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Heat Strain and Heat Stress for Workers Wearing Protective Suits at a Hazardous Waste Site

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In order to evaluate the effects of heat stress when full body protective suits are worn, heart rates, oral temperatures and environmental parameters were measured for five unacclimatized male workers (25-33 years of age) who performed sampling activities during hazardous waste clean-up operations. The protective ensembles included laminated PVC-Tyvec chemical resistant hood suits with rubber boots, gloves, full facepiece dual cartridge respirators and hard hats. For comparison, measurements also were performed when the men worked at a similar level of activity while they wore ordinary work clothes. A comparison of the heart rates for the men working with and without suits indicated that wearing the suits imposed a heat stress equivalent to adding 6° to 11° C (11° to 20° F) to the ambient WBGT index. A similar result was obtained by calculating the WBGT in the microclimate inside the suits and comparing it to the ambient WBGT. These results indicate the following: 1) there exists a significant risk of heat injury during hazardous waste work when full body protective clothing is worn, and 2) threshold limit values for heat stress established by the ACGIH must be lowered substantially before extending them to cover workers under these conditions.

Introduction

In the face of the uncertainty of chemical exposures at hazardous waste sites, conventional protective equipment decision logic suggests selection of high levels of protection such as self-contained breathing apparatus and vapor barrier whole body suits. The use of such equipment, however, significantly increases the risk of heat illness.

As early as 1938 it was reported that a worker wearing impermeable clothing experienced severe fatigue after 15 min of working in hot conditions.[1] The risk of heat illness is especially high for those personnel who are not accustomed to working at the high level of metabolic energy expenditure, often required in hazardous waste operations. Because of its effects on the central nervous system, excessive heat strain introduces a potential safety hazard both to the individual and to other members of a work crew — particularly where machinery and heavy equipment are being used.

As noted by several authors[2,3,4] as well as the American Conference of Governmental Industrial Hygienists,[5] standard heat stress indices such as the Heat Stress Index (HSI) and Wet Bulb Globe Temperature (WBGT) do not apply when heavy or impermeable protective clothing is worn by workers. To evaluate heat stress and heat strain under these conditions, a study was conducted on a group of workers wearing protective suits in hot weather at a hazardous waste site. The authors' aims were as follows: 1) to investigate the effect of wearing full-body protective clothing in a hot environment on physiological responses (heart rates, oral temperatures) and self-reported symptoms; and 2) to explore methods of relating the degree of heat strain for workers wearing full-body protective suits to environmental factors.

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Methods

This study was conducted at an EPA Superfund hazardous waste site in Epping, N.H. between 18-21 July 1983. The site was undergoing active clean-up and removal at the time of the study. The subjects were five young healthy males, who were members of a survey team that sampled and characterized a large wastewater lagoon prior to its decontamination and removal. The average age of the subjects was 31 (range: 25-33); their average body weight was 79 kg (range 68-92); and their average height was 178 cm (range: 170-188).

On the first day on-site subjects were dressed in light summer clothing (cotton trousers and short-sleeved shirts); the subjects performed pre-survey activities such as equipment unloading and set-up. On subsequent days, the work regimen consisted of the following survey activities: walking approximately 300 yards through the contaminated zone to the perimeter of the waste lagoon, lowering a boat into the lagoon; collecting samples from the lagoon, retrieving the boat, and walking back to the decontamination unit. Survey activities were conducted for 30 to 45-min periods with rest breaks in between corresponding to an approximate 75% to 25% work-rest regimen. Once in the rest area, the respirators were removed, the upper half of the protective suits were opened and drinking water was obtained. The protective ensemble used included a laminated PVC-Tyvec chemical resistant hooded suit with rubber boots, elbow length gloves, full facepiece dual cartridge respirator and hard hat. In addition, full-length cotton underwear was worn beneath the suit.

