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APPLICATION OF THE INFRA-RED GAS ANALYZER TO THE STUDY OF HUMAN ENERGY METABOLISM*

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from

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ABSTRACT

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OBJECT

The determination of the caloric expenditure of troops during maneuvers has resolved itself into the establishment of a suitable practical field method for measurement of respiratory changes in man in such physical situations that would not permit the use of existing apparatus. A method was desired which would offer 2 advantages over present field techniques: (1) graphic continuous analytical record over protracted periods rather than period averages for short duration effort, and (2) portable equipment which would measure actual expenditure of a particular activity rather than an additive effect of the exercise plus apparatus load.

RESULTS

A new technique for measurement of caloric expenditure during continuous activity has been developed. Both laboratory and field trials have proved the adaptability of the Leeds and Northrup selective gas analyzer to the estimation of carbon dioxide in expired air. Caloric expenditure studies on men undergoing mountain warfare training have been accomplished. The new method offered instantaneous analysis and continuous records over protracted periods of activity.

CONCLUSIONS

The infra-red analyzer equipped with an adequate pumping system for controlled air flow has been adapted to metabolic work and found satisfactory, both in the laboratory and in the field.

RECOMMENDATIONS

The apparatus developed and tested is satisfactory for routine study of respiratory exchange. To obtain absolute fidelity, i.e. synchronization of recorded response with respiratory excursion, and continuous analytical records of oxygen utilization, should be the aim of subsequent investigation.

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APPLICATION OF THE INFRA-RED GAS ANALYZER TO THE STUDY OF HUMAN ENERGY METABOLISM

I. INTRODUCTION

The problem of caloric expenditure studies on troops engaged in military maneuvers resolved itself into the establishment of a suitable practical field method for determining respiratory changes in man in such physical situations that would not permit the use of bulky apparatus. The method devised offers two advantages over present field techniques: (1) graphic continuous analytical record over protracted periods rather than period averages for short duration effort, and (2) portable equipment which will measure actual expenditure of particular exertion rather than special conditions of simulated exercise plus apparatus load. To obtain these objectives: (1) a Leeds and Northrup infra-red gas analyzer was adapted to quantitative detection of carbon dioxide, (2) continuous graphic data were recorded by an Esterline-Angus microammeter, and (3) portability was simulated by use of the A-13 oxygen demand mask to which was connected a long air line carried by cable and pulley rigging extending to the analysis assembly. The apparatus permitted continuous sampling of air over difficult terrain.

This report concerns itself with (1) the adaptation of the Leeds and Northrup infra-red gas analyzer and associated apparatus to measurement of human energy metabolism in the laboratory and (2) application to field studies of the energy metabolism of troops engaged in mountain warfare training.

II. EXPERIMENTAL

A. Apparatus and Methods

1. Gas Analyzer.

The Leeds and Northrup selective gas analyzer was designed to measure small concentrations of carbon monoxide (1). It has been adapted to quantitation of water vapor (2), and has been sensitized to carbon dioxide (3). The subject instrument is functionally based upon the selective absorption by the gas in question of radiation in the infra-red region of the spectrum (CO 4.7, H_2O 6.0 and CO_2 4.3 microns wave length absorption bands).

A complete technical description of the instrument, with detailed operating instructions has been previously reported (3). A brief description follows: Infra-red radiation is emitted by an electrically heated nichrome coil. The rays pass across a test chamber which contains the gas sample to be analyzed. After leaving the test chamber, the beam of radiation is split into 2 parts by an axially divided filter chamber, and then falls onto 2 thermopile sections. The instrument achieves its selectivity by the fillings of the filter chambers. One of these is filled with the gas under analysis (i.e. CO_2) and the other with non-absorbent gas (i.e. O_2). The oxygen side of the cone does not absorb an appreciable amount of radiation. The carbon dioxide side of the cone absorbs radiation maximally within its absorption bands. Both branches respond identically to non-absorbed radiation. Output of the two thermopiles is balanced. Then, introduction of carbon dioxide into the test chamber causes a change

in thermopile output because absorption decreases the radiation falling upon the oxygen cone thermopile. All foreign components absorb from each chamber equally except for those gases with absorption bands overlapping those of carbon dioxide. Possible effects of carbon monoxide and water vapor are avoided by eliminating these two as contaminants.

2. Expired Air Collection.

For the measurement of carbon dioxide concentration of expired air to be useful as a measure of metabolic expenditure, one of two conditions must be filled. First, the expiratory volume can be measured, from which the carbon dioxide concentration will give the per cent by volume as in the classical Haldane technique; second, the volume flow from the subject can be kept essentially constant by force pumping. Enrichment of this constant volume with carbon dioxide from expired air will permit expression of carbon dioxide as per cent of a flow. From data of this sort carbon dioxide, expelled by the subject for a period, can indicate directly his rate of production, regardless of the actual expired volume.

In this problem, we have utilized the latter principle, namely constant flow from the subject by means of force pumping of air through a large capacity hose leading from mask to machine. A schematic diagram of the assembly is given in Figure 1. An analyzer aliquot was drawn from the main flow line by means of a small constant speed rotary pump. In practice the only limiting factor on maneuverability of the subject in reference to analyzer and recorder was the length of air hose between subject and machine. The limit on this length was the ability to handle the hose mechanically. By use of cable and pulley rigging in the field, up to 400 feet of hose were handled with no more inconvenience to the subject than the usual laboratory mask assembly. In the laboratory during standardization of the apparatus various flow meters, mixing chambers, temperature baths and filtration columns for investigation of factors influencing instrument sensitivity and selectivity were inserted between the subject and the analyzer.

3. Air Flow Rates.

The determination of air flow rates in the main and aliquot circuits was very accurately accomplished because subsequent carbon dioxide concentrations were interpreted as percentage of a constant volume. These flow rates were ascertained in the laboratory by the following standard techniques:

a. Spirometer Calibration.

The laboratory spirometer, 500 liter capacity, was calibrated by filling it from an air compressor through a volumetric gas meter (Precision Scientific Co., Chicago, Ill.) recording liters. Direct measurement of filling volume per centimeter bell rise gave a value of 4.35 liters when corrected to standard conditions.

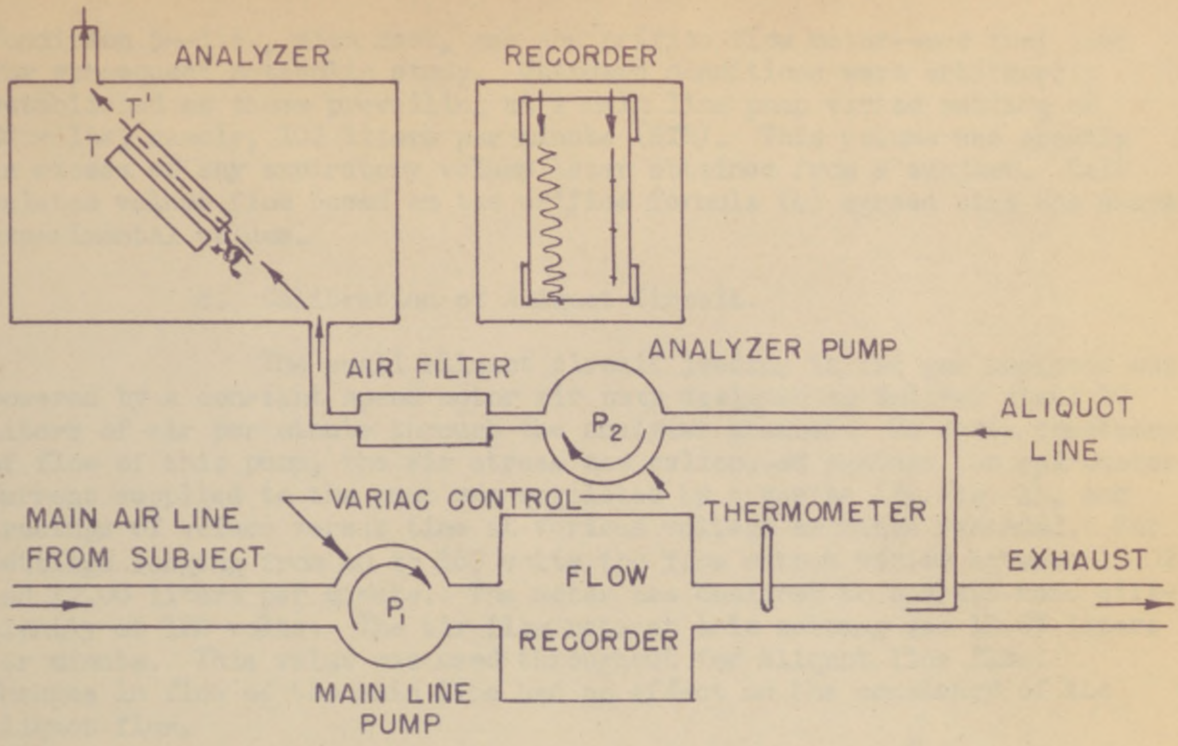

FIG.I. DIAGRAM OF ASSEMBLY

b. Calibration of Main Circuit.

