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ARMORED MEDICAL RESEARCH LABORATORY
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THERMAL EXCHANGES OF MAN AT HIGH TEMPERATURES

1. PROJECT: No. 2-17 - Report on Thermal Exchanges of Man by Evaporation, Convection, and Radiation as Functions of Temperature, Water Vapor Pressure, and Wind Velocity.

a. Authority: Letter Commanding General, Headquarters Armored Force, Fort Knox, Kentucky, File 400.112/6 GNOHD, dated 24 September 1942.

b. Purpose: To provide quantitative information on the influence of environmental factors on the thermal stress to man.

2. DISCUSSION:

One of the limitations on the usefulness of studies of the physiological responses of man to high temperatures is the difficulty of predicting behavior under one set of environmental conditions from information obtained under another set of conditions. A rational approach to this problem is to, first, provide for a means of evaluating total thermal stress to the man from known conditions of exposure: air and wall temperature, moisture content of air, wind velocity, metabolic rate of the man, etc. With this step accomplished one may proceed to correlation of the physiological response of man to the total thermal stress. The present report is concerned with the first aspect of this approach.

To this end, rates of heat exchange by evaporation, convection and radiation have been estimated at 5 wind velocities in each of 7 different environments. These measurements were made on nude men, on clothed men standing, and on clothed men walking. The results are discussed in detail in the Appendix.

3. CONCLUSIONS:

a. Coefficients of thermal exchange for nude and clothed men, standing and walking, have been estimated by partial calorimetry in a series of 7 environments and at 5 wind velocities.

b. In nude subjects the maximum coefficient of evaporation can be described by the equation $E/\Delta P = 1.4\ V^{0.4}$.

c. Sweating rates adequate to measure the maximum coefficients of surface evaporation in clothed men probably were not reached. Charts presenting the coefficients actually found are shown.

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skin and wall temperatures by accepted principles and subtracted from C + R.

Utilizing this approach three subjects were studied while standing nude, standing clothed, and walking clothed at 5 wind velocities in each of 7 environmental conditions, representing 3 moisture contents at 5 air temperatures (Table 1). It has been possible to make a fairly complete analysis of the standing nude experiments. The data from the clothed experiments are less satisfactory for reasons discussed more fully below.

EXPERIMENTAL

Test Conditions and Procedures:

Four healthy young men were the subjects of the experiment; their physical characteristics are given in Table 2. After preliminary training in the cool, they were trained and acclimatized to heat by working for 4 hours per day as follows: 4 days at 120°F. D. B. - 78°F. W. B., then 2 days at 120° - 86°, 2 days at 94° - 91°, 1 day at 96° - 92°, and finally 1 day at 120° - 88°. During this period clothing as described below was worn, and activity and environment were at least as severe as during the actual test days. Acclimatization, for these studies, has the advantages that it minimizes changes in storage and permits one to deal with well adjusted subjects.

At the start of the test program three of the subjects were used while the fourth was held in reserve, remaining in the hot room as a helper and receiving the same exposure as the 3 men in the test program. On the eleventh day of the experiment the man in reserve replaced one of the original subjects who was removed as a result of an upper respiratory infection. With this exception, all subjects were in good condition throughout the study. The subjects spent 7½ hours in the hot room each test day, but slept in barracks maintained at normal temperatures. Test data were collected on only 5 days in each week. Sunday was spent out of the hot room and Monday was devoted to 4 hour marches.

A regular sequence of environmental changes was followed, one wind velocity being covered each day (Table 1). After a test day in Environment 4, the succeeding experimental day was "Base Day". The calculated coefficients of convection, radiation and evaporation for all "Base Days" agreed well with each other. The repetition of this same test day at periodic intervals indicated that the physiological response of the subject to the same set of conditions remained reasonably constant throughout the study. Working metabolism fell by 10% over 8 weeks; rectal temperatures and heart rates showed little consistent change.

The tests were carried out in the hot room in a sheet metal wind tunnel 5½ ft. wide, 7½ ft. high and 20 ft. long (Photos 1 to 8). Six 24 inch fans at the discharge end of the tunnel produce air flow, the velocity of which is changed by adjusting either the fan speed or the louvre adjustment (louvres are located just upstream from the fans) or both. The entering end of the tunnel is packed over the entire section with 30 inch lengths of 8 inch galvanized pipe lying in the axis of the tunnel. This serves both as an air straightener and to protect the inside of the tunnel from air disturbances in the hot room proper. Air movement was virtually uniform across the cross-section of the tunnel to within 6

APPENDIX

Studies of the physiological response of men to high environmental temperatures require for their most general application a means of transfer of data secured under particular environmental conditions to other intermediate but untested conditions. This need would be fulfilled if there were available functional relationships capable of describing thermal stress to the man in terms of the various environmental factors. Such relationships for limited ranges of environmental conditions are available for convection (1 a,b,c,d) and for still more limited ranges in the case of evaporation (1 d,e). Evaluation of thermal exchange by low temperature radiation appears to be well founded on both theoretical and experimental grounds (1f, 2a). The urgent need for such descriptive relationships has led to attempts to extrapolate the meager data now available to conditions out of the range of the original experiments by means of generalizations used in the engineering field (3).

The ideal procedure for establishing these relationships is by means of complete calorimetry. The technical difficulties and elaborate equipment involved in this approach become almost prohibitive when higher wind velocities and working subjects are studied. The simpler method of partial calorimetry has been used at the Pierce Laboratory with considerable success over normal temperature ranges (1). This approach is less satisfactory under the more severe environmental conditions that have been of major interest in the war time study of high temperatures. This results largely from the greater difficulty of reaching thermal equilibrium and the consequent higher rates of storage (subject to considerable error in estimation) at high thermal loads. However, the potential usefulness and need of even roughly quantitative descriptions of convection and evaporation justifies their study by the available method of partial calorimetry. The results of such a study are presented in this report.

The principle involved in the use of partial calorimetry to allocate thermal flow into its several components is contained in the statement that at equilibrium (no increase or decrease in heat content of the body) the rate of thermal flow outward across the envelope of reference is equal to the rate of thermal flow inward. Or, in the absence of equilibrium, that these two rates differ by the rate of change of the heat content of the body. This statement can be mathematically expressed (neglecting conduction), as $M + S + E + R + C = 0$ where the symbols represent respectively: M, the rate of metabolic heat production, always positive in sign; S, the rate of storage (or the rate of gain or loss in heat content of the body), positive in sign when the heat content decreases, negative when heat is removed from the body; and C, the rate of thermal exchange by convection, and R by radiation, both positive when delivering heat to the body and negative when removing it. Of these variables, M can be measured in terms of the rate of oxygen consumption. S can be estimated from the changes in skin temperature and rectal temperature, unfortunately, with uncertain reliability. Consequently it is desirable to design the experiment so that S is minimal. E can be estimated from the evaporative weight loss of the subject and the latent heat of vaporization. With M, S, and E available, C + R can be calculated by difference. The separation of C from R can be accomplished mathematically by taking advantage of the fact that R is independent of wind velocity, or alternatively, R can be calculated from

d. Coefficients of convection on nude men can be described by the equation $C/\Delta T = 0.5\sqrt{V}$.

e. Estimates of the convection coefficient with clothed subjects gave values 23% and 24% higher than the coefficient found with nude subjects. This is consonant with estimates of the ratio of the surface area of clothed to nude men.

f. The coefficient or radiation for nude subjects was 5.7 Cal/M^2/Hr/°C. This value is in agreement with a theoretical coefficient based on emissivities of wall and skin of 1 and a radiation area equal to 93% of the surface area.

g. The coefficients of radiation found for clothed subjects were much lower than would be predicted from reasonable assumptions as to emissivity of the clothing surface. No explanation of this discrepancy is offered.

h. Movement of the arms and legs while walking results in an increase in the apparent wind velocity. This amounts to approximately 150 ft/ min. over the tunnel air flow.

4. RECOMMENDATIONS:

None.

Submitted by:

Norton A. Nelson, Major, SnC
Ludwig W. Eichna, Major, M.C.
Steven M. Horvath, Major, SnC
Walter B. Shelley, Capt., M.C.

APPROVED: Conn L. Milburn, Jr.
Conn L. Milburn, Jr.,
Colonel, Medical Corps,
Commanding.

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#1 - Appendix
#2 - Tables 1 thru 5
#3 - Figures 1 thru 16
#4 - Photographs 1 thru 8

inches of the walls. A treadmill on which the subject stood or walked constituted the central portion of the tunnel floor. The inside surface of the tunnel was painted flat black. Dry and wet bulb temperatures inside the tunnel were maintained at the designed conditions plus or minus 1°F. and were uniform laterally. Vertically there were, in the hotter situations, gradients of no more than 3°F. between head and floor levels.

On the test days three separate experiments were performed on each of the three subjects in the same sequence. These consisted of the walking clothed experiments in the morning, and the standing nude and standing clothed in the afternoon. The subject always faced into the air flow and was accompanied in the tunnel by one observer who remained behind the subject at all times.

The walking tests were performed on the treadmill at 3 mph and a 3% grade. This led to metabolic rates of approximately 160 Cal/M^2/Hr. The standing metabolic rates were in the range 40-60 Cal/M^2/Hr.

In each type of experiment the test period was 30 minutes long and was preceded by an equilibrating period designed to reduce storage during the test period. Before the walking experiments this equilibration period consisted of a 60 minute walk on the hot room track, (2.7 mph carrying a 20 lb. pack) followed by a 10 minute walk on the treadmill at the test wind velocity. Before the standing experiments it consisted of a 10 minute stand outside the tunnel either clothed or nude.

During the clothed tests the subjects were well laundered two piece herringbone twill (HBT) fatigue uniforms, light wool socks, underwear shorts and field shoes. To avoid sweat loss by drippage the jacket was tucked into the trousers, the trouser legs were tucked into the sock tops, and the ends of the jacket cuffs were tucked into 4 inch wristlets made of sock tops. In the nude experiments the subjects stood on wooden clogs in a shallow tray containing mineral oil which collected the dripping sweat. In the clothed experiments a full dry suit was donned immediately at the start of the test period just after the equilibration period. Water salted to 0.1% was given in amounts approximating sweat loss just before each test period and, in the walking experiments, at the end of the first 15 minutes of the test period.

Data Collected:

The environmental conditions inside the wind tunnel were determined during each test period as follows: (a) wet and dry bulb temperature, 6 ft. and 1 ft. above floor level, three times per test period, by calibrated motor driven psychrometers; (b) wall temperature, by radiometer at the beginning and end of both the morning and afternoon tests; (c) velocity of air flow, at a point waist high, 4 ft. in front of the subject, twice each period by a Velometer, and 3 times each period by hot wire anemometer.

The following data were obtained on each of the subjects: (a) rectal temperature, by calibrated clinical thermometers at the start and end of each test period; (b) skin temperature, at the start, mid-point and end of each test period by radiometer on exposed skin surfaces and by thermocouples (under clothing); (c) clothing temperature by radiometer at the same times; (d) oxygen consumption, in the walking tests for the first and last 10 minutes of each period by an open circuit system, and in the standing tests for the entire 30 minutes by a closed circuit

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system; (e) heart rate, 3 times each period by palpation of the carotid or radial arteries; (f) evaporated sweat loss, determined by the differences in weight at the start and end of a test period of the subject plus his accessories, which consisted of clothing in the walking experiments; clothing and towel in standing clothed experiments; and towel and drip pan in nude experiments; (g) total sweat loss, from the evaporated sweat loss plus the increase in weight of the accessories above mentioned.

Treatment of Data:

Weighted skin and surface temperatures were calculated for each of the 3 sets of reading in each period according to the weighting factors shown in Table 3. These factors in general are based on the surface area measurements of Hardy and Dubois (2b). The necessary readjustments required by the small number of zones measured were made by grouping unmeasured zones with those measured zones which in previous studies had been observed to have similar temperatures. Considering the significance to be attached to the weighted surface temperatures, this is admittedly a dangerous expedient. It receives some justification, however, in that at the high temperatures here observed, the maximum range of variation of skin temperature from zone to zone is small. The emissivity of both skin and clothing was taken as unity. The initial and final weighted skin temperatures were used in the calculation of storage and the average of the 3 values per period was used in calculation of vapor pressure and temperature gradients.

The 6 readings of dry bulb temperatures in each period were averaged to give the final value used. The final wet bulb temperature was similarly obtained. Vapor pressure was calculated from these averaged dry (T_a) and wet bulb temperatures(T_{wet}) by the formula:

$$P_{H2O} = P_{H2O}\ T_{wet} - 0.265\ (T_a - T_{wet})$$

This expression was based on calibration of the psychrometers used in this study against dew point measurements.

The wall temperature here used was the average of the 2 measurements of the 6 surfaces made each hot day. Wall temperatures so calculated deviated only slightly from air temperatures.

Air velocity was calculated as the average of the 5 measurements made per period.

The caloric equivalent of the oxygen consumption was calculated in the usual way; the actual R. Q. was used to determine the caloric equivalent in the open circuit runs, while the value 4.83 Calories was used in the standing experiments.

The actual interval between initial and final weights of the subject were used in calculating evaporation and sweat rates. This interval was longer than the tunnel exposure by about 2 minutes.

Sweat loss, total and evaporated, was calculated from weight differences and water intake, corrections being made for weight loss due to excess weight of CO_2 excreted over O_2 respired and for loss of water from the lungs. The excess CO_2 was determined by the formula, (CO_2-O_2) grams/hour = 118 x O_2(L/Min) (RQ-0.727). In the standing experiments the R. Q. was taken as 0.825.

Surface Area of Clothed Men:

The problem of the clothed surface area is a difficult one involving not only the actual area but also the effective area as determined by the folds. From measurements of exposed clothing areas carried out on 9 men representing different body builds the ratio of clothed man surface area to nude surface area was calculated. The results are shown in Table 4. These are maximum values since they are made on stretched clothing; it seems not unreasonable that the effective ratio would ordinarily fall in the range 1.20 to 1.35. This series did not include the subjects used in the calorimetry studies. Because of this variation from man to man, and even from time to time, depending on how the folds happen to fall, the coefficients for the clothed men have been calculated on the basis of the nude surface area. This gives the most predictable area and permits future correction should an acceptable factor be found. Thus, the coefficients for clothed men here calculated should be higher than those from the nude men by the ratio of the two surface areas (1.20 - 1.35 to 1).

Calculation of Thermal Exchange:

C + R was calculated from the basic heat equation,
$(C + R)' = -(-E') - M - S - W.$

Where the terms have the following significance and origin:

E' = Total heat exchange by evaporation, Cal/M^2/Hr.
= (kg sweat loss/Hr/M^2-CO_2 excess/Hr) 575.

H_o = Heat exchange by evaporation in the respiratory tract, Cal/M^2/Hr.*

E = $E' - H_o$ = Heat exchange by evaporation from the surface of the body, Cal/M^2/Hr.

$P_{(a,s,o)}$ = Vapor pressure of water in air, on skin, clothing, mm Hg.

$E/\Delta P$ = Coefficient of evaporation, Cal/M^2/Hr/mm Hg.

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* H_o was estimated by making the assumptions indicated below as to vapor pressure of expired air and spirometer air.

Walking (open circuit system):

$H_o = 0.0418\ (P_a - P_1)\ VR$, where

P_1 = vapor pressure, VR = ventilation rate, liter/min.

Standing (closed circuit system):

$H_o = 0.0418\ (P_{sp} - P_1)\ VR$, where

P_{sp} = spirometer vapor pressure; taken as 90% saturated

P_1 = 44.6 mm Hg, except for ambient temperatures of 105°F. and above, where 49.2 mm Hg. was taken.

VR, estimated from rate of oxygen consumption by a correlation between the two used in this Laboratory.