Dry-bulb temperature, WBGT, natural wet-bulb temperature, globe temperature and air velocity were measured with a Reuter-Stokes RSS-212 Portable Heat Stress Monitor. A Bendix Model 566 motor-driven ventilated psychrometer was used to derive relative humidities from dry-bulb and psychometric wet-bulb measurements. On the fourth day,

TABLE I
Environmental Measurements
(all temperatures are °C)

Time	Activity	Dry Bulb Temperature	Globe Temperature	Relative Humidity	Air Vel. (m/sec)	WBGT
6/18/83						
2:20 p.m.	Pre-survey tasks	33.5		46%		30.7
6/19/83						
5:30 a.m.	Arrive work				0.3-1.2	16.9
5:45 a.m.	Prepare equipment (unsuited)					
8:55 a.m.	Begin 1st work period					
9:25 a.m.	End 1st work period	27.2	37.9	45%	0.3-1.0	23.9
9:50 a.m.	Begin 2nd work period					
10:35 a.m.	End 2nd work period				0.4-1.4	25.0
10:50 a.m.	Begin 3rd work period					
11:30 a.m.	End 3rd work period	32.9	43.2	36%	0.4-1.6	27.1

dry and psychometric wetbulb temperatures from inside of two protective suits were measured by placing the psychrometer inside the workers' suits near the chest and allowing time for equilibration. Heart rates were measured using Respironics Exersentry III Digital Monitors that subjects wore throughout the day. For each subject, heart rate was recorded in the standing position within 1 min of their arrival at the rest area. Subjects arrived at the rest area after a 3-min walk from the work zone while they were fully suited and carrying equipment. Oral temperatures were measured using an Omron Model MC-20R digital thermometer.

Workload was assessed using tables given by the ACGIH.[5] The average metabolic rate was estimated at 300 kcal/hr during equipment unloading and set-up, 240 kcal/hr during survey activities and 100 kcal/hr during rest breaks.

Results

Table I shows environmental measurements taken during the middle of the first day (18 July 1983) when pre-survey activities were performed (without protective suits) and at four time points during the second day (when protective suits were worn). Table II shows physiological measurements as well as self-reported symptoms at the same time points.

The plot of heart rate *vs.* WBGT index for the five workers wearing full protective ensembles is presented in Figure 1. It is apparent from this figure that heart rates increased rapidly as WBGT increased for all subjects. A progression of complaints from discomfort to weakness and fatigue were noted for increasing WBGT. At the highest WBGT of 27.1°C (80.8°F) three of the five individuals reported extreme fatigue and one felt that he could not continue to work (Table II).

Dry and psychometric wet-bulb temperatures were measured inside the suits of two subjects on the fourth day of site activities. Both temperatures were 36.5°C (97.7°F) and were identical in both subjects. On this day the ambient dry bulb temperature was 34.3°C (93.7°F) and the ambient WBGT was 28.3°C (83°F).

Discussion

Assessment of Heat Strain From Heart Rates

The heart rate increases observed in the subjects may be compared to criteria established by Goldman.[6] Each subject's Heart Rate Increase Capacity (HRIC) is defined as the difference between the subject's maximum heart rate (as estimated from HRmax = 220 bpm-age) and his measured resting heart rate. Categories of physiological stress are associated with heart rate increases expressed as varying percentages of HRIC. Heart rate increases less than 20% of HRIC are considered to be in the comfortable range; increases of 20% to 40% are in the uncomfortable range; increases of 40% to 60% are in the performance decrement range; and increases of 60% to 80% are in the tolerance time limited range. Heat illness may result at increases greater than 80% of HRIC.[6]

Figure 2 compares the heart rates measured for each of these subjects with these strain categories. At a WBGT of 23.9°C (75°F), four of the five individuals were functioning in the uncomfortable zone; however, at a WBGT of 27.1°C (80.8°F), four of them were functioning in the performance decrement zone and one (Subject #4) was in the tolerance time limited zone. This latter subject reported an inability to continue work during the final sampling period of the day, whereupon he was removed to the rest area.