The volume flow of air through the large hose circuit from the subject depended upon the operating speed of the main line pump (P_1 Fig.1). The line flow was calibrated by measuring the rate of air flow at various motor rate control settings against the previously calibrated 500 liter spirometer. Tracings of time against distance (bell elevation) for "variac" settings of 20, 40, 50, 60 and 80 volts were obtained. Values from these curves (i.e. cm./min.) were converted to liters per minute by use of the STP conversion factor for the spirometer, namely 4.35 liters per centimeter rise. Line resistance in the system was induced by two distinct major factors: (1) the mask and man and (2) an orifice flow diaphragm used in conjunction with recording devices. Table 1 summarizes the data obtained. These data compare flow rates under the following conditions: (1) with neither mask, man nor flow meter; (2) with mask alone, without man or meter; (3) with mask and man, but no meter; (4) with meter and mask, without man; (5) with mask, man and orifice flow meter.

TABLE 1

MAIN LINE FLOW
Liters per Minute (STP) at Various Variac Settings

CONDITIONS	20 V	40 V	50 V	60 V	80 V
1	104	261		366	
2	42.8	115		168	
3	31.8	108		164	211
4		91.8	114	137	
5		83.4	102	124	

Condition 5—i.e., with mask, man and orifice flow meter—was that used for subsequent metabolic study. Standard conditions were arbitrarily established as those prevailing at a main line pump variac setting of 50 volts, namely, 102 liters per minute (STP). This volume was greatly in excess of any expiratory volume later obtained from a subject. Calculated volume flow based on the orifice formula (4) agreed with the above experimental values.

c. Calibration of Aliquot Circuit.

The small aliquot circuit leading to the gas analyzer was powered by a constant speed motor air pump designed to deliver about 10 liters of air per minute through the analyzer chamber. To check constancy of flow of this pump, the air stream was calibrated against the spirometer. Current supplied to the pump was regulated by a variac (P_2 Fig. 1), and tracings of volume versus time at various voltage settings recorded. For settings ranging from 40 to 160 volts the flow output varied between 10.02 and 12.00 liters per minute. The motor was designed to operate most efficiently at 120 volts. The air flow rate at this setting was 10.87 liters per minute. This value was used throughout for aliquot line flow. Changes in flow of the main line had no effect on the constancy of the aliquot flow.

4. Standardization of the Selective Gas Analyzer.

After air volume control was established, standardization of the infra-red gas analyzer against known carbon dioxide-oxygen gas mixtures was accomplished. An investigation of the factors influencing receptivity and interpretation accuracy of the instrument was undertaken.

a. Standard Carbon Dioxide Mixtures.

Known mixtures of carbon dioxide and oxygen covering the expected range of carbon dioxide concentration (0 - 5%) to be encountered were prepared. Analysis by the Haldane technique of different cylinders containing gas gave the following compositions: 0.267, 0.549, 1.26, 2.37 and 4.32 per cent carbon dioxide in oxygen. These, with outside air (0.03% CO_2) and pure oxygen, comprised the standard series. Air dilution at the source to 100 liters per minute was enough in excess over expiratory volume to insure analysis within this standard range. The standard gas mixtures were fed directly into the aliquot line to the analyzer. As stated, air flow to the analyzer was supplied at a constant rate of 10.86 liters per minute. Inserted into the air line between the pump (P_2 Fig. 1) and the analyzer was a "charcolite" air filter (Fig. 1). This served three purposes: (1) mechanical filtration of air, (2) removal of water vapor, and (3) removal of charcoal absorbable gases. For testing the effects of water vapor the filter was replaced by suitable apparatus. An initial series of responses of the gas analyzer to the various carbon dioxide mixtures is shown in Figure 2. The Esterline-Angus graphic records read from right to left. Tabulation of the results in terms of average and maximum microvolt deflection is given (Table 2).

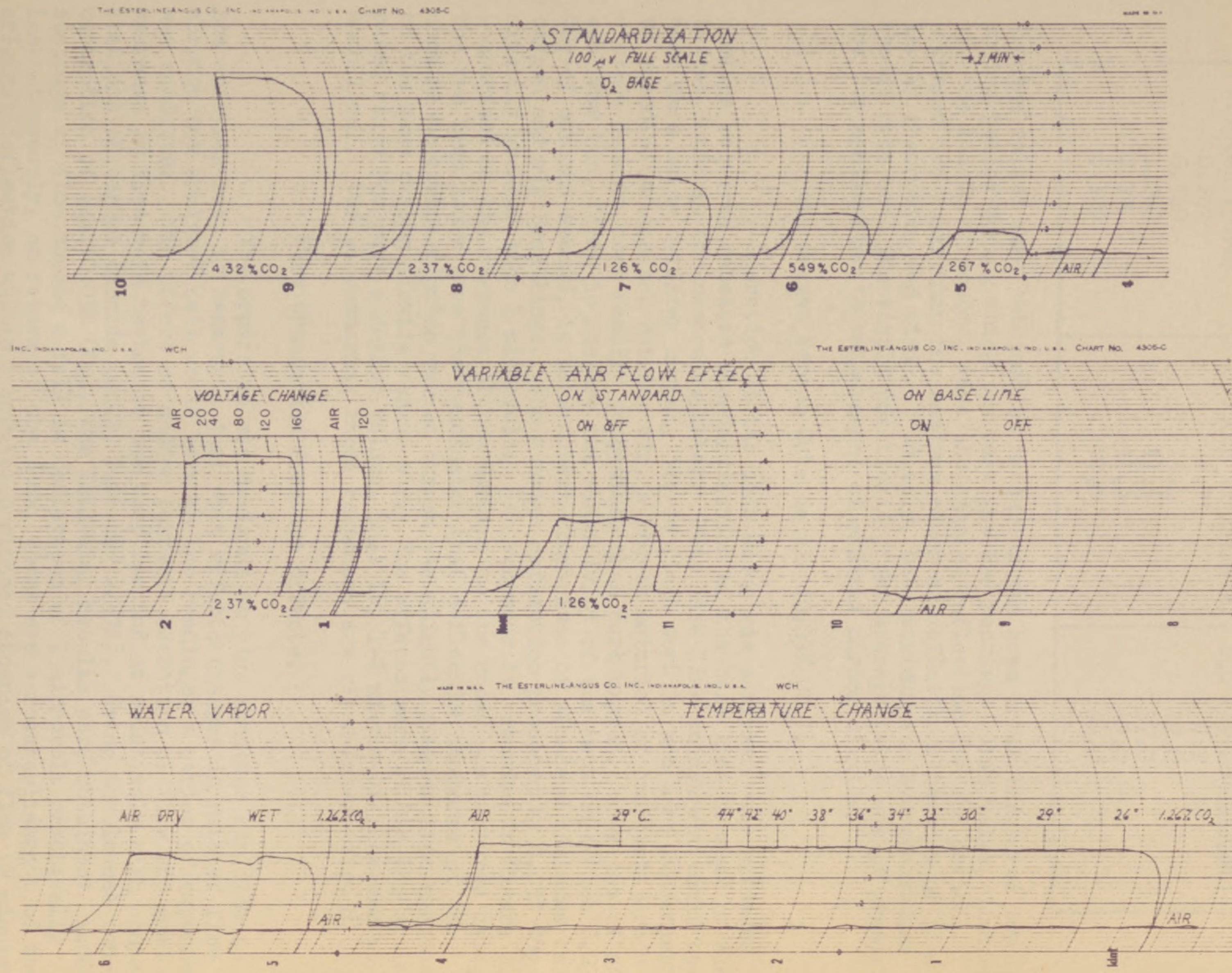

FIG. 2. STANDARDIZATION CURVES

TABLE 2

STANDARD CO_2 MIXTURES, MICROVOLT DEFLECTION

Per Cent CO_2	Average Microvolts	Maximum Microvolts
Oxygen (pure)	0.0 (by adjustment)	0.0 (by adjustment)
0.267	6.95	7.8
0.549	15.1	17.0
1.260	33.5	37.0
2.370	51.2	57.0
4.320	77.0	82.0

Average values were obtained by measuring the area under the curve for the entire period during which the test gas was running. This value, divided by the length of record, gave the average deflection for the period. Averages are lower than the maximum recorded deflections because of time lag in absorption and mixing. Ideally, both maximum and average values should have been identical; practically, the average value was of greater use for application to measurement of expired carbon dioxide.

b. Oxygen Versus Outside Air (0.03% CO_2).

Operation of the continuous gas analyzer over extended periods required repeated standardization of the base line because of electrical drift in the recording meter. This base line adjustment could have been made using cylinder oxygen, but in field work it was more convenient to standardize against outside air, a source material of constant carbon dioxide content more readily accessible than pure oxygen. A series of analyses was run, first to measure the sensitivity of the machine to the 0.03% CO_2 of air and second, to make direct comparison of standard mixtures using oxygen and air base lines. The average deflection produced by 0.03% CO_2 was slightly greater than 1 microvolt. The response is recorded in Figure 2. Comparison of the response of the machine to the known gas mixtures using the two base lines gave the conclusion that deflection response of the machine to carbon dioxide versus oxygen was slightly greater than response to the same carbon dioxide versus air. The effects were within the anticipated range for pure additive values, that is, 1-2 microvolt increase at each level. Curves comparing these responses are given later (Fig. 3).

c. Flow Change and Pressure Effects.

