9.—PHYSIOLOGIC MONITORING OF HEART RATE, SWEATING, BODY TEMPERATURE, AND METABOLIC COST DURING THE WORK SITUATION

Peter B. Raven

The development of procedures for monitoring physiological parameters such as heart rate, body temperature, weight losses due to sweating and job metabolic cost in industrial plants has been the practical concern of work physiologists for many years (*1–2*)[1]. The procedures to be described have been employed in studies conducted in a number of plants of the Aluminum Company of America (Alcoa) over an 11-year period. Standardization of procedures was a prerequisite before embarking on such projects and involved the rigorous training of personnel used in collection of the data. The techniques used and the reasons for choosing such techniques form the basis of the discussion outlined below. In all studies collection of the data was carried out by trained nurses. However, even though these nurses were adequately trained for the accident and routing examinations of the industrial plants it was felt necessary to review specific procedures for the collection of the data, for example exercise heart rates by palpation. This training was undertaken in a 2 day concentrated review session under the control of the consultant physiologist. Use of nurses in such situations greatly enhance the cooperation of the workers.

HEART RATE DETERMINATION

Recent advances in technical development such as telemetry and miniaturized tape recorders (*3*) allow recording of ECG and heart rates at distances from the subject (Figure 9–1). It is of interest to note that the aluminum industry, by reason of its methods of ore reduction (electrolysis at high temperatures), presents unique problems for all electronic monitors. The reduction process produces a powerful electromagnetic field strong enough to disrupt transmission and reception of electronic signals. Since similar interference may be inherent in other processes, it is suggested that the methods used for collection of heart rates should be dependent on the industrial environment.

Simple economics rules that one should use the established method of radial palpation. Since the early work of Johnson, Brouha, and many others at the Harvard Fatigue Laboratory (*4–5*), it has been well recognized that recovery heart rates could be used as an indicator of physical stress and of the individual's physical fitness. Also, by measurements of the pulse rate within 3 minutes at three distinct times following work stress, they were able to predict the exponential recovery curve of the heart rate from the work rate back to the resting level. Realizing these relationships and the difficulties in obtaining electrocardiographic recordings of the heart rate during aluminum production, it was decided to use a standardized approach in obtaining the recovery pulse rates described below. It was necessary for the nurses to practice obtaining pulse rates by

[1]Italic numbers in parenthesis refer to items in the list of references at the end of this chapter.

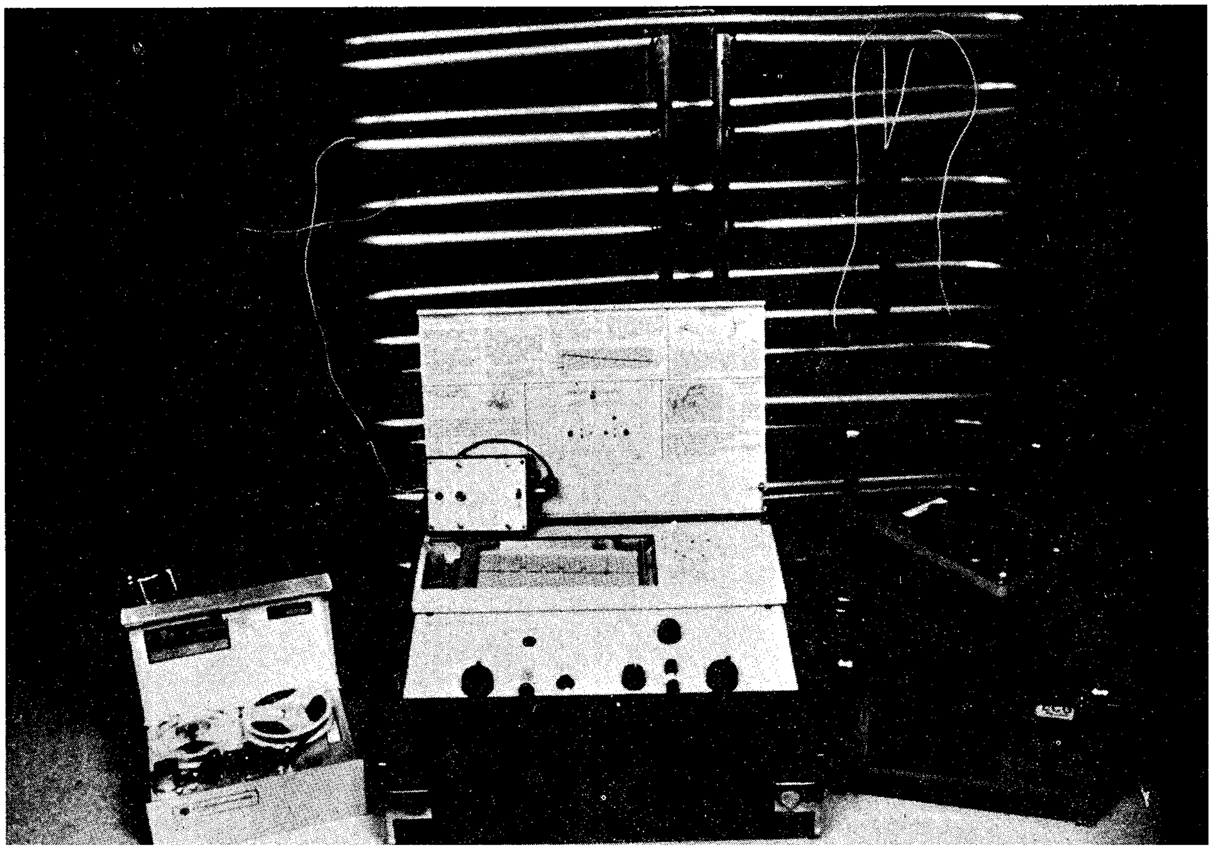

FIGURE 9–1.—Heart rate monitoring equipment.