$(C + R)'$ = Total heat exchange by convection and radiation, Cal/M^2/Hr; defined by $(C + R)' + S + E + W = 0$.

H_c = Heat exchange by convection in the respiratory passage, Cal/M^2/Hr.*

$C + R = (C + R)' - H_c$ = Heat exchange by convection and radiation from the surface of the body, Cal/M^2/Hr.

$T_{(a,w,s,c,r)}$ = Temperature of air, wall, skin, clothing, rectum, $^\circ$C.

$\frac{C + R}{\Delta T}$ = Combined coefficient of convection and radiation, Cal/M^2/Hr/$^\circ$C.

$C/\Delta T$, $R/\Delta T$ = Coefficients of convection and radiation, Cal/M^2/Hr/$^\circ$C.

M = Metabolic heat production, Cal/M^2/Hr.

W = Heat exchange by water intake, Cal/M^2/Hr. = kg water/Hr/M^2 x $(T_{water} - T_r)$

S = Storage, Cal/M^2/Hr. = $\frac{(0.83)\ (kg)\ (0.67\ \Delta T_r + 0.33 \Delta T_s)}{(\text{Time interval})\ (\text{Surface area})}$

Where 0.83 represents the average specific heat of the body, and 0.67 and 0.33 are the fractional portions of the body taken as conforming in average temperatures to T_r and T_s respectively (2b).

The general principle was followed of making legitimate corrections even though their order of magnitude was low in relation to the probable error of the measurements. Thus, the weight loss correction for excess CO_2 was at most only 12 grams/M^2/Hr. H_c in the walking experiments ranged from about 5 Cal/M^2/Hr. in the humid environments to about 15 Cal/M^2/Hr. in the dry environments. In the standing experiments H_c was independent of ambient vapor pressure, and ranged from -1 to + 4 Cal/M^2/Hr. H_c was ordinarily less than 1 Cal/M^2/Hr. in the standing experiments at 120°F, increasing in the walking experiments to about 2.5 Cal/M^2/Hr.

Reliability:

Granting the validity of determination of the thermal quantities E, M and S, the question arises whether the E experimentally measured is equivalent to the E required by the basic heat equation.

Consider first the case of evaporation from wet skin in the nude man illustrated in Fig. 9, A. In this situation, the rate of excess flow of heat to T_r from the environment will be equal to $K_a(T_a - T_r)$, where K_a represents the combined coefficients of C and R. Since the only other source of heat to the surface T_r is M, (taking S = 0) and since for a steady condition of heat flow, the rate of access of heat to the surface must equal the rate of heat dissipation, the following condition is fulfilled, $K_a\ (T_a - T_r) + M + (-E) = 0$. Since $K_a(T_a - T_r) = C + R$, the basic equation

* H_c was estimated from the ventilation rate and an assumed temperature of expired air thus:

$$H_c = 0.0187\ (T_a - T_{exp})\ VR, \text{ where}$$

$$T_{exp} = \frac{T_r + T_s}{2} \text{ and}$$

VR as defined under H_o

is satisfied with respect to the surface T_f. Since radiometric measurement of the temperature of wet skin actually measures the water film temperature, the significant temperature for the surface of reference is actually obtained.

Three possible paths of evaporation from clothed men are illustrated (Fig. 9,B,C,D). Equations of heat flow for these situations are developed in an analogous manner. For convenience, they are arranged as equations of temperature difference (See Burton (6)). It can be seen that equations 3 B,C and D all have the same form $I_a(M-E) = T_o - T_a$. Since this is equivalent to $K_a (T_o - T_a) = M - E$, the required condition is fulfilled for these 3 conditions of evaporation from the clothed man, when T_o is taken as the temperature of reference for C + R.* In case a water film of appreciable thickness is present on the clothing the correct surface temperature is no longer T_o but the temperature of the water film; this is the temperature actually measured.

The limiting factor in the reliability of the thermal difference

$$C + R = -(-E) - M - S$$

is the estimation of S; M and E can both be estimated with considerably greater precision. In the calculation of E, use of the same value for the latent heat of vaporization for all skin temperatures and disregard of the energy involved in vapor expansion or change in temperature are approximations which appear to be

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* This conclusion is not invalidated by the fact the amount of evaporation required for steady state conditions varies with the path of evaporation and with the insulation of the various layers through which the heat must flow. The difference in evaporation can be thought of as producing different temperatures of the outermost surfaces. Thus, in the case of evaporation from wet unclothed skin (Fig.(9,A) the equations of heat flow through the water film and from the water surface to the environment are:

$$T'_s - T_f = I_f M \qquad \text{(Skin to water film)}$$

$$T_f - T_a = I_a(M-S) \qquad \text{(Water to air)}$$

which upon adding gives

$$T'_s - T_a = (I_a + I_f)\left(M - S\,\frac{I_a}{I_f + I_a}\right) \qquad \text{(Skin to air)}$$

These equations show, first, that T_f is lower than the true skin temperature T'_s by $I_f M$ and second, that because of this lower temperature and the resulting increase in the rate of C + R transfer, the necessary S for equilibrium is higher than the S for an infinitely thin water film ($I_f = 0$) by the factor $\frac{I_a + I_f}{I_a}$. The extra evaporation can be thought of as producing the lower T_f.

A similar analysis of evaporation from clothed men (Fig.9) indicates that equivalence of equations 3B, C and D obtains even though S varies with the path of evaporation. As indicated by the coefficients of S in these equations, S will be smallest when the evaporation occurs from the skin without subsequent condensation in the clothing (B,5), and largest when it occurs initially from the skin and condenses and re-evaporates from the clothing (C,5). Initial evaporation from the clothing (D,5) requires an S intermediate between these two situations.

minor relative to other uncertainties. The same holds with the correction applied to M for external work in the walking experiment which disregards frictional losses.

A reliable calculation of storage from the data available and by the procedure here used appears to be hopeless. There is every reason to believe that the internal heat-distribution varied during the test period, making untenable the use of any fixed distribution ratio for calculation of storage. Moreover, the assumption that weighted skin and rectal temperatures are representative of any predictable mass of tissue remains questionable. With these uncertainties success in partial calorimetry depends largely on the degree to which negligible changes in storage are incurred. Because of these intrinsic sources of error, and those incurred in the temperature measurements used for calculation of the coefficients, useful study of the C + R exchange has been restricted to the two 120°F. environments. In these environments the large C + R exchange reduces the relative importance of these sources of error.

The factors entering into estimates of coefficients of C + R include not only the thermal difference, C + R, but the temperature differences $T_a - T_{(s \text{ or } e)}$: Two factors enter into the reliability of the $T_a - T_{(s \text{ or } e)}$. These are: (a) the accuracy of an individual measurement, and (b) the reliability of the weighting formula.

The weighting procedure as applied to T_s is reasonably reliable inasmuch as variations in temperature of individual areas are small. In the clothed man the weighting procedure is less reliable as a result of greater temperature differences between individual areas because of uneven wetting and the presence of folds in the clothing. Moreover, while the emissivity of skin may be taken as unity without error, a similar assumption in the case of clothing is not valid. The effect of a low clothing emissivity on the measurement of T_e, would be to under estimate $T_a - T_e$, both where the clothing temperature is above ambient (T_e as calculated would be too low) and where clothing temperature is below ambient (T_e as calculated would then be too high). If radiation exchange only were involved, the temperature error would be self-compensating inasmuch as the error could be considered as an apparent reduction in either emissivity or radiation area. However, a real error is incurred with convection exchange since this must be related to the true temperature. The assumed emissivity of 1 here used is probably not greatly in error. Crude measurements in this Laboratory gave a value between 0.85 and 0.9 for the emissivity of dry HST. Aldrich, quoted by Wulsin (7), gives the value 0.81 as the emissivity of HST at low temperatures (60°F). These values suggest a possible error in $T_s - T_e$ of 10% to 20% and a corresponding error in

$$\frac{C + R}{\Delta T}.$$

In the 120°F. environment, the measured T_e would be high by 1 to 2°C. Since water has a high emissivity at these temperatures, and since the clothing was at least partially wet in all the experiments, the error may be even smaller.

RESULTS

Nude Subjects

Evaporation:

Under normal circumstances, the sweat regulating mechanism adjusts sweat output to a rate adequate to maintain thermal equilibrium. As the thermal

stress increases, whether external or internal (metabolic), the sweating rate progressively increases until heat dissipation by evaporation compensates for the heat gain of the body. With increasing sweat rates or with decreasing evaporative capacity of the atmosphere (high vapor pressure, low wind velocity) the sweat output eventually becomes high enough to completely wet the surface of the subject. When that condition is reached the rate of evaporation becomes a function of two factors, wind velocity and the difference in vapor pressure between the water on the skin and in the atmosphere. However, when the wetting of the surface is not complete then the rate of sweat output, hence sweat evaporation, is determined by the imposed thermal stress, and the rate of evaporation, per se, is independent of environmental factors. Consequently, if one is to evaluate the influence of wind velocity and vapor pressure difference on rate of evaporation, it is necessary to confine study to those conditions where the rate of evaporation is limited by the capacity of the atmosphere to take up moisture, i.e., to the completely wetted condition.

The failure of wind velocity to influence the rate of evaporation at low sweating rates is shown in Fig. 1 in which the evaporation coefficient is plotted against wind velocity for the 7 environments studied. In the first two environments, the rate of evaporation is independent of wind velocity. The rate of evaporation begins to increase with wind velocity, with increases in dry bulb temperature alone (increased sweat rate) as in environments 3 and 4, or with decrease in the evaporative capacity of the atmosphere (increase in ambient vapor pressure) environment 5. Finally, with still greater reduction in the evaporative capacity of the atmosphere, as in environments 6 and 7, the rate of evaporation increases decisively with increasing wind velocity and appears to reach a limiting value.

By limiting consideration to those experiments where a high degree of wetting is present, data useful for characterizing the influence of wind velocity on evaporation can be obtained. An objective basis for selection is to include only those experiments where evaporation was less than 90% of the total sweat output, i.e., 10% or more of the sweat dripped from the man or remained on the skin. Data so selected are plotted in Fig. 2. These coefficients show reasonably good grouping and suggest an exponential relationship between the coefficient of evaporation and wind velocity. A line fitted to the data by the method of least squares yields the equation: $E/\Delta P = 1.44V^{0.37}$. The exponential relationship has precedent in the findings of Powell (4) on the rate of evaporation from cylinders, and has been suggested also on theoretical grounds (5). Studies of the influence of wind velocity on evaporation from completely wetted cylinders by Powell (4) and Fourt (quoted in (3)) have indicated that the coefficient varies approximately as $V^{0.6}$. In contrast, our results suggest that the coefficient is a function of $V^{0.4}$. The reasons for the difference are not clear. Two possibilities are suggested: one, that in our experiments complete wetting of the skin was not maintained at the higher wind velocities; two, that the human body, though consisting to a certain extent of a series of cylinders, may still differ sufficiently in its geometrical configuration to account for the difference.

In Fig. 3, the coefficients obtained in this study are compared with those from the two studies on cylinders mentioned above and with an extrapolation used by the Pierce Laboratory (1d). The extensive deviation of our results from those derived from the Pierce Laboratory equation is not surprising. Their equation is an extrapolation by a questionable procedure and is based on a still air evaporation coefficient. However, the differences between our results on man and those of Powell and Fourt on cylinders will require further study and eventual explanation.

Convection and Radiation: Fig. 10 shows the coefficients for C + R calculated from the nude experiments in environments 4 and 6. The points are moderately well grouped and fall around a smooth curve. Since a certain amount of leeway is possible in fitting a curve to these points, a number of curves considered equally probable were drawn and analysed. If the assumptions are made that the convection coefficient is related to an exponential function of V and that the radiation coefficient is independent of V, the following equation is suggested:

$$\frac{C + R}{\Delta T} = (a + bV^{c})$$

where a corresponds to the radiation coefficient. Differentation of this expression suggests that plotting of log $\frac{C + R}{\Delta T}/\Delta V$ against log V, should give a straight line having a slope equal to (c-1) and an intercept equal to log bc. Establishment of b and c permit calculation of a. Values of a can be calculated for each pair of C + R and V values, and the results so obtained can be averaged. Alternatively C + R can be plotted against the appropriate function of V, and a line fitted by the method of least squares. This procedure, which fixes both a and b is illustrated in Fig. 11A for $F(V) = V^{0.5}$. Treatment of the several curves in this way leads to a series of equations whose limiting values are expressed in the two equations:

$$\frac{C + R}{\Delta T} = 6.85 + 0.23\ V^{0.62}$$

and

$$\frac{C + R}{\Delta T} = 5.65 + 0.53\ V^{0.5}$$

The equation describing convection as function of $V^{0.5}$ is tentatively favored for several reasons. The $\sqrt{V}$ relationship leads to a more acceptable value for $R/\Delta T$. The theoretical value of the coefficient, $\frac{R}{T_1 - T_2} = 4.92 \times 10^{-8}(T_1^4 - T_2^4)$ is 6.07 at the approximate temperatures of these experiments (37°C and 48°C). The value of 6.85 is thus too high even if the effective radiation area were equal to the man surface area. The coefficient of 5.65 associated with $V^{0.5}$ in relation to the theoretical value of 6.07 indicates a radiation area of 93%; this is reasonably close to the estimated value of 80%. In addition, the first equation above leads to lower values for $C/\Delta T$, at very low wind velocities than does the second equation. Comparison with data available on $C/\Delta T$ at such wind velocities (1d) favors the higher convection coefficient given by the $V^{0.5}$ relationship.

Another approach to the separation of C from R is possible by calculation of R by accepted principles and subtraction of these values from the total C + R. Values for $C/\Delta T$ so calculated are shown in Fig. 12. The best line for these values is described by the equation $C/\Delta T + 0.77V^{0.45}$. For comparison the lines corresponding to the equations presented above are drawn on Fig. 12.

Measurements of convective exchange with cylinders have been satisfactorily correlated with air movement by means of dimensionless ratios over a wide range of air temperatures, cylinder sizes and wind velocities (5). These correlations favor the exponent of 0.6 for V for the range of wind velocities here studied. However, until available data permit a more definite choice than is now possible, the $\sqrt{V}$ relationship seems more satisfactory. It is perhaps surprising that

the indirect and inexact procedure here employed leads to such reasonable agreement with the theoretical values for $R/\Delta T$, and with the empiric results obtained on cylinders for $C/\Delta T$.

The dimensionless ratio procedure described above has been used to extrapolate the Pierce Laboratory data to higher wind velocities (3). Lines are drawn in Fig. 13 to represent the original Pierce Laboratory expression, the revised form as extrapolated, and the two expressions suggested by the present study. The deviation of the Pierce Laboratory data from ours probably derive from the different experimental conditions employed. Their air movement was turbulent, being secured by several fans in a small booth; in our studies the flow was linear.

The expressions suggested here for thermal exchanges are presented only as a convenience in correlating the data, and for use in interpolation. It would be foolhardy to use these equations to extrapolate beyond the conditions from which they were derived. Moreover, their application to conditions where air flow is not linear may not be valid.

Clothed Subjects

Evaporation:

Evaporation from clothed subjects may proceed according to several different paths. In certain situations, it is probable that at different points on the body several patterns of evaporation are occuring simultaneously. Three possible paths are illustrated in Fig. 9, B, C, and D. In an attempt to define a coefficient of evaporation, it is necessary to consider on what factors the coefficient depends. Whenever evaporation occurs from the surface of completely wet clothing, as in C or D, Fig. 9, the controlling variables are the same as those operative in the nude experiments, namely, vapor pressure difference, surface to air, and wind velocity. The situation changes, however, when as in B, Fig. 9, evaporation occurs from the skin and the water passes through the clothing as vapor. In this case, the significant vapor pressure difference is that from skin to air, not clothing to air. A new factor is introduced, the diffusion resistance offered to the vapor by the clothing barrier. And though wind velocity is still an influencing factor, its contribution is considerably reduced by the interposed diffusion resistance.