The apparatus was designed to give constant air flow to the analyzer but, to ascertain just what effects changes in rate of flow through the analyzer cell would have on the readings, a series of experiments was conducted. The effect of sudden complete cessation of flow and gradual decrease in flow were tested at the very low and at relatively high concentrations of carbon dioxide (0.03, 1.26 and 2.37%). Using the lowest concentration of gas (0.03% CO_2), the following results were obtained: sudden stoppage of flow caused a fall in deflection of 1 microvolt practically instantaneously; on return of the flow, there was a reestablishment of the original deflection within ½ minute; prolonged stoppage of flow (2 minutes) produced a decrease in deflection of 1 microvolt within ½ minute, then a

gradual fall of 1 microvolt over the succeeding $1\frac{1}{2}$ minutes; return of flow returned the deflection to its original level within $\frac{1}{2}$ minute. Similar effects although less marked, were seen with the higher concentrations of carbon dioxide: at levels of 1.26% CO_2, stoppage of flow caused a decrease in deflection of 2 microvolts within 1 minute; restoration of the previous level (29 microvolts in this case) required a little longer, 1 instead of $\frac{1}{2}$ minute. Gradual cessation of air flow was difficult to evaluate because with a constant speed motor variation from 12 to 10 liters per minute was the maximum obtainable (160 to 40 volts). Within this range no change in deflection toward 2.37% CO_2 could be shown. At a variac setting of 20 volts, the motor failed after a short period of 5 liters per minute flow. During this period, between 10 to 0 liters per minute flow, a fall of 3 microvolts occurred. The fall was probably identical with the effect of cessation of flow. All of the preceding data are illustrated in the second record of Figure 2.

d. Temperature Effects.

Previous work with the infra-red machine, when used for analysis of carbon monoxide, indicated that recordings were stable under gradual changes of temperature. Warning was implied to avoid sudden temperature change, although no commitment was made as to the magnitude of the error introduced (1). The influence of temperature change on carbon dioxide analysis has been investigated. Warm-up of the machine for $1\frac{1}{2}$ hours as recommended led to an analysis chamber temperature of 30°C. This temperature was maintained constantly while operating with ambient air of from 26° to 29°C. Preheating ingress air only slowly influenced the stabilized chamber temperature. Preheating inflowing air from 26° to 44°C. during a period of $\frac{1}{4}$ hour increased the analysis chamber temperature from 30° to 33°C. With the 3° rise in chamber temperature (exit air) the records showed a maximum upward deflection of 3-4 microvolts. The curve was flat between 30°-31°C with a 1 microvolt rise between 31°-31.5°C; a 2 microvolt rise between 31.5°-32°C; 3-4 microvolt rise between 32°-32.5°C; steady between 32.5°-33°C. Gradual increase in operating temperature caused positive deflection of the recorder pen for both outside air and 1.26% CO_2. This can be attributed to a shift in the base line. Sudden change of inflow gas from 44° to 29°C had no effect on the record. The only explanation of this fact is a lack of sensitivity of the instrument to sudden temperature change because the gas passing through the analyzer was not heated to chamber temperature. Esterline-Angus experimental records of these data are given in Figure 2.

e. Effect of Water Vapor.

The influence of water vapor upon carbon dioxide analysis was small, transitory and self-compensating. Air at 27°C saturated with water vapor caused an immediate downward displacement of the base line of approximately 2 microvolts. The effect was of 20 seconds duration, then the record reassumed its base line. With CO_2 mixtures, a similar but exaggerated downward shift occurred. Using a standard mixture containing 1.26% CO_2, saturation with water vapor caused a downward displacement of 3 microvolts which lasted 30 seconds at maximum, then decreased in effect until the original deflection was regained after 2 minutes. Dry gas replacing the moist which had reached balance caused no shift in deflection. The effects are probably not those of interference with flow because the time elapsed in

converting one mixture to another was very short. In addition, the immediate effects were greater than those produced by even prolonged flow stoppage. No flow change effect took place on converting from moist to dry gas. Records of these data are given in Figure 2.

f. Elapsed Time on Response.

Several factors have been reported as influencing the stability of the gas analyzer response to standard gas mixtures. The instrument has been regarded as satisfactorily stable if precautions have been taken to assure: (1) adequate warm-up, (2) well-charged batteries, (3) frequent zero adjustment of the established base line and (4) occasional standardization against a known gas mixture. The most likely factor to account for change in response has been stated to be an electrical leakage from terminals to ground. In those instances in which there has been a distinct loss of sensitivity with elapsed time the fault has been attributed to leakage of the filter cone (1). In the subject instrument leakage of gas had been minimized by a permanent cement seal of the analysis cell window to the filter cone assembly. Sensitivity control of the instrument had been incorporated so that one could adjust receptivity to a definite standard value. Duplication of standard curves by this means has been the practical way of controlling sensitivity loss (3).

During the accumulation of the following data, the sensitivity adjustment of the instrument was fixed in order to ascertain the absolute magnitude of inherent instrument sensitivity loss. Standardization curves taken at different times using both oxygen and air base have been run. Comparative curves for each series are given (Fig. 3). There was a loss of sensitivity during the 30 day period studied which was greater than casual variation between standardizations. There is insufficient evidence to attribute this loss to cone leakage on other than presumption from earlier reports. The practical method of adjustment of instrument sensitivity to a standard deflection with a known calibrating gas mixture nullifies the sensitivity loss.

g. Calibration of Curve.

The average deflection represented by each point in Figure 3 was arrived at by measurement, in square millimeters, of the area under each tracing during the test period. From this value, average deflection in millimeters was calculated. Each 10 microvolt deflection on the recording paper represented 11.5 millimeters. From these data the equation for standardization was obtained. All curves conformed roughly to the general equation:

$$C = K_1 \log K_2/K_2-E$$

where C is CO_2 concentration in per cent, K_1 and K_2 are empirical constants and E is the microvolt deflection. Equation values for the curves of 19 March are tabulated (Table 3).

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FIG. 3

STANDARDIZATION CURVES

TIME EFFECT

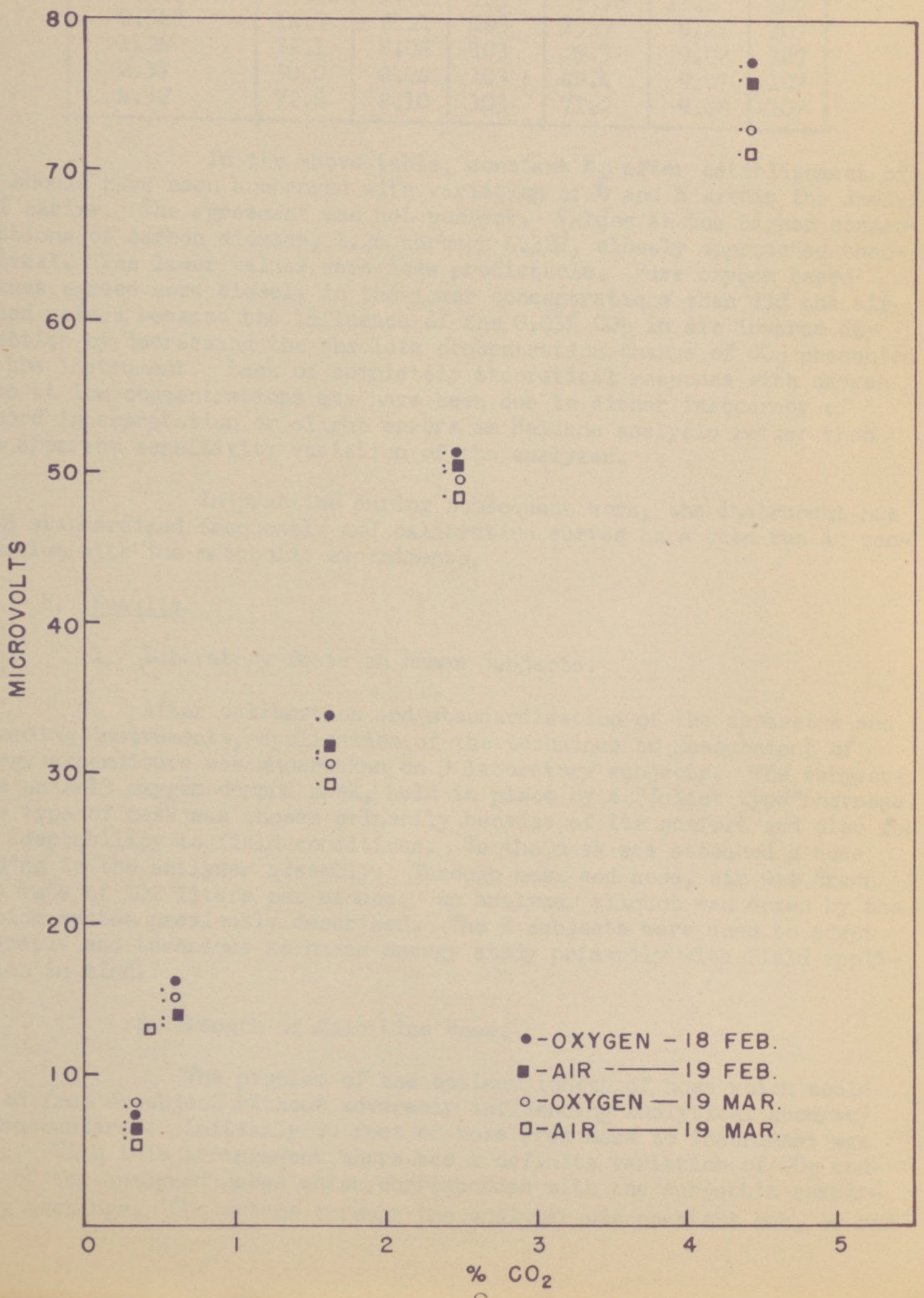


TABLE 3

CALIBRATION DATA FOR CURVES OF 19 MARCH

Conc. CO_2	Oxygen			Air		
%	μv	K_1	K_2	μv	K_1	K_2
0.267	7.70	7.90	103	5.76	11.2	107
0.549	14.7	8.21	103	13.7	9.21	107
1.26	31.1	8.08	103	29.3	9.08	107
2.37	50.0	8.04	103	48.4	9.07	107
4.32	72.8	8.10	103	71.2	9.08	107

