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DETERMINATION OF WIND CHILL ON A LIFE-SIZED CLOTHED COPPER MAN

by

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Prepared for the
Environmental Research Section, Protection Branch
Research and Development Division
Department of the Army
Office of the Quartermaster General
Washington 25, D. C.

Under Contract No. DA44-109-qm-584
O.I. No. 5967 (GFP-839)
Reqn. No. 49-106-653-51

June, 1952

FINAL REPORT

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LIST OF SYMBOLS

The following notation is used throughout the text. Unless otherwise noted, the units for each quantity will be as listed.

Symbol	Definition	Units
A	Clothing type (Ex-50)	
c_p	Heat capacitance of air at constant pressure	
D	Effective diameter of Copper Man	ft
h	Coefficient of heat transfer	kgcal/m^2hr ^oF
h_r	Relative humidity	
I_a	Insulation of air surrounding clothed Copper Man	clos*
I_{clo}	Intrinsic insulation of uniform	clos
J	Joules value	ft-lb/kgcal
k	Thermal conductivity of air	kgcal/m^2hr ^oF
L	Height of Copper Man	m
N	Nusselts number hD/k	
P	Average rate of power input to Copper Man	watts
R	Reynolds number VD/ν	
S.A.	Surface area of Copper Man	m^2
T_a	Ambient air temperature	^oF
T_c	Average temperature of outer layer of clothing	^oF
T_s	Average temperature of "skin"	^oF
T_w	Average temperature of tunnel walls	^oF
V	Ambient air speed	ft/sec

* 1 clo = 0.324 m^2 hr ^oF/kgcal

T	$T_s - T_a$	^oF
T_c	$T_c - T_a$	^oF
μ	Dynamic viscosity of air	$lb\text{-}sec/ft^2$
ν	Kinematic viscosity of air	ft^2/sec
ρ	Density of air	$slug/ft^3$

ABSTRACT

An experimental study was conducted in a wind tunnel to determine the wind chill of a standing life-sized Copper Man clothed in the Ex-50 Arctic uniform of the U. S. Quartermaster Corps, Department of the Army. The wind speed V used in testing ranged from about 0 ft/sec to 35 ft/sec and the temperature difference ΔT varied from about 25°F to 90°F. Insulation values of the uniform and temperature drops through the clothing layers were obtained in addition to wind chill values.

The experimental data were found to be accurately expressed by the equation

$$N = 17.37 + 0.000422\ R^{0.850}$$

in which N is the Nusselt number and R the Reynolds number. Use of this equation for cases in which the Reynolds number is in excess of about 300,000 is not recommended since no experimental data were obtained for Reynolds numbers greater than about 200,000.

Examination of the data verifies the validity of Newton's law of cooling -- no scattering of the data appears for different values of the parameter $\Delta T/T_a$. Comparison of the data with wind chill formulae proposed by investigators measuring heat transfer from various uninsulated bodies of different shapes reveals that not only do such formulae give values of wind chill which are too large but also values which increase too rapidly with increasing wind speed. However, the equations of Siple are similar up to wind speeds of about 60 ft/sec but give values of wind chill about 15 times greater than those obtained for the Ex-50 Arctic uniform.

CHAPTER I

INTRODUCTION

The problem of wind chill and protection against it has confronted mankind for centuries. Throughout most of this time, improvements in protection have come about through a trial and error process. In the past 20 years, however, a concerted effort has been made by various scientists to attack the problem scientifically through an analysis of the many factors involved in wind chill.

The investigations carried on have been conducted in both outdoor and indoor laboratories in the United States and Canada. These investigations have added much to the knowledge of the influence of the factors involved. They have shown that wind chill results from heat loss by radiation, free convection, and forced convection.

Although past research has been of great importance in the development of clothing to resist wind chill, no studies have been made under a wide range of controlled wind speeds using an object as large as a man. Therefore, the climatological laboratory of Colorado Agricultural and Mechanical College conducted an investigation of the rate of heat loss from a dry manikin made of copper and wearing a particular uniform for clothing.

The study involved only the standing position and a single type of clothing worn by the manikin. The important matter of effect of perspiration was not considered.

In direct charge of the study was Jack E. Cermak, Assistant Professor of Civil Engineering. His assistant was Robert K. Thomas, Graduate Fellow. The research was initiated by and conducted under the general technical direction of Maurice L. Albertson, Professor of Civil Engineering and Head of Fluid Mechanics Research. All research in Civil Engineering is under the administrative direction of D. F. Peterson, Head of Civil Engineering and T. H. Evans, Dean of Engineering.

CHAPTER II

THEORETICAL CONSIDERATIONS

By means of a dimensional analysis, the important variables involved in the problem of wind chill from a Copper Man were grouped into dimensionless parameters. The parameters of primary importance were selected for further study by experimental methods.

1. Dimensional Analysis. The variables which have more or less effect upon wind chill may be expressed as follows[1/]:

$$\phi_1\,(h_r, \mu, \rho, c_p, k, T_a, \Delta T, \Delta T_c, V, A, D, L, J, h) = 0.$$

Upon choosing V, μ, D, T_a and k as the repeating variables, a new functional relationship of dimensionless parameters results,

$$\phi_2\left(\frac{hD}{k}, \frac{VD\rho}{\mu}, \frac{\Delta T}{T_a}, \frac{\Delta T_c}{T_a}, \frac{c_p\mu}{k}, h_r, A, \frac{V^2}{JT_ac_p}, \frac{L}{D}\right) = 0. \qquad (1)$$

The first parameter $\frac{hD}{k}$ of Eq 1 is the Nusselt number and is the dependent quantity under investigation. Of major importance is the Reynolds number $\frac{VD\rho}{\mu}$. The Reynolds number is an index of the type of boundary layer and hence the intensity and scale of mixing which surrounds a model having a given type of clothing and placed in a certain position. Therefore, the convective heat transport is intimately related to this parameter.

In the case of no evaporation from the model, $\frac{\Delta T}{T_a}$ is relatively unimportant. If the insulation of the clothing were to change appreciably with temperature, $\frac{\Delta T}{T_a}$ would be an important factor. However, the physical constants for most clothing materials change little with changing temperature in the range of temperatures usually encountered in nature.

1/ See List of Symbols for meaning of notation.

The parameter $\frac{\Delta T_c}{T_a}$ is of importance if ΔT_c were larger than the values used in testing because of heat transfer by radiation which is proportional to $T_c^4 - T_w^4$. Under the conditions of testing which were used, ΔT_c was near zero; therefore, the parameter should be insignificant.

Since the model was tested only in air, the value of the Prandtl number $\frac{c_p \mu}{k}$ remained practically constant. Accordingly, the Prandtl number did not enter into the study as an independent parameter.

The relative humidity h_r under conditions of evaporation is an important factor affecting the rate of heat transfer. However, for the case of wind chill or dry convective heat loss, little effect should result from a variation in h_r.

For this study, the clothing type A was the same throughout and this factor may be omitted from further considerations.

In the range of testing, $\frac{V^2}{JT_a c_p}$ varied from zero to about 0.065. Under such conditions, this parameter is not expected to be significant since the kinetic energy of the air available for conversion to heat energy is small.

The final parameter in Eq 1 was constant at $\frac{L}{D} = 5.6$. However, this parameter is in effect a shape parameter; hence, an application of heat loss coefficients determined for a body having one value of $\frac{L}{D}$ to bodies having different values should be made with caution.

From the foregoing discussion, the determination of an empirical relationship for Eq 1 may be reduced to the determination of an equation of the following form:

$$\frac{hD}{k} = \phi_3 \left(\frac{VD}{\nu}, \frac{\Delta T}{T_a} \right) .$$

Furthermore, the effect of $\frac{\Delta T}{T_a}$ in Eq 2 is uncertain and will probably be insignificant as has been found by Breckenridge and Woodcock (1:4).[1/] If such is true, Eq 2 may be reduced to

$$\frac{hD}{k} = \phi_4 \left(\frac{VD}{\nu}\right) \tag{2}$$

where ϕ_4 may have the following form:

$$\phi_4\left(\frac{VD}{\nu}\right) = a + b\left(\frac{VD}{\nu}\right)^c$$

which has been found by McAdams (6:220) to represent the heat transfer coefficient for a right circular cylinder in perpendicular flow. The constants a, b and c must be determined experimentally.

1/ Numbers in parenthesis refer to the entry listed in the Bibliography. The first number is the bibliographical listing and a second number following the colon is the appropriate page number.

CHAPTER III

EXPERIMENTAL EQUIPMENT AND PROCEDURE

The research outlined in the previous sections was conducted in the Colorado Agricultural and Mechanical College wind tunnel at Fort Collins, Colorado, during the winter months of 1951-52. The environmental condition of wind speed was controlled by use of the wind tunnel in which the Copper Man was placed. Air temperature was not controlled and was dependent upon outdoor air temperature.

Experimental Equipment

1. The Wind Tunnel. The wind tunnel is of the single return, low-speed type. A plan view is given in Fig. 1, along with a velocity profile which will be discussed later. One-half of the structure lies outside of an unheated building while the other half, which includes the 9-foot square test section, is located in the interior. Owing to the large size of the test section, the maximum wind speed attainable is about 35 ft/sec, although higher speeds were anticipated in the original design. Reaching this speed was possible only after replacing the 60-hp automobile engine with a 200-hp diesel.

At present the wind tunnel has no temperature controlling devices, but temperatures in the test section closely approach those outside. Only slight temperature rise occurs when the air is drawn from the outside through the three large openings shown by Fig. 1 and then discharged immediately downstream from the propeller. About a 25 percent reduction of wind speed resulted because the air was not recirculated. Unfortunately, the winter of 1951-52 was mild, and the minimum temperatures ranged from 20°F to 30°F higher than those expected. The ambient air temperature was measured by a thermocouple placed at shoulder height about 2 ft to the left of the Copper Man.

