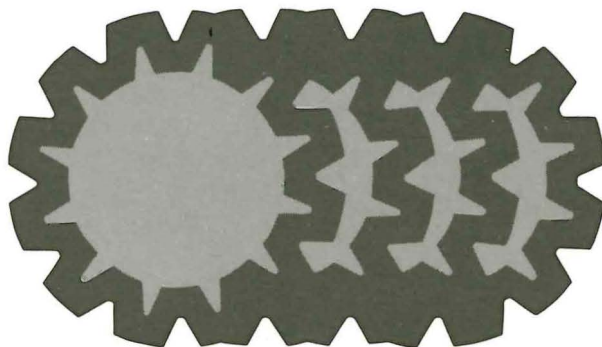


# **NIOSH**

**TECHNICAL INFORMATION**

## **MEASUREMENT OF WORK METABOLISM**



**U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE / Public Health Service  
Center For Disease Control / National Institute For Occupational Safety And Health**



MEASUREMENT OF  
WORK METABOLISM

Use of Cardiorespiratory Parameters for Estimating  
Metabolic Heat Production in Hot Environments

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## ABSTRACT

Measurement of metabolism for a variety of arm and leg work tasks is described. The tasks were performed in the laboratory in warm air temperatures and at work rates which may be encountered in industrial conditions. Equations are presented which allow prediction of metabolism from simple measurable variables including: body weight, heart rate and pulmonary ventilation.



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## Introduction

In many industrial occupations, physical work is often performed in hot environments. The contribution of metabolically produced heat to overall cardiovascular strain varies according to (1) the type, intensity, and duration of work performed, (2) the heat transfer capacity of the environment, (3) body temperatures, and (4) distribution of heat within the body. Work stress and heat stress produce different requirements for blood flow. In hot conditions, the circulatory system may not meet both demands adequately and temperature regulation may suffer. The concept that central body temperature is dependent on metabolic rate (possibly relative metabolic rate, i.e., relative to the maximum achievable aerobic metabolic rate) and independent of ambient temperature conditions up to certain limits, has substantial support (1, 2, 3). The definition of the upper limits of the ambient conditions requires additional investigation. However, metabolic rate (or metabolic rate relative to maximum) is basic to assessment of heat load on workers in hot environments. This study deals with the problem of assessing metabolic rate at work from simple measurable physiological variables. Equations are presented which were developed from data obtained with young and older men in hot environments while working at various tasks.

## Procedures (Phase I)

Selection and Screening of Subjects (Phase I): Table 1 summarizes the physical characteristics of the men who participated in the initial phase of the study. The subjects were volunteers from a group of men selected from the Rockview State Correctional Institution. A total of 15 men started the study. Seven of the men completed the experimental work while two men completed 50 percent of the experimental work. From Table 1, the final breakdown of subjects according to age was as follows:

<u>Age</u>	<u>n</u>
20 to 30	4
30 to 40	3
45 to 60	2

Because of the limited population in the ages of 40 to 65 (n=73) and because of the number of medical exclusions in this age group, the procedure of subject recruitment is outlined in Table 2. It should be noted that men from local industry or the University could not secure the necessary free time and release from their job commitments required by the experimental protocol.

The problems encountered in recruiting older men for the study who were "healthy" and had normal physiological responses to physical work on the treadmill are important. Although all of the men recruited had some job in the Institution, the fitness of most of them for work in the heat was tenuous. There is also the question as to whether the population of older men sampled in the prison represents the population of older men in industry. It would appear that

Table 1  
Physical Characteristics of Men Included in the Study (n = 9)

Subject I.D.	Age (yrs)	Height (cm)	Weight (kg)	1 Met* (kcal/min)	H.R. max (b/min)	$\dot{V}O_2$ max (cc/kg·min)	% Fat †
01	56	174.0	66.8	1.14	176	33.6	19.5
02	39	170.2	64.6	1.18	192	36.0	12.9
06	26	175.3	65.9	1.27	188	43.6	6.5
07	24	179.1	63.6	1.28	198	44.4	10.0
10	25	180.3	77.1	1.46	174	41.6	15.8
11	21	177.8	79.0	1.50	190	47.9	-----
13	47	170.2	86.4	1.37	178	37.9	-----
14	31	175.3	71.7	1.36	193	40.7	-----
15	34	170.2	68.7	1.25	188	51.8	-----

Subjects 02 and 06 completed approximately 50% of the total number of planned experimental sessions.

\* 1 Met = BMR\*\*kcal/min x 1.1.

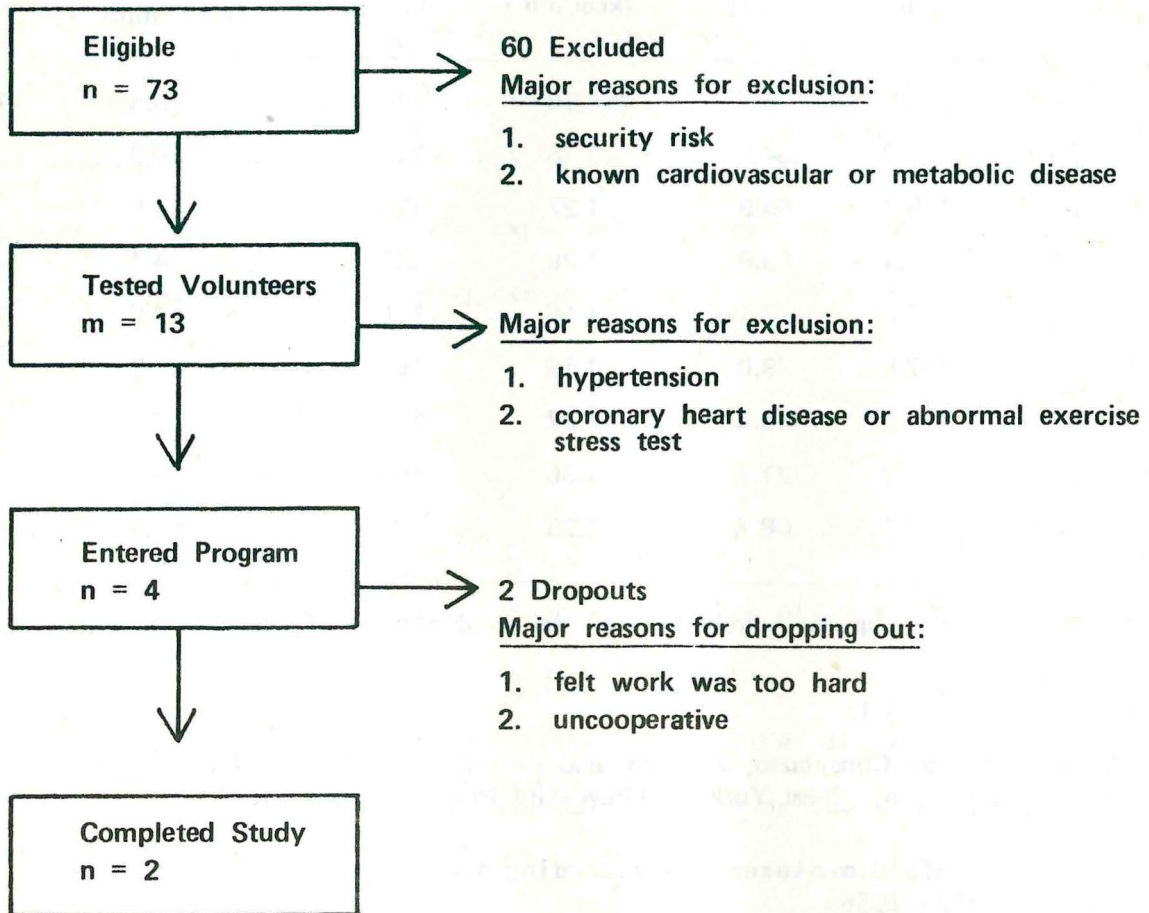
\*\*Carpenter, 1939. Cited by Consolazio, Johnson, and Pecora. Physiological Measurements of Metabolic Functions in Man. New York, McGraw-Hill Book Co., Inc. 1963.