radial palpation using both a 15- and 30-second count when the rate per minute was above 160. As soon as the worker was through with the operation being studied, the nurse seated him and started the stopwatch. An immediate 0–15 second rate to be multiplied by four was obtained, followed by 30-second counts expressed per minute obtained at 30–60 seconds, 90–120 seconds, and 150–180 seconds after completion of the work. All rates were obtained at the wrist. The obtained values represented heart rates at the end of work at 1 minute, 2 minutes, and 3 minutes following work. The same procedure was followed throughout the day. Also, the worker reported to the observer before starting each shift and a resting pulse rate was taken. Similarly, a final post shift heart rate was obtained by the nurse.

CORE TEMPERATURE DETERMINATION

There are many methods of obtaining core temperature, all of which have their own advantages and disadvantages. The most widely used method by physiologists is that of using an indwelling probe (either a thermistor or a thermocouple) at a depth of 12 cm into the rectum. Other places of measurement consist of the esophagus and tympanum (*6–7*), and it has been demonstrated by swallowing small transmitting devices that core temperature can be monitored by telemetry (*8*) (Figure 9–2). All these techniques allow continuous measurement of core temperature, of which esophageal and tympanic temperature have a faster response to rapid changes in core temperature than does rectal temperature (*9*). Both esophageal and tympanic temperature involve a large degree of subject discomfort compared to that of rectal temperature; however, the major drawback to the use of all three methods used in an industrial situation is the necessity to have trailing monitor cables or complex recording equipment. In most industrial work where rapid movement is a necessity, these types of monitoring devices would be a hindrance to the worker. Telemetry would be possible in some situations; however, as explained previously, not in the aluminum industry. Also, recovery of the type of devices which are swallowed would prove impractical, as would the use of rectal thermometry, because of the necessity to remove clothing and personal prejudice against such measurements.

Earlier work by Horvath and co-workers (*10–11*) has delineated the pattern of response of the rectal and oral temperatures taken simultaneously at different times of the day and also during heat exposure. These investigations demonstrated that the oral temperature response closely followed rectal temperatures and the average difference between oral and rectal temperatures during the day was 0.8 F (0.4 C) and averaged 1.2 F (0.7 C) difference when exposed to 120 F DB for 2 hours. The finding that under standardized measurement conditions the oral temperature both follows rectal temperature and closely approximates its absolute value leads one to suggest the use of oral thermometry for following core temperature in the industrial situation. Oral thermometry has many outstanding advantages in adaption of its use to the industrial situation, some of these being ease of application, economy, and more importantly, it will not physically or psychologically disturb the worker.

In the Alcoa studies, oral temperatures were obtained by means of a standard 3-minute clinical thermometer. In order to allow such a thermometer to reach equilibrium in the oral cavity, 3 to 4 minutes was required. All glass thermometers must be calibrated over their working range by using a constant temperature water bath and Bureau of Standards standardized thermometer. A methodological problem of using oral thermometers in hot environments was the rapid elevation of the mercury when the thermometer was exposed to the ambient environment. This was prevented by keeping the shaken down thermometer in alcohol baths surrounded by iced water until required by the nurses. Oral temperatures are satisfactory only when a controlled situation is maintained. Talking, mouth breathing, smoking, eating, and drinking all affect mouth temperature. In the industrial situation, during the measurement these factors can easily be controlled; however, such factors as talking and mouth breathing prior to the determination are difficult to control. Measurements of the oral temperature were made in conjunction with the heart rate determinations, providing adequate time to attain a correct value.