The installation of the Copper Man in the test section altered the flow pattern considerably. Typical profiles are given in Fig. 2. All ambient wind speeds used in this study were measured at a point about 2 ft directly upstream from and 1.5 ft above the head of the Copper Man.

Two instruments were used for the measurement of wind speed. For speeds less than 16 ft/sec, the constant-temperature hot-wire anemometer which was developed by Hubbard (5) in 1949 was used with an accuracy of within 3 percent. A Wahlen gage (15) and a pitot tube was used at the higher speeds with an accuracy of about 1 percent.

2. <u>The Copper Man</u>[1/] <u>and Auxiliary Equipment</u>. A Copper Man practically identical to the one used in this study was used by Breckenridge and Woodcock (1) in their studies at Mt. Washington and Fort Churchill. Fitzgerald (4) thoroughly described the original model, which was similar in shape but with different heating and temperature measurement and control circuits. The "skin" is a chemically blackened copper shell approximately 1/8-inch thick modeled after the physique of a representative young man. The main differences in shape from the physique of a man are the following:

1/ The "man" used in these studies was rented by Colorado Agricultural and Mechanical College from the Graduate School of Public Health, University of Pittsburgh.

1. A comparatively small waist--30 inches in circumference--in view of the broad hips--39 inches in circumference.

2. Flattened buttocks.

3. Unaccentuated normal body folds.

4. The omission of ears and male organs.

These, however, do not significantly alter the rate of cooling.

Except for the feet and hands, the entire shell is heated by a single circuit consisting of resistance units in series. These resistance units are distributed in such a manner as to maintain temperatures on the outer surface of the Copper Man similar to those of a resting man under standard one-clo conditions as described by Gagge, Burton, and Bazett (14). The temperatures of the feet and hands are controlled by separate variacs connected in parallel with the main heating system. All resistance units consist of several passes of thin wire (nichrome) which are wrapped in cloth carriers and fastened by them to the inside of the shell. The power input was regulated by a variac shown in Fig. 3 at a considerably higher rate than required for continuous operation in order to have the power on 50-60 percent of the time during the testing period. A timer, connected with the temperature control unit, was energized only when the power was on. Along with it a time totalizer was used, and the average power input was determined by the following relationship:

$$\text{Power} = \frac{\text{Time energized}}{\text{Totalized time}} \times \text{volts} \times \text{amperes}$$

The current and voltage were measured by an AC ammeter and an AC voltmeter connected as shown in Fig. 3. Skin temperatures are determined by eleven 20-gage copper-constantan thermocouples (Leeds and Northrup 1938 calibration) which are contained in 0.22-caliber cartridge cases pressed through holes in the shell. They are located such that the average skin temperature can be determined by averaging readings from the two located in the head and then averaging this average reading with the remaining nine readings which are all taken as equal in weight. Temperature regulation is accomplished by ten Western Electric V17A thermister resistance units, each one glued to the outer surface near a thermocouple, which form a series circuit leading to the temperature control box. Two cables passing through the throat carry the power, control, and thermocouple wires.

In addition to determining skin temperatures, thermocouples were used to determine ambient air temperature, relative humidity, tunnel wall temperatures and air temperatures between layers of clothing. The wires led to three ten-point rotary switches, and the temperatures were measured by a Leeds and Northrup precision potentiometer.

The six thermocouples used in obtaining the temperature drop through the clothing layers were attached to the outer surface of each of the six clothing layers in a normal line from the left kidney and just above the trousers top. Their placement is listed in Table VIII. Each thermocouple was placed approximately 1/16 inch from the outer surface of the garment to which it was attached.

The Copper Man was placed in a standing position facing directly into the wind (See Fig. 4) throughout the testing, except for one comparative run made with the man placed standing and facing downwind and one with the man standing and the left side upstream. He was supported by a steel collar fastened to four guy-wires, and by a wooden block placed behind his feet to which the ankles were tied. These fixtures were arranged to influence his rate of cooling as little as possible.

3. Clothing. The Copper Man was clothed in a new U. S. Arctic uniform, type Ex-50 which has recently been standardized for dry-cold usage. A complete itemization of the component parts of the uniform and how these items were worn is given in Table VII. The draw strings around the waist held the parka snug but were not tight enough to compress the inner layers. The split tails of the outer parka were tied together in the rear. The arms were set to prevent excessive compression between the arms and the sides of the trunk (the hands were located about 8 inches behind the trouser seams.) The snugness and drape of the uniform were kept as nearly constant as possible. In order to prevent excessive cooling on the face, a thick felt mat was used as a mask.

Experimental Procedure

The most significant combinations of wind speeds and ambient air temperatures were arranged before testing began. In order that duplication and uncertainity of the value of a test be kept at a minimum, the progress was recorded by means of a wall chart. The following procedure was followed in each individual test.

a. The feet and hands were normally 6-8°F colder than the legs and arms respectively. Since the feet and hands lose heat at a greater increasing rate than the rest of the body under low ambient air temperatures, it was necessary to regulate their temperatures to the anticipated steady-state condition.

b. The uniform was vigorously fluffed.

c. The Copper Man was heated as rapidly as possible. Because several hours often passed before all sections of the man reached equilibrium, this step was normally by-passed by keeping the power input at a low rate between tests. In testing with normal skin temperatures, the chest and kidney were set at approximately 92°F. This resulted in an average skin temperature near 88°F.

d. The tunnel engine was started and the air speed adjusted to the desired value.

e. After the power input to the man was set, short trial periods were timed to check whether equilibrium conditions were established. Two hours or more were usually required for establishment of equilibrium if the body was pre-heated.

f. Each test was divided into two separate periods, one immediately following the other. Each period was just long enough -- more than 1/2 hour -- to make the on-off power cycles complete. By using a period of time starting at the beginning of a power cycle and continuing to the end of a power cycle, rather than a predetermined test time, the time-average power input was accurately calculated and the results of the two independent periods usually checked with high accuracy.

g. The following data were recorded for each test:

1. Skin temperatures were determined twice during each 1/2 hour period. Although taken at different times in the on-off cycle, the skin temperature rarely varied more than 0.2°F during any one test.
2. Ambient air temperatures were usually recorded four times during each 1/2 hour period and the average value was used in all computations. A 2-3°F variation in temperature was seldom exceeded.
3. Dry bulb and wet bulb readings were taken for relative humidity.
4. The temperatures of all four surrounding walls were measured by thermocouples attached to the surface inside the tunnel.
5. The temperature of air spaces between selected layers of clothing were recorded. These measurements were not made until the latter tests because of a delay in the shipment of thermocouple wire.
6. Since there was some variation in line voltage, although a voltage regulator was installed, the voltage and current were usually read 2 or 3 times during each 1/2 hour period. The voltmeter

was disconnected while the ammeter was read.

7. The anemometer or Wahlen gage was checked continuously in case some variation should occur. The wind speed varied little.

CHAPTER IV

EXPERIMENTAL RESULTS, DISCUSSION, AND COMPARISONS

In this chapter the experimental data are presented in the significant form $N = \phi(R)$. This is followed by a discussion of the applicability and limitations of the equation. The insulation values for the uniform are discussed and the temperature drop through the individual clothing layers is analyzed. Finally, the wind chill data are compared with various existing wind chill formulae.

1. Presentation of Data. The following assumptions were made in order to evaluate the Nusselt and Reynolds numbers to be used in the analysis:

a. The diameter of the Copper Man is the same as the diameter of a cylinder having equal area (1.68 m^2) and height (1.73 m)

$$D = \frac{S.A.}{L \times \pi} = 0.3085 \text{ m} = 1.01 \text{ ft} \qquad (3)$$

b. The error in considering k to vary linearly with temperature in the ranges from $-100^{\circ}C$ to $0^{\circ}C$ and from $0^{\circ}C$ to $+100^{\circ}C$ is negligible -- see Jacob and Hawkins (7:8).

Computations were simplified and the calculated values were kept in the most usable form by evaluating N in metric units and R in English units. Although this may be slightly confusing, it is permissible because the values of dimensionless parameters are independent of the units as long as they are kept consistent within each parameter.

Fig. 5, in which N is plotted as a function of R, suggests a function having the general form of

$$N = a + bR^c \tag{4}$$

From a curve drawn through the plotted points, three points were chosen and approximate values of a, b and c were obtained by a simultaneous solution of three equations resulting from substitution of the three pairs of chosen values into Eq 4. The final formula

$$N = 17.37 + 0.000422\ R^{0.850} \tag{5}$$

was obtained by applying a least squares adjustment to the approximate values of a, b and c according to the method described by Sokolnikoff (11:539).

The presentation of insulation values for the uniform as a function of wind speed uses the standard clo formula,

$$I_{clo} + I_a = \frac{3.09\ (S.A.)\ (T_3 - T_a)}{0.86\ P}; \tag{6}$$

which can also be written as,

$$I_{clo} + I_a = \frac{3.09}{h}. \tag{7}$$

From Eq 5,

$$h = \frac{k}{D}\left[17.37 + 0.000422\left(\frac{VD}{\nu}\right)^{0.85}\right]. \tag{8}$$

The following equation for insulation obtained by substituting Eq (8) into Eq (7) was used in plotting the function as presented in Fig. 6:

$$I_{clo} + I_a = \frac{3.09}{0.617 + 0.0619\ V^{0.850}}. \tag{9}$$

The air speed was changed to mi/hr in this equation and the values of ν and k are based on an ambient air temperature of

$0^{o}F$ and an elevation of sea level. The evaluation of I_a is based on the equation of Winslow, Gagge, and Herrington (13),

$$I_a = \frac{1}{0.61 + 1.25\sqrt{V}}, \qquad (10)$$

where V is in mi/hr. Intrinsic insulation I_{clo} was then determined by subtracting I_a from the total insulation for each wind speed, as was done by Breckenridge and Woodcock (1).

