AN EVAPORATIVE INDIVIDUAL COOLING SUIT

By 6408

STEVEN J VAN HOLE

B.S.I.E., Kansas State University, 1967

A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

Kansas State University

Manhattan, Kansas

1971

Approved by

Corwin A. Bennett

Major Professor

TABLE OF CONTENTS

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to his major professor, Dr. Stephan Konz, whose guidance, support, and enthusiasm played a vital part in this work. An expression of gratitude is also due to Drs. Corwin Bennett and Clyde Sprague for their service on the advisory committee. The author also wishes to thank Tom Shrimplin and Jack Corn of the Institute for Environmental Research for their participation in this project. And finally thanks are due to Kevin Cahill and Malcolm Rodenberg for their help in conducting the experiments.

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

In order to survive, man must maintain his skin and internal temperatures within fairly narrow ranges. Slight deviations of temperature outside these ranges result in a quick demise. To cope with these limitations, nature has provided man with an involuntary thermo-regulatory system in addition to the intelligence necessary to adjust to the constantly changing thermal environments in which he exists.

In general, man must maintain an internal temperature in the range of 25-43 C° (80-109 F°). With a constant normal internal temperature, skin temperatures may vary in the range of 30-36 C° (86-97 F°) (Bazett, 1968). Under normal conditions, maintenance of these temperatures presents no problems to man. Ordinarily, due to clothing insulation and physiological adjustments, the individual is able to function in a variety of environmental conditions with no great discomfort or danger to his survival. However, there are cases in industry and other areas of man's endeavors, which require that man provide himself with additional thermal protection. It is in these extremes that man must use his technological knowledge in addition to his normal physiological adjustments in order to work efficiently and, in some cases, even to survive.

Survival at ambient temperatures below man's "comfort zone" has not been a serious problem. Additional layers of clothing usually provide the insulation necessary to maintain the proper body temperatures. When the ambient temperature rises above the "comfort zone", the problem is not as simple. Instead of conserving heat as is done at low ambient temperatures, man must dissipate internally produced heat in high ambient temperatures in order to maintain his own temperature balance. In many cases, the complete removal of all external insulation clothing is not enough to allow thermal balance. A considerable amount of research has been done in recent years in an effort to find solutions to this problem. In the following sections, several methods of keeping an individual comfortable in such environments are discussed. The discussion is preceded by an explanation of the basic factors in human heat exchange with the environment. And finally, the rationale for this work is set forth.

LITERATURE SURVEY

Physiology of Heat Transfer in Humans

In general, man gains heat through metabolism, and heat is lost or gained by radiation, conduction and convection. When necessary, heat is also lost by evaporation of sweat from the body surface. Several variations of the heat balance equation have been published (Nelson, Eichna, Harvath, Shelley, and Hatch, 1947; Herrington, 1958; Burriss, 1965; Fanger, 1967). The general form is as follows:

$$M - E \pm C \pm R \pm K = \pm S \qquad (1)$$

where

M = metabolic rate

E = evaporative rate

C = convective rate

R = radiative rate

K = conductive rate

S = storage rate

All of the above quantities are expressed in heat units per unit of time, kilocalories or British Thermal Units per hour. Most authorities combine the basal metabolic rate and muscle generated heat into one value of M for a particular activity. Evaporation takes the form of insensible and sensible water losses from the skin surface (skin surface includes the respiratory tract). Convection and radiation losses or gains are calculated from thermal properties of the skin and environment while conduction losses or gains are derived through skin contact with external non-gaseous materials. Whatever heat the body is unable to dissipate is stored in the body. Obviously, to remain in thermal comfort, heat storage, for any sustained length of time cannot be tolerated. As stated in Webb, 1964, (p. 105):

> Whenever delivery of internally produced body heat to the environment requires a displacement of physiological parameters from the levels typical of comfort for the activity level concerned, the displacement represents a "heat strain." If the heat stress is beyond the body's ability to compensate by means of physiological readjustment, a state of steadily increasing strain results, terminating in collapse.

Each of the above terms in equation (1) are discussed in detail in the following paragraphs.

Metabolism. Metabolic rates for a variety of activities have been well documented. When asleep, man's metabolic rate is approximately 70 kilocalories per hour while at the other extreme, the Harvard Step

Test requires 971 kilocalories per hour (Burris, 1965). Therefore, for any sustained activity, there is a corresponding metabolic heat production which must be dissipated.

Convection. Convective rate of heat transfer is given by Fanger (1967) as

$$C = A_{du}h_c(T_a - T_{cl}), \text{ Kcal./hr.} \tag{2}$$

where

A_{du} = DuBois area of the body, m^2

h_c = convective heat transfer coefficient, Kcal./m.^{2}hr.

= $2.05\ (T_a - T_{cl})^{0.25}$ (free convection)

= $10.4\ (V)^{0.5}$Kcal./m.^{2}hr. (forced convection) V = m/sec

T_a = temperature of the ambient air, C°

T_{cl} = temperature of the clothing, C°

By inspection, it is obvious that a man would gain heat by convection while working in an environment in which the ambient temperature was above his clothing temperature. When wearing clothing, the ambient temperature under the clothing usually will differ from the temperature outside the clothing.

Radiation. Radiative heat transfer is calculated from the following equation (Fanger, 1967)

$$R = A_{eff}\varepsilon\sigma[(T_{mrt} + 273)^4 - (T_{cl} + 273)^4] \text{ Kcal./hr.} \tag{3}$$

where

$A_{eff} = f_{cl}f_{eff}A_{du}$, m^2

f_{eff} = ratio of the effective radiation area of the clothed body to the surface area of the clothed body. For a standing person = 0.75.

f_{cl} = ratio of surface area of the clothed body to the nude body. For indoor work clothing, f_{cl} = 1.1.

ε = emissivity of the outer surface of the clothed body $\tilde{=}$ 0.97.

σ = Stefan-Boltzmann constant, 4.96×10^{-8} Kcal./m.^{2} hr. K°^{4}

T_{mrt} = mean radiant temperature of the environment, C°

Once again at ambient temperatures above clothing temperatures, the clothing (and usually the underlying skin) will gain heat by radiation. The clothing radiates to the skin at temperatures different than the external environment temperature.

<u>Conduction</u>. The dry heat conduction from the skin to the outer surface of the clothing is a complicated process. Based on Gagge's work, (1941), Fanger (1967) found that heat conduction from skin through clothing could be calculated as follows:

$$K = A_{du}(T_s - T_{cl})/(0.18\ I_{cl})\text{Kcal./hr.} \qquad (4)$$

where

K = heat conducted, Kcal./hr.

A_{du} = surface area of the body, m.^{2}

T_s = temperature of the skin, C°

T_{cl} = temperature of the clothing, C°

I_{cl} = R_{cl}/0.18 clo

R_{cl} = total heat transfer resistance from skin to outer surface of clothed body, m.^{2}hr. C°/Kcal.

Values for I_{cl} for common clothing ensembles have been summarized in table form by Fanger (1967).

Evaporation. The rate of evaporative loss from totally wet skin has been empirically derived by Clifford (1959) to be:

$$E = k_e A_{du}(P_s - P_a) \text{ Kcal./hr.} \tag{5}$$

where

E = evaporative loss, Kcal./hr.

k_e = coefficient depending on air velocity, posture, and orientation to the wind = $0.45\ V^{0.63}$ V in ft./min. (standing subjects)

P_s = saturated vapor pressure at temperature of skin surface, mm Hg,

P_a = partial vapor pressure of the ambient air, mm Hg.

It should be stated, for completeness, that Fanger included other terms in his comfort equation. These terms represent respiratory and diffusion losses which are small when compared to metabolism, evaporation, and convection.

Heat storage. The remaining term in the thermal balance equation, heat storage, has been determined by a variety of authorities (Burton, 1935; Nelson, et al., 1947; Burriss, 1965; Webb, 1969). If all of the above quantities are known, then calculation of heat storage in the body simply becomes a matter of subtraction in equation (1). Burriss (1965) proposed that heat storage could be calculated independently by the following equation:

$$S = mc\ (2/3 \Delta T_r + 1/3 \Delta T_s) \tag{6}$$

where

S = heat storage, Kcal.

m = weight of body (kg.)

c = specific heat of the human body = 0.83 Kcal./kg. C°

ΔT_r = change in rectal temperature, from basal conditions, C°

ΔT_s = change in skin temperature, from basal conditions, C°

Webb (1969) espouses a similar equation but gives a 0.8 weight to rectal temperature and 0.2 to skin temperature. It should be noted here that although the heat storage equations are not rate equations, they can be made so by taking the ΔT measurements at equal time intervals such as one hour intervals. Ideally, the body heat storage should be zero. However, Belding, and Hatch (1955) stated that the average man (150 lbs.) can withstand a total cumulative storage of 62 Kcal. (250 BTU) without any adverse effects. Wortz (1964) claimed that exercising subjects were able to store a cumulative total of 250 Kcal. (1000 BTU) in a short exercise period without any ill effects. This represents a 4 C° rise in body temperature when inserted in equation (6) and seems somewhat extreme.

The Thermoregulatory System

As mentioned earlier, the human body possesses a thermoregulatory system. The system constantly appraises the ambient surroundings through temperature sensitive nerves in the blood stream in the brain and in the skin. When a rising or lowering trend in temperature is detected, the body reacts to counter the trend and maintain equilibrium. The body maintains its temperature by (1) control of blood flow to the skin surface, (2) control of sweat production, and (3) by control of metabolic rate by shivering. The body has the ability to either increase or choke off the supply of blood near the skin surface. To get rid of excess heat, blood is allowed to flow in great quantities near the skin surface in order to give up heat to the environment through radiation and convection. To conserve heat, the muscles around the arteries contract and blood is restricted from the skin surface. Since skin is a very good insulator, heat loss from the body is reduced. When the body cannot dissipate enough heat through radiation and convection, sweating commences. Kerslake (1955) stated that sweat glands are not directly stimulated by local temperature changes, but are stimulated by sympathetic nerves coming from the heat regulating center to the locally heated area. In addition, the body does not sweat equally over all the body. Funk, Moeglin, Drake, Hall, Klemm, and Buehring (1966) classified all areas of the body as to high, low, and variable sweat producing areas. Burriss (1965) stated that general sweating commences when the mean skin temperature reaches 34.4 C° (94 F°). There is some evaporative cooling below this skin temperature. There are insensible moisture losses from the respiratory tract and from diffusion through the skin. Burriss also stated that, at the maximum evaporative level, these insensible sources account for 10% of the total evaporative loss. DuBois (1938) found that evaporation accounts for 18-20% of body heat loss at normal temperatures; 25-40% for rising temperatures above normal temperatures (up to 31.5 C° or 89 F°); and

100% at skin temperatures above 35 C° (95 F°). One can see from the basic heat exchange equation that radiation, convection, and conduction all represent heat gains at ambient temperatures higher than skin temperatures. Evaporative loss is the body's only means of cooling at high ambient temperatures.

Belding and Hatch (1955) stated that man can secrete one pound of sweat per hour for a sustained period (others have estimated one kilogram per hour). This represents the maximum sweat rate man can sustain for a working day of eight hours. If all of this pound of sweat evaporates, the heat loss would be approximately 260 Kcal./hour. All the sweat produced does not evaporate from the body surface, however. At maximum sweat rates, a good deal of sweat drips off the body. The cooling effect of the dripping is minimal compared to evaporative cooling. Woodcock (1962), in fact, stated that the limiting factor in evaporative cooling is not the amount of sweat secreted, but the amount that can be evaporated.

As one can see from the evaporative heat loss equation (5), the evaporative rate is dependent only on vapor pressures and air velocity when the skin or clothing surface is completely wet. At this condition, the vapor pressures become essentially fixed, leaving only air velocity as a variable. In still air, the air next to a wet skin surface becomes nearly saturated. This reduces the vapor pressure differential between the ambient air and the wet skin boundary. In the moving air, a constant fresh supply of ambient air is forced next to the skin to maintain the maximum pressure differential possible for a given set of dry and wet bulb temperatures. Therefore, air velocity and whatever insulating properties a man's clothing possesses determine the amount of heat that can be evaporated for cooling.