† Obtained from 10 skinfold measurements according to procedure of Allen et al. *Metabolism*, 5:346-362, 1956.

Table 2  
Subject Recruitment  
Age 40 to 65

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Source of Subjects:  
State Correctional Institution at Rockview, Pennsylvania

since only 4 out of 13 older men were eligible to participate in this study, we may have introduced excessive bias, which minimized possible age-induced differences, by selecting for study those with essentially normal physiology from the prison population. In industry, the exclusion rate could well be lower (self-selection by jobs certainly occurs), but it is implied that the industrial population might not be able to tolerate work in the heat as well as reported in this study and that the physiological strain would be different.

Experimental Procedures (Phase I). After a subject was screened using information from his institutional records and a physical examination, the objectives and procedures of the study were outlined, and questions were answered regarding informed consent. With acceptance into the study, a treadmill exercise stress test was performed. If the exercise stress test was within normal limits, heat acclimation sessions were initiated.

At least seven acclimation sessions per subject were conducted with the environmental conditions maintained at approximately 29.4 C (85 F) WBGT. During the acclimation sessions, which were about 60 minutes in duration, the subjects worked either on a treadmill<sup>1</sup> (walking at 3.0 mph and 5% grade) or on a bicycle<sup>2</sup> (70 watts at 50 rpm). These sessions were conducted on alternate days during the month of April, 1973, and demonstrated acclimation. The experimental work tasks were performed in each of three environmental conditions during the months of

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<sup>1</sup>Quinton Model 18-69, Quinton Instruments, 3051 44th Ave., West, Seattle, Washington

<sup>2</sup>Fleisch-Jacquet, Instrumentation Associates, Inc., 17 West 60th St., New York, New York

May, June, and July: 26.7 C (80 F), 29.4 C (85 F), 32.2 C (90 F) WBGT.

Table 3 shows the average chamber conditions (mean and standard deviation) during the last 30 minutes of each session.

The subjects engaged in only one work task per day and work sessions were conducted every day or every other day except for weekends. Tests were conducted between 8 a.m. and 4 p.m. each day. Work in the heat chamber was started at least 90 minutes after meals. Because of the rigid institutional routine, each subject was tested at about the same time each day.

The work tasks and the work loads imposed are summarized in Table 4. Each work task was performed at two different intensities (on separate days). No work load exceeded the upper limit of moderate work for industrial tasks defined as 5.0 to 7.5 Mets. The tasks requiring the greatest energy expenditure involved stepping and treadmill walking. The tasks which required the greatest energy expenditure involved stepping and treadmill walking. The tasks which required the least energy expenditure were weight lifting (5.25 kg) and isometric work with the hand dynamometer. In all the tasks except treadmill walking and stepping, the work rate was the same for each subject in an age group. In walking and stepping, work rate depends on body weight and was different for each individual. Stepping consisted of moving the body up and down a single step with both feet touching at the top of the bench and again at the floor. Both the rate and the height of the step were varied to achieve appropriate changes in work intensity. Arm cranking was conducted on the Fleisch-Jacquet ergometer at a rate of 30 rpm. Work intensity was adjusted by a change in the weight that provided resistance for the flywheel.

Lifting was restricted to arm lifting. A bench with an adjustable height was placed in front of the subject at the level of

Table 3

## Chamber Conditions During the Last 30 Minutes of Each Work Session

Desired WBGT	Actual WBGT	$T_a$	$T_{wb}$	$P_w$ , mmHg	RH%
26.7 C (80F)	Mean 26.9 C (80.4 F) S.D. 0.8	35.1 C (95.2 F) 2.0	23.4 C (74.1 F) 1.0	15.5 2.5	36.3 8.7
29.4 C (85 F)	Mean 29.4 C (85.5 F) S.D. 1.0	40.1 C (104.2 F) 2.2	24.8 C (76.6 F) 1.0	15.5 2.3	27.5 6.6
32.2 C (90 F)	Mean 32.4 C (90.3 F) S.D. 1.1	44.5 C (112.1 F) 1.4	27.2 C (81.0 F) 1.2	17.7 2.0	24.5 3.0

Where: WBGT — wet bulb globe temperature  
 $T_a$  — dry bulb ambient temperature  
 $T_{wb}$  — wet bulb ambient temperature  
 $P_w$  — water vapor pressure  
RH — relative humidity

Table 4

## Tasks and Workloads Imposed in Hot Environments

<u>Treadmill</u>		<u>Men, Age 21–40</u>	<u>Men, Age 45–60</u>
Load 1	1.34 m/sec (3.0 mph)	2.5% grade	0% grade
Load 2	1.34 m/sec (3.0 mph)	7.5% grade	5% grade
<u>Stepping</u>			
Load 1	22.9 cm (9 in.) step	12/min	10/min
Load 2	20.3 cm (8 in.) step	24/min	20/min
<u>Cranking</u>			
Load 1	30 rpm	30 watts	25 watts
Load 2	30 rpm	50 watts	40 watts
<u>Lifting</u>			
Load 1	5.25 kg (11.6 lb)	10/min	9/min
Load 2	5.25 kg (11.6 lb)	15/min	15/min
Load 3	10.5 kg (23.1 lb)	10/min	9/min
Load 4	10.5 kg (23.1 lb)	15/min	15/min
<u>Shoveling</u>			
Load 1	6/min	5.2 kg (11.4 lb)	5.2 kg (11.4 lb)
Load 2	6/min	9.0 kg (19.8 lb)	9.0 kg (19.8 lb)
<u>Handgrip</u>			
Load 1	20/min	30% MVC*	30% MVC
Load 2	20/min	50% MVC	50% MVC

\* Maximum voluntary contraction (isometric).

the waist. The shelf to which the weight was lifted was 30 cm above the bench. The weight was lifted up and down from the bench to the shelf and back at different rates. Restricting the lifting to arm work limited the weight which could be lifted. A weight of 16.8 kg (30 lbs) was found to be too heavy to lift repeatedly for 30 minutes or more, so the lighter weight of 10.5 kg was selected. For some subjects even this weight proved to be, subjectively, very difficult to lift repeatedly in the 32.2 C (90 F) WBGT environment.

Shoveling involved the movement of a dust-free material (with a density similar to that of coal) from a bin to a hopper which recycled the "coal" for shoveling. In this study, the rate of shoveling was kept constant and the load was varied to change work intensity. Work with the hand dynamometer (isometric handgrip) was performed with an adjustable device (one for each hand) to which a strain gauge was mounted. The force applied for the lightest work was 30% of maximum voluntary isometric contraction (MVC) and 50% MVC for the heavier work. MVC was determined for both right and left hand. During the work session the appropriate force was applied with one hand for 3 seconds followed immediately with relaxation and the appropriate force with the opposite hand for 3 seconds. The subject had a meter to watch for the appropriate force application and a metronome for pacing. The output of the strain gauges was recorded, and the force measured for the light work was between 6 and 12 kg and for heavier work was between 10 and 20 kg.