The results of temperature measurements between layers of clothing are plotted in Fig. 7. They are based on the percent of the total temperature drop from the kidney to the outside temperature, as determined by the outermost thermocouple, to each respective thermocouple.

2. <u>Discussion</u>. Several tests were run with the Copper Man approximately $20^{o}F$ warmer than normal body temperatures and the results compared with the other data. As can be observed in Fig. 5 the validity of the results are not impaired by this practice as long as the differences in k and ν are accounted for. The rate of cooling was found directly proportional to the temperature differential, and extending the experimental results to include air temperatures ranging as low as $-50^{o}F$ should introduce no significant error. The use of above normal body temperatures and extending the results to lower air temperatures depend upon the insignificance of the parameter $\Delta T/T_a$ in affecting the thermal conductivity of the clothing and radiation losses. That $\Delta T/T_a$ is of no practical importance in affecting the wind chill under temperature conditions to be encountered by man and where the skin is kept dry, may be observed from Fig. 5. This would probably be an important parameter if evaporation of

skin moisture were to occur.

The limitation on R of 200,000 imposed by the maximum available wind speed of 35 ft/sec is more restrictive to the range of usefulness of Eq 5 than that imposed by the limited range of T_a available. Fig. 5 indicates that the empirical relationship of Eq 5 could be extended to 50 or 60 ft/sec with a fair degree of accuracy. However, Eq 5 should not be used for calculating the wind chill for a Reynolds number in excess of about 300,000.

The data for zero wind speed, see Tables I-V, could not be plotted in Fig. 5; however, these values were used in obtaining Eq 5.

The definition of D was purely arbitrary. Since the body is composed of several cylinders and the outer dimensions of the uniform are variable, there is no precise value which will define the effective diameter. Also the value of such a precise effective diameter is of dubious value. By using the same D as was used in evaluating N and R, h for the Copper Man is determined directly in accordance with the experimental data. Eq 5 should be applicable to all similarly clothed bodies of the same L/D ratio regardless of their size.

One run was made with the Copper Man standing facing downstream and one run standing with the left side upstream. The results are plotted in Fig. 5. A lower h resulting from different body positions relative to the wind would be expected, but the results are by no means conclusive.

The effects of different air temperature and altitude are shown in Fig. 8. Values for h were computed for sea level and

5,000 feet elevation at air temperatures of $-30^{\circ}F$, $0^{\circ}F$ and $+30^{\circ}F$ by using Eq 5. The curves indicate the important influence of air temperatures at low speeds where a $60^{\circ}F$ temperature difference can vary h by 10 percent. Altitude, by influencing air density, becomes increasingly important as the wind speed increases and can vary h by 10 percent at 60 ft/sec. Owing to natural convection currents air speed never reaches zero which causes altitude to have some effect on h at all times, but the effect at low speeds is negligible.

The data on the temperature drops through the clothing may be classified in the following three distinct categories as indicated in Table VI:

a. High speed with the Copper Man facing the wind.

b. Low speed with the Copper Man facing the wind.

c. Relatively high speed with the Copper Man facing downwind.

That the categories were so distinct is surprising since the thermocouples were intended to provide merely qualitative measurements of air temperatures within each air layer. However, the readings are believed to give a fair representation of the temperature within each air layer. Fig. 7 illustrates the insulation loss when the uniform is compressed by the wind acting upon it. The curves merely provide a schematic picture of temperature variations and the distances between thermocouples are not intended to represent true linear distances between the various clothing layers. In fact, the distances vary and thereby account for the varying insulation. The curves show that the steepest gradient occurs when the wind strikes the affected area directly and that the most gradual gradient occurs when the back is protected from the high wind velocities and is therefore in an area of negative pressure. The sideward position gives no definite picture since the thermocouples are practically shielded by an arm. The significance of these results is that the steeper gradients near the skin, caused by diminished thickness of the layers and increased air penetration, indicate more rapid heat removal. The foregoing is not a new concept, but does provide a clear picture of the mechanism and illustrates the value to be obtained from non-compressing and impermeable uniforms.

Readings of tunnel wall temperatures and wet bulb temperatures were taken during each run to check the significance of radiation and relative humidity. Both were found to be of negligible significance.

The insulation values of the U. S. Uniform Ex-50 tested in this study were compared to those of the U. S. Fiberglass-Lined Arctic uniform Ex-48-1, coated with latex and having only one pair of trousers, which was one of the uniforms tested by Breckenridge and Woodcock (1:8). The following values were taken from their curve for comparison:

2 mi/hr	Ex-48-1	4.05 clos
	Ex-50	4.77 clos
16 mi/hr	Ex-48-1	3.25 clos
	Ex-50	2.92 clos

The considerably greater insulation losses with increasing wind speed in the uniform not made impermeable, illustrates that considerable heat loss results from the air passing through the nylon uniform.

3. Comparison With Other Wind Chill Formulae. The Ft. Churchill data on the U. S. Fiberglass-Lined Arctic Uniform Ex-48-1 of Breckenridge and Woodcock (1:39) were converted to dimensionless parameters under the assumed barometric pressure of 29.5 in. mercury. The resulting values are plotted in Fig. 5 and bring out the same general trend which was discussed in making insulation comparisons.

The experimental results of the wind tunnel study were also compared (see Fig. 9) with the most important wind chill formulae which were analyzed by Court (2) and Stone (12). For a better comparison, the formulae are kept in the units as used by Court which are h in mcal/cm^2°C sec and V in m/sec. Those formulae used in this comparison are as follows:

Lehmann (No. 1)	$h = 0.113 + 0.34\ V^{0.622}$	(11)
Buttner	$h = 0.23 + 0.47\ V^{0.52}$	(12)
Siple (No. 1)	$h = 0.29 + 0.278\ V^{0.50} - 0.0278\ V$	(13)
Siple (No. 2)	$h = 0.25 + 0.303\ V^{0.50} - 0.0278\ V$	(14)
Plummer	$h = 0.0086 + 0.231\ V^{0.050} + 0.05175\ V$	(15)

All of these formulae have one condition in common as completely different from the conditions of this study. They were derived from heat loss measurements on simple shaped uninsulated objects, which were intended to describe the cooling of a human body. Lehmann in Eq 11 used a katathermometer, which is cylindrical in shape, Buttner used a frigorimeter of spherical shape in obtaining Eq 12 and Siple used a cylinder to obtain data for Eq 13 and 14. Eq 15 of Plummer is based on the cooling of a long cylinder 3 inches in diameter. Lehmann and Buttner were the first to apply the general form of Eq 4, as was done in this study.

The form of Eq 13-15 is based on the experiments of Gagge, Herrington, and Winslow (14:512) on a nude human body which indicated that convective heat losses vary in proportion to the square root of the wind velocity. Eq 10, based on further investigations of Gagge, Herrington, and Winslow (13) with a lightly clothed human subject, is of the same form. Both were limited to very low wind speeds. Both Plummer and Siple added a term involving V in addition to the term involving $\sqrt{V}$. The object of the derivation by Plummer (16:8) was to determine a size of cylinder having a heat loss similar to the nude body; thereby making it possible to extend the results to higher wind speeds. A very high degree of agreement with the data of McAdams (7:221) was obtained when a 3-inch diameter cylinder was used to compute h from the formula $hD/k = 1 + 0.407\ R^{\frac{1}{2}} + 0.00123\ R$ which was given by Plummer (16:11). Outside of the greater ease in computations there appears to be no justification for this reliance upon the square-root term.

For comparison, Eq 5 was converted to

$$h = 0.0328 + 0.00354\ V^{0.850} \tag{16}$$

in which the units correspond to those of Eq 11-15. As might be expected the differences are so great that the results can hardly be compared on the same graph, thereby illustrating the effectiveness of the insulation. The important fact brought out in Fig. 9 is the different shapes of the curves for Eq 11, 12 and 15, rather than the actual convective heat loss magnitudes. Although Eq 11, 12, and 15 may be applicable to uninsulated objects of similar shapes, they indicate a much more rapid increase in h with increasing wind speed than Eq 5; therefore, applying a correction factor to these formulae for heat loss in a heavily clothed man is not feasible. The equations of Siple, especially Eq 14, give approximately correct values if divided by a factor of 15.

CHAPTER V

SUMMARY AND ADDITIONAL RESEARCH NEEDED

The purpose of this work was to determine experimentally the wind chill of a Copper Man clothed in the Ex-50 Arctic uniform while standing facing upstream in a wind tunnel. Important findings from the tests conducted are as follows:

1. Within the range of wind speed from 0 to 60 ft/sec wind chill may be computed from the following equation:

$$N = 17.37 + 0.000422\ R^{0.850}$$

   Wind chill should not be calculated from this equation if the Reynolds number is above 300,000.

2. No correlation or scatter of the data occurred for different values of the parameter $\Delta T/T_a$ which indicates that Newton's law of cooling is valid.

3. Wind chill Eq 11, 12, and 15 give values which are too large and also slopes which are too great for use in computing wind chill values. Eq 14 of Siple will yield fairly accurate values for wind chill up to values of wind speed of about 60 ft/sec if divided by approximately 15.

The results obtained from the investigations carried out under Contract DA44-109-qm-584 indicate that additional research in the field of heat transfer from a model man (Copper Man) is both desirable and feasible. Areas for continued research which are of practical importance to these concerned with providing adequate protective clothing and shelter for our men in the

Armed Services are as follows:

1. An experimental determination of heat transfer from a Copper Man placed in standard sleeping bags when exposed to a range of low air temperatures and controlled air speeds. Studies of this nature should be conducted for cases in which the Copper Man is "sleeping" in the open with no additional shelter other than the sleeping bag and also when sheltered in small tents.
2. The addition of controlled moisture to the "skin" of a Copper Man. Under such conditions the effect of moisture upon the insulation of various uniforms could be evaluated.