Individual Cooling Suit Studies

In the 1960's, man made major strides in outer space exploration. A vital factor to the success of the space program was the development of systems to enable man to maintain his thermal balance in extraterrestrial environments. Although the cooling suits developed for the astronauts are far too complicated and expensive to be of practical value to industry, the development of these suits has provided some useful applications for industry. In the course of development, engineers have investigated all possible methods of removing heat from the body-convection, conduction, radiation, and evaporation. Veghte (1965) demonstrated that conduction cooling via tubes circulating cold water is the most efficient in terms of maintaining skin and rectal temperatures in the "comfort zone" and avoiding high sweat rates. In fact, this is the method used in the Apollo space flights. This type of body cooling, while efficient, has several disadvantages. The biggest drawback for industrial use is the restriction of wearer mobility both from the suit and from the inherent equipment necessary for water flow. Radiation and convection cooling do not afford the rate of heat removal necessary for high metabolic loads of industrial work. Evaporative cooling, on the other hand, has the potential for large heat removal rates. As an illustrative example, if in a conduction cooling system, one kilogram of water is heated 20 C°, 20 kilocalories are absorbed from the body. If that same kilogram of water is at skin temperature and is allowed to evaporate, 580 kilocalories are absorbed from the body.

Evaporative or ventilation suits have been in use for high altitude flights for many years. The fact that pilots are relatively immobile has simplified the design of such suits.

Some success has been attained by engineers working on industrial ventilating suits. Crockford, Hellon, Humphreys, and Lind (1964) tested dynamic cooling suits. Dynamic cooling involves a radial flow of air from the body through a permeable suit fabric. In their studies, they tested five subjects at a metabolic rate of 250 kilocalories per hour and 72 C° (162 F°) dry bulb temperature. Dynamic cooling reduced the sweat loss by one-third and oral temperature rises by one-half compared to three other conventional Air Force ventilation suits. Linehard, Hughes, and Brassette (1964) used a vortex tube to provide cool air to cool the torso. Their apparatus included a tubing harness under standard work clothes. The environmental conditions were 58 C° (136 F°) and 20% relative humidity. Heat storage was reduced by 50% and sweat loss was reduced by a factor of 3 over the control condition of no vortex tube in the clothing.

Veghte (1965) tested both air and conduction cooling methods. The conduction cooling method proved superior in maintaining skin and rectal temperatures in the "comfort zone" even though the evaporative methods were able to remove large quantities of heat with high sweat rates.

Several air cooling experiments have been conducted at Kansas

State University. Sharma (1970), Gandhok (1970), Byrnes (1970) and Aurora (1970) all have carried out tests of ventilation cooling. Variations in location cooled, air velocity, vortex tubes, and clothing have all been tested. The one inherent drawback in these systems is the trailing apparatus. Any worker in these suits is necessarily tied to the ventilating equipment. The ordinary industrial worker may not accept such a limitation to mobility.

PROBLEM

The objective of this work was to determine the feasibility of using continuously wetted clothing and moving air as a means for protecting and cooling an individual in a heat stress environment. Of primary importance was that the cooling system had to be simple, completely mobile, and not cumbersome to the wearer. It was felt that these conditions had to be met in order for the system to be successfully applied to industry. The major question to be answered was: Would evaporative cooling reduce the incremental increases in heart rate, rectal temperature, skin temperature, and sweating in a heat stress environment?

METHOD

General Description

It is common practice for American workers to remove clothing from the torso while working in environments in which the temperature approaches or exceeds 100 F°. A considerable amount of sweat drips from the body under these exposed conditions. This lessens the effectiveness of the natural cooling mechanism. Sweat which does not evaporate does very little to cool the individual. In addition, a bare-chested worker exposes a large portion of his skin surface to the full effect of radiation and convection from the environment.

This is a study of the feasibility of using an evaporative wet suit as a means for protecting industrial workers in hot environments. Evaporative cooling offers several advantages over the other methods of individual cooling. Foremost are complete mobility, economy of fabrication, and relatively high heat removal rates. The suit consisted of a set of long underwear of 100% cotton and a small inner tube used as a water-filled collar as shown in Figure 1. The inner tube had two holes on its underside which allowed water to flow onto the garment. One other piece of equipment was needed to provide moving air. In this study, two 15-inch diameter blade floor fans were used to provide moving air by the subjects. The complete system was very simple. The subject wore the continuously wetted clothing in a moving air stream in and about his work station.

Operationally, the evaporative cooling suit had two functions. First of all, the absorbent cotton fabric tended to hold the sweat

Figure 1. Instrumented subject wearing wet suit and collar.

produced by the body and prevented it from dripping on the floor. Secondly, and more importantly, the wet clothing provided alternate paths for dissipation of high convective and radiative heat gains from the environment. Heat was not allowed to reach the human body, but instead was dissipated through evaporation and some conduction from the suit. By adjusting the air velocity around the saturated cloth, one can establish an evaporation rate which will exceed the rate of convection and radiation to the cloth. The human body, then, does not experience the full effects of the ambient environment.

To illustrate the above, the elements of equation (1) are plotted in Figure 2 to depict the conditions of this study. In this illustration, the environment is at 43 C° (110 F°) and 40% RH. It is assumed that a man with two square meters of surface area is in this environment wearing completely wet clothing. It is also assumed that the outside surface of the clothing and the exposed skin temperature is 34.4 C° (94 F°). This temperature is based on preliminary studies by this experimenter. In these studies, clothing temperatures and exposed skin temperatures averaged about 9 C° (16 F°) lower than the ambient temperature of 43.3 C°. The flowing water from the collar tended to equalize the skin and clothing surface temperature. A final assumption is that the man is working at a metabolic rate of 100 $Kcal./hr.m^2$. Using equations (1-5), the total heat gain and evaporative heat loss of the clothing and exposed skin are plotted for a range of feasible air velocities. In theory, any air velocity to the right of the intersection of the two curves should provide sufficient evaporation to protect the worker from the environment.

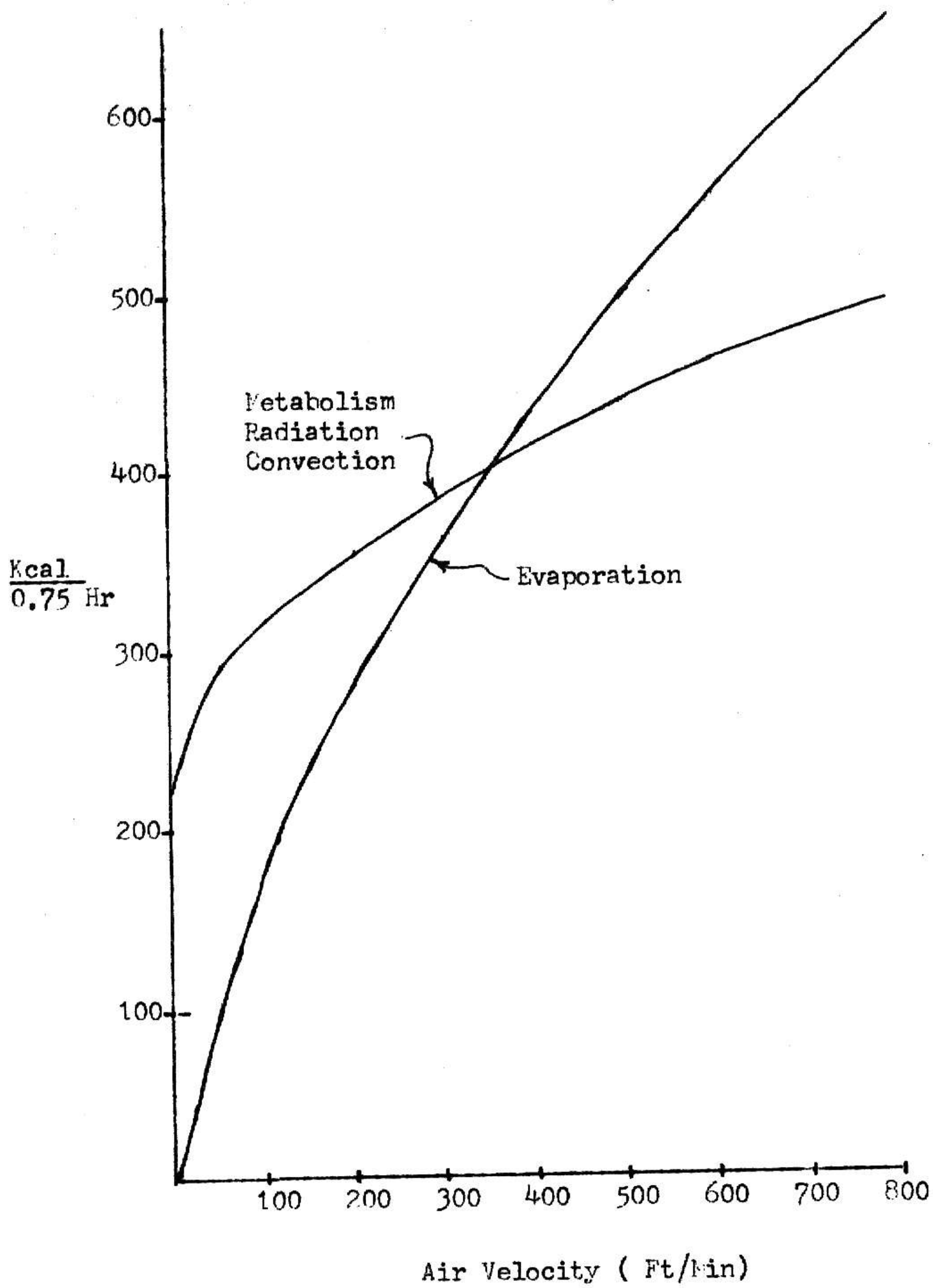

Figure 2. Comparison of heat transfer terms in an example situation.

Task

In this study, the subjects performed a standing task simulating medium assembly work (estimated at 100 $Kcal.hr.m^2$.). The work consisted of sliding a ten-pound weight laterally back and forth on a work bench which was forty-three inches from the floor. A metronome set at a pace of one beat per second was used to enable the subjects to work at the same rate (one movement per second).

The subjects were instructed to slide the weight back and forth ten times on the bench, place it on a table immediately behind them, rest for five seconds, return the weight to the bench, and repeat the cycle. This motion pattern simulated the movement of an actual work station in addition to causing the subject to expose more than one side of his body to the wind of the floor fan. The fan was blowing parallel to the work station as shown in Figure 3. The task was performed in an environment of 43 C° (110 F°) and 40% RH with average air velocities of 650 and 130 feet per minute. The air velocities were the average of measurements taken from the knee to eye level of the work station. At an air velocity of 650 feet per minute, the evaporative rate, in theory, exceeds the sum of metabolic, convective, and radiative rates by about 100 kilocalories per 0.75 hour. At a velocity of 130 feet per minute, the sum of metabolic, convective, and radiative rates exceeds the evaporative rate by approximately 125 kilocalories per 0.75 hour as depicted in Figure 2.

Figure 3. Subjects and equipment in test chamber.

Apparatus

The apparatus for this study consisted of:

1 work bench, 43 inches in height

1 metronome

2 ten pound weights

4 sets of long underwear, 100% cotton knit

1 8" diameter rubber inner tube

14 Yellow Springs skin thermister, Type 500

2 Yellow Springs rectal thermisters, Type 500

1 Digitec thermometer, Model 500

1 E & M telemetry system with 2 transmitters and 2 sets of electrodes

1 Beckman Dynagraph recorder

1 weight scales

1 Sony television monitor system

1 water tank with pump

1 Anemostat Anemotherm air velocity guage

Experimental Procedure

The sequence of events of each test run was:

1. Both subjects were weighted nude.
2. Both subjects put on dry sets of underwear, and thermisters and telemetry equipment was attached.
3. Heart rates, rectal temperatures, and skin temperatures were recorded at 5 minute intervals for 15 minutes.