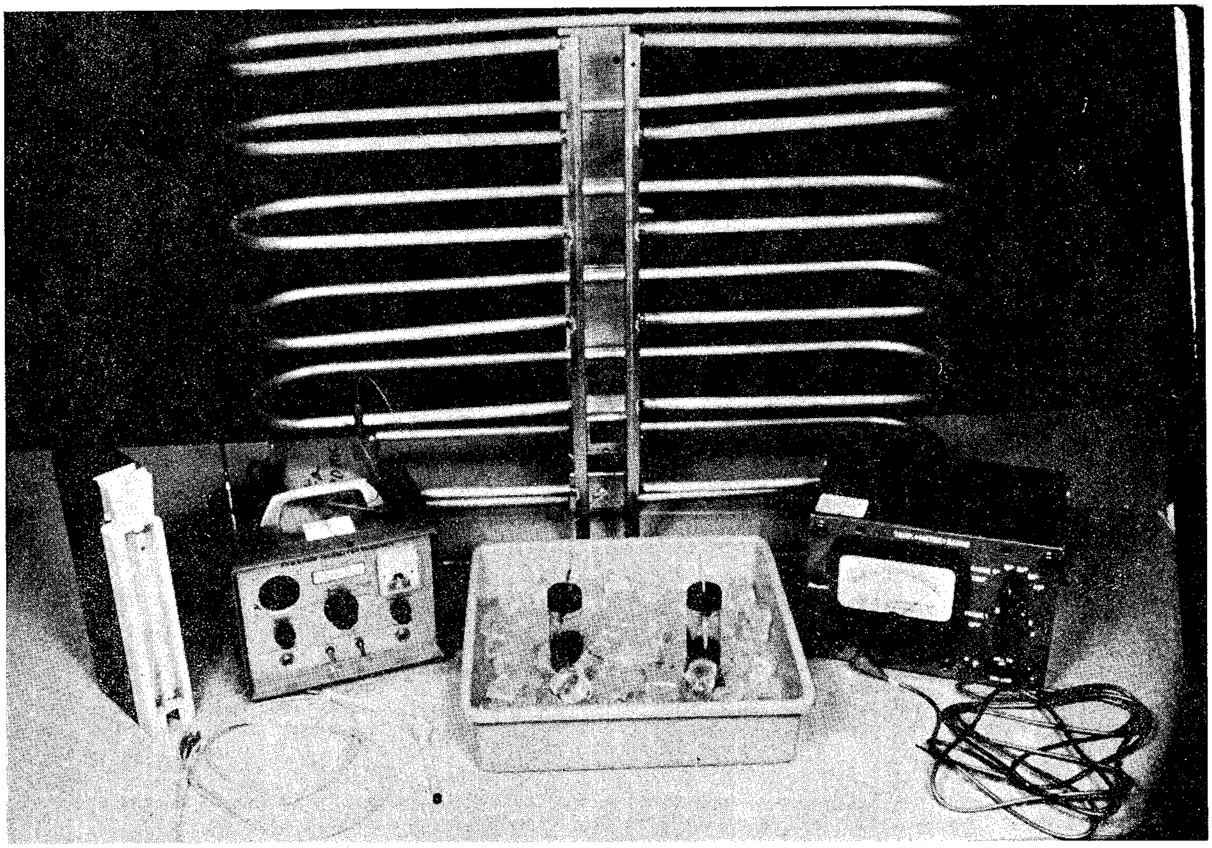

FIGURE 9–2.—Body temperature monitoring equipment.

Following each task being studied, the worker reported to the nurse and was seated. The nurse started the stopwatch and placed the thermometer under the worker's tongue and ensured mouth closure for 4 minutes. During this time, the required heart rate measurements were made. The oral temperature was read and recorded at the end of 4 minutes. The thermometer was then immediately shaken down and placed in the alcohol bath in the ice water. Workers were instructed not to drink before the oral temperature was taken and also to keep the lips closed during the measurement. As described for heart rates, a pre and post shift oral temperature was taken for each day of the survey.

The same procedure for the measurement of oral temperature and heart rate was followed throughout the day and each day of the survey. Other devices for recording oral temperature involve the use of thermistors, which have the advantage of a more rapid response, but electrical fields may produce improper values.

BODY WEIGHT LOSSES DUE TO SWEATING

The need for adequate hydration and salt intake during heat stress has been demonstrated many times since the classical investigations of Dill and Talbott at the Boulder (nee Hoover) Dam works indicated the necessity of adequate salt and water replacement in order to maintain working efficiency (*12*). More recently, Pitts et al. (*13*), by continuously maintaining water balance, demonstrated that a large percentage of the physiologic strain resultant to working in the heat was alleviated. Hence, for all industries in which a heat stress is imposed a close watch on the degree of dehydration of a worker should be maintained and ready for both water and salt are prerequisites. It was Dill and Talbott's (*12*) suggestion that with adequate salt replacement water balance would be maintained as a corollary. Unfortunately, man does not have the ability of the physiological drive to carefully regulate his intake to his losses, nor is he able to judge his salt or water balance finely enough to satisfy short-term losses. Salt and water were made available to all workers. In order to determine the degree of sweat production and water loss, careful measurement of weight change and water intake was made both on a daily shift basis and over the usual 7-day work week.

The primary and most simple method of determining the amount of sweat produced is by monitoring the total amount of body weight lost and making appropriate fluid intake and output corrections. A simple way of looking at this is by the simple equation:

$$\text{Balance} = \text{input} - \text{output} \qquad (1)$$

If in equation (1) input is greater than output, then we are said to be in positive balance in terms of water balance, or hyperhydrated. The reverse is true when the output is greater than input and one is said to be hypohydrated (or dehydrated); that is, in negative balance. However, the balanced state or euhydrated state is the optimal condition for all workers. In the industrial situation water losses due to sweat can be expressed as follows:

$$\begin{aligned}\text{Sweat loss} = {} & (\text{pre shift nude weight} \\ & - \text{post shift nude weight}) + (\text{mass } CO_2 \\ & - \text{mass } O_2 \text{ uptake}) - (\text{solids excreted} \\ & - \text{solids consumed}) - (\text{mass urine excreted} \\ & - \text{mass of } H_2O \text{ consumed}) + \text{mass } H_2O \text{ respired}\end{aligned} \qquad (2)$$

However, the only accurately determined factors of equation (2) in the industrial situation will be the pre and post shift nude weights, the mass of urine excreted and the mass of water consumed. Weight changes due to respiratory water loss (a possible thermoregulatory process) and the differences in mass of carbon dioxide and oxygen can be and were ignored in the Alcoa studies. Those nurses involved in the studies were asked to list the food intake and the approximate amounts of food eaten to stress the amount of solids consumed and so their water content could be estimated. The subjects were asked to regulate their bowel movements, if possible, to times before the pre weighing and following post weighing. Water consumed was measured directly in volume by giving the subject a known volume prior to the shift in a labelled plastic container with caps and determining the amount drunk by difference following the shift. This eliminates the possibility of changes in weight due to dust and dirt contamination, and also this provides the workers with some indication of the volume of water he needs to drink. Any extra fluids such as coke, etc., were recorded by the nurses. Urinary volumes and specific gravity were determined on the pooled collection of each subject throughout the shift. The urine samples were collected in labelled plastic bottles with caps so that subjects did not mix the samples. Both water bottles and urine collection bottles were collected by the observers at the end of each shift. Prior to the shift, at the end of the first work period (lunch time), and following the second work period (that is at the end of the shift), each subject was weighed nude. Hence, the equation for sweat loss throughout the day in the Alcoa studies becomes:

$$\text{Sweat loss} = (\text{pre shift nude weight} - \text{post shift nude weight}) + (\text{water consumed} - \text{urine excreted}) + \text{solids consumed} \quad (3)$$