The measurements made during each work task were rectal temperature, skin temperature at five sites (forehead, chest, lateral upper arm, lateral thigh, and lateral calf), heart rate, ventilation rate, respiration rate, oxygen consumption, and carbon dioxide production. Body weight changes and fluid intake were recorded to determine sweat rate. Heart rate, body temperatures, wet and dry bulb temperatures were recorded every 5 minutes during the work session. Oxygen consumption, ventilation, and respiration rate were determined every 15 to 20 minutes during the work session. The work tests were performed in clothing consisting of shorts, socks, and low cut, rubber soled running shoes. Rectal temperature was measured with a YSI thermistor placed 11 cm beyond the sphincter ani. Skin temperatures were measured with copper constantan thermocouples. The duration of the work sessions varied from 30 to 90 minutes depending on the work rate and the environment. A steady state rectal temperature was defined as a temperature with a change of less than 0.06 C in 10 minutes (0.03 C on two successive 5-minute readings). In many of the work sessions involving higher metabolic rates and higher environmental temperatures, the steady state criteria was exceeded. The general rule for stopping the test under these conditions was a rectal temperature increasing at a rate greater than 0.10 each 5 minutes after 60 minutes of work, a rectal temperature approaching or exceeding 39 C, or a heart rate exceeding 90% of maximum. A physician was in attendance at all

work sessions and the appearance of symptoms of induced heat disorders required that the test be stopped and the subject removed from the heat chamber. The data were analyzed using multiple regression techniques with metabolic heat production (Mets and kcal) as the dependent variable and body weight (Wt), heart rate (HR) and minute ventilation ( $\dot{V}_{E_{BTPS}}$ ) as independent variables.

### Procedures (Phase II)

Selection and Screening of Subjects (Phase II): Table 5 summarizes the physical characteristics of the men aged 39 to 53 who participated in the study for the purpose of evaluating the prediction equations developed in the initial phase of the study. The men were selected from The Pennsylvania State University Faculty and Staff on the basis of their relative weight ( $30.0 \pm 3.8\%$  Fat). Each subject was given an oral explanation of the purposes and procedures of the investigation, and after obtaining the subject's expressed interest to participate, he was given a written consent form for signature. The subjects were given a medical examination to check general health and to exclude those individuals with cardiopulmonary pathologies, heat sensitivity, or other conditions which may have modified their reaction to heat. A 12-lead resting electrocardiogram was taken as well.

Experimental Procedures (Phase II): Exercise was performed on the treadmill within a temperature and humidity controlled

Table 5  
Physical Characteristics of Overweight Men (n = 8)  
Used in Evaluating Prediction Equations

Subject I.D.	Age (yrs)	Height (cm)	Weight (kg)	1 Met* (kcal/min)	% Fat †
21	39	169.3	85.3	1.39	34.1
22	46	170.5	91.9	1.43	32.4
23	47	178.5	114.2	1.69	33.1
24	40	188.3	126.8	1.90	29.0
25	40	184.6	102.5	1.63	31.7
26	49	177.4	125.2	1.79	31.0
27	51	177.8	95.3	1.47	23.4
28	53	180.3	89.5	1.41	25.2

\* 1 Met = BMR (kcal/min) x 1.1. BMR calculated according to method of Carpenter, 1939. Cited by Consolazio, Johnson, and Pecora, Physiological Measurements of Metabolic Functions in Man. New York, McGraw-Hill Book Co., Inc., 1963.

† Obtained from 10 skinfold measurements according to procedure of Allen et al. Metabolism, 5:346-362, 1956.

environmental chamber. The treadmill was operated at 4.8 km/hr (3 mph), 5% grade which provided a standardized work load. This was the same work load (load 2) as used in the initial phase of the study for men ages 45 to 60 (see Table 4). The energy requirement per unit body weight for the work task was approximately the same for all subjects. Each subject participated in six to eight exercise sessions. Each session included three 30-minute walking bouts on the treadmill with 5-minute rest periods between each bout. Exercise clothing for all sessions included shorts low socks and low cut, rubber soled shoes. At least 48 hours were allotted between sessions per individual. Each subject was instructed not to eat a heavy meal within the two hour period prior to an exercise session. Drinking liquids during the same period was encouraged to enhance optimal hydration.

The first three exercise sessions in the heat for each subject were termed acclimation sessions. Those sessions were designed for the purpose of acclimation to working in a warm environment, and also to acquaint the subject with the equipment used for experimental measurement. The three environmental conditions (WBGT) for the acclimation sessions were 26.7 C (80 F), 29.4 C (85 F) and 32.2 C (90F) respectively.

Following the acclimation sessions, each subject was exposed to a series of three experimental sessions. These sessions were characterized by progressively higher Wet Bulb Globe temperatures

of 26.7 C (80 F), 29.4 C (85 F) and 32.2 C (90 F). The methods of measurement were similar to those in the initial phase of the study.

The observed metabolic heat produced was compared with metabolic heat predicted from equations developed in the first phase of the study.

### Results (Phase I)

The primary purpose of this phase of the study was to develop equations to estimate metabolic rate of men who were working at various tasks in warm environments and to study the inter-relationship of the many physical and physiological factors involved. A correlation matrix (Table 6) was constructed from all the data. The correlation coefficients indicate that total metabolic heat production minus external work (M-W), and simple measurable variables such as heart rate (HR) and minute ventilation ( $\dot{V}_E$ ) were associated with heat production as assessed by measurement of oxygen consumption ( $\dot{V}_{O_2}$ ). Other variables such as age, height, weight and environmental conditions had very little association with measures of body heat production under the limitations of the environmental conditions and workloads imposed in this phase of the study.

