HEAT TRANSFER FROM THE HUMAN BODY TO A ONE ATMOSPHERE HELIUM ENVIRONMENT

by

NORMAN EUGENE SMITH

B. S., Kansas State University, 1965

A THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

Approved by:

Major Professor

TABLE OF CONTENTS

Page

INTRODUCTION 1

Literature Review 3

THEORETICAL ANALYSIS 4

Energy Balance 4
Metabolism - Heat Production 6
Radiative Heat Transfer 8
Conductive Heat Transfer 9
Heat Storage 10
Evaporative Heat Loss 10
Convective Heat Transfer 12

EXPERIMENTAL METHOD 20

Subject 20
Equipment 21
Pre-Test Preparation 26
Testing Procedure 29
Evaluation of Physical Parameters 31

RESULTS AND DISCUSSION 37

Theoretical Analysis 37
Experimental Analysis 50

RECOMMENDATIONS 60

REFERENCES 62

ACKNOWLEDGEMENTS 65

APPENDIX 66

LIST OF TABLES

Table Page

I. Average Metabolic Rates for Various Activities . . . 6

II. Caloric Value of One Liter of O_2 7

III. Skin Temperature Weighting Factors 32

IV. Composition of Atmosphere Vs. Depth of Dive 39

V. Experimental Comfort Response 51

VI. Summary of Heat Loss Calculations 53

LIST OF FIGURES

Figure Page

1. Inflated Polyethylene Test Cell and Supporting Structure . . 22

2. Subject Seated in Test Configuration, Test Cell Removed . . 24

3. Gasometer, X-Y Recorder, Gas Bottles and Digital Thermometer System . . 25

4. Collapsed Test Cell Showing Extent of Air Evacuation 28

5. Subject in Thermister Harness, Front View 33

6. Subject in Thermister Harness, Back View 34

7. Test Room Floor Showing Location of Subject and Division of Floor for Determination of Shape Factors 35

8. Modified Convection Coefficient vs Pressure T_f = 90F 40

9. Ambient Temperature vs Mean Radiant Temperature 41
Air P = 1 atm, T_s = 90F
Test Point MRT from Page 51. Numeral Indicates Test Number.

10. Ambient Temperature vs Mean Radiant Tempersture 42
Air P = 1 atm, T_s = 92F
Test Point MRT from Page 51. Numeral indicates Test Number.

11. Ambient Temperature vs Mean Radiant Temperature 43
Air P = 1 atm, T_s = 94F
Test Point MRT from Page 51. Numeral indicates Test Number.

12. Ambient Temperature vs Mean Radiant Temperature 44
Air P = 1 atm, T_s = 96F
Test Point MRT from Page 51. Numeral indicates Test Number.

13. Ambient Temperature vs Mean Radiant Temperature 45
Helium = 1 atm, T_s = 90F
Test Point MRT from Page 51. Numeral indicates Test Number.

14. Ambient Temperature vs Mean Radiant Temperature 46
Helium = 1 atm, T_s = 92F
Test Point MRT from Page 51. Numeral indicates Test Number.

15. Ambient Temperature vs Mean Radiant Temperature 47
Helium = 1 atm, T_s = 94F
Test Point MRT from Page 51. Numeral indicates Test Number.

Figures Page

16. Ambient Temperature vs Mean Radiant Temperature 48
Helium = 1 atm, T_s = 96F
Test Point MRT from Page 51. Numeral indicates Test Number.

17. Ambient Temperature vs Mean Radiant Temperature 49
Helium = 20 atm, T_s = 90-96F
Test Point MRT from Page 51. Numeral indicates Test Number.

18. Evaporative Heat Loss vs Skin Temperature 56

NOMENCLATURE

A_b - Total body surface area (DuBois) ft^2

A_c - Convective area, ft^2

A_e - Surface area of the environment, ft^2

A_r - Radiative surface area of the body, ft^2

C - Rate of convective heat transfer, Btu/hr

C_c - Modified coefficient of convective heat transfer, $Btu/hr\text{-}ft^2\text{-}F^{1.25}$

CF - Conversion factor 1.90633 $\frac{Btu}{Kcal}\ \frac{cmHg}{psia}\ \frac{m^2}{ft^2}$

C_p - Specific heat at constant pressure, Btu/lb-F

E - Rate of evaporative heat loss, Btu/hr

F_{nm} - Shape factor from body n to body m

g - Acceleration of gravity, ft/hr^2

Gr - Grashof number

H - Height of an individual, in

h_c - Coefficient of convective heat transfer, $Btu/hr\text{-}ft^2\text{-}F$

h_{fg} - Heat of vaporization, Btu/lb

K - Rate of radiative heat transfer, Btu/hr

k - Thermal conductivity, Btu/hr-ft-F

L - Characteristic geometrical dimension, ft

M - Rate of metabolic heat produced within the body, Btu/hr

m - Mass of the body, lbm

Nu - Nusselt number

Pa - Saturation vapor pressure at ambient temperature, psia

Pr - Prandtl number

Ps - Saturation vapor pressure at skin temperature, psia

R - Rate of radiative heat transfer, Btu/hr

Re - Reynolds number

RH - Relative Humidity, %

S - Rate of heat storage, Btu/hr

Ta - Dry bulb temperature of the ambient fluid, F

T_{MRT} & MRT - Mean radiant temperature, F

T_s - Skin temperature, F

ΔT - Temperature difference between the skin and the ambient fluid, F

dT/dt - Time rate of change of temperature, F/hr

V - Velocity of fluid, ft/hr

VCO_2 - Volume of CO_2 produced, liters/hr

VO_2 - Volume of O_2 consumed, liters/hr

W - Rate of work output, Btu/hr

W - Weight of an individual, lb

W - Fraction

W_f - Subject weight after 1 hour, lb

W_i - Subject initial weight, lb

β - Coefficient of volumetric expansion, F

ε_1 - Emissivity of the human skin

ε_2 - Emissivity of the surroundings

μ - Coefficient of heat transfer by evaporation Btu/ft^2-hr-psia

μ - Viscosity lb/hr-ft

ρ - Density lb/ft^3

σ - Stefan Boltzman constant $0.1713 \cdot 10^{-8}$ Btu/hr-ft^2-R^4

ϕ - Functional relationship between variables

INTRODUCTION

Deep sea diving and the prospect of living and working on the ocean floor (continental shelf) pose several problems not encountered in normal surface living. One of the major problems is that the composition of normal atmospheric air is no longer suitable at the pressures encountered in the deep. The oxygen partial pressure (PO_2) must remain within the limits of 1.0 - 0.17 atmospheres. If it drops lower than this, the symptoms of anoxia become evident and eventually death will result. If the PO_2 becomes considerably higher, oxygen poisoning becomes a problem (1). The nitrogen which makes up practically all of the remaining air becomes narcotic at partial pressures above 29 psi, which for normal air is a compression to a depth of 50 ft (2).

Helium lacks the anesthetic effects of nitrogen. For this reason, the Navy uses Helium - Oxygen mixtures rather than air for its deep diving and such deep sea explorers as Link of Ocean Systems, Costeau of Conshelf and Bond of Sealab all use helium as their diluent gas.

The question now arises; since helium has different physical and thermal properties than nitrogen, how are the basic heat transfer and comfort equations for the human body altered due to the use of helium?

The objectives of this study were (1) to determine environmental conditions which produced subjective comfort in helium at one atmosphere and to determine the heat losses which occur at these conditions for a nude human subject seated at rest and (2) to formulate the appropriate theoretical equations to predict the environmental conditions for thermal balance in helium at twenty atmospheres pressure which corresponds to a depth of 645 ft, i.e. ocean exploration on the continental shelf.

Literature Review

A review of published literature revealed only two publications (3, 4) in which a heat balance study had been done on a human subject in a helium environment. Epperson et al. (3) studied four male subjects at rest and during exercise at atmospheric and reduced pressure while exposed to a helium-oxygen environment, and compared the results with those obtained for the same test in an air environment. A lowering of skin temperature in the helium-oxygen environment as compared to the air environment was reported. The heat loss by convection was greater in the helium-oxygen environment and attempts to explain the difference dealt with forced convection parameters only, and not free convection parameters.

Fox et al. (4) also studied the thermal response of several subjects exposed to an atmosphere of helium-oxygen while resting and during exercise. These studies were concerned mainly with the differences in skin and rectal temperatures of the subjects in the two media as affected by environmental temperature and relative humidity. It was concluded that the skin temperature is lower in $He-O_2$ than in air and that the difference is a linear function of the temperature difference between the skin and gas. It was concluded also that the evaporation of moisture from the body was not significantly different in the two media. There was no interaction between the relative humidity, the thermal properties of the gas media and the evaporative weight loss rate. The attempt to explain differences in convective heat loss also used forced convection parameters only.

THEORETICAL ANALYSIS

Energy Balance

When man is in thermal balance with his environment, his energy input equals his energy output. This is true whether he is lying still, walking slowly or running rapidly. If someone is subjectively "comfortable", they are, or should be, in thermal equilibrium with their environment.

In the zone of thermal equilibrium a person requires no effort on his part to maintain equilibrium, other than the normal physiological mechanisms of vaso-motor regulation and sweating. These mechanisms are continuously in operation to maintain the body at the desired temperature. If the body starts to cool the blood vessels adjacent to the skin constrict, reducing the flow of blood to the extremities and outer skin layers and in this way restrict the heat flow to the outer surfaces. This is the mechanism of vaso-motor regulation against cold. If the body becomes over-heated, the blood vessels near the body surface dilate in an attempt to lose heat more rapidly. This is the mechanism of vaso-motor regulation against heat. A point is reached in the heating or cooling process when the normal vaso-motor mechanisms are not capable of maintaining the body temperature. When this occurs during cooling, the mechanism of shivering is employed by the body to generate energy internally and thus offset the high heat loss at the body surface. When the body begins to overheat, the sweat glands put additional moisture on the body surface. This moisture evaporates taking the necessary heat of vaporization from the body and cooling the body in the process. This high sweat rate may be called "sensible sweating" to distinguish it from the low moisture loss rate which is occurring continuously. Once the entire body surface area is covered with moisture, a maximum evaporative heat loss will occur. If this heat loss is not enough to compensate for the heat gained and/or produced, the body temperature will rise.

Since shivering is actually muscular work which requires internal energy, it will be considered outside the category of continuous normal physiological processes. This places the zone of thermal equilibrium between the onset of shivering and point of maximum cooling by evaporation of sweat. The comfort zone must lie between these points, depending upon the individual. For general purposes, maximum subjective comfort for a sedentary individual will occur between a point just above the onset of shivering and a point just below the onset of visible sweating.

The zone of thermal equilibrium and the zone of subjective comfort within it occur when the energy gained or produced equals the energy lost. The physical mechanisms by which this energy is gained or lost can be represented by a mathematical equation. This report is concerned with the effect of environmental conditions on that equation.

In the following sections, the heat balance equation will be first stated in general terms, and then analyzed term by term, as it applies to the experiment of man in a helium environment.

The general heat loss equation may be stated as:

$$M - W = -E \pm K \pm R \pm C \pm S \qquad |1|$$

where

M = rate of metabolic heat produced within the body, Btu/hour

W = rate of mechanical work output, Btu/hr

E = rate of evaporative heat loss, Btu/hr

K = rate of conductive heat loss, Btu/hr

F = rate of radiation heat loss, Btu/hr

C = rate of convective heat loss or gain, Btu/hr

S = rate of storage of energy in the body, Btu/hr

Metabolism - Heat Production

Energy is produced within the body by the oxidation of foodstuffs. The rate at which the oxidation, and with it production of energy takes place depends to a large extent upon the activity level of the individual. Reference (5) gives typical values for heat production of man for various activities as shown in Table I.