Though there is little reason to anticipate that the rate of evaporation from completely wetted clothing would differ significantly from the rate of evaporation from skin, several factors in the present data prevent the demonstration of this probability. After the initial warm-up period, the subject donned a fresh dry uniform and then entered the wind tunnel for the 30 minute exposure period. Consequently, even in the case of the highest sweating rates, the clothing was dry during a portion of the test period. Therefore, in none of the clothed experiments was evaporation confined exclusively to the clothing surface; a portion of the evaporation must have occurred from the skin through the clothing.

The increased difficulties in the assignment of a mean temperature to the surface of a clothed, as compared to a nude man have been described; these uncertainties influence the reliability of P_o since P_o is based on T_o (hence $P_a - P_o$ and the evaporation coefficient, $E/\Delta P$).

An evaluation of the effective wind velocity on a man walking in a moving air stream will be presented later. The data now to be considered have been plotted against the tunnel wind velocity.

Figures 4 and 6 indicate the effect of wind velocity on the coefficient of evaporation for standing clothed and walking clothed men in the 7 test environments. As in the case of the nude subjects, the rate of evaporation at low sweat rates (less severe environments) is virtually independent of wind velocity, but becomes progressively more dependent on wind velocity as the environmental severity increases. In the nude experiments it was found that by restricting the data to those situations where less than 90% of the sweat was evaporated, maximal coefficients were approached. With the clothed subjects (Figs. 4 and 6) even with a still more generous allowance for wetting (evaporation less than 80%, 20% or more unevaporated), a progressive increase in the coefficient continues to occur as the sweating rate increases and evaporative capacity of the environment decreases. This suggests that the allowance for wetting of the clothing is still inadequate. To test this possibility, the data were further separated into groups according to total sweat output (Figs. 5 and 7). This analysis shows progressive increase in the coefficient of evaporation with higher sweat rates, but there is little to suggest that maximal rates are being approached, except perhaps for group 4, Fig. 7, which includes the highest sweat rates encountered.

In a further analysis of group 4, the wind velocity was corrected for the increased motion of the arms and legs by adding 150 feet/minute (the basis for this value is presented in the next section) to all wind velocities, and the coefficients were corrected to a clothed surface area, using a factor of 1.3. These corrections permit comparison of the coefficients for clothed men directly with the coefficients determined on nude subjects (Fig. 8). Since most of the points fall below the values for the nude subjects, incomplete wetting of the clothed surface occurred in even the most favorable situation. It is clear then that in none of the clothed experiments have maximal surface coefficients of evaporation been reached.

It is probable that the 20% allowance of unevaporated sweat is more than adequate to ensure complete wetting of skin. Hence, it seems likely that the measured rates of evaporation under such condition can be considered as maximal coefficients, not for completely wetted clothing, but for partially wetted clothing where the evaporation occurs to varying degrees through several paths: (a) from wet skin through the dry clothing (b) from the surface of wet clothing.

The situation is obviously a complex one and is not susceptible to simple analysis, or presentation in a form likely to be generally useful. The presentation given in Figs. 5 and 7 may be useful for some purposes. It should be noted, however, that the coefficients are calculated on the gradient from the clothing surface to air. This is, of course, not the significant gradient for evaporation from the skin through dry clothing. Data are available on the influence of fabric porosity on the evaporation coefficient (Fourt (3)). However, they are of little help in the absence of a basis for determining the proportion of evaporation that occurs from the skin through clothing. Lacking such information, the most useful purpose of the present data is to give gross coefficients of evaporation for a range of rates of sweat production.

Convection and Radiation:

The effective wind velocity increase resulting from the arm and leg motion of walking has been estimated by direct comparison of the coefficients of evaporation and convection of standing and walking men (Fig. 14). The chart shows $\frac{C + R}{\Delta T}$ for the 120°F. environments (4 and 6) and $E/\Delta P$ for those experiments where the total sweat output was between 1400 and 2100 gms/hour. The abscissal differences between the curves drawn through the points are given in Table 5 and suggest that the effective wind velocity for a walking man is increased by 80 to 200 ft/min above the measured air velocity in the tunnel. The intermediate value of 150 ft/min is used below (also Fig. 8) to correct the measured wind velocity in the walking experiments. Where this is done the symbol V' is used, where $V' = V + 150$.

The procedure used for separating C from R in the clothed experiments is based on the assumption that $C/\Delta T$ is functionally related to wind velocity in the same way in the clothed tests as in the nude ones. To this end, the calculated values of $\frac{C + R}{\Delta T}$ (a - e) are plotted against $\sqrt{V}$ in Fig. 11 (B) and (C). Lines fitted to the points by the method of least squares give the equations:

$$\text{Standing clothed, } \frac{C + R}{\Delta T} = 2.66 + 0.65 \sqrt{V}$$

$$\text{Walking clothed, } \frac{C + R}{\Delta T} = 3.43 + 0.66 \sqrt{V'}$$

Consider first the coefficients of R. Since the walking man has a larger effective radiation area than the standing man, the values 2.66 and 3.43 qualitatively bear the correct relationship to each other. Quantitatively their ratio of 0.79 is somewhat lower than would have been expected on the basis of estimated radiation area of 80% and 90% for the two conditions.

The absolute values of these radiation coefficients are much lower than anticipated; and no reasonable explanation has been found for the discrepancy. Due to the larger surface area of the clothed subject, it would be anticipated that for the clothed man $R/\Delta T$ would be in the neighborhood of 20% to 30% higher than the nude coefficient unless the clothing emissivity is low; this possibility appears to be ruled out by the data available on the emissivity of HBT.

The convection coefficients, $C/\Delta T = 0.65 \sqrt{V}$ and $0.66 \sqrt{V'}$ are in good agreement. Their ratios to the corresponding value (0.53) for the nude subjects is 1.23 and 1.24 which is perfectly compatible with the anticipated increase in surface area of the clothed man.

However, one cannot escape the fact that the total $\frac{C + R}{\Delta T}$ is lower than can be explained. The question may therefore be raised as to whether the satisfactory values found for $C/\Delta T$ may not be fortuitous, and that the net deficit of C + R should be distributed between both the convection and radiation coefficients. Since the possible error in measurement of $T_a - T_e$ from assuming too high a value for clothing emmissivity tends to underestimate $T_a - T_e$, $\frac{C + R}{\Delta T}$ would be still lower if the correct $T_a - T_e$ were used. Thus, though $\frac{C + R}{\Delta T}$ as calculated is low, the full extent of this deficit may have been concealed by dividing by a too small ΔT.

From a practical standpoint, convection or radiation to clothed men is most satisfactorily defined in terms of the effective insulation of the clothing. However, the earlier statement that all other factors being constant, E can vary accordingly to the path of evaporation independently of clothing insulation, indicates that difficulty may be expected in an attempt to measure clothing insulation with the data available. This is further shown by equations (8) B, C and D, Fig. 9, where $\frac{T_s - T_e}{T_e - T_a}$ is related to the various insulation coefficients and to K and E. In the simplest situation, (8) B, the clothing insulation $I_c + I_i$, is equal to $I_a \frac{T_s - T_e}{T_e - T_a}$ and in this case $I_c + I_i$ can be calculated. When, however, evaporation deviates from this route as in C and D, $I_a \frac{T_s - T_e}{T_e - T_a}$ is no longer a simple function of the clothing insulation.

Recognizing this, but in an effort to cast some light on the effect of clothing wetness on its insulation, $I_a \frac{T_s - T_e}{T_e - T_a}$ (or $\frac{1}{K_a} \frac{T_s - T_e}{T_e - T_a}$) has been plotted against sweat unevaporated in Fig. 15. The result, as would be anticipated, suggests that with increasing wetness of clothing its conductance increases.

Two factors suggest that the apparent insulation as plotted in Fig. 15 may be reasonably valid: First, in condition C the value plotted, $\frac{1}{K_a} \frac{T_s - T_e}{T_e - T_a}$ should differ only slightly from the true clothing insulation, $I_i + I_c$, since the coefficient of E in the denominator of equation C (6) can be expected to be very close to one. Second, condition D, Fig. 9, requires that T_e be lower than T_s. In the condition here treated where T_a is higher than T_e, a negative ratio, $\frac{T_s - T_e}{T_e - T_a}$, would result if condition D dominated. The absence of negative values in Fig. 15 suggests that evaporation according to path D is relatively minor.

DISCUSSION

The results of the analysis of the experiments with nude subjects appear fruitful. The coefficients of the three exchange paths studied, convection, radiation, and evaporation, are all consistent with expectations and with the limited data available for comparison. The data for evaporation has no counterpart; the only reasonable comparison is with the data of Powell and Fourt (4,3). The differences revealed by this comparison are perhaps not larger than would be anticipated, taking into account the scatter of our results and the inherent difference in the type of experiment. Further study is desirable on many grounds, but especially needed is an answer to the possible criticism that incomplete wetting was obtained in our experiments at the higher wind velocities.

The independent estimation of the radiation coefficients yeilds a satisfying confirmation of earlier work. As more information accumulates over extended ranges of conditions, the adequacy of the theoretical description of radiation exchange as applied to nude men becomes more apparent.

As with radiation, the descriptions here offered for convection fall largely into the category of extension of available information to different conditions of air flow and to more severe environmental conditions. It seems probable that the most useful information on convection exchange at high wind velocities will arise from study of linear air flow; this is much more frequent in occurence at high wind velocities than is turbulent flow.

For practical use, the following rounded values are suggested for the coefficients derived from the nude experiments:

Evaporation - $E/\Delta P = 1.4V^{0.4}$

Convection - $C/\Delta T = 0.5V^{0.5}$

Radiation + Convection (120°F.) $\frac{C + R}{\Delta T} = 5.7 + 0.5V^{0.5}$

In these equations thermal exchange has the units, Cal/M^2/Hr/°C or mmHg, and velocity is expressed as feet/minute.

Lines drawn from these equations are shown in Fig. 16. Note that the exponent of V is higher in the equation for $C/\Delta T$ than for $E/\Delta P$, therefore, increasing wind velocity increases thermal stress more rapidly than the cooling possible by evaporation.

The results from the experiments with the clothed subjects are perhaps most useful insofar as they point out the complexity of the problem and the difficulties likely to be encountered in applying the method of partial calorimetry. Most of the uncertainties of the present analysis would be eliminated if a complete heat balance were available. The evaporation coefficients require complete restudy under conditions insuring better control and greater uniformity of wetting. This is a difficult task, but a very practical and important one.

The data presented here on the gross coefficients of evaporation for clothed men are of very limited usefulness, but until better information is available, may serve to fix the order of magnitude of evaporation from partially wet clothing.

With respect to the convection and radiation coefficients from the clothed men, two alternatives are offered. The easiest course at the moment is to disregard the results on the basis of inadequate definition of the surface temperature, or measurement of storage, or both. On the other hand, if we are to accept the eminently reasonable values found for $C/\Delta T$ with the clothed subjects we are forced into the necessity of accepting what at present appears to be an unacceptable value for clothing emissivity.

SUMMARY

1. Coefficients of thermal exchange for nude and clothed men, standing and walking, have been estimated by partial calorimetry in a series of 7 environments and at 5 wind velocities. Dry bulb temperatures ranged from 90°F. to 120°F; vapor pressures, 13 to 36 mmHg; wind velocities, 30 to 600 ft/minute.

2. In nude subjects the maximum coefficient of evaporation can be described by the equation $E/\Delta P = 1.4V^{0.4}$.

3. Sweating rates adequate to measure the maximum coefficients of surface evaporation in clothed men probably were not reached. Charts presenting the coefficients actually found are shown.

4. Coefficients of convection for nude men can be described by the equation $C/\Delta T = 0.5\sqrt{V}$.

5. Estimates of the convection coefficient with clothed subjects gave values 23% and 24% higher than the coefficient found with nude subjects. This is consonant with estimates of the ratio of the surface area of clothed to nude men.

6. The coefficient of radiation for nude subjects was 5.7 $Cal/M^2/Hr/^oC$. This value is in agreement with a theoretical coefficient based on emissivities of wall and skin of 1 and a radiation area equal to 93% of the surface area.

7. The coefficients of radiation found for clothed subjects were much lower than would be predicted from reasonable assumptions as to emissivity of the clothing surface. No explanation of this discrepancy is offered.

8. Movement of the arms and legs while walking resulted in an increase in the apparent wind velocity. This amounts to approximately 150 ft/min over the tunnel air flow.

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Incl. #1

TABLE 1

ENVIRONMENTAL CONDITIONS AND SEQUENCE STUDY

Environment No. and Corresponding
Wet Bulb Temperature, °F

Dry Bulb Temp. °F.	Vapor Pressure mm Hg.		
	13	25	36
90	(1) 69.5°	X	X
96	(2) 71.5°	(5) 82.8°	(7) 91.0°
105	(3) 74.0°	X	X
120	(4) 78.0°	(6) 83.0°	X

WIND VELOCITIES

Code	Ft/Min
a	30
b	75
c	150
d	300
e	600

SEQUENCE OF ENVIRONMENTS

The number refers to environment,
letter to wind velocity

Week*	M (Acc**)	T	W	T	F	S
1	120-88	Bd***	6a	7a	5a	2d
2	120-78	1c	3c	4a	Bd	6c
3	96-91	7e	5a	2c	1c	3a
4	120-78	4c	Bd	6c	7a	5c
5	120-78	2c	1a	3c	4c	Bd
6	120-88	6b	7d	5b	2d	1b
7	120-88	4d	7d	6d	7b	5d
8	120-88	2b		3d	4b	Bd

* Starting 9 October, 1944
** Acc= Re-acclimatization, no data collection.
*** Bd = Base Day; 120° - 88°, 300 Ft/min

Incl. #2

TABLE 2

PHYSICAL CHARACTERISTICS OF THE SUBJECTS

Subject	Complexion	Age Years	Height Cm.	Weight Kg.	Surface Area M^2
Mil	light	20	166	62.4	1.68
Lon	light	23	170	65.5	1.75
God*	brunette	20	185	62.5	1.82
McG	brunette	22	177	74.4	1.90

*God replaced McG after 11 test days.

TABLE 3

FACTORS USED FOR CALCULATION OF WEIGHTED
SKIN AND SURFACE TEMPERATURES

Hardy, Dubois Areas		Zones Measured	Weighting Factors				
			Nude	Clothed			
				Standing		Walking	
Zone	Area		Ts	Skin Ts	Surface Ts (d)	Skin Ts	Surface Ts (d)
Head	0.07	Cheek	0.07	0.07	0.05	0.14e	0.12e
Trunk	0.35	Chest	0.18	0.35tb	0.19	0.35tb	0.19
		Back	0.17		0.17		0.17
Arms	0.14	Upper Arm	0.14	0.14t	0.15	0.14t	0.15
Hands	0.05	Palm	0.05	0.05	0.04	0.05	0.04
Thigh	0.19	Thigh	0.39a	0.19t	0.40a	0.19t	0.33f
Legs	0.13	Calf		0.20tc		0.13t	
Feet	0.07						

t - Obtained by thermocouple; all other temperatures by radiometer.
a - Feet and legs grouped with thigh.
b - Back and chest grouped.
c - Feet grouped with calf.
d - Because of increased surface area of clothed man, head and hand factors decreased by $\frac{0.12}{1.00}$ to $\frac{0.12}{1.3}$, all other factors increased.
e - Feet grouped with cheek.
f - Legs grouped with thigh.

