American Industrial Hygiene Association Journal

ISSN: 0002-8894 (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/aiha20

Physiological Evaluation of Industrial Heat Stress

DAVID MINARD , RAINER GOLDSMITH , PAUL H. FARRIER & BENJAMIN J. LAMBIOTTE

To cite this article: DAVID MINARD , RAINER GOLDSMITH , PAUL H. FARRIER & BENJAMIN J. LAMBIOTTE (1971) Physiological Evaluation of Industrial Heat Stress, American Industrial Hygiene Association Journal, 32:1, 17-28, DOI: 10.1080/0002889718506402

To link to this article: https://doi.org/10.1080/0002889718506402

Published online: 04 Jun 2010.

Physiological Evaluation of Industrial Heat Stress

DAVID MINARD, M.D., Ph.D., RAINER GOLDSMITH,* M.B., B.Ch.,
PAUL H. FARRIER, JR.,† M.D., and BENJAMIN J. LAMBIOTTE, JR.,‡ M.D.

Graduate School of Public Health, University of Pittsburgh, Pittsburgh, Pennsylvania 15213

Heart rate (*HR*) and body temperature (t_b) were studied in men on jobs in the open hearth department of a Pittsburgh steel mill. In 19 subjects on various jobs, mean *HR* for the shift was compared with mean *HR* off work and during sleep. Results showed these men expend 31 to 36% of maximum cardiocirculatory capacity on the job. In 12 tests on five second helpers, continuous ECG records on magnetic tape revealed individual mean *HR*'s for the shift ranged from 99 to 136/min in summer and 97 to 111/min in winter. *HR* on the job varied inversely with individual work capacity estimated from pre-shift performance on an ergometer. Performance decrement was observed post-shift in two subjects with the lowest work capacity. *HR* responses, counted each 0.5 minute of the shift, were analyzed by computer with task effort and heat exposure as independent variables. *HR* gradients to heat levels are nearly as great as to task levels in summer. In winter, *HR* gradient to heat is only 33% of that in summer, but *HR* responses to task are unchanged.

Introduction

JOBS IN PRIMARY METAL industries and in glass manufacture, among others, expose workers intermittently to intense heat stress during performance of moderate to strenuous physical work.[1-4] The metabolic requirement for increased blood flow to active muscles as well as thermoregulatory needs for heat transfer are both reflected in circulatory responses manifested as an increased cardiac output for which heart rate (*HR*) serves as a useful index.[5,6,7]

Effects of metabolic heat load (*M*) and environmental heat load (*HS*) are additive on *HR* but not in a 1:1 relationship.[8] Thus each different combination of *HS* and *M* equivalent in total load is associated with a unique demand on the circulation, hence on cardiac output and *HR*.

In a recent review, Snook[9] has indicated that *HR*, in the absence of *HS*, can be equated with *M*. In his studies and those of others he cites (eg Astrand[10]) *HR* attained during self-paced work is between 40 and 50% of the subject's maximum aerobic work capacity (MWC). This, he states, is closely equivalent to the upper limit for mean *M* recommended by Lehmann[11] (5.2 kcal/min) for 8-hour industrial work. For men working under *HS*, Brouha et al[6] found *HR* exceeds the levels resulting from elevated M alone, and recommends *HR* as a better index of cardiocirculatory strain in the heat. Previously Brouha[5] had proposed the one minute recovery *HR* of 110/min as the upper desirable limit.

Lind[12] introduced the term "prescriptive zone" which is defined as the range in thermal environment in which a subject can work without his rectal temperature (t_b) exceeding the regulated rise which depends only on *M* and is independent of ambient temperature in cool to moderately warm environments (Nielsen[13]). According to Lind,[14] the upper limit of the prescriptive zone for unacclimatized men working at 5 kcal/min is 27.5°C Effective Temperature (ET). This will be

Supported in part by USPHS Research Grant EC 00310-01 (1 RO1).
*Present Address: Medical School of the University of Nottingham, England.
†Present Address: U.S. Naval Experimental Diving Unit, Washington, D. C.
‡Present Address: Chestnut Road, Sewickley, Pennsylvania.

lower or higher when M is greater or less. Saltin and Hermansen,[15] however, demonstrated that the degree of rise in t_b in the prescriptive zone depends directly on the proportion between M required by the task and MWC of the individual. For a given M, the rise in t_b will be higher in a subject of low MWC than in another of larger MWC. Wyndham[16] has reported, moreover, that the rise in t_b in men working at equal rates under HS is less in those with higher MWC. Hence in a group ranging widely in work capacity one would predict that the prescriptive zone for a given level of M would be lower in those with lesser MWC.

Among the questions we sought to answer were these:

(1) In complex industrial jobs can environmental factors contributing to cardiocirculatory strain, namely workload and heat stress, be evaluated separately using HR as a physiological index?

(2) Can the degree of strain in an individual be predicted from a simple assessment of his work capacity before the shift?

(3) Can excessive strain during work be measured by the elevation of HR during post-shift standard exercise above the pre-shift level?

(4) Can total heart count during the shift be used to express overall work demands on the individual?

Studies during the summer of 1967-68 helped us to solve technical problems involved in continuous ECG monitoring under rigorous work conditions imposed by the job and the mill environment,[17] and to develop the methods for data recording and analysis.[18] These preliminary findings in nine subjects led to the conclusion that the level of HR attained during pre-shift standard submaximal exercise was useful as an index in predicting on-the-job cardiocirculatory strains in furnacemen differing in MWC but performing the same job.

Methods

Subjects were volunteers from the work force of the open hearth department of a large Pittsburgh steel mill.

Series A

This series consisted of 19 men representing three job categories: (a) six furnacemen, (b) eleven crane or tractor operators, and (c) nine maintenance men. Total heart beats were monitored separately during work, during waking hours off work, and during sleep. Mean temperature of the skin (t_s) of the anterior chest wall during each period was also monitored. Both HR and t_s in Series A were monitored by SAMI devices,[19] which are miniature transistorized instruments utilizing an electrolytic E-cell for storing input signals from suitable transducers.