4. The subject to be tested under wet conditions was placed in a warm shower (approximately 34 C° or 94 F°) to completely wet his clothing.
5. In the test at the lower air velocity, the subjects were weighed in their clothing just prior to entering the test chamber.
6. The subjects entered the test chamber and began the task.
7. The inner tube full of water (approximately 85 F°) was weighed and placed on the shoulders of the wetted subject.
8. At 5 minute intervals, heart rate, skin temperatures, and rectal temperatures were recorded for the entire 45 minute exposure (10 readings total).
9. When necessary, the inner tube was weighed, refilled, weighed, and replaced on the subject.
10. At the end of 45 minutes of exposure, the subjects were brought out of the test chamber and seated in the pretest room with sheets wrapped aound them to avoid chilling. (The subjects were weighed clothed immediately after leaving the test chamber in the lower velocity test.)
11. Heart rate, skin temperature, and rectal temperature were recorded at 5 minute intervals for 15 minutes.
12. The subjects were weighed nude.
13. Each subject voted as to the degree of comfort he experienced during the test.

All test runs followed the same sequence. In the higher velocity test, Subject A wore the wet suit on the first and fourth days, and the dry suit on the second and third days. Subject B wore the wet suit on the second and third days and the dry on the first and fourth. It became apparent after the first three sessions that an experimental error had been made concerning the change in weight of clothing during the tests. In addition, it seemed desireable to conduct tests in a more stressful situation. For those reasons, two of the original subjects were tested in an identical environment with an air velocity of 130 feet per minute. In the lower velocity tests, only two sessions were conducted, with the subjects each wearing the wet suit once and the dry suit once (see Table 1).

Subjects

The subjects for this study were four college-age males. Their physical dimensions are summarized in Table 2. They were tested in pairs and paid five dollars for each test session.

Techniques of Measurement

The physiological parameters of this study were heart rate, skin temperature, rectal temperature, and sweat loss.

Heart rate via telemetry was recorded on a Beckman Dynagraph recorder. A thirty-second sample was taken at five minute intervals. The heart rate in beats per minute was determined by counting the number of pulses for a twenty second interval and multiplying that number by three.

TABLE 1

Experimental Design

Velocity = 650 ft./min.		Day		
Subject	1	2	3	4
JT	W	D	D	W
CS	D	W	W	D
TT	W	D	D	W
RG	D	W	W	D

Velocity = 130 ft./min.		Day
Subject	1	2
CS	W	D
TT	D	W

W = wet condition

D = dry condition

TABLE 2

Dimensions of Subjects

Subject	Weight	Height	Surface Area[1]
JT	61.7 kg.	1.71 m.	1.73 $m.^2$
	(136 lbs.)	(67.5 in.)	(18.7 $ft.^2$)
CS	77.8 kg.	1.78 m.	1.95 $m.^2$
	(172 lbs.)	(70 in.)	(21.0 $ft.^2$)
TT	82.8 kg.	1.80 m.	2.03 $m.^2$
	(183 lbs.)	(71 in.)	(21.9 $ft.^2$)
RG	86.2 kg.	1.80 m.	2.15 $m.^2$
	(190 lbs.)	(71 in.)	(23.2 $ft.^2$)

[1]Based on chart developed by DuBois (1915).

Skin temperatures were recorded by using four thermisters taped to the skin at the points designated by Ramanthan (1964) and verified by Mitchell and Wyndham (1969). The four points were the upper chest, the outer upper arm, the outer front thigh, and the outer mid-calf. Since the subjects faced each other, the thermisters were attached to the right side of the dry subject and the left side of the wet subject. The thermisters were plugged into a junction box and cable which, in turn, was plugged into a Digitec Model 500 temperature recorder. The recorder was equipped with a printing device which provided a permanent record of the temperatures. Figure 4 shows the recording equipment in use during a session. Average skin temperatures were calculated from the temperatures of the above four points in the following equation (Ramanatham, 1964):

$$T_s = 0.3 \text{ (Chest - Arm)} + 0.2 \text{ (Thigh + Calf)} \qquad (7)$$

The average clothing surface temperature was calculated using the same formula. Thermisters were taped to the outside surface of the clothing very near the points where the thermisters were attached to the skin underneath the clothing. Since the calf was exposed, only the skin thermister was attached to that area of the body. For this reason, thigh temperature was given double weight in the clothing temperature calculations.

Rectal temperatures were obtained by using rectal thermisters which were inserted six inches into the rectal canal. These thermisters were also plugged into the junction box, and the temperatures were

Figure 4. Control room operation during a test session.

printed along with the skin temperatures.

Sweat loss was obtained by weighing the subjects nude before and after each test session. All weights were obtained by using a beam balance scale located in the pre-test room.

The amount of sweat lost and the amount of sweat evaporated are two related but different quantities. To find the amount of sweat evaporated from the dry subjects, one must obtain the quantities in the following equation:

$$\text{Sweat evaporated} = (\text{initial weight of subject + clothes}) - (\text{Final weight of subject + clothes}) \tag{8}$$

The dry subjects clothing stayed dry to the touch throughout the test sessions. There were also no drops of sweat on the floor around these subjects during any test session. This would imply that the air velocity was sufficient to evaporate most of the sweat they were secreting. Unfortunately, due to experimental error, data on nude weight changes was not recorded in the high velocity tests. This necessitated making estimates from data gathered in the low velocity tests.

A slightly more complicated equation is needed to calculate the amount of water evaporated from the wet subjects. This is so because not all of the water supplied by the collar and by sweating evaporates. A large amount drips from the clothing. Any meaningful calculations on evaporation in such a situation must necessarily allow for the amount of water lost by dripping. In this study, the problem was overcome by having the wet subject stand in a tub partially filled with mineral oil

(Figure 3). The water from the clothing and skin fell into the tub and sank below the oil surface, thereby preventing unwanted evaporation. The tub was weighed before and after each test. The amount of water introduced into the tube was found by weighing the tube before and after each filling and after each test session. Therefore, the amount of water evaporated from the wet subjects was calculated as follows:

$$\text{Water evaporated} = (\text{Change in weight of clothed subject}) + (\text{Weight of water from collar} - \text{Weight of water which dripped from system}) \quad (9)$$

Once again, only nude weight changes were recorded for the high velocity tests. In addition, some water dripped from the suit as the subjects walked from the test room to the scales and from the scales to the tub in the test chamber. The amount of uncollected drippage was estimated on the basis of a post experiment run by this experimenter.

Air velocity was measured by using an Anemostat anemotherm. The desired air velocity was obtained by adjusting the distance the floor fans were from the work bench. One fan was directed at each subject. The fans supplied a turbulent flow of air around the subjects. The two velocities quoted for this study represent an average velocity in the area in which the subjects stood as determined by the indicator fluctuations of the anemotherm. Measurements were taken from knee to eye level. In the higher velocity tests, the indicator fluctuated between 600 and 700 feet per minute. In the lower velocity tests, the air velocity varied between 110 and 150 feet per minute.

Instrument Accuracy

All tests were conducted in the test chamber of the Institute for Environmental Research at Kansas State University. According to the Institute technicians, this facility is capable of maintaining environmental conditions to within ±0.6 C° (1 F°) dry bulb temperature and ±2% relative humidity in the vicinity of the conditions for this study.

As explained earlier, heart rates in beats per minute were found by hand counting the number of beats recorded for a twenty second period and multiplying by three. An arbitrary maximum error of ±3 beats per minute is assigned here since an error in counting of ±1 beat per twenty seconds would become ±3 beats per minute in the stated data.

The manufacturer's stated accuracy for the Digitec Model 500 thermometer is ±0.083 C° (0.15 F°) with a repeatability of 0.03 C° (0.05 F°). The thermister probes have an even greater repeatability according to the manufacturer and frequent users at the test facility. Each subject wore the same thermister on the same spot for each test session. Since the printing device printed data in tenths of a degree Farenheit, it seems safe to assume that all temperature readings were accurate to ±0.1 C° (±0.2 F°).

In the absence of any manufacturer's data, it is assumed that the beam balance scale had a maximum error of ±0.05 pound. The scale divisions on the beam were 0.01 pound. In any case, the importance of absolute accuracy is reduced since only weight variations of the same body were needed.

The air velocity measurements were probably the least accurate of all measurements taken. For the most part this was due to the floor fans supplying a gusty air flow to the work stations. Turbulence was not as much of a problem at the higher air velocity as it was at the lower. To reduce the air velocity, the distance between the work station and fans was increased. As the distance increased, the fans interacted and a turbulent flow developed. This naturally caused fluctuations in the anemotherm indicator, and necessitated taking an average of the indicator readings. This probably resulted in a maximum error of ±50 feet per minute in the air velocity readings.

RESULTS

The parameters of this study are discussed individually below. The actual data for all experiments is summarized in Appendix B.

Heart Rate

In Figure 5, the mean heart rates per condition (wet and dry) are plotted for all subjects. The curves represent the full length of each test session. This includes fifteen minutes of pretest readings, forty-five minutes of heat exposure, and fifteen minutes of resting after the test. Although at first glance, it might appear that the heart rates were affected by the wet suit, such is not the case. As mentioned earlier, only the increment in heart rate is of interest here. A difference in starting levels, would naturally bias any uncorrected wet to dry comparisons. The incremental increases in heart rates for each subject are summarized in Table 3. In the table, the mean pretest levels for all subjects are entered for both the wet and dry conditions. The second line of numbers represents the average of the modes of last fifteen minutes of exposure. The mode was taken as an indication of the steady state condition of the heart rate after thirty minutes of exercise. Several times near the end of the sessions, the subjects would either slow down or anticipate leaving the chamber. Their heart rates would either slow down or accelerate accordingly. By examining the data and taking the mode of the last readings this deviation from the true heart rate is corrected. The next line of the table is a summary of the mean increment in heart rate for each subject. The second half

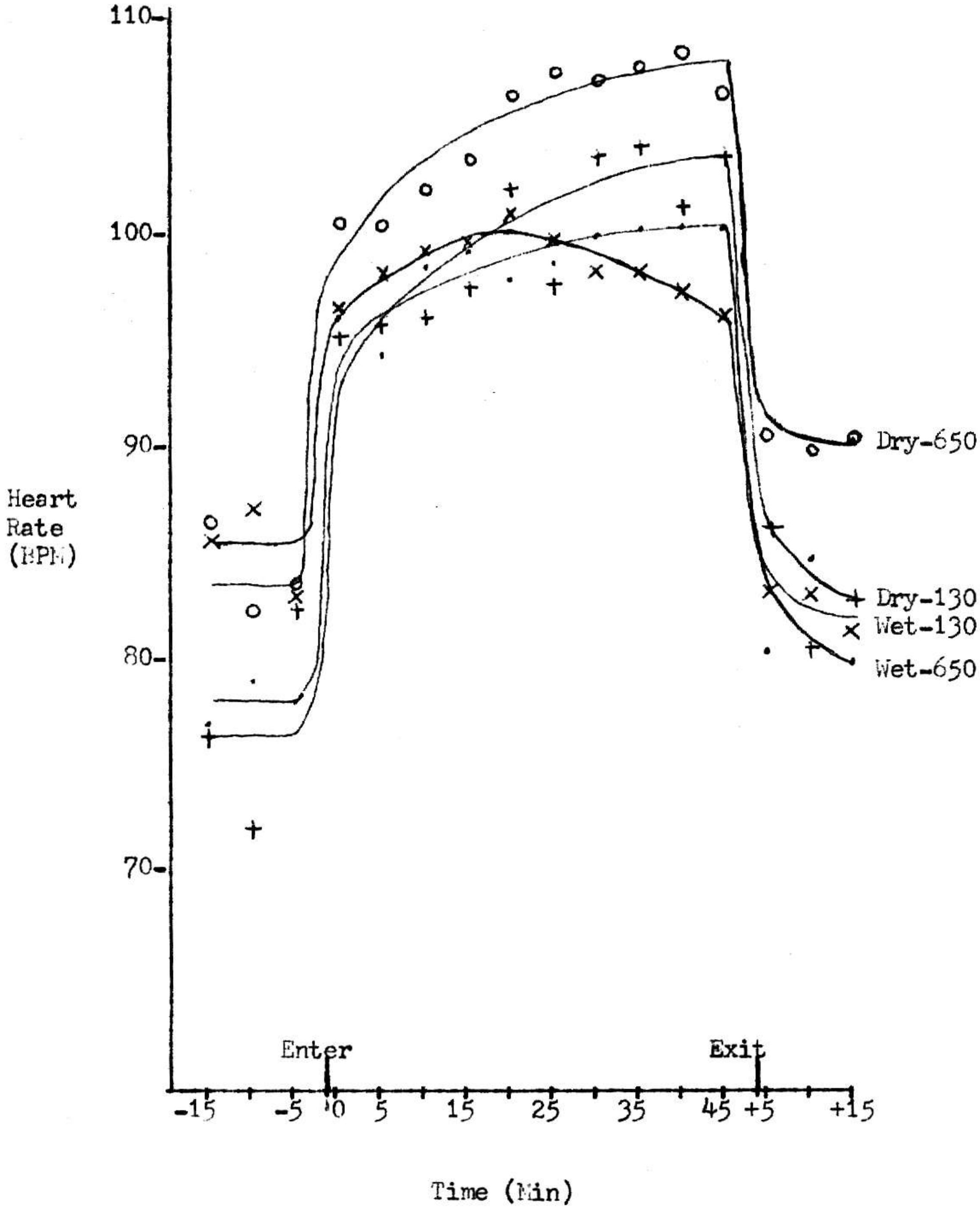

Figure 5. Mean heart of all subjects by condition and velocity.