In the above table, constant K_1 after establishment of K_2 should have been unchanged with variation of C and E within the individual series. The agreement was not perfect. Values at the higher concentrations of carbon dioxide, 1.26 through 4.32%, closely approached theoretical. The lower values were less predictable. Pure oxygen based values agreed more closely in the lower concentrations than did the air based values because the influence of the 0.03% CO_2 in air lowered deflection by decreasing the absolute concentration change of CO_2 presented to the instrument. Lack of completely theoretical response with oxygen base at low concentrations may have been due to either inaccuracy of record interpretation or slight errors in Haldane analysis rather than the apparent sensitivity variation of the analyzer.

In practice during subsequent work, the instrument has been standardized frequently and calibration curves have been run in conjunction with the metabolic experiments.

B. Results

1. Laboratory Tests on Human Subjects.

After calibration and standardization of the apparatus and recording instruments, application of the technique to measurement of energy expenditure was undertaken on 3 laboratory subjects. The subjects wore an A-13 oxygen demand mask, held in place by a "Juliet type" harness. This type of mask was chosen primarily because of its comfort and also for its adaptability to field conditions. To the mask was attached a hose leading to the analyzer assembly. Through mask and hose, air was drawn at a rate of 102 liters per minute. An analyzer aliquot was drawn by the pumping system previously described. The 3 subjects were used to adapt apparatus and technique to human energy study primarily with field application in mind.

a. Length of Main Line Hose.

The problem of the optimum length of hose which could be led from a subject without adversely influencing analytical accuracy was encountered. Initially 20 feet of hose from mask to instrument was tried. With this arrangement there was a definite variation of CO_2 content of the analyzed gases which corresponded with the subject's respiratory exchange. The volume through the analyzer was constant but, as had

been expected, air passing through the mask was richer in carbon dioxide during expiration than during inspiration. No attempts were made to synchronize these concentration changes with respiratory excursion during this study: first, because of inherent machine lag and second, because some line mixing made for distortion of the record. For ease of calculation and clarity of record a smooth curve was desired. This was obtained in two ways: (1) by use of a cyclonic type mixing chamber inserted in the analyzer flow line just ahead of the recording instrument, and (2) by use of a much longer (400 feet) lead hose from mask to machine. The latter method was adapted for field trials, the former for the laboratory work. Exercise curves obtained with 20 foot, 400 foot and 20 foot lead line with the mixer have been obtained. Each experiment was run on a different day and the time duration of each effort was adjusted by the subject to his ability rather than to a fixed schedule. There was no essential difference in average deflection produced by any type system. The variations seen are within the range of individual response to an exercise on repetition. A graphic interpretation of these data in terms of the average microvolt deflection during periods of rest, treadmill activity and recovery is given (Fig. 4).

b. Comparison of Energy Expenditure.

To compare energy expenditure between subjects, the CO_2 values obtained for each must be converted into caloric equivalent for a unit area of body surface over a definite period of time. Convention calls for expenditure per square meter body surface per hour or minute. Our subjects had been chosen as representative of the soldier group upon whom field studies were made. Their characteristics are tabulated (Table 4).

TABLE 4

PHYSICAL DATA OF LABORATORY SUBJECTS

Subject	Age	Weight	Height	Body Surface
R.P.	19	135	5' 10½"	1.77 M^2
W.H.	20	190	5' 8"	2.02
J.S.	19	158	5' 11"	1.90

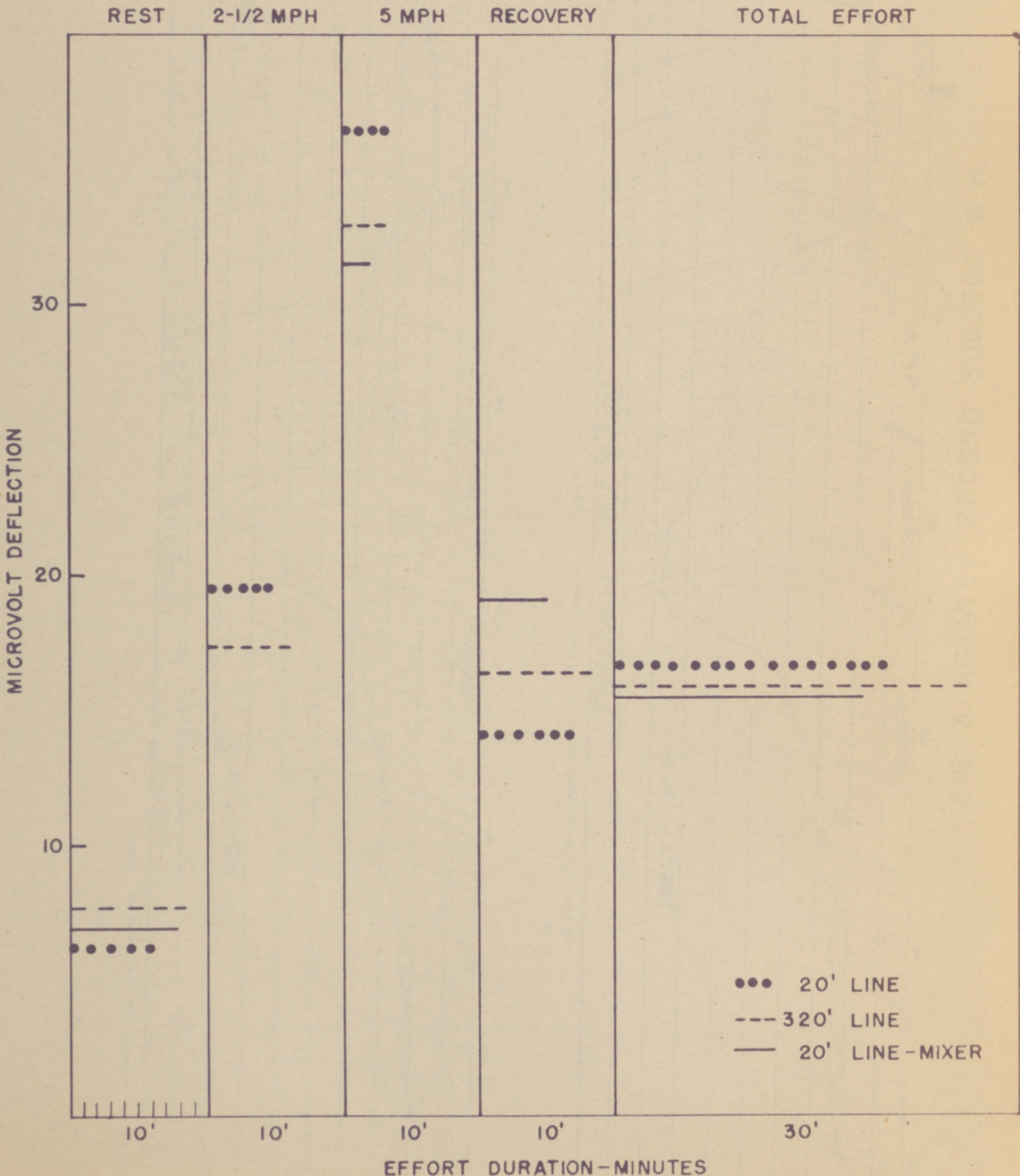
Using the laboratory technique of a 20 foot lead line and cyclonic air mixing chamber, a series of treadmill exercises was obtained on each subject. The severity and duration of each phase of the exercise were made strictly uniform between subjects. From these data the energy expenditure of the 3 men for each phase of the activity was compared.

A representative curve from 1 subject (W.H.) is given in Figure 5. Deflection in microvolts on the tracing represents CO_2 output during rest, level walking (2½ and 5 mph), a recovery period, additional rest, grade walking (10%, 2½ and 3½ mph) and recovery. The type curve was typical of all, although actual quantity output of carbon dioxide depended upon the individual. Equilibration of microvolt deflection to per cent carbon dioxide for any point on the curve was obtained from standard values. The air flow rate was maintained constant at 102 liters per minute. All air passing through the system came through the mask. All CO_2 recorded was that produced by the subject. An outside air base line was used and standardization against air had been accomplished. Deflection of the recording pen

FIG. 4

TREADMILL ACITIVTY

SUBJECT R.P.



