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Reduced Work Tolerance Associated with Wearing Protective Clothing and Respirators*

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This study examined worker tolerance and physiological responses to two levels of work while subjects wore various types of protective clothing and respirators. Nine healthy men (mean age = 24.8 years, weight = 75.3 kg, max $\dot{V}O_2$ = 44.6 mL/kg/min), experienced with the use of respirators, each performed a randomized series of eight experimental tests, each test scheduled to last 180 min. Work was performed on a motor-driven treadmill at a set walking speed and elevation indicative of either 30% (low work intensity) or 60% (high work intensity) of maximum work capacity for each individual. Four protective clothing ensembles were examined: light work clothing (LIGHT), light work clothing with SCBA (SCBA), firefighter's turnout gear with SCBA (FF) and chemical protective clothing with SCBA (CHEM). Physiological measurements included heart rate, skin and rectal temperature, and minute ventilation. Measurements were obtained every 2.5 min until test termination (tolerance time). If less than 180 min, tolerance time was defined by subjective or objective signs of near maximal stress. Mean tolerance times at the low work intensity were 167, 130, 26 and 73 min, respectively, for the LIGHT, SCBA, FF and CHEM ensembles. At the high intensity, mean tolerance times were 91, 23, 4 and 13 min, respectively. At the low work intensity, heart rate with SCBA rose very slowly during the tests and remained approximately 15 beats/min higher than the heart rate for subjects wearing the LIGHT ensemble. In contrast, heart rate with the FF and CHEM ensembles rose sharply and did not approach steady-state values. At the low work intensity, skin temperatures at the end of the test were 32.7° C, 33.1° C, 36.7° C and 36.3° C for the LIGHT, SCBA, FF and CHEM ensembles respectively, whereas core temperatures were 37.6° C, 37.9° C, 37.9° C and 38.5° C. Tidal volume and minute ventilation increases with exercise were greatest with FF, followed in order by the CHEM, SCBA and LIGHT ensembles. It is concluded that wearing protective clothing and respirators causes significant stress to the cardiorespiratory and thermoregulatory systems, even at low work intensities in a neutral environment. The most stressful responses were observed in subjects wearing the firefighter's turnout gear (the heaviest ensemble). Weight of the ensembles alone, however, did not account for all of the observed differences.

Introduction

It is estimated that more than one million workers in the United States potentially are exposed to hazardous materials as members of active emergency services (200 000 as paid firefighters;[1] 500 000 as volunteer firefighters; and 300 000 as law enforcement officers). Additionally, scores of hazardous materials handling and clean-up companies employ hundreds to thousands of full-time employees and numerous part-time employees. These workers must rely on respirators and other personal equipment for their protection; however, personal protective equipment itself may present a hazard to the wearer, especially the potential for thermal stress. As noted recently[2] there is a lack of knowledge and specific safety guidelines for these workers using respirators and protective clothing. For example, a heat stress standard published by the National Institute for Occupational Safety and Health (NIOSH) in 1972 states that "the provisions of this standard are applicable to all places of employment, indoors and outdoors, and to all employees except those who are required to wear impermeable protective clothing."[3] Abbreviated guidelines for heat stress exposure have been proposed, taking into consideration factors such as state of acclimatization, amount of clothing, age, obesity and sex.[4] While the intent behind making such recommendations appears justified, scientific literature supporting the use in that study of the Wet-Bulb Globe Temperature (WBGT) for individuals working in protective clothing is limited.

Several studies have examined the physiological effects and physical requirements of firefighter equipment[5-10] and chemical protective clothing.[11-20] These studies have indicated that the thermoregulatory and cardiorespiratory stresses involved in wearing such personal protective equipment may be significant, but gaps in our knowledge remain. Some studies have not examined the actual clothing ensemble commonly worn by individuals involved in hazardous materials incidents; most have evaluated only one workload condition; and some have not made comparisons with appropriate control (or reference) conditions.

The purpose of this study was to evaluate two prime factors that determine the cardiorespiratory and thermal stress of a given work condition: clothing ensemble (through the extent to which it adds weight and alters heat transfer) and work level (through metabolic heat production). The study compared worker tolerance and physiological responses to performing two levels of work while subjects wore various types of protective ensembles.

*Mention of brand names does not constitute endorsement by NIOSH, CDC, USPHS or DHHS.