Table I

Average Metabolic Rates
for Various Activities

Activity	Btu/hr, Room Temperature Between 60 F and 90F
Sleeping	280
Lying, relaxed	290
At rest, seated	400
At rest, standing	440
Writing, seated	430
Typing, seated	550
Slow movement about room	600
Slow walking	900
Swimming breat-stroke 1 mph	1620
Wrestling	3100

Many investigators have attempted to measure effectively the rate of production of body heat. DuBois (6) details the many methods used in 1939 the principles of which are still used today.

It was found that the metabolic rate can best be determined by measuring either the O_2 consumed or the CO_2 produced. The first method is the one generally employed.

Once the O_2 consumption is measured, it becomes necessary to evaluate the consumption in terms of units of energy produced.

The caloric value of a liter of oxygen consumed by an individual will depend upon his previous diet. DuBois (6) points out that a person who has fasted a minimum of 12 hours will have a respiratory quotient $\frac{CO_2 \text{ produced (Volume)}}{O_2 \text{ consumed (Volume)}}$ of 0.82.

Table II

Caloric Value of 1 Liter O_2

Substance	Caloric Value 1 Liter O_2, KCal
Carbohydrate	5.047
Fat	4.686
Protein	4.485
For Average Fasting R.Q.	4.8

Therefore, employing the average figure of 4.8 for the caloric value of a liter of O_2 can give results whose error may be as much as 2% but generally less than 1% (6).

Radiative Heat Transfer

The net radiative heat exchange between a human body and its surroundings is given by the following equation:

$$R = \sigma A_r \frac{1}{\frac{1}{\varepsilon_1} + \frac{A_r}{A_e}\left(\frac{1}{\varepsilon_2} - 1\right)} \left(T_s^4 - T_{mrt}^4\right) \qquad |2|$$

where

σ = Stefan-Boltzman constant = 0.1713×10^{-8} Btu/ft^2 hr - R^4

A_r = Radiative surface area of the body, ft^2

A_e = Surface area of the environment, ft^2

ε_1 = Emissivity of the human skin

ε_2 = Emissivity of the surroundings

T_s = Average skin temperature, R

T_{mrt} = Mean radiant temperature, R

However when the surface area of the environment is large compared to the area of the person the equation reduces to:

$$R = \sigma A_r \varepsilon_1 \left(T_s^4 - T_{mrt}^4\right) \qquad |3|$$

The radiative surface area, A_r, is that portion of the total surface area which is seen by the surroundings. When a person is in a sitting position, some areas of his skin will be blocked from "seeing" the surroudnings by other areas of the skin and only a part of the total body surface area will be contributing to the radiative heat exchange.

An equation for determing the total body surface area of an individual based upon his height and weight was developed by DuBois and DuBois (7).

A_b = $(0.108)\ (W)^{0.425}\ (H)^{0.725}$

A_b = Total body surface area, ft^2

W = Weight of an individual, lb

H = Height of an individual, in

For the normal seated position, Nielsen and Pedersen (8) found the effective radiation area to be approximately 60% of the DuBois surface area.

Hardy and Muschenchin (9) have shown that the emissivity of human skin approaches that of a black body. Since the surroundings usually radiate in the infrared region a value of $\varepsilon = 0.94$ for the emissivity of human skin can be used.

Conductive Heat Transfer, K

Thermal conduction is considered as a transportation of heat energy due to microscopic motion, such as molecular motion in gases or solids, whereas heat transmission connected with macroscopic motion such as the ordinary flow of a fluid belongs to thermal convection (10).

For the purposes of this paper, conductive heat transfer was considered to be that associated with the exchange of heat between two intimately touching solid objects.

Conductive heat loss from a human's body would then occur when a portion of the body surface area was in contact with a cooled or heated solid surface. A person seated in a form fitting couch would have a relatively large conductive heat loss. The minimum conductive loss would probably occur during swimming or sky-diving when the body touches no solid surfaces.

When a person is seated in a chair, especially one with webbing only a small area in proportion to the total body surface area is in contact with the chair. For such a small area, Jenssen (11) states that the conductive coefficient is probably not too different from the combined convective and radiative coefficients.

Therefore, the conductive heat loss can be considered negligible and the term set equal to zero in the comfort equation.

Heat Storage, S

The storage term, "S", may be plus or minus as the temperature of the tissues of the body rise or fall. To find the amount of heat gained or lost the equation $S = m C_p \frac{dT}{dt}$ would be employed. m, the mass of the human body, is determined by weighing the subject. C_p, the specific heat of the human body tissues is usually taken to be 0.83 Btu/lbs F (12) (13).

The average temperature of the human body tissues has been given as

$T_{avg} = 0.65\ T_{rectal} + 0.35\ T_{skin}$ by Burton (14).

Another formula, only slightly different, was given as

$T_{avg} = 0.8\ T_r + 0.2\ T_s$ by DuBois (6).

Winslow and Herrington (15) compared the two equations and state that for the ambient temperature range 77-93.5 F, the DuBois formula is better but for the lower ambient temperature, the Burton formula is better.

With a little reflection, it can be seen that the storage term could be positive or negative for a short period of time and the human body remain in the comfort zone. However, for longer periods of time, if the body continues to lose or gain heat, it will leave the zone of thermal equilibrium and the comfort equation will no longer be applicable.

Since equation $|1|$ is to be used in cases where thermal equilibrium is to be maintained the storage term S will be set equal to zero.

Evaporative Heat Loss, E

The loss of heat by evaporation of moisture from the surfaces of the skin and lungs is one of the easiest terms in the heat balance to determine, yet the most difficult to describe analytically.

By examining experimental data Gagge (16) introduced the following equation for calculating the heat loss due to evaporation.

$$E = (W\mu)\ A_b\ (P_s - RH \times P_a)CF \qquad |4|$$

where

W = Fraction of body area completely wet

μ = Coefficient of heat transfer by evaporation, containing the constants for evaporization, air motion and direction Btu/ft^2-hr-psia vapor pressure

A_b = Total body area (DuBois formula), ft^2

P_s = Saturation vapor pressure at skin temperature, psia

RH = Relative humidity, %

P_a = Saturation vapor pressure at ambient temperature, psia

CF = Conversion factor, (1.90633) $\frac{Btu}{KCal}\ \frac{cm\ Hg}{psia}\ \frac{m^2}{ft^2}$

Gagge points out that the $(W\mu)$ term cannot be separated into its components. Winslow and Herrington (15) clarify this by saying that this index concerns the physiological reaction of the body governing the rate of sweat secretion and not merely what area of the body is covered with sweat.

Gagge found there is a maximum value for $(W\mu)$ of 29.9 $K_{cal/cmHg} - m^2$ for the total moist surfaces of the body, beyond which the evaporative heat loss does not increase. As can be seen by examining the above equation, the maximum evaporative heat loss, when $(W\mu)$ is maximum, will depend upon the skin temperature, air temperature, and relative humidity for low air velocity.

Gagge also found that $(W\mu)$ does not go to zero, but remains at approximately 12-15% of $(W\mu)$ maximum regardless of how cold the skin becomes. A value of $(W\mu) = 4.7$ KCal/cmHg-m^2 can be used to represent the minimum value. The resulting minimum evaporative heat loss is due to the evaporation of water which diffuses through the epidermis from the deeper layers of skin and the evaporation of moisture from the moist surfaces of the respiratory system. Since vapor pressure is the driving force for this minimum evaporative cooling, it will be independent of the total ambient pressure, and of the gas surrounding the skin.

Convective Heat Transfer, C

Heat transfer by convection between a solid boundary (skin) and a fluid, liquid or gas, is evaluated by means of the equation:

$$C = A_c\, h_c\, (T_s - T_a) \qquad |5|$$

where

C = rate of convective heat loss, Btu/hr

A_c = convective area, ft^2 = A_b

T_s = average skin temperature, F

T_a = dry bulb temperature of ambient fluid, F

h_c = average convective heat transfer coefficient, Btu/hr ft^2 F

The convection equation in this form seems quite simple. The simplicity is misleading, however, due to the difficulty in evaluating h_c. The convective heat transfer coefficient is actually a complicated function of the thermal properties of the fluid, the geometry of the system and the fluid flow. This coefficient may be expressed as a function of the following parameters:

$$h_c = f(L, \mu, \rho, k, C_p, \Delta T, \beta, g, V)$$

where

L = characteristic geometrical dimension, ft

μ = viscosity of the fluid, lb/hr-ft

ρ = density of the fluid, lb/ft^3

k = thermal conductivity of the fluid, Btu/hr-ft-F

C_p = specific heat at constant pressure of the fluid, Btu/lb-F

ΔT = temperature difference between body surface and ambient fluid, F

β = coefficient of volumetric expansion, F

V = velocity of fluid, ft/hr

g = acceleration due to gravity, ft/hr^2

In order to facilitate handling of so many properties of systems, scientists through the years have developed sets of dimensionless relationships. One such combination called the Nusselt modulus or Nusselt number, Nu, combines the convective heat transfer coefficient h_c, the significant dimension L, and the thermal conductivity of the fluid, K.

$$Nu = h_c \frac{L}{k} \qquad |6|$$

Other dimensionless groups with wich the paper will be concerned are:

$$\text{Prandtl number (Pr)} = \frac{C_p \mu}{k}$$

$$\text{Grashof number (Gr)} = \frac{p^2 g L^3 (\Delta T)}{\mu^2}$$

$$\text{Reynolds number (Re)} = \frac{L\, V\rho}{\mu}$$

The complicated geometrical shape of the human body makes it extremely difficult, if not impossible, to determine the value of the convective heat transfer coefficient accurately. Some attempts have been made (17), however the results are valid only in special cases and even then are not conclusive.

The next step is to approximate the human body by a simple geometrical shape, for which correlation groupings of the appropriate dimensionless groups and the resulting equations exist. The two shapes considered were spheres and cylinders with cylinders generally being used.

Before the actual equation is written, the type of fluid flow should be considered.

Convection heat transfer can be divided into two types; forced convection and free or natural convection, depending upon the velocity of the fluid.

Forced Convection

Forced convection is usually considered to be that which occurs when the velocity of the fluid is great enough to have an effect upon the heat transfer process. A person outdoors on a windy day would lose heat by the process of forced convection. McNall and Sutton (18) suggest that for air velocities of 50 ft/min or greater, an equation for forced convection should be used.

Assuming that the fluid flows in a horizontal direction normal to the cylinder, McAdams (19) suggests an equation of the type

$$Nu = \phi (Re)^n (Pr)^m \qquad |7|$$

where

ϕ = denotes a functional relationship and n and m are constants.

Free Convection

Free convection heat transfer occurs whenever a body is placed in a fluid at a higher or lower temperature than that of the body. As a result of the temperature difference heat flows between the fluid and the body causing a change in the density of the fluid layers in the vicinity of the surface. The difference in density leads to a downward flow of the heavier fluid and an upward flow of the lighter fluid. If the motion of the fluid is caused solely by differences in density resulting from temperature gradients, without the aid of a pump or fan, the associated heat transfer mechanism is called natural or free convection. Free convection currents transfer internal energy stored in the fluid in essentially the same manner as forced convection currents. However, the intensity of the mixing motion is generally less in free convection, and consequently the heat transfer coefficients are lower than in forced convection (20).

In many practical situations, man is seated and relatively motionless while at work. In such cases, free convection equations usually will be applicable.

For free convection heat transfer McAdams (19) suggests an equation of the form:

$Nu = \phi(Gr\ Pr)^{0.25}$, which for a vertical cylinder becomes

$$Nu = 0.59\ (Gr\ Pr)^{0.25} \qquad |8|$$

When the buoyancy is the only driving force the fluid velocity is determined entirely by the quantities contained in the Grashof number. Therefore, the Reynolds number is superfluous for free convection and is dropped from the equation.