TABLE 3

Heart Rate, Beats/Minute, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Mean pretest level	85	70	81	79	79	88	74	88	83	83
Mean of exposure modes	104	92	106	101	100	111	99	111	110	107
(Last 15 minutes)										
Mean increment	19	22	25	22	21	24	25	23	27	24
Velocity = 130 ft./min.										
Pretest level		84	88		86		64	90		77
Mode of exposure		99	96		98		99	105		102
(Last 15 minutes)										
Increment		15	8		12		35	15		25

of the table is a summary of the above quantities in the low velocity tests. No means are given since the two subjects, CS and TT, were tested only once in each condition.

A paired comparison sign test was used to analyze the incremental heart rate of each subject. The increment was taken to be the mean pretest level subtracted from the mode of the last fifteen minutes of the exposure readings. At the $\alpha = .05$ level, the paired increments in heart rates of wet and dry conditions were not statistically significant. On the average, however, the increment in heart rate was three beats per minute higher for the dry condition. An illustration of the quantities in the statistical test is given in Table 4. There were insufficient tests run in the low velocity tests to make a statistical analysis of the data.

Rectal Temperature

In Figure 6, the mean rectal temperatures of all subjects are plotted for each condition. In Table 5, the incremental increases in rectal temperature are summarized for each subject in the same format as the heart rate results.

As one can see from the table, the increment in rectal temperature was not large for any subject in either the wet or dry condition. The increment was taken to be the pretest test level subtracted from the last exposure reading. Only one subject experienced an increment as high as 0.9 F°. The increment was 0.1 F° higher for the dry condition than the wet when averaged over all subjects. A sign test revealed this was not significantly higher.

TABLE 4

Sign Test of Heart Rate Data

Velocity = 650 ft./min.

Subject	JT		CS		TT		RG	
Comparison	1	2	1	2	1	2	1	2
Increment								
Dry	22	25	33	18	19	28	33	20
Wet	16	22	23	20	15	35	23	20
Difference	6	3	10	-2	4	-7	10	0

For 8 comparisons, $r = 1$ ($\alpha = 0.125$). In this test $r = 2$, therefore, there is no difference in incremental heart rate between wet and dry conditions.

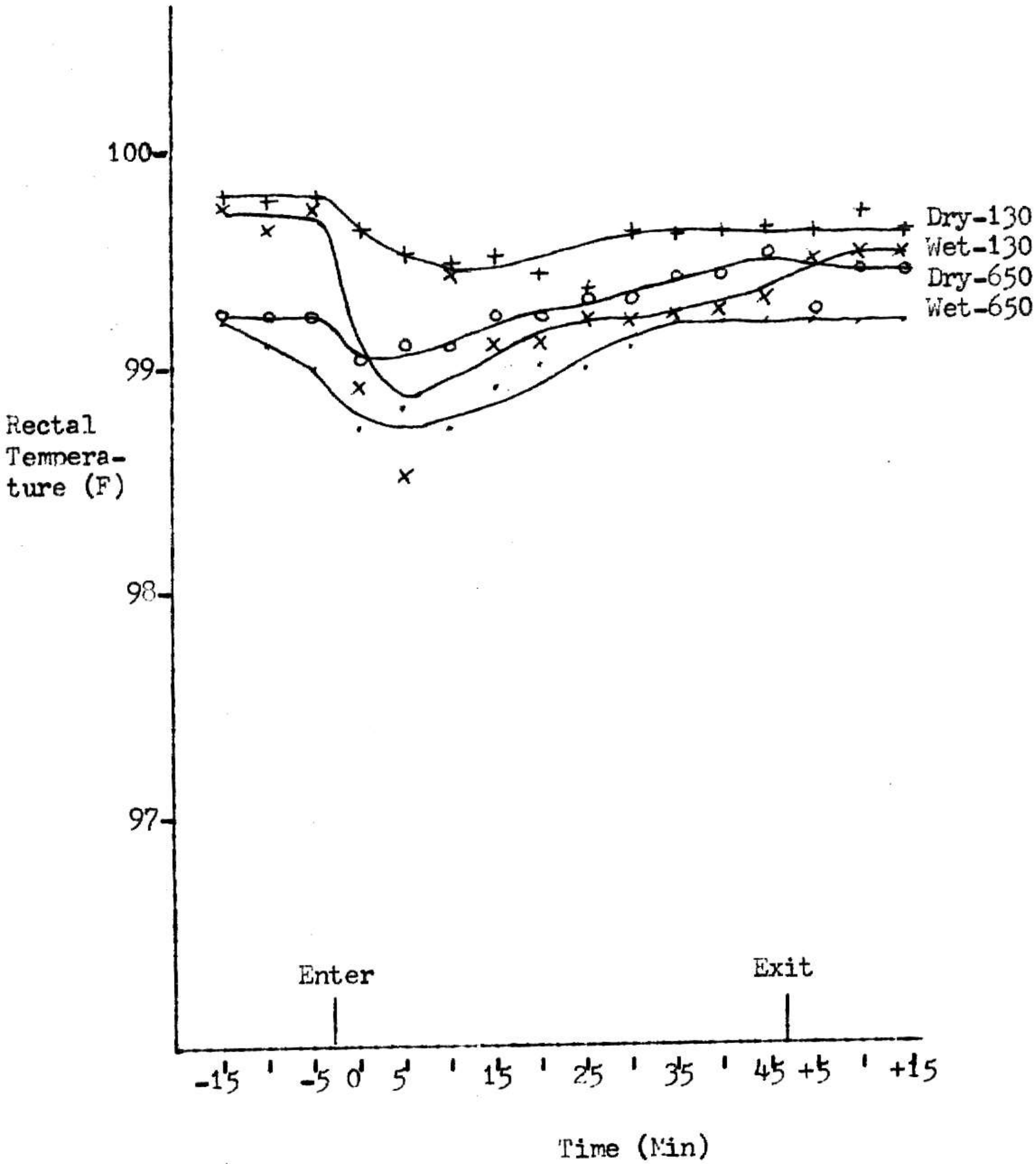

Figure 6. Mean rectal temperature of all subjects by condition and velocity.

TABLE 5

Rectal Temperature, Degrees Farenheit by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Mean pretest level	98.7	99.2	99.3	99.0	99.1	99.0	99.4	99.2	99.3	99.2
Mean of last exposure temperature	98.6	99.2	99.9	99.3	99.2	99.1	99.4	99.6	99.8	99.5
Mean increment	-0.1	0.0	0.6	0.3	0.1	0.1	0.0	0.4	0.5	0.3
Velocity = 130 ft./min.										
Mean pretest level		99.6	99.6		99.6		99.1	100.2		99.7
Last exposure temperature		99.5	99.0		99.3		99.2	100.0		99.6
Increment		-0.1	-0.6		-0.4		0.1	-0.2		-0.1

Skin Temperature

As might be expected, skin temperature was the parameter which was most affected by the wet suit. In Figure 7, mean skin temperatures of all subjects are plotted for each condition. In Table 6, the incremental skin temperatures of all subjects are summarized in the same format as the previous results tables. As one can see, the mean incremental increase of 7.4 F° of skin temperature in the dry condition was much greater than the 1.8 F° mean incremental rise in the wet condition for all subjects. The mean paired comparison difference was 5.6 F° which was significant (α = 0.01) in a sign test. Therefore, the wet clothing did significantly reduce skin temperature.

Sweat Loss and Evaporation

Although it is unfortunate that more complete data was not gathered in this regard, the information that was collected provides some idea as to what was taking place. Table 7 summarizes the data.

First of all, a sign test (α = 0.05) verified that the subjects sweated more when their clothing was not pre-wetted. On the average, the subjects sweated 0.57 pound/0.75 hour in the wet condition and 1.26 pounds/0.75 hour in the dry condition. This fact alone demonstrates a virtue of the wet suit--it reduces the need for sweat.

Since clothing weight changes were only measured in the wet condition of one high velocity session, the calculations of sweat and water evaporation in the high velocity tests are not as precise as they could be. This was one of the reasons why more tests were conducted in the lower velocity condition. Clothing gains were measured and an estimate

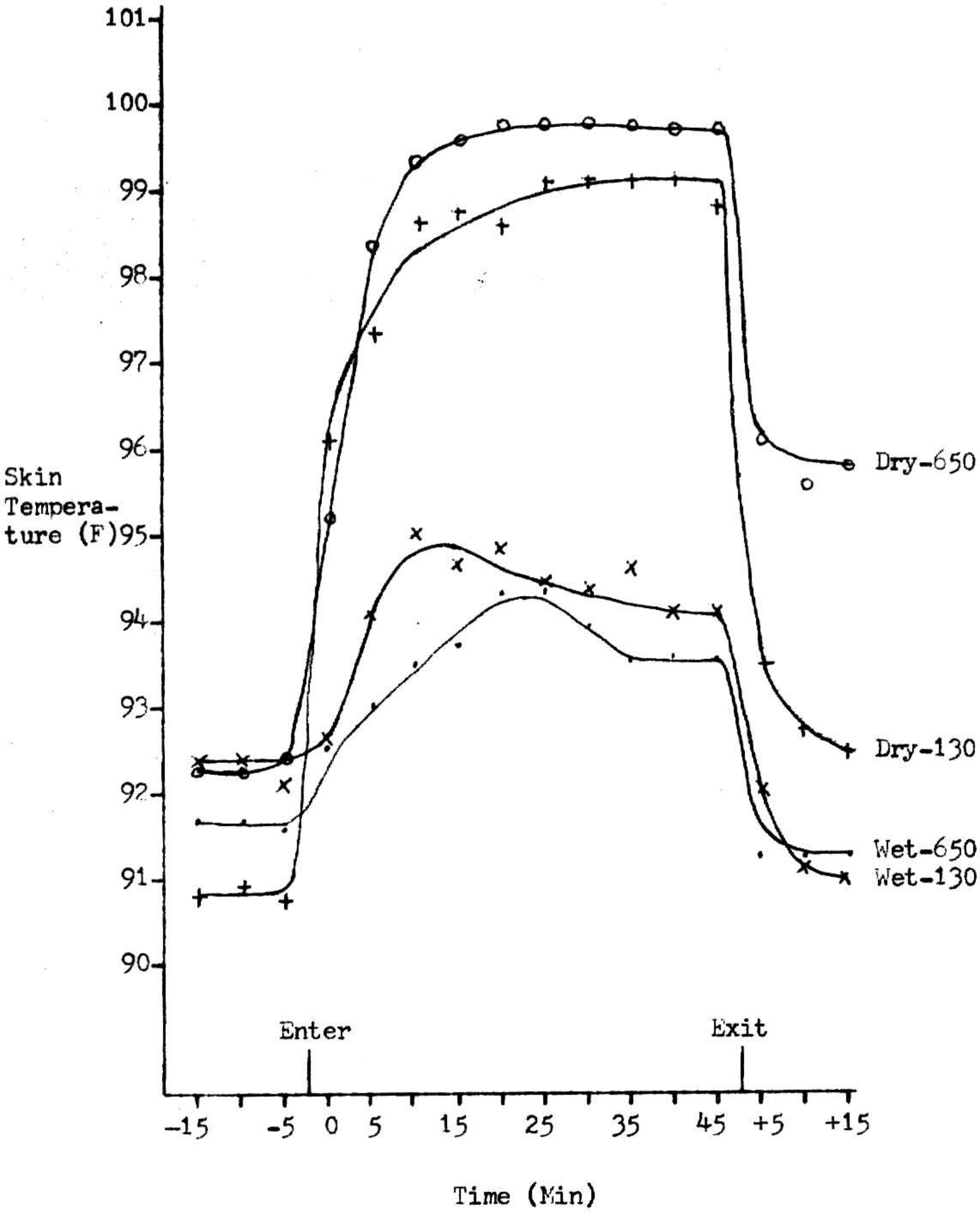

Figure 7. Mean skin temperature of all subjects by condition and velocity.