Assessment of Heat Strain from Oral Temperature

Despite high ambient temperature and the wearing of protective suits, there was no significant difference ($p>0.05$) in mean oral temperature measured before work activities and after the final work period (Table II). It is difficult to compare the measured oral temperatures to criteria for heat exposure since these criteria were developed for core tem-

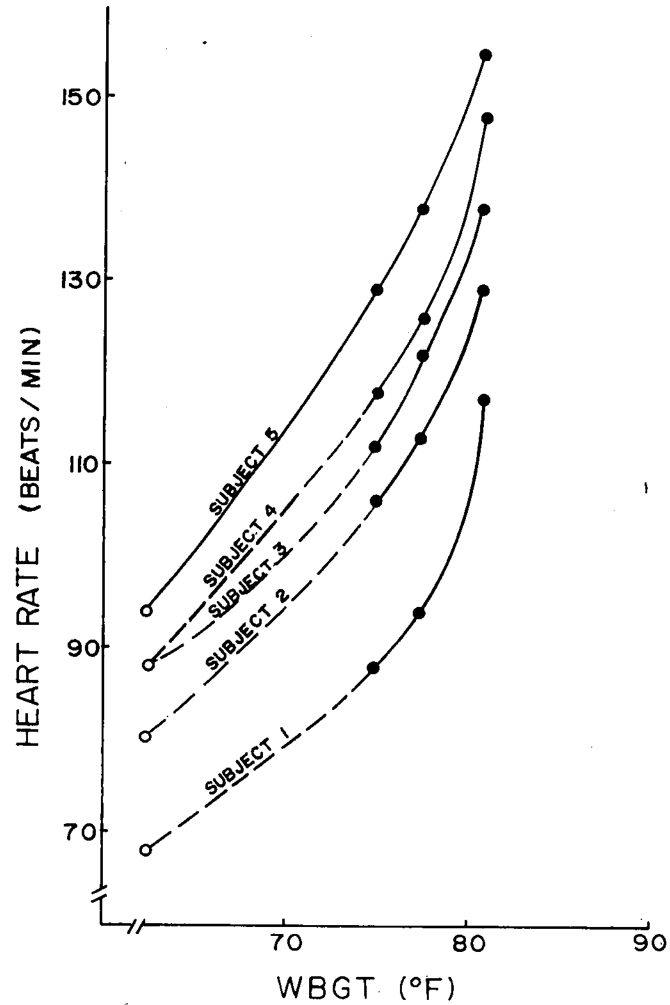

Figure 1 — Heart rates *vs.* WBGT for five subjects on 19 July 1983; open circles indicate resting heart rates.

perature, as measured rectally. Oral temperature may differ substantially from rectal temperature and may be influenced by such extraneous factors as the extent of mouth breathing prior to measurement. Nevertheless, some investigators have assumed that core temperature is approximately 1°F higher than oral temperature.[7,8] With this assumption, none of the subjects exceeded the maximum permissible core temperature of 38°C (100.4°F) specified by the ACGIH.[5]

Core to Skin Temperature Convergence

As noted by Goldman,[6] any tolerance limit established simply on deep-body temperature or heart rate does not address the critical problem of convergence between core and skin temperatures. Protective clothing interferes with heat loss from the skin — primarily by limiting sweat evaporation — and causes skin temperature to rise. As skin temperature converges toward deep-body temperature, each liter of blood has a reduced capacity for moving heat from the deep-body centers to the skin. Under these conditions, Goldman has reported heat exhaustion collapse occurring in individuals with deep-body temperatures less than 100.6°F and with heart rates on the order of 120-130 beats/minute, after these individuals worked 30 min in the heat while they wore impermeable protective garments.[6]

It is possible that the relatively severe symptoms observed in the subjects in this study, who experienced only modest heart rate increases may have been due to skin to core temperature convergence. This possibility should be tested in future studies by monitoring both core temperature and skin temperature simultaneously.

Heat Exchange Between the Body and the Environment

To evaluate heat exchange with the environment in the subjects, the heat balance equation originally developed by Belding[9] and Hatch was applied:

$$M \pm R \pm C - E = S \quad (1)$$

where: M = rate of metabolic heat production;
R = rate of radiative heat gain or loss;
C = rate of convective heat gain or loss;
E = rate of evaporative heat loss; and
S = rate of heat storage.

From this equation E_{req}, the evaporative rate of heat loss required to maintain thermal equilibrium is $M \pm R \pm C$. The ratio of E_{req} to E_{max}, the maximum rate of evaporative heat loss, has been defined as the heat stress index, HSI.