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TABLE I

WIND CHILL DATA -- $\Delta T < 45^\circ F$

T_a $^\circ F$	T_s $^\circ F$	ΔT $^\circ F$	Power Input watts	h $\frac{\text{kg-cal}}{m^2\ \text{hr}\ ^\circ F}$	k $\frac{\text{kg-cal}}{\text{m hr}\ ^\circ F}$	N	V $\frac{ft}{sec}$	ν $\frac{ft^2}{sec} x10^4$	R
59.4	88.4	29.0	41.2	0.727	0.0121	18.6	0	---	0
46.7	88.9	42.2	57.7	0.700	0.0119	18.18	0.53	1.78	2,980
64.3	89.7	25.4	40.8	0.822	0.0121	21.0	4.8	1.91	25,100
56.9	89.0	32.1	60.8	0.970	0.0120	24.9	16.0	1.86	86,000
54.4	88.8	34.4	66.0	0.982	0.0120	25.1	18.4	1.85	99,400
*51.6	89.6	38.0	63.8	0.859	0.0119	22.3	13.2	1.83	72,100
**55.1	90.1	35.0	63.0	0.021	0.0120	23.7	13.4	1.85	72,400

* Left side upstream
** Facing downstream

TABLE II

WIND CHILL DATA -- $45^{o}F < \Delta T < 55^{o}F$

T_a	T_s	ΔT	Power Input	h	k	N	V	ν	R
^{o}F	^{o}F	^{o}F	watts	$\frac{kg\text{-}cal}{m^2\ hr\ ^{o}F}$	$\frac{kg\text{-}cal}{m\ hr\ ^{o}F}$		$\frac{ft}{sec}$	$\frac{ft^2}{sec} x10^4$	
41.1	88.8	47.7	62.45	0.670	0.0118	17.5	0	---	0
35.4	88.4	53.0	68.3	0.660	0.0117	17.42	0.41	1.73	2,370
39.5	87.4	47.9	63.8	0.682	0.0118	17.83	1.0	1.76	5,680
39.4	87.6	52.7	68.8	0.667	0.0117	17.6	1.8	1.73	10,410
39.0	87.8	48.8	62.0	0.651	0.0118	17.05	1.9	1.76	10,800
38.7	88.5	49.8	67.0	0.689	0.0118	18.0	2.0	1.75	11,420
39.1	89.3	50.2	68.4	0.697	0.0118	18.23	4.2	1.75	24,000
41.6	88.9	47.3	72.9	0.788	0.0118	20.6	8.8	1.77	49,700
39.3	88.4	49.1	89.6	0.934	0.0118	24.4	14.9	1.76	84,700

TABLE III

WIND CHILL DATA — $55^{o}F < \Delta T < 65^{o}F$

Ta	Ts	ΔT	Power Input	h	k	N	V	ν	R
^{o}F	^{o}F	^{o}F	watts	$\frac{\text{kg-cal}}{m^2\ hr\ ^{o}F}$	$\frac{\text{kg-cal}}{m\ hr\ ^{o}F}$		$\frac{ft}{sec}$	$\frac{ft^2}{sec} \times 10^4$	
31.5	87.6	56.1	70.9	0.646	0.0116	17.2	0	---	0
29.7	87.9	58.2	77.25	0.680	0.0116	18.1	1.03	1.70	6,050
27.6	88.1	60.5	79.1	0.670	0.0116	17.8	2.1	1.68	12,520
27.8	87.7	59.9	80.8	0.691	0.0116	18.4	4.04	1.68	24,000
29.8	88.7	58.9	94.1	0.818	0.0116	21.8	8.1	1.68	48,200
41.2	102.6*	61.4	102.0	0.851	0.0118	22.2	10.0	1.77	56,500
32.3	87.2	54.9	92.1	0.860	0.0116	22.8	10.9	1.71	63,750
31.8	87.4	55.6	94.0	0.864	0.0116	23.0	11.5	1.71	67,300
45.0	108.0*	63.0	112.6	0.915	0.0118	23.9	15.5	1.79	86,700
32.8	89.9	57.1	103.7	0.929	0.0116	24.6	16.0	1.72	93,100
25.3	88.5	63.2	126.8	1.026	0.0115	27.5	26.5	1.67	158,700
24.2	88.8	64.6	141.7	1.121	0.0115	29.8	30.1	1.66	181,500
32.4	90.8	58.4	131.8	1.157	0.0116	30.8	34.4	1.71	201,000

* T_s above normal

TABLE IV

WIND CHILL DATA -- $65^\circ F < \Delta T < 75^\circ F$

T_a $^\circ F$	T_s $^\circ F$	ΔT $^\circ F$	Power Input watts	h $\frac{\text{kg-cal}}{m^2\ hr\ ^\circ F}$	k $\frac{\text{kg-cal}}{m\ hr\ ^\circ F}$	N	V $\frac{ft}{sec}$	ν $\frac{ft^2}{sec} x10^3$	R
38.8	108.1*	69.3	94.6	0.699	0.0118	18.3	0.66	1.75	3,770
22.1	89.7	67.6	84.4	0.638	0.0114	17.3	0.99	1.64	6,040
38.8	105.0*	66.2	88.0	0.680	0.0118	17.8	1.0	1.75	5,720
15.8	88.0	72.2	91.65	0.651	0.0113	17.8	1.95	1.63	12,100
23.0	88.3	65.3	92.0	0.721	0.0114	19.5	4.7	1.65	28,500
41.0	109.6*	68.6	107.7	0.802	0.0118	21.0	4.8	1.77	27,500
18.4	108.6*	70.2	105.0	0.766	0.0113	20.9	7.95	1.62	49,100
33.6	107.8*	74.2	121.4	0.838	0.0117	22.1	8.0	1.72	46,500
17.9	87.8	69.9	111.2	0.815	0.0113	22.3	9.2	1.62	56,800
18.1	87.5	69.4	120.5	0.890	0.0113	24.3	13.9	1.62	85,900
17.2	88.6	71.4	135.7	0.973	0.0113	26.6	20.4	1.62	127,300
37.4	108.6*	71.2	161.5	1.161	0.0117	30.6	34.3	1.74	197,200

* T_s above normal

TABLE V

WIND CHILL DATA -- $75^{\circ}F < \Delta T < 95^{\circ}F$

T_a	T_s	ΔT	Power Input	h	k	N	V	ν	R
$^{\circ}F$	$^{\circ}F$	$^{\circ}F$	watts	$\frac{\text{kg-cal}}{\text{m}^2\text{ hr }^{\circ}\text{F}}$	$\frac{\text{kg-cal}}{\text{m hr }^{\circ}\text{F}}$		$\frac{\text{ft}}{\text{sec}}$	$\frac{\text{ft}^2}{\text{sec}} \times 10^4$	
19.2	107.6*	88.4	111.4	0.673	0.0114	18.2	1.07	1.62	6,610
26.7	109.5*	82.8	115.4	0.714	0.0115	19.2	1.85	1.68	11,010
18.0	107.5*	89.5	120.9	0.691	0.0113	18.7	2.2	1.62	13,590
25.1	110.4*	85.3	125.2	0.752	0.0115	20.2	4.6	1.67	27,670
27.8	104.5*	76.7	119.1	0.795	0.0116	21.2	6.8	1.68	40,500
27.4	106.6*	79.2	139.0	0.899	0.0116	23.9	16.2	1.68	96,300
20.5	107.5*	87.0	164.9	0.970	0.0114	26.3	18.8	1.63	115,300

* T_s above normal

TABLE VI

TEMPERATURE DROPS THROUGH CLOTHING

(From left kidney)

Wind Velocity ft/sec	Kidney Temperature °F	Temperature outside of clothes °F	Total Temperature drop °F	% of total temperature drop from left kidney to thermocouple 1	2	3	4	5	6
34.4*	94.8	33.6	61.2	18.2	24.2	44.8	73.2	90.3	100
18.8*	115.5	23.4	92.0	19.1	25.4	41.5	73.0	91.3	100
16.2*	114.4	29.4	85.0	19.8	27.5	43.0	72.5	89.9	100
4.8**	92.3	65.1	27.2	24.8	40.0	57.6	77.5	92.2	100
0.66**	113.5	51.6	61.9	25.4	41.0	59.6	72.2	89.5	100
0.0**	91.3	59.3	32.0	23.4	38.4	57.8	67.8	89.6	100
0.53	92.7	48.2	44.5	20.4	33.6	49.6	59.0	78.0	100
13.2 ±	93.9	50.9	43.0	24.0	36.5	54.5	76.7	91.4	100
13.4 ±±	93.0	54.4	38.6	38.6	60.1	84.0	87.7	93.6	100

* Data used on high wind velocity curve.
** Data used on low wind velocity curve.
± Copper Man placed with left side upstream.
±± Copper Man placed with back upstream.

TABLE VII

ELEMENTS OF THE UNIFORM

(tabulated from the skin outward)

I. Trunk

1. Undershirt, winter - M-1950 (tucked in drawers)
2. Shirtcoat, Ex-50-5 (outside of trousers)
3. Jacket-liner, field, Ex:50-7*
4. Jacket-shell, field, Ex:50-11
5. Parka-liner, Arctic, Ex:50-7
6. Parka-shell, Arctic, Ex:50-6

II. Legs

1. Drawers, winter - M-1950
2. Trousers-liner, field, Ex:50-7
3. Trousers-shell, field, Ex:50-8
4. Trousers-liner, Arctic, Ex:50-4
5. Trousers-shell, Arctic, Ex:50-6

III. Hands

1. Inserts, mitten
2. Mittens, Arctic, Ex-49-3

IV. Feet

1. Socks, cushion sole (brown)
2. Socks, ski (white)
3. Socks, ski (white)
4. Socks, duffel, felt
5. Insoles, "Saran" and felt
6. Boots, Mukluk, Ex-49-3

* All liners buttoned into their respective enclosing shells with the white frieze next to the shell.