For a horizontal cylinder McAdams (19) recommends $Nu = 0.53 (Gr\ Pr)^{0.25}$. When an individual is lying flat or standing upright, the choice is obvious. However, for the seated person the choice is more complicated since the thighs, feet, hands and arms are nearly horizontal while the rest of the body can be considered vertical. Since the horizontal surface area would be approximately 45% of the total surface area the equation, $Nu = \{(0.45)(0.53) + (0.55)(0.59)\} (Gr\ Pr)^{0.25}$ resulting in $Nu = 0.56 (Gr\ Pr)^{0.25}$. This is very close to the value of $Nu = 0.555 (Gr\ Pr)^{0.25}$ suggested by Kreith (20) for vertical cylinders when the Grashof number is less than 10^8 as it is in experiments involving the human body in thermal equilibrium.

The convection heat transfer equation now reads:

$$C = A_b\, h_c\, \Delta T \qquad |9|$$

where

$$h_c = \frac{k}{L}\ (\phi)\ \frac{(L^3\ g\ \beta\ \rho^2\ \Delta T\ Pr)}{\mu^2}^{0.25} \qquad |10|$$

by defining

$$C_c = \frac{h_c}{\Delta T^{0.25}} \qquad \text{Therefore, } C = A_b\ C_c\ (\Delta T)^{1.25} \qquad |11|$$

The (ΔT) term has been removed from the convection coefficient and a more general form has been achieved, namely

$$C_c = \frac{k}{L^{0.25}}\ (\phi)\ \frac{(g\ \beta\ \rho^2\ Pr)}{\mu^2}^{0.25} \qquad |12|$$

The terms in C_c which are temperature dependent are evaluated at film temperature T_f which is the average of the temperature of the skin and the temperature of the ambient fluid. Those terms in C_c which are independent of the fluid considered are:

L = unknown, ft

ϕ = unknown, dimensionless

g = 4.17×10^8, ft/hr^2

β = $1/T_f$, 1/R

For air all properties were obtained from reference (21).

For helium

Pr = 0.6871 and is a constant for the temperatures and pressures considered (22).

In the following relationships for ρ, μ, and k as function of temperature and pressure, T = temperature in degrees R, and P = pressure in psia.

$$\rho = \frac{P}{2.6829\, T_f + P\ \beta^{0.25}\,(0.3059 - 1.824\, \beta^{0.5} - 0.822\beta)} \quad \text{lb/ft}^3 \ (23)$$

$$\mu = 8.315\, (T_f)^{0.647}\, 10^{-4} \text{ lb/hr ft } (24)$$

$$= 0.0792 + 0.962\, 10^{-4}\, (T_f - 459.59) + 10\, 10^{-5} \left(\frac{P}{14.696} - 1\right) \ (23)$$

This leaves only ϕ and L to be defined. Since they cannot be specifically determined, the combination $\frac{\phi}{L^{0.25}}$ needs to be found.

Nielsen and Pedersen (8) found by experimentation a value for C_c for the human body in a seated position. The experiments were run with an air velocity less than 20 ft/min; therefore, the equation for free convection heat transfer would apply. The value they found for C_c in metric units is $2.03 \frac{k_{cal}}{m^2 hr\ C^{1.25}}$. When this is converted to English units it becomes $0.359 \frac{\text{Btu}}{\text{ft}^2 \text{ hr F}^{1.25}}$.

By setting this equal to equation |12| for C_c with the values for the thermal properties of helium at 90F and one atmosphere C_c He = 0.754.

Final Heat Balance Equation

Substituting equations |4| |11| and |3| for their respective symbols into equation |1| , the following relationship is obtained.

$$M = (W\mu)A_b (P_s - RH\ P_a)\ CF \pm A_b C_c (T_s - T_a)^{1.25} \pm \sigma A_r \varepsilon_1 (T_s{}^4 - T_{mrt}{}^4) \quad |13|$$

where

$(W\mu)$ = Constant representing the fraction of body area completely wet and containing the constant for evaporation. $(W\mu)$ minimum = 4.7 KCal/cmHgm^2

A_b = Total body surface area, ft^2

P_s = Saturation vapor pressure at skin temperature, psia

RH = Relative humidity, %

P_a = Saturation vapor pressure at ambient temperature, psia

CF = Conversion factor, (1.90633) $\frac{\text{Btu cmHgm}^2}{\text{KCal psia ft}^2}$

C_c = Modified coefficient of convective heat transfer Btu/ft^{2}hr F$^{1.25}$

T_s = Skin temperature

T_a = Dry bulb temperature of the ambient gas, F

σ = Stefan-Boltzman constant 0.1713×10^{-8} Btu/ft^{2}hr R^4

A_r = Radiative surface area of the body, ft^2

ε_1 = Emissivity of the human skin, 0.94

T_{mrt} = Mean radiant temperature, R

One purpose for deriving equation |13| is to be able to predict the environmental conditions for thermal equilibrium and hopefully comfort. It should be noted that equation |13| applies only when the person is sedentary or near sedentary and free convection terms are applicable. In deep diving expeditions, it is assumed the occupants will be relatively inactive while in the diving capsule and will save their energy for their work in the water.

In order to apply equation |13| an average value for skin temperature must be assumed. Although man may be in thermal equilibrium over a range of skin temperatures, 91-93 F was found to be optimum (24). Once a skin temperature has been chosen, the heat balance equation can be solved to determine the environmental dry bulb temperature necessary to produce thermal comfort for a given mean radiant temperature.

EXPERIMENTAL METHOD

Six tests were conducted involving a seated subject exposed to a helium environment contained in a polyethylene test cell using the equipment and techniques described in the body of this report. In addition, a test was conducted in the test cell with air as the ambient gas and two tests were conducted in air using the same equipment but outside the polyethylene test cell. The subject recorded his subjective thermal comfort during the tests. Also the parameters necessary to determine the subject's heat balance were measured and calculations according to theory were made.

Subject

The subject was an engineering graduate student 25 years of age in good health and good physical condition.

His build was average with a height of 70.25 inches and a weight of 157 pounds. While the subject would not be classified as a trained subject, he was not naive to environmental and physiological experiments and their procedure.

In order to use the caloric value of oxygen determined for a fasting person (see p. 7), the subject did not eat after 8:00 p.m. of the evening preceding the test. The subject had a minimum of six hours sleep the preceding night and refrained from strenuous activity the evening before and the morning of the test. In the weeks preceding the tests, the subject followed the pre-test fasting procedure on selected days and his metabolic rate was determined for the sedentary sitting position in air at a mean temperature of 74 F. This acquainted the subject with the experimental procedure.

Equipment

The experiment was conducted in the Environmental Test Room of the Environmental Research Institute, Kansas State University. The room is 12 x 24 x 8 feet in its present configuration. The walls, floor and ceiling consist of aluminum panels backed with copper tubing. By controlling the temperature of the liquid flowing through the tubing, the surface temperature of the enclosure can be maintained within ±1 F dry bulb and wet bulb.

A polyethylene bag (Figure 1) 7 x 5.5 x 4.5 feet was constructed by heat sealing "Visqueen", a product of Ethyl Corporation, Baton Rouge, La.

The bag will hereinafter be referred to as the test cell.

At first the test cell was without openings except for a slit approximately 4 feet wide, 1 foot above the floor. This opening allowed the subject to enter the test cell.

Since the dew-point of the gas in the test cell was to be controlled by maintaining the floor of the test cell at a low temperature, it was necessary that the floor temperature be uniform and that good heat transfer exist between the test room floor and test cell floor. With the polyethylene bottom taped to the test room floor, this could not be done. A 4 x 8 ft sheet of 1/8 inch Alcoa Aluminum was then placed on the test room floor, the bottom cut out of the test cell, and the edges of the test cell taped to the aluminum with polyethylene tape and ducting tape. The aluminum sheet temperature was within ±0.5 F of the test room floor temperature and could be controlled easily.

Figure 1. Inflated Polyethylene Test Cell Supporting Structure

The supporting structure shown in Figure 1 was used to support the test cell between tests and during the inflation process. The test cell remained attached to the structure during the actual test although it was probably not necessary due to the buoyancy of the helium. A Fairbanks-Morse beam balance scale, accurate to ±0.01 lbs, was placed inside the test cell and a lawn chair with most of the webbing removed placed upon it and taped in place (see Figure 2).

Twenty-three thermisters, Model 409, manufactured by the Yellow Spring Instrument Company, Yellow Springs, Ohio, were used to monitor skin temperature and the temperature of the test cell. And one YSI Model 410 thermister was used to monitor deep body temperature. Since the thermisters were equipped with only six foot leads, a junction board was built and attached to the scale (see Figure 2). The junction board leads were passed through the umbilical connector to the outside where they were plugged into the read-out device.

A United Systems Corporation, Dayton, Ohio, Series 500 Digitec Thermometer was used to read the thermister temperatures and a Digitec Series 500 Digital Printer was used to simultaneously record the readings (see Figure 3). The accuracy of the thermometer was ±0.15 F.

The calibration of the thermisters was checked by placing them with a mercury thermometer in a water vessel and allowing them to reach equilibrium. The thermister readings checked with each other and the mercury thermometer to within ±0.1 F.

A face mask Model 133-054 adult size obtained from the Puritan Compressed Gas Corporation, Kansas City, Missouri was worn by the

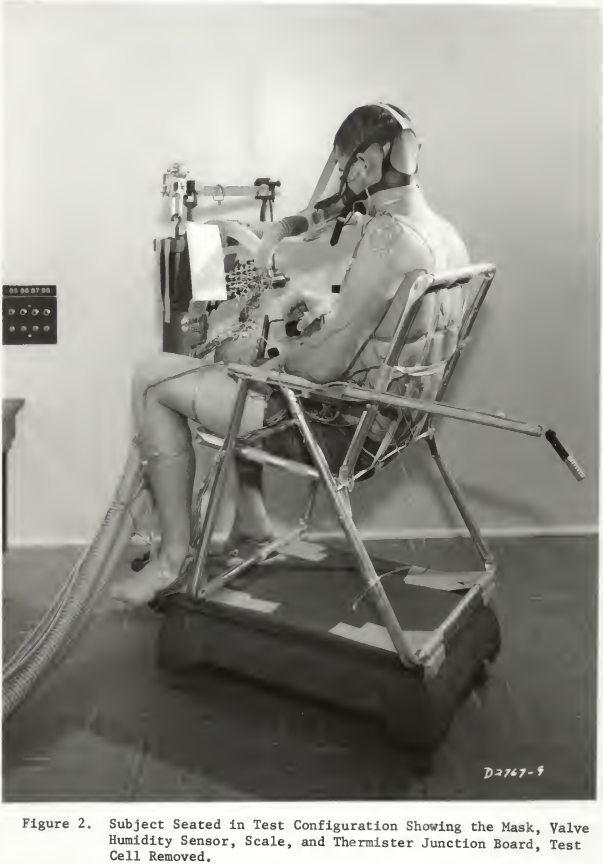

Figure 2. Subject Seated in Test Configuration Showing the Mask, Valve Humidity Sensor, Scale, and Thermister Junction Board, Test Cell Removed.

Figure 3. Gasometer, X-Y Recorder, Gas Bottles and Digital Thermometer System

subject during all test runs (see Figure 2). The inflatable rim allows the straps to pull the mask tight enough to seal, yet not be uncomfortable.

The mask was connected with practically no dead space to a modified Otis-McKerrow two-way intake-exhaust valve (see Figure 2). Each side of the valve was connected to the air outside the bag by a 1½ inch flexible vinyl tube which passed through the umbilical connection.

A chain-compensated 172 liter gasometer manufactured by the Collins Corporation was used to measure oxygen consumption. The level of oxygen in the gasometer tank was transformed to an output voltage which was recorded on an Omnigraph Corporation, Bellaire, Texas, Model HR-95 X-Y Recorder.