It was observed from the data of the earlier studies that it was the practice of the workers to divide their work day into two sections, sometimes doing all their work in the pre lunch (four hours) and resting in the post lunch (4 hours) or vice versa. Therefore, it was decided to include a mid-shift weighing and measurement of fluids, etc., to enable the investigators to determine the influence of the individual's pattern of work and the WBGT on his fluid intake and sweat production.

DETERMINATION OF JOB METABOLIC COST

The only practical means of determining energy requirements of specific tasks in an industrial situation is to use the technique of indirect calorimetry. Indirect calorimetry requires the determination of oxygen uptake per unit time for a given task. Laboratory methods for collecting, metering, and analyzing expired air have been established for 70 years or more, and the techniques of determination in a laboratory are excellently described by Consolazio et al. (*14*). Despite early confirmation that there existed little or no error between direct and indirect calorimetric determinations of energy cost (*15*), it has recently been suggested that use of the Haldane transformation to obtain the true amount of oxygen used from analysis of expired gases was in error (*16–17*). Such a suggestion would mean that field studies for the determination of the energy cost of a task would not be feasible. However, a careful evaluation of this problem indicates that the use of the Haldane transformation for the determination of oxygen uptake showed no difference from that determined from a direct measurement of oxygen uptake from the inspired side (*18*). Hence, in all studies carried out at the Alcoa plants indirect calorimetry was the technique of choice.

The best procedure for determining daily metabolic costs of a job situation is to break down the job into the component tasks (i.e., walking, lifting, hammering, etc.), determining accurately the time spent at each task, and then measuring the metabolic cost of the component tasks. A summation of the product of each task's time and energy cost will provide a daily job total of energy cost. Timing studies are the means of obtaining an accurate time allocation for each task; however, obtaining accurate estimates of the energy cost of each task is more difficult. Despite the existence of standardized tables outlining energy costs of tasks found in specific industries (*1–2, 19*), the specific job of the worker in other industries may involve a slightly different energy requirement, and therefore investigations of jobs found within many industries have not been carried out.

The only two practical methods for determining energy cost of industrial tasks are the Douglas bag method and the use of a Kofranyi-Michaelis (K-M) respirometer. Both of these methods have their advantages and disadvantages. Until World War II, job energy costs were determined by the Douglas bag method; however, this method's major disadvantage was the large bulk of the collecting apparatus, which has been corrected in present-day studies. Without doubt, the development of the K-M respirometer in 1940 (*20*) at the Institut für Arbeitsphysiologie and its modification (*21*) enabled greater in-depth assessments of the metabolic cost of all forms of activity (Figures 10–3 and 10–4). However, the K-M respirometer, because of its sampling system, is only really suitable for the determination of energy costs where steady-state and repetitive tasks are performed. Hence, in an industry where tasks are nonrepetitive on a time sequence