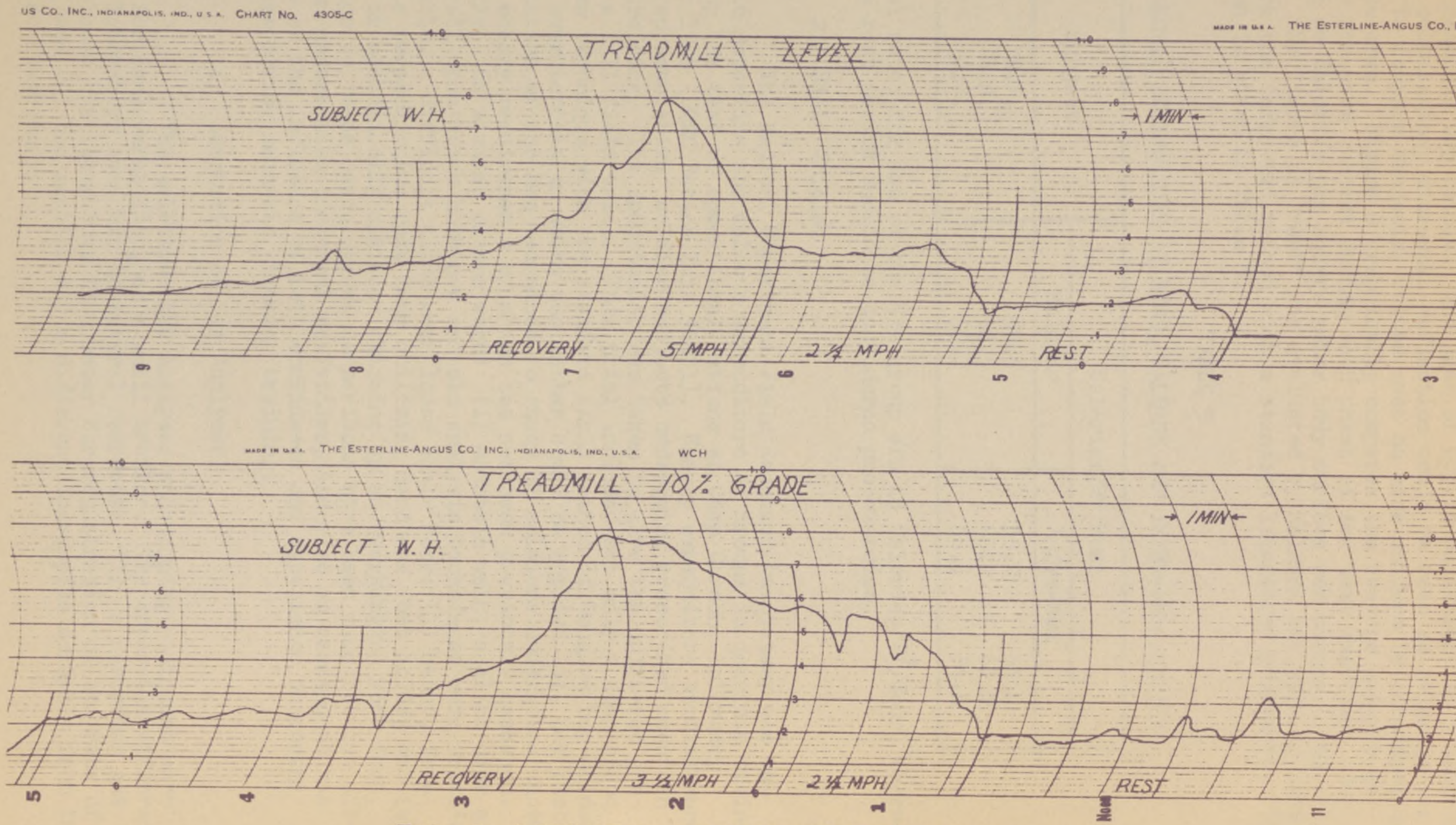


FIG. 5 ACTIVITY RECORD SUBJECT W. H.

directly measured CO_2 output. One gram of CO_2 is equivalent to 3 calories (5). By calculation, microvolt deflection could be read as calories per minute. To compare subjects, values must be made uniform by consideration of surface area. Figure 6 graphically compares the average caloric expenditure for each subject during each phase of the test exercise. The data are given as Calories per square meter body surface per minute. The value given in the figure as "rest" was evaluated by Haldane analysis in order to compare the infra-red method with a standard laboratory procedure. The comparison is given in Table 5.

TABLE 5

CALORIC EXPENDITURE AT REST, HALDANE AND INFRA-RED ANALYSIS

Subject	Calories/M²/Hour		
	Haldane	Infra-Red	
R.P.	57.5	55.2	58.4
W.H.	58.5	60.2	61.2
J.S.	59.0	58.3	54.4

True basal rates for men of the age group are 45 Calories/M^2/Hour, therefore, the rest period should be considered pre-exercise.

2. Field Trials.

The Medical Department Field Research Laboratory was requested to determine the caloric expenditure of troops in mountain training during the test of operational rations at Camp Carson, Colorado, September 1946 (OQMG Ration Test #4631). Energy expenditure studies were made on representative soldier subjects undergoing prescribed mountain warfare training. The opportunity was taken to give the infra-red gas analyzer a full field trial. This trial included not only a comparison of the new technique with the standard field method of Douglas bag-Haldane analysis over terrain on which the latter could be applied (6), but also the the adaptation of the new technique to study of soldiers undergoing maneuvers the energy requirements of which had not been previously assessed. Technically, the studied climbs were: (1) mountain walk, a climb over a marked trail upon which both new and old analysis techniques were practiced; (2) scramble, a difficult climb over loose shale rock; (3) belay, free climb up a perpendicular rock face utilizing hand and foot holds; and (4) tension, or mechanically assisted climbing up an overhanging rock face. In addition to these data, direct comparisons have been made between different men undertaking identical activities, and also an assessment has been made of the influence of both confidence and experience on energy expenditure during mountain climbing training.

a. Adaptation of Gas Analyzer.

The selective gas analyzer and pumping equipment were mounted, for maneuverability, on a small trailer. The apparatus differed from the laboratory assembly in several respects: (1) a recording gas meter replaced the laboratory flow meter for registration of the rate of air flow, and (2) the machine had a different thermopile assembly from that used in the laboratory.

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61.2	60.2	58.5	V.H.
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True basal rates for men of the age group are 45 Calories/M^2/hour, therefore, the rest period should be considered pre-exercise.

2. Field Trials.

The Medical Department Field Research Laboratory was requested to determine the caloric expenditure of troops in mountain training during the test of operational rations at Camp Carson, Colorado, September 1946 (CCMT Ration Test #6011). Energy expenditure studies were made on representative soldier subjects undergoing prescribed mountain warfare training. The opportunity was taken to give the infra-red gas analyzer a full field trial. This trial included not only a comparison of the new technique with the standard field method of Douglas bag-Haldane analysis over terrain on which the latter could be applied (6), but also the adaptation of the new technique to study of soldiers undergoing maneuvers the energy requirements of which had not been previously assessed. Technically, the studied climbs were: (1) mountain walk, a climb over a marked trail upon which both new and old analysis techniques were practiced; (2) scramble, a difficult climb over loose shale rock; (3) belay, free climb up a perpendicular rock face utilizing hand and foot holds; and (4) tension, or mechanically assisted climbing up an overhanging rock face. In addition to these data, direct comparisons have been made between different men undertaking identical activities, and also an assessment has been made of the influence of both confidence and experience on energy expenditure during mountain climbing training.