TABLE VIII

THERMOCOUPLE LOCATIONS

I. Installed on Copper Man for T_s

	Location	Weight for T_s % of total
1.	Back of head	5
2.	Left cheek	5
3.	Left shoulder	10
4.	Right chest	10
5.	Left kidney	10
6.	Right arm (Paralleled to left arm)	10
7.	Back left hand (Paralleled to back of right hand)	10
8.	Right thigh (Paralleled to left thigh)	10
9.	Left thigh (Paralleled to right thigh)	10
10.	Right calf (Paralleled to left calf)	10
11.	Left instep	10
		100

II. Determination of temperature drops through clothing

0. Left kidney (same as 5 m Copper Man)
1. Undershirt*
2. Wool shirt
3. Inner liner
4. Inner shell
5. Outer liner
6. Outer shell

* All fastened approximately 1/16" on outer surface of garment.

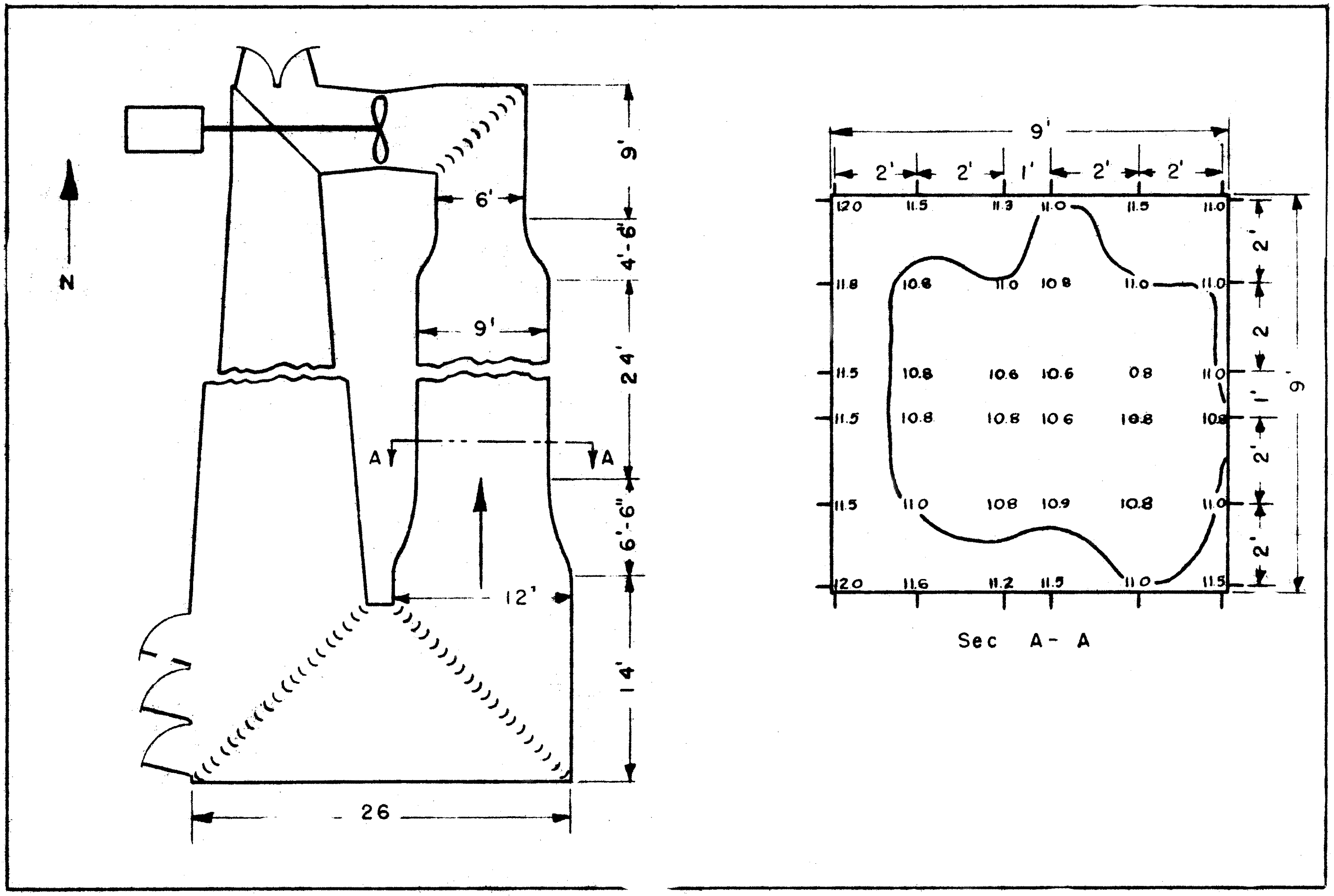


Fig. 1 Plan view of wind tunnel and typical velocity distribution in test section.

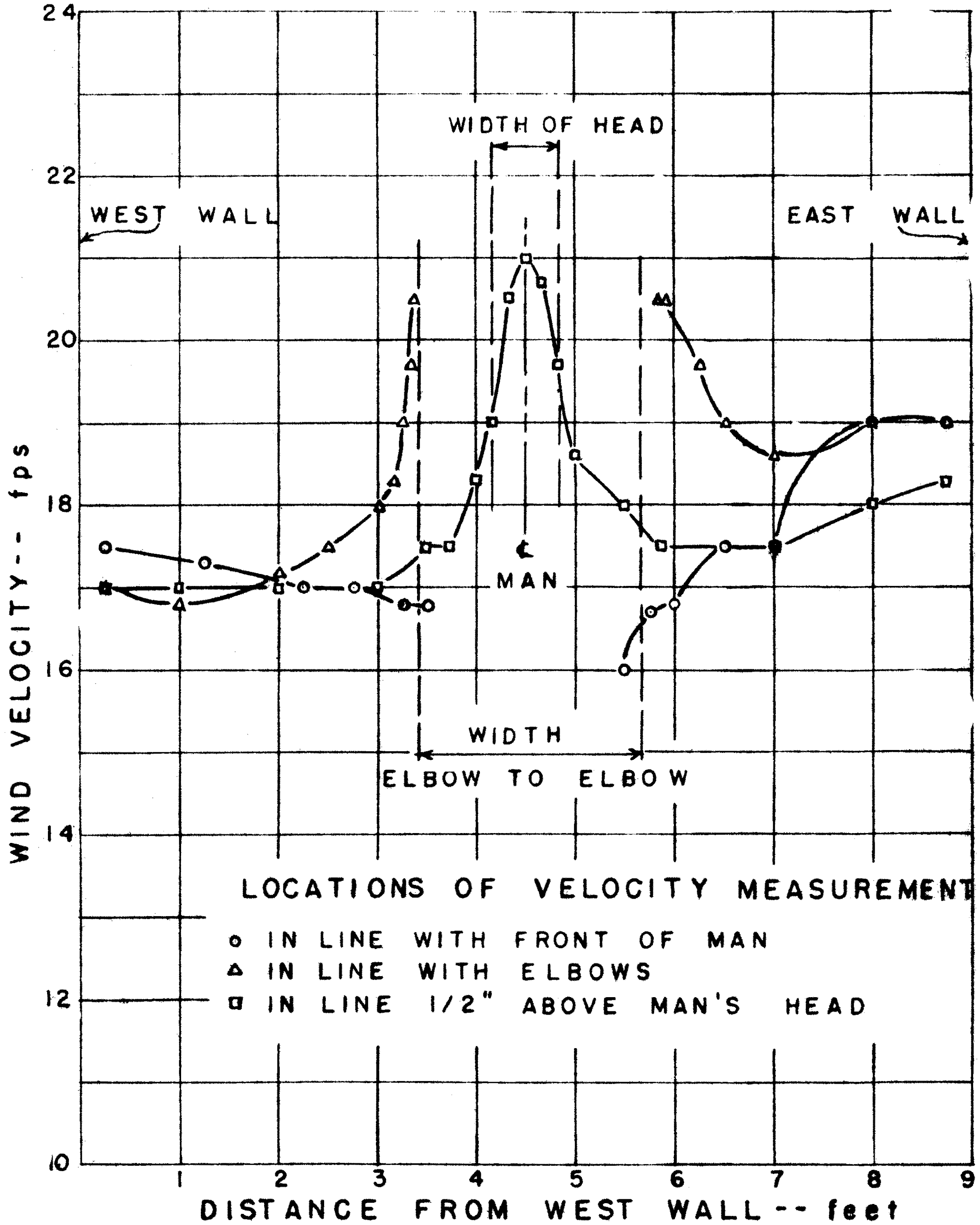


Fig. 2 Typical velocity distribution across section including the Copper Man.