TABLE I
Physical Characteristics of the Subjects
(N=9)

	Mean	Standard Deviation
Age (yr)	24.8	4.5
Height (cm)	177.0	3.8
Weight (kg)	75.3	8.3
Maximal Oxygen Consumption ($mL\ O_2/kg/min$)	44.6	4.9

Methods

The subjects in this investigation were nine male volunteers ranging in age from 21 to 34 years (mean = 24.8 years). All subjects had prior experience using respirators and protective clothing and were familiar with their use. Most were local firefighters or emergency service personnel. The physical characteristics of the subjects are shown in Table I. Subjects were compensated financially for their participation. Prior to inclusion in the study, subjects signed an informed consent statement (as approved by the Institute's Human Subject Review Board) and were screened using a medical examination (including 12-lead electrocardiogram) and an exercise tolerance test.[21] These tests were performed to ensure that the subjects were healthy and to determine their maximal aerobic capacity.

Subsequent to the maximal exercise test, each of the nine subjects completed a series of eight submaximal exercise tests in random order. Thus, a total of 72 tests was included in the experimental design. Most tests were spaced one week apart, although in all cases a minimum of 48 hr separated each test. Two workloads representing 30% and 60% of each subject's aerobic capacity were chosen for these submaximal tests. Both workloads were performed on a motor driven treadmill at an environmental temperature averaging 22.6°C dry bulb, 17°C wet bulb (73°F, 55% RH) under each of the following four clothing ensembles:

1) Light (wearing light work clothing with a low resistance mask);
2) SCBA (wearing light work clothing with a self-contained breathing apparatus);
3) Firefighter (wearing firefighter's turnout gear with a self-contained breathing apparatus); and
4) Chemical (wearing chemical protective ensemble with a self-contained breathing apparatus).

Clothing Ensemble

The light (LIGHT) clothing ensemble consisted of Chemklos II one-piece coveralls (made of a modacrylic material which was lightweight, flame resistant and had good air permeability), Servus industrial neoprene boots, and a lightweight (.08 kg) low resistance mask (Vacumed Speak-Easy II). The resistance offered by this mask-valve combination was less than 5 mm H_2O for both inspiratory and expiratory resistance at 100 L/min flow, and mask dead space was 172 mL. The total weight of this ensemble was 3.8 kg.

The SCBA ensemble consisted of the same clothing as the LIGHT ensemble, with the addition of a Mine Safety Appliances (MSA Model 401) open circuit, pressure demand self-contained breathing apparatus (SCBA). This unit was equipped with a full facepiece and a 30 min composite compressed air cylinder. The measurement of respiratory response was made possible by mechanical modification of the mask so that the resistance and protection offered by the respirator were not altered, while continuous monitoring and collection of expired air were made possible. Mask dead space was 757 mL. Total weight of the SCBA ensemble was 15.6 kg, with the SCBA component (mask, harness and air cylinder) weighing 11.8 kg.

The firefighter ensemble (FF) consisted of the Chemklos II coveralls and MSA SCBA with the addition of the following: Janesville NFPA turnout coat and pants (with a 7.5 oz quilted nomex liner and neoprene-coated poly/cotton vapor barrier), Ziamatic nomex hood, Firecraft glove, Cairns 660C metro helmet, Servus bunker boots and suspenders. Total weight of this ensemble was 23.1 kg.

The chemical protective ensemble (CHEM) consisted of the Chemklos II coveralls and MSA SCBA with the addition of a three-piece Edmont chemical protective suit made of polyurethane on nylon (Wet-Wear 900 including coveralls, jacket and hood), Edmont nitrile gloves and Servus neoprene industrial boots. The cuffs of both the pants and jacket were taped and the hood drawn tight, as is common practice in actual use. Total weight of this ensemble was 16.7 kg.

Workload

Work was performed on a Quinton motor-driven treadmill (Model Q55) at a predetermined walking speed and elevation indicative of either 30% or 60% of the maximum work capacity for each individual. Average treadmill speeds and elevations were 5.3 km/hr (3.3 mph), 0.67% grade for the low intensity (which is equivalent to 3.9 METS or 290 kcal/hr) and 5.6 km/hr (3.5 mph), 8.5% grade for the high intensity (7.7 METS or 580 kcal/hr). The low work rate was chosen to be representative of that which could be continued for an entire work shift,[22,23] whereas the high work rate was representative of that which might be performed during an escape maneuver.[7,24]

The periods of work and rest were 25 min work/5 min rest for the low intensity tests and 10 min work/5 min rest for the high intensity tests. All tests lasted 180 min or until one of the following criteria was met: 1) 90% of maximum heart rate; 2) rectal temperature of 39.0°C; 3) a crossover between rectal and skin temperature; 4) objective signs of severe discomfort or fatigue; or 5) subjective feelings of inability to proceed. The time at which any one of these criteria was met was recorded as tolerance time.