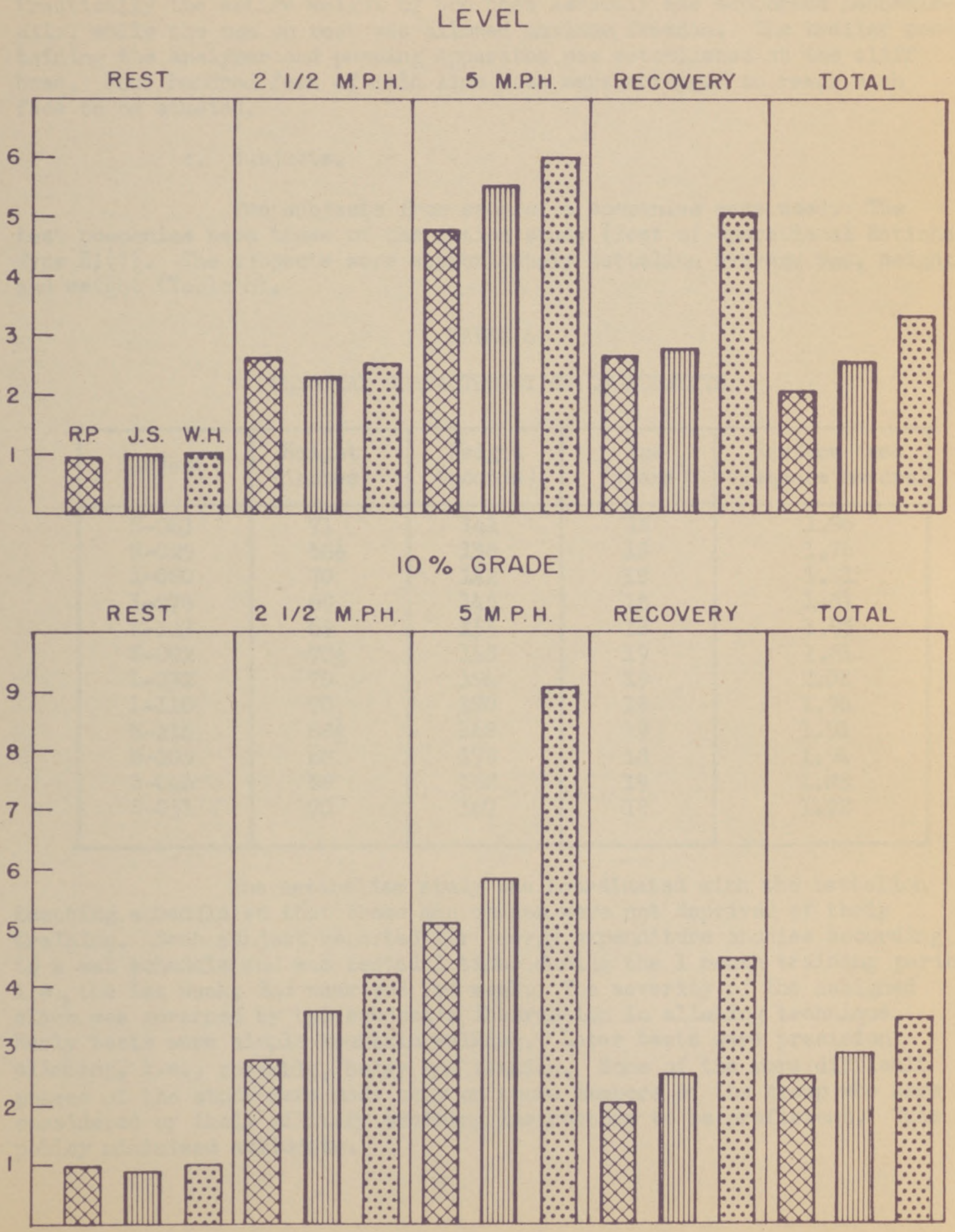
a. Adaptation of the Analyzer.

The selective gas analyzer and pumping equipment were mounted, for maneuverability, on a small trailer. The apparatus differed from the laboratory assembly in several respects: (1) a recording gas meter replaced the laboratory flow meter for registration of the rate of air flow, and (2) the machine had a different thermopile assembly from that used in the laboratory.

FIG. 6

TREADMILL ACTIVITY

CAL / M^2 / MIN.



b. Lead Line Maneuverability.

A method for conveying the lead line hose which extended between the subject and recorder was developed on the basis of cable and pulley rigging. Taut cables were drawn between objectives on the particular rock-climbing terrain to be studied. Movable pulleys were mounted on the cables and from these pulleys was suspended the main line hose. A short lead of light hose connected the subject to the main line. Practically the entire weight of the hose assembly was supported mechanically, while the man on test was allowed maximum freedom. The trailer containing the analyzer and pumping apparatus was established at the cliff base. Four hundred feet of main line hose were arranged to reach each face to be studied.

c. Subjects.

Two subjects from each of 6 companies were used. The test companies were those of the ration study (Test of Operational Rations, Type E)(7). The subjects were approximately battalion average age, height and weight (Table 6).

TABLE 6

PHYSICAL CHARACTERISTICS OF SUBJECTS

Subject	Height (inches)	Weight (pounds)	Age (years)	Surface Area (square meters)
H-063	71	141	18	1.86
H-025	68½	138	18	1.76
I-080	70	142	18	1.81
I-078	69	145	18	1.81
K-103	69	155	18	1.85
K-092	70½	148	19	1.84
L-032	70	194	19	2.08
L-110	70	170	19	1.96
M-114	68½	168	19	1.91
M-105	68	178	18	1.94
S-046	68	168	19	1.88
S-051	70	167	18	1.92

The metabolism study was coordinated with the battalion teaching schedule so that those men chosen were not deprived of their training. Each subject reported for energy expenditure studies according to a set schedule and was tested 3 times during the 1 month training period i.e., the 1st week, 2nd week and 3rd week. The severity of the assigned climb was governed by the subject's instruction in climbing technique. Early tests were simple mountain walking. Later tests were precision climbing, i.e., scramble, belay and tension. Some of the more difficult phases of the study were made only on those members of the group who were considered by their military training instructors to be proficient. This policy minimized accidents.

d. Analyses.

Two methods of analysis were used: the field adaptation of the classical Douglas bag-Haldane analysis technique, and the infra-red analyzer. The Haldane values for oxygen and carbon dioxide, with the metered respired volume obtained from the Douglas bag, were used to compute energy expenditure in terms of Calories per minute. The method of calculation for the infra-red analysis was identical with that used in the laboratory. Standard mixtures of carbon dioxide were used to establish calibration curves during the experimental period. The standardization curves for the analyzer conformed to the equation previously noted.

e. Comparison Between Haldane and Infra-red Analyses.

A relatively rugged mountain walk was chosen as a standard effort for the subjects in order to compare the caloric expenditure values obtained by both the Haldane and the infra-red techniques. This course consisted of a 200 foot uphill path, the average grade of which approximated 58 per cent. Douglas bag samples were taken at rest, during ascent, while recovering after ascent and during descent of the standard grade. Over the same course, at a different time, an infra-red analysis was made. The energy expenditure for each phase of the standard exertion for each subject is given in Table 7. Values obtained with the 2 methods were in closest agreement at resting levels. Increased exertion gave outputs which were comparable in trend and average only. The discrepancy between the 2 methods is best explained as due to individual variation in energy expenditure by a subject upon repetition of the same effort.

f. Comparison of Infra-red Analysis Curves Between Subjects.

The analysis curves for output of CO_2 demonstrated rather close contour agreement between subjects when taken as initial exposure to a particular type of exercise. In Figure 7 the analyzer curves, obtained from paired subjects undergoing 3 types of climbing training, are compared. They represent: (1) paired subjects undertaking quick time (120 steps per minute) and double time (180 steps per minute) marching; (2) climbing the 200 foot mountain walk previously described; and (3) ascent and descent of a 400 foot course of mountain walk and shale scramble. The curves have been superimposed. The elapsed times differ slightly. On both of the climbs between ascent and descent there was a five minute "break" or recovery period.

The 400 foot course was a continuation of the 200 foot standard grade, and consisted of an additional 200 feet of very difficult shale rock scramble. The grade was somewhat steeper than that of the previous effort. The carbon dioxide output, converted to Cals/M^2/min. for the total course showed fairly good agreement between men (Table 8).

TABLE 7

ENERGY EXPENDITURE CAL/M^2/MIN.

Subject	Area Sq. M.	Rest-before exercise		Ascent 200'		Recovery-post ascent		Descent 200'	
		Haldane	Infra-Red	Haldane	Infra-Red	Haldane	Infra-Red	Haldane	Infra-Red
L-032	2.08	.891	.802	4.86	5.21	1.27	2.58	2.20	3.78
L-110	1.96	.832	.796	4.26	4.35	2.12	2.61	2.39	3.28
H-025	1.76	.768	1.191	4.23	3.64	1.97	2.47	2.12	2.03
H-063	1.86	.661	.791	2.39	3.06	1.60	2.23	1.66	3.03
K-103	1.85	1.000	1.230	4.38	4.07	1.92	1.99	2.78	2.45
K-092	1.84	.952	.858	4.04	3.92	1.86	1.38	2.99	2.24
M-105	1.94	.944	1.000	4.35	2.94	1.53	2.48	3.12	2.37
M-114	1.91	.734	.644	3.48	4.02	1.29	2.04	1.94	2.65
S-046	1.88	.632	.665	4.89	4.33	1.70	1.98	2.49	2.59
S-051	1.92	.876	.906	3.74	3.34	1.37	2.08	2.73	2.43
I-078	1.81	1.022	.951	3.62	3.48	1.41	1.63	2.79	2.40
I-080	1.81	1.022	.813	4.86	2.94	1.82	1.60	2.84	2.36

