EMPLOYEE SAFETY

Hazardous Waste Abatement Simulation in Three Controlled Environments

Heat stress is a major risk faced by waste abatement workers.

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Hazardous waste abatement workers perform physically demanding tasks, often in hot environments, while wearing completely encapsulating chemical protective clothing and full respiratory protection. Many are construction industry employees involved in cleanup of hazardous waste disposal sites under the Comprehensive Environmental Response, Compensation and Liability Act.

Three factors increase the risk of heat stress among this worker population: 1) mandatory use of vapor-barrier clothing; 2) outdoor exposure to hot environments; and 3) high level of energy expenditure (Favata, et al 79+). Presently, American Conference of Governmental Industrial Hygienists (ACGIH) threshold limit values for work in hot environments apply only to normally clothed workers.

Those working in extremely hazardous environments must protect themselves by wearing totally encapsulating protective clothing. In order to provide maximum protection against harmful liquids, gases, fumes or vapors, this protective clothing must be impermeable.

Such ensembles can cause heat-stress illnesses because they limit the body's ability to lose heat via evaporation and convection. Since metabolic heat cannot be adequately dissipated, the body's heat storage increases, which results in greater heat stress and cardiovascular strain. Significant stresses associated with wearing protective ensembles have been well-documented. (See References, pg. 36.)

Beyond adherence to safety rules that mandate heart rate monitoring, adequate fluid consumption and empirical work and rest charts, this employee population relies primarily on self-determination and the buddy system to prevent heat stress incidents (Turpin and Taft 404+). Because protective equipment often hinders interpersonnel communication in the field, specific, scientifically valid work/rest tables are needed.

This study was the first phase of a multi-year research project designed to develop such tables. The initial study's objective was to determine, in three different thermal environments and with one level of exercise intensity, not only time required to reach threshold core temperature (TCT), but also time required to return to pre-test temperature.

EXPERIMENTAL DESIGN

Subjects

The seven healthy male subjects recruited for the study 1) were between 20 and 40 years of age; 2) weighed within -5 to +15 percent of standard weight and 3) were able to work in a totally encapsulated suit with self-contained breathing apparatus (SCBA). All were West Virginia University (WVU) maintenance employees and had experience in waste abatement work. Table 1 lists various physical characteristics.

After signing an informed consent form, all subjects completed a medical history questionnaire and underwent a physical examination. Upon receiving physician's approval, a maximal graded exercise test (GXT) was conducted on a motor-driven treadmill in order to measure each subject's maximal oxygen consumption (VO_2 max). Gas analysis and minute ventilation were measured with a Beckman MMC Horizon system, which was calibrated with known gases.

Clothing and Respiratory Equipment

Subjects performed all tests while wearing a vapor-barrier Mine Safety Appliance (MSA) Bluemax™ chemical protective suit, typically used during hazardous waste operations that require the highest level of protection. They are impermeable and heavier than a Tyvek ensemble (a semi-permeable disposable coverall). An MSA Ultralite pressure-demand, 30-minute SCBA was also worn.

Due to the limited duration of personal air-supply cylinders, the SCBA regulator was connected to an air line, and breathing-quality air was supplied from a compressed-air cylinder located outside the climatic chamber. In addition, subjects wore butyl gloves, and boots were secured over the suits with duct tape to ensure total isolation.

Thermal Conditions

The climatic chamber at WVU's Institute of Occupational and Environmental Health was the test site. Evaluations were conducted in three controlled environments. Dry bulb temperatures in the chamber were maintained at 32°±0.2°C (90°±0.7°F); 26°±0.2°C (80°±0.7°F); and 21°±0.2°C (70°±0.7°F). Although wet bulb temperature and wind velocity were not controlled, conditions inside the chamber were dry (relative humidity below 35 percent), and wind velocity was minimal.

Physiological Measurements

Upon arrival at the chamber, subjects drank 16 oz. of water within 5 to 10 minutes. A heart rate transmitter was strapped around each subject's chest, and a flexible, vinyl-covered rectal thermistor was self-inserted 10 centimeters. Subjects were weighed (with all sensors attached) on a precision scale featuring an accuracy of ± 20 grams. Body weight and pre-exercise heart rate (while at ease) were recorded before protective gear was donned. Heart rate, core and skin temperatures were monitored continuously and recorded every five minutes.

Following each test, subjects exited the chamber, removed their gear and proceeded (wearing only shorts) to a 20°C (70°F) temperature-controlled room. Here, they towel dried and were weighed again. Subjects then relaxed in front of a fan. Water was freely available. Heart rate and rectal temperature were monitored until they returned to pre-test values.