Physiologic Measurements

A Physiocontrol Life-Pak 6 was used to monitor and record heart rate and electrocardiographic signals. A Beckman Horizon Metabolic Measurement System was utilized to measure minute ventilation, tidal volume and respiratory rate.

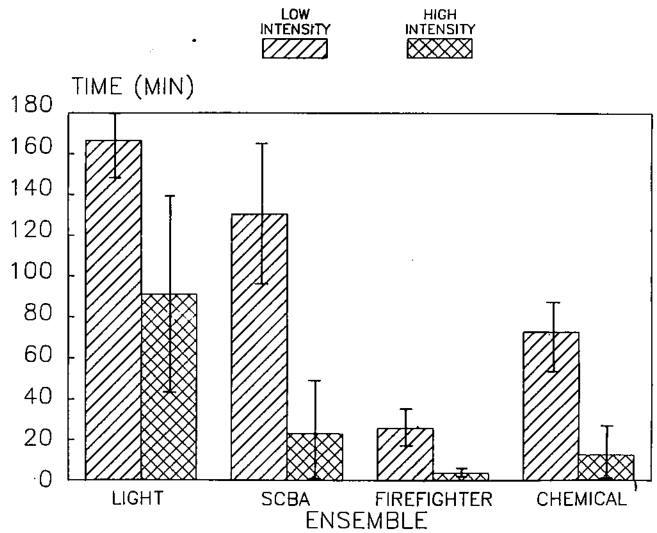

Figure 1 — Tolerance times at the low and high work intensities.

Temperature measurements were made at 2.5-min intervals with a Yellow Springs Instruments telethermometer (Model 49TA) with utilization of Series 400 thermisters. These thermisters (Type 409) were secured properly to the skin surface with Blenderm surgical tape. Core temperature was measured with a flexible vinyl-covered probe (Type 401) inserted 10 cm in the rectum. Skin temperature was calculated as the mean-weighted temperature of six body sites by the use of the following calculation: $T_{skin} = (.125\,(T_1) + .125\,(T_2) + .125\,(T_3) + .125\,(T_4) + .07\,(T_5) + .1\,(T_6))/.67$, where T_1 = lateral thigh, T_2 = medial thigh, T_3 = back, T_4 = chest, T_5 = arm, T_6 = cheek.[25]

Total sweat production was estimated as the change in nude body weight, measured before and after the experimental session and corrected for water intake. Water drinking was allowed *ad libitum* during the rest periods only. A platform scale (GSE Inc.), accurate to ±5 g, was used for precise weighing of the subjects.

Results

The mean tolerance times with low intensity exercise for the LIGHT, SCBA, FF and CHEM ensembles were 167, 130, 26 and 73 min, respectively (Figure 1). The values for the SCBA, FF and CHEM ensembles were compared to the LIGHT condition by use of an analysis of variance. The results indicated significant ($p<.01$) decreases in tolerance time of 22.2%, and 84.4% and 56.3%, respectively. The high intensity mean tolerance times were 91, 23, 4 and 13 min, respectively. Analysis of variance indicated significant ($p<.01$) decreases of 74.7%, 95.6% and 85.6% in tolerance times. Tolerance times for the low intensity-FF ensemble were similar to the high intensity-SCBA condition. Subjects were always able to work much longer at the high intensity-LIGHT ensemble than at the low intensity-FF ensemble.

Figure 2 graphically depicts the reason for test termination. At the high intensity level, all but four of the 36 tests were terminated because of attainment of the heart rate criterion (90% of maximal heart rate). These four tests continued for the entire 3 hr. The only test terminated due to attainment of temperature criteria occurred during the low intensity workload.