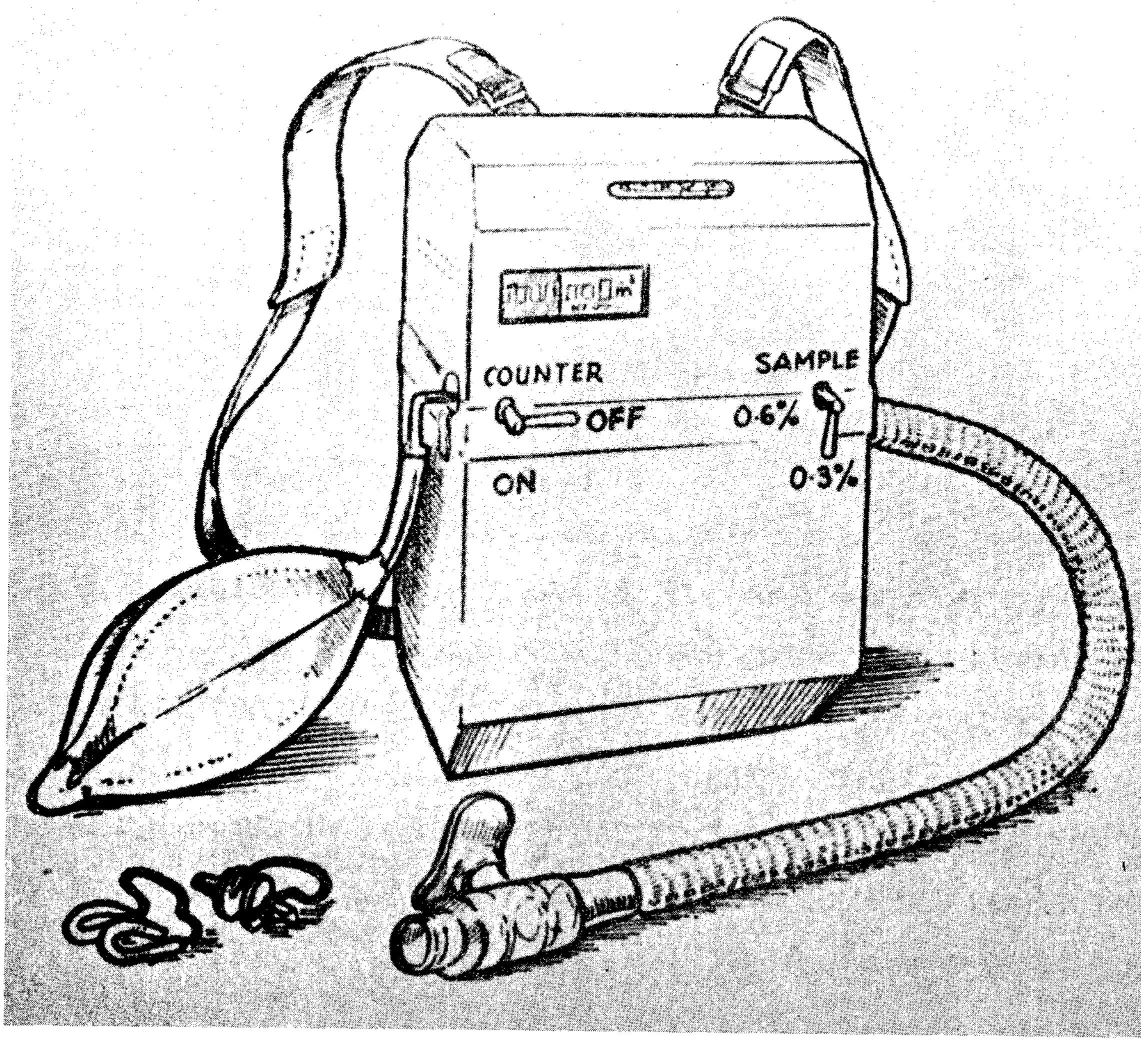

FIGURE 9–3.—The Max Planck respirometer.

basis and require only fractions of a minute to perform, a more accurate method of actual job energy determination can be obtained by a "spot" sampling technique using a modified lightweight Douglas bag method. A comparison of the methodology of the two is outlined below. The K-M respirometer consists of a small dry gas meter weighing 3 kilograms (6.6 pounds) which is connected by a hose to a lightweight expiratory valve. The gas meter contains a device by which a small fraction of the expired air is diverted into a rubber aliquot bag, which is subsequently analyzed for oxygen and carbon dioxide. Specific calibration and operational procedures are adequately described by Consolazio et al. (*14*) and do not need repeating, except that one must be extremely careful in obtaining the correct calibration factor for the gas meter. The aliquot bag becomes full in approximately 10 to 30 minutes, dependent upon sampling rate, bag size, and ventilatory volumes, and in effect averages the variations in energy expenditure over the sampling time.

The "spot" sampling technique requires a lightweight gas collection system designed as a modification of the Douglas bag technique

