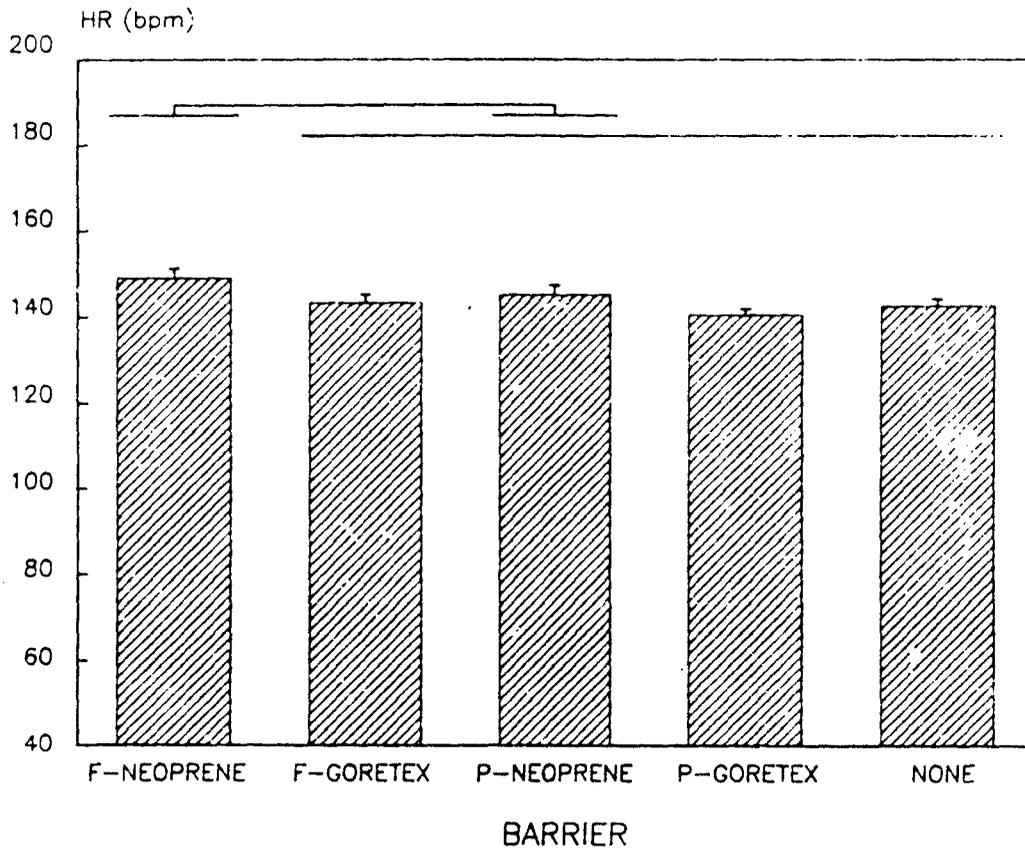


Figure II-5

Commensurate with the accepted norms of actual deep body temperature, a rise of 2° C in rectal temperature is considered safe during laboratory work on heat stress, while a rise of 5° C could be fatal.

### HEART RATE (7 SUBJECTS)



**Figure II-6**

Resting heart rate normally ranges from 50 - 72 beats/min (bpm). For a healthy individual, a predicted maximum heart rate is 220 minus his age. In terms of work levels for fit individuals under 40 yr of age, heart rates below 120 bpm are considered light work, rates from 120 - 160 bpm are moderate to heavy work, and rates exceeding 160 bpm are very heavy work.

### FLUID LOSS (7 SUBJECTS)

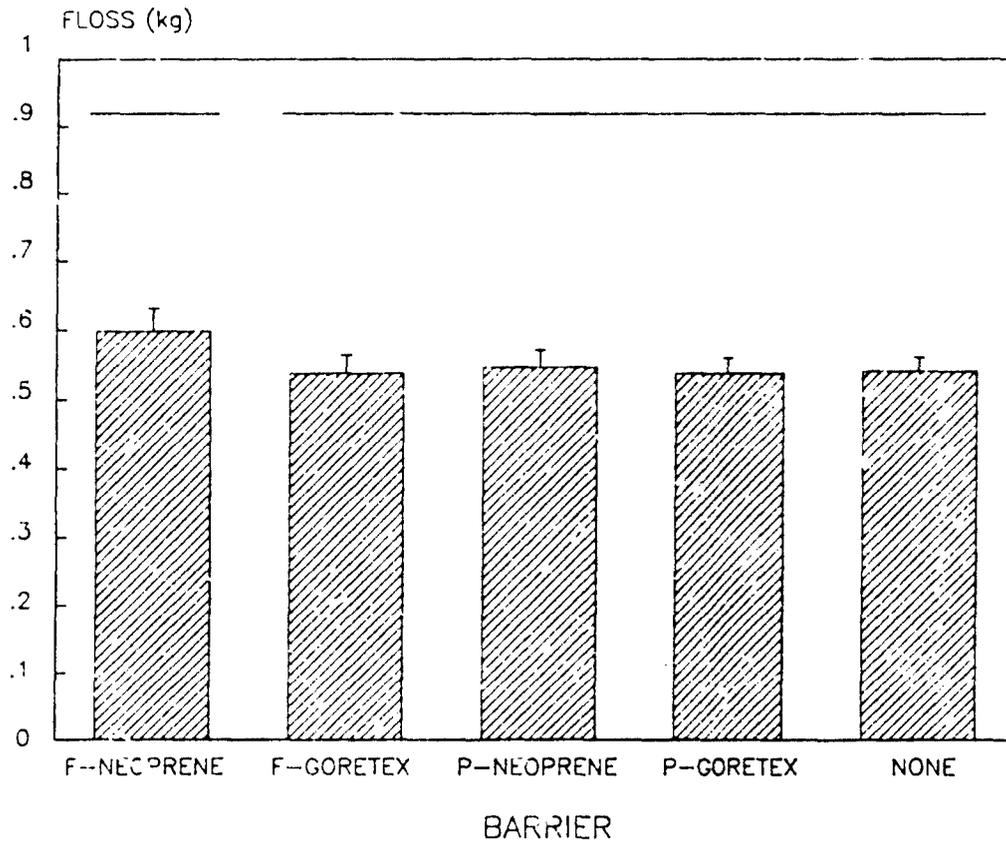
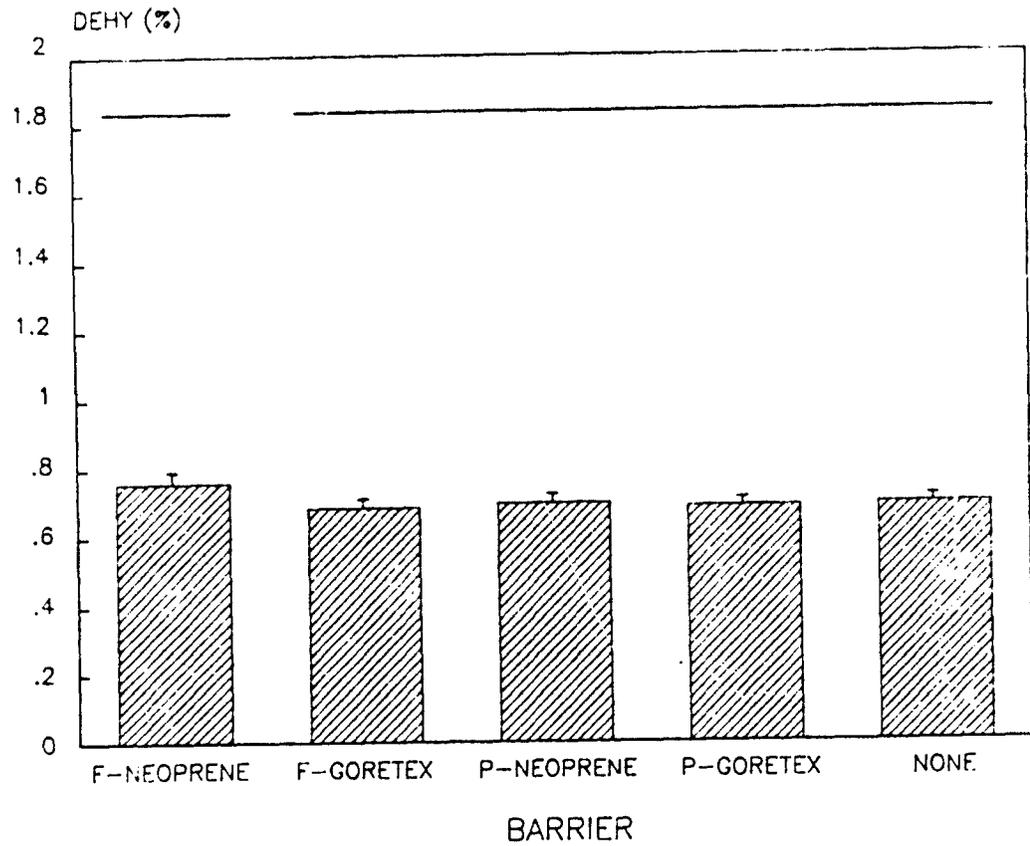


Figure II-7

This data shows total fluid lost from the body. The relative importance of such losses depends on body mass and is usually expressed as percent dehydration (see next figure).

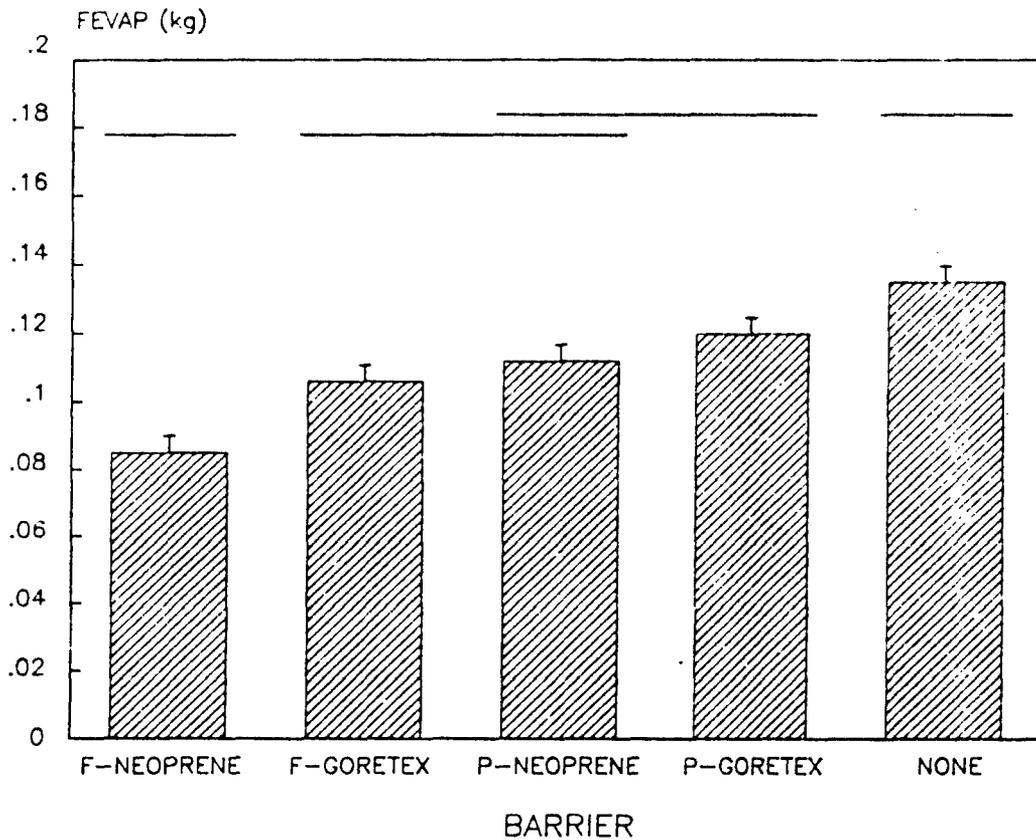
### DEHYDRATION (7 SUBJECTS)



**Figure II-8**

Fluid loss expressed as a percentage of pre-exposure body weight. A sensation of thirst sets in near 1% dehydration, discomfort is felt above 2%, and dehydration exceeding 4% begins to impair performance. The time duration over which this dehydration occurs must also be considered in assessing the severity of the imposed stress.