Series B

This series consisted of seven medically screened subjects in the open hearth department. Tests in this series included the following procedures:

A. Direct recording of the ECG and HR during standard 5-minute exercise at 125 watts work output on a bicycle ergometer: The ECG was recorded using bipolar trunk leads with the subject wearing only lower underwear and socks. After a warm-up period of one minute at 50 watts and 60 rpm, ECG was recorded at a work output of 125 watts. A recovery ECG was recorded from 15 to 30 seconds after exercise stopped. Exercise in the summer tests was carried out in an air-conditioned boiler control room in the mill one level below the charging floor. In January 1970, a climate chamber was assembled in a room on the main mill floor within two to three minutes walk of the furnaces. This chamber was used for the winter series of tests. Temperatures were controlled at 23.6 ± 0.5°C dry bulb (DB) and 17.0 ± 1.0° wet bulb (WB). After completing his shift, the subject returned to the test room and the ECG tape recorder was disconnected. He then removed his clothes, voided urine, was weighed, and the five minutes of exercise was repeated as before but without the warm-up period, again with a direct tracing of the ECG.

B. Continuous recording of the ECG during the shift using a miniature battery operated tape recorder (Avionics Electrocardiocorder, Model 350)[20] with bipolar electrode

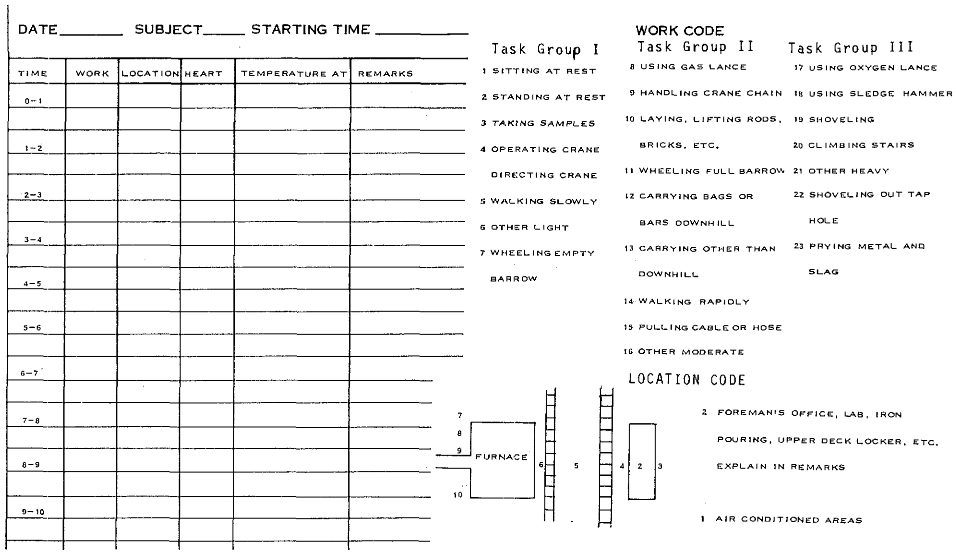

FIGURE 1. Work sheet, showing code for tasks and locations.

leads from the trunk: To minimize artifacts from skeletal muscle potentials during vigorous work, a number of electrode configurations were tried. By trial and error it was found that bipolar leads with one electrode attached to the midline of the lower sternum ventrally and one electrode attached over the seventh cervical spine dorsally resulted in satisfactory suppression of skeletal muscle potentials.

C. Recording by an observer of the task being performed and the location of the worker each 0.5 minute throughout the shift: Data were kept on a work sheet (Figure 1) using a task code number for 23 tasks in rank order of estimated energy demand, and a location code number from 1 to 10 in rank order of increasing proximity to the furnace.

D. Measurement of total sweat rate (*SR*): The subject was weighed before and after the shift on a portable beam balance accurate to ± 10 gm. Weight change was corrected for water intake, food intake, and urine output.

E. Intermittent measurement of internal temperature by radiosonde capsule: In six tests on five subjects internal temperature was measured using a calibrated radiosonde capsule swallowed 12 hours before the test began.[21] The signal frequency varied linearly with temperature in the range from 35 to 45°C. An observer standing near the subject tuned the signal on a radio receiver.

In these same six tests, skin temperature of the chest was measured using a temperature SAMI. SAMI *HR* was used in these tests simultaneously with the ECG tape recorder

TABLE I

Results of SAMI/*HR* Measurements during Work (F_{H_W}), Sleep (F_{H_S}) and Leisure (F_{H_L}) and Mean Skin Temperature of Chest (T_S) during Work on Unsupervised Subjects

Category	(a)*	(b)*	(c)*
Number of subjects	6	11	9
Age, years	52.8	45.3	46.3
Leisure F_{H_L} bt/min	78.7	80.8	85.8
Work F_{H_W} bt/min	104.3	100.4	99.1
Sleep F_{H_S} bt/min	63.7	63.9	62.3
F_{H_W}/F_{H_S}	1.64	1.57	1.59
F_{H_L}/F_{H_S}	1.24	1.26	1.38
Postulated $F_{H_{max}}$ bt/min	175	180	180
% of $F_{H_{max}}$ at work	36	31	31
% of $F_{H_{max}}$ at leisure	13	14	20
T_S (°C)	35.6	35.5	35.1

*The categories are:

(a) Open hearth workers
(b) Crane or tractor operators
(c) Maintenance workers

to compare performance. The E-cell was changed about every two hours during the shift.

F. Intermittent reading of ambient temperatures at the various locations using wet bulb, dry bulb and black globe thermometers: Psychrometer readings were taken in conjunction with readings used to obtain the Wet Bulb-Globe Temperature (WBGT) index of heat stress.[22] For this purpose a natural (unventilated and unshielded) wet bulb thermometer was mounted with a 6 in black globe thermometer on a tripod, whose legs were extended so that the thermometer bulbs were 4 ft from the floor. This provided a convenient and portable means for obtaining wet bulb and globe temperature readings in areas where suspension of thermometers was impossible. Twenty-minutes was allowed for the globe thermometer to equilibrate.