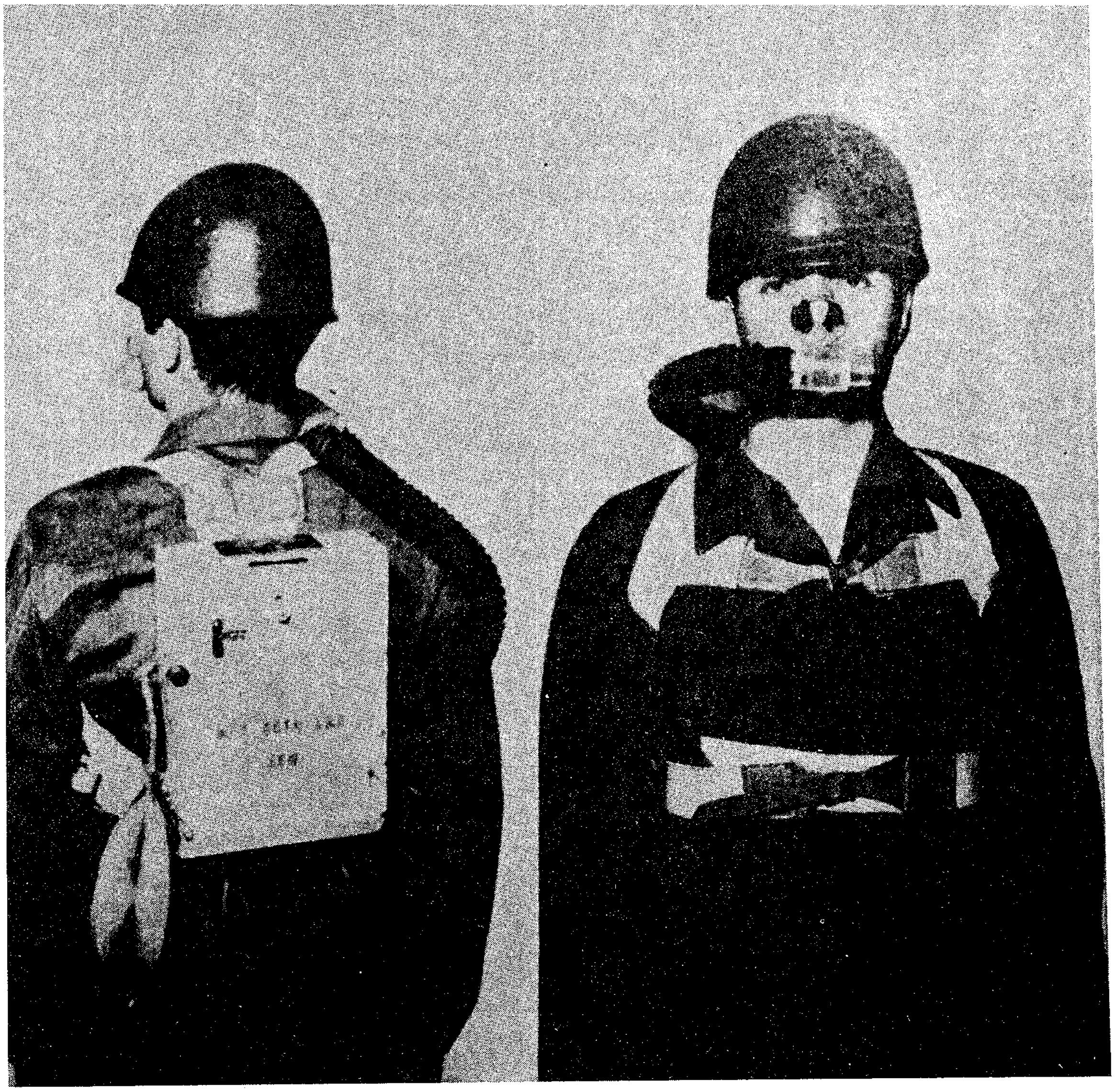

FIGURE 9–4.—Kofranyi-Michaelis meter in use on subject. (From *Physiological Measurements of Metabolic Functions in Man,* by C. F. Consolazio, R. E. Johnson, and L. J. Pecora. Copyright 1963 by McGraw-Hill Book Company. Used with permission of McGraw-Hill Book Company.)

(Figure 9–5). A 30-liter plastic weather balloon was attached to a manually operated acrylic "piston throw" valve unit. The valve unit formed a T-junction between the balloon and a plastic breathing hose connected to the expired side of a low resistance breathing valve (weight — 78 grams) or between the air and the expired hose. A shoulder harness was used to support the valve and balloon while an acrylic head harness supported the breathing valve and hose. Also, a noseclip was used to ensure mouth breathing. The total weight of the collection system, inclusive of head and shoulder harness and hose, was 1000 grams (2.2 pounds). This system was found not to impede working movements, even when the men were working at high levels of energy expenditure. The time spent on a particular task and the time used for collection of the sample were measured with a stopwatch. The volume of expired air collected was measured with a Tissot calibrated dry gas meter, and

FIGURE 9–5.—Lightweight gas collection system used for calculation of job energy costs.

oxygen content of the gas was analyzed by means of a paramagnetic oxygen analyzer (Beckman Model C2). Carbon dioxide content was determined indirectly using a carbon dioxide absorber and calculating back from the difference in oxygen volume. Other more complicated gas analyzing devices are available and should be used if possible.

$$\frac{V_{O_2}{}^{F} - V_{O_2}{}^{I}}{V_{O_2}{}^{F}} \times 100 = \text{percent } CO_2 \qquad (4)$$

The obtained data volume of expired air, oxygen, and carbon dioxide contents of the expired air enables one to calculate the oxygen requirement of the task. Determination of the carbon dioxide content of the expired air allows calculation of a respiratory exchange ratio ($\dot{R}$), which further permits a more specific calculation of energy equivalent of oxygen at the specific $\dot{R}$ (*22*). However, a simplification of this method was formulated by Weir (*23*) in 1949 in which he calculated the energy equivalent of a task from the expired oxygen content of the air. Determination of R also enables the investigator to evaluate the degree of hyperventilation that is occurring during the task. The "spot" sampling technique permits many samples to be collected at one time on many different tasks. The plastic weather balloons are impermeable to carbon dioxide and oxygen. However, working in industrial environments one must be extremely careful to avoid damage by not allowing the balloons to make contact with sharp edges or high radiant sources. It should be noted that this technique does not permit one to evaluate the total volume of oxygen required, thereby ignoring oxygen debt for a task, but does allow one to get a level of oxygen uptake (liters/minute) necessary to complete the task.

Considering the large range of ages of workers (20–65 years), an absolute level of energy required to do the job has little meaning unless related to the individual's maximal capacity at his age. For example, in the Alcoa studies maximal aerobic capacity ($\dot{V}_{O_2\ max}$) of the workers was determined (Figures 9–6 and 9–7) both directly and indirectly using a bicycle ergometer (*24–25*). It is well known that maximal aerobic capacity decreases with age after 30; therefore, an age correction factor (*26*) was used for the prediction of the individual's aerobic capacity. In either case, when the $\dot{V}_{O_2\ max}$ was finally obtained, the investigators were able to relate the job energy requirements to the worker's maximal capacity and ascertain the level of reserve capacity that the worker has during the specific task. It was found that the average percentage $\dot{V}_{O_2\ max}$ of the job energy requirements was 33 percent (Table 9–1). Table 9–2 outlines the absolute energy levels of the tasks found in two aluminum smelting plants and gives ranges of variability to be found.