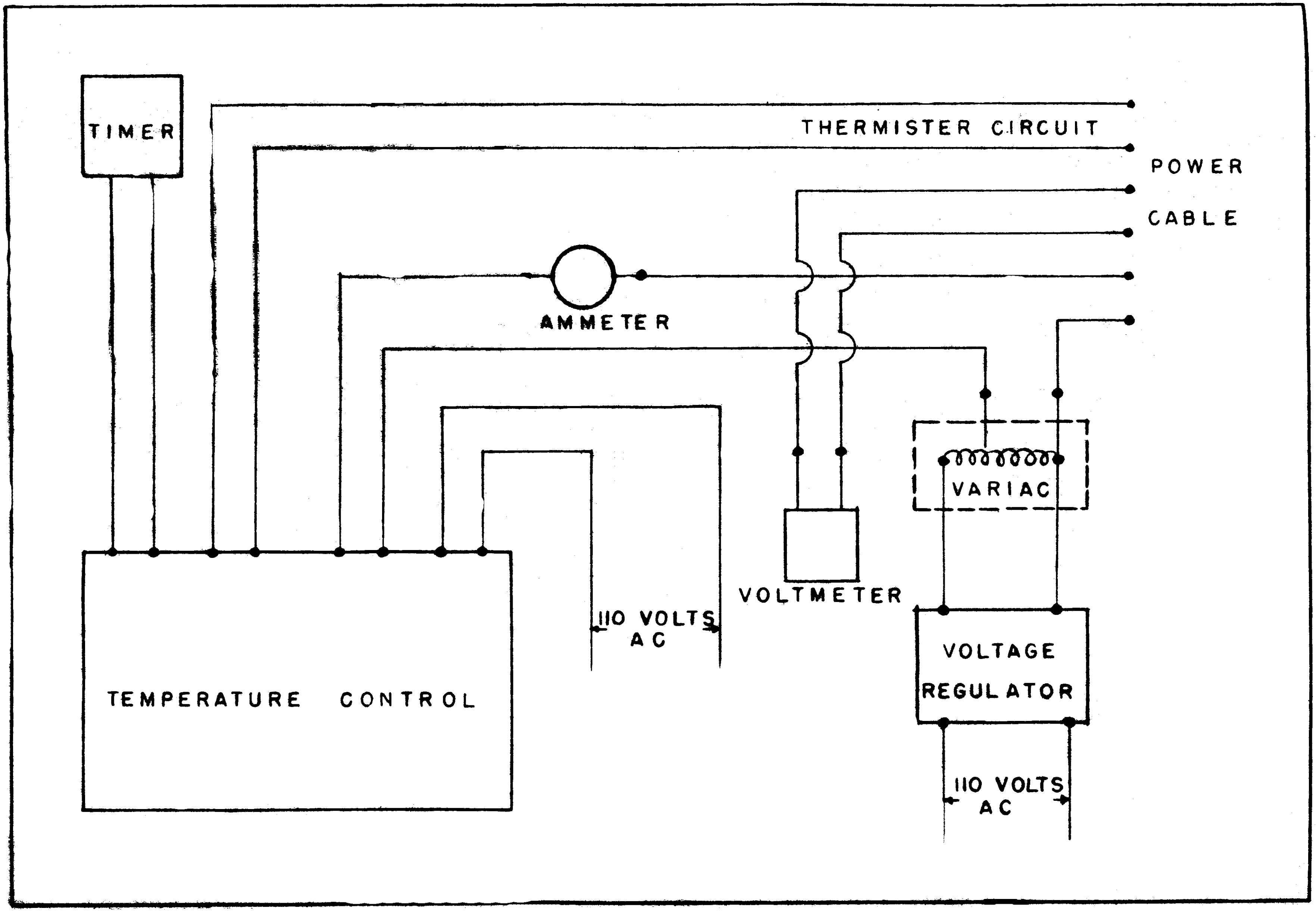
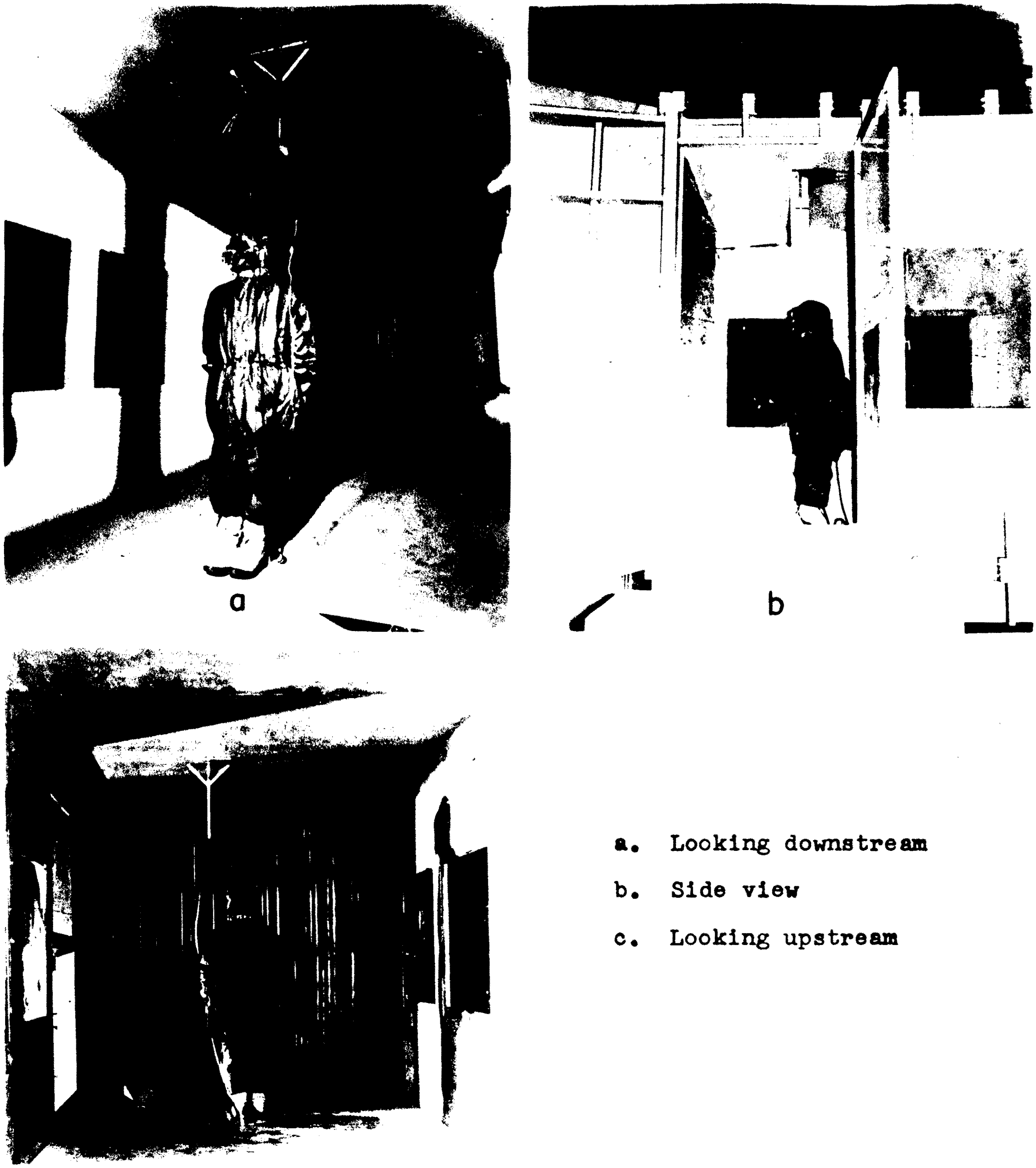


Fig. 3 Electrical arrangement (schematic).



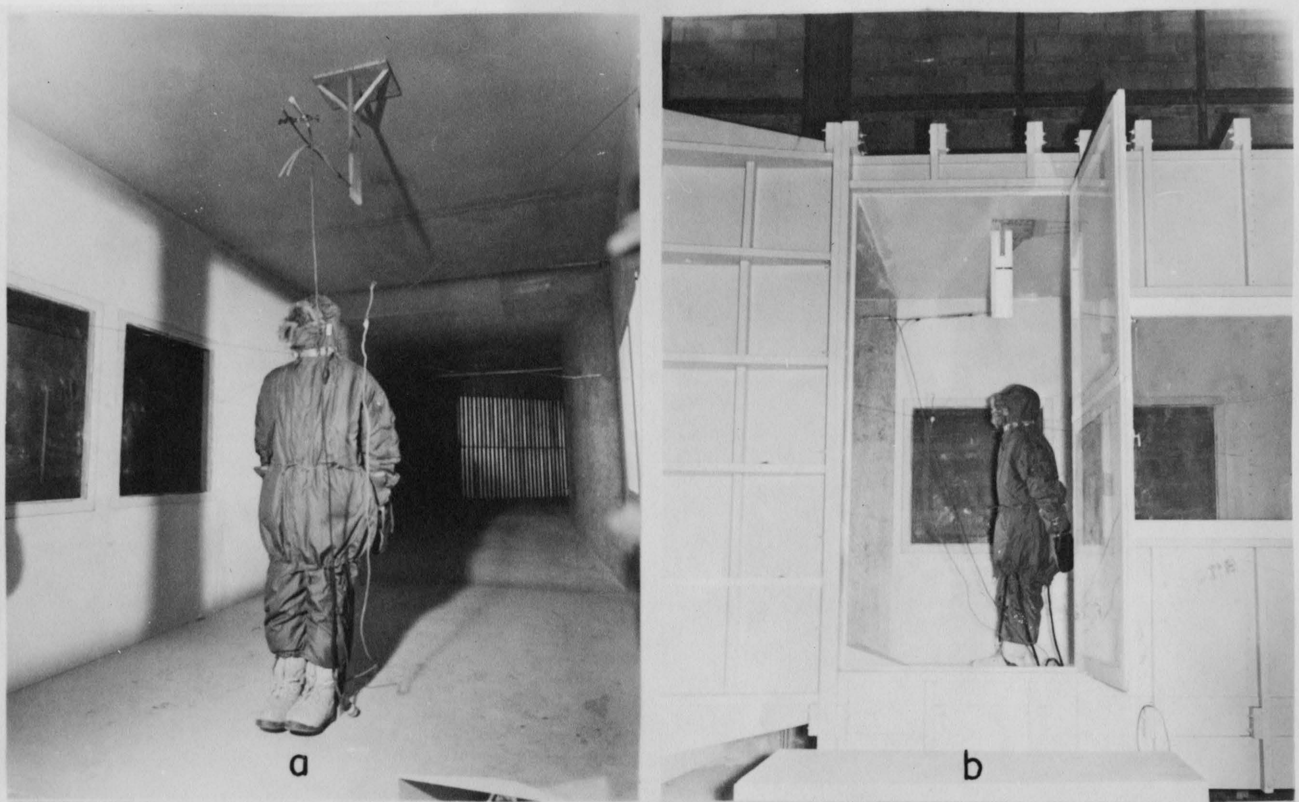
c

a. Looking downstream

b. Side view

c. Looking upstream

Fig. 4 View of Copper Man in wind tunnel.



a. Looking downstream

b. Side view

c. Looking upstream

Fig. 4 View of Copper Man in wind tunnel.