Exercise Mode

Each subject's workload remained constant within each environment. Exercise intensity was set at 75 watts on a motorized treadmill. This resulted in speeds of 2.2 to 2.5 mph and grades of 1.5 or 2 percent. This intensity represents only a fraction of total energy expenditure.

For this workload, approximate total energy expenditure was calculated to be 310 kilocalories per hour (kcal/h) (Henane 909+). This figure is consistent with what Tochihara, et al found to be the energy cost of actual waste abatement work (Tochihara, et al 17+). Expenditure of 330 kcal/h is synonymous with moderate work, according to ACGIH published data. This value represents almost 34 percent of these subjects' average VO_2 max. The protective gear's weight was also factored when calculating oxygen consumption.

Test Termination Procedures

Tests were terminated when a subject either reached TCT value or 90 percent of maximum heart rate, or asked to stop. TCT was determined to be 1°C above resting core temperature, which is consistent with World Health Organization recommendations on exposure to hot environments (Technical Report Series 412). Maximum heart rate was derived from subjects' maximum GXT data. Subjects could stop tests at will.

THE RESULTS

Table 2 shows study results, focusing on times needed to reach TCT, heart rate (HR) threshold and fatigue.

Hot Environment

Five subjects reached 1°C above resting core temperature in this environment, with exercise times ranging from 37 to 57 minutes (TCT mean = 41.7 ± 10.9 minutes). Two reached HR threshold at the same time they reached TCT; two others were within four beats per minute (bpm) of HR threshold when they reached TCT. Subject 3 reached 90 percent of HR threshold in 22 minutes, while subject 6 stopped due to fatigue. Neither reached TCT.

Heart rate range at five minutes was 95 to 130 bpm, increasing to 105 to 150 bpm after 20 minutes. Time needed to return to pre-test core temperature ranged from 34 to 100 minutes (mean = 62.8±3.3 minutes). Figure 1 shows the variations in core temperature response during exercise within the hot environment before reaching TCT.

Figure 2 shows the variation in each subject's core temperature response after exercise was completed, gear was removed, and subjects were able to relax and drink water. Despite resting in a relatively cool environment, each subject's core temperature continued to rise 0.2° to 0.3°C during the first 10 minutes of rest. Average weight loss during this test was

TABLE 1
SUBJECTS' PHYSICAL CHARACTERISTICS

Subject #	Age (years)	Height (cm)	Weight (kg)	B.M.I. ($kg \cdot m^{-2}$)	VO_2 max ($ml \cdot kg^{-1} \cdot m^{-1}$)	Max HR (bpm)
1	39	177	89.2	29	36.1	189
2	35	180	100.1	31	39.7	176
3	34	167	85.0	30	30.6	169
4	32	176	82.8	26	38.4	193
5	28	177	99.2	32	39.5	203
6	37	180	71.0	22	36.2	181
7	37	167	89.4	32	33.7	179
Mean	34.6	175.9	89.3	28.8	36.3	186.3
± SD	±3.6	±5.6	±10.8	±3.7	±3.2	±11.4

TABLE 2
TOLERANCE TIMES IN MINUTES
at 75 Watts in Three Different Dry Bulb Temperatures

Subject #	90° F (32°C)		80° F (26°C)		70° F (20°C)	
1	TCT	@38	F	@65	F	@65
2	TCT	@57	F	@65	F	@65
3	HR	@22	F	@25	F	@50
4	TCT	@40	TCT	@55	F	@70
5	TCT	@50	TCT	@70	F	@50
6	F	@37	F	@25	F	@35
7	TCT	@48	F	@75	F	@65
Mean Time	41.71		54.28		57.14	
Std. Deviation	10.48		19.35		11.6	

TCT = Threshold Core Temperature; HR = 90 % Maximum Heart Rate; F = Fatigue

0.55 kilogram (kg), with the average rate being 0.74 kg per hour.

Warm Environment

On average, subjects were able to exercise 50 minutes in this setting, with actual times ranging from 25 to 70 minutes. Only subjects 4 and 5 reached TCT (in 55 and 70 minutes, respectively). All others asked to stop due to fatigue (i.e., leg fatigue or cramp, shoulder pain and dizziness). Core temperature rose between 0.3° and 0.6°C. Upon test termination, average heart rate was 40 bpm below HR threshold. Average weight loss was 0.47 kg (values ranging from 0.1 to 0.9 kg). The average rate of loss was 0.5 kg per hour.