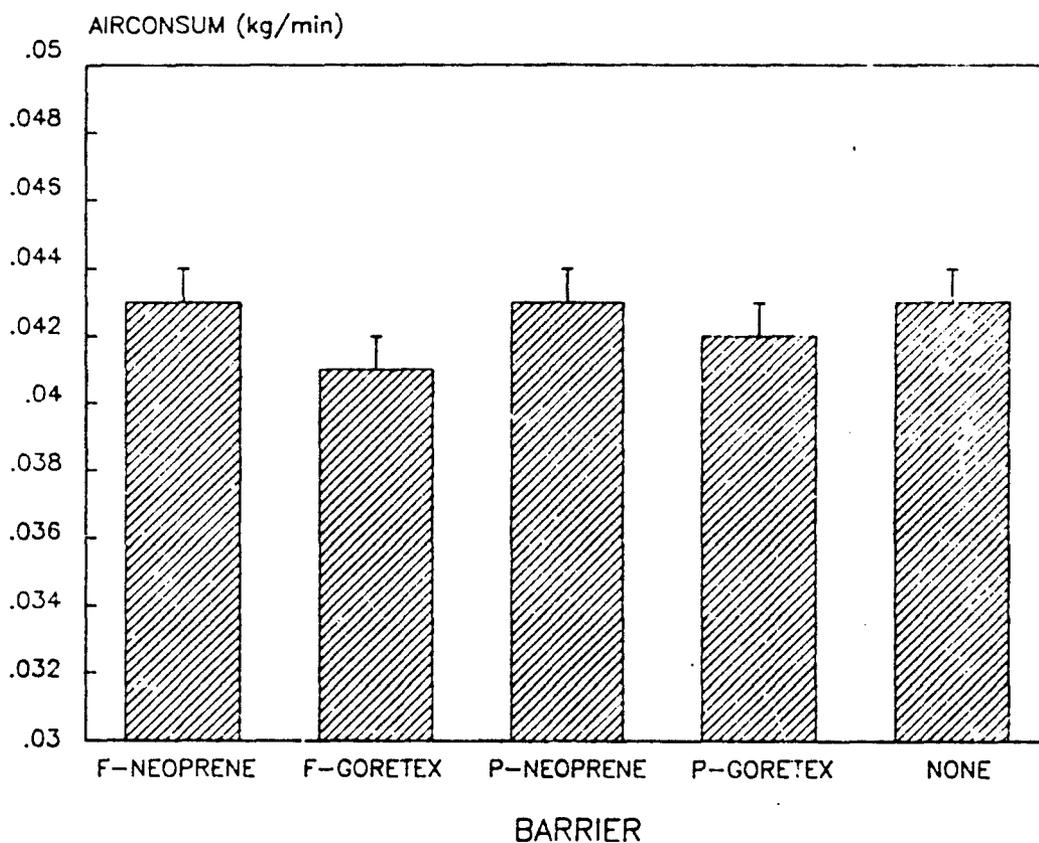
### FLUID EVAPORATION (5 SUBJECTS)



**Figure II-9**

Fluid evaporation is a potential source of body cooling. However, if the evaporation is occurring primarily in the clothing at a considerable distance from the body surface, very little cooling effect will be noticeable. Evaporation of 0.1 kg water over 30 min represents an average rate of heat loss of  $\approx 125$  W.

### AIR CONSUMPTION (8 SUBJECTS)



**Figure II-10**

These data were obtained from the change in weight of the SCBA air bottle over the duration that the bottle was in use. This parameter was measured to see if respiratory rate was dependent on the clothing configuration, and the values are not interpreted physiologically.

COMFORT  
(7 SUBJECTS)

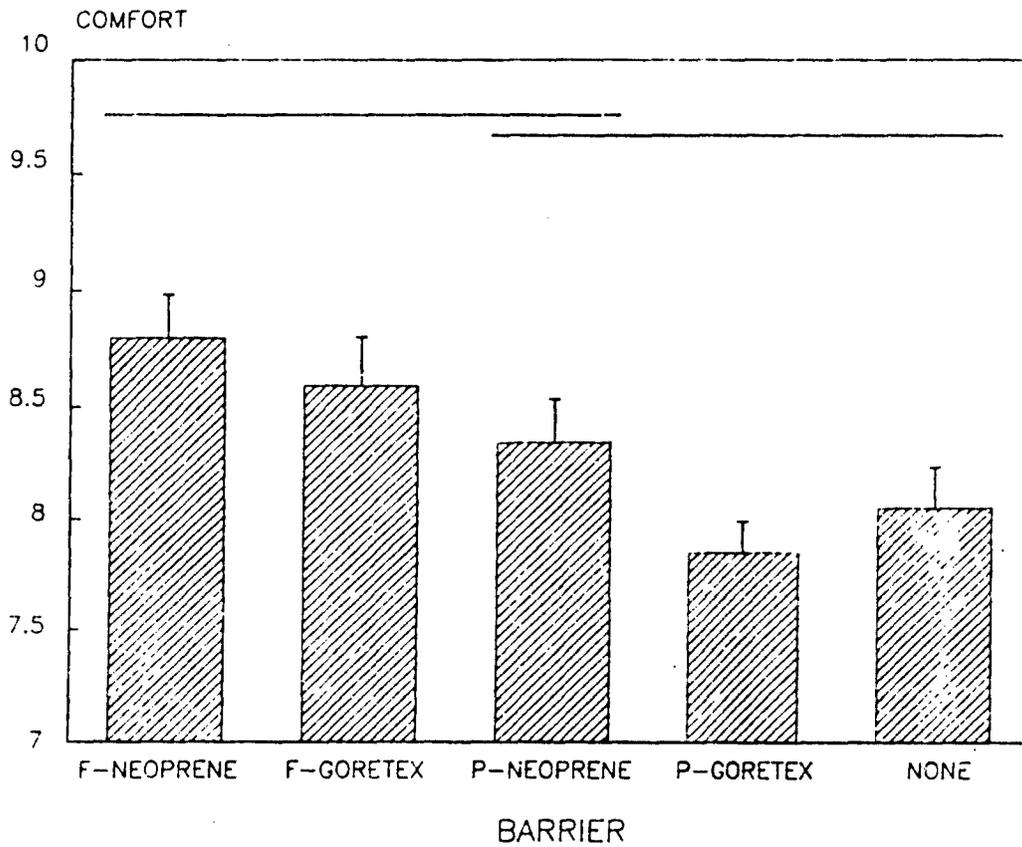


Figure II-11

The subjective comfort scale ranged from 1 - 13, spanning the entire range from hot to cold. The descriptors for the range displayed here were: 7 -- comfortable; 8 -- warm but fairly comfortable; 9 -- uncomfortably warm; and 10 -- hot.

DMST, and IIR which respond more quickly, may be better parameters as early indicators of thermal stress.

*Conclusions:*

Statistical analyses of the Phase II HOT condition data indicated a significant effect of BARRIER for 8 of the 10 physiological parameters of thermal strain; the exceptions were FTRE and AIRCONSUM. Deep body temperature probably did not have sufficient time to rise appreciably during the 30 min of the test, and AIRCONSUM results suggest that breathing rates were not significantly influenced by BARRIER.

In addition, FEVAP was affected by SHELL, the order being NOMEX, WOOL, and COTTON from best to worst, and LINER affected COMFORT, with NOMEX being more desirable than WOOL as a thermal liner. The fact that most synthetic fibers tend to "wick" moisture, rather than absorb it, may account for both of the above observations.

The results indicate that a full neoprene barrier leads to more thermal physiological strain than any of the other barrier materials and/or configurations tested. The results further show that the differences between the remaining four barriers may often be insignificant, depending upon which parameter is being studied. Thus, a full Gore-tex® barrier, a partial barrier of either neoprene or Gore-tex®, or no barrier at all might be expected to give somewhat similar results in terms of thermal strain.

However, the data for FMST, DMST, FTRE, DTRE, and FEVAP indicated fairly smooth trends in the levels of thermal strain as a function of barrier composition. The trends are, in fact, in agreement with what one would have predicted for the order of the barriers based upon the physical properties of the materials alone [3, 4], and with what some other studies have shown [5, 6, 7]. If longer exposure times or harsher working conditions are imposed on fire fighters, these small differences in barrier influences on metabolic heat retention may become substantially larger. That this supposition is, in fact, true is shown by the next test condition of this study.

## CONDITION: VERY HOT

### *Methods:*

This portion of Phase II was essentially a repeat of the condition HOT study with four major changes. First, the environmental conditions were somewhat more severe:  $T_{db} = 35^{\circ}C$ ;  $T_{wb} = 26^{\circ}C$ ; relative humidity = 45%. Second, the subjects performed the activities of condition HOT twice, separated by a 10 min rest period inside the chamber while still wearing the full complement of turnout gear. Total exposure time was, therefore, 70 min. The rest period was also used to replenish the air supply of the SCBA with a second bottle. Third, only the full neoprene (F-NEOPRENE), full Gore-tex<sup>®</sup> (F-GORETEX), and no barrier (NONE) combinations were tested, reducing the number of clothing configurations to 18. As noted before, this was because there was little difference between the partial barriers and no barrier, and the prohibitive cost of carrying out this portion of the test with all eight subjects and 30 clothing ensembles. Finally, only three of the eight subjects were available for this part of Phase II. All other procedures and monitoring techniques were identical to condition HOT.

### *Data Analyses:*

Since this portion of the study was carried out using only three subjects, a meaningful statistical analysis was already precluded. Furthermore, since each subject missed a BARRIER test condition at least once for reasons beyond control, the data set was completely unusable for any form of AOV statistical analysis. The study did, however, contain some very interesting observations, so it was decided to analyze the data set simply by computing means collapsed on BARRIER for the 10 physiological parameters and then examining the results on a purely descriptive basis as well as comparing them with the HOT condition.

To obtain an idea of how results might vary with changes in the method of computing mean values for a given barrier, the much larger data base of the Phase II HOT study was again used. Mean values for the 10 physiological parameters were computed as follows: using only the four subjects that had complete

data for all parameters under all conditions; using all subjects who had complete data for a given parameter under all conditions (i.e., variable N); and using all non-zero data for a given barrier. A visual inspection of graphs of the means computed by the three methods showed that there would be little change in the overall interpretation of the results using any method. The method of calculating means by using all available data for a barrier was, therefore, deemed acceptable, and the following discussion is based upon such an analysis of the VERY HOT data.

*Results and Discussion:*

To summarize the results of condition VERY HOT concisely, all trends established during condition HOT with regard to the effect of BARRIER were upheld during this series of tests. In fact, the differences in physiological strain in relation to the barrier material/configuration were amplified to clearly demonstrate that F-NEOPRENE is the most stressful barrier, followed by F-GORETEX, and finally followed by no barrier (NONE) as the least stressful.

Extremely important was the fact that the levels of physiological strain reached by the subjects during condition VERY HOT were much higher than during condition HOT. This confirmed the earlier prediction that a more stressful situation may be required to more clearly visualize the influence of barrier composition on metabolic heat retention. Viewed from a different perspective, during mild stress any of the clothing ensembles tested may be safe, but as the stress level increases the permeability of the barrier becomes increasingly important.