G. Data reduction and analysis: The electronic tape record of ECG from each test was scanned at 60× real time using the playback device which generated square wave pulses at the same frequency as the ECG complexes recurred on the oscilloscope screen. These pulses were counted by a digital counter for each successive 30-second period of recording on the tape, printing these counts on paper tape. Thus, an 8-hour tape record could be scanned, and a print-out of 960 successive 30-second counts of *HR* obtained in 8 minutes. *HR* was then transferred from the printed tape to the work sheet. These data, ie, code number for task, code number for location and *HR* for each 30-second interval of the 8-hour shift, were key-punched onto IBM cards for further analysis by computer.

The computer was programmed to carry out the following operations: Total observations and mean heart rate for the shift; percentage time spent on each of the 23 tasks with corresponding mean *HR* and standard deviation (S.D.); percentage time spent at each of the 10 locations with corresponding *HR* and S.D.; percentage time spent in tasks grouped into three levels of estimated energy expenditure; percentage time spent at locations grouped into three levels of heat stress with corresponding *HR* and S.D.; finally, the

TABLE II
Twelve Tests in Five Second Helpers on the Open Hearth Furnace
Daytime Shift (0800-1600)

Date	Subject	Age	Wt (kg)	Ht (cm)	Years on Job	Heart Rate Standard Exercise[a] Pre-shift	Heart Rate Standard Exercise[a] Post-shift	Heart Rate During Shift Range	Heart Rate During Shift Mean	SE	Sweat Rate (kg/hr)
					Summer Tests						
5-26-69	3	43	71.4	179	18	145	140	71-178	122.8		—
5-27-69						149	160[b]	76-178	124.4		.67
5-28-69						145	138	72-172	109.8		.61
8- 6-69						141	137	66-170	103.2		.61
					Mean	144	143	71-175	117.7	.184	.63
7-25-69	4	42	107.3	189	21	125	122	62-184	98.9	.838	.79
6-19-69	5	45	83.2	183	23	128	134	76-168	103.3	.652	.64
8-29-69	2	37	81.4	179	19	150	168[b]	80-188	136.0	.688	.97
9-16-69	7	45	96.4	175	26	133	155	76-176	115.7	.650	.57
										Mean	.72
					Winter Tests						
1-15-70	7	45	98.2	175	26	128	136	76-162	97.0	.560	.31
2-24-70						117	114	62-154	90.5	.489	.50
					Mean	123	125	69-158	93.8	.382	.40
3-20-70	4	42	107.3	189	21	146	146	64-154	111.0	—	.59
4- 9-70						146	152	72-162	100.8	—	.48
					Mean	146	149	68-158	105.9	.456	.53
										Mean	.46

[a]Exercise was at 125 watts on bicycle ergometer for all subjects except S4 who exercised at 150 watts (except as noted in Figure 6).
[b]Unable to complete more than 4 minutes of post-shift exercise.

computer printed a 3x3 table, giving *HR* and S.E. for any of the nine possible combinations of task group and location group.

Results

Series A

Table I is a summary of data obtained using SAMI monitors in 19 workers in the open hearth department. A detailed report of these tests as well as results using these monitors in some of the tests in Series B to be described below will be published separately.[23]

Series B

In 25 tests on seven subjects, technically satisfactory magnetic tape records of ECG were obtained on men performing jobs as first helper, second helper, alloy man, and laborer.

Tests vary in terms of job, shift, and season. Common to each of 12 tests in five subjects is the job (second helper) and the shift (0800-1600). Results in these 12 tests constitute the basis for this section of the report (Table II).

Thermal Environment

Figure 2 depicts mean values for the globe temperature (t_g) and natural wet bulb (t_{nwb}) readings observed in ten summer tests at locations 3 to 10 and in seven winter tests at locations 4 to 10. Psychrometer readings in all ten locations as well as weather air outside were also taken.

In the presence of radiant heat t_g integrates effects of air velocity, dry bulb temperature (t_a), and radiant heat. The natural wet bulb value is the same as that of the psychrometric wet bulb at high air velocities but at low velocities may be up to 5°C higher, depending on air temperature, vapor pressure, and radiant heat. The WBGT index is derived from $0.7t_{nwb} + 0.3t_g$.[22] It is one of the modifications of the ET scale. Heat stress for working men becomes significant at 29°C WBGT (or ET) and above.

The values of t_g and t_a at location 3 (Figure 1) are equal, indicating that mean radiant temperature is the same as t_a, but t_g increases progressively above t_a as the distance from