Heart rate data are presented in Figures 3 and 4 (note that heart rate generally drops during the rest intervals, reflecting partial recovery of the heart rate). The mean heart rates recorded at the end of the test for the LIGHT, SCBA, FF and CHEM ensembles were 119, 136, 172 and 166 beats per min (BPM), respectively, for the low intensity level and 161, 169, 169 and 169 BPM for the high intensity exercise. During the low intensity tests, heart rates for the LIGHT and SCBA ensembles rose very slowly over time. The heart rate for the SCBA ensemble (Figure 3) was significantly higher than that observed with the LIGHT ensemble and remained approximately 15 BPM higher throughout the test. Heart rate during the FF and CHEM ensembles rose at a significantly faster rate and did not approach steady-state levels. The heart rate while the CHEM ensemble was worn was slightly lower than the FF ensemble, averaging 15-45 BPM higher than the LIGHT condition. During the 5-min rest periods, heart rate in both the FF and CHEM ensembles did not recover to near resting levels and remained higher than that which occurred during work in the LIGHT ensemble. Data obtained at high intensity showed a similar trend and are illustrated in Figure 4.

Figure 5 graphically depicts the changes in both rectal and skin temperatures at the low intensity for each of the four clothing ensembles. The mean skin temperatures at the end of the test were 32.7°C, 33.1°C, 36.7°C and 36.3°C for the LIGHT, SCBA, FF and CHEM ensembles, respectively. Both the core and skin temperature responses in the LIGHT and SCBA ensembles were statistically similar and did not appear to change much over time, indicating a state of thermal equilibrium. Beginning with the first measurement during the exercise, skin temperatures for both the FF and CHEM ensembles were significantly higher than for the

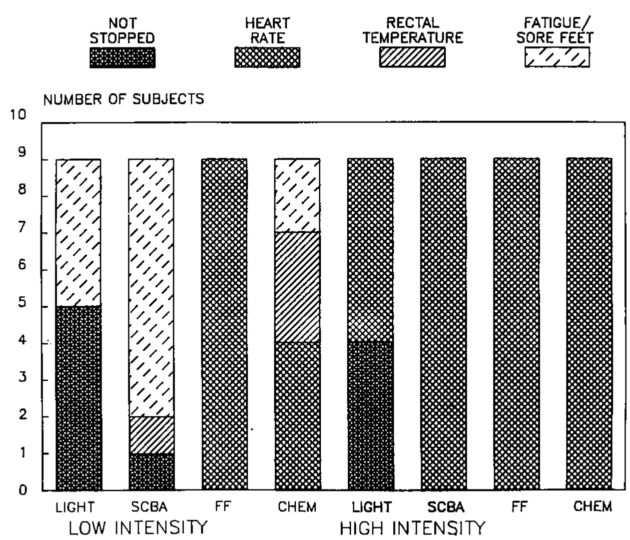

Figure 2 — Reason for test termination.

other two ensembles and increased sharply as the test progressed. Mean rectal temperatures at the end of the low intensity test were 37.6°C, 37.9°C, 37.9°C and 38.5°C for the LIGHT, SCBA, FF and CHEM ensembles, respectively. These values would represent rises per hour of .20°C, .41°C, 1.85°C, and 1.07°C for each of the four conditions. Using linear extrapolation, it would be predicted that at a low work intensity, core temperatures of 39.0°C would be reached after 62 min in the FF ensemble and after 101 min in the CHEM ensemble.

Mean weight losses for the LIGHT, SCBA, FF and CHEM ensembles were 1.173, 1.285, .658 and 1.175 kg, respectively, during the low intensity exercise. These values represent losses of 7.0, 9.9, 25.3 and 16.1 g/min, respectively.

Temperature responses for the high intensity conditions are presented in Figure 6. The short duration of the exercise sessions did not allow heat stress *per se* to become the limiting factor for the exercise. Heart rate, which responded quite rapidly, was the termination criterion in 32 of 36 tests. Mean skin temperatures at the end of the high intensity test were 33.3°C, 33.1°C, 34.2°C and 34.1°C for the LIGHT, SCBA, FF and CHEM ensembles, respectively. Comparable mean rectal temperatures at the end of the test were 37.9°C, 37.6°C, 37.2°C and 37.5°C, reflecting rates of increases of .62°C, 1.49°C, 1.50°C and 1.80°C per hr.

Ventilatory parameters measured during the last 2 min of each test are shown in Table II. At both the low and high intensities, the ranking (from lowest to highest) for minute ventilation ($\dot{V}_E$) and tidal volume was LIGHT, followed by SCBA, CHEM and FF. The mechanism by which $\dot{V}_E$ increased was primarily through an increase in tidal volume, with only a slight change in respiratory rate. In fact, with the large minute ventilations seen at the high work intensity, the increase in $\dot{V}_E$ was accounted for entirely by tidal volume changes. In this case, respiration rate actually decreased with SCBA usage.