Medical oxygen was used in the gasometer while medical helium provided the environment for the experiment. The equipment needed by the subject consisted of the following items: pencil, paper, foam cushions, extra scale weights and relative humidity sensor. The pencil and paper were needed for taking notes and recording data, the foam cushions were placed over sharp portions of the scale while the bag was collapsed and the extra weights were used to keep the subject's weight at a value that could be easily read.

Pre-Test Preparation

The subject entered the pre-test room which was maintained at a temperature between 72-76 F, at least thirty minutes prior to the time for the test. At this time he changed clothes putting on the swimsuit he would wear during the test.

For the first three tests in the series, the thermister harness was taped on while the subject was in the pre-test room. Later, after a few of the thermisters had been moved from the body to locations on the chair and exposed to the gas in order to determine the thermal gradients within the test cell, the thermisters were taped on after the subject was seated in the chair within the test cell. It was found that this required about the same amount of time and eliminated the re-taping of those thermisters which were pulled loose while the subject entered the test cell and was seated in the chair. The rectal probe had been inserted by the subject while dressing.

After the subject was seated and all thermisters checked, the air bubble on the scale was checked to insure that the scale was level, and if not, the scale was leveled. The next step was to put on the breathing mask and to check it for leaks. This was done by the subject by placing a hand on the exhaust port of the valve and blowing. The hoses were then connected to the mask and the assistant left the test cell.

At this point the test cell was unhooked from its support and allowed to collapse around the subject and scale. That section of the test cell containing the opening was flattened against the floor and the opening sealed with polyethylene tape.

After the cushions had been properly placed on the scale to avoid puncturing the test cell, a vacuum cleaner was attached to a tube included in the umbilical for this purpose, and the suction used to draw the air from the test cell. As shown in Figure 4, the test cell, after the vacuum cleaner was turned off, was very tight around the subject. Helium was then leaked into the test cell at a slow rate

Figure 4. Polyethylene Test Cell Collapsed Showing the Degree of Evacuation of Air From the Test Cell

until the test cell had moved several inches from the subject. The vacuum cleaner was turned on again and the test cell evacuated for a second time. The vacuum cleaner was turned off and the helium flow started once again. The helium remained flowing continuously at various rates until the end of the test.

This evacuation process and the fact that a constant positive pressure was maintained inside the test cell were the bases for the assumption that the environment was for practical purposes 100% helium.

The test cell was then slowly filled with helium; this required approximately 15-20 minutes.

Testing Procedure

The actual test procedure began as the test cell was filling slowly to its inflated configuration, (see Figure 1). During this time, the subject's weight was taken and an initial relative humidity and temperature check made by the subject. The assistant monitoring the skin thermister read-out and printer noted the various skin temperatures and compared them with the previous tests. If any were found to be approximately 2 degrees F high or low, a check was made to see if the sensors were still in contact with the skin, between the skin and chair or not in the proper location. Then, the skin and gas temperatures were allowed to reach equilibrium.

The test room walls, ceiling, and floor were set at a specified temperature before testing began and remained constant during the test. The temperature of the air in the test room was varied as needed to help control the test cell gas temperature. The only other control used was the rate of helium flow into the test cell. The expansion of the helium proved to be a very good heat sink and was used to control the gas temperature.

Once the gas and skin temperature were stable, the actual test began. The subject's initial weight was determined and the temperature and relative humidity recorded. Temperatures were recorded every ten minutes; subject weight, relative humidity and temperature of the gas were recorded every twenty minutes.

The subject quickly learned that he must assume the same position each time he recorded his weight since the tubes connected to the valve were taped to the scale. The position of the head was very important and was maintained constant by resting the chin on the left hand and sighting across the face mask and valve to the same point each time. Also, it was learned that the scale was so sensitive that all persons in the test room had to refrain from walking during weighing.

Once each test, a metabolic rate was determined by measuring the subject's oxygen consumption. Suffice it to say that the only difference to the subject when the oxygen consumption was being measured was the difference in humidity between the saturated oxygen and the room air usually inhaled by the subject and that the subject refrained from taking any measurements in order to obtain a more regular oxygen consumption curve.

As the wearing of the mask was not a new experience to the subject, its affect on the metabolic rate should have been constant throughout the test series.

After the metabolic rate was determined, the test proceded until a weight loss of at least 0.1 pounds was recorded. This was usually a period of two hours after stabilization.

At the conclusion of the test, the helium was turned off, the tape was removed from the test cell opening, and the vacuum cleaner used to draw air through the test cell. In this way, the helium environment was diluted and the subject could remove the mask before leaving the chair.

Evaluation of Physical Parameters

In order to determine the radiation term of equation |13| , the following parameters were to be evaluated: skin temperature, the mean radiant temperature of the surroundings and the radiation area of the subject.

The subject in the experiment weighed 147 pounds with a height of 70.25 inches. Using the DuBois formula his total body surface area was calculated to be 20.3 square feet. Therefore $A_r = (0.60)(20.32) =$ 12.2 square feet.

Since all parts of the human body are not the same temperature, it is necessary to calculate an average skin temperature. This was done by measuring the skin temperature at nineteen points after Hardy and DuBois (25), (see Figures 5 and 6). The skin temperatures for the various parts are then weighted according to the following table to give the mean skin temperature. The weighting factor corresponds to the percent of total body area for that part.

The following equation was used to compute the skin temperature.

$$T_s = 0.07\ T_1 + 0.14\ T_2 + 0.05\ T_3 + 0.07\ T_4 + 0.13\ T_5 + 0.19\ T_6 + 0.35\ T_7 \quad |14|$$

Table III

Skin Temperature Weighting Factors

Part of the body	Temperature	Weighting Factor
Head	T_1	0.07
Arms	T_2	0.14
Hands	T_3	0.05
Feet	T_4	0.07
Legs	T_5	0.13
Thighs	T_6	0.19
Trunk	T_7	0.35
	Total	1.00

An equation for mean radiant temperature is given by Raber and Hutchinson (26) as

$$T_{mrt} = F_{12} T_2 + F_{13} T_3 + \cdots F_n T_n \qquad |15|$$

where

F_{1n} = the shape factor from body one, in this case the seated person , to body n

T_n = Temperature of body n, F

This equation for the evaluation of T_{mrt} is valid when the surfacing materials have an emissivity in excess of 0.90.

Since the floor was maintained sometimes at a lower temperature than the walls and ceiling, it was necessary to evaluate the shape factor from the seated test subject to the floor. This was done using the method of Tripp (27). The man's radiative surface area was represented by a cylinder 4 feet high with a radius of 0.465 feet. This cylinder placed in the location shown by Figure 7 approximates the location of the test

Figure 5. Subject in Thermister Harness, Front View

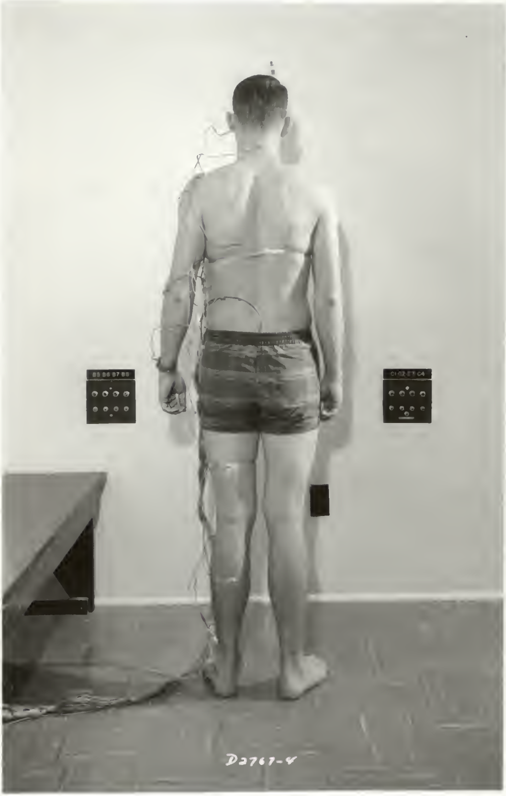

Figure 6. Subject in Thermister Harness, Back View

subject (4 feet from the west wall and 8 feet from the south wall).

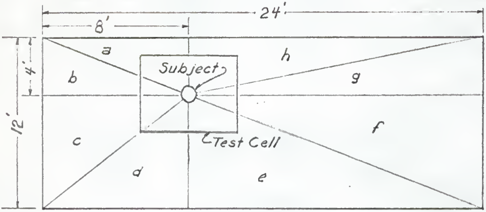

Figure 7. Test Room Floor Showing Location of Subject and Division of Floor for Determination of shape factors.

In order to use the graphs provided by Tripp, the test room floor was divided into the eight sections as shown in Figure 7. The shape factor was then found from the right circular cylinder to each of the right triangles. The summation of these shape factors yielded a shape factor from the man to the floor of $F_{man-floor} = 0.33$. The shape factor from the man to the walls and ceiling then equals 0.67.

The walls of the environmental test room are covered with at least five coats of light green enamel (glossy) the emissivity of which is approximately equal to 0.95. The floor is covered with a vinyl carpet for which the emissivity is also assumed to be 0.95 (28).

A spectral analysis of the polyethylene used in the construction of the test cell was done by Mr. H. T. Leventhal (29). This analysis showed the test cell to have a transmittance of 0.84 in the infrared range. The film was, therefore, considered to be "transparent" for purposes of radiation heat transfer.

A_e = 1152 square feet for the test room (12 x 24 x 8 feet), therefore the term $\frac{1}{\frac{1}{\varepsilon_1} + A_r\,(\frac{1}{\varepsilon_2} - 1)}$ becomes $\frac{1}{\frac{1}{\varepsilon_1} + \frac{12.2}{1152}\,(0.05)} = \frac{1}{\frac{1}{\varepsilon_1} + 0.0005} \approx \varepsilon_1$

(within the accuracy of this report) and

$$R = \sigma A_r \varepsilon_1 (T_s^4 - T_{mrt}^4).$$

Due to the low floor temperature and low air circulation, a thermal gradient existed in the ambient gas. The gas temperature was measured with skin thermisters attached to the chair and exposed to the atmosphere; also, a thermister was attached to the rod shown extending behind the chair in Figure 2. The arithmetic mean of the measurements was used as T_a. The ΔT over the approximate height of the subject varied from 3.8 to 0.8 F.

In an attempt to simulate the minimum condition of heat transfer by conduction the chair used in the experiment was modified such that only a small area was in contact with any part of it. Therefore, the conductive heat loss K was set equal to zero in the heat balance equation.

The experiment was conducted such that the mean body temperature did not change appreciably and the storage term S was set equal to zero.

RESULTS AND DISCUSSION

Theoretical Analysis

The heat balance equation, |13| p. 18 can be used to describe the experiment of this report by substituting values of A_b = 20.3 square feet and A_r = 12.2 square feet which were calculated for the subject. For each selected value of T_s, a value of T_{mrt} was calculated for all combinations of T_a = 60, 65 ···110 F, RH = 20, 40, 60, 80% and (Wμ) = 4.7 and 29.9 KCal/cm Hg-m^2.

The solutions of equation |13| for air and helium at one atmosphere pressure and for helium at 20 atmospheres pressure with assumed skin temperatures of 90, 92, 94 and 96 F are shown in Figures 9 through 17. These data were generated by an IBM 1410 digital computer. A copy of the Fortran program is included in the appendix.

Since most sedentary people are comfortable when their only perspiration is of the insensible type, a value of (Wμ) Minimum has been chosen to represent the minimum wetted area. This indicates a minimum evaporation rate which is shown by the shaded band of $E_{minimum}$ in Figures 9 through 17 and is therefore called the "comfort zone" for the designated skin temperature. The region below this band is the zone of body cooling, and although a person may "live" at this point, he is compensating for his heat loss by means other than normal vasomotor regulation against cold. The area above the comfort band is the area of evaporative regulation. In this area, the sweat rate is increased and the evaporative cooling which results maintains the body in thermal balance with the environment. If the body demands it, the sweat rate will increase until the body is covered with moisture.