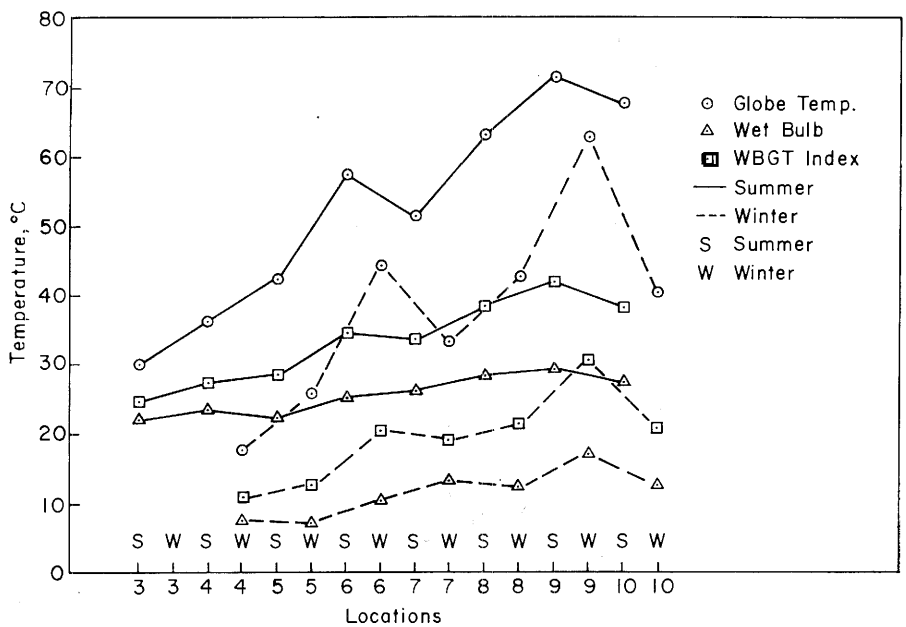

FIGURE 2. Natural (unventilated) wet bulb temperature, 6-inch black globe temperature, and Wet Bulb—Globe Temperature index[22] at locations 3-10 in summer (1968) and locations 4-10 in winter (1970). Summer readings are means from ten test days. Winter readings are means from seven test days. Location 9 cooled by fan in summer. Often not cooled in winter (see text).

the furnace decreases. At location 6, t_g is higher than at location 7, and t_g at location 10 is lower than location 9 but otherwise t_g, t_{nwb}, and the WBGT follow a reasonably orderly progression. In winter the values parallel closely those for summer but at a level approximately 15°C lower for t_{nwb} and WBGT.

For statistical comparison of *HR*'s, locations were grouped according to level of heat exposure in summer tests. Location Group I (LI) combines locations 1 through 4, representing no significant heat stress, Location Group II (LII) combines locations 5 and 6 representing moderate heat stress, and Location Group III (LIII) combines locations 7, 8, 9, and 10 representing severe heat stress.

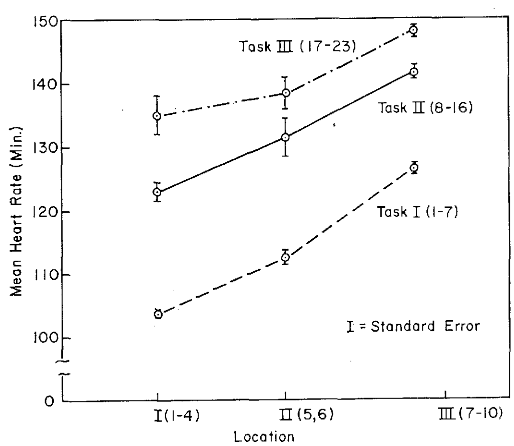

FIGURE 3. Combined data from five tests in five subjects on jobs as second helper, daylight shift (0800-1600), summer 1969. Test for S3 is that dated 5-27-69 in Table II. For n, means, and standard errors, see Table III.

The WBGT index for location 9 was derived from readings during relatively steady conditions prior to "tapping the heat" (drawing off the molten metal from the furnace) and during preparation for the next heat. During the tap, readings indicate that the WBGT at location 9 exceeds 55°C. In one observation t_g was still rising at 10 minutes when the thermometer range of 110°C was exceeded and the measurement was discontinued. At this time, t_{nwb} was 31.9°C.

Mean HR in Relation to Task and Location

Mean *HR*'s for eight summer tests on five second helpers is shown in Figure 3. Task Groups (TI, TII, and TIII) are indicated in Figure 1 and represent light, moderate, and heavy work. Task is plotted on the ordinate in Figure 3 and heat exposure (LI, LII, and LIII) on the abscissa. The data from which Figure 3 is derived appears in Table III. The gradient in heart rate with task level is steepest at LI and least at LIII. The gradient in *HR* from work effort exceeds that from heat exposure by 30%. Standard errors of the means are indicated by the bars.

Individual mean *HR*'s for five subjects at three levels of heat exposure are shown in Figure 4. In order to obtain sufficient numbers of observations for statistical comparison, data for all tasks are combined for each subject, thus each point represents the effect of heat on *HR*, regardless of task. The mean for all subjects is indicated by the heavy line. Differences are greatest at LI and least at LIII. Slopes suggest that one factor which may reduce individual differences under conditions of highest heat exposure is that of heat

TABLE III
Mean Heart Rate per Minute by Task and Location
(5 second helpers—shift 0800-1600—summer 1969)[a]

Task Group	Location Group: Group I n	mean	s.e.	Group II n	mean	s.e.	Group III n	mean	s.e.
I	2629	106.3	.38	334	112.6	1.12	707	126.6	.78
II	85	123.0	1.70	46	131.6	2.94	346	141.8	1.02
III	36	135.0	2.88	55	138.0	2.60	404	148.0	.86

[a]Data on five summer tests in five subjects on jobs as second helper, daylight shift, (0800-1600). Task Group I combines tasks 1-7, Task Group II, 8-16, and Task Group III, 17-23. Location Group I combines locations 1-4, Location Group II combines 5, 6, and Location Group III combines locations 7-10.

tolerance, Subject 4 (S4) showing the greatest effect of heat and S3 the least.

Standard Exercise Before and After the Shift

Pre- and post-shift *HR*'s averaged for the fourth and fifth minute of the bicycle ergometer test are shown in Table II for each of the twelve tests. In Figure 5A data for minute by minute HR during standard exercise are shown for four subjects in six summer tests in which both pre- and post-shift exercises were successfully completed.

In Figure 5A a plateau in *HR* at 133/min is reached during the fourth and fifth minute of pre-shift exercise. After work, *HR* was elevated above pre-shift levels reaching 136/min and 139/min for the fourth and fifth minute. As shown in Table II, however, post-shift elevation above pre-shift levels was not an invariable finding.

In Figure 5B pre- and post-shift *HR*'s are illustrated for S2 and S3 who failed to complete the post-shift exercise. Judged by *HR* elevation in the pre-shift exercise, S2 and S3 had lower predicted maximum work capacities[24] than the other three subjects (Table II). Both S2 and S3 were unable to complete more than four minutes of post-shift exercise, although in three other tests, S3 had done so (Table II). The mean for *HR*'s in S3's successful tests are included in values shown in Figure 5A. For S3, the test illustrated in Figure 5B (5/27/69) occurred on the second consecutive workday after his returning from a three-week vacation. On the following (third workday) day (5/28/69) he continued to complain of feeling "played out."