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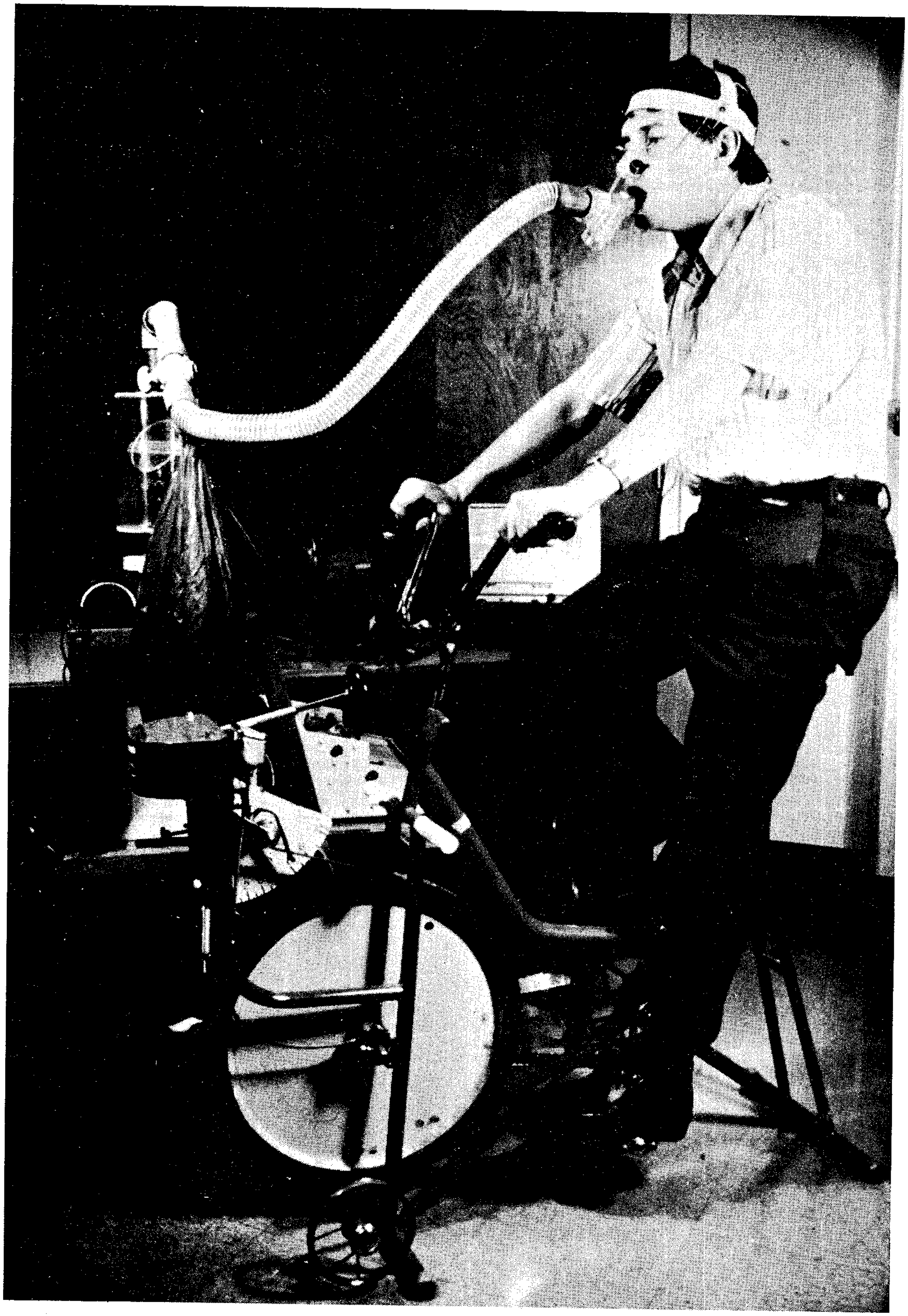

FIGURE 9–6.—Equipment utilized in the field to determine maximal work capacity.