TABLE 4

RELATION OF CLOTHED SURFACE AREA TO MAN SURFACE AREA

Subject No.	Type*		Height cm.	Weight Kgm.	Size		Surface Area M^2					Ratio Clothed S.A. / Man S.A.
	Height	Weight			Jacket	Trousers	Jacket	Trousers	Jacket & Trousers	Clothed Manes	Nude Man	
1	S	L	163.8	45.0	34R	30-33	0.875	1.057	1.932	2.308	1.45	1.52
2	I	L	168.9	57.5	34R	32-33	0.981	1.146	2.127	2.439	1.64	1.48
3	T	L	183.5	57.3	36R	32-33	1.0[illegible]	1.203	2.244	2.577	1.75	1.[illegible]
4	S	I	157.5	60.5	34R	30-33	0.830	1.057	1.887	2.191	1.60	1.36
5	I	I	172.1	68.2	34R	32-33	0.950	1.167	2.097	2.457	1.79	1.36
6	T	I	193.0	[illegible].2	38L	34-33	1.036	1.160	2.266	2.660	2.18	1.33
7	S	H	161.3	66.6	34R	34-33	0.882	0.9[illegible]	1.874	2.195	1.69	1.39
8	I	H	176.5	85.5	38L	33-33	1.045	1.378	2.323	2.703	2.00	1.35
9	T	H	182.9	101.4	40R	40-33	1.169	1.424	2.593	3.013	2.21	1.36

*S = Short

I = Intermediate

T = Tall

H = Heavy

L = Light

** = Surface area of head + hands + feet + clothing = 0.19 Nude Man S.A. + Clothing S.A.

Incl. 1/2

TABLE 5

APPARENT INCREASE IN WIND VELOCITY WITH WALKING

Cals/M²/Hr	Wind Velocity Feet/Minute		
	Standing Clothed	Walking Clothed	Δ
E/ΔP 1400 to 2100 gms/hr			
8	300	145	143
7	215	80	135
6.5	180	40	140
$\frac{C + R}{\Delta T}$ Env. 4			
15	610	420	190
12	360	150	210
10	225	45	180
$\frac{C + R}{\Delta T}$ Env. 6			
22	580	480	100
15	260	180	80
13	190	50	140

Incl. #2

FIG. 1

EVAPORATION VS. WIND VELOCITY

STANDING - NUDE

LINE DRAWN ACCORDING TO EQUATION: $E/\Delta P = 1.44\ V^{0.57}$

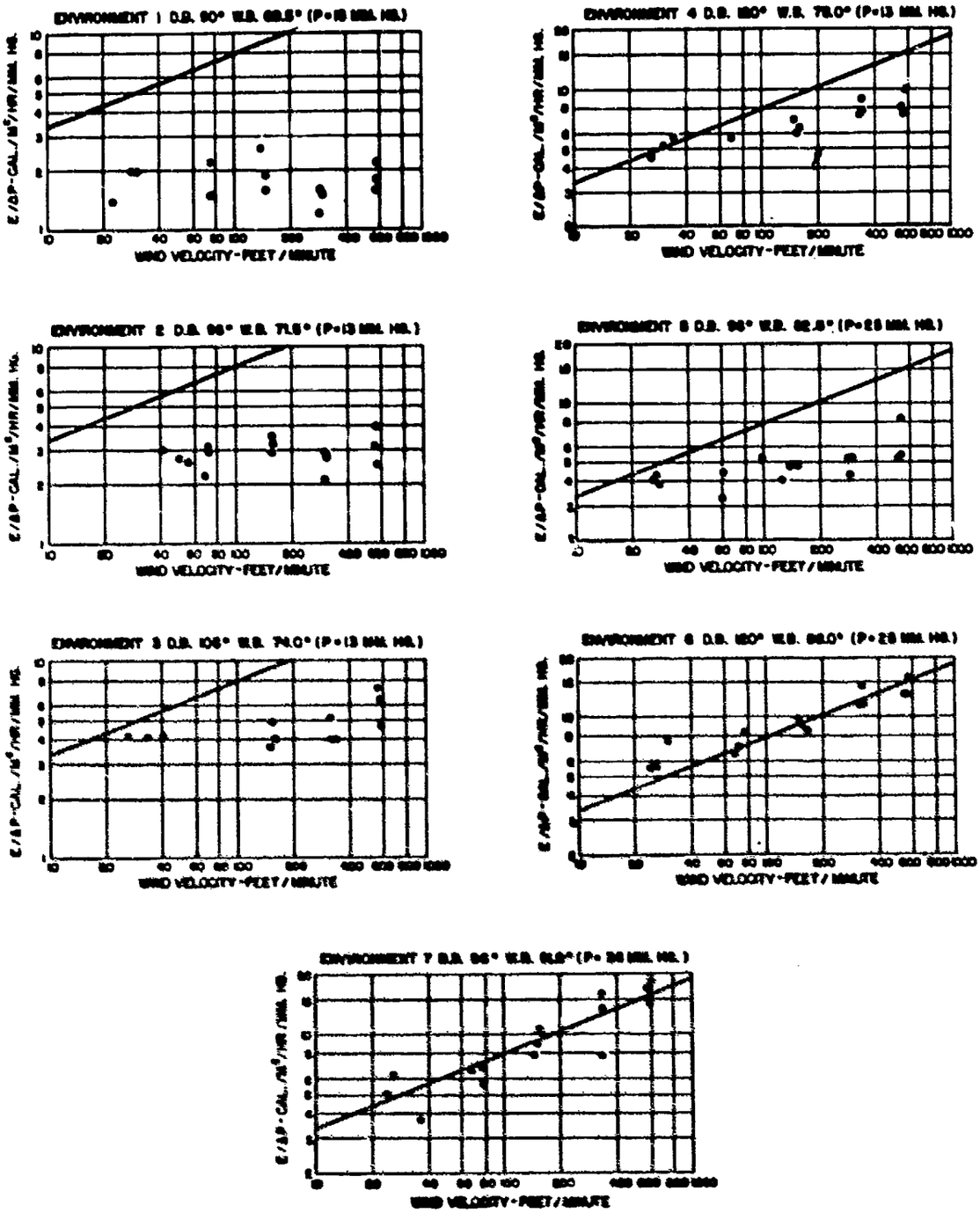
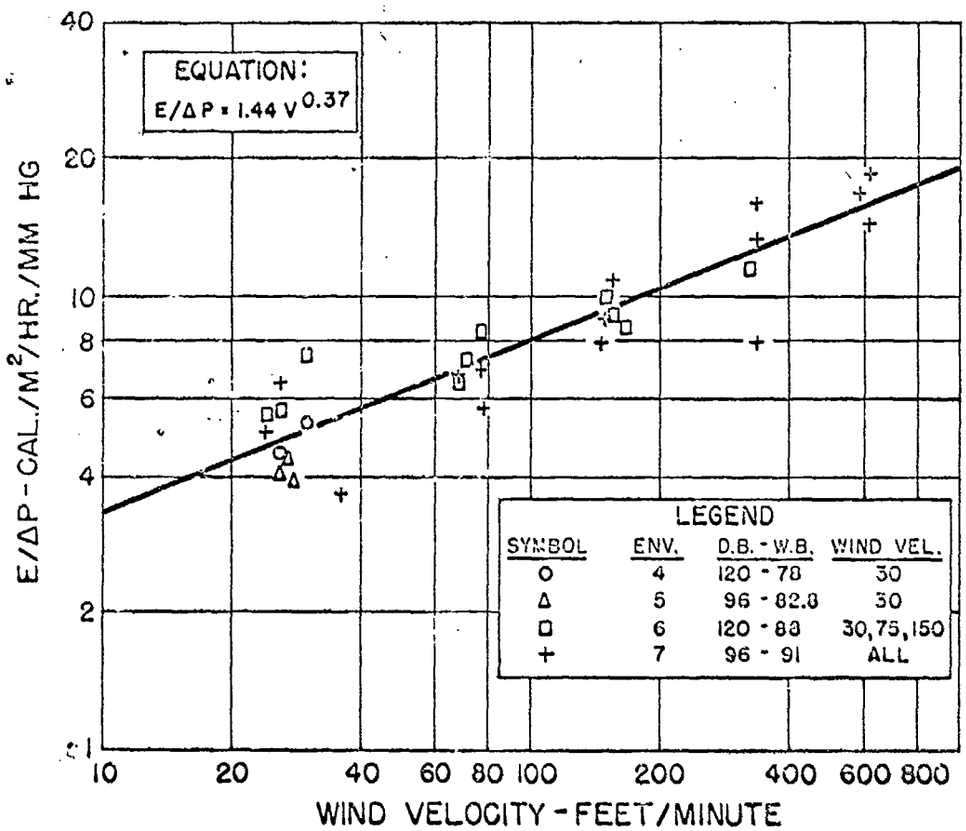


FIG. 2

EVAPORATION VS. WIND VELOCITY

STANDING-NUDE

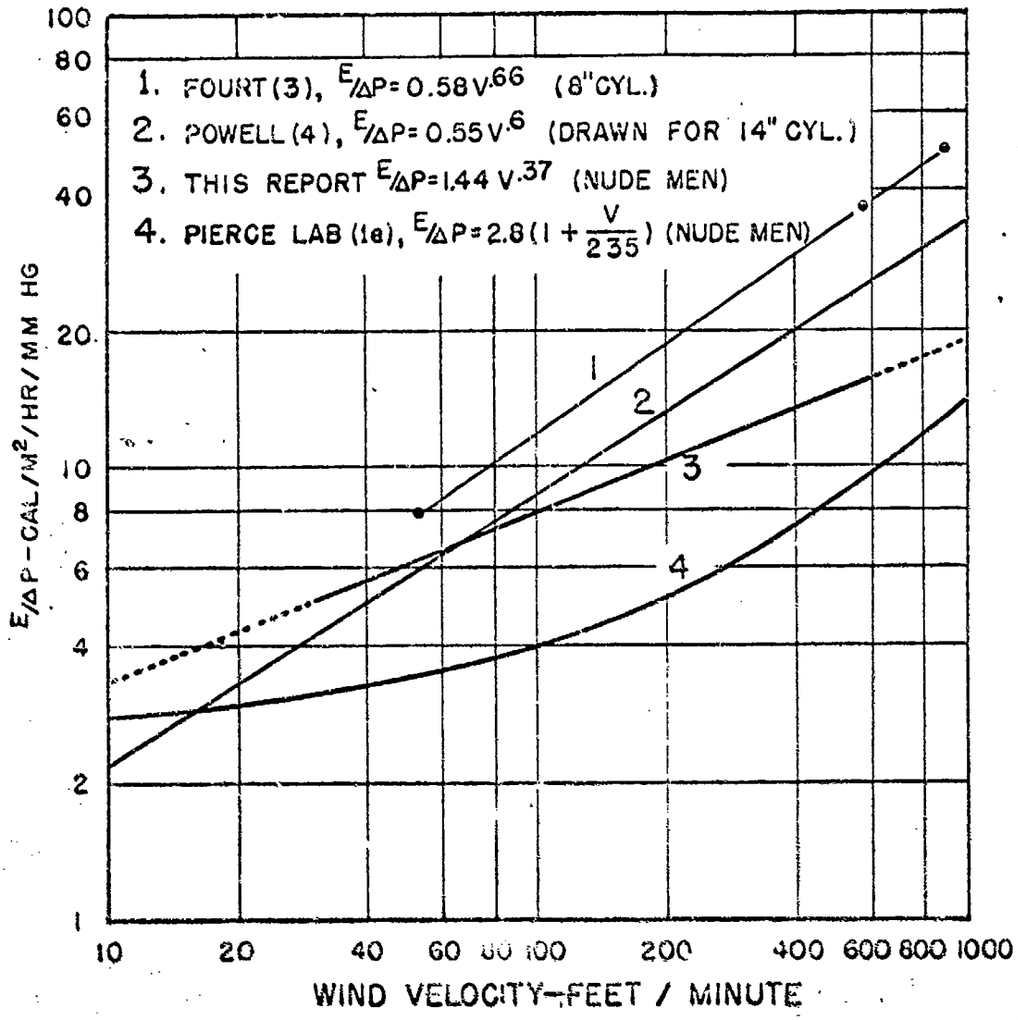
E/ΔP, EVAPORATION LESS THAN 90%



Incl. #2

FIG. 3

COMPARISON OF RELATIONSHIPS
DESCRIBING EVAPORATION AS A FUNCTION OF
WIND VELOCITY



Incl. #3

FIG.4

EVAPORATION VS. WIND VELOCITY

STANDING - CLOTHED

E / ΔP (n - e), EVAPORATION LESS THAN 50 %

(CALCULATED FROM MAN SURFACE AREA)

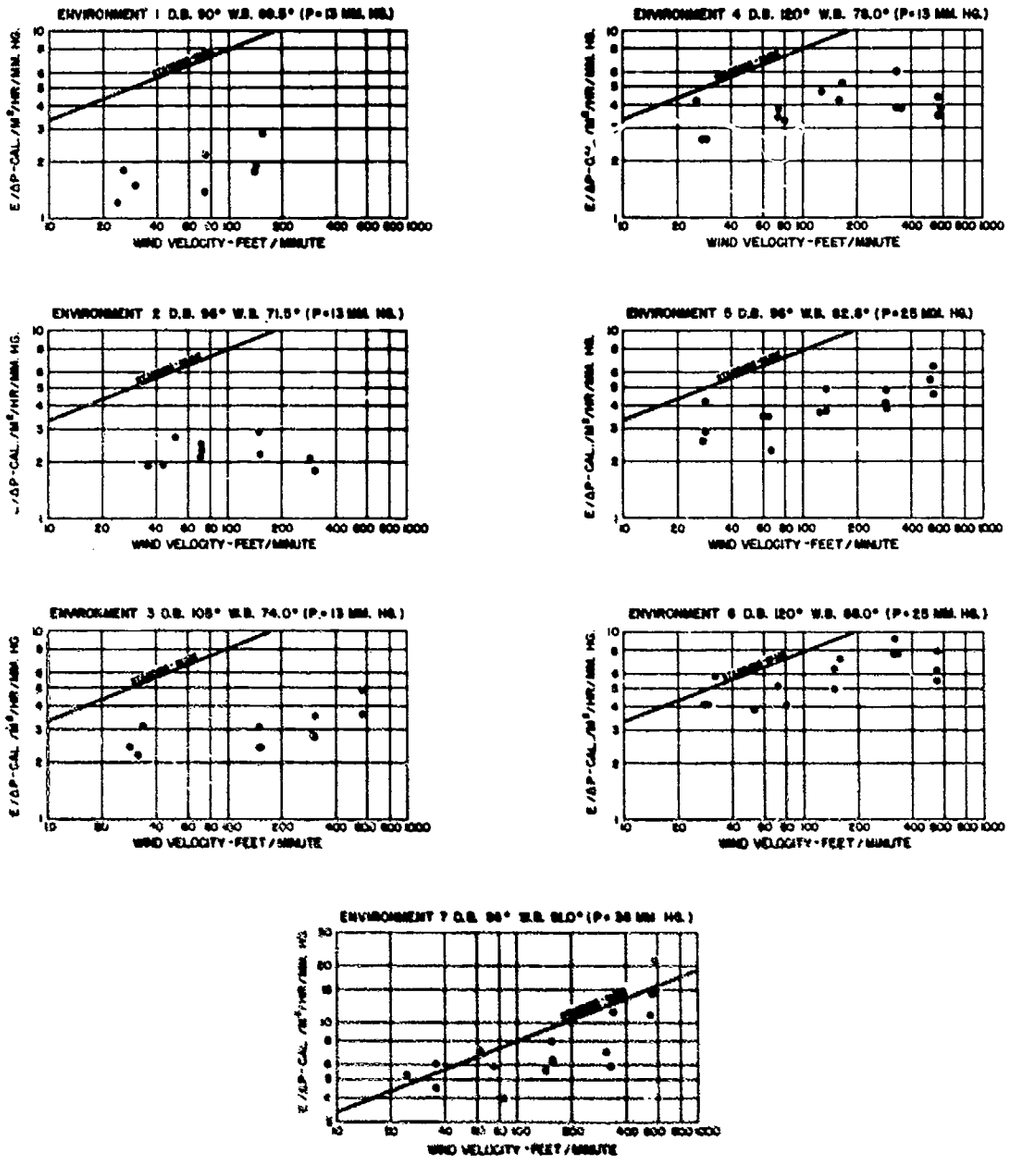


FIG. 5

EVAPORATION VS. WIND VELOCITY

STANDING - CLOTHED

E/ΔP(σ - e), EVAPORATION LESS THAN 90 %
(CALCULATED FROM MAN SURFACE AREA AND GROUPED
ACCORDING TO AMOUNT OF TOTAL SWEAT)