TABLE 6

Skin Temperature, Degrees Farenheit, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\overline{X}$	JT	CS	TT	RG	$\overline{X}$
Mean pretest temperature	91.9	91.8	92.4	90.6	91.7	92.2	91.7	92.2	93.1	92.3
Mean of last exposure temperature	93.3	92.5	93.6	94.7	93.5	99.0	99.4	100.1	100.5	99.8
Mean increment	1.4	0.7	1.2	4.1	1.8	6.8	7.7	7.9	7.4	7.5
Velocity = 130 ft./min.										
Mean pretest temperature		92.2	92.1		92.2		90.2	91.6		90.9
Last exposure temperature		94.3	93.9		94.1		98.8	98.9		98.8
Increment		2.1	1.8		1.9		8.6	7.3		7.9

of clothing gains was then used for the high velocity evaporation calculations.

In the lower air velocity tests, the subjects were weighed immediately prior to entering the chamber and just after leaving the chamber. The difference in these weights was a fairly accurate measure of dry clothing gain. The average weight gain was used as an estimate of dry clothing gain in the high velocity tests. The wet clothing difference measured in this fashion required a further adjustment. The wet subjects stood on the beam balance scale long enough to drip a pool of water on the platform. In order to get a true measure of clothing weight change in the chamber, the amount of water that dripped on the scale in the pre-entry weighing had to be known. It was found in six repetitions of weighing a subject in wetted clothing that an average of 0.5 pound of water dripped on the scale. With this information and the low velocity clothing information, an estimate of the wet clothing gain in the high velocity tests was made. These estimates appear in Table 7.

A sign test ($\alpha = 0.05$) on the data available shows that the amount of water evaporated in the wet condition was significantly greater than the water that evaporated from the dry condition. On the average, in the high velocity tests, the wet subjects evaporated 2.5 pounds and the dry subjects evaporated 0.9 pound. The estimates of clothing gains were used in attaining these averages. In the low velocity tests, the wet subjects evaporated 2.5 pounds while the dry subjects evaporated 0.7 pounds. The fact that the wet subjects evaporated an equal amount of water in the two air velocities is unexplainable.

TABLE 7

Measured Evaporation/0.75 Hour, Pounds of Water, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Mean body weight loss	1.01[1]	0.54	0.73	0.56	0.59	1.19	1.31	1.22	1.36	1.26
Clothing gain[2]	-0.25[3]	-0.27	-0.27	-0.27	-0.27	0.38	0.38	0.38	0.38	0.38
Mean external water difference (Tube - Tub)	1.35	1.61	1.69	2.00	1.67	-	-	-	-	-
Mean total water difference	2.65[1]	2.41	2.68	2.83	2.50[4]	0.79	0.93	0.84	0.98	0.88
Mean evaporation, Kcal.	696[1]	632	704	740	656[4]	206	244	219	257	230
Velocity = 130 ft./min.										
Body weight loss		0.82	0.67		0.74		0.92	1.22		1.07
Clothing gain		-0.36[3]	-0.23[3]		-0.29		0.34	0.42		0.38
External water difference		1.32	1.58		1.45		-	-		-
Total water difference		2.50	2.48		2.49		0.58	0.80		0.69
Evaporation, Kcal.		655	650		653		152	210		181

[1]Beer dehydration - Outlier

[2]Estimated from Vel. = 130 ft./min. and 1-Vel. = 650 ft./min.

[3]Gain minus drip allowance

[4]Subject JT omitted

It should be pointed out here, that Subject JT experienced an abnormally high weight loss in one of his wet test sessions. After that particular test, he stated that he consumed a fair amount of beer the evening before the test. It is felt that this fact accounts for his abnormal sweat rate in that particular session.

Clothing Temperatures

As one might expect, the temperature of the clothing at its outside surface was generally somewhere between the skin temperature and the ambient temperature in both the wet and dry conditions. In Figure 8 and Table 8, one can see that the dry clothing temperature was consistently higher than the paired wet clothing temperature. A sign test (α = 0.05) verified this fact. If the technique of measuring clothing temperatures did not introduce errors of large magnitude, it would appear that the wet clothing temperatures in the high velocity tests averaged 34.4 C° (94.1 F°) during exposure while the dry clothing averaged 40.5 C° (105 F°) during exposure. In the lower velocity tests, the wet clothing temperatures averaged 35.2 C° (95.5 F°) and the dry clothing temperatures averaged 40 C° (104 F°). In Table 9, a comparison, by location, of skin and clothing temperatures is made.

Heat Storage

As mentioned earlier, heat storage is calculated by using equation (6) involving changes in body temperatures. Table 10 is a summary of heat storage calculations for this study. A paired comparison sign test (α = 0.05) indicates that heat storage was greater in the dry subjects

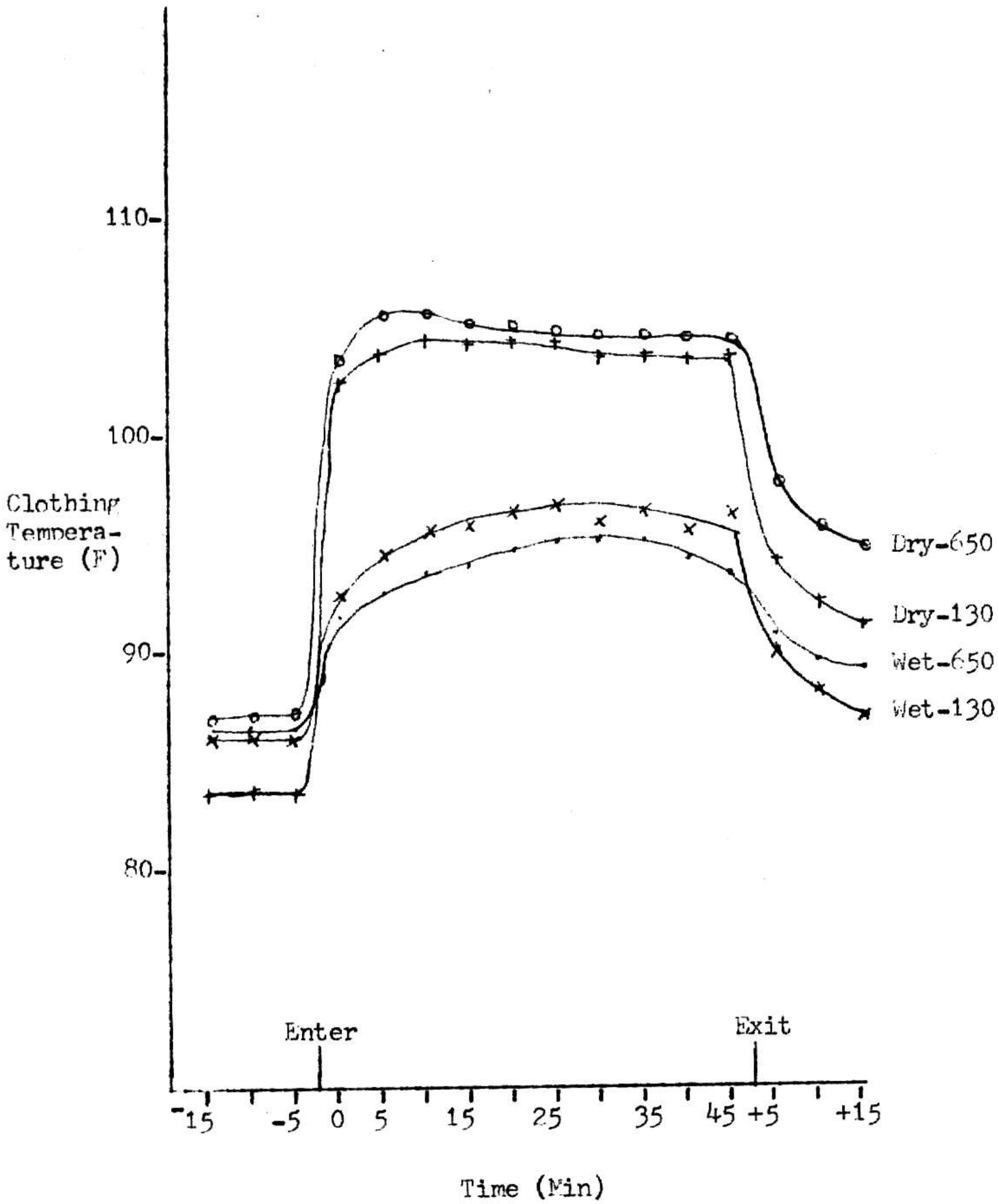

Figure 8. Mean clothing temperature of all subjects by condition and velocity.

TABLE 8

Clothing Temperatures, Degrees Farenheit, by Subject and Condition

	Wet Subjects					Dry Subjects				
Velocity = 650 ft./min.	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Mean pretest temperature	83.4	86.3	89.0	85.4	86.2	84.6	86.0	86.6	91.0	87.0
Mean exposure temperature	93.0	93.8	96.4	93.4	94.1	106.9	103.4	103.0	106.6	105.0
Mean increment	7.6	7.5	7.4	8.0	7.9	22.3	17.4	16.4	15.6	18.0
Velocity = 130 ft./min.										
Mean pretest temperature		87.0	85.5		86.2		83.6	83.9		83.7
Mean exposure temperature		95.3	95.8		95.5		103.8	104.1		104.0
Increment		8.3	10.3		9.3		20.2	20.2		20.3

TABLE 9

Ending Skin and Clothing Temperatures During Exposure, Degrees Farenheit, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Last chest temperature										
Skin	96.6	94.1	95.8	94.8	95.3	98.5	98.9	99.8	100.3	99.4
Clothing	91.0	92.5	93.4	90.8	91.9	104.7	102.3	101.9	106.3	103.8
Last arm temperature										
Skin	93.1	91.4	91.2	92.4	92.0	100.2	99.0	101.0	100.6	100.2
Clothing	94.0	96.9	95.8	95.9	95.7	106.5	104.8	103.5	109.1	106.0
Last thigh temperature										
Skin	89.3	88.5	89.0	91.6	89.6	97.4	99.1	98.8	99.8	98.8
Clothing	93.6	90.1	96.0	94.3	93.5	106.2	101.8	102.0	104.3	103.6
Last calf temperature - skin	94.1	95.8	98.5	100.4	97.2	99.6	100.9	100.2	101.5	100.6
Velocity = 130 ft./min.										
Last chest temperature										
Skin		98.1	93.4		95.7		98.5	97.7		98.1
Clothing		95.6	97.2		96.4		102.9	104.1		103.5
Last arm temperature										
Skin		93.5	93.4		93.5		98.4	98.4		98.4
Clothing		98.8	97.8		98.3		105.6	102.7		104.1
Last thigh temperature										
Skin		90.9	92.0		91.4		98.8	99.7		99.2
Clothing		92.5	96.4		94.4		101.0	105.6		103.3
Last calf temperature - skin		93.3	97.5		95.4		100.0	101.0		100.5

TABLE 10

Heat Storage, Kcal./0.75 Hour, by Subject and Condition

	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Velocity = 650 ft./min.										
Body weight, kg.	61.7	77.8	82.8	86.2	77.1	61.7	77.8	82.8	86.2	77.1
Mean ΔT_r, C°[1]	-0.09	-0.05	0.34	0.14	0.09	0.06	-0.03	0.22	0.31	0.14
Mean ΔT_s, C°[2]	0.75	0.39	0.70	2.26	0.99	3.81	4.29	4.37	4.11	4.13
Mean storage[3] Kcal./0.75 hr.	9.9	7.5	31.3	60.6	27.3	63.8	91.3	104.7	112.4	94.3
Velocity = 130 ft./min.										
ΔT_r, C°[1]		-0.06	-0.33		-0.19		0.06	-0.11		-0.02
ΔT_s, C°[2]		1.17	1.00		1.06		4.78	4.07		4.40
Storage[3] Kcal./0.75 hour		22.6	7.6		14.6		104.5	87.2		95.9

[1]Converted from Table 3.