Because of the lack of association between work metabolic rate and age

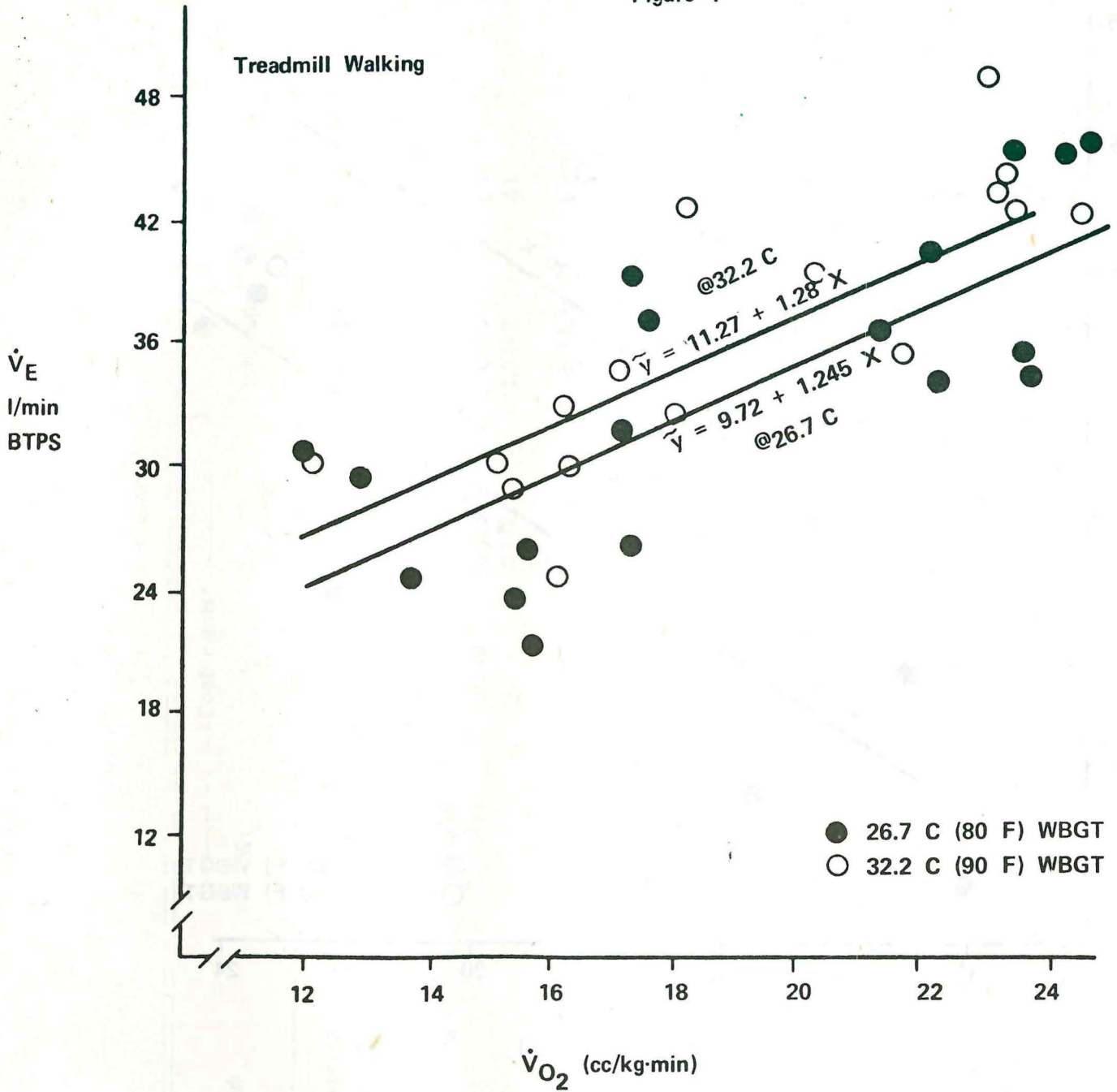
Table 6  
Table of Correlation Coefficients for Physical, Physiological, and Environmental Measures

	Mets	M-W (kcal/min)	Age (yrs)	Ht. (cm)	Wt. (kg)	Work Rate (Watts)	$\dot{V}_{O_2}$ (L/min)	HR (b/min)	$\dot{V}_E$ (L/min) BTPS	$\bar{T}_s$	$T_a$	$T_{wb}$
Mets	-----											
M-W	.96	-----										
Age	-.04	-.16	-----									
Ht.	-.06	.04	-.59	-----								
Wt.	-.07	.13	-.09	.00	-----							
Work Rate	.68	.55	-.09	-.02	-.06	-----						
$\dot{V}_{O_2}$	.97	.99	-.16	.03	.10	.67	-----					
HR	.72	.61	.00	-.03	-.30	.61	.66	-----				
$\dot{V}_E$	.86	.81	-.01	.00	-.14	.62	.83	.69	-----			
$\bar{T}_s$	.08	.06	-.03	-.04	.02	.12	.08	.15	.04	-----		
$T_a$	.10	.05	.05	-.03	-.03	.19	.08	.32	.12	.19	-----	
$T_{wb}$	.06	.03	.06	-.03	.03	.15	.06	.29	.15	.16	.74	-----

equations for individual tasks were inspected by combining the data for each task for those in each age group. Figure 1 and 2 are illustrations of the results obtained for treadmill work. Figure 1 shows the relationship of  $\dot{V}_E$  to oxygen consumption ( $\dot{V}O_2$ ), which is directly related to metabolic heat production, at two extremes of temperature used in the study (26.7 and 32.2 C WBGT). Figure 2 illustrates the relationship of HR to  $\dot{V}O_2$ . All subjects from phase I were included. Most evident in figures 1 and 2 is the high association of  $\dot{V}_E$  and HR to  $\dot{V}O_2$ . The second point, important for consideration of the objectives of the study, is that  $\dot{V}_E$  was not markedly affected by the range of temperatures employed while HR was clearly elevated at all levels of  $\dot{V}O_2$  in the hotter environment. If pulmonary ventilation ( $\dot{V}_E$ ) was to be influenced by the environmental conditions used in the study, it would have been expected to be evident during treadmill work which required the greatest percent (40%) of the maximum aerobic power of any of the tasks that were undertaken.

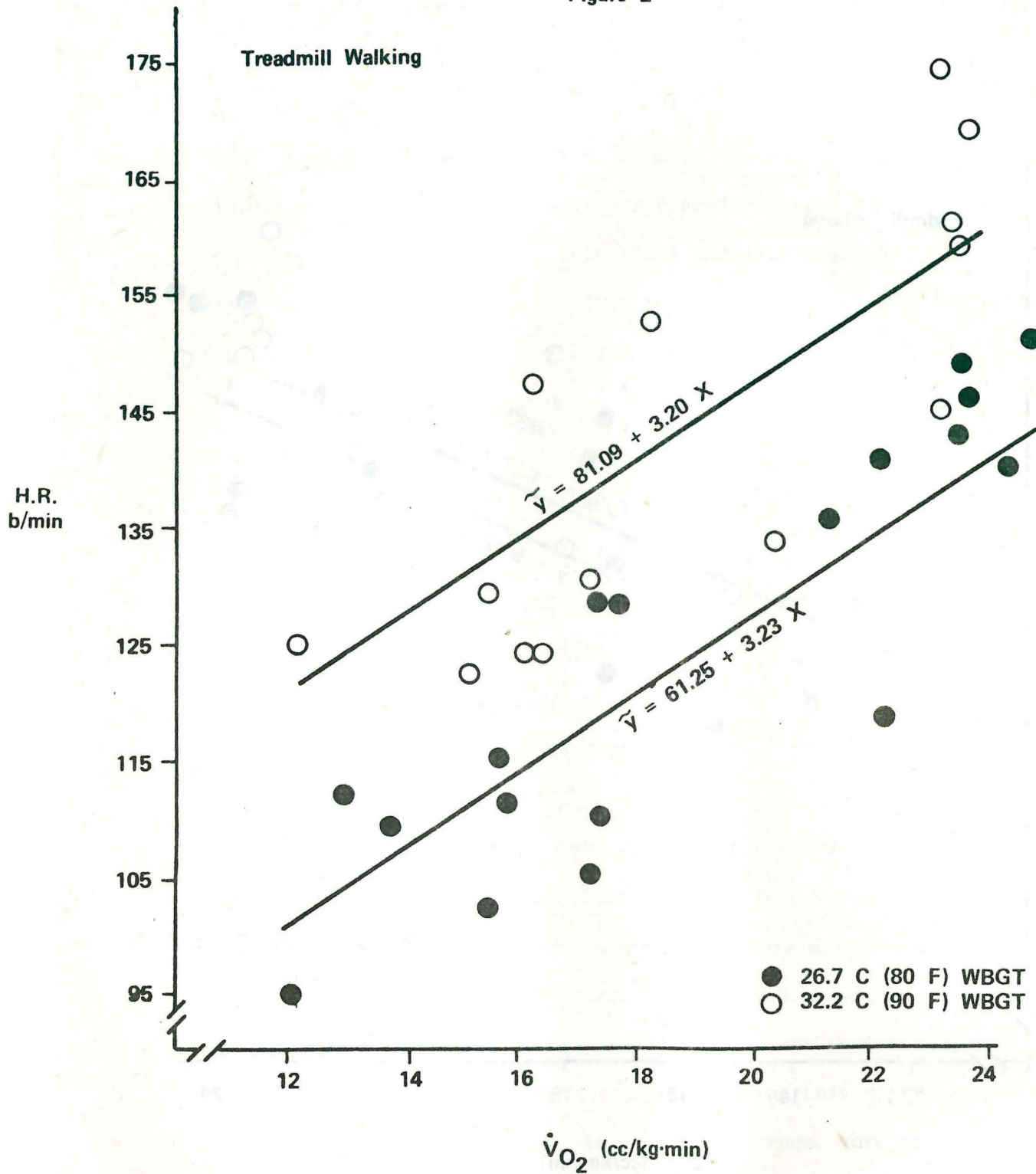
These observations and the results of a previous study (pulmonary function at work intensities common to coal mining operations, 4) suggested that energy expenditure may be estimated from ventilation and that heart rate and/or weight might improve the ability to estimate energy expenditure in hot environments. The constants developed for the equations using this approach are summarized in Table 7 where relative energy expenditure in Mets