It is probably very significant that whereas during the 30 min exposures of condition HOT all subjects completed all tests, not one could tolerate 70 min of exposure to condition VERY HOT. As might have been expected, the full neoprene barrier was the ensemble that resulted in the shortest exposures.

For brevity, the data from this portion of the study are not presented separately. They are included with the results of Phase III where a 3-way comparison is made between conditions HOT, VERY HOT, and the FIELD TRIAL of Phase III.

*Conclusions:*

Concluding remarks are reserved until Phase III data are presented and the 3-way comparison is made.

**CONDITION: COLD**

*Methods:*

The Phase II condition COLD portion of the study was also essentially a repeat of condition HOT with three major changes. First, the environmental conditions were as follows:  $T_{db} = -18^{\circ}C$ ; relative humidity neither controlled nor measured. Second, only the full neoprene (F-NEOPRENE), full Gore-tex<sup>®</sup> (F-GORETEX), and no barrier (NONE) combinations were tested, reducing the number of clothing configurations to 18. Finally, only four of the eight subjects were available for this part of Phase II. All other procedures and monitoring techniques were identical to condition HOT.

Again, due to the limited number of subjects in this portion of the study, data analyses were limited to visual inspection of mean values from four subjects collapsed on BARRIER over the factors SHELL and LINER.

*Results and Discussion:*

There were no physiologically significant differences observed in this data either within barriers, or between barriers. The results can be succinctly summarized by stating there were no surprises -- body temperatures responded just as one would expect, given the test conditions. As is often observed in cold exposures involving moderate exercise in well insulated garments, rectal temperatures rose slightly (about  $0.5^{\circ}C$ ) while mean skin temperatures cooled slightly (about  $2.7 - 3.0^{\circ}C$ ). This was probably the result of vasoconstriction to reduce heat loss, coupled with an increased heat production from the exercise, and possibly a small heat production increase due to the sensation of surface cooling. Heart rates were 115 - 120 beats/min, indicating only light to moderate work levels.

Sweat parameters showed considerably less heat strain in the cold, as would be expected. Parameter FEVAP showed values of 0.04 - 0.05 kg in condition COLD compared to values of 0.08 - 0.14 kg in condition HOT, while parameter FLOSS showed 0.14 - 0.19 kg during COLD compared to 0.50 - 0.60 kg during HOT. These FLOSS results for both the HOT and COLD conditions are consistent with the values of 480 g and 190 g of sweat loss observed by Duncan et al [1] after 20 min of work in hot and cold environments, respectively. Subjective evaluations of thermal comfort indicated 7 (comfortable) for all clothing ensembles during condition COLD.

*Conclusions:*

This study was undertaken primarily to see if bunker clothing would be suitable for cold weather without major changes in design. The impetus behind this was that turnout clothing can be expensive, and it would be cost effective for a fire service to purchase only one garment suitable for all seasons.

The data show that bunker clothing provides adequate warmth under the conditions tested, with no major differences as a function of shell, barrier, or liner composition. There was certainly no indication of thermal strain in the body, and the fire fighters were comfortable with all clothing combinations evaluated.

## FIRE FIGHTER METABOLIC HEAT STRESS STUDY

### PHASE III: FIELD STUDY #2 -- CFB BORDEN

#### *Background:*

This phase of the overall study was carried out to validate the results of Phase II in the field. More specifically, the objective was to see if the differences in thermal strain observed in the Phase II HOT and VERY HOT studies as a function of the barrier material/configuration would still exist under more realistic operational fire fighting conditions involving ladder climbing, chopping, hose handling, exposure to fire, etc. To aid in this comparison, the laboratory and field data were made as comparable as possible by using the same clothing as that used in Phase II, and using six of the eight subjects from Phase II.

#### *Methods:*

In contrast to the field study of Phase I, Phase III was carried out under semi-controlled conditions in that the fire fighting activities were completely under the control of the DCIEM investigators. The tasks were well defined and were carried out repeatedly by each subject while wearing the various clothing ensembles. Although environmental conditions could not be controlled, the weather was remarkably consistent for the five days of the study, with sunshine every day and afternoon high temperatures of 25 - 30 ° C.

As in Phase II condition VERY HOT, only the three barrier conditions of F-NEOPRENE, F-GORETEX, and NONE were evaluated.

Each subject underwent two exposures/day for five consecutive days, performing 50 min of activity for each exposure. Activities consisted of the following tasks and durations: walking, 5 min; hose work, 5 min; chopping, 8 min; rest, 12 min; casualty search and rescue, 10 min; fire tending, 10 min (a detailed description of the tasks can be found in Appendix C). Each task involved picking up a piece of fire fighting equipment from a designated location, using it to

perform the required activity, and then returning it to its original state and location to be used by the next subject. These procedures permitted several tasks to be carried out simultaneously by staggering subjects at 15 min intervals, and six man-runs were carried out each morning and afternoon.

The Vitalog PMS-8 solid state data recorder system as used in the Phase I field trial was again used to sample heart rate, rectal, chest, and rear thigh temperatures at 15 sec intervals throughout the exposure. Sweat production and dehydration were determined from nude weights taken before and after each exposure. Unfortunately, sweat evaporation data from dressed weights were unreliable due to wetting of the clothing during the exposures (from hose spray).

HR data from this study was computed somewhat differently than in Phase II, due to the differences in protocol. During the laboratory studies, the maximum HR consistently occurred at the end of the exposure, and it was the average HR over the final 3 min of the test that was compared. In Phase III, subjects spent several minutes breaking down, draining, and folding the hose at their own pace near the end of the work period, followed by a leisurely walk back to the dressing area. To obtain a better picture of the degree of stress imposed by the actual fire fighting tasks, HR data were scanned to determine the maximum values recorded. Thus, although the relative times during the work period at which the maximum HR occurred differed with respect to Phase II, it is still maximum HR data that are being compared.

#### *Data Analyses:*

Again, because of an unbalanced experimental design and the inadvertent loss of some data values, AOV with Repeated Measures could not be used to statistically analyze the data. Instead, mean values for the parameters over all tests of each barrier were obtained, i.e., all non-zero data were used. Note that this is the same approach as was used in calculating mean values for condition VERY HOT in Phase II. Since this approach would give different results for the data of the HOT condition of Phase II, those means were re-calculated using all non-zero data, and it is these values that are presented below.

*Results and Discussion:*

Figures III-1 through III-6 provide comparisons of six physiological parameters for conditions HOT and VERY HOT of Phase II, as well as the field trial (condition FIELD TRIAL) of Phase III. The histograms represent the mean values of the parameters as a function of factor BARRIER. It was assumed that SHELL and LINER would have no significant effects on the results, as was observed in Phase II. Three general observations can be made about these results.

First, the levels of thermal strain reached by the subjects during conditions VERY HOT and FIELD TRIAL were considerably higher than those reached during condition HOT. In fact, the parameters FTRE, DTRE, and HR showed levels that were more consistent with expectation, given the work loads and conditions under which fire fighters normally work. This strongly supports the contention that the test conditions under which the Phase III FIELD TRIAL was conducted yielded a realistic evaluation of the clothing. The changes in deep body temperature were actually very similar to the levels found in the Phase I field study, and were approaching commonly accepted thresholds of performance impairment and/or danger to health.

Also very encouraging and vital to the credibility of this study was the fact that conditions VERY HOT and FIELD TRIAL gave almost identical physiological results in several parameters. This confirms that the results obtained in the laboratory from carefully designed and properly executed experiments are applicable to the field environment. Further, because of the similarity in design of the Phase II HOT and VERY HOT studies, one can infer that the Phase II HOT and Phase III FIELD TRIAL results are also compatible.

Therefore, notwithstanding the differences from condition HOT, the statistically significant trends of thermal strain as a function of BARRIER established in the detailed laboratory study of Phase II condition HOT were consistently upheld, and often amplified, in the VERY HOT and FIELD TRIAL conditions. The conclusions that a full neoprene barrier is the most stressful of the combinations tested, and that more taxing conditions, be they increased thermal stress or extended work times, would make such barrier differences more important, were clearly demonstrated. Clearly, should physiological strain become the limiting

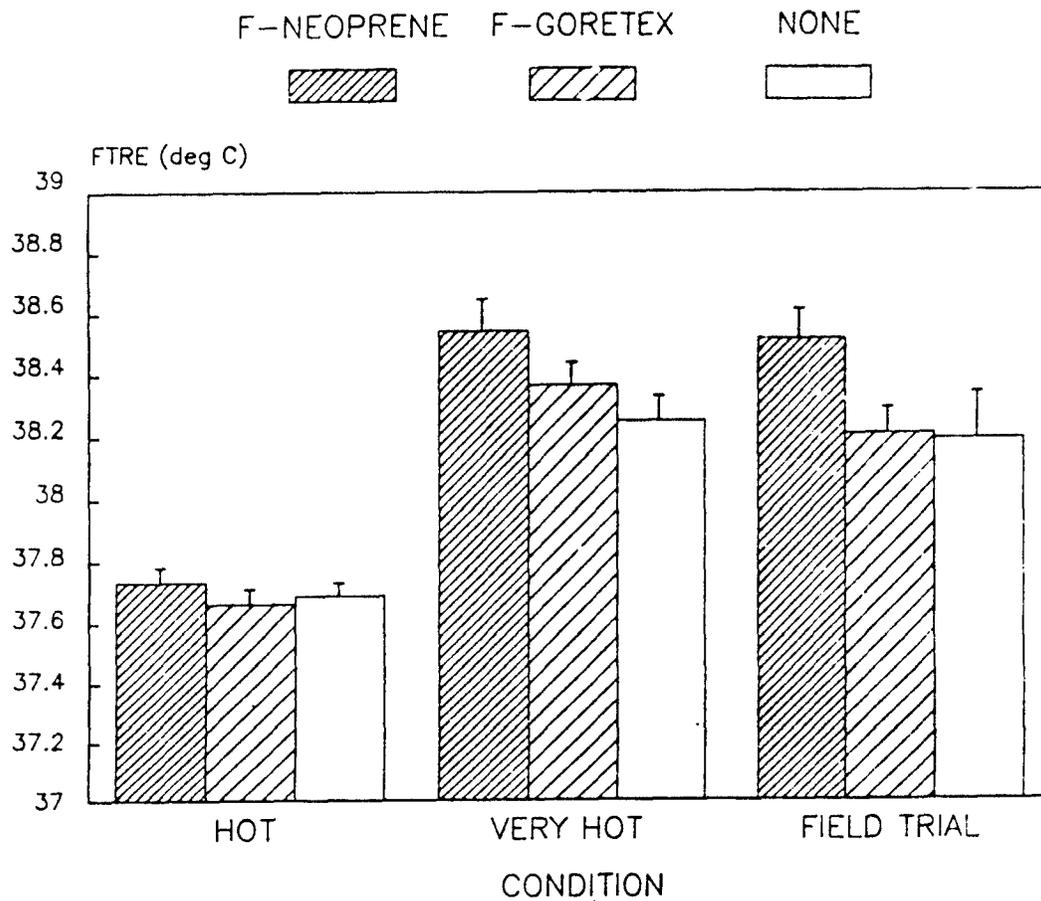
**General Legend and Notes  
for Figures III-1 through III-6**

Figures III-1 through III-6 are histogram plots comparing the results of the Phase II HOT, VERY HOT, and Phase III FIELD TRIAL test conditions for six physiological parameters. Only three barrier configurations are presented, since partial barrier configurations were not evaluated in the latter two test conditions.