The test on S2 was his first during this series but he had been a subject in four tests during the preceding summer and hence was thoroughly familiar with the procedures. S2 had, however, undergone a laminectomy for

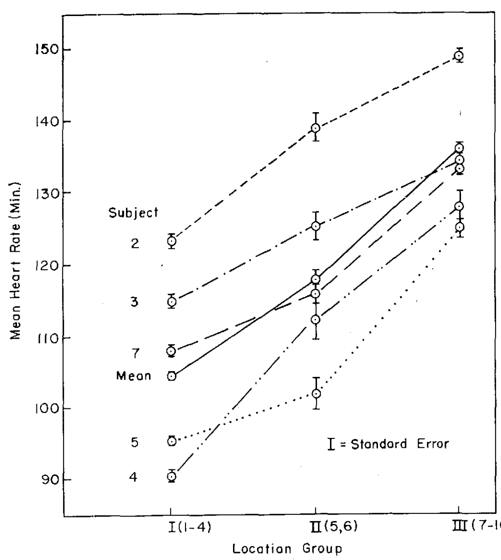

FIGURE 4. Individual mean heart rates for all tasks at Location Group I (locations 1-4), Location Group II (locations 5, 6), and Location Group III (locations 7-10) from five tests in five subjects on jobs as second helper, daylight shift (0800-1600), summer 1969, n values as follows:

		LI	LII	LIII
Subject	S2	444	72	410
	S3	441	61	410
	S7	595	131	244
	S5	633	77	236
	S4	637	94	157

S3 data are from test dated 5-27-69 (Table II).

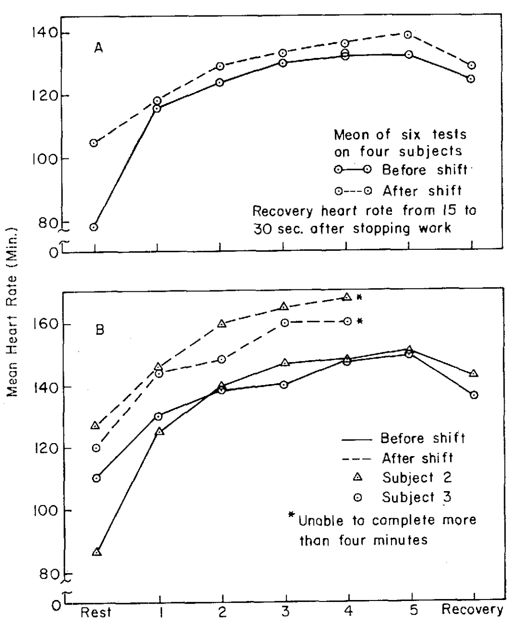

FIGURE 5*A*. Mean resting *HR* and mean *HR* for pre- and post-shift 5-minute exercise at 125 watts on bicycle ergometer. Means of four subjects who completed post-shift exercise test. Data for S3 are from three tests in which he completed 5-minute post-exercise test.

B Same for two subjects (S2 and S3) who were unable to complete more than 4 minutes of post-shift exercise. Data for S3 are from test dated 5-27-69.

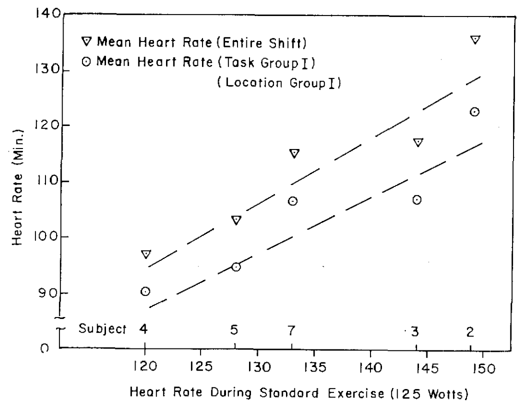

FIGURE 6. *HR* during pre-shift standard exercise for each of five subjects, plotted against mean *HR* on shift and against mean *HR* for Location Group I and Task Group I. For S4, *HR* during standard exercise was that observed while exercising at 125 watts. In tests shown in Table II for S4, pre-shift exercise load was 150 watts. For S3, mean *HR's* are overall means for the four tests on S3 shown in Table II.

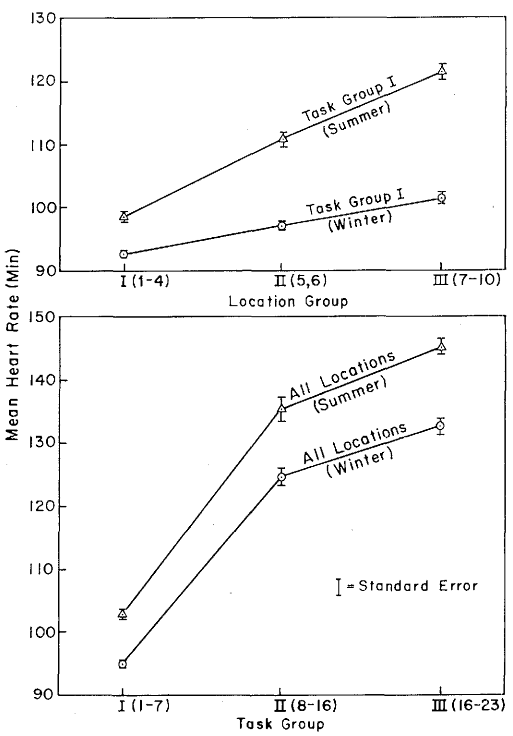

FIGURE 7. Summer and winter tests in S4 and S7 on jobs as second helper, daylight shift (0800-1600). Values are mean *HR* for one test on each in summer and two tests on each in winter. Upper curve: mean *HR* at Location Group I, II, and III for Task Group I values. Lower curve: mean *HR* for Task Group I, II, and III for all locations.

a herniated disc in January 1969. The demands on S2 for the test day reported here, moreover, were great. He had helped in taps on two other furnaces as well as his own. He refused to participate further in these studies expressing fear that the bicycle exercise might injure his back.