[2]Converted from Table 4.

[3]S = Weight x C ($0.67\ \Delta T_r + 0.33\ \Delta T_s$); where C = 0.83 Kcal./kg. C°

than in the wet. In the high velocity tests, the wet subjects' average storage was 27.3 kilocalories per 0.75 hour while the dry subjects stored an average of 94.2 kilocalories per 0.75 hour. In the low velocity tests, the wet subjects stored an average of 14.6 kilocalories per 0.75 hour, and the dry subjects stored an average of 95.9 kilocalories per 0.75 hour. It is felt that a change in experimental procedure caused the inconsistency in the heat storage for the wet subjects in the two air velocities. One would logically expect that the subjects in the lower air velocity would store more heat. In the lower velocity tests, the wet subjects were weighed in their wet clothes just prior to entering the chamber. The subjects in the high velocity tests were not weighed at that point in the sequence. It is felt that in the thirty or forty seconds it took to weigh the subjects in the pretest room, they experienced negative heat storage to such a degree as to bias the results.

Prediction of Evaporation

By using the equation (5), one can calculate the amount of evaporation that should have taken place from each of the subjects. Since Clifford used nude subjects in his studies, some modifications have to be made in order for equation (5) to describe the conditions of this study. First of all, the dry subjects in this study had two different average surface temperatures--skin and clothing. This necessitated dividing equation (5) into two terms--one for skin and one for clothing. It was estimated by using DuBois body area percentages that the clothing covered two-thirds of the subjects' bodies. Secondly, Clifford stated that his subjects were completely wet. Equation (5) was based on 100% wet subjects. To calculate the amount of sweat that evaporated from the dry subjects a percentage of wetness was estimated. The complete equation for the above situation is as follows:

$$E = W\, A_{du}(0.45)\, V^{0.63}\, [A_{cl}(P_{cl} - P_a) + A_s(P_s - P_a)]\, (0.75 \text{ hr.})\, \frac{\text{Kcal.}}{0.75 \text{ hr.}} \qquad (10)$$

where

W = percentage of wetness; W = 100% for wet and 20% for dry when Velocity = 650 ft./min., W = 100% for wet and 50% for dry when Velocity = 130 ft./min.

A_{cl} = percent of total body area covered by clothing

A_s = percent of body area exposed to the environment

P_a = partial vapor of ambient air

P_s = saturated vapor pressure at skin temperature, mm Hg.

P_{cl} = saturated vapor pressure at clothing temperature, mm Hg.

P_s = P_{cl} for wet subjects

Table 11 is a summary of the above calculations for all subjects.

In Table 12, an attempt was made to determine how much water and/or sweat evaporated from the subjects by using estimated metabolic rate and equations (2, 3, and 6). Again by using percentages of total body area of sections of the human body, it was estimated that approximately two-thirds of the subjects' bodies were covered by the test clothing. The remaining one-third of the subjects' bodies was exposed to the

TABLE 11

Evaporation Calculation, Using Equation 10, Kcal./0.75 Hour, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
A_{du}, $m.^2$	1.73	1.95	2.03	2.15	1.96	1.73	1.95	2.03	2.15	1.96
W (0.45) $V^{0.63}$ (1)	19.9	19.9	19.9	19.9	19.9	4.0	4.0	4.0	4.0	4.0
Mean P_{cl}, mm Hg.	39.7	40.4	43.9	40.1	41.0	59.9	54.2	53.5	59.4	56.8
Mean P_s, mm Hg.	39.9	39.1	40.2	42.3	40.4	47.8	48.2	49.3	49.9	48.8
Mean evaporation 0.75 hour	461	529	618	620	567	204	201	209	256	217
Velocity = 130 ft./min.										
W (0.45) $V^{0.63}$ x (0.75 hr.)[1]		7.3	7.3		7.3		3.7	3.7		3.7
P_{cl}, mm Hg.		42.4	42.9		42.7		54.4	55.2		54.8
P_s, mm Hg.		41.4	40.6		41.0		47.3	47.5		47.4
Evaporation 0.75 hour		223	234		228		183	194		188

[1]When Velocity = 650 ft./min., W = 100% for wet subjects and 20% for dry subjects. When Velocity = 130 ft./min., W = 100% for wet subjects and 50% for dry subjects.

TABLE 12

Evaporation Calculation Using Equation (1), Kcal./0.75 Hour, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\bar{X}$	JT	CS	TT	RG	$\bar{X}$
Mean convection to skin	74.9	87.2	81.1	85.7	83.4	49.4	52.9	52.3	52.9	51.8
Mean radiation to skin	17.4	20.6	19.8	20.3	19.5	11.7	12.5	12.2	12.2	12.1
Metabolism	130	146	152	161	147	130	146	152	161	147
Mean convection to clothing	151	157	141	176	156	43.8	73.9	78.9	44.4	60.3
Mean radiation to clothing	34.8	36.8	33.1	41.6	36.6	10.9	17.8	19.8	10.4	14.7
Mean storage	9.7	1.9	31.3	60.6	25.9	63.8	91.0	110.0	113.0	94.3
Mean evaporation	398	445	400	424	417	182	246	206	169	201
Velocity = 130 ft./min.										
Convection to skin		35.7	38.1		36.9		25.4	27.8		26.6
Radiation to skin		18.6	19.6		19.1		13.3	14.7		14.0
Metabolism		146	152		149		146	152		149
Convection to clothing		66.4	67.5		66.9		34.6	32.4		33.5
Radiation to clothing		34.2	34.4		34.3		17.6	17.5		17.5
Storage		24.1	7.6		15.8		105.5	79		92.2
Evaporation		277	304		290		131	165		148

radiation and convection of the environment. If one were to subtract the heat storage for a 0.75 hour period from the summation of convective and radiative rates on the exposed skin, the metabolic rate of the entire body, and the convective and radiative rates on the clothing for the same time period, the evaporative rate should be the result. The recorded skin and clothing temperatures for wet and dry conditions were used for these calculations. The equation for the above would be as follows:

$$0.75\ \text{hr.}[0.33A_{du}10.4\ {}^{*}V^{0.5}(T_a - T_s) + 0.33\ A_{du}\ 0.75\ (0.97)\ 4.96 \times 10^{-8}\ \{(T_{mrt} + 273)^4 - (T_s + 273)^4\} + A_{du}\ M + 0.67\ A_{du}\ 10.4\ {}^{*}V^{0.5} (T_a - T_{cl}) + 0.67\ A_{du}\ 0.75\ (0.97)\ 4.96 \times 10^{-8}\ \{(\overset{**}{T}_{mrt} + 273)^4 - (T_{cl} + 273)^4\}] - S/0.75\ \text{hr.} = E\ \text{Kcal.}/0.75\ \text{hr.} \qquad (11)$$

*   V in m./sec.

** T_{mrt} = 43 C° (110 F°)

In Table 13, a comparison is made of the three methods used here to determine evaporation. At Velocity = 650 ft. minute, the ratios of wet/dry comparisons are close to equivalent (about 2.7) for both measured evaporation and evaporation calculated from equation (10). The method of equation (11) yields a slightly lower evaporation ratio (about 2.0) between wet and dry conditions. The wide divergence of evaporation comparisons in the lower velocity tests is unexplained. It is possible that the attempt to gain accuracy (by weighing the wetted subjects)

TABLE 13

Evaporation Comparisons, Kcal./0.75 Hour, by Subject and Condition

Velocity = 650 ft./min.	Wet Subjects					Dry Subjects				
	JT	CS	TT	RG	$\overline{X}$	JT	CS	TT	RG	X
Mean measured evaporation	696	632	704	740	656[1]	206	244	219	257	230
Mean predicted evaporation from equation (10)	461	529	659	620	567	204	201	209	256	217
Mean predicted evaporation from equation (11)	398	445	400	424	417	182	246	206	169	201
Velocity = 130 ft./min.										
Measured evaporation		656	650		653		152	210		181
Predicted evaporation from equation (10)		223	234		228		183	194		188
Predicted evaporation from equation (11)		277	304		290		131	165		148

[1] Subject JT omitted.

actually resulted in a loss of accuracy.

Subject Evaluation of the Cooling Suit

In Table 14, the results of the subjective evaluation given by each subject immediately following the test sessions are summarized. A sign test verified that the subjects felt cooler in the wet suit than in the dry clothing. It is not implied that all subjects felt comfortable in the wet suit but they did feel cooler than when they were in the dry clothing.

TABLE 14

Subject Evaluation of the Wet Suit

Velocity = 650 ft./min.

Subject	Comparison	Wet	Dry
JT	1	Comfortable	Warm
	2	Comfortable	Warm
CS	1	Comfortable	Warm
	2	Comfortable	-
TT	1	Warm	Very hot
	2	Warm	Warm
RG	1	Warm	Hot
	2	Comfortable	Hot

Velocity = 130 ft./min.

Subject	Comparison	Wet	Dry
CS	1	Comfortable	Hot
TT	1	Warm	Warm

DISCUSSION

As stated in the previous section, the wet suit was successful in maintaining lower skin temperatures and sweat rates. These two points along with the fact that the subjects felt cooler in the wet suit indicate that the evaporative suit concept offers a possible solution to heat stress problems. At present there are still many unanswered questions, however.

In this study, the rather broad approach to the problem seemingly did not allow changes in some of the more delicate parameters to become significant. One would expect heart rate, for instance, to be less with the wet clothing. Perhaps more control over the subject's off-duty time coupled with more vigorous exercise during the exposure would have shown through reduced heart rates the wet suit to be better than dry clothing. A longer exposure may have proven from an internal temperature standpoint that the wet suit was superior.

Perhaps more refined equipment and streamlined experimental procedures would have prevented the unexplainable discrepancies in heat storage and evaporation. An electronic weighing device inside the test chamber which could have provided instantaneous weights would have saved enough time in manual operations to allow additional data to be taken on parameters whose values had to be assumed. For instance data on the temperature of the water entering and leaving the system could have provided information on heat conduction. The mechanics of skin temperature measurement could have been more refined to increase accuracy and save time.

The surface of this subject has just been scratched. Still unanswered are questions on what types of fabrics are best for evaporation, what type of clothing fit and coverage is best, what is the optimum flow rate and water temperature, or even still what are the evaporation and conduction rates attainable? All these questions could be topics for further research.

All in all, it would appear that in the absence of more elaborate cooling equipment, evaporative cooling as defined herein offers an economical, workable means of protecting individuals who must work in hot environments. This type of cooling could easily be applied in many areas. Appendix A outlines the results of an actual test of the suit in a bakery. The concept could also be applied in athletics, firefighting, and steel making to name a few. Since moving through air is inherent in vehicle operation, operators of farm machinery and construction equipment would be in an ideal situation to benefit from evaporative cooling.