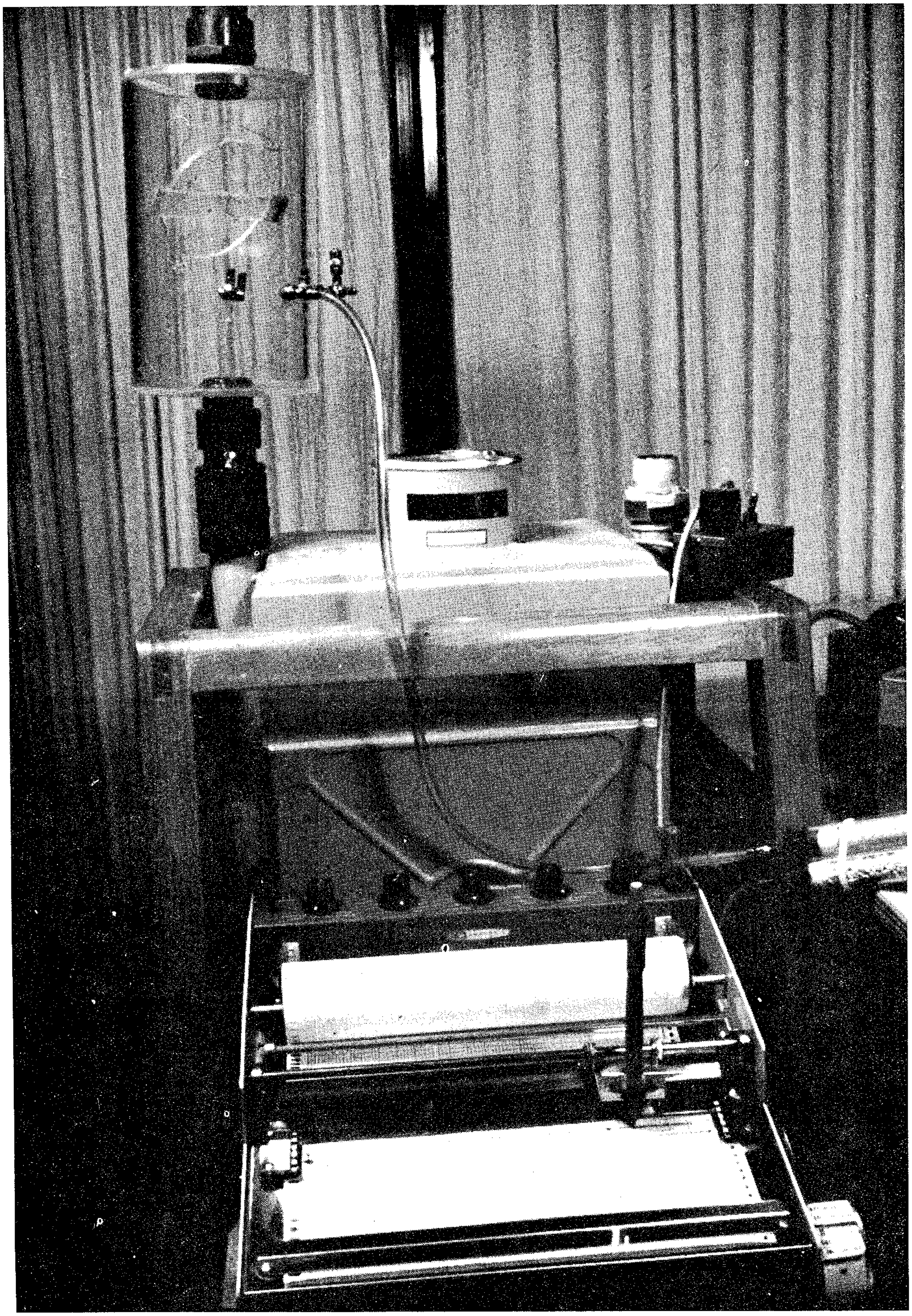

FIGURE 9–7.—Ventilation volume monitoring equipment.

TABLE 9-1.—Energy cost of selected jobs in aluminum reduction plant

Subject, number	Description of job	Sodaberg Operations: Job measurements $\dot{V}_{O_2}$ (L/min)	$\dot{V}_E$ BTPS (L/min)	$\dot{R}$	Time of collection, secs	Total time of job, secs	Pred. BMR (kcal/ $m^2 \cdot hr$)	Metabolic cost of job: mets	Percent $\dot{V}_{O_2\,max}$
1.	Sitting	0.37	15.1	0.94	92.8	92.8	36.73	1.6	17.0
	Using Automatic CB on 1 Pot	07.5	21.2	0.84	75	75	36.73	3.0	34.5
	Using Automatic CB on 1 Pot	0.76	23.2	0.93	66	66	36.73	3.1	35.0
	Using Automatic CB on 1 Pot	0.89	26.7	0.89	51	51	36.73	3.7	32.0
	Using Automatic CB on 1 Pot	0.94	28.7	0.84	35	35	36.73	3.7	43.0
	Using Automatic CB on 1 Pot	0.94	26.5	0.84	48	48	36.73	3.7	43.0
	Oreing Pot	0.75	21.5	0.89	58.2	58.2	36.73	3.1	34.5
2.	Sitting	0.27	8.7	1.01	150	150	36.10	1.1	7.7
	Auto CB Front of Pot	0.61	14.0	0.91	80	80	36.10	2.5	17.5
	2 Pots CB Front of Pot	0.62	14.1	0.93	83	83	36.10	2.6	17.5
	Walking, Sweeping and Oreing 2 Pots	0.82	17.6	0.86	64.2	64.2	36.10	3.4	23.0

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TABLE 9–2.—Summary of energy expenditures of aluminum workers (cals/min) in the smelting plant

Job description	Plant 1	(range)	Plant 2	(range)
Prebake Plant:				
Walking	3.0	(2.5–3.5)	2.5	(2.0–3.0)
Sitting			1.5	(1.1–1.6)
Using 14 lb. Hammer to Break Carbon Butts	5.5			
Crowbar Breaking Crust	6.5	(6.0–7.5)	5.5	
Crowbar on Carbon	8.0	(7.5–8.5)		
Picking up and Throwing Carbon Butt	8.5			
Rowelling Pot	5.5		4.5	
Setting Siphon	3.4		4.9	
Working Around Crucible	4.9		4.0	
Skimming Metal in Crucible	6.0	(5.5–6.5)		
Setting Carbons	3.5	(3.1–8.0)	3.0	
Working Carbons Into Alignment	4.0	(3.0–8.0)	3.6	
Ored 2 Carbons	4.5	(4.1–5.1)		
Ored 3 Carbons	5.5	(4.5–6.9)		
Pneumatic Crust Breaker	4.0	(3.0–5.1)		
Remove Radiant Shield			5.5	
Unhook Carbons			3.0	
Loosen Bolts on Carbons With Air Gun			4.0	
Cleaned 1½ Carbon Butts With Jack Hammer			5.0	
Using Jack Hammer to Clean Crucible			4.8	(2.8–6.0)
Riding Tricycle at Inspection Speed			2.5	
Sodaberg Plant:				
Pneumatic Crust Breaker			3.7	(2.6–3.8)
Walking, Sweeping and Oreing			3.1	(2.9–3.4)
Crust Breaking With Jack Hammer			4.5	(4.3–4.6)
Standing, Recovery From Breaking Crust			2.5	

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STANDARDS FOR OCCUPATIONAL EXPOSURES TO HOT ENVIRONMENTS

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