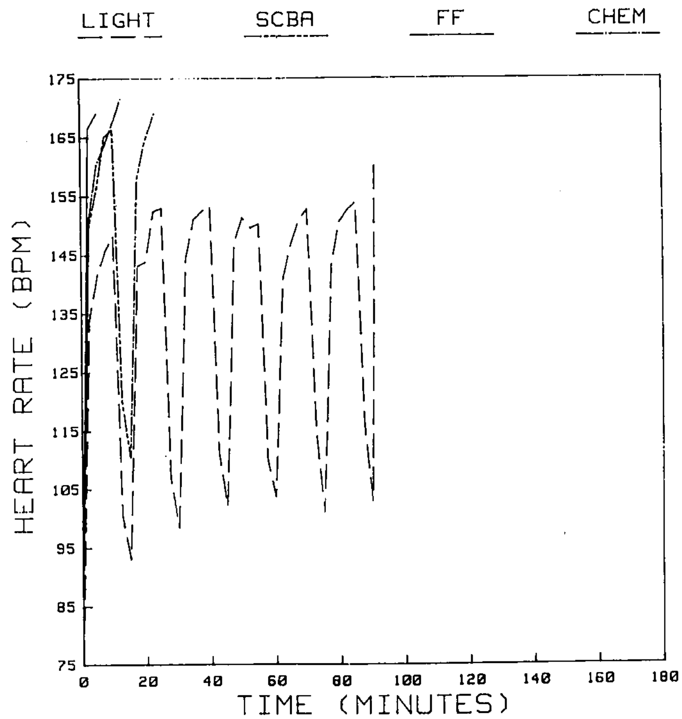

Figure 4 — Mean heart rate response during the high intensity tests.

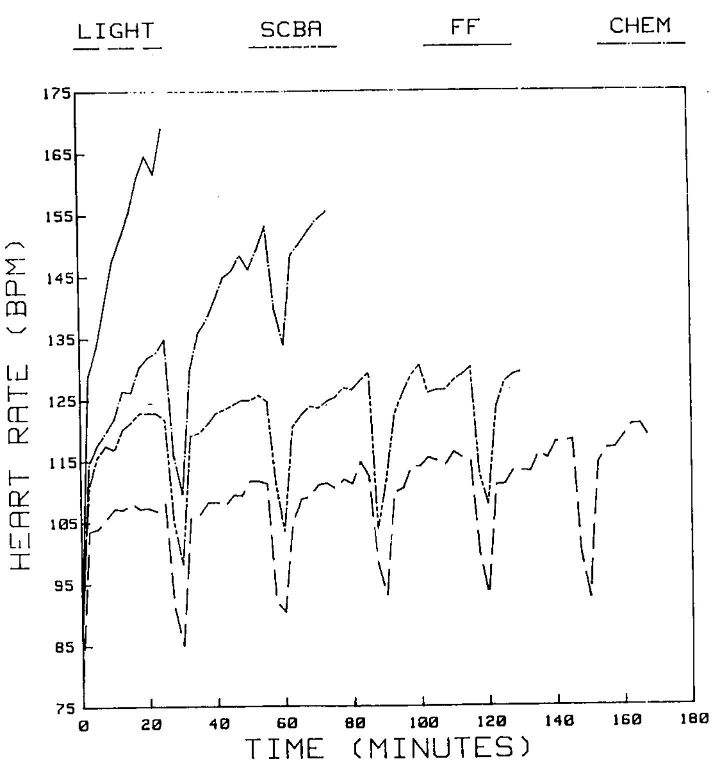

Figure 3 — Mean heart rate response during the low intensity tests.

Discussion

In this study, subjects wearing protective clothing and respirators during exercise exhibited a significant degree of cardiorespiratory and thermoregulatory stress even in a neutral environment. When compared to lightweight clothing, the use of a SCBA and impervious clothing ensembles resulted in decrements in exercise tolerance time of as much as 95.6% (Figure 1). Even at low work intensities (30% of maximum), neither heart rate, rectal temperature nor skin temperature showed signs of reaching equilibrium when subjects wore either an FF or CHEM protective clothing ensemble (Figures 3 and 5). On the other hand, subjects wearing the LIGHT and SCBA ensembles approached thermal equilibrium. Heart rate with both of these ensembles tended to rise slightly during each 25-min exercise period, probably because of exercise-related shift of plasma water out of the intravascular space[26] and perhaps fatigue.