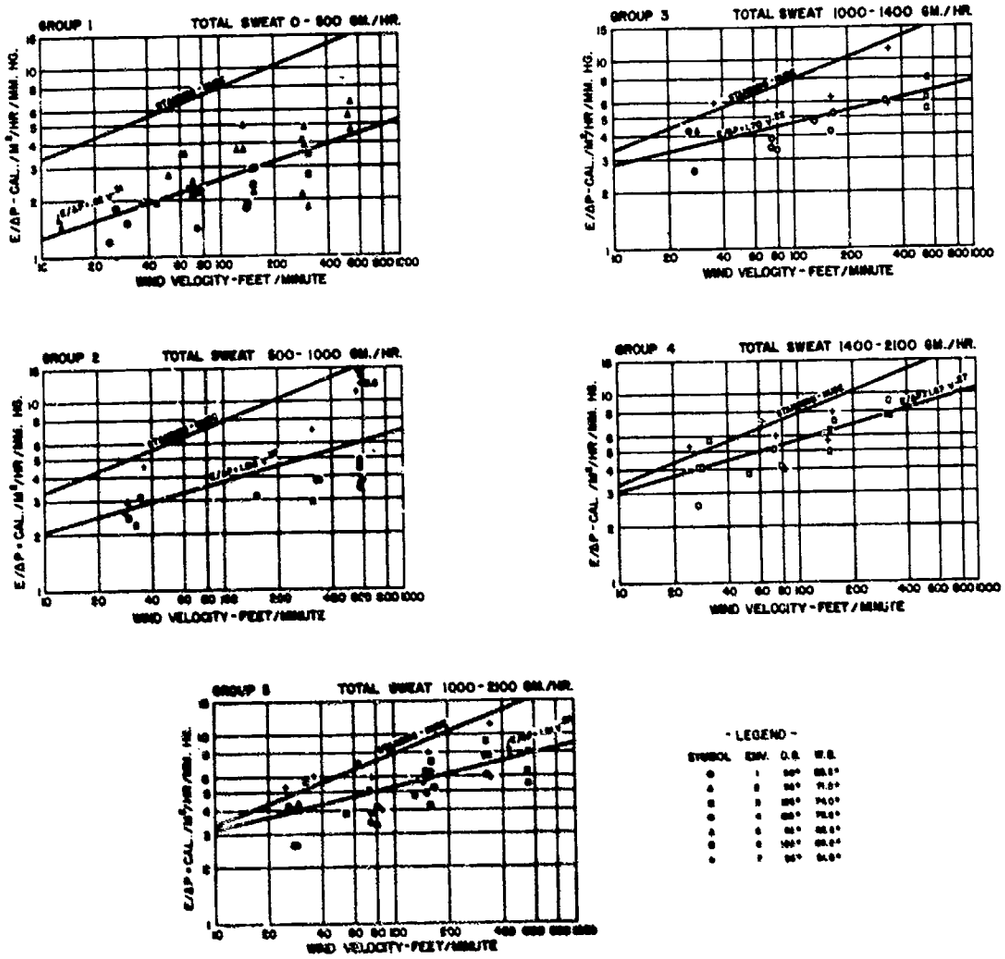


FIG. 6

EVAPORATION VS. WIND VELOCITY
WALKING - CLOTHED

E / ΔP (α - e), EVAPORATION LESS THAN 80 %
(CALCULATED FROM MAN SURFACE AREA)

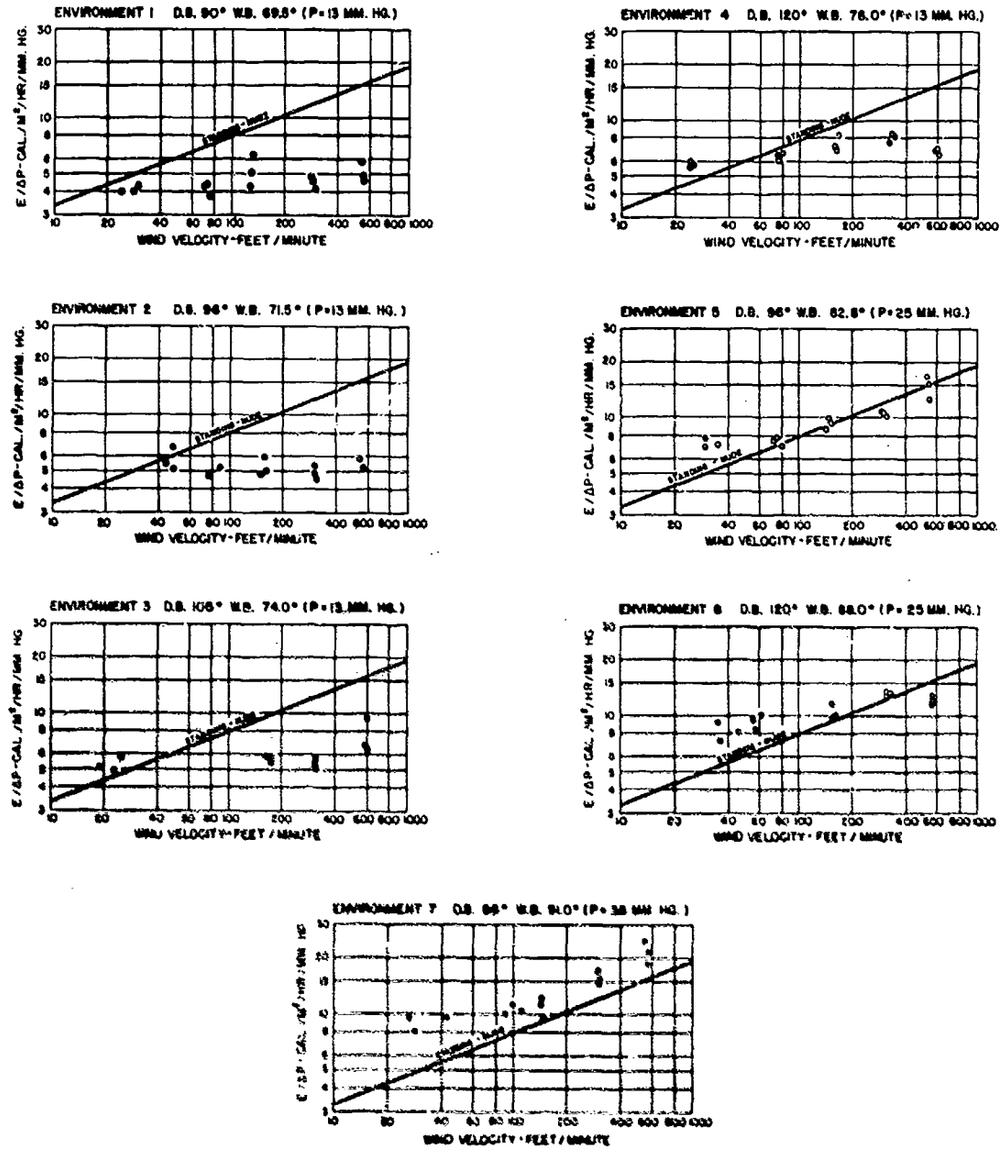


FIG. 7

EVAPORATION VS. WIND VELOCITY

WALKING - CLOTHED

E/ΔP(e-v), EVAPORATION LESS THAN 60 %
(CALCULATED FROM MAN SURFACE AREA AND GROUPED
ACCORDING TO AMOUNT OF TOTAL SWEAT)

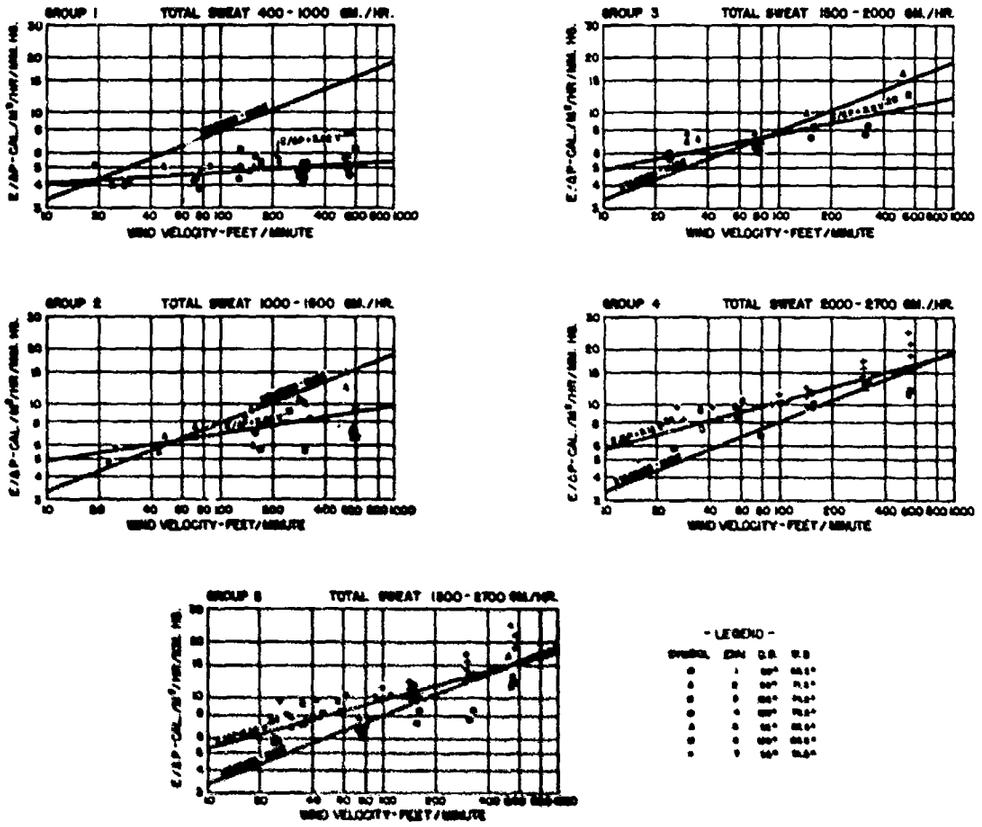


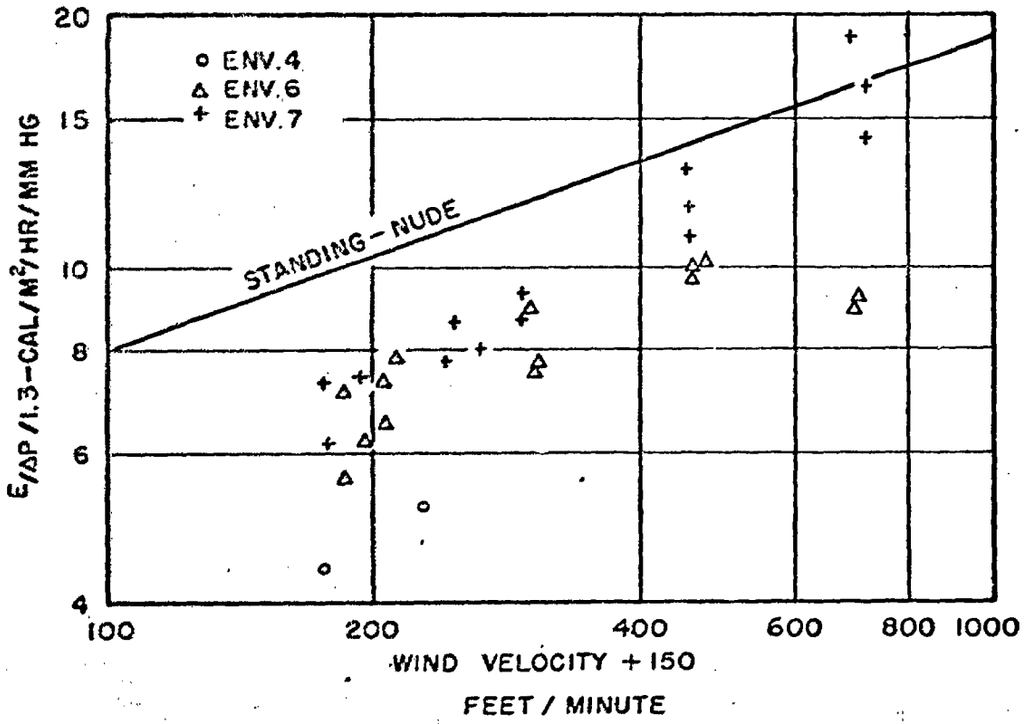
FIG.8

CORRECTED COEFFICIENTS OF EVAPORATION
WALKING CLOTHED

TOTAL SWEAT 2000-2700 GMS./HR.