There is a limit, however, to how much moisture the air will hold, and how fast it will take it. This depends upon the difference in the vapor pressure at the skin surface and in the ambient air for the given body surface area. As the ambient temperature decreases and the relative humidity decreases, the air will accept more and more water-vapor. A point is then reached where the air can take no more moisture. E_{max} is then the maximum cooling to be obtained by the evaporation of sweat under those environmental conditions. A higher sweat rate will produce no more body cooling and if this is not sufficient, the body will store heat. As can be seen from any of the Figures (9-17) , if the relative humidity can be maintained at a low value, the zone of evaporative regulation is considerably wider than for a high value of RH.

The effect of helium on the comfort zone is to increase its slope and make it narrower. Increasing pressure has the same effect since equation |11| shows that an increase in C_c increases the influence of each degree F difference between skin temperature and ambient temperature.

By comparing the curves for one atmosphere helium with those for helium at 20 atmospheres, it can be seen that a much higher ambient temperature is needed at twenty atmospheres to offset the same radiant temperature. This is due to the increase in convection heat transfer with pressure as shown in Figure (8) . While convection is increasing, metabolism, radiation and evaporation remain relatively unchanged. It is, therefore, necessary to bring the ambient temperature closer and closer to skin temperature in order to reduce the convective heat loss. Since thin walled oceanographic research vessels will have their wall temperatures governed by the temperature of the water which surrounds them, it will probably become necessary in the larger vessels to construct a radiation shield between the walls and the occupants. When this is done, the T_{mrt} will approximate T_a.

Comparing the $T_a = T_{mrt}$ line on the graphs for one and twenty atmospheres for a skin temperature of 92 F, it is seen that this line crosses the zone of minimal evaporative cooling at 84 F on the one atmosphere chart and 89 F on the chart for twenty atmospheres.

While a one atmosphere 100% helium environment is not a practical environment in which to live, Table IV shows that at a dive depth of 645 feet, the atmosphere for heat transfer purposes is 100% helium.

Table IV

Composition of the Atmosphere vs Depth of Dive

Depth	Pressure		O_2		He	
ft	atm	psia	PO_2 psia	% Vol	P_{He} psia	% Vol
0	1	14.7	3.09	21	11.6	79
32.3	2	29.4	3.09	10.5	26.3	89.5
64.5	3	44.1	3.09	7.0	41.0	93
96.8	4	58.8	3.09	5.25	55.7	94.75
161.5	5	73.5	3.09	4.20	70.4	95.8
290.5	10	147.0	3.09	2.1	143.9	97.9
645	20	294.0	3.09	1.05	290.9	98.95

Figure 8 shows the effect of this dive depth on the modified coefficient of convection.

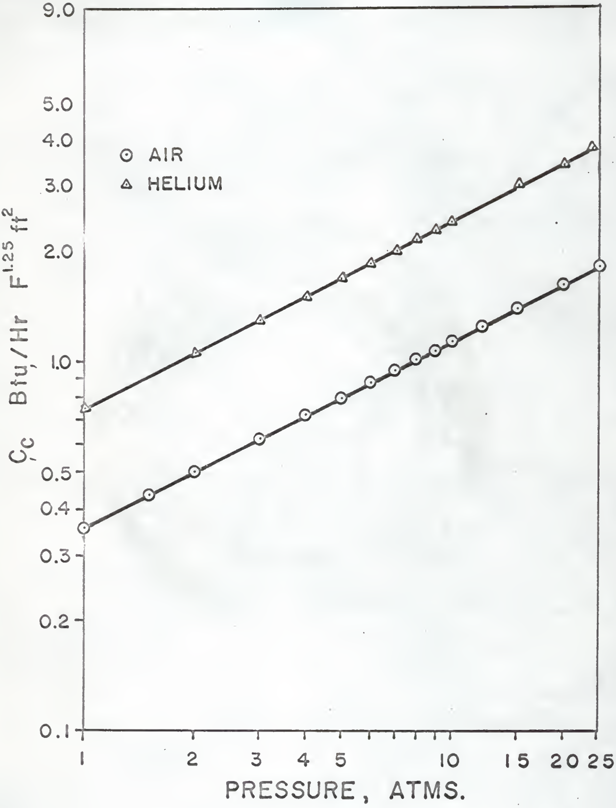

Figure 8. Modified Convection Coefficient vs Pressure T_f = 90F

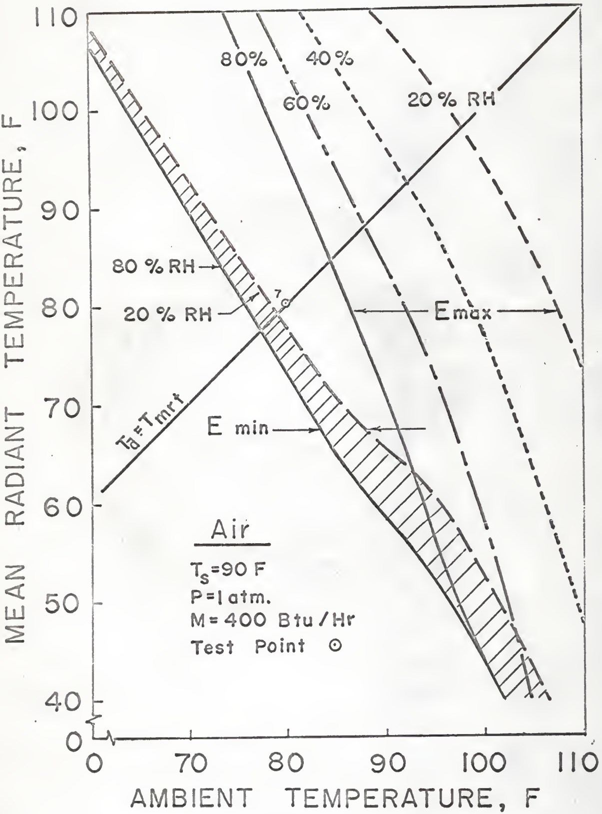

Figure 9. Ambient Temperature vs Mean Radiant Temperature
Air P = 1 atm, T_s = 90F
Test Point MRT from Page 51. Numeral indicates Test Number.

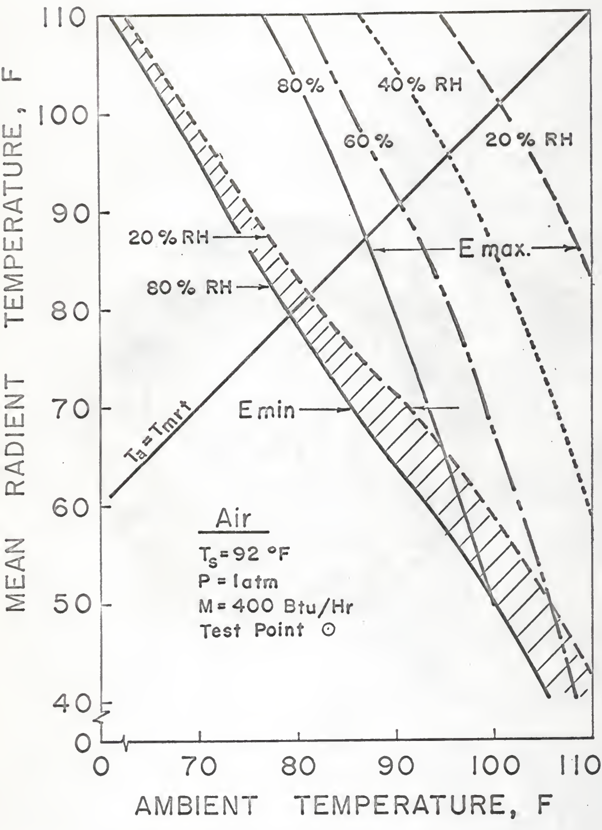

Figure 10. Ambient Temperature vs Mean Radiant Temperature Air P = 1 atm, T_s = 92F Test Point MRT from Page 51. Numeral indicates Test Number.

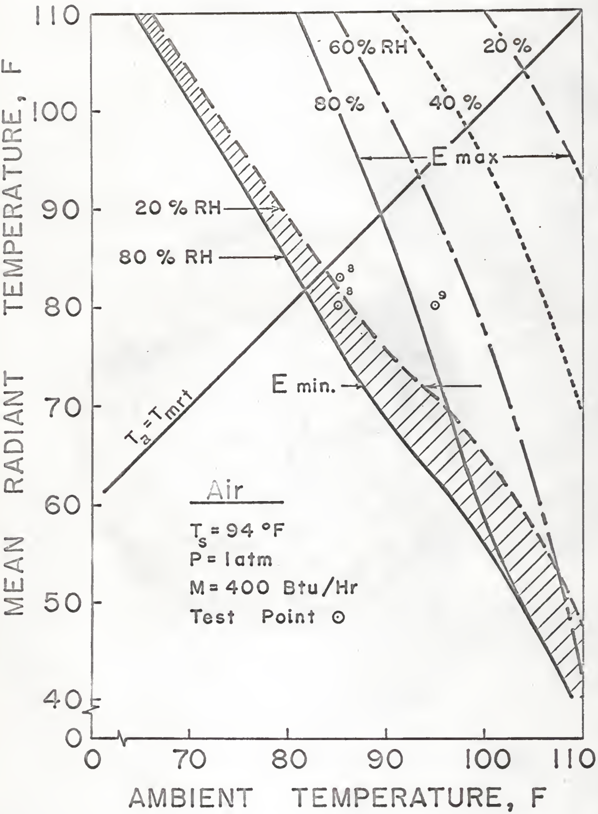

Figure 11. Ambient Temperature vs Mean Radiant Temperature Air P = 1 atm, T_s = 94F Test Point MRT from Page 51. Numeral indicates Test Number.

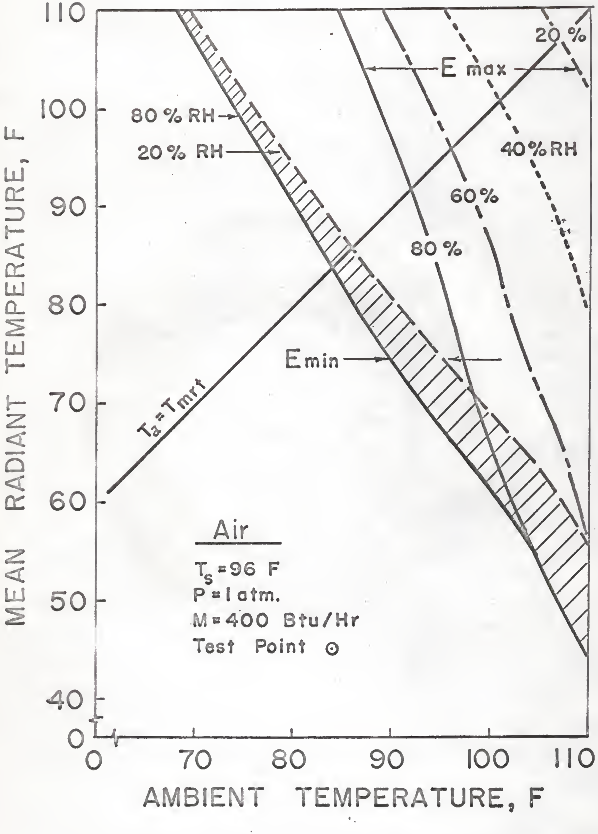

Figure 12. Ambient Temperature vs Mean Radiant Temperature
Air P = 1 atm. T_s = 96 F

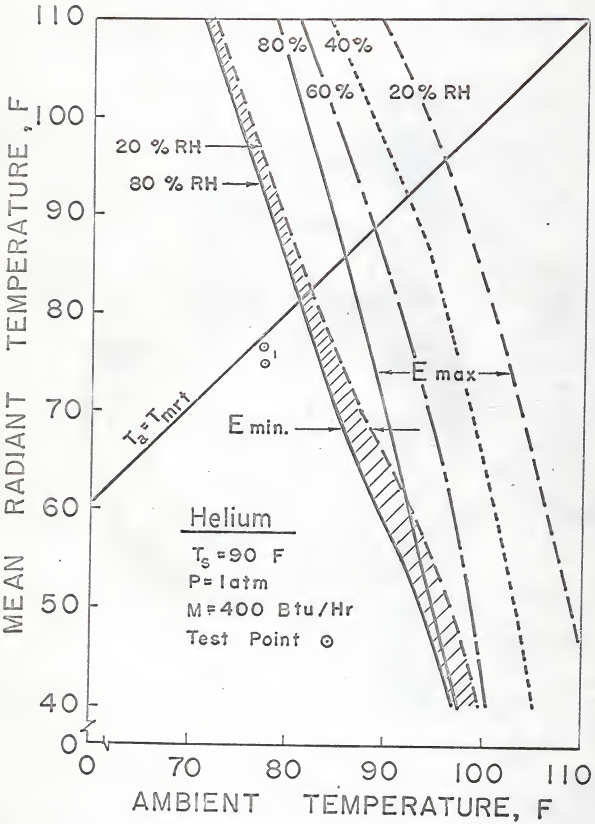

Figure 13. Ambient Temperature vs Mean Radiant Temperature
Helium = 1 atm, T_S = 90F
Test Point MRT from Page 51. Numeral indicates Test Number.