Neutral Environment

All subjects asked to stop in an average time of 57.1±11.6 minutes, with actual values ranging from 35 to 70 minutes. Average heart rate upon test termination was 48 bpm below HR threshold. Core temperature increases ranged from 0.3° to 0.7°C. Average weight loss was 0.45 kg, at an average rate of 0.46 kg per hour.

DISCUSSION OF THE RESULTS

Study participants were waste abatement workers (mean age = 34.6±3.6) whose VO_2 max values ranged from 30.6 to 39.5 mlkg^{-1}min^{-1}. According to the Palo Alto cardiorespiratory fitness classification system, average maximal oxygen uptake for 30- to 40-year-old males is 31 to 38 mlkg^{-1}min^{-1} (Noble 248). Accordingly, most subjects were classified as "average" in fitness. In addition, five had a body mass index above 28 (indicating that they were overweight). Six subjects had a present or past history of smoking.

It is difficult to compare these data with recent similar studies; subjects in those studies had different physiological characteristics and wore lighter protective clothing. Ohnaka, et al tested young (mean age = 19.1±4.1 years), fit subjects, who wore lightweight, semi-permeable Tyvek coveralls. Bishop, et al used slightly older subjects (mean age= 24.7±4.1 years) who were more fit (mean VO_2 max= 47.6±8.1 mlkg^{-1}min^{-1}). The five subjects tested by Dessureault, et al were cyclists engaged in a strenuous physical training program. (See References, pg. 36.)

Since five subjects in this study reached HR threshold (or were within 4 bpm of it) during tests within the hot environment (32°C/90°F), this parameter should be monitored when moderate intensity exercise is performed in the heat. It becomes less critical when environmental temperature is lower. As the tests at 26°C/80°F and 21°C/70°F showed, average heart rate was well below threshold. Only five subjects reached TCT during the "hot" test. Subject 3 (who had the lowest VO_2 max) was the first subject to reach his HR threshold. Subject 6, who was slim and participated in no physical activities outside of work, asked to stop the test due to fatigue.

Interestingly, core temperature continued to rise for up to 10 minutes (after reaching TCT) while subjects rested without gear. This immediate after-test increase in core temperature ranged from 0.1° to 0.3°C, which may be partially explained by the slow response of rectal temperature to various thermal transients (Melette 734).

The difference between the highest and lowest time to reach TCT was 20 minutes; this occurred when subjects exercised within the hot environment. Variation in time needed to return to pre-test temperature was much greater—a range spanning 66 minutes. No significant relationship between weight or VO_2 max and time to reach either 90 percent of heart rate or TCT was identified in this study.

In the warm setting, two subjects reached TCT in 70 and 55 minutes, respectively. Time to return to pre-test core temperature was 50 percent greater (90 and 85 minutes, respectively). Subjects who

FIGURE 1
TIME TO REACH THRESHOLD CORE TEMPERATURE (TCT)