The histogram bars represent mean values for each barrier calculated by using all available data, as described in the text. The small vertical bars are the standard error of the mean.

The ordinates for each parameter again represent physiologically relevant ranges (see Figures II-2 through II-11 for an interpretation of the ordinal values).

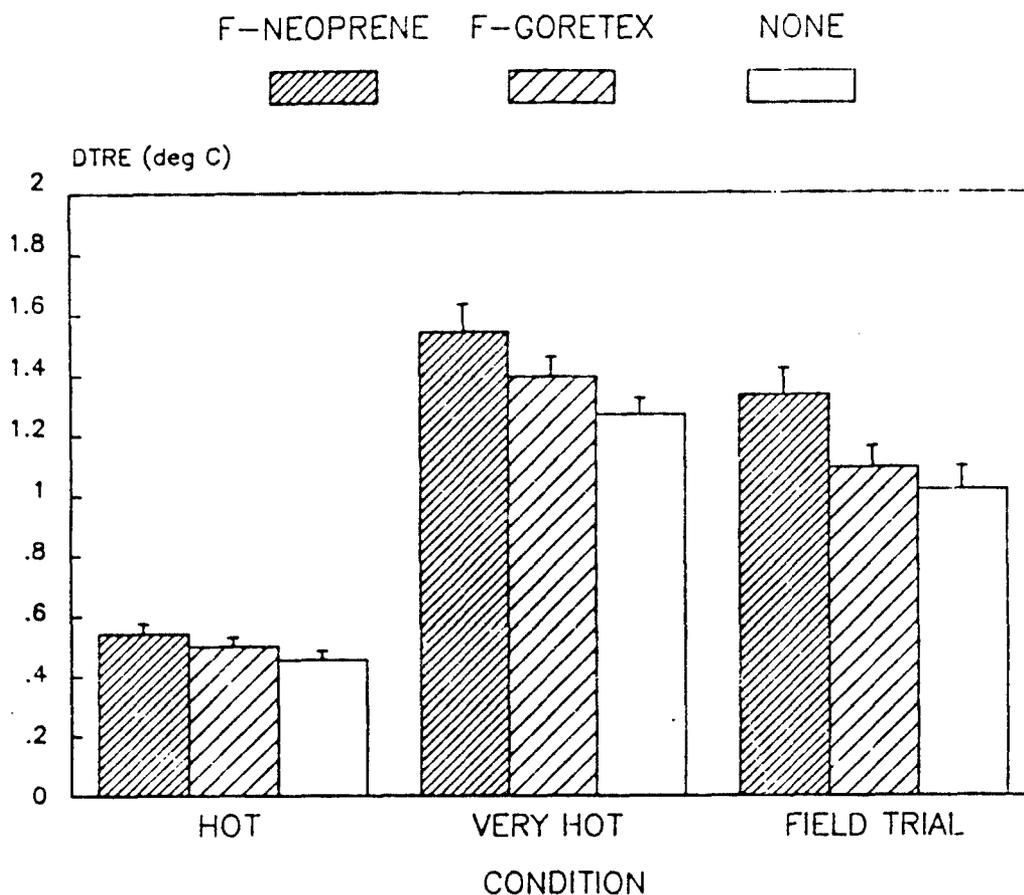
### FINAL RECTAL TEMPERATURE



**Figure III-1**

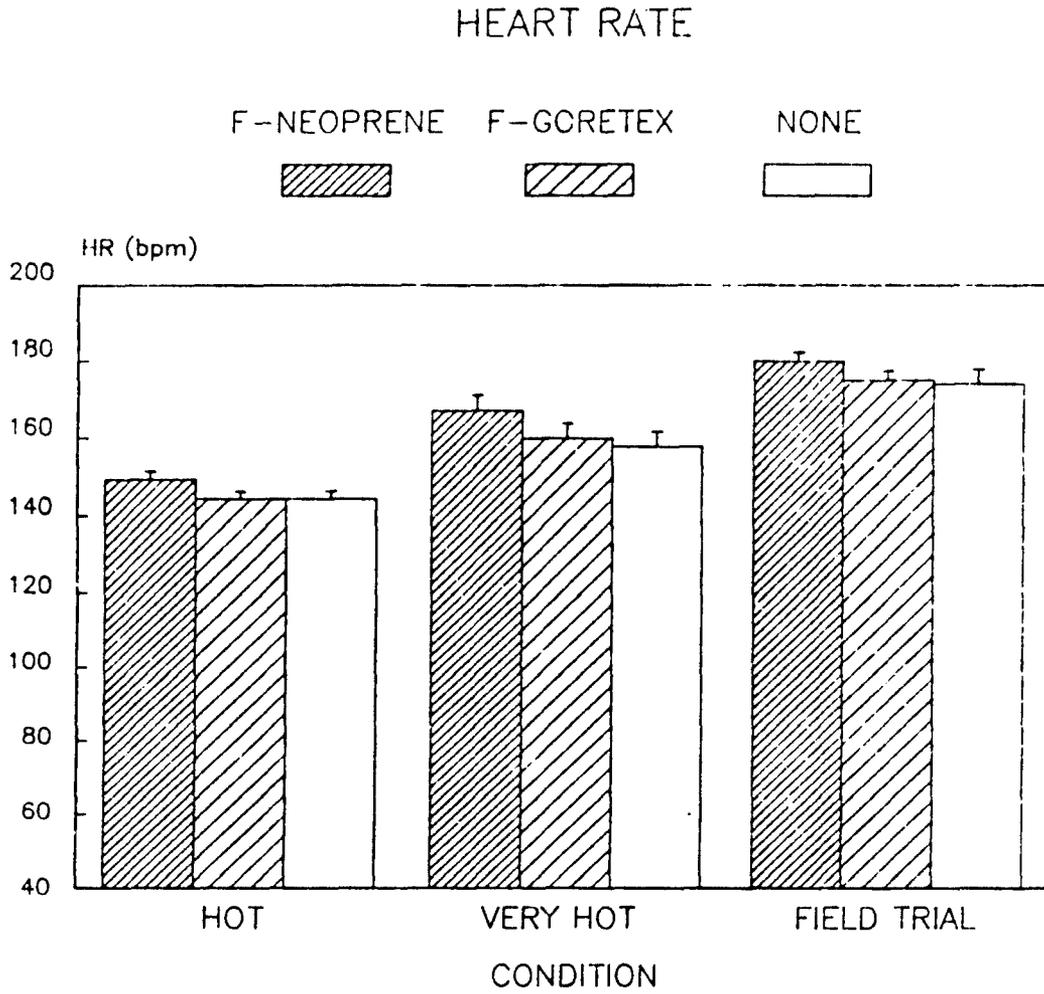
Final rectal temperatures during conditions VERY HOT and FIELD TRIAL, were considerably higher than during condition HOT and, with a full neoprene barrier, were approaching the laboratory safety limit of 39°C. Note the strong similarity in results for conditions VERY HOT and FIELD TRIAL.

### DELTA RECTAL TEMPERATURE



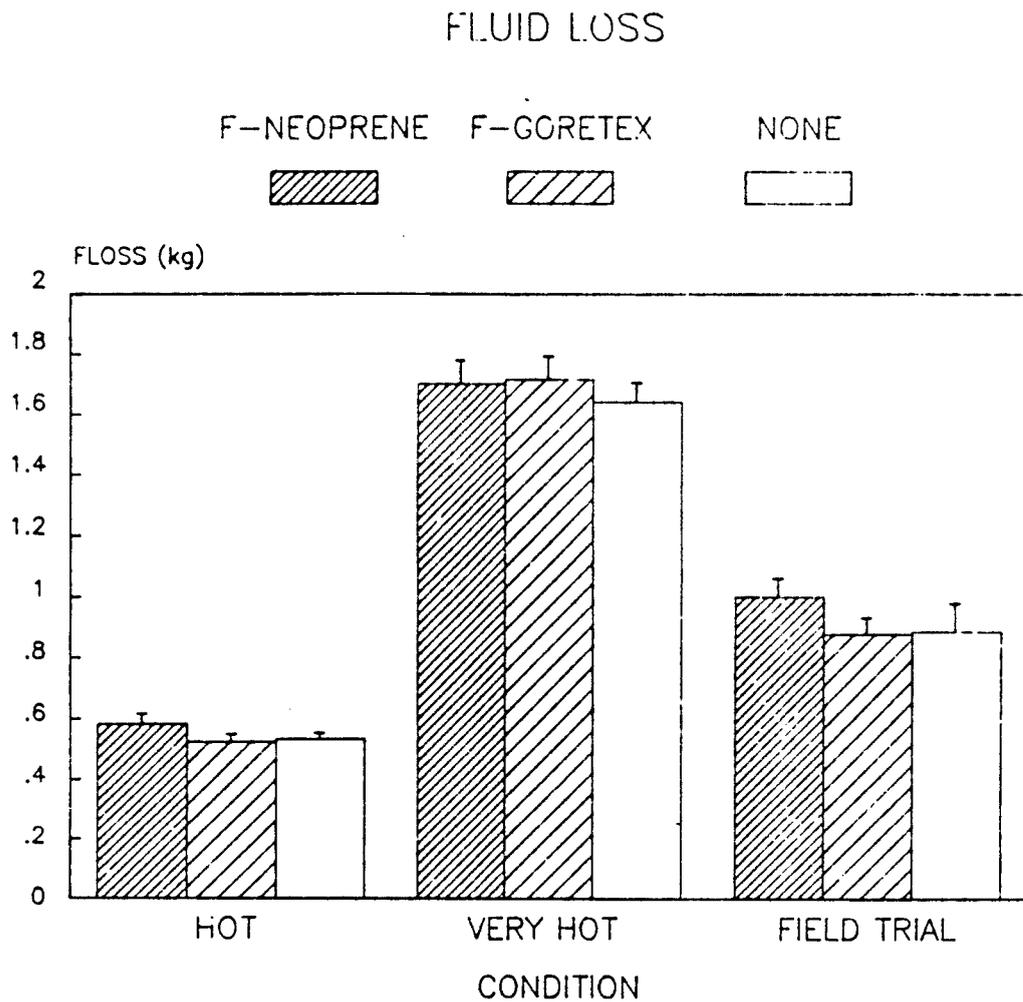
**Figure III-2**

As in the previous figure, the changes in rectal temperature indicate that the thermal stresses under conditions VERY HOT and FIELD TRIAL were more severe than during condition HOT, and that the laboratory results were strongly indicative of results one would obtain in the field.