Figure 1



The Relationship between Oxygen Consumption ( $\dot{V}_{O_2}$ ) and Ventilation ( $\dot{V}_E$ ) for Treadmill Work at 26.7 and 32.2 C WBGT.

Figure 2



The Relationship between Oxygen Consumption ( $\dot{V}_{O_2}$ ) and heart rate (H.R.) for Treadmill Work at 26.7 and 32.2 C WBGT. 2

Table 7

Regression Equation of Energy Expenditure During Work in Mets on Weight (Wt.),  
Heart Rate (H.R.), and Minute Ventilation ( $\dot{V}_{E_{BTPS}}$ )  
For Each Work Task

Task		Coefficients*			Intercept <sub>d</sub>	Explained Variance	Multiple Correlation Coefficient <sub>r</sub>
		Wt <sub>a</sub>	HR <sub>b</sub>	$\dot{V}_{E_{BTPS}}$ <sub>c</sub>			
Treadmill walking	1	.0062	.0286	.0749	-.0146	.75	.86
	2		.0273	.0794	-.9819	.75	.86
	3			.1236	.9832	.65	.81
Cranking	1	.0058	.0157	.0547	-.4543	.50	.70
	2		.0149	.0535	.0969	.49	.70
	3			.0742	1.3443	.41	.64
Shoveling	1	.0443	.0296	.0602	-5.3295	.81	.90
	2	.0448	.0530		-5.0722	.73	.85
	3		.0388		-.0562	.60	.77
Stepping	1	.0145	.0327	.0425	-2.2379	.67	.82
	2		.0295	.0483	.9540	.66	.81
	3		.0440		-1.2807	.56	.75
Lifting	1	.0068	.0090	.0286	.3247	.25	.50
	2		.0075	.0240	1.0909	.23	.48
	3		.0093		1.4184	.16	.39
Gripping	1	.0018	.0004	.0334	.9873	.37	.60
	2	.0017		.0337	1.0233	.37	.60
	3			.0329	1.1660	.36	.60
Gen. Eqn. all tasks	1	.0169	.0194	.1157	-3.0419	.78	.88
	2		.0165	.1181	-1.5181	.77	.88
	3			.1450	-.3530	.74	.86

\*Regression coefficients employed in the following regression equation:  $Mets = a Wt + b HR + c \dot{V}_E + d$   
a, b, and c are regression coefficients and d is the intercept.

is the dependent variable and  $\dot{V}_E$ , WT and HR are the independent variables. Mets are related directly to heat production since the units for 1 Met are kcal/min. In this study, the average 1 Met value was  $1.31 \pm .12$  kcal/min. Coefficients of the equations for each task are given based on data for all men in phase I in each environment. A general equation using data from all the tasks is given at the bottom of the table.

The task specific equations for leg work (treadmill walking and stepping) and shoveling were adequate predictors, at least by the criteria of variance accounted for with the three variables used. The equations for arm work (cranking, lifting and gripping), by the same criteria, were poor. This was possibly due to the fact that these tasks required relatively narrow range of heat production. The general equation:

Mets =  $0.017 (Wt) + 0.019 (HR) + 0.116 (\dot{V}_E) - 3.0419$ ---Eqn 1  
(where weight is in kg and  $\dot{V}_E$  in L/min BTPS) for all tasks, men and conditions employing weight, heart rate and minute ventilation accounted for 78 percent of the variance in Mets. Table 8 summarizes the prediction results of the equation above when applied to each individual task.

The average difference between observed and predicted results, disregarding sign, was .28 Mets or 8.3 percent of the observed mean. The variability of individual estimates within each task was considerable (between 10 and 20 percent of the observed mean) especially for the gripping task (31 percent).

Table 8

A Comparison of Observed and Predicted Mets for Each Work Condition  
Using a General Equation\* with Wt., H.R., and  $\dot{V}_{E_{BTPTS}}$  as Independent Variables

Condition	n	Observed Mets (O)		Predicted Mets (P)		Difference $\Delta = (O-P)$		% Variation $\frac{S.D.\Delta}{O} \times 100$
		Mean	S.D.	Mean	S.D.	Mean	S.D.	
Treadmill walking	52	5.16	1.01	4.56	1.03	0.60	0.56	10.8
Cranking	53	3.25	0.68	3.48	0.84	-0.22	0.61	18.8
Shoveling	41	4.43	0.80	4.11	0.78	0.32	0.44	9.9
Stepping	52	4.07	0.85	3.99	1.01	0.07	0.63	15.5
Lifting	81	2.40	0.34	2.76	0.53	-0.36	0.47	19.6
Gripping	42	1.68	0.21	1.81	0.58	-0.13	0.52	31.0
All Tasks	321	3.42	1.35	3.42	1.19	.01	0.64	18.7

\*Mets =  $0.017 (Wt.) + 0.019 (H.R.) + 0.116 (\dot{V}_{E_{BTPTS}}) - 3.042$

To further examine this approach and the effects of age and environment, several other equations were developed (see Table 9) using the same variables as predictors. Except for the oldest age group (n = 2), no apparent advantage in prediction of Mets was achieved by this separation data. Note from Table 10 that when the general equation (Eqn 1) was used the mean estimated heat production agreed well with the observed heat production in Mets for each age group and for each set of environmental conditions. Note the similarity in average observed heat productions in each environment 3.41 Mets at 80 F WBGT, 3.42 Mets at 85 F WBGT and 3.45 Mets at 90 F WBGT.