E/ΔP (a-e)

CORRECTED FOR SURFACE AREA AND WIND VELOCITY



Incl. #3

FIG. 9

EQUATIONS OF THERMAL FLOW FOR EVAPORATION FROM VARIOUS SURFACES

IN ALL CASES IT IS ASSUMED THAT $S=0$, AND THE CONDITION $C+R+M+E=0$ IS FULFILLED. E IS ALWAYS NEGATIVE FOR THE CONDITIONS CONSIDERED HERE. THE RATES OF HEAT TRANSFER BY C AND BY R ARE COMBINED IN A COMMON COEFFICIENT $K = 1/I$

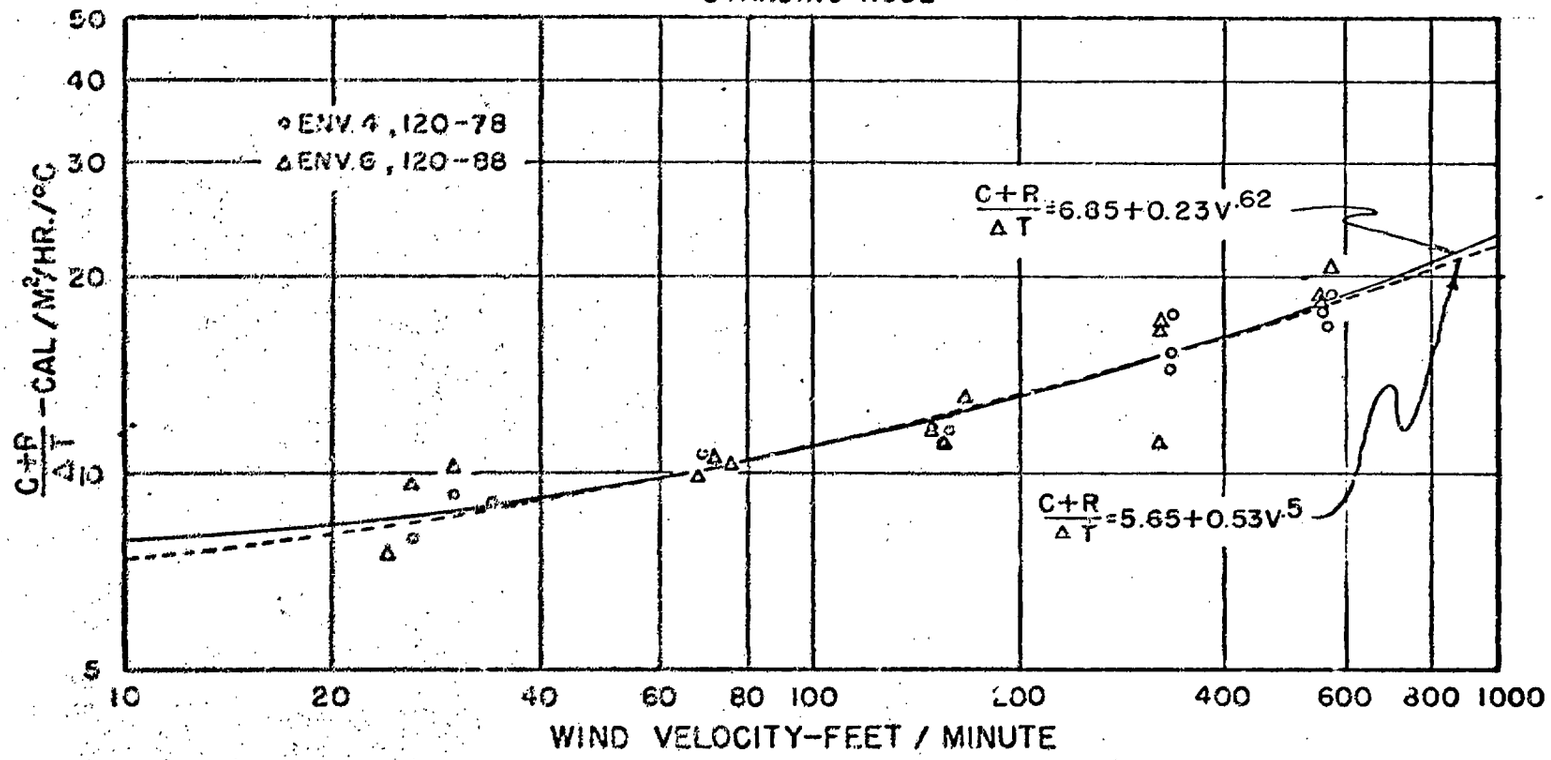
	A NUDE	B CLOTHED	C CLOTHED	D CLOTHED
	EVAPORATION FROM WET SKIN.	EVAPORATION FROM SKIN THROUGH DRY CLOTHING.	EVAPORATION FROM SKIN, CONDENSATION ON WET CLOTHING, EVAPORATION FROM WET CLOTHING.	EVAPORATION FROM WET CLOTHING WITHOUT PRELIMINARY EVAPORATION FROM SKIN. WATER REACHES CLOTHING BY DRIP OR CAPILLARITY.
TEMPERATURE FLOW	T_a T_f (T_s) T_s'	T_a T_s T T_s	T_a T_s T T_s	T_a T_s T T_s
	M-E, M	M-E, M-E, M-E	M-E, M, M-E	M-E, M, M
	AIR, WATER FILM	AIR, DRY CLOTHING, AIR	AIR, WET CLOTHING, AIR	AIR, WET CLOTHING, AIR
INSULATION CONDUCTANCE	I_a I_f	I_a I_c I_i	I_a I_b I_i	I_a I_b I_i
	K_a K_f	K_a K_c K_i	K_a K_b' K_i	K_a K_b K_i

	A	B	C	D
1)	$E - M = C + R$	$T_s - T = I_i(M-E)$	$T_s - T = I_i(M-E)$	$T_s - T = I_i M$
2)	$M - E = -(C+R)$	$T - T_a = I_c(M-E)$	$T + T_a = I_b' M$	$T - T_a = I_i M$
3)	$K_a(T_s - T_a) = C+R$	$T_s - T_a = I_a(M-E)$	$T_s - T_a = I_a(M-E)$	$T_s - T_a = I_a(M-E)$
4)	$\frac{T_s - T_a}{I_a} = C+R$	$T_s - T_a = (I_i + I_c)(M-E)$	$T_s - T_a = (I_i + I_b')\left(M - E\frac{I_i}{I_i + I_b'}\right)$	$T_s - T_a = (I_i + I_b)M$
5)	$\frac{T_s - T_a}{I_a} = -(C+R)$	$T_s - T_a = (I_i + I_c + I_a)(M-E)$	$T_s - T_a = (I_i + I_b' + I_a)\left(M - E\frac{I_a + I_i}{I_i + I_b' + I_a}\right)$	$T_s - T_a = (I_i + I_b + I_a)\left(M - E\frac{I_a}{I_i + I_b + I_a}\right)$
6)	$\frac{T_s - T_a}{I_a} = M-E$	$\frac{T_s - T_a}{T_s - T_a} = \frac{I_c + I_i}{I_a}$	$\frac{T_s - T_a}{T_s - T_a} = \frac{I_i + I_b'}{I_a} \cdot \frac{M - E\frac{I_i}{I_i + I_b'}}{M-E}$	$\frac{T_s - T_a}{T_s - T_a} = \frac{I_i + I_b'}{I_a} \cdot \frac{M}{M-E}$
7)	$T_s - T_a = I_a(M-E)$			
8)	$T_s' - T_f = I_f M$			

FIG. 10

COEFFICIENTS OF CONVECTION AND RADIATION
AS A FUNCTION OF WIND VELOCITY

STANDING NUDE



Incl. #3

FIG. 11

CONVECTION AND RADIATION VERSUS WIND VELOCITY

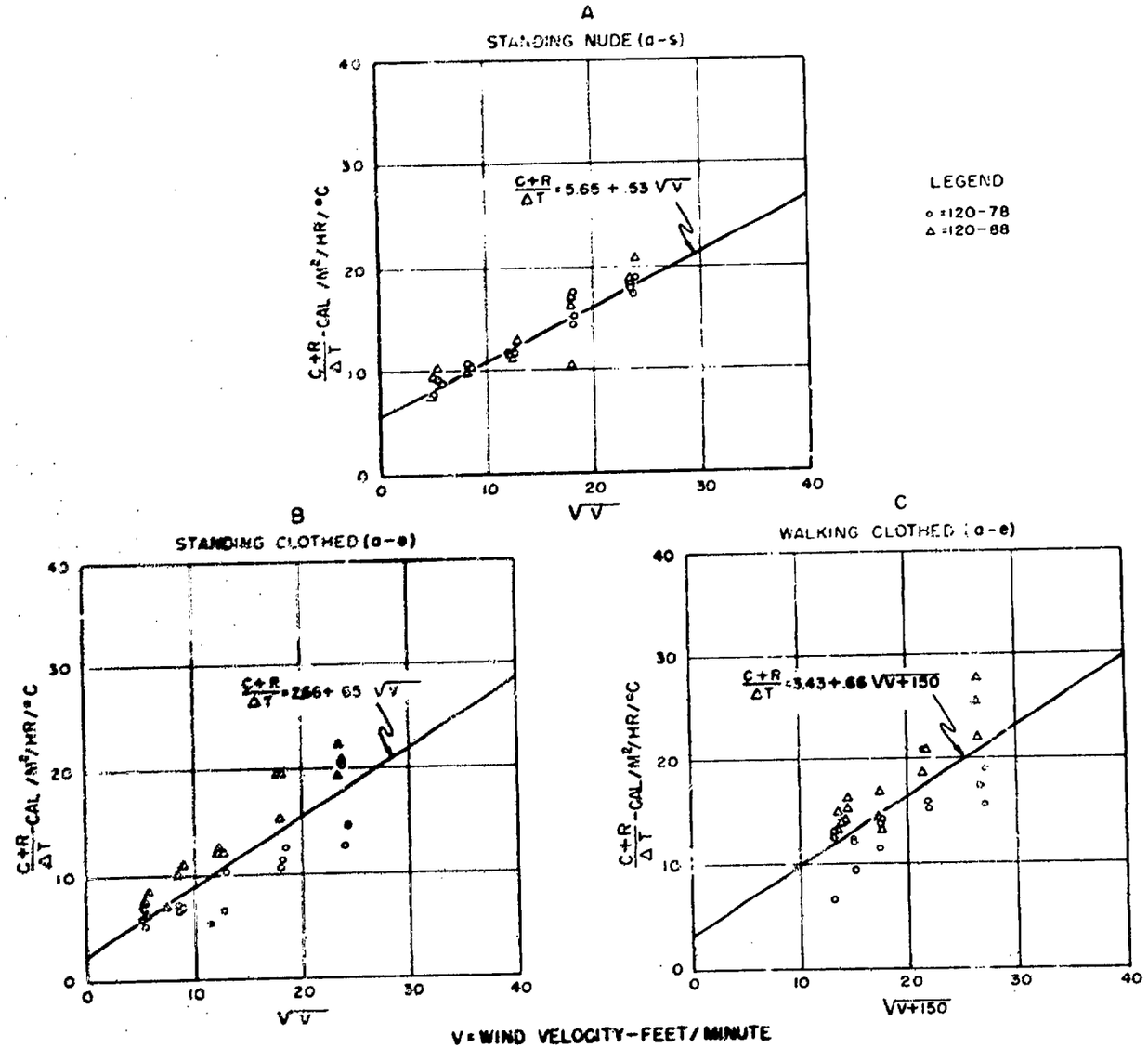
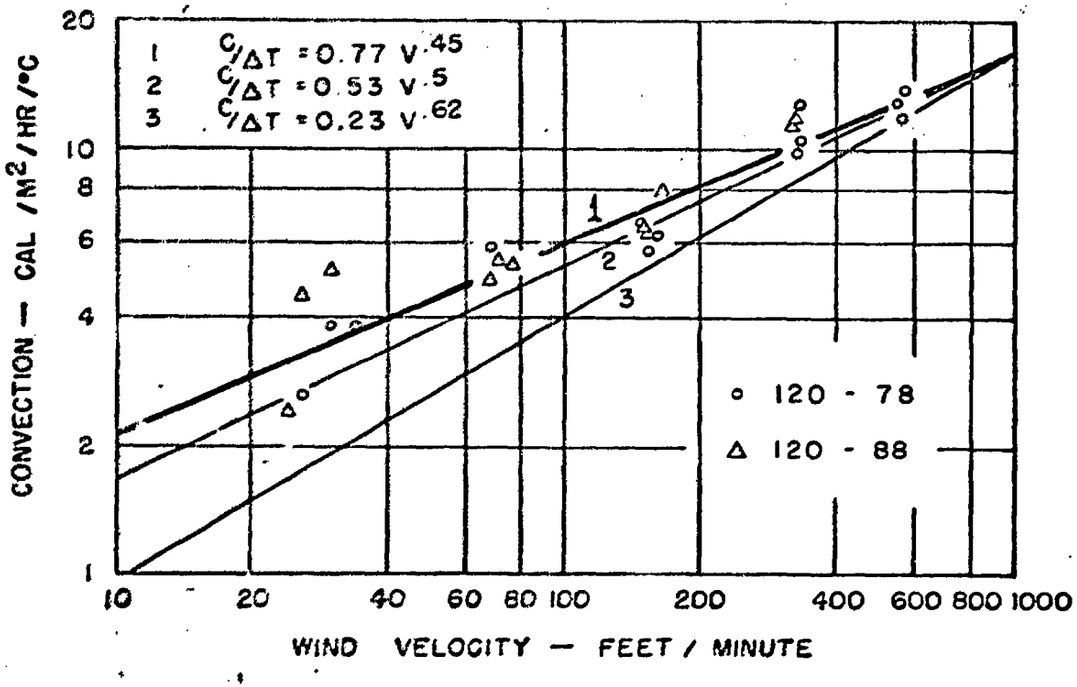


FIG.12

CONVECTION Vs WIND VELOCITY

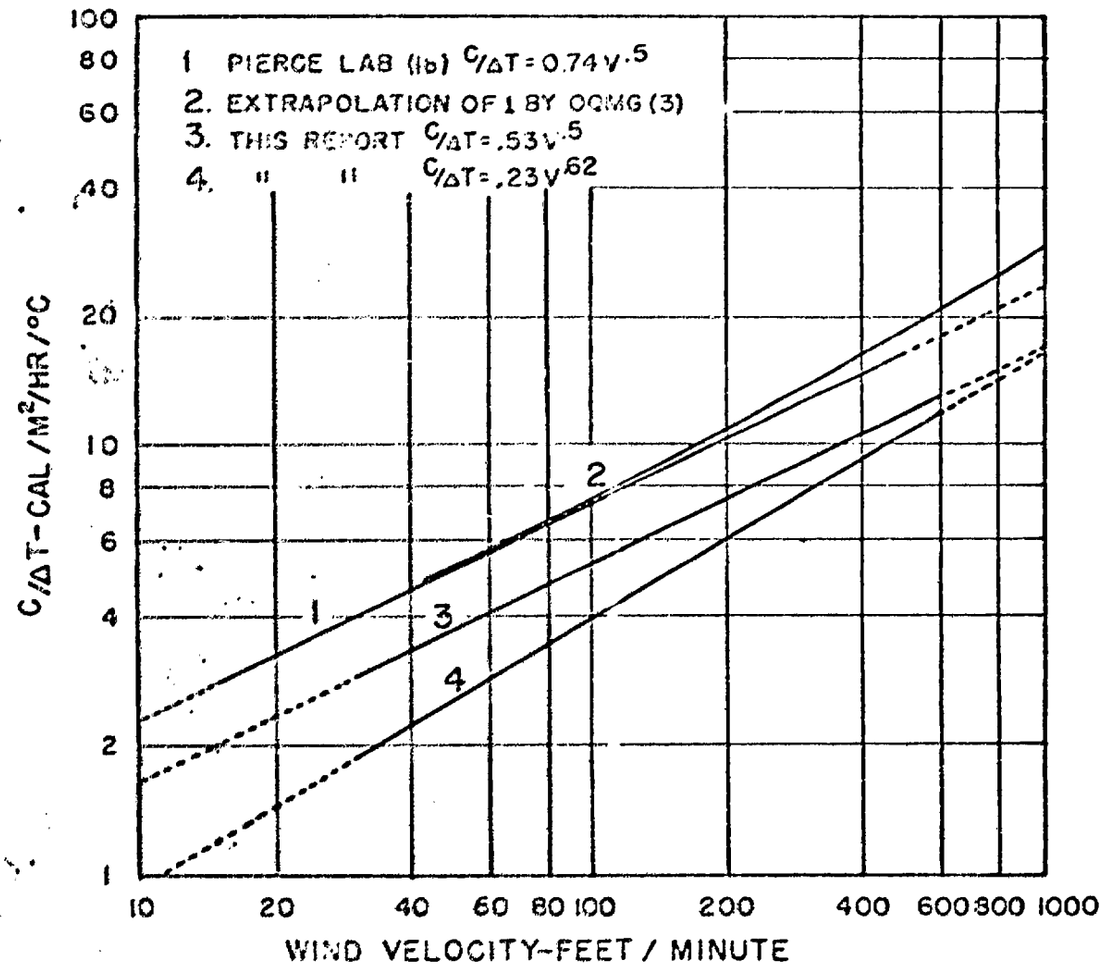
CORRECTED FOR RADIANT EXCHANGE
BY $R = 0.8 \times 4.92 \times 10^{-8} (T_W^4 - T_S^4)$
STANDING NUDE