Relation of HR During the Workshift to HR During Pre-Shift Exercise

Data from eight summer tests are plotted in Figure 6. In case of S4 *HR* during standard exercise is that observed in an earlier test at 125 watts. Values shown in Table II for S4 are those observed at 150 watts. Values for S3 are means of his four tests (Table II). Data for S3's single test (5/27/69) would raise his *HR* along both the ordinate and abscissa.

The graph indicates a direct relationship between *HR* observed during standard exercise and *HR* during work on the shift. Expressed differently, *HR's* observed on the shift vary inversely with the subjects' predicted maximum aerobic work capacities.[24]

Summer vs Winter Tests

In Figure 7 the effect of season is indicated principally in the flattening of the location gradient in *HR* in winter compared with summer, the winter gradient being only one-third as steep. Complete flattening would not be expected in view of a significant level of heat stress at location 9 in winter (Figure 2).

In contrast, the winter gradient in *HR* for TI-III is displaced downward but the magnitude is essentially unchanged, indicating that cardiocirculatory load from metabolic demands is not significantly affected by season.

Other Results

Total sweat rates for five subjects in eight summer tests averaged 0.72 Kg/hr. Mean sweat rates in two subjects in four winter tests was 0.46 Kg/hr.

Measurements with the heart rate SAMI were made in ten summer tests, including some not reported here, in subjects whose *HR's* were also monitored continuously by the ECG tape recorder. The E-cell of the SAMI was changed every two hours when possible. In any case, the recording period was exactly timed. Readout of the SAMI Ecells for total heart beats over two-hour periods and for the entire shift agreed with the corresponding total for the tape readout within $\pm$ 6%.

Internal temperatures were measured by radiosonde capsule[21] in five tests, including four of the summer tests listed in Table II. Transient elevations reached maxima of 37.8 to 38.8°C in the five tests. The highest was in S2 (Table II). His body temperature was still elevated at the time of the post-shift ergometer test and doubtless contributed in part to the *HR* increment of 18 counts/min observed at four minutes (Figure 5B). His *HR* at that time was still rising when S2 was unable to continue.

Except for occasional premature ventricular contractions (PVC), changes in pattern of the ECG in three subjects did not exceed normal limits associated with high *HR*'s. In S3, however, depression and notching of the T-wave was a consistent finding, usually during bouts of work and early recovery. A 12-lead resting ECG obtained in his screening examination was normal, and there was no history or clinical findings of cardiac abnormality. In S2, multiple PVC's occurred during the 4th minute of exercise (Figure 5B). These disappeared on resting. The changes observed in these two subjects are not diagnostic. Hence the question remains open as to whether or not these non-specific ECG changes during work represent short-term cardiac strain.

Discussion

The experimental design used in our tests divided the eight hour work shift into 960 samples of 30 seconds each, in which *HR* was the dependent variable and task level and heat level were the independent variables. By utilizing the computer we could determine mean *HR* for any of three task levels at any of the three heat stress levels. Confidence limits for differences of the means were also derived by computer from the standard errors. By this means it has been possible in a complex job to evaluate comparative effects of heat and work effort on cardiocirculatory responses to work stresses.

Lacking in our study were direct measurements of *M*, the metabolic heat load. Ford, Hellerstein, and Turell,[1] reported that the average energy expenditure of second helpers in a Cleveland steel mill closely approached 5.0 kcal/min, a level representing approximately 50% of the maximum aerobic capacity which Lehmann[11] regards as the upper tolerable limit for an eight-hour shift. Our data, however, from winter tests in which heat stress was not an important factor, revealed mean *HR*'s of 99.8/min in two subjects on four shifts. From this we would judge that our subjects were either expending considerably less than 50% of their work capacity, which according to I. Astrand[24] should produce a mean *HR* of 113 for men in this age group or our subjects' maximum aerobic capacities were higher on the average than those of Astrand's nine subjects.

Measurement of work capacity from a single submaximal exercise test provided a useful scale for comparing relative work capacities of our subjects. The extent to which this has value in predicting strain on the job is indicated in Figure 6. The relationship between work capacity measured by this method and *HR* on the job has proved consistent in 14 subjects, including the nine some of us reported previously.[17,18]

In S2 and S3 (Figure 5B) the decrement in post-shift performance appeared to be a valid measure of temporary physiological impairment, ie, fatigue. Whether lesser elevations of *HR* during the post-shift exercise signify decrement in work capacity or merely indicate a circadian periodicity in frequency of *HR* as reported by Crockford and Davies[25] will require further study. These authors found that O_2 uptake at a given work rate did not change as did heart rate and pulmonary ventilation rate in observations repeated every 90 minutes for 27 hours.

The SAMI monitor proved to be a rugged, convenient, and reliable instrument for obtaining total heart counts and mean t_s on unsupervised workers performing various jobs in the mill. By comparing mean *HR* at work with mean *HR* off work and during sleep one can assess total demands on cardiocirculatory capacities imposed by the job and by waking activities off the job (Table I). The SAMI seems to be well suited for larger scale studies on industrial populations from which overall circulatory strain could be related to job demands and heat exposure as well as to individual variables such as work capacity, age, and acclimatization. Simultaneous use of the temperature SAMI can be used to assess mean heat exposure as an independent environmental variable. Our studies have demonstrated also the feasibility of using the radiosonde capsule in measuring internal temperature and thermoregulatory strain in industrial workers.

Our results which show an inverse relationship between predicted maximum work capacity and cardiocirculatory strain on the job provide field confirmation of laboratory studies reported by others.[15,16] They suggest that the limits of the prescriptive zone[12,14] should be defined not only in terms of M but also in terms of the percent M represents of the subject's MWC.