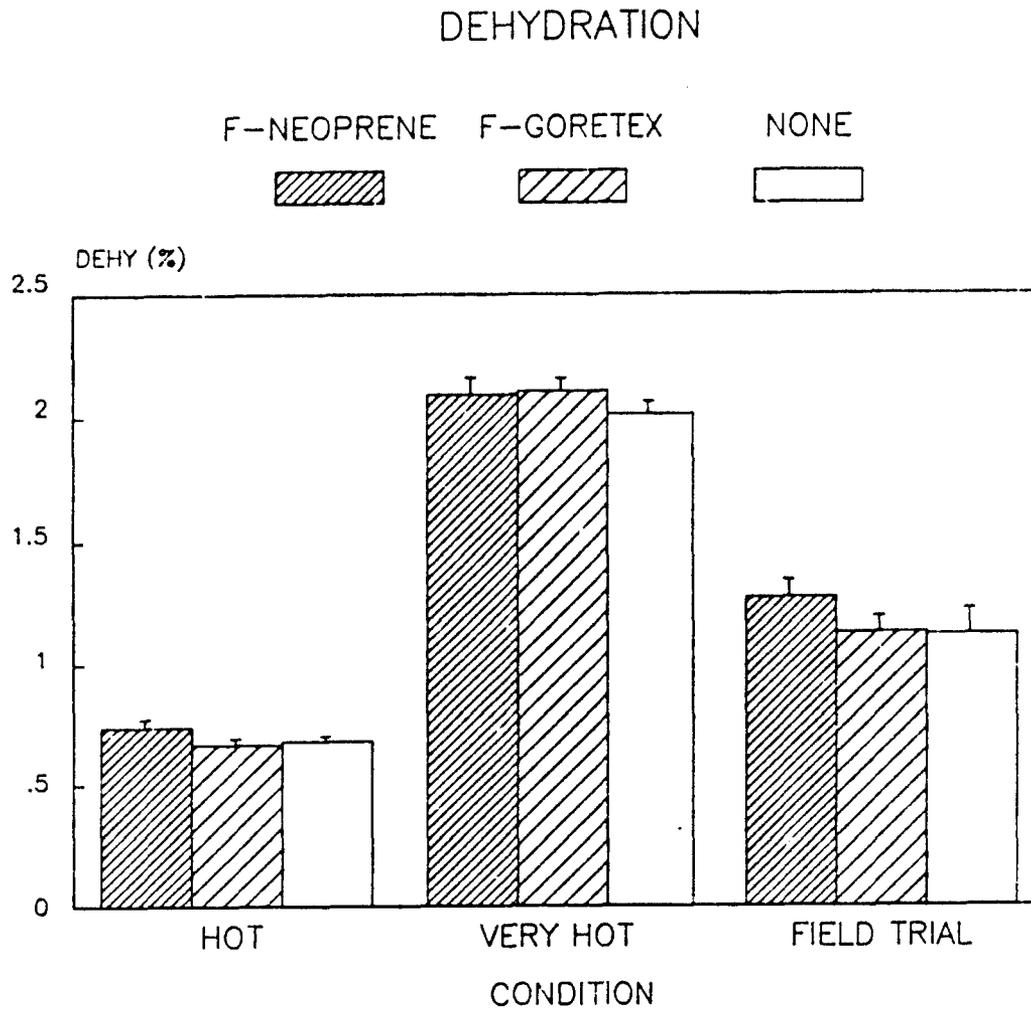
**Figure III-3**

These data show that FIELD TRIAL was the most strenuous of the three test conditions in terms of maximum HR achieved. There is, however, a noticeable and consistent difference in HR across all test conditions as a function of BARRIER.



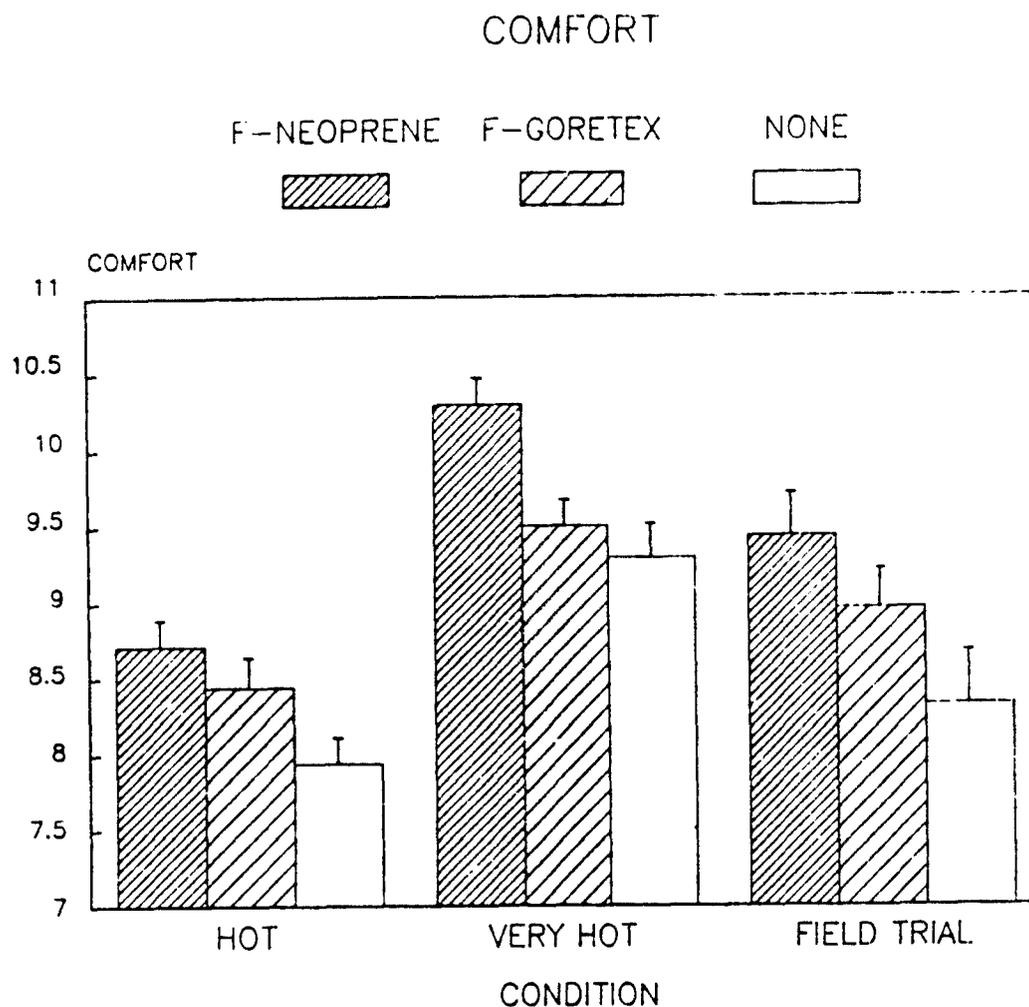
**Figure III-4**

These data show that fluid loss depended more on time than on the clothing configuration. Exposures lasted 30, 70, and 50 min for conditions HOT, VERY HOT, and FIELD TRIAL, respectively.



**Figure III-5**

The dehydration data show that condition VERY HOT was indeed very stressful on the subjects. As pointed out earlier, 2% dehydration is uncomfortable. The fact that this was the only test series that not all subjects were able to complete suggests that dehydration may have been the limiting factor in the VERY HOT exposures.



**Figure III-6**

These subjective thermal comfort scores clearly show that the subjects were able to discern the differences in overall stress between test conditions, as well as the differences in the clothing configurations. Clearly, a full neoprene barrier is the least comfortable, while the absence of a barrier is most desirable from a comfort perspective.

factor in a fire fighter performing his duties, that limit would be reached sooner while wearing a clothing ensemble containing a full vapour impermeable barrier.

Third, the sweat loss parameters FLOSS and DEHY reached three distinct levels under the three test conditions (parameter COMFORT also did this to some extent). When the time taken to complete the test activities for these three conditions is considered (i.e., 30, 70, and 50 min for conditions HOT, VERY HOT, and FIELD TRIAL, respectively), it appears that the amount of fluid lost by the body depended more upon the duration of the test than upon differences in the clothing configurations.

*Conclusions:*

Despite the widely different test conditions under which the Phase II VERY HOT and Phase III FIELD TRIAL studies were carried out, the indicators of thermal physiological strain used to assess the effect of the barrier showed remarkably similar values. The strong parallel between the FIELD TRIAL and VERY HOT results shows that laboratory data can indeed be reliable predictors of field responses.

Further, the comparison of the VERY HOT and HOT data, which were both collected under simulated fire fighting conditions, shows that the trends of thermal stress as a function of barrier material and/or composition established during condition HOT are upheld or even amplified under more stressful conditions. Therefore, the conclusions arrived at in the more extensive and intensive Phase II condition HOT study should be considered reliable.

By inference, then, the statistically significant results obtained in Phase II condition HOT can be expected to apply to true fire fighting conditions. A full neoprene vapour barrier imposes a high thermal stress on the body during fire fighting, and as the vapour permeability of the barrier increases, the capacity to cool the body by evaporation increases. An increase in the vapour permeability of the clothing can be achieved by using a material such as Gore-tex<sup>®</sup>, or by using a neoprene material only partially covering the body. If no barrier is acceptable based upon other protection criteria, this is certainly the most desirable

configuration from a metabolic thermal stress perspective.

## FIRE FIGHTER METABOLIC HEAT STRESS STUDY

### Overall Summary and Conclusions

The physiological impact of including a moisture/vapour barrier in fire fighter turnout clothing was examined under a wide variety of test conditions. The study commenced with a field survey of physiological responses during an advanced fire fighter training exercise. This field survey provided the baseline from which the intensity of exercise and thermal stress was determined for the Phase II laboratory study. An extensive series of laboratory evaluations was then carried out under cold, hot, and extended very hot conditions to obtain detailed physiological data under carefully controlled conditions. The laboratory studies were followed by a field trial which involved fire fighters performing actual fire fighting tasks, including exposure to the heat of a fire, under semi-controlled and reproducible field conditions.

The Phase I field study showed that fire fighting is indeed strenuous work that can lead to elevated deep body temperatures, high heart rates, and other manifestations of thermal strain. However, the degree of thermal strain reached depends heavily upon the nature of the work being done. A recommendation for reducing the incidence of heat related illnesses is frequent rotation of duties among the fire fighters, perhaps using depletion of the SCBA air bottle as a timing aid.

The Phase II laboratory studies showed statistically significant effects of the barrier material/composition on 8 of 10 physiological indicators of thermal strain. The order of barriers followed the pattern expected on the basis of the predicted relative vapour permeability of the barriers. A full coverage vapour impermeable barrier such as neoprene imposes the greatest thermal stress on the body, while omission of the barrier entirely provides for the greatest dissipation of body heat. Full coverage vapour permeable barriers, or partial coverage impermeable or permeable barriers, provide intermediate levels of stress or heat dissipation.

The Phase III field study showed that the statistically significant results obtained in the laboratory are applicable to fire fighters working in the field.

Although statistical power was lacking in Phase III, the strong parallel in physiological responses between the laboratory and field responses showed that those trends and results established in the laboratory are upheld under more realistic fire fighting conditions.

Modern fire fighter turnout clothing is being designed with protection of the fire fighter against outside sources of heat and other hazards as the prime objective. This protection is often achieved at the expense of adequate dissipation of internally generated metabolic heat. High levels of thermal strain in the body may be equally as, or perhaps even more important than, environmental hazards in fire fighter injury and death. Clearly, the optimum degree of protection afforded by turnout clothing must be a compromise between these two factors, and the material/composition of the vapour/liquid barrier currently included in the clothing is a very important element in this tradeoff. It is hoped that the results of this study will assist in defining the design characteristics of not the *most*, but rather the *best* protective clothing for the fire fighter.

### Acknowledgements

The authors wish to express their gratitude to all staff of DCIEM, CFFM, DCGEM, and CFFA/CFB Borden who assisted in this project for their part in making this study possible. Although it is difficult to rank and compare the contributions of those concerned, a very special note of thanks is extended to Capt. Jim Wright for his assistance in the planning of the studies, obtaining equipment and supplies, recruiting subjects, testing protocols, organizing facilities and support, dragging dummies out of dark smoke-filled buildings, etc., etc., etc., ... in short -- thanks, Jim!

A special note of appreciation is also extended to Mr. Robert Limmer for his expert and undaunted support in computer programming for data collection/reduction/analysis/presentation, as well as almost every other facet of these experiments.

The study would, of course, not have been possible without the excellent cooperation of all the test subjects who tolerated everything they were put through so well. To dress in turnout clothing and face 30 min or more of hard work in a hot environment when there really is no fire is questionable -- to repeat such actions almost 60 times is incredible! To all of our test subjects, a sincere and well deserved note of thanks.