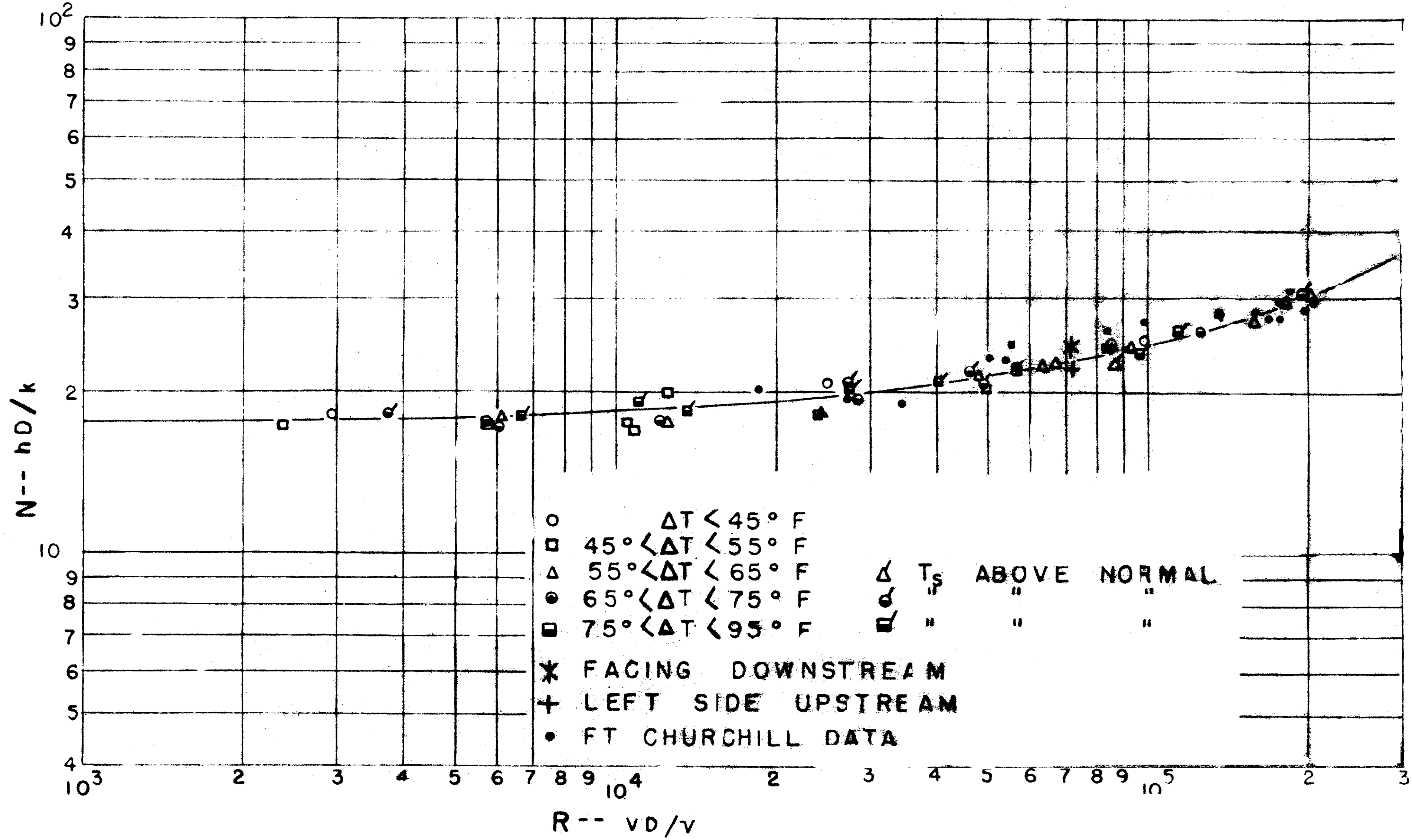


Fig. 5 Nusselts number as a function of Reynolds number for wind chill from a Copper Man in Ex-50 Arctic uniform.

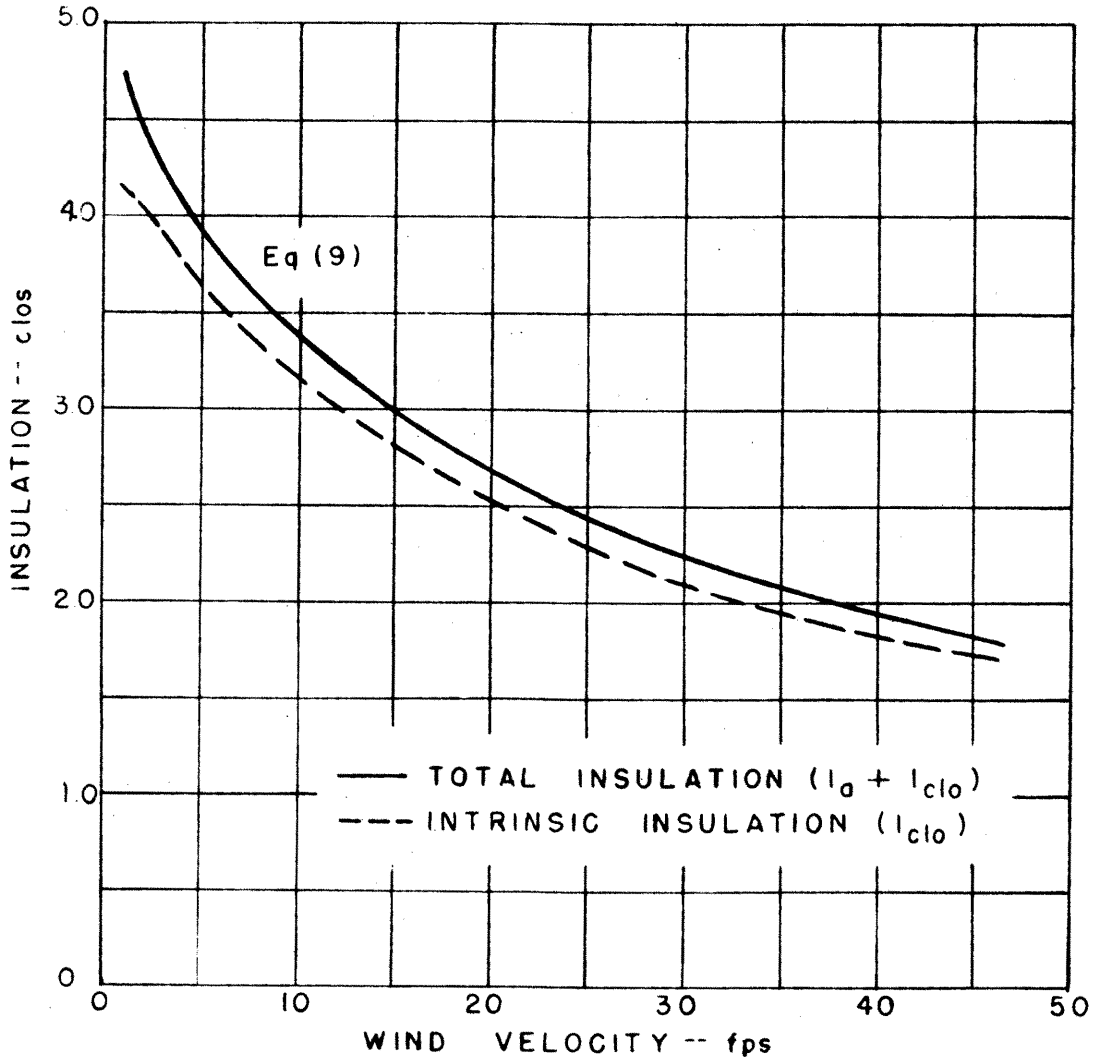


Fig. 6 Insulation values for the Ex-50 Arctic uniform.