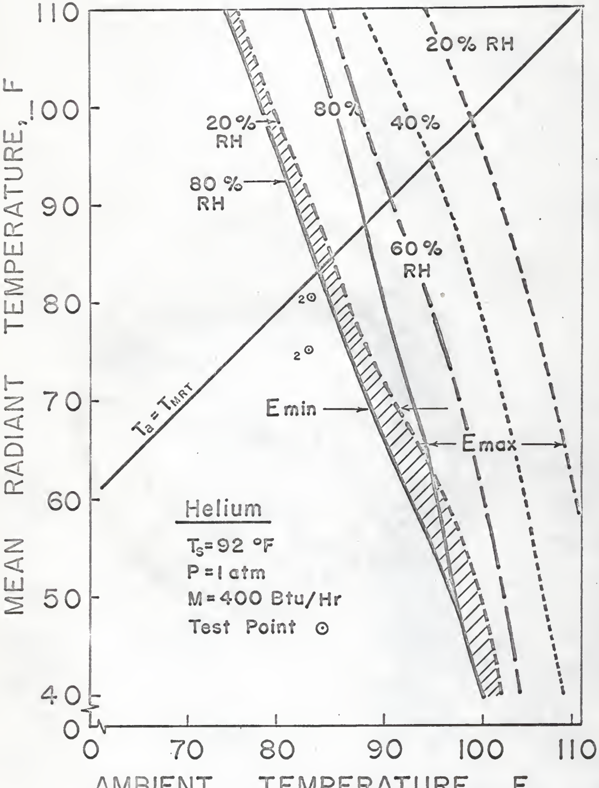

Figure 14. Ambient Temperature vs Mean Radiant Temperature
Helium = 1 atm, T_s = 92F.
Test Point MRT from Page 51. Numeral indicates Test Number.

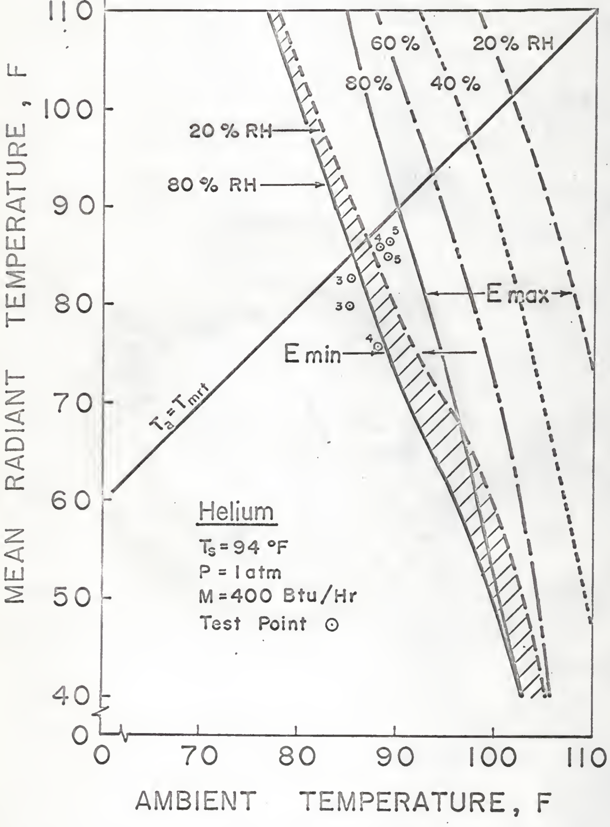

Figure 15. Ambient Temperature vs Mean Radiant Temperature
Helium = 1 atm, T_s = 94F
Test Point MRT from Page 51. Numeral indicates Test Number.

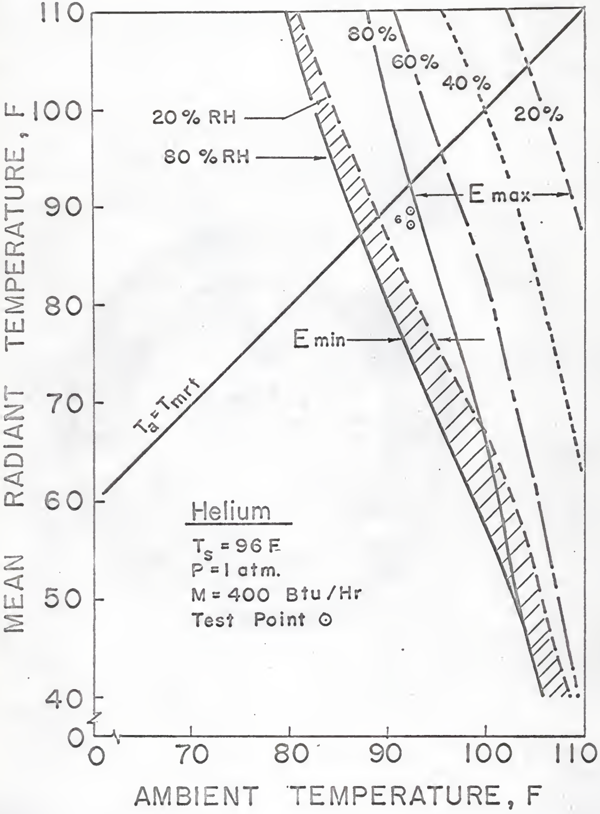

Figure 16. Ambient Temperature vs Mean Radiant Temperature
Helium = 1 atm, T_s = 96F
Test Point MRT from Page 51. Numeral indicates Test Number.

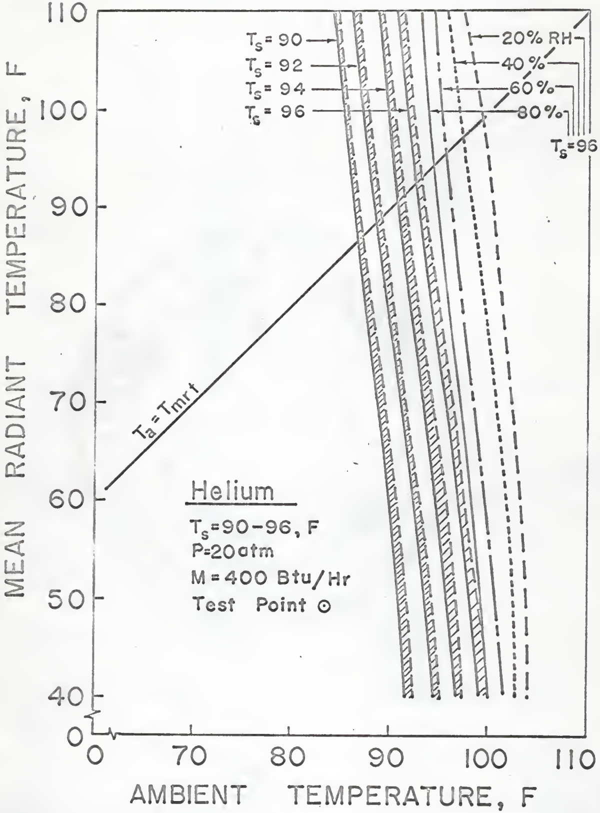

Figure 17. Ambient Temperature vs Mean Radiant Temperature Helium = 20 atm, T_s = 90-96F Test Point MRT from Page 51. Numeral indicates Test Number.

Experimental Results

Comfort vote data are shown in Table V. Investigators experimenting with helium-oxygen atmospheres at high pressures have reported ambient temperatures adjusted for comfort higher than in an environment of one atmosphere air (30)(31). This is not wholly explained by the higher conductivity of helium, however, since Figure (8) shows that the convection coefficient for air also increases as the square root of the pressure ratio.

Referring to Table V, in two tests, practically all conditions were identical except that No. 3 was in helium while No. 8 was in air. Comparing the subjective response, it is seen that the subject was slightly warm in air while he was comfortable in helium. Although this one comparison is not enough to form a conclusion, it is an indication that the comfort zone in helium occurs at higher values of ambient gas temperatures.

It should be also noted that the mean skin temperature in test No. 3, helium, was approximately 0.6 F lower than in No. 8 air. This is in agreement qualitatively with the reports of Fox et al. (4) and Dianov (32). Tests Nos. 1 and 7 appear comparable, yet the skin temperature is the same or even a little higher in helium. It should be noted that the subject was "cool" in both cases and the skin was, therefore, deprived of blood due to constriction of blood vessels in an attempt to conserve body heat. Since the body was losing too much heat in either case, regardless of the rate, the skin temperature was probably lowered an equal amount.

The experimental conditions corresponding to the measured skin

Table V

Experimental Comfort Responses

Helium

Test Number	T_{He} (F)	RH %	MRT_1 F	MRT_2 F	T_s F	Response
1	77.6	22	75	76.8	90.2	Cool
2	82.5	24	75	80.9	91.7	Comfortable
3	85.3	33	80	82.8	94.0	Comfortable
4	88.2	28	75	86	94.6	Warm
5	89.3	34	85	86.8	94.6	Warm - Some Sweating
6	92.6	54	88	89.5	95.9	Warm - Profuse Sweating

Air

Test Number	T_{He} (F)	RH %	MRT_1 F	MRT_2 F	T_s F	Response
Test Room 7	80	30	80		89.9	Cool
Test Cell 8	85	50	80	82.8	94.6	Slightly warm
Test Room 9	95	30	80		94.8	Warm

where

T_{He} = Helium temperature, F

RH = Relative Humicity, %

T_s = Mean skin temperature, F

MRT_1 = Surface temperature of test room walls, F

MRT_2 = Surface temperature of polyethylene test cell, F temperatures have been plotted in Figures 9 through 16 unadjusted for the difference in metabolic rate of 400 Btu/hr and the subject's recorded metabolic rate. Unadjusted, the position of the test points on the curves correlate very well with the subject's comfort response. There is reason to believe that the subject's metabolic rate was nearly 400 Btu/hr. This is explained later when the heat balance is discussed. The results of the heat transfer calculations are shown in Table VI. The experimental analysis was done for the most part using equations stated earlier in the text.

Radiation heat loss, R, was evaluated using equation |3| p. 8 and was also evaluated using Gebhart's method (33) for enclosure problems. Although this method takes into account radiation which reaches the body due to reflections from other sources, the results were not significantly different from those obtained by using equation |3|.