The simplest prediction of energy expenditure for all conditions was from the minute ventilation measurement. The results of the prediction using the equation:

$$\text{Mets} = 0.145 (\dot{V}_E) - 0.353 \text{ -----Eqn 2}$$

(where  $\dot{V}_E$  is in L/min BTPS) are shown in Table 11. The correlation between predicted and observed energy expenditure values in Mets was  $r = 0.86$  as contrasted with  $r = 0.88$  when heart rate and weight were included in the equation. The difference between observed and predicted values for each task using the above equation was not appreciably different from that obtained by Equation 1.

To further examine the basic approach of using  $\dot{V}_E$ , HR and Wt. in the estimation of heat produced during work in hot environments, heat production directly in kcal was used in developing constants

Table 9

Regression Equation of Energy Expenditure During Work in Mets on Weight (Wt.)  
Heart Rate (H.R.), and Minute Ventilation ( $\dot{V}_{E_{BTPS}}$ ) for Each Age Group and in Each Environment

Condition	Coefficients			Intercept <sub>d</sub>	Explained Variance	Multiple Correlation Coefficient $r$
	Wt <sub>a</sub>	H.R. <sub>b</sub>	$\dot{V}_{E_{BTPS}}$ <sub>c</sub>			
Group I Age 20 to 29	-.0046	.0081	.1500	-.9448	.89	.94
Group II Age 30 to 39	-.0812	.0214	.1096	3.7842	.72	.85
Group III Age 47 to 56	.0730	-.0050	.1632	-5.9424	.95	.97
80 F WBGT	.0187	.0372	.0929	-4.4122	.80	.90
85 F WBGT	.0238	.0268	.1063	-4.1035	.81	.90
90 F WBGT	.0187	.0147	.1178	-2.8664	.77	.88

\*Regression coefficients employed in the following regression:  $\text{Mets} = a \text{ Wt.} + b \text{ H.R.} + c \dot{V}_E + d$   
a, b, and c are regression coefficients and d is the intercept.

Table 10

A Comparison of Observed and Predicted Mets for Each Age Group and Each Environmental Condition Using a General Equation\* with Wt., H.R. and  $\dot{V}_{E_{BTPS}}$  as Independent Variables

Condition (all tasks)	Observed Mets (O)		Predicted Mets (P)		Difference $\Delta = (O-P)$		% Variation $\frac{S.D.\Delta}{O} \times 100$
	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Group I Age 20 to 29	3.44	1.41	3.37	1.24	0.07	0.52	15.1
Group II Age 30 to 39	3.52	1.30	3.58	1.10	-0.06	0.81	23.0
Group III Age 47 to 56	3.29	1.32	3.31	1.20	-0.02	0.57	17.3
80 F WBGT	3.41	1.41	3.28	1.18	0.13	0.65	19.1
85 F WBGT	3.42	1.33	3.37	1.17	0.05	0.59	17.2
90 F WBGT	3.45	1.31	3.62	1.21	-0.17	0.64	18.6

\*Mets = 0.017 (Wt.) + 0.019 (H.R.) + 0.116 ( $\dot{V}_{E_{BTPS}}$ ) - 3.042

Table 11

A Comparison of Observed and Predicted Mets for Each Work Condition  
Using a General Equation\* with  $\dot{V}_{E_{BTPTS}}$  as an Independent Variable

Condition	n	Observed Mets (O)		Predicted Mets (P)		Difference $\Delta = (O-P)$		% Variation $\frac{S.D.\Delta}{O} \times 100$
		Mean	S.D.	Mean	S.D.	Mean	S.D.	
Treadmill walking	52	5.16	1.01	4.55	0.96	0.61	0.61	11.8
Cranking	53	3.25	0.68	3.37	0.85	-0.12	0.67	20.6
Shoveling	41	4.43	0.80	4.21	0.75	0.22	0.56	12.6
Stepping	52	4.07	0.85	3.87	0.99	0.10	0.71	17.4
Lifting	81	2.40	0.34	2.76	0.58	-0.36	0.55	22.9
Gripping	42	1.68	0.21	1.95	0.59	-0.27	0.51	30.4
All Tasks	321	3.42	1.35	3.43	1.16	-0.01	0.69	20.2

\*Mets =  $0.145 (\dot{V}_{E_{BTPTS}}) - 0.353$

for an equation rather than the relative units of Mets. The resulting regression constants are given in Table 12.

In terms of correlation and correspondingly the explained variance, the best equation was that employing HR and Wt in addition to  $\dot{V}_E$ . Whether the improvement in prediction effectiveness is outweighed by the difficulty in obtaining both heart rate and ventilation is questionable. The application of the equation:

$$\text{kcal} = 0.061 (\text{Wt}) + 0.025 (\text{HR}) + 0.158 (\dot{V}_E) - 6.94 \text{---Eqn 3}$$

(where weight is in kg and  $\dot{V}_E$  in L/min BTPS) to each task is shown in Table 13. The results are no better or worse than for the estimation of total energy expenditure in Mets or the estimation of net energy expenditure (total heat production minus heat required to do work, M-W). The equation used for this prediction was:

$$\text{M-W} = 0.056 (\text{Wt}) + 0.018 (\text{HR}) + 0.141 (\dot{V}_E) - 5.720 \text{---Eqn 4}$$

( $r = 0.85$ ,  $r^2 = 0.73$ )

With all of these equations, the average coefficient of variation  $\frac{(\text{SD } \Delta \text{'s} \times 100)}{\text{Mean}}$  was about 20 percent of the observed mean.

Applied to each individual task, the coefficient of variation of the differences was less (10 to 20 percent) except for gripping where the coefficient was 30 percent. The coefficient of variation was of similar magnitude (10 to 20 percent) for each age group and each environment using the same equations.

Table 12

Regression Equations of Energy Expenditure During Work in kcal on Weight (Wt.)  
Heart Rate (H.R.), and Minute Ventilation ( $\dot{V}_{E_{BTPS}}$ ) for all Data

Coefficients			Intercept	Explained Variance	Multiple Correlation Coefficient
Wt.	H.R.	$\dot{V}_{E_{BTPS}}$			
0.061	0.025	0.158	-6.94	0.77	0.88
0.049	-----	0.197	-4.22	0.74	0.86
-----	-----	0.190	-0.423	0.69	0.83

Table 13

A Comparison of Observed and Predicted Energy Expended (Heat + Work) in kcal for Each Work Condition Using a General Equation\* from all Data

Condition	Observed kcals (O)		Predicted kcals (P)		Difference $\Delta = (O-P)$		% Variation
	Mean	S.D.	Mean	S.D.	Mean	S.D.	
Treadmill walking	6.81	1.58	6.05	1.53	0.76	0.78	11.4
Cranking	4.27	0.95	4.57	1.12	-0.30	0.86	20.1
Shoveling	5.93	1.07	5.52	0.97	0.41	0.75	12.6
Stepping	5.36	1.26	5.28	1.44	0.08	0.86	16.0
Lifting	3.20	0.46	3.69	0.68	-0.49	0.64	20.0
Gripping	2.25	0.35	2.41	0.82	-0.17	0.71	31.6
All Tasks	4.53	1.83	4.54	1.61	-0.01	0.88	19.4

\*Energy Expenditure (kcal) = 0.061 (Wt.) + 0.025 (H.R.) + 0.158 ( $\dot{V}_{E_{BTPS}}$ ) - 6.94

## Results (Phase II)

In phase II of the study, eight overweight (average  $30 \pm 3.8$  percent body fat) adult men (age 39 to 53 years) walked on the treadmill in 70 F, 80 F and 85 F WBGT environmental conditions. The subjects walked in a 90 F WBGT environment but did not achieve a steady state rectal temperature and the data were not included. The average energy expenditure for the treadmill work was 6.25 Mets or 9.5 kcal/min. In phase I of the study, the average percent fat of six men was  $13.5 \pm 4.7$  (see Table 1). Of the three men without skinfold measurements, none were judged to be over 25 percent fat and two were apparently less than 20 percent fat. The point to be made is that in terms of body composition, the men selected for phase II of the study were clearly from a different population than the men selected for phase I of the study.