FIG. 7

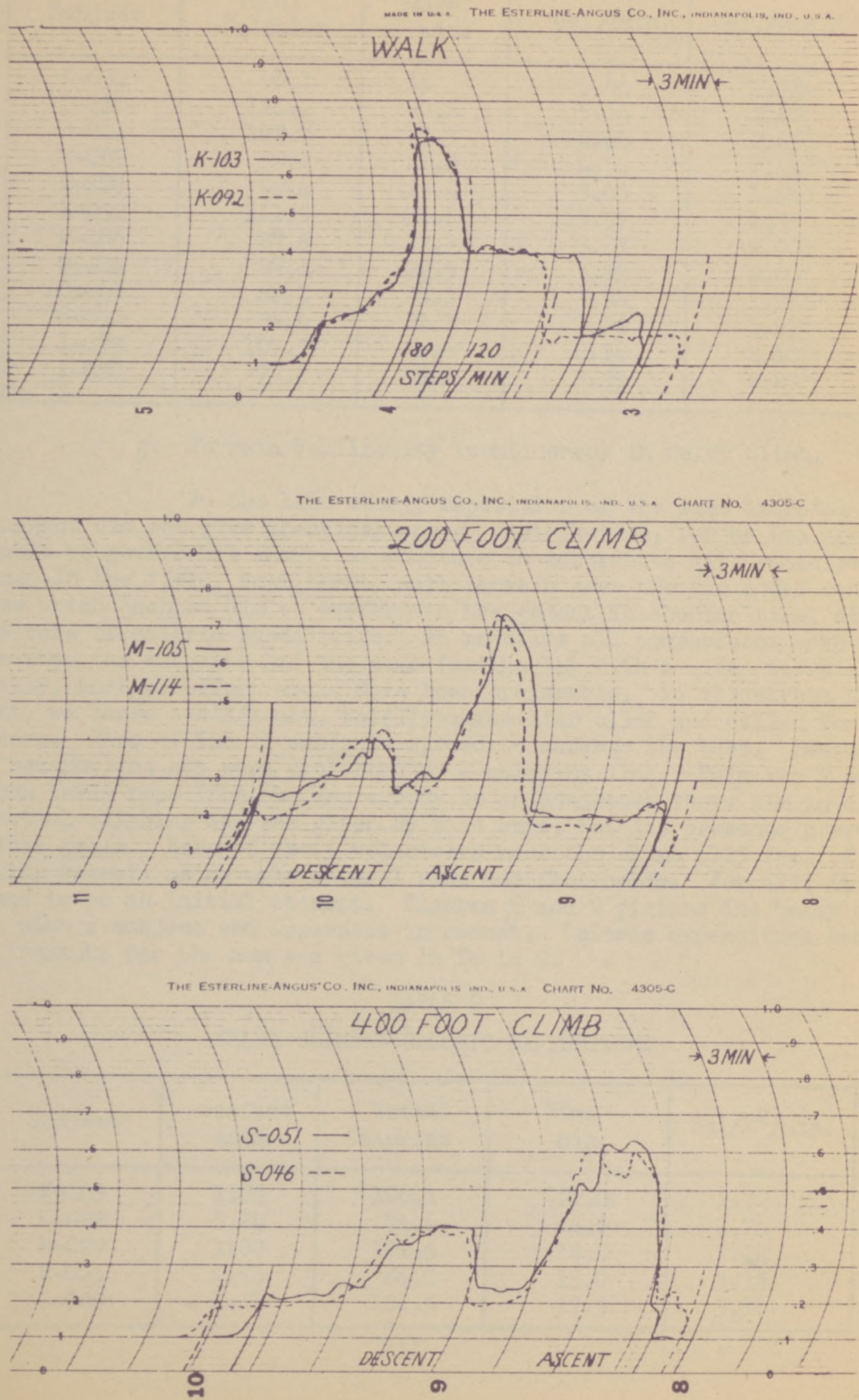

MADE IN U.S.A. THE ESTERLINE-ANGUS CO., INC., INDIANAPOLIS, IND., U.S.A.
WALK
→3MIN←
K-103 ——
K-092 - - -
180 120
STEPS/MIN
THE ESTERLINE-ANGUS CO., INC., INDIANAPOLIS, IND., U.S.A. CHART NO. 4305-C
200 FOOT CLIMB
→3MIN←
M-105 ——
M-114 - - -
DESCENT
ASCENT
THE ESTERLINE-ANGUS CO., INC., INDIANAPOLIS, IND., U.S.A. CHART NO. 4305-C
400 FOOT CLIMB
→3MIN←
S-051 ——
S-046 - - -
DESCENT
ASCENT

TABLE 8

FREE CLIMB AND SCRAMBLE - 400 FEET AND RETURN

Subject	Total Calories	Time min.	Cal./min.	Cal./min/M^2
L-032	90.1	16	5.64	2.71
L-110	111.2	20.2	5.54	2.82
H-025	108.7	23.3	4.66	2.65
H-063	99.1	21.8	4.54	2.44
K-103	92.4	25.4	3.63	1.96
K-092	111.5	31.0	3.59	1.95
M-105	87.5	22.3	3.93	2.02
M-114	87.4	22.9	3.82	2.00
S-046	82.1	23.2	3.54	1.88
S-051	84.4	22.7	3.72	1.93
I-078	107.7	24.8	4.34	2.40
I-080	77.8	19.5	3.99	2.20

g. Terrain Familiarity (confidence) in Belay Climb.

In the laboratory, repetition of the same exercise by a subject did not give identical energy distribution, for he was apparently able to govern his energy expenditure in accordance with anticipated need. In the field, familiarity with terrain gave the man added confidence which enabled him to perform an assignment in shorter time, at the same rate of caloric expenditure. In practice all comparisons have been made when the subjects had the same familiarity with a given terrain. Ideally, initial effort would have been preferable. To illustrate this point, we chose a difficult, totally unfamiliar climb and called for volunteers. Five of the 12 subjects agreed to undergo the test. Because of the hazard, the men were protected by a belaying line. This was a safety "check fall" rope from the man's body to an assistant above him in climb. No actual climbing aid was given by this rope, but its presence prevented serious falls. Each of the 5 volunteers made the climb (125 feet of perpendicular ascent) using only natural hand and foot holds. For all, it was avowed to be an initial attempt. Figures 8 and 9 picture the belay climb area with a subject and apparatus in ascent. Caloric expenditure and time requirements for the men are given in Table 9.

TABLE 9

BELAY CLIMB - CALORIC EXPENDITURE

Subject	Surface Area	Total Calories	Time min.	Cal/M^2/min.
K-103	1.85	106.1	21.0	2.72
K-092	1.84	74.6	14.6	2.74
H-029	1.80	101.5	18.0	3.14
H-025	1.76	84.0	15.0	3.18
I-080	1.81	104.5	17.3	3.36

FIG. 8. BELAY CLIMB AREA

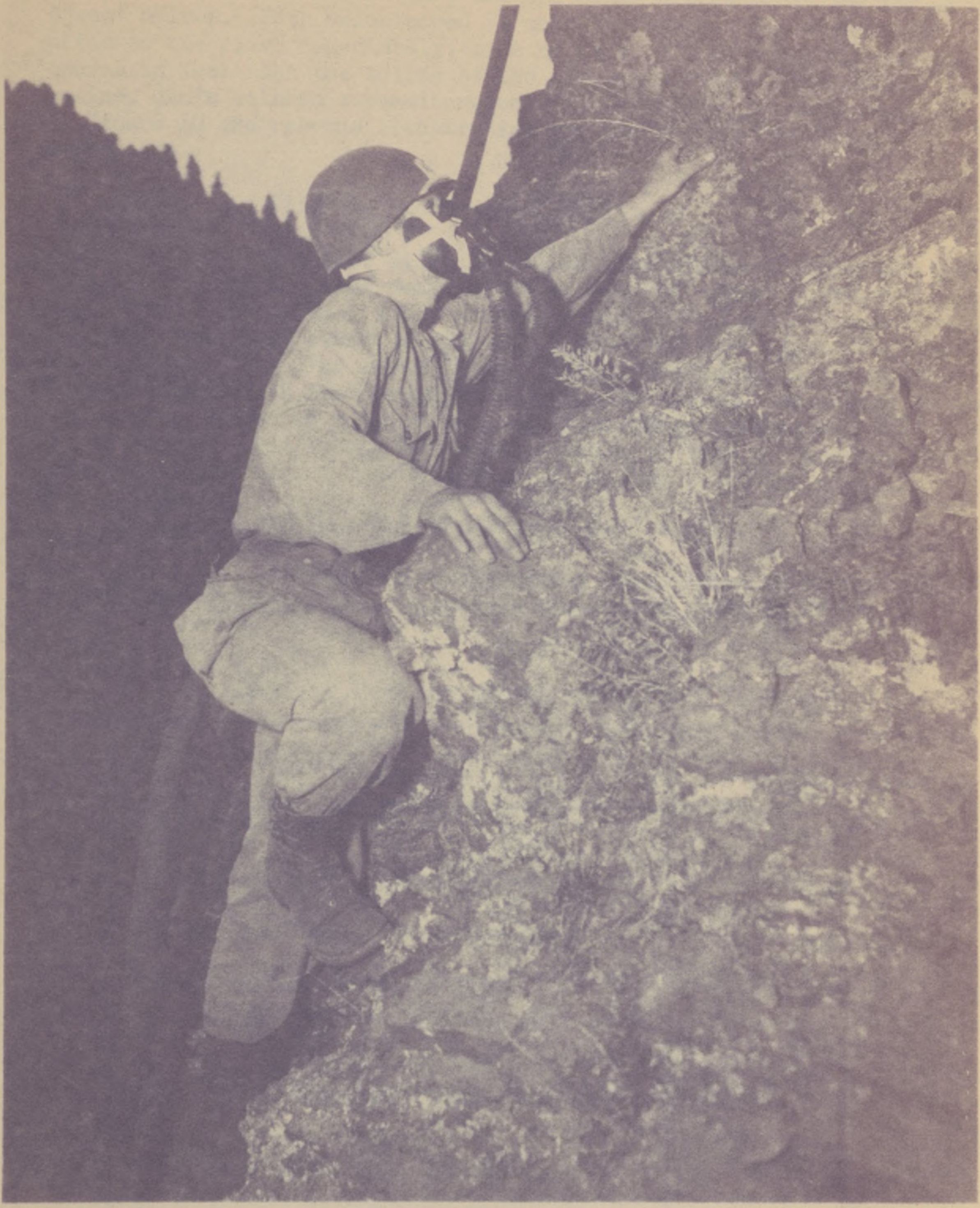


FIG. 9. BELAY CLIMB

On the second attempt at the same belay climb, required time was cut by one third without proportionate rise in energy expenditure. This improvement was the result of confidence. The role of experience was checked on two men from outside of the test group. One of these was a mountain climbing instructor, and the other a presumably inexperienced "jeep" driver. Each volunteered to make the climb. The instructor attacked the climb immediately, made no false starts and completed the course in less than two thirds of the time required by the novice. The trained man's caloric expenditure was less than that of the untrained. In Figure 10 are records illustrating the influence of confidence and of experience.