Clearly, a study of this magnitude requires the assistance of more people than can be acknowledged in a small space. To all those unnamed individuals who contributed in their own way, no matter how small, a final *thank you*.

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## APPENDIX A

Figures A-1 through A-7 are photographs of a subject at various stages of dressing/exercising during Phase II test condition HOT. The subject instrumentation/dressing/exercising procedures were essentially the same during the Phase II conditions COLD and VERY HOT, except for the changes in environmental temperature and duration of the tests.

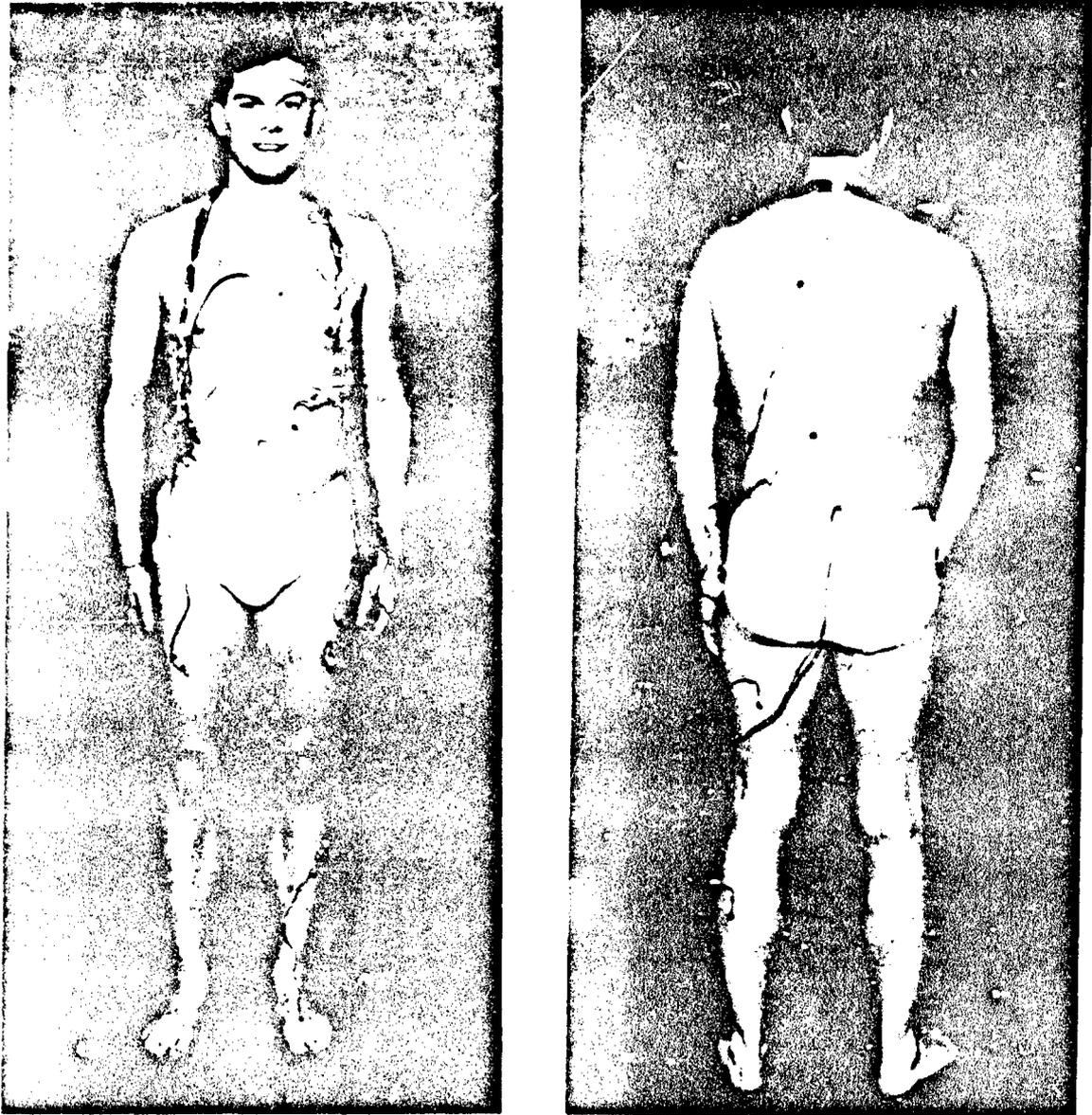


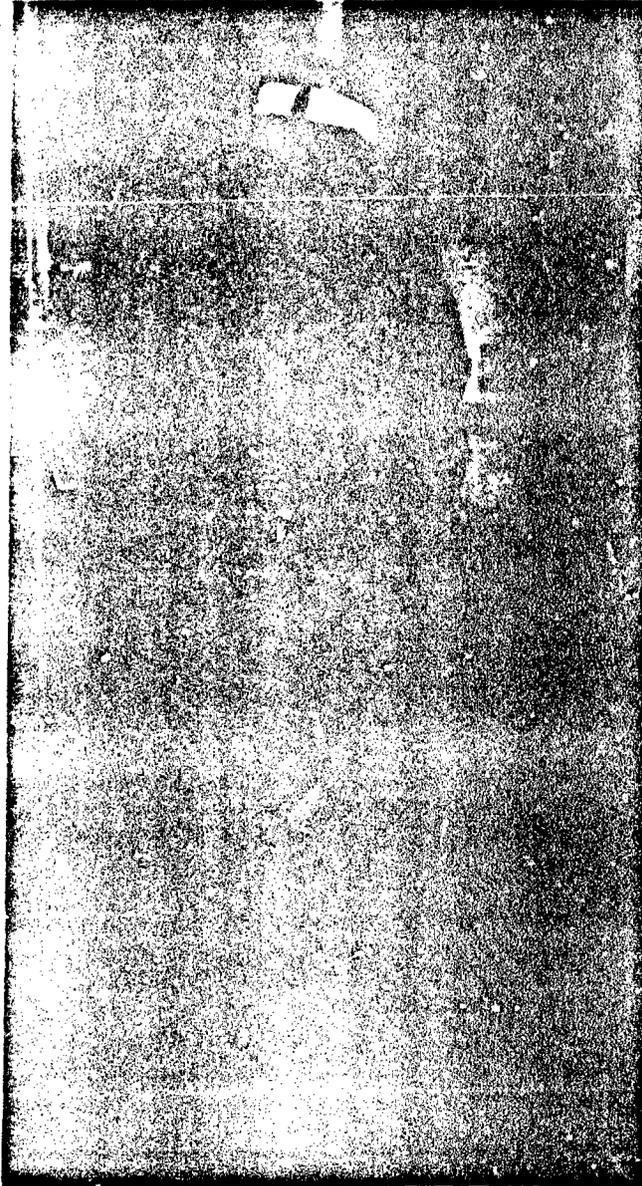
Figure A-1

The person in the photograph is wearing a light-colored jumpsuit. The jumpsuit has a high collar and a zipper down the front. The person is standing with their arms at their sides. The background is a dark, textured surface.



**Figure A-2**

Subject being weighed nude (weights for undershorts and monitoring leads accounted for) and fully dressed (holding helmet and gloves). The SCBA air bottle was weighed independently of the subject.



**Figure A-3**

Fully dressed subject entering the climatic chamber. The umbilical cable clipped to the coat coupled all physiological data to the computer system.

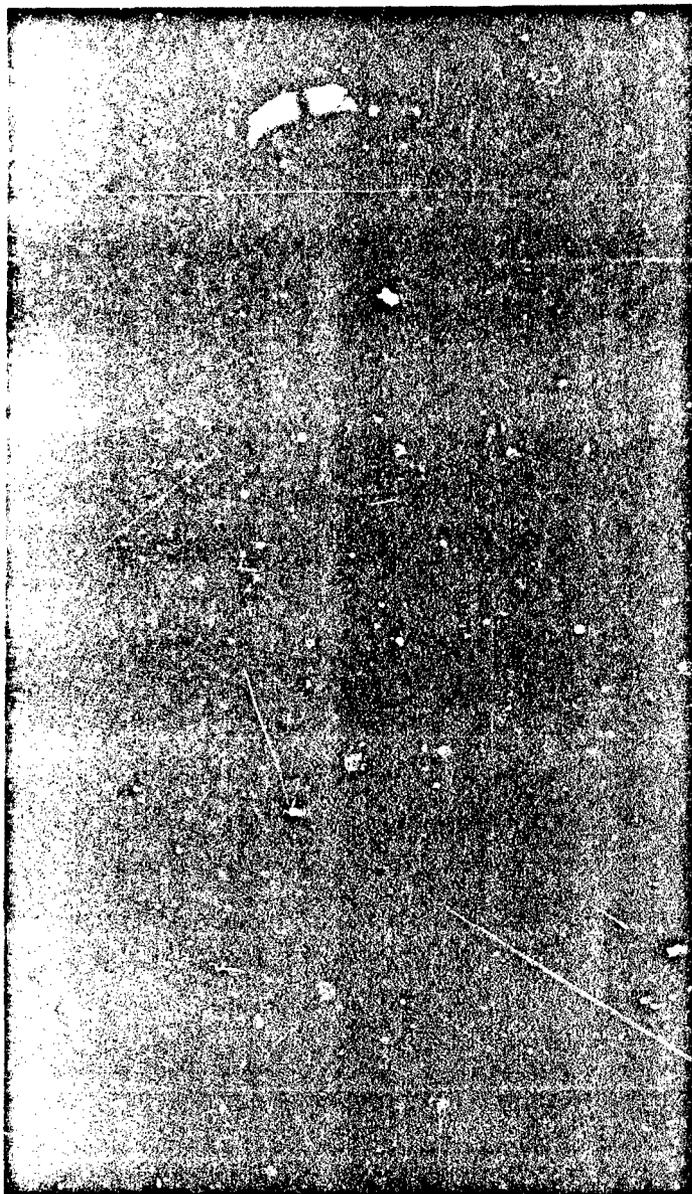


Figure A-4

Subject walking on a treadmill set to 4.5 km/h. All work activities in the chamber lasted 9.5 min. allowing 0.5 min for the subject to rotate to the next work station.