The convection heat loss C was calculated using equation |11| p. 16. The total DuBois surface area was used for A_c. The experiment described in this report would fall into the free convection category since the subject was essentially motionless and the tube leaking helium into the test cell was blocked to prevent the helium from blowing on the subject. In fact, the subject was unable to detect the flow of helium without bringing his foot within inches of the tube opening. The evaporative heat loss was calculated by the following formula.

$$E = h_{fg} (W_f - W_i) - (0.004355)\ VCO_2 - (0.003286)\ VCO_2 \text{ Btu/hr} \qquad |15|$$

where

h_{fg} = heat of vaporization at mean skin temperature, Btu/lb

W_f = subject weight after 1 hour, lb

Table VI

Summary of Heat Loss Calculations

	T_a	T_s	MRT_1	MRT_2	RH	Metabolism Btu/hr	Helium Evaporation Btu/hr	M-E	Radiation $R_1(MRT_1)$	Btu/hr $R_2(MRT_2)$	M-E-C	Convection Theoretical	Btu/hr $M-E-R_2$
1)	77.6	90.2	75	76.8	22	369	52	252	191	169	-51	368	83
2)	82.5	91.7	75	80.9	24	300	104	196	205	138	-51	247	58
3)	85.3	94.0	80	82.8	33	339	68	271	180	145	42	229	126
4)	88.2	94.0	75	86.0	28	336	114	222	240	104	87	135	118
5)	89.3	94.6	85	86.8	34	322	228	94	125	102	-130	124	-6
6)	92.6	95.9	88	89.5	55	311	296	15	104	85	-55	70	-70
							Air (Test Cell)						
8)	85.2	94.6	80	82.8	50	320	114	206	185	150	117	56	89
							Air (Test Room w/o Test Cell)						
7)	80	89.9	80		30	326	77	249	126	---	125	123	124
9)	95	94.8	80		30	327	145	182	190	---	1	-8	181

T_a = Ambient Gas, F

T_s = Mean Skin Temperature, F

MRT = Mean Radiant Temperature, F

RH = Relative Humidity, %

C = Theoretical Convection, Btu/hr

W_i = subject initial weight, lb

VCO_2 = CO_2 produced, liters/hr

VO_2 = O_2 consumed, liters/hr

0.004355 = weight of one standard liter of CO_2 in lbs

0.003286 = weight of one standard liter of O_2 in lbs

For a respiratory quotient of 0.82, the equation becomes:

$$\begin{aligned} E &= h_{fg}\,(W_f - W_i) - (0.004355)(0.82) - (0.003286)\,VO_2 \\ &= h_{fg}\,\Delta W - (0.000285)\,VO_2 \end{aligned}$$

Also since the subject's mean O_2 consumption was 15.2 l/hr, the equation reduces to:

$$\begin{aligned} E &= h_{fg}\,\Delta W - (0.000285)(16.2) \\ &= h_{fg}\,\Delta W - 0.0046,\ \text{Btu/hr} \end{aligned}$$

The measured O_2 consumption was corrected to standard temperature and pressure (dry). The caloric value of 4.8 KCal/liter is equivalent to 0.0189 Btu/cc. Since the O_2 consumption was measured in cc/min, this was multiplied by 1.138 Btu/cc-hr to give the metabolic rate in Btu/hr.

In the discussion which follows, the metabolic rate will be represented by an M, the radiative heat loss by an R, the convective heat loss by a C and the evaporative heat loss by an E, all Btu/hr.

When M, E, R, and C, were calculated, it became apparent that using the existing equations the metabolic rate would not equal the theoretical heat loss, although the storage of heat was assumed to be zero. In test No. 6, an attempt was made to obtain a helium temperature equal to the skin temperature. The test room walls were maintained at 95 F and the floor at 75 F. According to equation |3| , this would give a value for R_1 = 85 Btu/hr which when subtracted from a metabolic rate of 325 would leave 240 for E which the body would be able to handle. At T_a = 93 F, the sweat rate was such that a further increase in T_a would have caused the sweat to run off so T_a was lowered 0.5 F. When the data were analyzed, it was found that both the calculated C and R_1 exceeded M-E.

An experiment was run with air in the test cell, No. 8, with the conditions of No. 3 in hopes that the change from helium to air would not only affect the comfort vote, but would bring the calculated heat exchange of the subject with his environment to zero.

Two tests, Nos. 7 and 9, were then run with the same subject in the same equipment only outside the test cell. The heat balances then checked.

By achieveing $T_a = T_s$ in Test No. 9, the convection term was zero and M-E-R = 0.

The evaporative weight loss was measured on a scale graduated in increments of 0.01 lbs. Therefore, an accuracy of ±0.01 lbs is reasonable. This, when multiplied by an average heat of vaporization of 1040 Btu/lb_w equals an error of ±10.4 Btu. The evaporative heat losses versus skin temperatures for the tests are plotted in Figure 18 with similar data reported by Gagge (16). The agreement is good and lends credence to the experimental measurements of weight loss. One explanation for the two low readings is that the short time period of the experiment did not allow the "corneum stratum", horny layer of the skin, to become saturated, and diffusion of water vapor was inhibited, Fanger (34). This also shows that the evaporative weight loss is independent of the gas to which the skin is exposed and is a function of skin temperature.

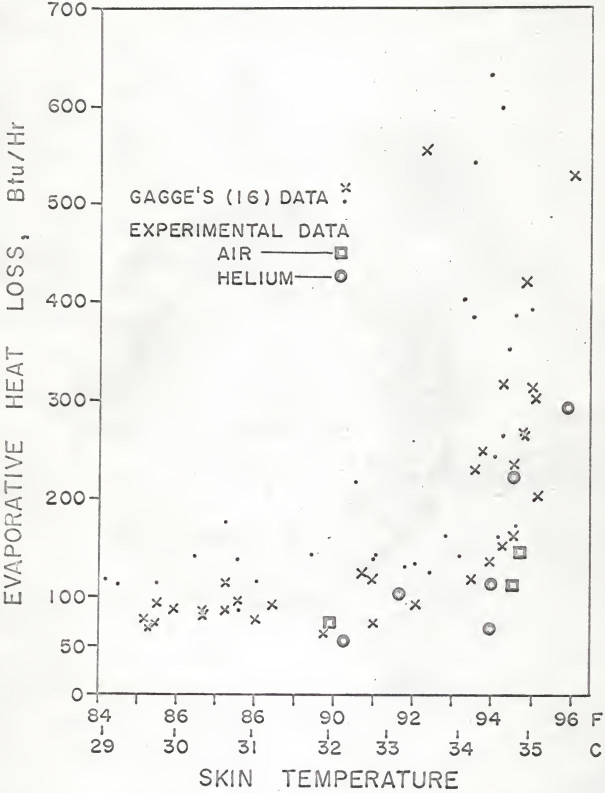

Figure 18. Evaporative Heat Loss vs Skin Temperature

It may also be noted (Figure 18) that as the need for more evaporative cooling arises, the skin temperature also increases due to vasomotor regulation. Thus, in terms of the comfort lines in Figures 8 through 16 seldom, if ever, will E_{max} be reached for T_s = 90 or 92 F. When the environmental conditions are such that larger amounts of evaporative cooling are required the skin temperature will have risen to 94 or 96 F.

The measured metabolic rate appears low when compared with values from the literature, (5)(6). However, the subject's metabolic rate while seated and sedentary was measured seven times while in the test cell and at least five times outside the test cell. The equipment had been used previously by the same operator with good results and was considered in excellent condition. As can be seen in Table VI the differences among the tests are no greater than would be expected. The subject's basal metabolic rate measured at the Kansas State University Student Health Center was found to be 280 Btu/hr which is within the normal range. It was suggested that since the subject completely relaxed during the time the metabolic rate was being measured, this rate was not the same as it would have been had he continued to measure his weight, operate the relative humidity sensor and record his pulse and subjective reactions as he did otherwise. A metabolic rate was measured for the subject while typing and was found to be 400 Btu/hr. This is lower than the 550 Btu/hr suggested for this activity level (5). However, no typing rate was recorded in either case. If the subject was assumed to have had a metabolic rate of 400 Btu/hr, for 45 minutes and a metabolic rate of 325 Btu/hr for 15 minutes, his combined metabolic rate would have been 381 Btu/hr. This does not bring the heat exchange into balance, but it would influence the correction of the experimental points plotted on Figures 9 through 16. Since this discrepancy existed between expected and measured metabolic rates, the calculations were checked for errors. None were found and the discrepancy remains unexplained.

In test No. 9, M-E-R = 0, and there is substantial reason to believe M and E are valid. Therefore, the value for R and its method of calculation should also be valid. In test No. 8 a convection term is added and the energy produced by the subject equals the energy lost.

Once the subject enters the test cell, however, the equations no longer check. The heat loss due to radiation exchange is now complicated by the presence of the polyethylene test cell. As mentioned earlier, this material when clean and dry will transmit 85% of the infrared radiation incident upon it. Therefore, one solution was to consider the test cell transparent and keep the shape factor $F_{man-floor} = 0.33$. This is MRT_1 in Table V and results in a radiation heat exchange R_1. The second approach was to consider the test cell covered on the inside with a thin film of moisture which it had acquired while in the configuration shown in Figure 3, collapsed. The shape factor $F_{man-floor} = 0.15$ and the wall temperature of the test cell replaces the wall temperature of the test room in the calculation of MRT. This resulted in MRT_2 and R_2 in Table V. As can be seen by comparing the M-E-R_2 column with the theoretical convection column, the heat transfer equation did not balance.

A complicated radiation heat exchange analysis was attempted assuming a transmissivity of (0.85) for infrared radiation incident upon the test cell. This resulted in a higher radiation heat loss and a greater heat balance discrepancy than did the other solutions. The only factor in the radiation term which could change besides the MRT would be the radiation area of the body and this seems fixed.

The convection heat transfer equation is affected by T_s, T_a, A_b, a characteristic dimension and the thermal properties of the ambient gas. Mean skin temperatures were in the normal range of 90-96 F. Due to the fact a T_s calculated from equation 13 will vary with individual shapes, any error in the measured and calculated skin temperature is probably no greater than the error inherent in the assumptions made to obtain the value. Since the subject is of average height and weight this error should be small. By placing the thermisters at approximately the same location for each test and monitoring them every ten minutes of each test, it was quickly noticed when a thermister was loose and exposed to the atmosphere or was being pressed between the skin and the chair and thereby was measuring an invalid skin temperature.

The surface area of the subject is a factor also to be considered. DuBois (8) claims his height-weight formula is accurate to one decimal place or has an error less than 2%. In the sitting position, the convection area should be within the 2% error of the total body surface area.

The lower skin temperature in the one helium test compared to its air counterpart shows that the higher convection loss in helium does exist. At this point there does not appear to be a sound reason why the equation |13| should not give valid results.

RECOMMENDATIONS

In any project of this nature a lot of time is taken finding out the who, what, where, and how of assembling equipment and conducting the research. Hindsight is greater than or equal to foresight, and the following suggestions could be considered part of the "delta experience" gained from this work.

To avoid the problems with radiation heat transfer reported in this paper, two approaches are suggested. (1) Coat the test cell with a flexible paint. This would assure the experimenter that the subject was radiating to the test cell alone. (2) Purchase a custom-made test cell with known thermal radiation properties.

Silica gel could be used inside the test cell to control the relative humidity. The floor temperature could be maintained equal to the test cell wall temperature. This would minimize the radiation shape factor difficulties.

Although the evaporative weight losses appear to be reasonable, a better method of measurement should be devised. It would be better to have someone other than the subject record the weights. Although if there is any chance the subject's position may affect the reading, then the subject must be instructed to find a reference position and assume this position whenever a weight is taken. The best system would be to continuously record the body weight. This could be done with a device employing strain gauges and a strip chart recorder.

The mask and valve are cumbersome and somewhat uncomfortable. However, they are far superior to a mouthpiece and noseclip combination, especially for a test of one hour or longer. Both the mask and mouthpiece cannot be eliminated without going to a mixture of helium and oxygen.