SUMMARY

The purpose of this study was to test the feasibility of using continuously wetted clothing and increased air velocity as a means for protecting and cooling industrial workers in environments of 100 F° or higher dry bulb temperatures and relative humidities in the range of 30 - 60%. Two experiments were run in a 43 C° (110 F°) dry bulb and 40% relative humidity environment using four male subjects who worked at a simulated industrial task with and without wet clothing. An effort was made (with some loss of experimental accuracy) to use equipment and materials that are readily available and economically feasible to use in actual industrial situations. (See the Appendix A for the results of an actual industrial test of this method).

The results of this study indicate that heart rate and rectal temperature were not significantly affected by the wet clothing. Skin temperature and body sweat loss were affected, however. Specifically, skin temperatures averaged 5.6 F° lower in the wet clothing than in the identical clothing for a 45 minute exposure. Sweat loss was reduced by 0.5 pound/0.75 hour by the wet clothing over the dry.

It is concluded that evaporation and conduction from the wet clothing provided an alternate path for dissipation of heat from convection and radiation. The human body, therefore, did not receive the full effect of the ambient surroundings and did not need to sweat as much. It would appear then, with more research, that this method of protection may be proved beneficial in industry.

REFERENCES

Aurora, D. D. K. Physiological evaluation of an air cooled shirt utilizing dynamic insulation. Unpublished master's thesis. Kansas State University, Manhattan, Kansas, 1970.

Bazett, H. C. in L. H. Newburgh (Ed.) Physiology of heat regulation. New York, Hafner Publishing Co., 1968.

Belding, H. S. and Hatch, T. F. Index for evaluating heat stress in terms of resulting physiological strains. ASHRAE Journal Section, Heating, Piping, and Air Conditioning, 1955, 27, 129-136.

Burriss, W. L. Study of the thermal processes for man-in-space. Los Angeles: Airesearch Manufacturing Company, NASA Contractor Report, April 1965.

Burton, A. C. Human calorimetry. Journal of Nutrition, 1935, 9, 261-280.

Byrnes, D. F. The effect of heat stress on saliva. Unpublished master's thesis. Kansas State University, Manhattan, Kansas, 1970.

Clifford, J., Kerslake, D., and Waddel, J. The effect of wind speed on maximum evaporative capacity in man. Journal of Physiology, 1959, 147, 253-259.

Crockford, G. W., Hellon, R. F., Humphreys, P. W., and Lind, A. R. An air-ventilated suit for wear in very hot environments. Ergonomics, 1961, 4, (1), 63-72.

DuBois, D. and DuBois, E. F. The measurement of the surface area of man. Archives of Internal Medicine, 1915, 15, 868-881.

DuBois, E. F. Heat loss from the human body. Harvey Lecture Series, 1938, 88-103.

Fanger, P. O. Calculation of thermal comfort: Introduction of a basic comfort equation. ASHRAE Transactions, 1967, 73, Part II, 1-20.

Funk, J. E., Moegling, J. B., Drake, R. M., Hall, J. F., Klemm, F. K., and Buehring, W. Sensible heat transfer in the Gemini and Apollo pressure suits. AMRL-TR-66-173, Aerospace Medical Research Laboratories, Wright-Patterson AFB, Dayton, Ohio, December 1966.

Gagge, A. P., Burton, A. C., Bazett, H. C. A practical system of units for the description of the heat exchange of man with his environment. Science, 1941, 94, 428-430.

Gandhok, G. S. An evaluation of an air-ventilated jacket in a heat stress environment. Unpublished master's thesis. Kansas State University, Manhattan, Kansas, 1970.

Herrington, L. P. The biotechnical problem of the human body as a heat exchanger. Transactions ASME, February 1958, 343-346.

Kerslake, D. Factors concerned in the regulation of sweat production in man. Journal of Physiology, 1955, 127, 280-296.

Leinhard, W. F., Hughes, J. P., and Brassette, T. A. Man cooling by a vortex tube device. Archives of Environmental Health, September 1964, 9, 377-386.

Mitchell, D., and Wyndham, C. H. Comparison of weighting formulas for calculating mean skin temperature. Journal of Applied Physiology, May 1969, 26 (5), 616-622.

Nelson, N., Eichna, L. W., Horvath, S. M., Sheeley, W. B., and Hatch, T. F. Thermal exchanges of man at high temperatures. American Journal of Physiology, 1947, 151, 626-652.

Ramanathan, N. L. A new weighting system for mean surface temperature of the human body. Journal of Applied Physiology, 1964, 19, 531-533.

Sharma, S. Physiological evaluation of an air cooled helmet system. Unpublished master's thesis. Kansas State University, Manhattan, Kansas, 1970.

Veghte, J. G. Efficiency of pressure suit cooling systems in hot environments. USAF: AMRL-TR-65-58, Aerospace Medical Research Laboratories, Wright-Patterson AFB, Ohio, October, 1965.

Webb, P. (Ed.) Bioastronautics data book. Washington: National Aeronautics and Space Administration, NASA AP 3006, 1964.

Webb, P. The physiological effects of cooling. Proceedings of the Symposium on Individual Cooling, Kansas State University, 1969.

Woodcock, A. H. Moisture transfer in textile systems, Parts I and II. Textile Research Journal, 1962, 32, (8 and 9), 628-633, 719-723.

Wortz, E. C. Full pressure suit heat balance studies. Los Angeles: Airesearch Manufacturing Company, Report No. LS-140, January 1965.

APPENDIX A

On December 6, 1970, the evaporative cooling suit was tested on an employee at the Dillon's Bakery in Hutchinson, Kansas. The employee worked in the pan washing area of the bakery. It was his job to place the used pans and trays into a large hot water washer. On the day of the test, the temperature of the room was approximately 90 F°. The employees stated that in the summer, the temperature in the wash room surpassed 100 F°. Although the high humidity in the room was less than ideal for a test of the wet suit, there were other aspects which made it seem worthwhile to conduct the test.

First of all, the employees working around the washer were already utilizing evaporative cooling. They had two floor fans blowing in their general direction, and the washer periodically threw hot water on them. The fans, however, were quite far away from the workers. The employees could have lessened their misery simply by moving the fans much closer to their workplace.

A second encouraging aspect was the interest and willingness to cooperate in such a test shown by the employees and management. It was evident that they were concerned and were interested in finding a solution to the uncomfortable conditions in that part of the bakery.

The experiment was conducted in three sessions. In the first session, the subject simply worked at his job in his normal work clothes. In the second session, he wore the long underwear which was dry. In the third session, the long underwear was wetted by the collar. In all sessions the fans generated a breeze of approximately 200 feet per minute by the work station.

For obvious reasons, oral temperature was taken instead of rectal. The subject simply held a thermister under his tongue with his mouth closed. It was decided that it would be of interest to also record a chest temperature and the temperatures on the inner and outer surface of the wet suit in the same general location. Three thermisters were attached (with tape) within a three-inch circle on the subject's chest and clothing.

The temperatures were measured with a Digitec Model 1515 digital thermometer and air velocity was measured with an Anemostat Anemothern.

The results of this study were encouraging. In the first session the subject experienced a 1.3 F° rise in oral temperature in a 25 minute work session. In the second session, oral temperature rose by 0.5 F° in a 25 minute work session. In the third session, oral temperature rose 0.6 F° in a 25 minute work session. The ending chest temperature in sessions 1, 2, and 3 were 97.2 F°, 95.5 F°, and 92.0 F° respectively. The inside surface of the wet clothing had an ending temperature of 89.8 F° while the inside surface of the same garment dry had an ending temperature of 96.0 F°. The outside surface of the wet garment had an ending temperature of 89.0 F°, and the outside surface of the same garment dry had an ending temperature of 94.2 F°. The chest temperature under the wet clothing ended at 92.0 F° and under dry, it ended at 95.5 F°.

It is felt that the rise in oral temperature was less in the test clothing (wet or dry) simply because the subject was wearing less clothing than his normal work clothes. His body was able to dissipate the metabolic heat easier. This experiment again demonstrated that the wet suit can maintain skin temperatures lower than dry clothing.

As a final note, it quickly became obvious in this test that the collar of the suit must be securely fastened to the clothing. The collar tended to slide whenever the subject bent over. In addition, a collar which prevented water from flowing to the front from the rear section during a bending motion would be beneficial from a balance and uniform flow standpoint.

APPENDIX B

EXPERIMENTAL DATA BY SUBJECT, CONDITION, AND AIR VELOCITY.

Subject JT, Trial 1, Wet Condition, Vel = 650 ft/min

Body weight loss = 1.65 pounds

Total evaporation = 3.80 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	-	-	-	-
-10	91	98.5	91.7	83.1
-5	81	98.5	91.4	83.1
0	102	98.2	92.5	91.1
5	108	98.1	93.6	93.0
10	105	97.3	94.8	93.3
15	108	98.4	95.1	93.9
20	108	98.4	95.7	93.7
25	105	98.5	95.5	94.7
30	102	98.5	94.1	95.3
35	105	98.6	93.8	94.4
40	102	98.7	93.8	92.0
45	99	98.7	93.9	93.7
+5	75	98.5	91.3	84.5
+10	87	98.5	91.1	83.8
+15	75	98.6	91.5	84.1

Subject JT, Trial 2, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.17 pounds

Total evaporation = 0.79 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	96	99.0	92.3	83.8
-10	99	99.0	92.5	83.8
-5	90	99.0	92.5	83.5
0	114	98.6	95.1	105.5
5	112	98.7	98.5	108.6
10	114	98.9	99.2	108.7
15	118	99.0	99.5	108.6
20	114	99.1	99.6	108.5
25	117	99.1	99.7	108.5
30	117	99.2	99.6	108.3
35	117	99.2	99.6	108.2
40	117	99.3	99.5	108.2
45	120	99.3	99.5	108.1
+5	102	99.1	97.2	95.8
+10	99	99.2	96.8	95.2
+15	105	99.2	96.5	95.0

Subject JT, Trial 3, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.16 pounds

Total evaporation = 0.78 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	87	99.1	91.8	85.5
-10	72	99.0	91.9	85.7
-5	81	99.0	92.0	85.0
0	-	-	-	-
5	96	98.9	96.7	105.6
10	102	98.8	98.0	106.2
15	102	98.9	98.4	106.2
20	105	98.9	98.7	106.1
25	102	98.8	98.7	105.7
30	105	98.8	98.8	105.4
35	99	98.8	98.8	104.8
40	102	98.9	98.7	104.4
45	105	98.9	98.5	103.7
+5	96	99.0	96.2	92.3
+10	96	99.1	94.4	89.7
+15	93	99.0	94.0	86.7

Subject JT, Trial 4, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.38 pounds

Total evaporation = 1.50 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	81	98.9	92.1	85.1
-10	87	98.9	92.2	85.2
-5	81	98.8	92.4	86.3
0	102	98.5	92.1	89.4
5	105	98.4	93.4	91.9
10	105	98.2	94.2	91.8
15	99	98.5	93.7	92.5
20	99	98.5	93.7	92.7
25	99	98.6	92.7	93.4
30	105	98.6	92.6	93.9
35	102	98.7	91.8	84.2
40	105	98.4	92.9	92.7
45	105	98.4	92.6	92.2
+5	72	98.8	92.2	88.1
+10	87	98.8	91.4	87.3
+15	81	98.9	89.6	85.4

Subject CS, Trial 1, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.11 pounds

Total evaporation = 0.73 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	-	-	-	-
-10	66	99.0	91.0	85.0
-5	72	99.1	91.3	85.5
0	93	99.0	94.2	99.6
5	99	99.1	98.9	105.5
10	102	99.1	99.3	105.1
15	105	99.1	99.6	104.4
20	105	99.1	99.5	104.1
25	102	99.1	99.5	103.8
30	102	99.2	99.4	103.3
35	105	99.2	99.3	103.3
40	105	99.2	99.3	103.2
45	102	99.3	99.4	102.9
+5	81	99.4	96.3	92.4
+10	84	99.5	95.7	90.7
+15	87	99.5	94.8	89.2

Subject CS, Trial 2, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.69 pounds