The 15 BPM heart rate difference between the LIGHT and SCBA ensembles during low intensity exercise (Figure 3) indicates that the SCBA imposes a substantial additional stress to the wearer, although not nearly as great as that observed with the FF or CHEM ensembles. The magnitude of heart rate increase from the SCBA alone in the present study is similar to the 7-24 BPM reported by some authors,[27-29] and also compares favorably with the 20%

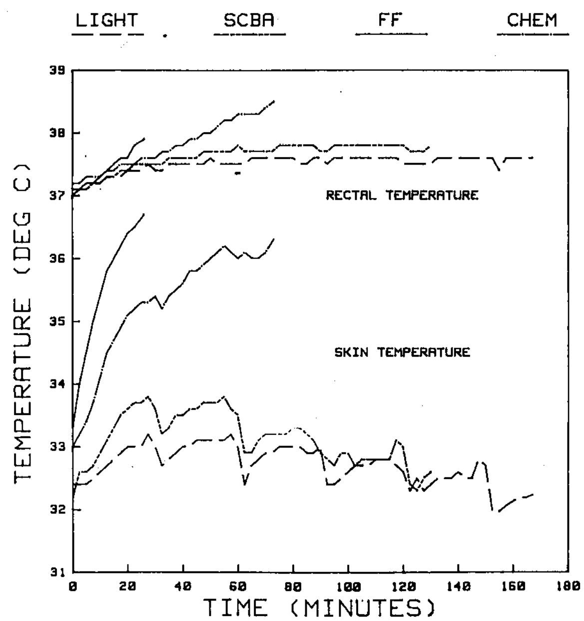

Figure 5 — Mean skin and rectal temperature response during the low intensity work conditions.

decrement in performance due to respirator usage reported by other researchers.[9,30] This heart rate response may be attributed primarily to the added weight of the SCBA, as well as its added dead space and resistance.

Additional stresses occurred when protective clothing was worn in addition to the SCBA. Previous investigators have reported a heart rate elevation of 37 BPM after 15 min of work in subjects wearing firefighter equipment.[5] The authors' data comparing LIGHT *vs.* FF heart rates at low work intensity (Figure 3) are similar, but show that the difference increases as the exercise progresses, varying between 25-50 BPM. Heart rate while wearing the CHEM ensemble followed a similar trend, increasing over the duration of the test. Although the CHEM and SCBA ensembles were similar in weight (1.1 kg difference), heart rate responses were significantly different, probably because of the thermal stress of the CHEM clothing. The CHEM ensemble reduces the capability for evaporative cooling, resulting in a redistribution of blood flow to the skin.[26] This effect would result in a decreased central blood flow and cardiac stroke volume. Heart rate then would tend to increase in an attempt to maintain adequate cardiac output.

Three of the nine tests had to be terminated because the rectal temperatures of each subject were in excess of 39.0°C when the subjects exercised at the low intensity wearing CHEM ensemble. This occurred at minutes 75, 93 and 104 for the three subjects. In contrast, all tests involving the FF ensemble (at both low and high intensities) were terminated because of attainment of the heart rate criterion. This is not to say that heat stress does not create a potential problem while an FF ensemble is worn at neutral temperatures. On the contrary, both skin (T_{sk}) and rectal (T_{re}) temperatures rose during the tests, but did not respond as quickly as heart rate. In fact, during the low intensity tests, the gradient for heat exchange ($T_{re} - T_{sk}$), suggested as a good indicator of heart strain,[31] was smallest for FF. These gradients at the end of the test for LIGHT, SCBA, FF and CHEM were 4.9°C, 4.8°C, 1.2°C and 2.2°C, respectively. This data, plus the rapid rise in T_{re} for FF (Figure 5), suggest that this ensemble presented the highest potential thermal stress.

The ventilatory data showed substantial increases in $\dot{V}_E$ and tidal volume caused by the clothing ensembles (Table II). $\dot{V}_E$ in the low intensity tests was 14 L/min higher for the SCBA compared to the LIGHT ensemble — twice the increase noted elsewhere[27] where comparable values of 38 and 45 L/min were found. Even larger increases in $\dot{V}_E$ were noted with the FF and CHEM ensembles. The increases ventilation represents an increased physiological stress and also would reduce the duration of a SCBA by one third to one half, as has been reported in field tests.[9,32]

Compared to the LIGHT ensemble, the respiratory rate at the high intensity workload decreased for the SCBA, FF and CHEM ensembles. This interesting finding has been reported previously by other investigators[33-35] with added resistance alone. Our results, however extend this finding to situations in which $\dot{V}_E$ is elevated because of the wearing of heavy respirators during high intensity exercise. The result presumably would be a more efficient, deeper breathing pattern. It is not clear whether this same effect would be observed in inexperienced or less fit respirator users.