Values of E_{req}, E_{max}, HSI and S were calculated for the subjects in this study using expressions developed by Givoni

TABLE II
Heart Rates, Oral Temperatures and Self-Reported Symptoms
(heart rate/oral temp./symptoms[A])

	6/18/83[B]	6/19/83			
Subject	2:20 p.m.	Arrive work	9:25 a.m.	10:35 a.m.	11:30 a.m.
1	76/ 36.6/ 0	68/ 36.3/ 0	88/ - / 0	94/ - / 1	117/ 36.3/ 2
2	110/ 36.2/ 0	80/ 36.4/ 0	106/ - / 0	113/ - / 1	129/ 36.4/ 2
3	112/ 36.5/ 0	88/ 35.8/ 0	112/ - / 0	122/ - / 2	138/ 36.9/ 3
4	100/ 36.8/ 0	88/ 36.2/ 0	118/ - / 0	126/ - / 2	148/ 36.7/ 4
5	112/ 37.3/ 0	96/ 35.6/ 0	129/ - / 0	138/ - / 3	155/ 36.1/ 3
Mean	102/ 36.7/ 0	84/ 36.1/ 0	111/ - / 0	119/ - / 1.8	137/ 36.4/ 2.8
SD	15/ 0.4/ 0	11/ 0.4/ 0	15/ - / 0	16/ - / 0.8	15/ 0.3/ 0.8

[A]Symptoms Code: 1 = Feeling "overheated"; 2 = Fatigue: 3 = Extreme fatigue; 4 = Inability to Continue.
[B]Working without protective suits.

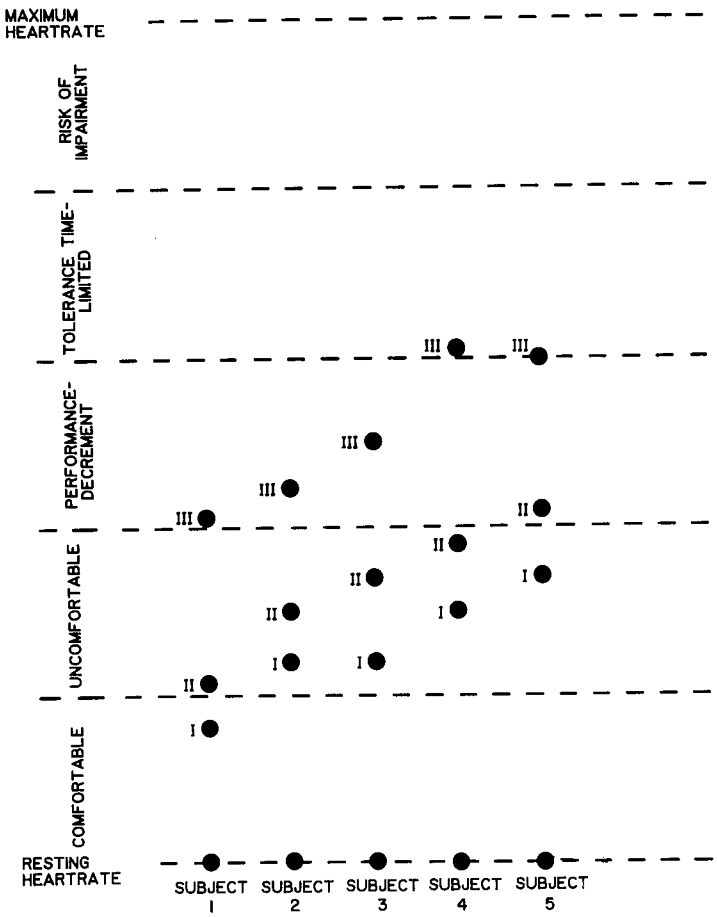

Figure 2 — Degree of physiological strain experienced by five subjects on 19 July 1983. Criteria are taken from Goldman.[6] I = end of first work period; II = end of second work period; III = end of third work period.

and Goldman.[10] For an average man having 1.8 m^2 of surface area, these authors estimate (R) + (C) as follows:

$$R + C = (10/\text{ins})(TA - TS)\ (\text{kcal/hr}) \quad (2)$$

where: TA = average of mean radiant temperature (MRT) and dry bulb temperature (°C);
TS = temperature of the skin; and
ins = insulative capacity of the clothing in "clo" units.

$$(1\text{clo} = 0.18\ \text{kcal/hr-m}^2\text{-°C})$$

and E_{max} as:

$$E_{max} = 22 \times (\text{im/clo}) \times (PS - PA)\ (\text{kcal/hr}) \quad (3)$$

where: im = dimensionless index of relative vapor permeability;
PS = vapor pressure of water at the skin temperature (mm Hg);
PA = vapor pressure of water in air (mm Hg).