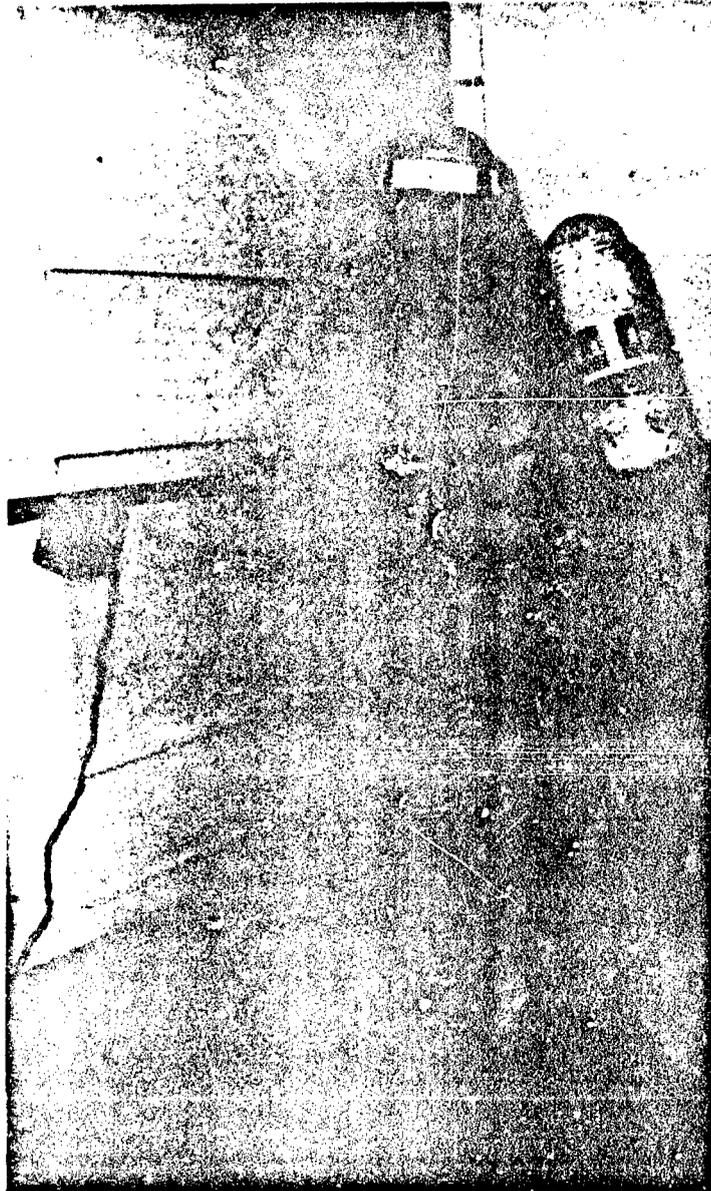


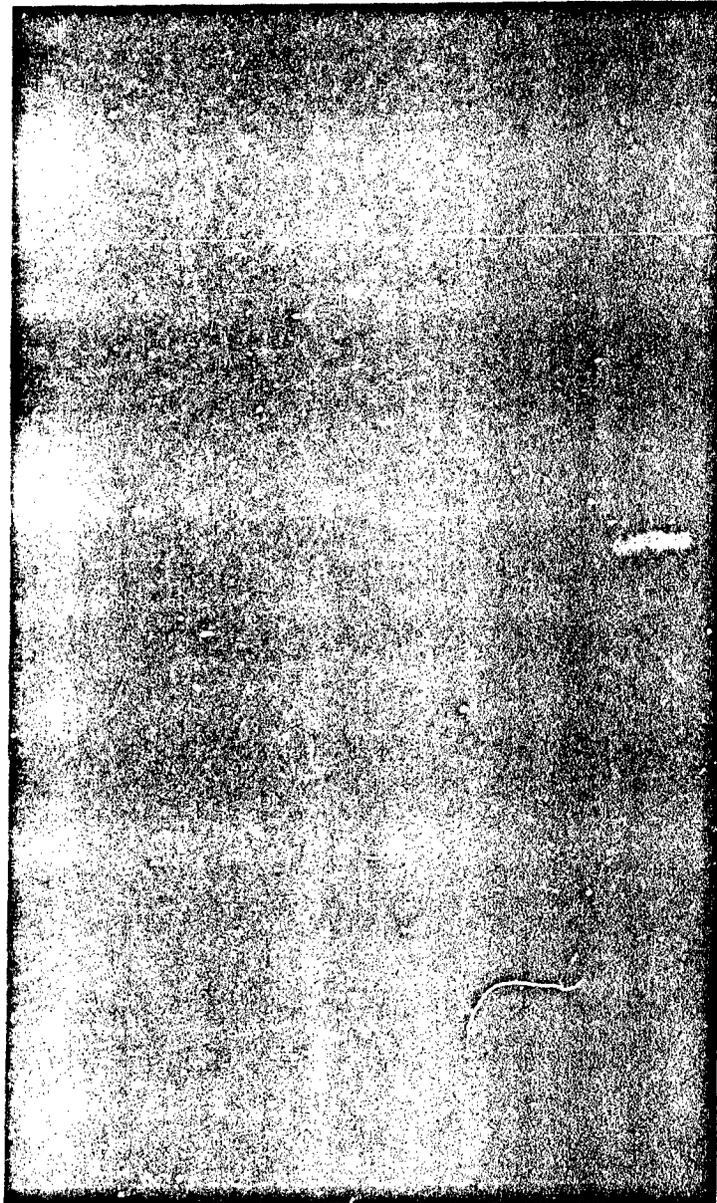
Figure A-5

Subject performing bench stepping on two standard 8-in steps. The metronome on the guard rail provide both audio and visual timing signals to regulate the stepping rate at 60 steps/min. A complete cycle involved six footsteps in the pattern up-up-together-down-down-together foot movements.



Figure A-6

Subject performing the box carrying task. Four medical transfer cases weighing 20 kg each were moved one at a time from one stack to another 2 m behind the subject at a rate of six box transports/min. Work rate was regulated by audio and visual timing signals.

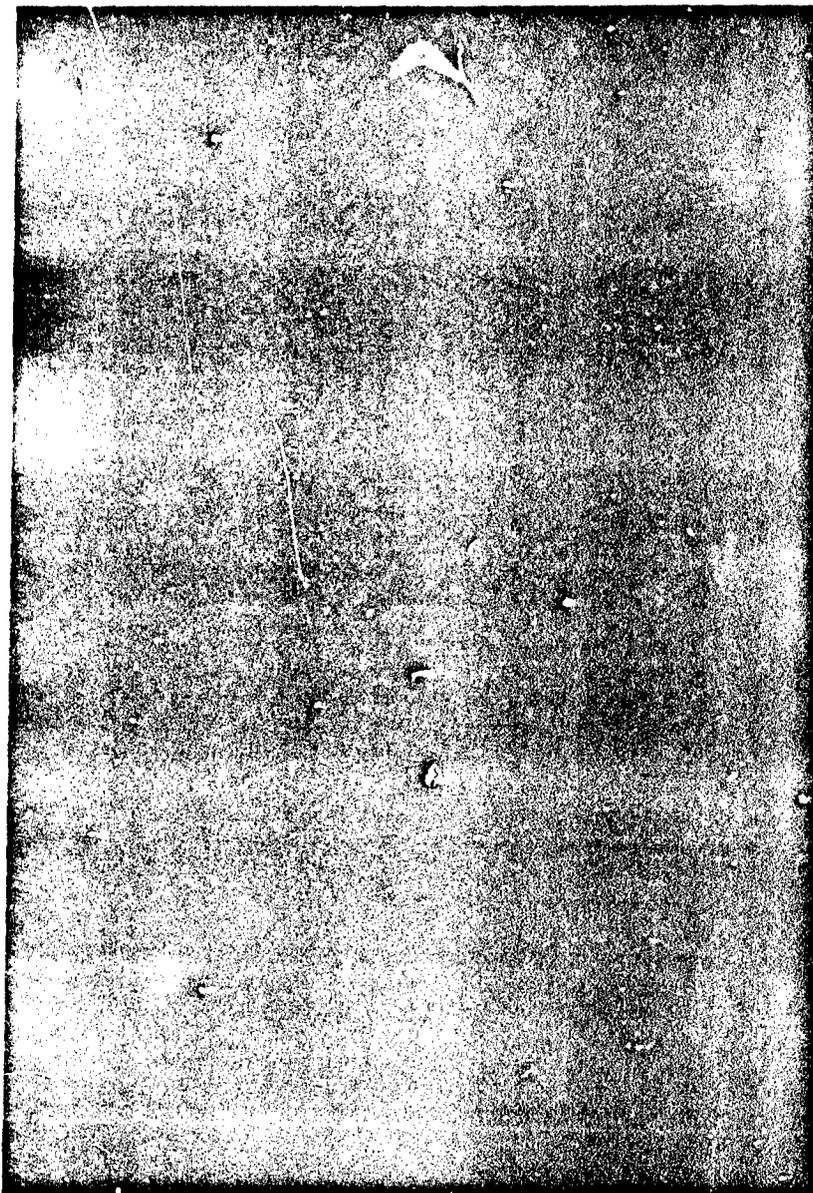


**Figure A-7**

Tired and sweating subject leaving the climatic chamber after 30 min of work during condition HOT.

## APPENDIX B

Figures B-1 through B-7 are photographs of the test clothing used in Phases II and III of the study. The shells, barriers, and liners were made interchangeable to reduce the overall number of garments required in the study. Partial barriers were formed by sewing the required barrier materials directly onto separate sets of liners. The required clothing ensemble was assembled by a technician, and subjects could not identify the composition of the ensemble apart from recognizing the colour of the outer shell.



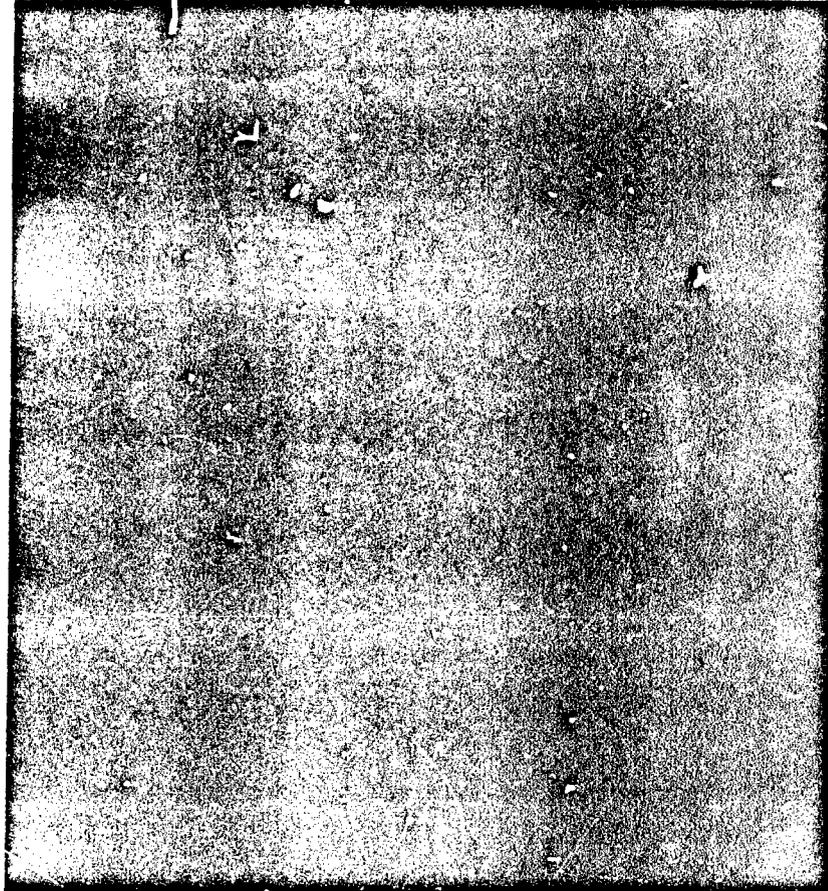
**Figure B-1**

Outer shell element of the turnout clothing used in Phases II and III. The Nomex<sup>®</sup> and cotton outer shells were identical in design to the wool shell shown here.