h. Climbing Under Mental Tension.

The most difficult climb in mountain training was the "tension" climb, so named because the subject was under stress while climbing. There were no hand holds or foot holds; the climber ascended by driving steel pegs into clefts in the cliff face, and drew himself up from peg to peg by means of a sling rope. This climb was forbidden to the soldier subjects because of the danger, but the instructor who cooperated on the belay climb agreed to a demonstration. His energy expenditure was relatively low, and ascent very slow. During 10 feet of climbing which required 15 minutes, the caloric expenditure was 2.84 Cal/M^2/min.

i. Summary Values for Mountain Training.

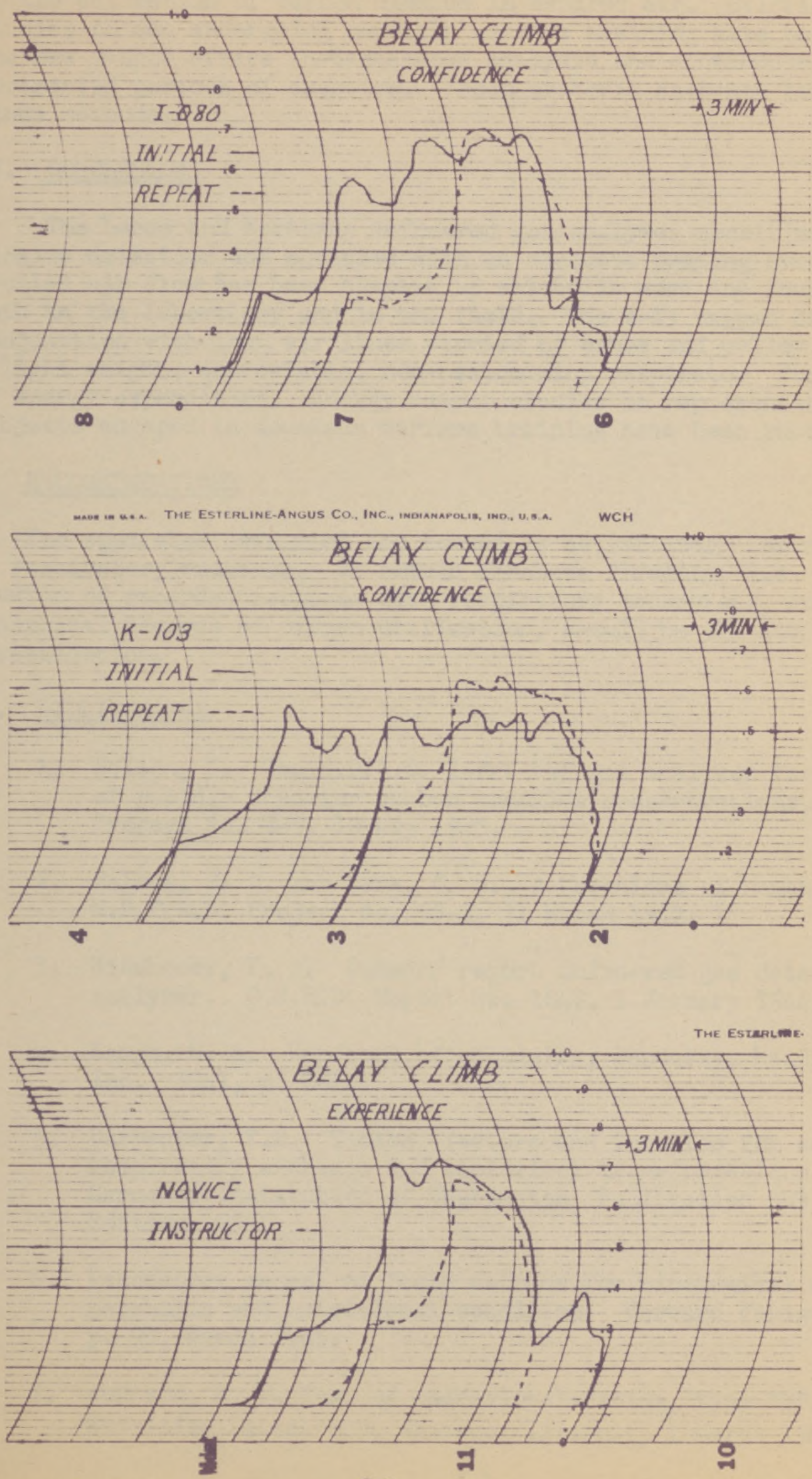
Summary values for energy expenditure of troops engaged in mountain training during the field trials are given in Table 10.

TABLE 10

MOUNTAIN TRAINING ENERGY EXPENDITURE (AVERAGES)

Activity	Cal/M^2/Minute
Rest (before exertion)	0.89
Quick Time March (120 steps/min.)	2.59
Double Time March (180 steps/min.)	5.04
Free Climb and Mountain Walk (200' course & return)	2.04
Ascent	3.77
Descent	2.09
Recovery (break period)	2.55
Free Climb and Scramble (400' course and return)	2.25
Belay Climb	3.03

FIG. 10



BELAY CLIMB
CONFIDENCE
I-080
INITIAL —
REPEAT ---
3MIN
8
7
6
MADE IN U.S.A. THE ESTERLINE-ANGUS CO., INC., INDIANAPOLIS, IND., U.S.A.
WCH
BELAY CLIMB
CONFIDENCE
K-103
INITIAL —
REPEAT ---
3MIN
4
3
2
THE ESTERLINE-
BELAY CLIMB
EXPERIENCE
NOVICE —
INSTRUCTOR --
3MIN
11
10

III. DISCUSSION

A new technique for measurement of caloric expenditure during continuous activity has been developed. Both laboratory and field trials have proved the adaptability of the Leeds and Northrup selective gas analyzer to the estimation of carbon dioxide in expired air. Caloric expenditure studies on men undergoing mountain warfare training have been accomplished. The new method offers instantaneous analysis and continuous records over protracted periods of exercise. These criteria have not been met by previous methods.

IV. CONCLUSIONS

The Leeds and Northrup infra-red gas analyzer sensitized for carbon dioxide detection and equipped with an adequate pumping system for controlled air flow has been adapted to metabolic work and found satisfactory both in the laboratory and in the field. The A-13 oxygen demand mask in conjunction with long air lines carried by cable and pulley rigging offered a light weight, comfortable, non-restraining respirator for field study of energy expenditure. Energy output studies on representative soldier subjects engaged in mountain warfare training have been recorded.

V. RECOMMENDATIONS

The apparatus developed and tested is satisfactory for routine study of respiratory exchange. To obtain absolute fidelity, i.e. synchronization of recorded response with respiratory excursions, and continuous analytical records of oxygen utilization, should be the aim of subsequent investigation.

VI. BIBLIOGRAPHY

1. Nelson, N. The N.D.R.C. Infra-red gas analyzer for determination of rapidly changing carbon monoxide concentrations. A.M.R.L. Project No. T-9, 18 May 1945.

2. Palmes, E. D. and Park, C. R. A technique of human calorimetry. M.D.F.R.L. Project No. 55-3, 31 March 1947.

3. Hitchcock, F. A. Summary report infra-red gas detector and gas analyzer. O.S.R.D. Report No. 1642, 1 January 1944.

4. Lange, N. A. Handbook of chemistry, Sandusky, Handbook Publishers, Inc., 1941, p. 666.

5. Carpenter, T.M. Tables, factors and formulas for computing respiratory exchange and biological transformations of energy. Carnegie Institution of Washington, Publication 303 B, Third Edition 1939.

6. Laboratory manual of field methods for biochemical assessment of metabolic and nutritional condition. Harvard Fatigue Laboratory, p. 93, March 1945.

7. Johnson, R. E. Test of operational ration, type "E". Medical Nutrition Laboratory, Chicago, Illinois, 1 March 1947.