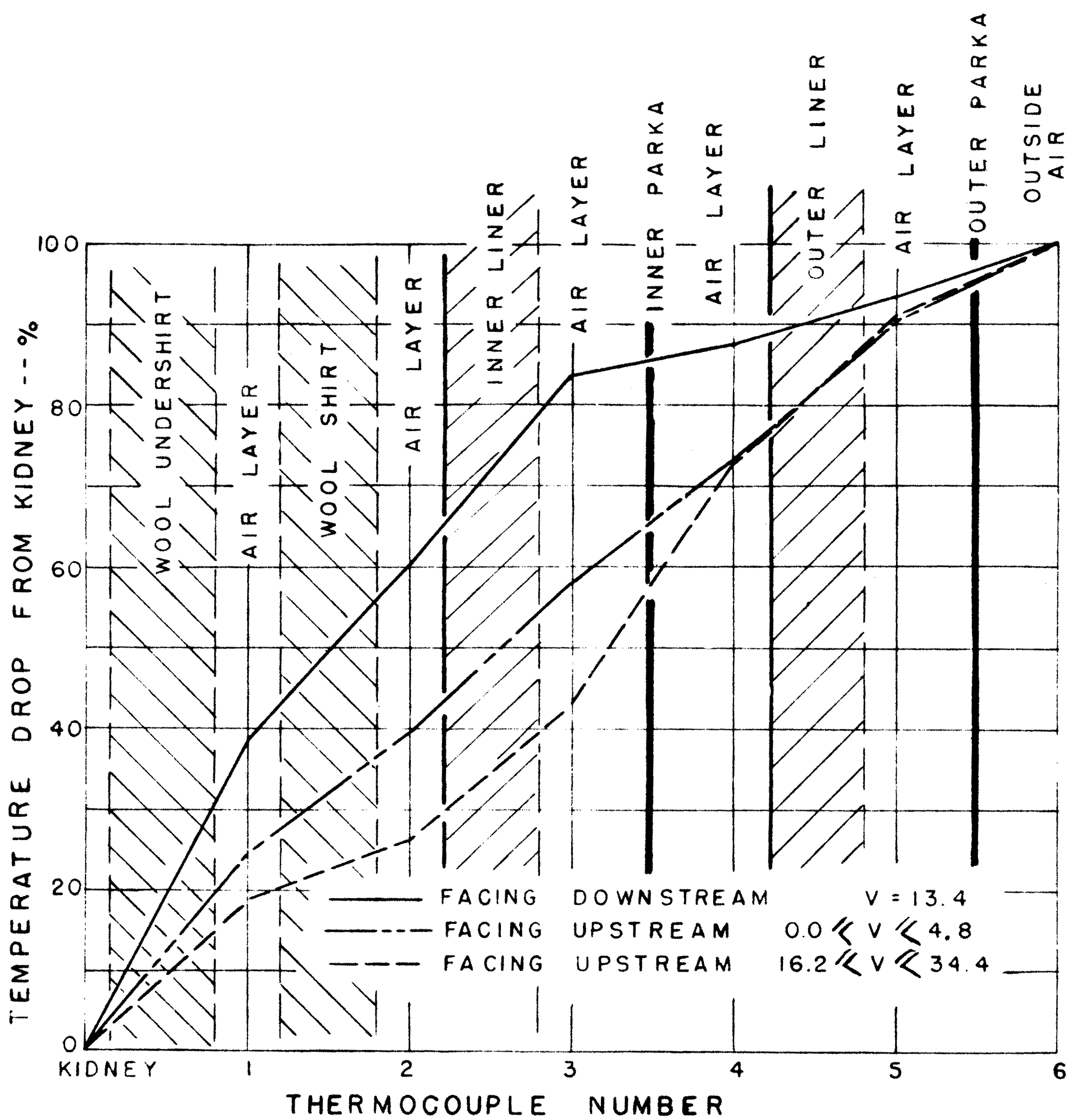


Fig. 7 Temperature drops through uniform.

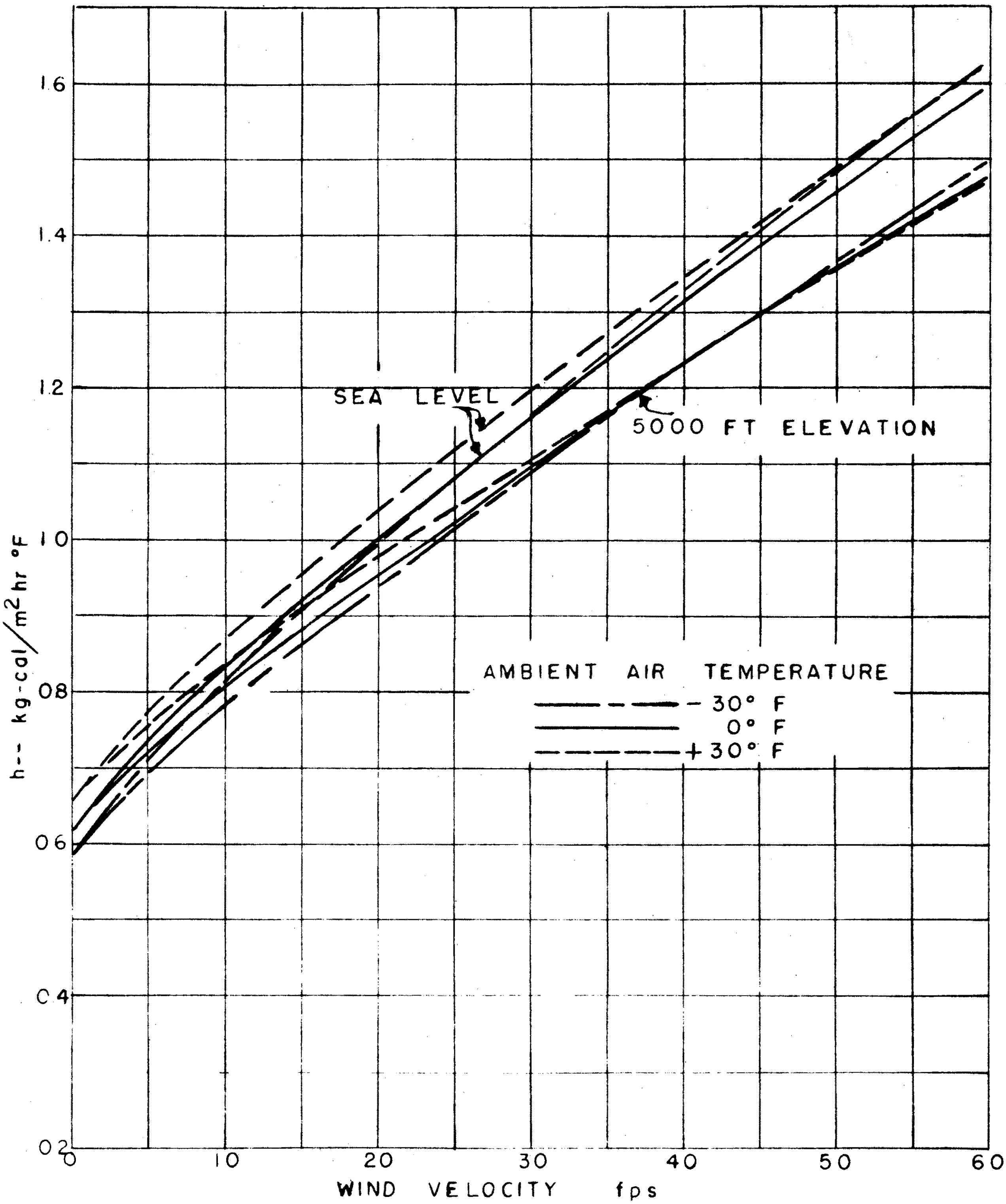


Fig. 8 Effects of ambient air temperature and elevation above sea level upon wind chill.

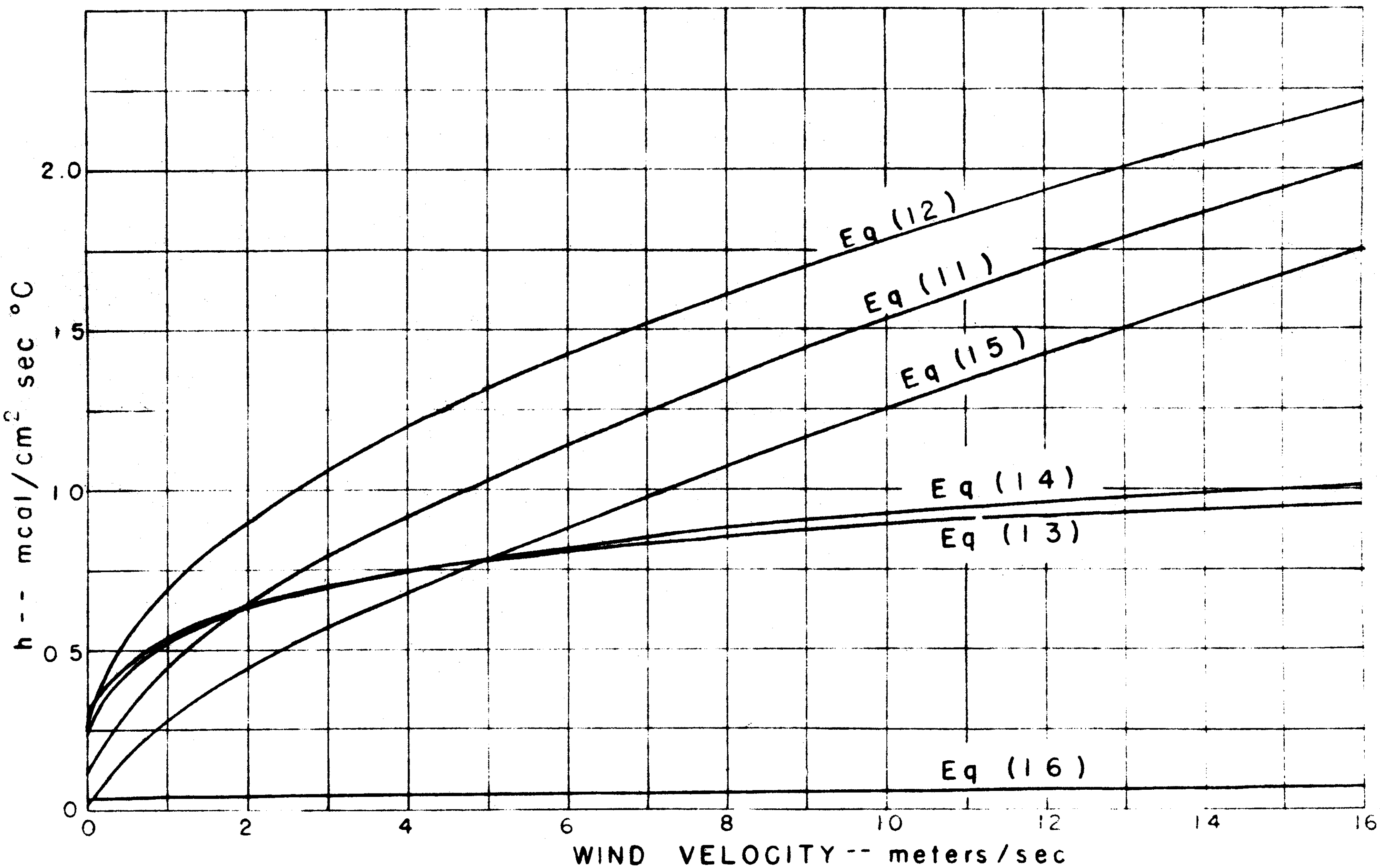


Fig. 9 Comparison of various wind chill formulae.