For the workers of this study, the average rate of metabolic heat production — based on a 75%-25% work-rest schedule and the use of metabolic rate tables in the ACGIH guidelines[5] — was 205 kcal/hr (240 × 0.75 + 100 × 0.25). The insulative value of the protective clothing ensemble worn by the subjects during sampling activities was estimated at 2.0, and the value of im was estimated at 0.2.[6] During the third and final sampling period of the second day of the survey the mean radiant temperature, calculated by using Reference 6, was 65.9°C (150.6°F). Skin temperature was estimated at 38.4°C (101.1°F) based on the data of Tanaka *et al.*[11] for 10 subjects similarly suited, performing similar tasks at the same ambient temperature. At the estimated skin temperature, PS equals 51 mm Hg. At ambient temperature and 36% relative humidity, PA equals 13 mm Hg. With the use of these values in Equations 2 and 3, R + C = 55 kcal/hr, E_{req} equals 260 kcal/hr and E_{max} equals 83 kcal/hr.

The Heat Stress Index (E_{req}/E_{max}) × 100 is equal to 313%. According to the criteria of Belding and Hatch[9] this value represents a level of heat stress that is in excess of three times the maximum stress tolerated daily by fit, acclimated young men.

Heat storage in these subjects as a function of time may be computed from the rate of heat storage:

$$S = M + R + C - E_{max} = 260 - 83 = 178\ \text{kcal/hr}.$$

Goldman[12] has presented the following criteria for heat storage; 1) heat storage of 0.25 kcal may not be sensed if incurred at a slow rate; 2) storage of 80 kcal is the usual voluntary tolerance limit for continued exposure; 3) storage of 160 kcal represents a 50% risk of heat exhaustion collapse; and 4) storage of greater than 240 kcal cannot be tolerated by fit young men.

According to these criteria and assuming no storage of heat as workers began the final work period, the subjects would have a 50% risk of heat exhaustion collapse after they worked approximately 54 min. (If the subjects did have heat storage as they began the final work period, the time period would be shorter.) This prediction is consistent with the self-reported symptoms: after 40 min of activity, two survey team members experienced extreme fatigue, a third was unable to continue work, and all complained of feeling extremely overheated.

The rate of heat storage can be used to predict the Allowable Exposure Time (AET), which is defined as the time for core temperature to rise by 1°C.[13] With the assumption of a 79 kg man (the mean weight of our subjects) and a specific heat of 0.83 cal/g/°C,[14] this time is equal to 66 kcal/(E_{req} - E_{max}). For the conditions during the final sampling period of the day:

$$AET = 66\ \text{kcal}/(178)\ \text{kcal/hr} = 0.37\ \text{hr or 22 min.}$$

Corrections to the WBGT Index When Protective Suits are Worn

In order to investigate an appropriate adjustment to the WBGT index from the authors' data, physiological strain (indicated by heart rate) was compared for work both with and without the protective suits. The data from the first survey day provided the heartrate of each subject working in light summer clothing at an ambient WBGT of 30.7°C (87.3°F) (Table I). From the plot of heart rate *vs.* WBGT for the second survey day (Figure 1), the WBGT value that was associated with a matching heart rate when the subject wore a protective suit was estimated.

As an example, Subject 1 who did not wear a protective suit had a heart rate of 76 bpm at a WBGT of 30.7°C (87.3°F) (Table II). From Figure 1, it is estimated that if this individual had worn a protective suit, he would have had a heart rate of 76 bpm at a WBGT value of 20.0°C (68.0°F) — a 10.7°C (19.3°F) difference.

Table III presents the WBGT adjustments calculated in this manner for the five subjects. The mean difference in WBGT values determined by this method is 8.9 ± 2.1°C (16.0 ± 3.7°F). [This differential represents a minimum value, since the metabolic heat for work done by subjects without protective suits was estimated to be somewhat higher than that for work done by subjects when protective suits were worn (300 kcal/hr *vs.* 240 kcal/hr).]