It becomes increasingly clear that application of ergonomic principles to hot industrial jobs can be successful only if the engineering assessment of heat stress and workloads is coupled with a quantitative evaluation of the physiological capacities and tolerance limits not simply of the "standard man" but more appropriately of each individual worker at risk.

It might be argued that industrial engineering design for the job of second helper on the open hearth furnace was indeed successful in light of the long work history which each of our subjects presented (Table II). This argument, it seems to us, fails on two counts:

First, it does not take into account the self-selection process, whereby we encounter only those who survived the rigors of the job, so to speak. Lack of a control group prevents our measuring and comparing responses to these stresses in a representative age-adjusted sample of the male population. It may well be significant that of 16 second helpers we have tested thus far, only two were 50 years of age or over.

Secondly, the success of the job design may be questioned on the basis that even among workers whose tolerances meet the minimum requirements for the job, those of marginal capacities may encounter random combinations of heat stress and work demands which exceed the normal range of statistical variation, thus leading to excessive strain and fatigue, as in the case of S2. On the other hand, temporary loss of physiological tolerance in a worker who is usually able to maintain adequate homeostatic balance may reduce his capacities below the required level, as in case of S3 subsequent to returning from a three-week vacation.

Our results further indicate that the primary environmental factor imposing limits on work output is that of heat exposure rather than energy output in completing tasks. The job permits workers periods of rest in essentially comfortable locations (Table III). Such long work pauses seem highly appropriate in the summer season particularly for workers with relatively low physiological capacities. On the contrary, we are inclined to believe, on the basis of limited observations in winter tests, that these men, by and large, work at rates below the optimum level during cold weather.

Alternative solutions to the problem of controlling stresses during summer work are three: (a) provide more effective heat protection through shielding, improved ventilation, or better protective clothing practices; (b) select workers for assignment to such jobs who demonstrate superior physiological capacities; (c) mechanize tasks performed at the rear of the furnace, to reduce M and thus also the total heat load.

Of the three, selection of workers does not appear to be the option of choice, except to avoid assigning workers inferior in work capacity or heat tolerance to such jobs. To select only those of superior capacities would compound the under-utilization of manpower in cool seasons by understressing them to an even greater degree than workers of average capacities.

Although mechanization of heavy lifting, prying slag, and other heavy tasks would reduce M, it seems clear that the method of choice is the first, namely improved heat protection.

An example of ventilation protection was seen at location 9. In Figure 2, one notes that the slope of the rise in t_g from location 7 to 8 is not continued but flattens between locations 8 and 9. This can be attributed to a spot-cooling fan directed at the working area of location 9. This was invariably used in summer work. By contrast, the slope from location 8 to 9 in winter tests (Figure 2) becomes steeper. This is because often the fan was not used. At one furnace, in fact, it had been dismounted. One winter test day, measurements were made at location 9 with fan on and fan off with the following results (°C):

	t_g	t_{nwb}	WBGT
Fan off	92	25.3	45.3
Fan on	42	17.6	25.1

Thus the fan converted an intolerable environment into a comfortable one.

Water cooled grids reduce radiant heat load judging by the lower t_g with fan off on the right of the the tap hole as compared with a symmetrical position on the left without such a grid.

In the job of skimmer in an aluminum plant in the southern U.S., Leinhard et al[3] observed at the work site the following temperatures (°C) before reflective shielding: t_g 71.7, DB 47.8, and WB 30.5 (WBGT 42.9) and after shielding, t_g 43.3, DB 43.3, WB 32.2 (WBGT 35.5). Pulse rate of the skimmer before shielding was 168; after shielding 116. The unshielded position closely approximates summer conditions at location 9 in heat stress level (Figure 2). Their results suggest reflective shielding might be a useful approach to reducing summer heat exposure of furnacemen.

It was observed that men use aluminized protective clothing only during the tap. They seemed to recognize radiant heat and its effects when the radiation was visible but tended to ignore it when invisible. In any event, workers quickly discarded the reflective garment as soon as the flow of molten metal had ceased. More rational use of the protective garment might help in controlling heat strain.

Special cooling devices, such as the vortex tube or air supplied ventilated suits should be considered but these might introduce an accident hazard. Self-contained cooling units worn under reflective garments are used in other departments of the mill but not in the open hearth department.

The careful analysis of work stresses reported by Dukes-Dobos et al[4] reveal that aluminum pot workers in summer sustain somewhat higher radiant heat loads than furnacemen at location 9. Mean sweat rates for the shift, however, were somewhat lower than we observed in our summer tests (Table II). We agree with these authors that peak sweat rates in their workers and in ours probably exceed 1 Kg/hr in view of the long rest periods in relatively cool locations.

The methods for sampling and analysis we used in evaluating effects of heat and work on *HR* do not take the time sequence of events into account. Hence data for LI-II (Table III) include many observations immediately after work and/or heat exposure as well as those following prolonged rest. Moreover, if a decrement in performance occurs during the shift as well as in the post-shift exercise, this may depend on the patterns of activity, rest, and heat exposure as well as on the total sum of time in each category. Studies are now in progress to evaluate patterns of work activity and changes in location during the shift, and to relate these to physiological responses and manifestations of fatigue.

Acknowledgments

The authors wish to express their deep appreciation for the active interest and willing cooperation extended to us by the medical staff and managers of the plant. Particularly we appreciate the participation in this research by workers in the open hearth department who served so ably as subjects.

We are indebted to Dr. Robert J. Halen, medical director of the Jones and Laughlin Steel Corporation and also Mr. Robert Lyon, superintendent, and Mr. Stephen Glumac, supervisor, of the open hearth department of The Pittsburgh Works who provided the support so essential to the success of this project.

We wish also to thank Mr. Arthur A. LeGasse, Department of Biostatistics, Graduate School of Public Health, for his invaluable advice and help in computer programming.

Finally, we owe much to the technical skill

and constructive ideas of our assistant, Mr. David Shaw.