In conclusion, these data indicate that protective clothing and respirators can be potentially dangerous to the wearer by causing significant stress to the thermoregulatory and cardiovascular systems, even at low work intensities in a neutral environment. The firefighter's ensemble (the heaviest of the four ensembles studied) produces the most physiological stress, followed by the chemical protective ensemble. The permeability characteristics of the clothing ensemble are important, as illustrated by the large differences in physiological responses between the SCBA and CHEM ensembles (differing in weight by only 1.1 kg). When CHEM and FF

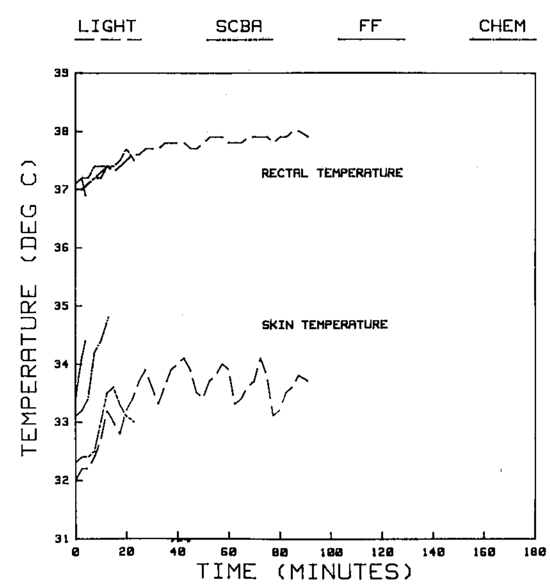

Figure 6 — Mean skin and rectal temperature response during the high intensity work conditions.

TABLE II
Ventilatory Responses

Clothing Ensemble	Minute Ventilation (L/min) Workload	
	Low Intensity	High Intensity
LIGHT	32.6(4.0)	63.5(10.3)
SCBA	46.8(9.6)	74.5(11.8)
FF	65.3(8.0)	83.8(12.9)
CHEM	53.9(6.6)	78.2(11.2)

Clothing Ensemble	Tidal Volume (L) Workload	
	Low Intensity	High Intensity
LIGHT	1.00(.14)	1.55(.20)
SCBA	1.24(.28)	2.10(.26)
FF	1.71(.32)	2.47(.26)
CHEM	1.53(.25)	2.26(.24)

Clothing Ensemble	Respiratory Rate (/min) Workload	
	Low Intensity	High Intensity
LIGHT	32.6(5.0)	41.0(8.2)
SCBA	37.7(7.4)	35.5(3.7)
FF	38.2(7.0)	33.9(4.8)
CHEM	35.2(7.0)	34.6(4.8)

Values represent mean (±SD) obtained during the last two minutes of the test.

ensembles are used, the non steady-state responses indicate that the duration of work period also is an important stress factor, even at low work intensities (30% of maximum). Finally, it should be noted that our test subjects, while of average size, were young, healthy, moderately fit, and carefully screened medically. Greater reductions in work tolerance when protective clothing and respirators are worn might well be expected for individuals not fitting these criteria.

Our data show that during high intensity exercise, protective clothing and respirators severely limit the ability of the subjects to perform work. It would appear unreasonable to expect workers wearing a protective ensemble to sustain workloads of 60% of maximum for any extended period of time, except perhaps in emergency or life threatening situations. Even with low intensity exercise, significant physiological responses occur, indicating an obvious need to adjust work/rest regimens, depending on the particular clothing ensemble to be worn. The responses observed in this study indicate that heart rate is an indicator both of work intensity and thermal stress. In the field, it may be more practical and more acceptable to use heart rate as an indicator of overall work tolerance in workers, instead of skin or rectal temperature.

Further research is indicated to assess the effect of various temperature/relative humidity combinations, as well as the effect of other types of protective equipment (*i.e.*, permeable and impermeable vapor barriers, cooling devices, design modifications, *etc.*).

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