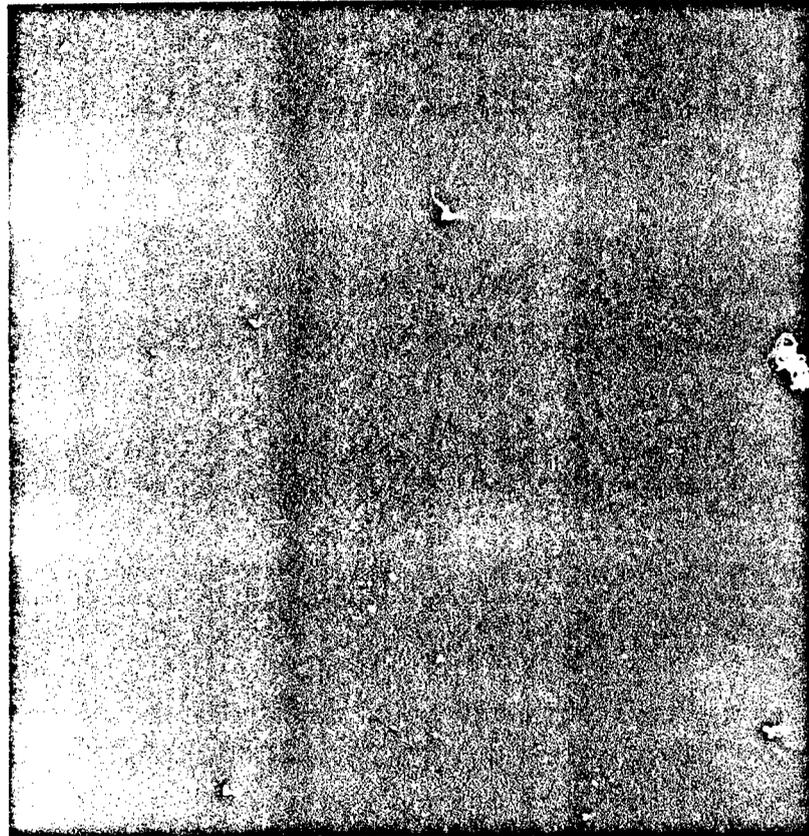
**Figure B-2**

Upper portion of the full barrier element of the clothing. Velcro patches secured the full barrier to the liner.



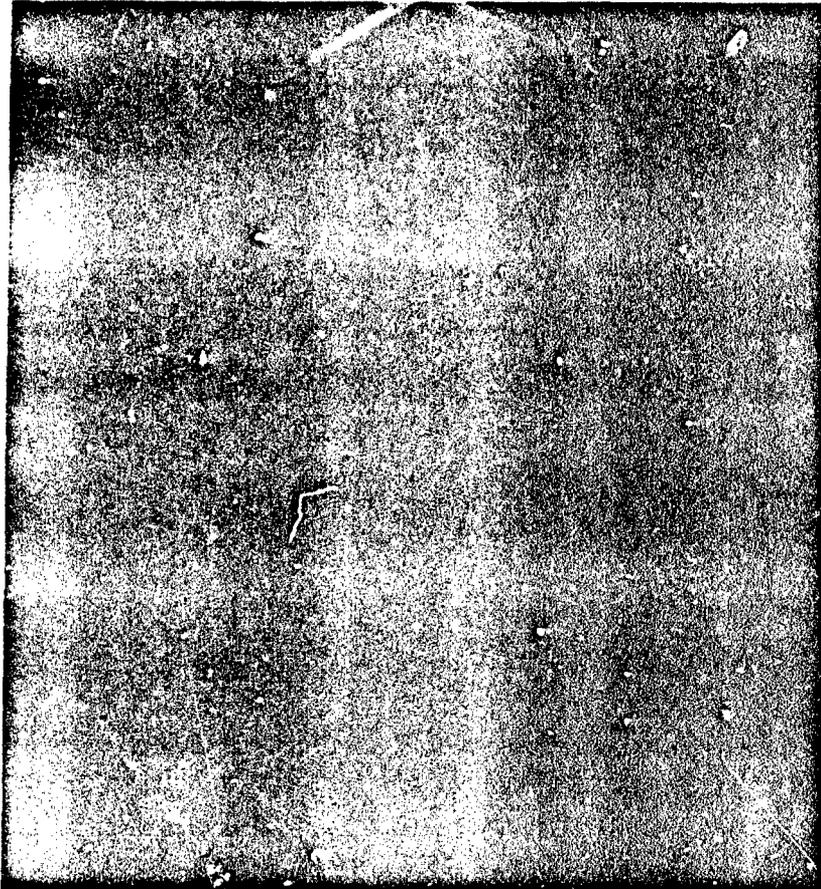
**Figure B-3**

Lower portion of the full barrier element of the clothing. The full neoprene and full Gore-tex® barriers were constructed identically and were fully interchangeable.



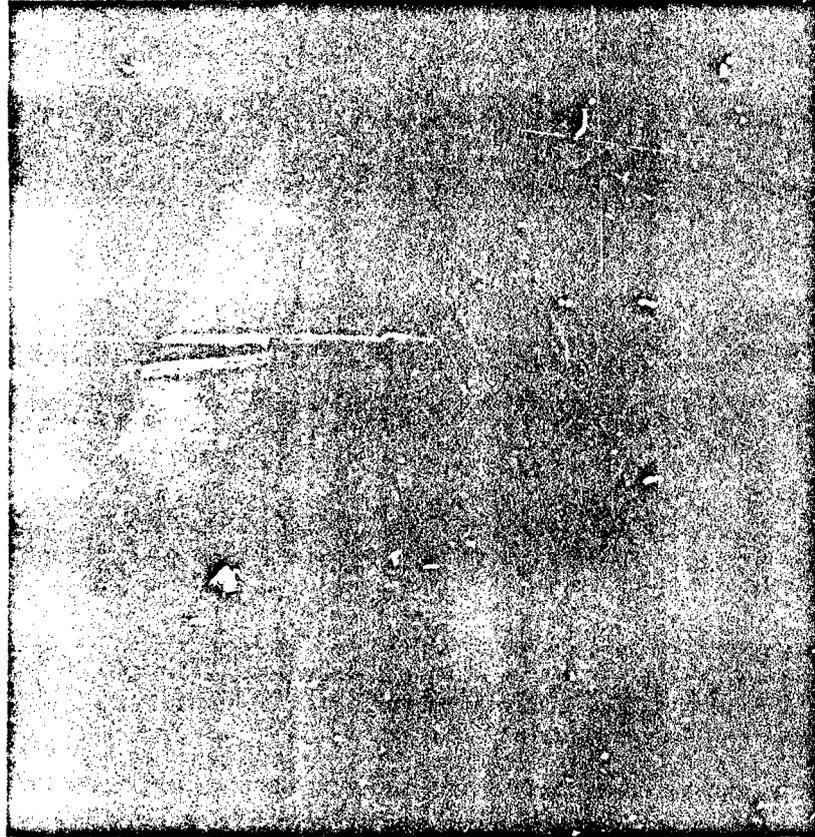
**Figure B-4**

Upper portion of the liner element of the clothing. The velcro patches for securing the full barrier to the liner are clearly visible.



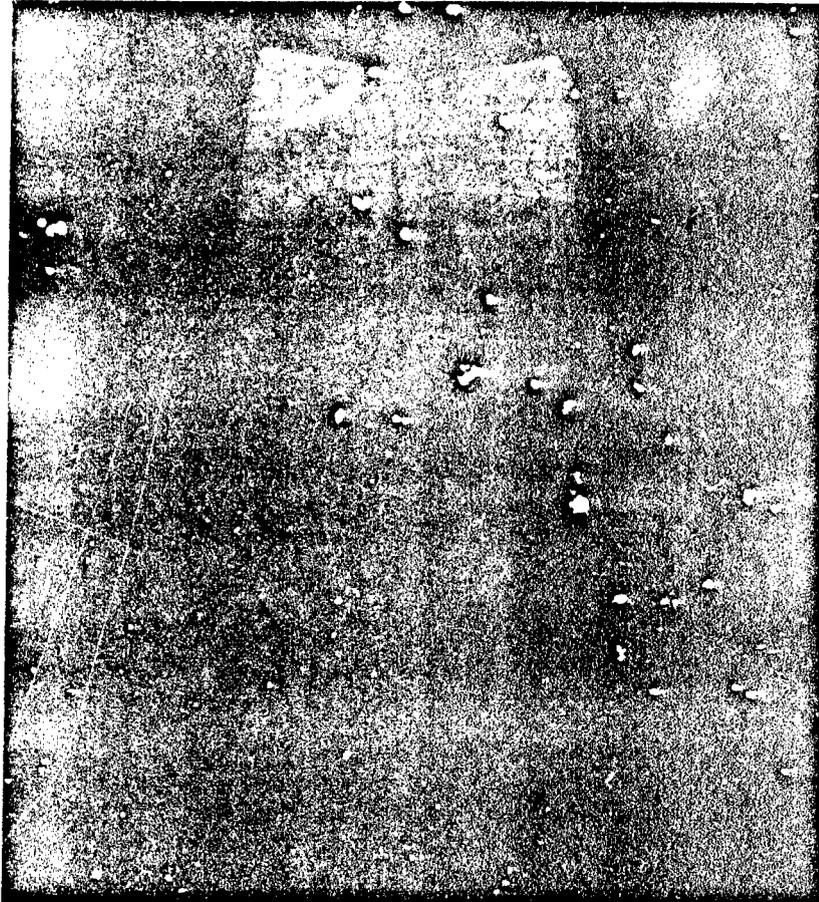
**Figure B-5**

Lower portion of the liner element of the clothing. The pyjama check outer fabric of the liners was filled with either wool or Nomex® needle punch batting.



**Figure B-6**

Front view of the upper portion of the liner with partial barrier (coverage on the back was comparable to that on the chest). The partial barriers had to be attached directly to the thermal liners to avoid their shifting during the tests.



**Figure B-7**

Rear view of the lower portion of the liner with partial barrier attached. There was no frontal coverage of the lower garment by a partial barrier.

## APPENDIX C

### Detailed Description of Phase III Fire Fighting Tasks

Task	Duration	Activity
Walking	5 min	- walk outdoors from dressing area to smoke house
Hose Work	5 min	- extend 60 m of 38 mm flaked hose - spray for 1 min at 700 kPa - remove nozzle, under-run to drain - flake hose, replace nozzle
Chopping	8 min	- remove ladder from truck - carry to building, raise to roof - get axe from truck, climb to roof - descend with axe, proceed to chopping area - chop for 45 s, clear chips for 15 s - repeat chopping for 3 min - replace axe, return ladder to truck
Rest	12 min	- proceed to rest area - exchange SCBA air bottle - rest on bale of hay in shade
Search and Rescue	10 min	- enter building and search all rooms - locate 60 kg dummy, drag out with assistance - replace dummy in back room via rear door
Tend Fire	10 min	- extend hose to building - pressurize hose, vent air - proceed to hot room on second floor w. hose - crouch near flame for 2 min (fire at 300 ° C) - drain hose, flake next to pumper truck

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The relationship between metabolic heat build-up and the vapour permeability of the barrier layer in fire fighter turnout clothing was examined under a variety of conditions. Laboratory exercise tasks were used to simulate the work of fire fighters performing under three different environmental conditions, cold, hot, and extended very hot conditions. The laboratory studies were followed by a field trial in which true fire fighting activities were performed. The clothing elements examined included three outer shells, five moisture/vapour barrier configurations, and two thermal liners. Ten parameters indicative of thermal physiological strain were monitored in eight professional fire fighters to assess the role of the barrier in the retention of metabolic heat.

The results showed that the moisture/vapour barrier material/configuration was the dominant factor in determining thermal physiological strain, with the shell and liner playing very minor roles. Differences in strain as a function of barrier were discernible even under low to moderate stress, but became more pronounced with higher ambient temperatures and longer work periods. The laboratory results were clearly substantiated during the field trial.

It is concluded that a full vapour barrier of a material such as neoprene leads to significantly higher thermal physiological strain than a vapour permeable water barrier of a material such as Gore-tex<sup>®</sup>. Partial coverage barriers of either material provide even greater reduction in strain, and omission of the barrier entirely is best from a physiological perspective. The best fire fighter turnout clothing will be a compromise between the requirement to protect against external hazards and the need to dissipate metabolically generated heat.

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Core Temperature  
Skin Temperature  
Evaporation Fluid Loss  
Heart Rate  
Neoprene  
Gore-tex  
Fire Fighters Clothing  
Thermal Comfort  
Field Trial  
Laboratory Study