By using an alternate approach, a WBGT value was calculated for the microclimate of the protective suit on the basis of measuring temperatures inside the suit. This WBGT value then was compared to the ambient WBGT level. For Subjects 1 and 2, on the fourth day of site activities, dry-bulb and psychometric wet-bulb temperatures were the same at 36.5°C (97.7°F), indicating 100% saturation of the air. If it can be assumed that the protective suits do not alter radiative heat exchange significantly, then the ambient globe temperature can be used to represent the of the suit microclimate. The WBGT value for the inside-suit microclimate then can be calculated as follows:

$$\text{WBGT suit} = 0.7(36.5°\text{C}) + 0.2(43.2°\text{C}) + 0.1(36.5°\text{C}) = 37.8°\text{C}(100.1°\text{F}).$$

The difference between the calculated inside-suit WBGT of 37.8°C (100.1°F) and the measured ambient WBGT of 28.3°C (83.0°F) is 9.5°C (17.1°F), which is close to the mean WGBT differential of 8.9±2.1°C (16.0±3.7°F) that was calculated on the basis of the heart rate data.

These WBGT differentials suggest that the wearing of the protective clothing ensembles by the members of the survey team produced an increased level of environmental heat stress, causing a physiological heat strain comparable to adding approximately 6° to 11°C (11° to 20°F) to the WBGT index. This modification to the WBGT Index is comparable to the findings of Toner *et al.*[15] They compared the data of Goldman *et al.*[16] on resting unclothed individuals exposed to hot-wet environments to the environment experienced by thoroughly heat-acclimated fit Marine tank crewman wearing fully-enclosed protective suits. Based on sweat production rates, the chemical protective clothing (in addition to the light workloads) produced an effect comparable to adding approximately 6° to 10°C (10° to 18°F) to the WBGT index.

Other investigators have proposed somewhat smaller adjustments to the WBGT index. Goldman[3] suggested a lowering of WBGT threshold criteria by 3° to 5°C or more for men wearing impermeable suits, and Ramsey[4] suggested an adjustment of 9°F to the WBGT threshold limits for the wearing of impervious, completely enclosed suits.

The WBGT differentials found in this study apply only to one workrate, one type of protective suit and one set of environmental conditions. For these reasons and because of the small sample size, it is recommended that further comparisons of heat strain with and without protective suits be performed under laboratory and field conditions.

TABLE III
Comparison of WBGT With and Without Protective Suits for for the Same Heart Rate

Subject	Heart Rate	WBGT (°C) Light Summer Clothing[A]	WBGT (°C) Protective Suit[B]	Difference
1	76	30.7	20.0	10.7
2	110	30.7	24.7	6.0
3	112	30.7	23.9	6.8
4	100	30.7	19.8	10.9
5	112	30.7	20.8	9.9
			Mean	8.9
			SD	2.1

[A]Estimated work rate = 300 kcal/hr (6/18/83).
[B]Estimated work rate = 240 kcal/hr (6/19/83).

Conclusions

The wearing of vapor barrier clothing, such as that typically worn on hazardous waste sites, may greatly increase heat stress and the risk of incurring heat-induced illness. As a result, it is necessary to monitor workers at frequent intervals in order to ensure that heat illness does not occur.

Adjustments to the WBGT index for evaluating heat stress exposures when workers wear protective clothing were calculated as follows: 1) by matching heart rates for work performed with and without protective suits; and 2) by comparing inside- and outside-suit WBGT values. The WBGT differentials calculated by each of these methods were found to be comparable (8.9±2.1°C *vs.* 9.5°C). It was concluded that the wearing of the protective clothing ensembles by the subjects produced an increased level of environmental heat stress comparable to adding approximately 6° to 11°C (11° to 20°F) to the WBGT index.

Since heat exhaustion collapse can occur at deep-body temperatures as low as 38°C (100.4°F) under conditions of convergence of skin and core temperatures, it may be useful to monitor skin temperature in addition to heart rate and core temperature to provide an additional criterion for cessation of work in the heat.

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