References

1. FORD, A. B., H. K. HELLERSTEIN, and D. J. TURELL: Work and Heart Disease. II. A Physiologic Study in a Steel Mill. *Circulation 20:* 537 (1959).
2. LEITHEAD, C. S., and A. R. LIND: *Heat Stress and Heat Disorders.* F. A. Davis Co., Philadelphia, Pa. (1964).
3. LIENHARD, W. F., R. S. McCLINTOCK, and J. P. HUGHES: Appraisal of Heat Exposures in an Aluminum Plant. Proceedings of the Thirteenth International Congress on Occupational Health, p. 879, Book Craftsmen Assoc. Inc., NYC (1961).
4. DUKES-DOBOS, F., *et al.*: *Industrial Heat Stress. Southern Phase.* USPHS Division of Occupational Health, Cincinnati, Ohio, RR-5 (Dec. 1966).
5. BROUHA, L.: *Physiology in Industry.* Pergamon Press, NYC (1960).
6. BROUHA, L., M. E. MAXFIELD, P. E. SMITH JR., and G. J. STOPPS: Discrepancy Between Heart Rate and Oxygen Consumption During Work in the Warmth. *J. Appl. Physiol. 18:* 1095 (Nov. 1963).
7. ROWELL, L. B., J. A. MURRAY, G. L. BRENGELMANN, and K. K. KRANING II: Human Cardiovascular Adjustments to Rapid Changes in Skin Temperature During Exercise: *Circulation Res. 24:* 711 (May 1969).
8. KRANING II, K. K., H. S. BELDING, and B. A. HERTIG: Use of Sweating Rate to Predict Other Physiological Responses to Heat. *J. Appl. Physiol. 21:* 111 (Jan. 1966).
9. SNOOK, S. H., and C. H. IRVINE: Psychophysical Studies of Physiological Fatigue Criteria. *Human Factors 11:* 291 (1969).
10. ASTRAND, I.: Degree of Strain During Building Work as Related to Individual Work Capacity. *Ergonomics 10(3):* 293 (1967).
11. LEHMANN, G.: Physiological Measurements as a Basis of Work Organization in Industry. *Ergonomics 1(4):* 238 (1958).
12. LIND, A. R.: A Physiological Criterion for Setting Thermal Environmental Limits for Everyday Work. *J. Appl. Physiol. 18:* 57 (Jan. 1963).
13. NIELSEN, M.: Die Regulation der Korpertemperatur bei Muskelarbeit. *Skand. Arch. Physiol. 79:* 193 (1938).
14. LIND, A. R.: Effect of Individual Variation on Upper Limit of Prescriptive Zone of Climates. *J. Appl. Physiol. 28:* 57 (Jan. 1970).
15. SALTIN, B., and L. HERMANSEN: Esophageal, Rectal, and Muscle Temperatures during Exercise. *J. Appl. Physiol. 21:* 1757 (1966).
16. WYNDHAM, C. H., N. B. STRYDOM, C. G. WILLIAMS, and A. HEYNS: An Examination of Certain Individual Factors Affecting the Heat Tolerance of Mine Workers. *J. So. Afr. Inst. Mining and Metallurgy* (Sept. 1967), pp 79-91.
17. LAMBIOTTE, B., and D. MINARD: Heart Rate During Industrial Work in Relation to Estimated Aerobic Work Capacity. (Abst) *Fed. Proc. 27:* 231 (Mar.-Apr. 1968).
18. FARRIER, P., and D. MINARD: Physiologic Responses to Work Stress in Steelworkers. (Abst) *Fed. Proc. 28:* 527 (Mar.-Apr. 1969).
19. BAKER, J. A., S. J. E. HUMPHREY, and H. S. WOLFF: Socially Acceptable Monitoring Instruments (SAMI). *J. Physiol. (London) 88:* 4 P (1967).
20. HOLTER, N. J.: New Method for Heart Studies. *Science 134:* 1214 (1961).
21. FOX, R. H., R. GOLDSMITH, and H. S. WOLFF: The Use of Radio Pill to Measure Deep Body Temperature. *J. Physiol (London) 160:* 22 (1962).
22. YAGLOU, C. P., and D. MINARD: Control of Heat Casualties at Military Training Centers. *AMA Arch. Ind. Health 16:* 302 (Oct. 1957).
23. GOLDSMITH, R.: (in preparation).
24. ASTRAND, I.: Aerobic Work Capacity in Men and Women with Special Reference to Age. *Acta Physiol. Scandinav. 49:* Suppl. 169 (1960).
25. CROCKFORD, G. W., and C. T. M. DAVIES: Circadian Variations in Responses to Submaximal Exercise on a Bicycle Ergometer. *J. Physiol. (London) 201:* 94 P (1969).

Received June 8, 1970

Electron Gun for Cutting Rock

Under a contract awarded by the U. S. Bureau of Mines, a gun that cuts rock with a high-energy electron beam has been developed by the Westinghouse Electric Corporation. A contract also has been awarded to this corporation to fieldtest the new device this year.

The gun is derived from an electron beam welding devices but is much less bulky and more portable. Its rock-cutting potential has been successfully demonstrated in the laboratory, where it has been used to melt narrow grooves in sample blocks of various types of rock. Its practical value in mining and tunneling has not been tested as yet.

This electron beam gun may offer a significant advance in mining and technology. There has been little change in mining technology for a great many years. Most hard rock mines still rely on drilling and explosives to break rock with the attendant hazards known for these many years. More recently the continuous mining machine has come into use, principally in coal mines, but these devices are heavy, expensive and not yet capable of cutting the harder types of rock. A preliminary cost analysis indicates that the electron beam gun could be developed to be economically competitive with conventional rock-breaking methods.

Mining or tunneling with the electron gun would involve cutting spaced kerfs in the rock and breaking out the material between cuts. In the process there would be some molten rock produced with the possibility of fume and vapors released from the rock. This appears to be a development which will need some study and possibly will pose some problems for the industrial hygienist, if it comes into significant usage.