The  $V_E$ , HR and Wt data from the tests were tabulated and applied to several equations with constants developed from data in phase I of the study. Observed and predicted values were then compared. The equations tested were 1, 2, and 3, and included two equations developed for the specific task of treadmill walking given in Table 7. Of the equations tested, the one best describing the data was equation 3. The relationship between the predicted and observed total metabolic

heat produced was described by the equation:

Predicted heat produced in kcal = 1.124 (observed kcal of heat produced) + 0.925---Eq. 5

$$\text{S.E.} = \pm 9.315$$

$$r = 0.73$$

It was apparent that prediction of metabolic heat generated in hot environments was not very satisfactory for overweight older men using the equations developed in Phase I. At the metabolic rate of 10 kcal/min, the average estimated metabolic rate was 21.6 percent greater (observed metabolic rate = 0.82 estimated metabolic rate). The major reason for the overestimate of heat production appeared to be a large minute ventilation at a given oxygen consumption in the older overweight group. Weight had a contribution to the overestimate but heart rate had little effect.

#### Summary

Nine healthy men of normal weight between the ages of 21 and 56 performed several tasks in three hot but relatively dry environments. The tasks (walking on a treadmill, stepping, arm cranking, arm lifting, shoveling and isometric handgrip) were performed at two intensities in each environment until a steady-state rectal temperature was observed or until rectal temperature reached 39.0 C (102.2 F). The lightest task was the handgrip (average  $1.68 \pm 0.21$  Mets) and the heaviest task was treadmill walking ( $5.16 \pm 1.01$  Mets).

The environmental conditions were 26.7 C (80 F), 29.4 C (85 F) and 32.2 C (90 F) WBGT. Several equations were developed using heart rate (HR), weight (Wt.), and minute ventilation ( $\dot{V}_{E_{BTPS}}$ ) to predicted metabolic heat generated (Mets and kcal/min) during work.

Three equations predicted heat generated equally well. They were as follows:

$$\text{Mets} + 0.017 (\text{Wt.}_{\text{kg}}) + 0.019 (\text{HR}) + 0.116 (\dot{V}_{E_{L/\text{min}}}) - 3.0419 \text{---Eqn. 1}$$

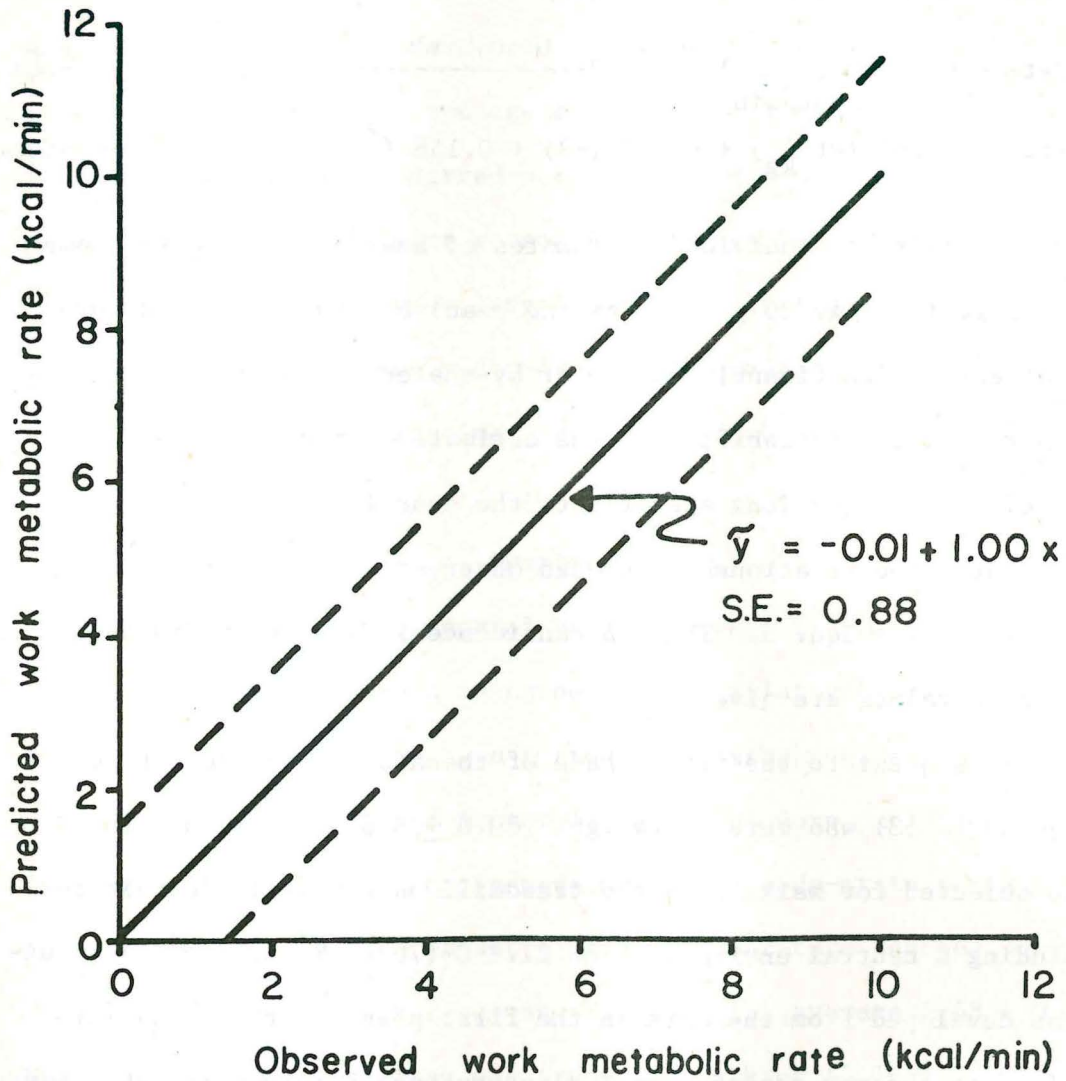
$$\text{Mets} = 0.145 (\dot{V}_{E_{L/\text{min}}}) - 0.353 \text{-----Eqn. 2}$$

$$\text{kcal} = 0.061 (\text{Wt.}_{\text{kg}}) + 0.025 (\text{HR}) + 0.158 (\dot{V}_{E_{L/\text{min}}}) - 6.94 \text{-----Eqn. 3}$$

The variability of individual estimates of heat production was somewhat large (average 20 percent of the mean) but the estimates were not affected significantly by age or by the environmental conditions. Furthermore, the variability of the estimates was not reduced appreciably by equations specific to the task involved. Figure 3 illustrates the relationship between observed and predicted heat generated using Eqn. 3. The 90% confidence limits for individual predicted values are given.