Incl. #3

FIG. 13

COMPARISON OF RELATIONSHIPS FOR CALCULATION OF CONVECTION AS A FUNCTION OF WIND VELOCITY



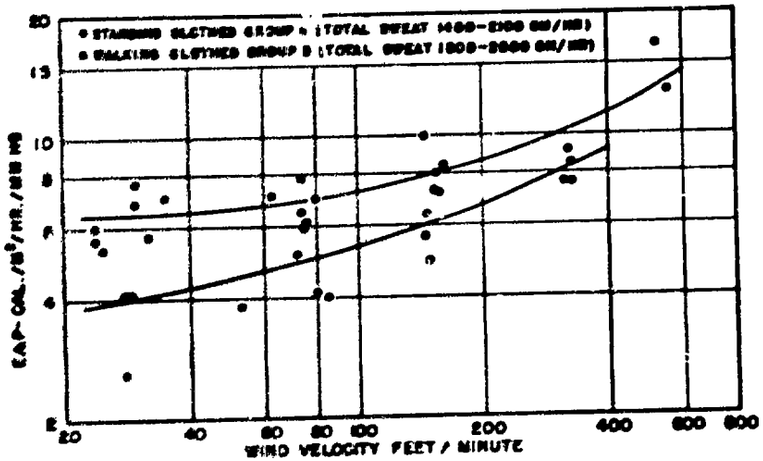
Incl. #3

FIG. 14

INFLUENCE OF WALKING ON THE APPARENT WIND VELOCITY

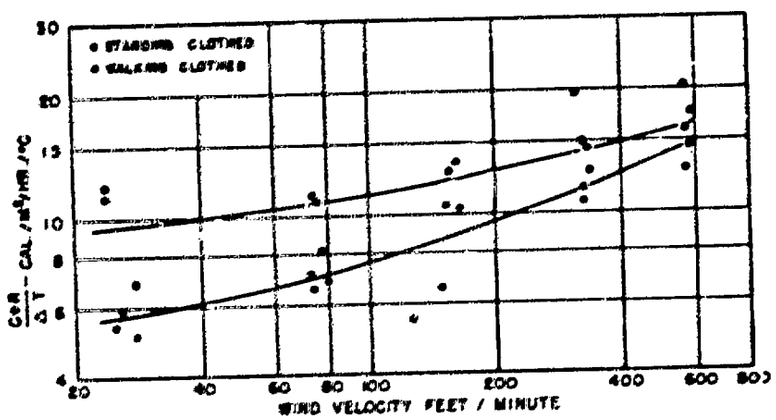
A

EVAPORATION



B

C+R ENV. 4



C

C+R ENV. 6

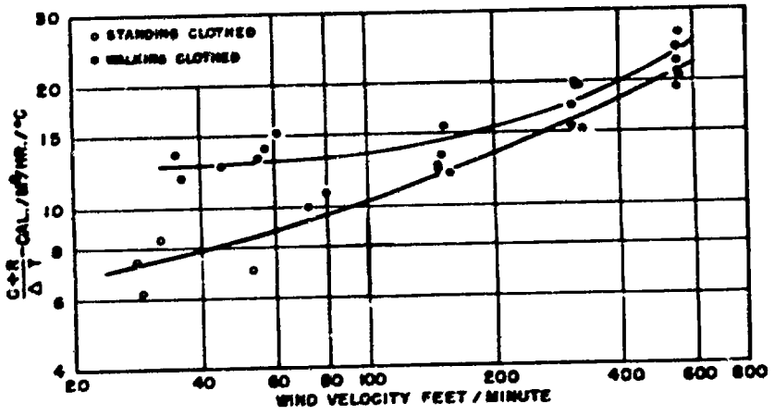
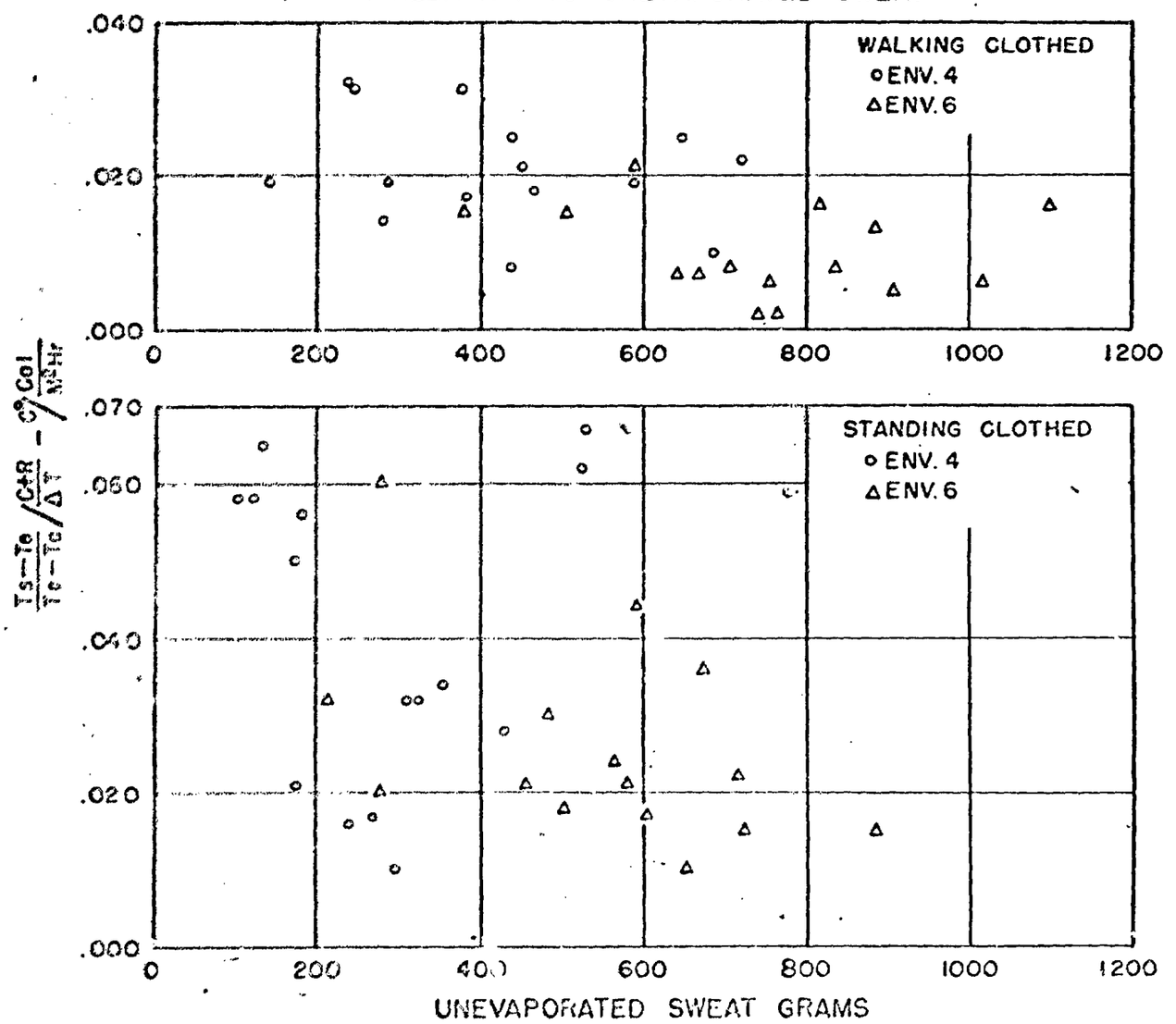


FIG. 15

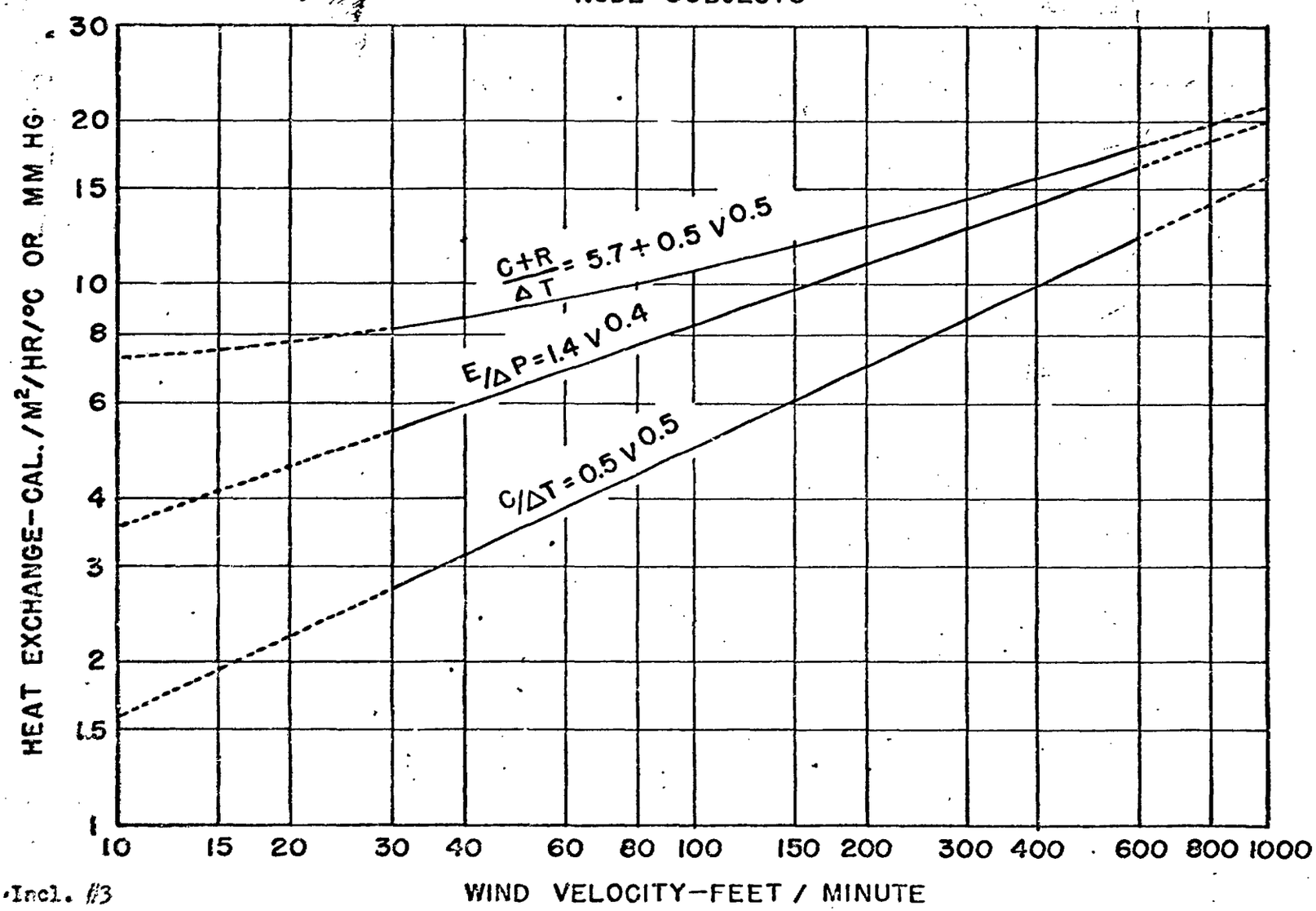
APPARENT CLOTHING INSULATION
IN RELATION TO UNEVAPORATED SWEAT



Incl. #3

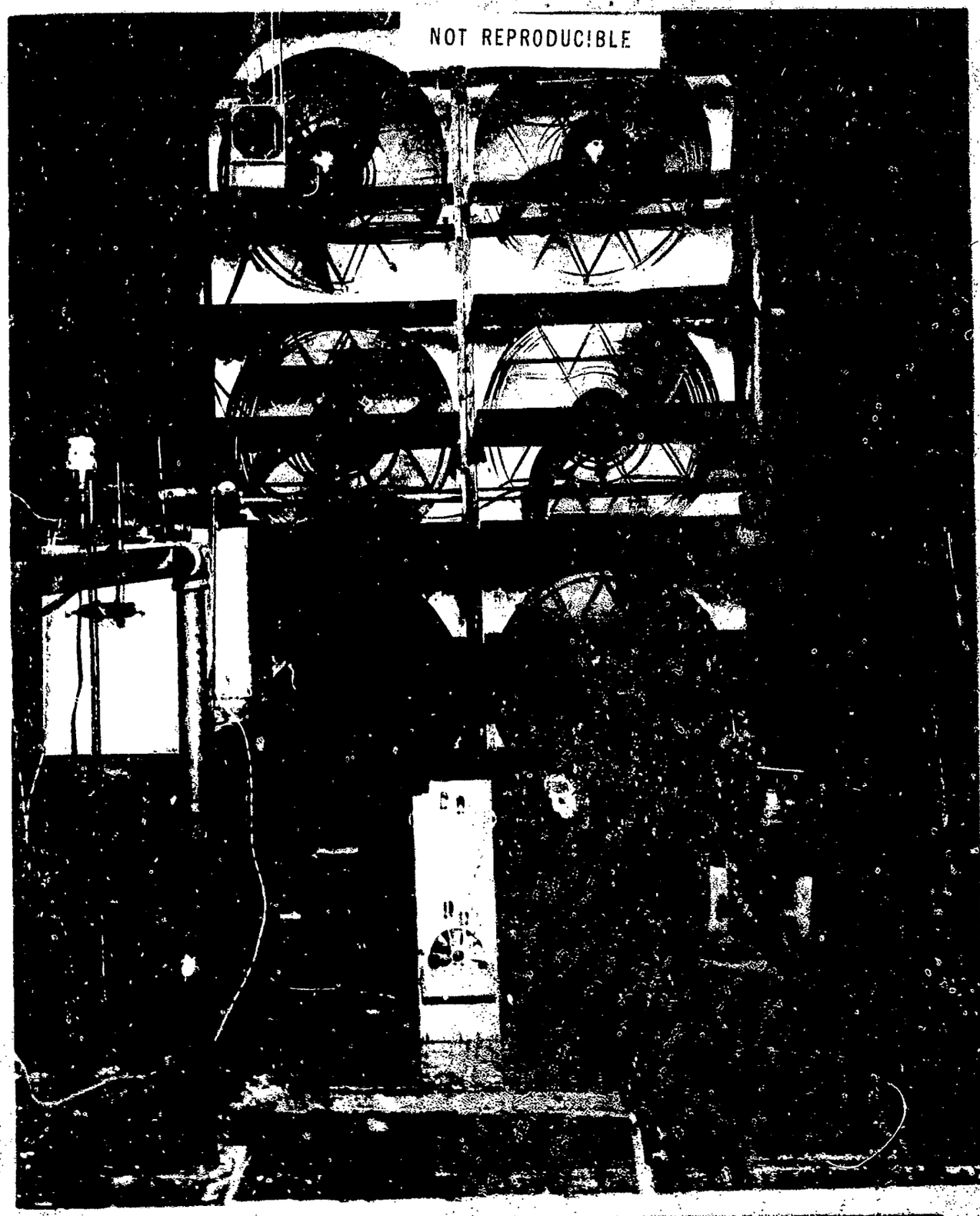
FIG. 16

ROUNDED VALUES OF
COEFFICIENTS FOR CONVECTION, EVAPORATION
AND RADIATION
NUDE SUBJECTS



Incl. #3

NOT REPRODUCIBLE



Rear View of Interior of Tunnel
Showing Fans, Temperature Measuring Devices and Part of Treadmill.