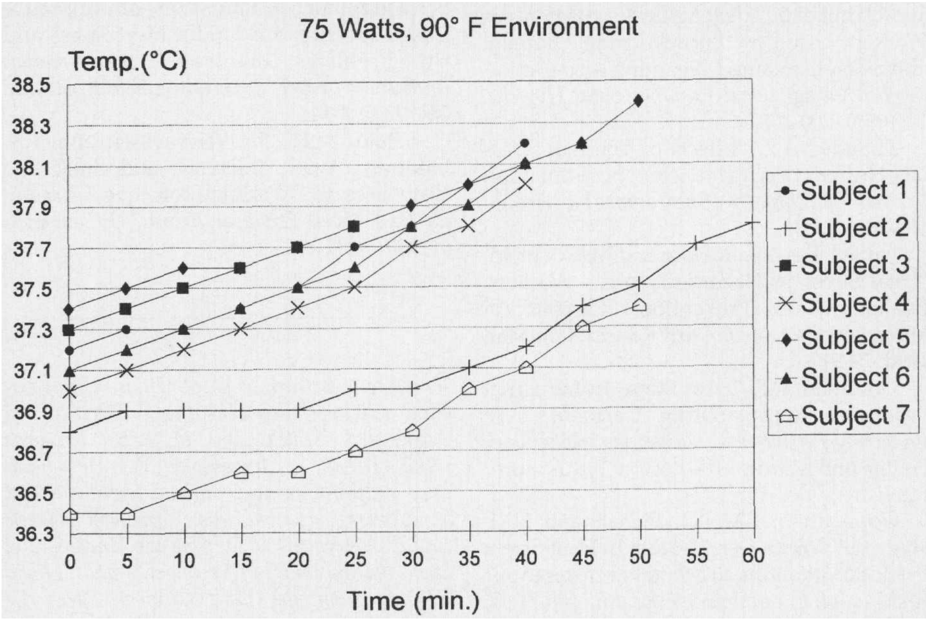
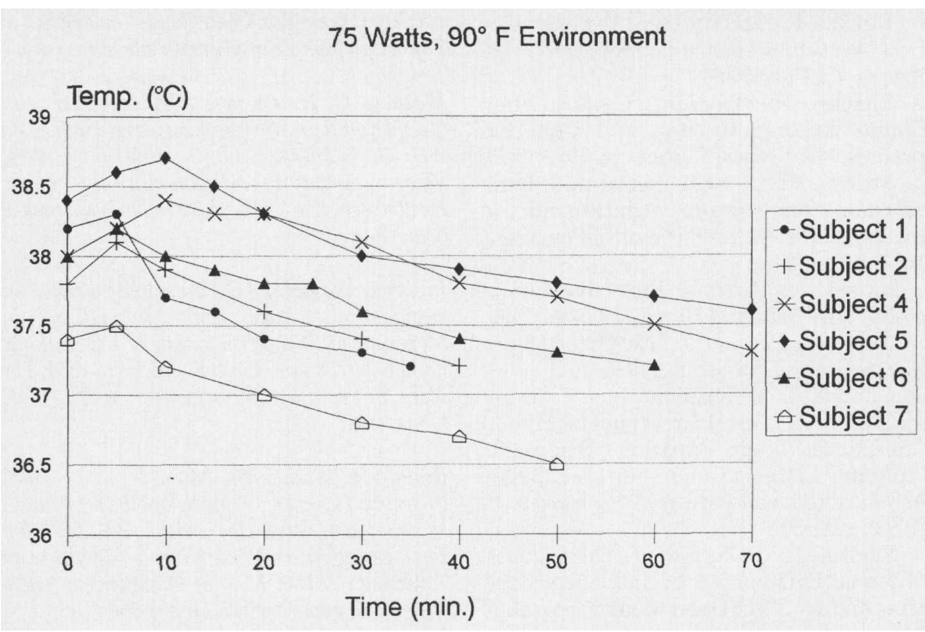


FIGURE 2
TIME TO RETURN TO PRE-TEST CORE TEMPERATURE



stopped cited SCBA weight as a primary contributor to fatigue.

In the neutral environment, all subjects stopped due to fatigue. As in the other environmental settings, exercise duration varied greatly, the longest being twice the shortest.

This study included only seven subjects and used continuous work (which may not closely simulate waste abatement work). Even with such a small group, time needed to reach TCT and return to resting values when exercising within a hot environment varied greatly.

When temperature decreased, key variations in test durations were still observed, even though (as in the case of the neutral environment) physical fatigue became the only reason to stop the test. These variations effectively prevent the creation of a work/rest table applicable to all waste abatement workers.

National Institute for Occupational Safety and Health (NIOSH) recommends frequent water consumption when working in the heat, even when the individual is not thirsty (NIOSH Publication No. 86/113). During this study, weight loss rates ranged from 0.75 kg per hour (hot environment) to 0.45 kg per hour (neutral environment). These rates suggest that water intake should be carefully monitored whenever complete chemical protective clothing is worn, regardless of environmental conditions.

CONCLUSION

Data presented here are consistent with previous findings which show that wearing a totally encapsulating suit when working in the heat is potentially dangerous due to significant thermoregulatory and cardiovascular stresses imposed on the user. Under such conditions, core temperature will likely increase 0.1° to 0.3°C, even when employees rest (without gear) in a cooler area.

Even under ideal conditions, cooling down takes a long time. This suggests that, in settings with less-than-ideal cooling conditions, heat stress is likely. In less-stressing environments (i.e., warm or neutral), physical fatigue is the critical issue, according to these findings. In addition, physiological responses to wearing prescribed protective gear while working in these three environments vary greatly. Such variabilities in key factors hinder the design of universal work/rest recommendations.

Microcooling systems are a potential solution to heat stress. However, the exact energy expenditure of typical tasks performed by waste abatement workers must first be determined because operating time and capacity of a such systems are a function of workload. This expenditure can be determined by using portable, oxygen-consumption measurement devices. Such data will be the key in evaluating specific microcooling systems for this worker population. ■

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