Subsequent to the first phase of the study, eight older men (ages 39 to 53) who were overweight ( $30.0 \pm 3.8$  percent body fat) were selected for walking on the treadmill under similar conditions including a neutral environment of 21.1 C (70 F) WBGT. Several equations developed from the data in the first phase of the study were applied to the new set of data for the purpose of comparing the observed and predicted heat generated while walking on the treadmill. The

Figure 3



Observed versus Predicted Work Metabolic Rate for 9 Normal Weight Men, Age 21 to 56, for All Tasks Studied in Each Environment. Predicted Values from Eqn. 3 with 90% Confidence Limits.

single equation which described the data better than others was

Equation 3:

$$\text{kcal} = 0.061 (\text{Wt.}_{\text{kg}}) + 0.025 (\text{HR}) + 0.158 (\dot{V}_{\text{E}}) - 6.94 \text{---Eqn. 3}$$

The average predicted heat produced during walking was 22.6 percent higher than the observed values. The observed and predicted values were related by the equation:

$$\text{Predicted heat produced in kcal} = 0.925 + 1.24 (\text{observed kcal of heat produced})$$

$$\text{SEE} = \pm 1.315$$

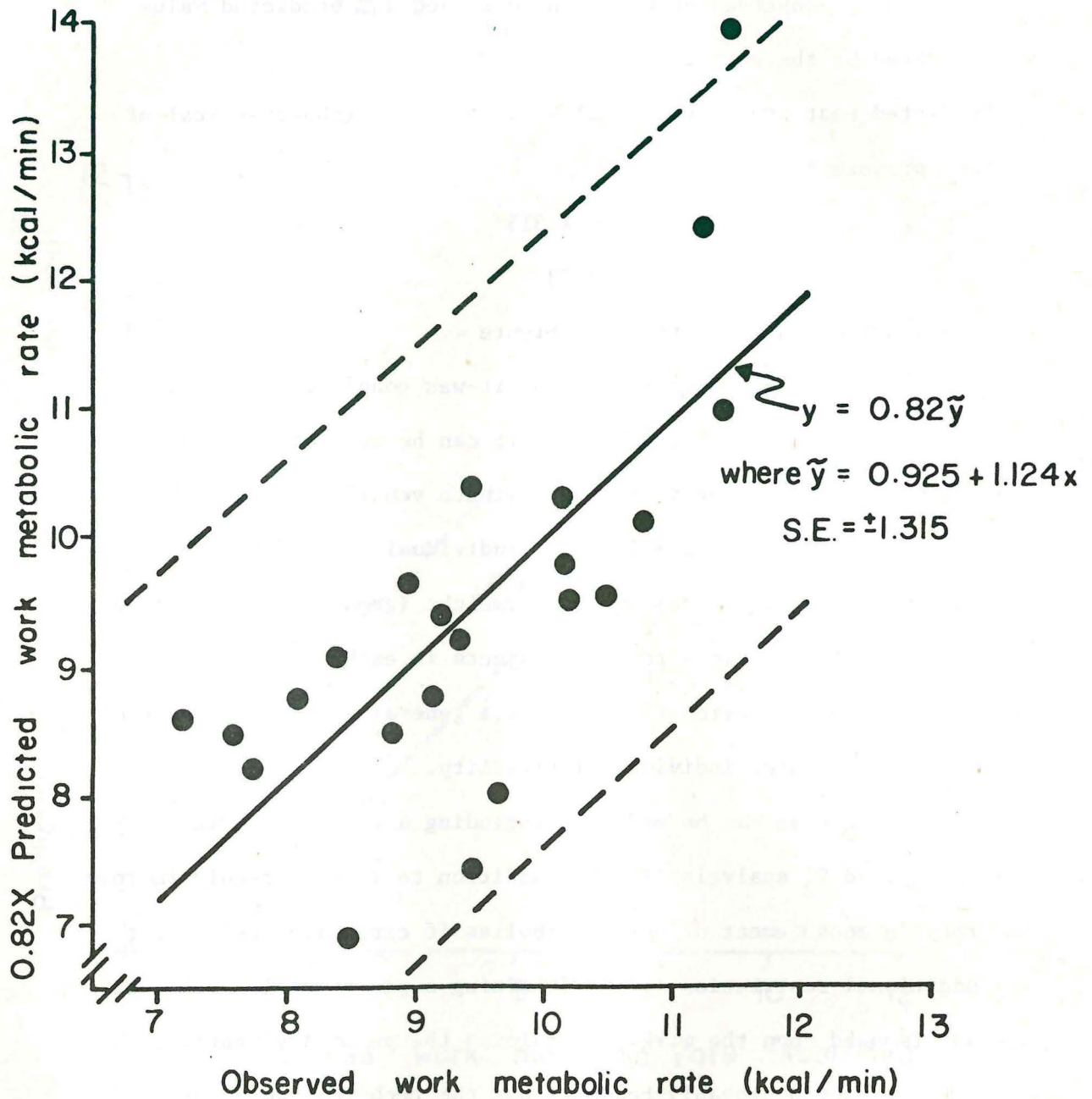
$$r = 0.73$$

This equation is illustrated in Figure 4.

On the basis of this comparison, it was concluded that heat produced during work in hot environments can be estimated from measurement of weight, heart rate and minute ventilation, but the equations developed for normal weight individuals should not be used to estimate the heat production of overweight (greater than 25 percent body fat) men. There were too few subjects in each study group to enable accurate prediction formulas for a general population because of demonstrated inter-individual variability.

A strong case can be made for including a sampling device to obtain expired  $\text{O}_2$  analysis ( $F_{\text{O}_2}$ ) in addition to  $\dot{V}_{\text{E}}$  to markedly improve accuracy in measurement of work metabolism if circumstances warrant. Any additional restriction (while obtaining a gas sample), over that already imposed upon the work in obtaining the pulmonary ventilation measurement, would probably be small but the technical work involved in monitoring energy expenditure utilizing  $\dot{V}_{\text{E}}$  and  $F_{\text{O}_2}$  is an order of magnitude greater than when utilizing  $\dot{V}_{\text{E}}$  alone.

Figure 4



Observed versus Predicted Work Metabolic Rate for Overweight Men, Age 39 to 52 during Treadmill Walking.

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ID	WBGT (F)	Wt (kg)	H.R. (Beats/min)	$\dot{V}_{E\text{BTPS}}$ (L/min)	$\dot{V}_{O_2}$ (L/min)
21	70	86.5	126	53.7	1.55
	80	87.3	125	55.8	1.52
	85	87.2	165	58.7	1.79
22	70	93.8	127	57.6	1.68
	80	93.2	136	54.1	1.62
	85	93.5	143	51.5	1.44
23	70	115.8	134	51.7	2.10
	80	115.0	146	51.8	2.04
	85	120.5	153	52.9	2.03
24	70	126.9	110	55.7	2.16
	80	127.8	114	53.5	2.04
	85	126.7	121	51.3	2.08
25	70	105.0	108	57.5	1.87
	80	104.3	125	56.4	1.84
	85	106.3	139	61.2	1.89
26	70	126.1	139	58.0	2.28
	80	127.6	146	67.4	2.25
	85	127.2	164	76.6	2.29
27	70	96.4	109	42.8	1.70
	80	95.0	122	45.3	1.89
	85	93.5	146	46.6	1.93
28	80	90.2	151	50.9	1.77
	85	91.0	152	52.3	1.83



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