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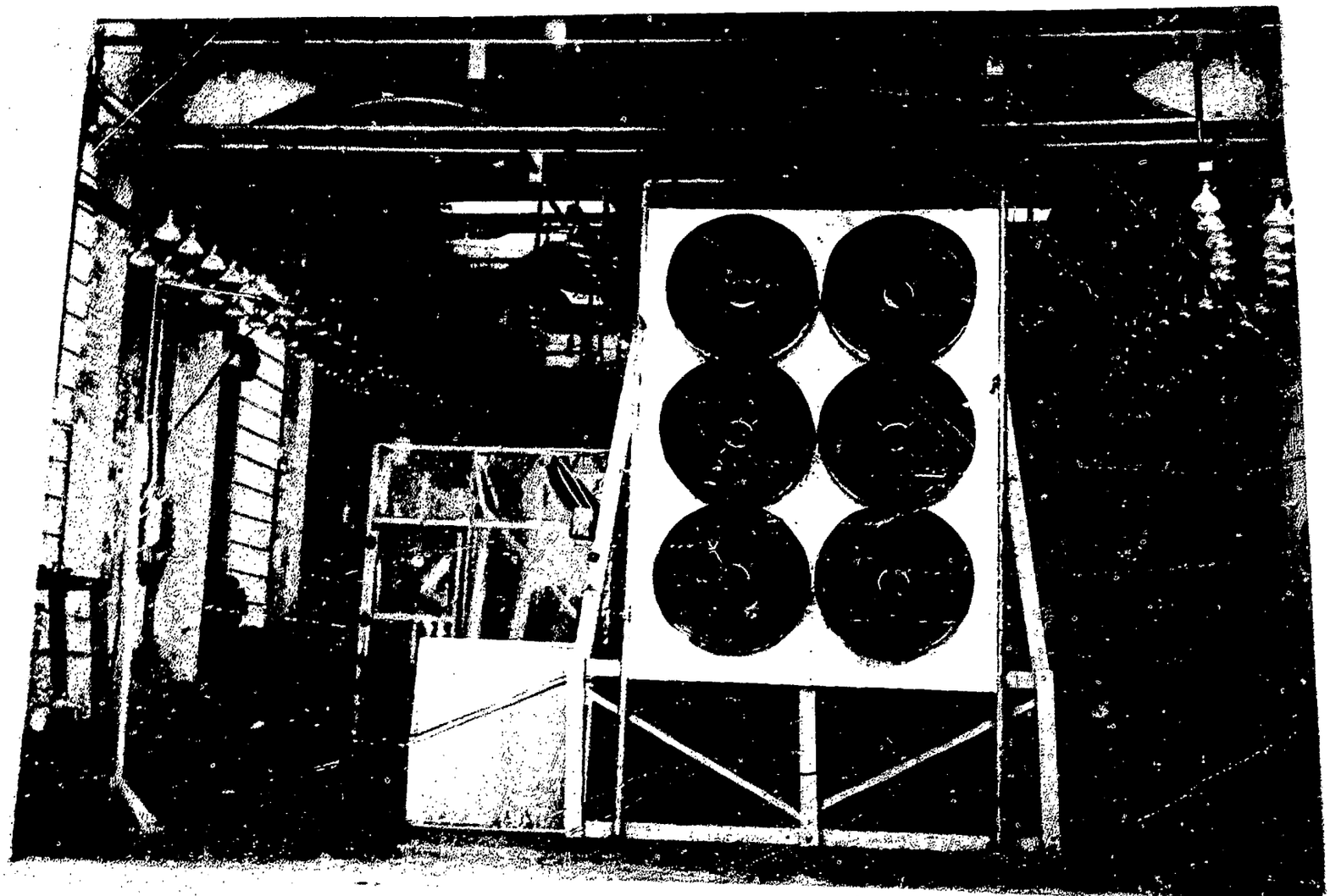
FORT KNOX, KY.

Project No. 2-17 Photograph #2



View of Hot Room Showing Fans at End of Wind Tunnel.
Weighing Chambers for Clothes and Man are Seen on Left.

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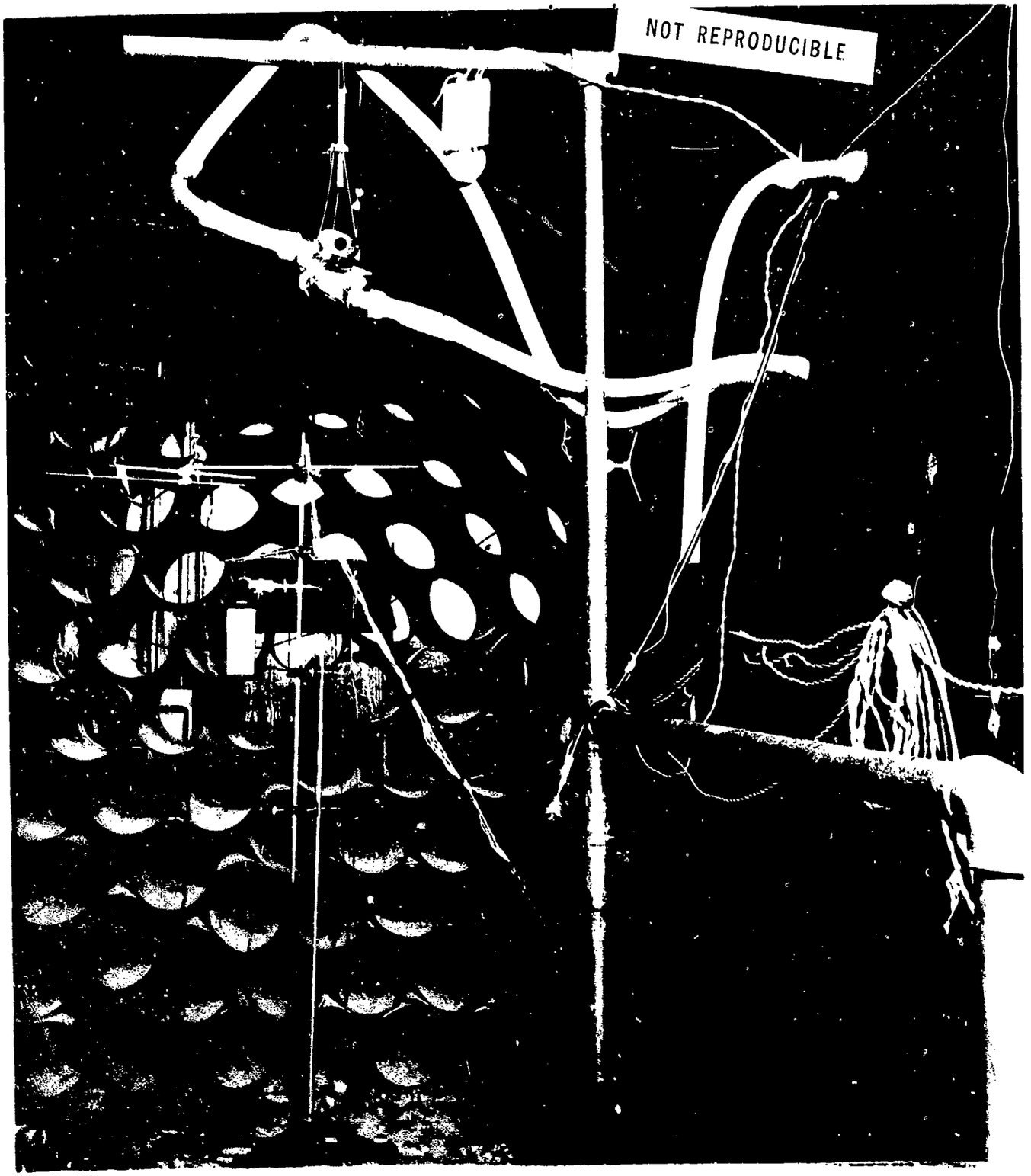
FORT KNOX, KY.

Project No. 2-17 Photograph #1



Interior of Tunnel
View of Front End Showing Straighteners

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FORT KNOX, KY.

Project No. 2-17 Photograph #3

View of Subject. Metabolism and Clothing Temperatures are Being Measured.

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Project No. 2-17 Photograph #4

View of Subject Marching in Herringbone Twill Uniform.
Observer is Determining Heart Rate.

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FORT KNOX, KY.

Project No. 2-17 Photograph #5

Lateral View of Tunnel Showing Metabolic Apparatus Used.

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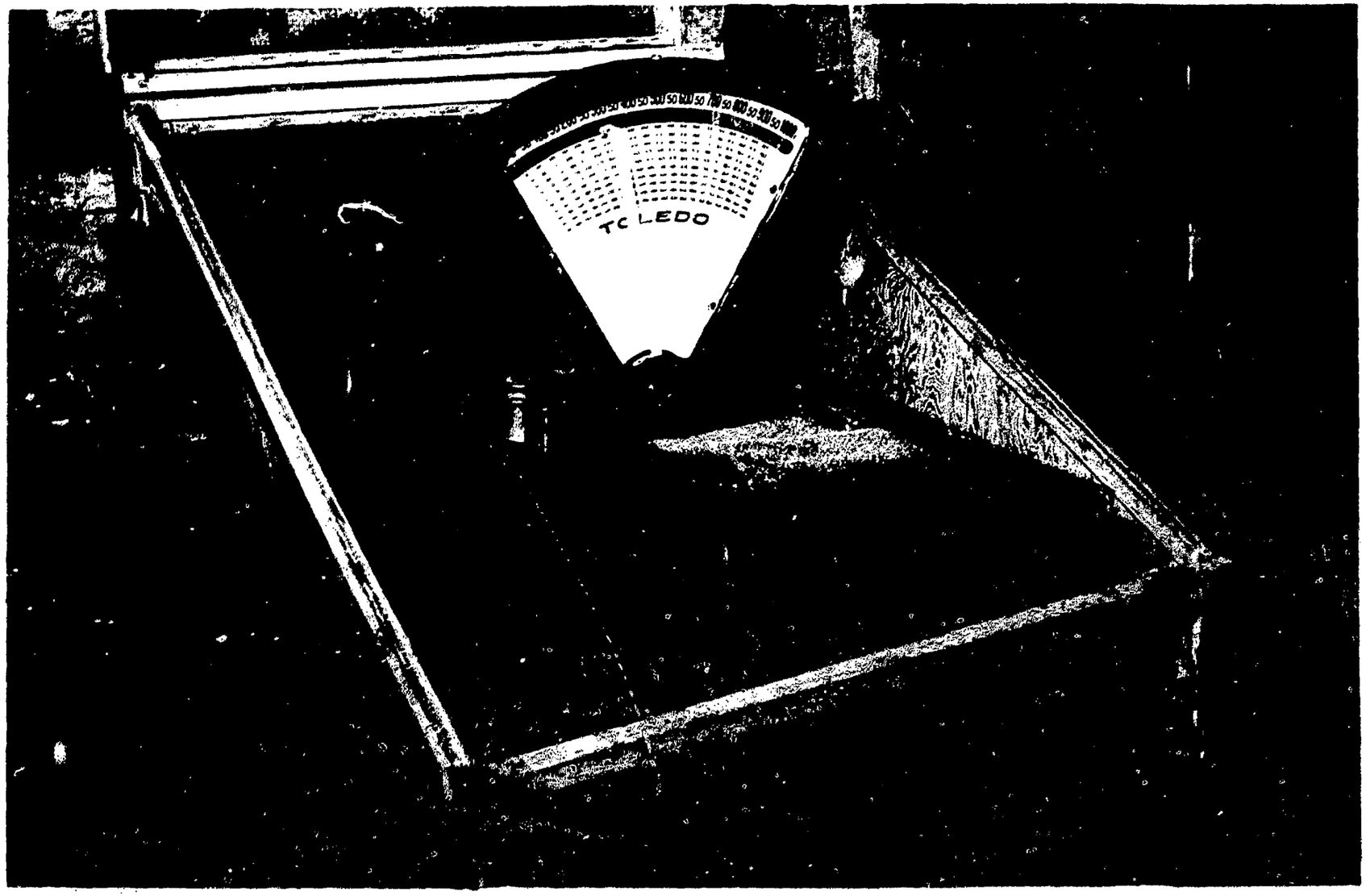
Project No. 2-17 Photograph #6



Weighing of Mineral Oil Foot Bath Used in Collecting
Unevaporated Sweat in Experiments on Standing Subjects.

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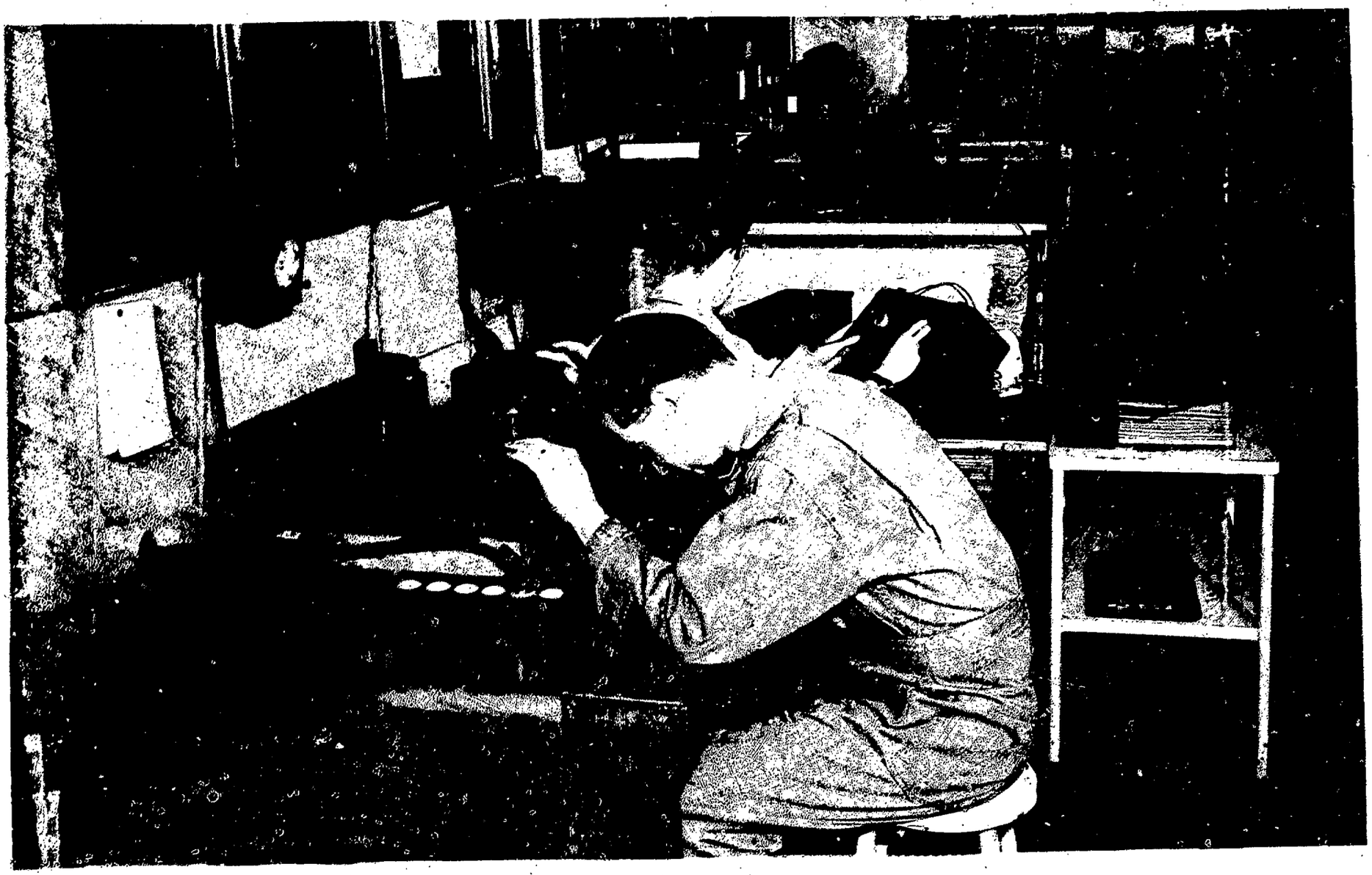
FORT KNOX, KY.

Project No. 4-17 Photograph #7



Control Room. Observers Measuring Skin and Clothing Temperatures of Subject in Hot Room Wind Tunnel.

ARMORED MEDICAL RESEARCH LABORATORY

FORT KNOX, KY.

Project No. 2-17

Photograph #8