Total evaporation = 2.85 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	75	99.6	92.3	87.1
-10	72	99.6	92.5	87.0
-5	72	99.6	92.2	87.6
0	93	99.4	93.0	93.5
5	100	99.4	94.9	92.6
10	100	99.5	95.2	94.4
15	94	99.5	94.4	95.0
20	96	99.4	95.9	96.5
25	99	99.4	96.1	96.5
30	96	99.4	94.8	96.1
35	99	99.4	95.3	93.9
40	96	99.4	94.8	93.4
45	96	99.4	94.2	94.4
+5	81	99.5	92.6	91.7
+10	87	99.5	92.9	92.1
+15	78	99.5	93.2	91.4

Subject CS, Trial 3, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.38 pounds

Total evaporation = 1.97 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	66	99.0	91.5	84.9
-10	69	98.9	91.5	84.9
-5	66	98.7	90.6	85.1
0	-	-	-	-
5	72	98.8	93.1	91.4
10	81	98.8	94.3	92.2
15	87	98.8	94.0	92.4
20	87	98.8	93.4	94.1
25	84	98.7	93.8	94.7
30	87	98.7	93.8	94.3
35	87	98.8	92.3	93.0
40	90	98.8	92.5	92.5
45	87	98.9	90.8	91.3
+5	93	98.9	90.6	87.3
+10	66	98.8	90.8	87.2
+15	63	98.9	90.7	86.2

Subject CS, Trial 4, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.50 pounds

Total evaporation = 1.12 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	96	-	92.2	86.4
-10	78	99.8	92.1	85.3
-5	78	99.8	92.4	88.2
0	99	99.7	95.2	101.1
5	93	99.6	98.5	103.6
10	90	99.5	99.3	103.4
15	99	99.3	99.4	103.1
20	99	99.3	99.3	102.8
25	99	99.2	99.4	102.8
30	96	99.3	99.4	102.8
35	96	99.4	99.4	102.5
40	96	99.4	99.4	102.5
45	96	99.4	99.3	102.8
+5	69	99.2	96.2	93.0
+10	72	99.2	95.4	92.5
+15	69	99.2	94.7	92.1

Subject TT, Trial 1, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.19 pounds

Total evaporation = 0.81 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	93	99.7	92.0	85.8
-10	99	99.6	92.0	85.6
-5	93	99.6	92.2	85.5
0	-	-	-	-
5	102	99.6	95.9	101.9
10	108	99.5	98.5	103.3
15	108	99.5	99.3	102.6
20	114	99.5	99.5	102.1
25	114	99.5	99.6	101.8
30	117	99.5	99.8	101.7
35	111	99.5	99.5	101.9
40	114	99.5	99.2	101.4
45	99	99.5	99.4	101.5
+5	84	99.5	96.9	94.7
+10	96	99.5	93.8	91.1
+15	-	-	-	-

Subject TT, Trial 2, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.75 pounds

Total evaporation = 2.63 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	84	99.5	93.2	88.6
-10	87	99.4	93.3	89.3
-5	90	99.3	93.4	90.3
0	-	-	-	-
5	96	99.2	93.4	95.1
10	102	99.3	93.0	95.9
15	108	99.3	93.6	96.8
20	99	99.5	93.3	95.8
25	105	99.5	93.6	95.5
30	102	99.6	94.2	95.9
35	102	99.7	93.6	97.4
40	99	99.8	93.6	96.8
45	108	99.9	93.9	95.4
+5	90	99.8	93.7	88.4
+10	93	99.8	92.4	88.2
+15	96	99.9	91.3	87.6

Subject TT, Trial 3, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.70 pounds

Total evaporation = 2.73 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	72	99.2	91.7	88.6
-10	78	99.3	91.1	88.5
-5	84	99.2	91.3	88.6
0	-	-	-	-
5	87	99.3	93.1	95.0
10	111	99.4	93.6	95.1
15	99	99.4	93.2	95.7
20	96	99.5	95.1	97.4
25	102	99.7	95.4	98.1
30	102	99.7	93.1	98.7
35	105	99.7	92.6	97.8
40	111	99.8	92.5	96.8
45	114	99.9	93.3	95.0
+5	96	100.0	91.4	90.8
+10	90	99.9	90.1	89.2
+15	87	99.8	88.2	86.2

Subject TT, Trial 4, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.24 pounds

Total evaporation = 0.86 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	81	98.7	92.1	87.2
-10	78	98.8	92.2	88.2
-5	81	98.8	92.5	87.4
0	96	98.8	96.2	103.8
5	102	98.9	99.5	105.1
10	90	98.9	100.2	104.8
15	93	99.0	100.2	104.2
20	102	99.0	100.2	103.9
25	102	99.1	100.1	103.5
30	102	99.3	100.3	103.7
35	108	99.5	100.3	104.0
40	108	99.6	100.4	103.7
45	108	99.7	100.7	103.4
+5	90	99.7	97.9	92.6
+10	96	99.8	96.0	89.2
+15	96	99.8	94.5	88.9

Subject RG, Trial 1, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.58 pounds

Total evaporation = 2.52 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	80	99.1	90.4	83.1
-10	81	99.0	90.1	82.9
-5	84	99.1	90.5	83.0
0	-	-	-	-
5	90	98.2	90.5	90.0
10	96	98.5	93.5	92.2
15	99	98.3	92.7	91.8
20	102	98.5	93.8	93.0
25	102	98.5	94.0	94.4
30	105	98.8	96.0	94.1
35	105	98.9	96.5	95.0
40	102	98.9	94.9	94.5
45	108	98.9	95.1	93.4
+5	84	98.9	92.6	90.3
+10	84	98.8	91.6	89.7
+15	-	-	-	-

Subject RG, Trial 2, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.35 pounds

Total evaporation = 0.97 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	75	99.5	93.1	91.3
-10	81	99.5	93.3	91.5
-5	87	99.4	93.4	91.0
0	-	-	-	-
5	99	99.2	98.9	105.5
10	99	98.8	100.0	105.8
15	102	99.5	100.2	105.4
20	114	99.6	100.4	105.3
25	117	99.7	100.5	105.3
30	114	99.7	100.5	105.4
35	122	99.7	100.4	105.2
40	120	99.8	100.5	105.2
45	114	99.8	100.4	105.1
+5	96	98.8	97.8	96.7
+10	93	99.2	96.8	95.7
+15	93	99.5	96.4	94.9

Subject RG, Trial 3, Dry Condition, Vel = 650 ft/min

Body weight loss = 1.36 pounds

Total evaporation = 0.98 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	-	-	-	-
-10	84	99.0	92.9	90.5
-5	87	99.0	93.1	90.9
0	-	-	-	-
5	102	98.8	99.7	107.8
10	111	99.0	100.7	108.4
15	102	99.3	100.8	108.3
20	102	99.3	100.7	107.9
25	108	99.5	100.9	108.0
30	102	99.6	100.9	108.0
35	105	99.6	100.7	107.7
40	108	99.7	100.8	107.8
45	105	99.8	100.6	107.6
+5	99	99.1	97.8	95.2
+10	93	99.5	95.1	92.2
+15	87	99.6	94.5	88.7

Subject RG, Trial 4, Wet Condition, Vel = 650 ft/min

Body weight loss = 0.53 pounds

Total evaporation = 3.13 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	78	98.9	90.5	88.0
-10	75	98.9	90.9	87.5
-5	75	98.9	91.4	87.6
0	87	98.6	92.6	92.6
5	96	98.8	91.9	92.9
10	87	98.9	92.8	92.9
15	99	99.1	92.8	93.5
20	96	99.2	93.2	94.5
25	92	99.3	93.7	94.9
30	99	99.4	92.7	93.9
35	96	99.5	92.5	93.8
40	96	99.6	93.7	93.9
45	90	99.6	94.2	94.1
+5	81	99.1	95.0	91.4
+10	93	-	92.8	90.0
+15	75	99.1	89.2	88.3

Subject CS, Trial 1, Dry Condition, Vel = 130 ft/min

Body weight loss = 0.92 pounds

Total evaporation = 0.58 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	63	99.1	90.2	83.7
-10	57	99.1	90.2	83.7
-5	72	99.1	90.1	83.4
0	90	99.0	94.9	96.0
5	90	99.0	95.9	104.1
10	93	98.9	97.7	104.6
15	93	99.0	98.3	104.4
20	99	98.9	98.5	104.2
25	93	98.5	98.6	104.1
30	99	99.0	98.7	103.6
35	102	99.1	98.7	103.4
40	96	99.2	98.9	103.1
45	99	99.2	98.8	103.0
+5	81	99.0	95.8	89.4
+10	69	99.1	94.8	89.6
+15	72	99.0	94.0	88.8

Subject CS, Trial 2, Wet Condition, Vel = 130 ft/min

Body weight loss = 0.82 pounds

Total evaporation = 2.50 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	84	99.6	92.1	86.6
-10	84	99.6	92.4	86.8
-5	84	99.7	92.3	87.6
0	93	98.8	97.2	93.1
5	96	98.2	95.1	95.2
10	96	99.3	95.5	95.9
15	99	98.9	94.7	95.4
20	102	99.4	95.3	95.6
25	99	99.5	94.5	96.2
30	99	99.4	94.3	95.5
35	102	99.5	93.8	96.0
40	99	99.5	93.8	95.1
45	96	99.5	94.3	95.3
+5	81	99.3	90.4	88.4
+10	81	99.7	89.3	90.0
+15	81	99.7	88.7	89.6

Subject TT, Trial 1, Wet Condition, Vel = 130 ft/min

Body weight loss = 0.67 pounds

Total evaporation = 2.48 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	87	99.7	92.5	86.4
-10	90	99.6	92.2	85.1
-5	87	99.6	91.8	85.2
0	99	99.0	92.4	92.7
5	99	98.8	93.1	93.6
10	102	99.4	94.5	95.0
15	99	99.3	94.7	96.0
20	99	98.8	94.4	97.2
25	99	98.9	94.5	97.6
30	96	98.9	94.4	96.4
35	93	98.8	95.2	96.4
40	96	98.9	94.4	95.9
45	96	99.0	93.9	97.1
+5	84	99.1	91.0	87.2
+10	84	99.3	89.4	85.6
+15	81	99.3	87.8	83.2

Subject TT, Trial 2, Dry Condition, Vel = 130 ft/min

Body weight loss = 1.22 pounds

Total evaporation = 0.80 pounds

Time	Heart Rate	Rectal Temp.	Skin Temp.	Clothing Temp.
-15	90	100.2	91.5	83.8
-10	87	100.2	91.7	83.9
-5	93	100.2	91.5	83.9
0	99	100.1	97.3	102.6
5	102	100.0	98.9	103.8
10	99	99.9	99.7	104.5
15	102	99.9	99.3	104.4
20	105	99.9	98.8	104.4
25	102	100.0	99.5	104.5
30	108	100.1	99.5	104.0
35	105	100.0	99.6	104.5
40	105	100.0	99.5	104.4
45	108	100.0	99.0	104.3
+5	90	100.1	93.2	89.6
+10	93	100.2	95.9	88.8
+15	93	100.2	92.4	86.9

AN EVAPORATIVE INDIVIDUAL COOLING SUIT

By

STEVEN J VAN HOLE

B.S.I.E., Kansas State University, 1967

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Industrial Engineering

Kansas State University

Manhattan, Kansas

1971

ABSTRACT

The purpose of this study was to test the feasibility of using continuously wetted clothing and increased air velocity as a means for protecting and cooling industrial workers. Two experiments were run in a 43 C° (110 F°) dry bulb and 40% relative humidity environment using four male subjects. The subjects worked for 45 minutes at a simulated industrial task with and without wet clothing. An effort was made (with some loss of experimental accuracy) to use equipment and materials that are readily available and economically feasible to use in actual industrial situations.

Heart rate and rectal temperature were not significantly affected by the wet clothing. Skin temperature and body sweat loss were reduced. Skin temperatures averaged 5.6 F° lower with the wet clothing than with the identical dry clothing. Sweat loss was 0.5 pound less with the wet clothing than with the dry.

Through evaporation and some conduction, the wet clothing was able to dissipate much of the heat gained by convection and radiation from the environment. The subjects, therefore, did not need to sweat as much. It would appear then, with more research, that this method of protection may be proved beneficial in industry.