More subjects would be desirable to allow a statistical analysis of the results. The subjects should be thoroughly calibrated in air for metabolic rates at various activities, mean skin and rectal temperatures, sweat rates and comfort zones. Several trials in air at various conditions includint $T_s = T_a$ and $T_s = T_{mrt}$ should be made and heat balances calculated.

After this calibration any irregularities which occur in the actual test should be quickly noticed.

Two sets of test under the conditions $T_s = T_a$ and $T_s = T_{mrt}$ should be conducted and carefully analyzed to try to determine coefficients of radiation and convection heat transfer before any other tests are attempted.

Several tests at each condition with each subject should be made. The subject should be exposed to the test conditions one and one-half hours before a steady state experiment is conducted, (in the comfort zone).

The mass spectrometer in the Biochemistry department can be used to obtain a gas analysis which will show the percentage of helium and the percentage of air in a sample. The only person qualified to perform this analysis left Kansas State University the week-end preceding the first test in helium. The biochemistry personnel are very helpful and a gas analysis should be made of each test.

REFERENCES

1. *U.S. Navy Diving Manual*, July, 1963, Page 59, Navy Department, Washington D.C.

2. Empleton, B.E., E. H. Larphier, J. E. Young, L. G. Goff. *The New Science of Skin and Scuba Diving*, Association Press, New York 7, New York, 1962, p. 64.

3. Epperson, W. L, D. G. Quigley, W. G. Robertson, V. S. Behar, B. E. Welch. "Observations on Man in an Oxygen-Helium Environment at 380 mmHg Total Pressure: III Heat Exchange." *Aerospace Medicine*, May 1966, p. 467.

4. Fox, E. L., H. L. Weiss, R. L. Bartels, E. P. Hiatt. "Thermal Responses of Man During Rest and Exercise in a Helium-Oxygen Environment." *Archives of Environmental Health*, Vol. 13, July 1966, p. 23.

5. *Bioastronautics Data Book*, National Aeronautics and Space Administration, Washington D. C., 1964, p. 173.

6. DuBois, E. F. *Basal Metabolism in Health and Disease*, Philadelphia: Lea and Febiger, 1936.

7. DuBois, E. F. and D. DuBois, "Formula to Estimate the Approximate Surface Area if Height and Weight are Known." *The Archives of Internal Medicine*, Vol. 17, 1916, p. 863.

8. Nielsen, M. and F. Pedersen. "Studies on the Heat Loss by Radiation and Convection from the Clothed Human Body". *Acta. Physiol. Scand.* 27:272, 1932.

9. Hardy, J. D. and C. Muschenshin. "The Radiation of Heat from the Human Body, IV, The Infrared Radiation by Human Skin." *Journal of Clinical Investigations*, 1934:13, p. 817.

10. Jakob, M. and G. A. Hawkins, *Elements of Heat Transfer*, New York: John Wiley and Sons, 1957, p. 7.

11. Jenssen, J. E. "Thermal Comfort in Space Vehicles." ASME Paper No. 59-A-207.

12. Pembreg, M. S. "Animal Heat' in *Textbook of Physiology*, E. A. Schafer, Vol. I, London: Hodder and Stoughton, 1898, p. 838.

13. Hart, J. S. "Calorimetric Determination of Average Body Temperature of Small Laboratory Animals and Its' Variation with Environmental Conditions." *Canadian Journal of Zoology*, 1951, 29:224.

14. Burton, A. C. "Human Calorimetry II The Average Temperature of the Tissues of the Body." *Journal of Nutrition*, Vol. 9, 1935, p. 261.

15. Winslow, C. E. A. and L. P. Herrington, *Temperature and Human Life*, Princeton, New Jersey: Princeton University Press, 1949, p. 53:92.

16. Gagge, A. P. "A New Physiological Variable Associated with Sensible and Insensible Perspiration." *American Journal of Physiology*, 1937, 120, p. 277.

17. Hardy, J. D. "Heat Transfer", Chapter 3, *Physiology of Heat Regulation* edited by L. H. Newburg, Saunders Company, Philadelphia, 1964, p.95.

18. McNall,P. E. and D. J. Sutton. "Thermal Comfort and Comfort Equations." *Minneapolis-Honeywell Research Report GR 1823-R2*.

19. McAdams, W. H. *Heat Transmission*. Second Edition. New York: McGraw-Hill, 1942, p. 221:242.

20. Kreith, F. *Principles of Heat Transfer*, Scranton: International Textbook, 1958, p. 297:306.

21. *Tables of Thermal Properties of Gases*. "Circular 564", National Bureau of Standards, No. 1, 1955.

22. Lick. W. J. and H. W. Emmons *Transport Properties of Helium from 200 to 50,000 k*, Cambridge: Harvard University Press, 1965.

23. Aiken, S. W. "The Thermodynamic Properties of Helium" *ASME Transactions*, Vol. 72, p. 751-7, 1950.

24. Yaglou, C. P. "A Method for Improving the Effective Temperature Index." *Trans. ASHVE*, Vol. 53, 1947, p. 307.

25. Hardy, J. D. and DuBois, E. F. "Basal Metabolism, Radiation, Convection and Evaporization at Temperature of 22-35 C" *Journal of Nutrition* 15:477, 1938.

26. Raber, B. F. and F. W. Hutchinsion, Panel Heating and Cooling Analysis, New York: John Wiley and Sons, 1947, p. 72.

27. Tripp. W., C. Hwang, and R. E. Crank. "Radiation Shape Factors for Plane Surfaces and Spheres, Circles or Cylinders." *Kansas State University Bulletin*, Vol. 46, April 1962, No. 4, Special Report No. 16, Manhattan, Kansas.

28. McNall, P. E., Personal Discussion.

29. Leventhal, H. T., Technical Director, Ethyl Corporation, Visqueen Division, personal correspondence.

30. Link, E. A., "Tomorrow on the Deep Frontier." *National Geographic*, June 1964, Vol. 125, No. 6. p. 778.

31. Hamilton, R. W., J. B. MacInnis, A. D. Noble, H. R. Schreiner "Saturation Diving at 650 feet." Toncwanda, New York: Ocean Systems, Inc. Toncwanda Research Laboratory, March 15, 1966.

32. Dianov, A. G. "The Possibilities of Replacing the Nitrogen in the Air with Helium in Space Vehicle Cabins and the Effectiveness of Using a Helium Oxygen Mixture for Ventilation of a Space Pressure Suit." Kosmicheskige Isledovaniya, 2:498, 1964, Translated by Milan Copic.

33. Gebhart, B., "Unified Treatment for Thermal Radiation Transfer Processes Gray, Diffuse Radiators and Absorbers, ASME Paper 57-A-34, 1957.

34. Fanger, P. O., Visiting Professor from Tech. University of Denmark, personal discussion.

ACKNOWLEDGEMENT

The author would like to express his gratitude to Dr. R. G. Nevins to whom should go much of the credit for this report. In the role of major professor he provided the idea for the experiment and made himself available for consultation until its completion in spite of a very busy schedule. Also deserving acknowledgement are Mr. Jay C. Schlegel and Mr. Patrick W. Ryan, instructors, for their help in conducting the experiment. The assistance of Mr. Glen R. Correll in programming the 1410 was very much appreciated. The author would also like to give special acknowledgement to The Link Foundation, New York City, New York, whose financial support made this experiment possible.

APPENDIX

```
  MON$$      JOB  TMRT HELIUM OR AIR  W/ -E+/-C+/-R
  MON$$      COMT 20,10.     G. SMITH     MECH. DEPT.
  MON$$      ASGN MJB,12
  MON$$      ASGN MGO,16
  MON$$      MODE GO,TEST
  MON$$      EXEQ FORTRAN,,,,,,,SOLVE
   REAL M
   DIMENSION TS(6),TA(11),WU(2),RH(4),A(6)
   COMMON C1,RL,PR,AB,G,L
 1 FORMAT (4E18.8)
 2 FORMAT (8F10.1)
 3 FORMAT (2F10.1,I10)
 5 FORMAT (4F10.1,-8PF10.1)
 6 FORMAT (1H1,40X,2HM=,F4.0,6X,2HP=,F8.3,6X,6HHELIUM///)
 7 FORMAT (31X,2HTS,10X,2HTA,9X,2HWU,9X,2HRH,9X,1HE,11X,1HC,
  B11X,4HTMRT)
 8 FORMAT (22X,2F12.2,F11.2,F10.2,2F12.2,F13.2)
   READ(1,3)M,P,L
   READ(1,2)TS
   READ (1,2)TA
   READ (1,2)WU
   READ (1,2)RH
   READ(1,1)A
   READ (1,5) C1,RL,PR,AB,G
   READ (1,2) SIG,AR,EPS,CF
   DO 4I=1,4
   WRITE (3,6)M,P
   WRITE (3,7)
   TSI = TS(I)+460.
   TSI2 =TSI*TSI
   TSJ = (TS(I)+459.69)/100.
   VPS=A(1)+A(2)*TSI+A(3)*TSI2+A(4)*TSI*TSI2+A(5)*TSI2*TSI2+A(6)*
  BTSI*TSI2*TSI2
   DO 4I3=1,11
   CALL C CALC (TS(I),TA(I3),TF,P,CC,C)
   TAI=TA(I3)+460.
   TAI2=TAI*TAI
   VPA=A(1)+A(2)*TAI+A(3)*TAI2+A(4)*TAI*TAI2+A(5)*TAI2*TAI2+A(6)*
  BTAI*TAI2*TAI2
   IF(TA(I3).LE.TS(I)) GO TO 10
   C=-C
10 DO 4I1=1,2
   DO 4I2=1,4
   IF(VPS-RH(I2)*VPA)11,11,12
11 E=0.
   GO TO 13
12 E=WU(I1)*AB*CF*(VPS-RH(I2)*VPA)
13 TMRT =(TSJ**4-(M-C-E)/(SIG*AR*EPS))**.25
   TMRT =(TMRT*100.)-459.69
 4 WRITE(3,8)TS(I),TA(I3),WU(I1),RH(I2),E,C,TMRT
   STOP
   END
  MON$$      EXEQ FORTRAN
   SUBROUTINECCALC(TS1,TE1,TF,P,CC,C)
   COMMONC1,RL,PR,AB,G,L
   TS=TS1+459.69
   TE=TE1+459.69
   TF=.5*(TS+TE)
   BETA=1./TF
   GO TO(7,8),L
 7 RHO=P/(2.6829*TF+P*BETA**.25*(.3059-1.845*SQRT(BETA)-.822*BETA))
   RMU=.8315*.1E-02*TF**.647
   RK=(7920.+9.62*(TF-459.69)+9.*(P/14.696-1.))*.1E-04
   GO TO 10
 8 PR=PR+.0319
   RHO=P/(0.370484*TF)
   TFK=0.555*TF
   RMU=((TFK*SQRT(TFK))/(TFK+110.4))*3.527E-03
   RK=(242.*.6325*SQRT(TFK)*1.E-05)/(1.+245.4*10.**(-12./TFK)/TFK)
10 CC=C1*RK*(G*PR*BETA*RHO*RHO/(RL*RMU*RMU))**.25
   C=AB*CC*(ABS(TS-TE))**1.25
   TF=TF-459.69
 5 RETURN
   END
```

Explanation of Fortran Program

This program is written for the IBM 1410 computer using the fortran language found in the IBM manual File No. 1410/7010-25 Form C28-0328-2.

Before attempting to use this program enough of the theoretical analysis presented in the text of this report should be read to familiarize the user with the nomenclature.

The program solves the heat balance equation, No. 13 in the text of this report, which reads, metabolic rate (M) = evaporative heat loss (E) ± convective heat loss C ± radiative heat loss R. The metabolic rate M is read into the machine. The evaporative heat loss, E, is calculated in statement No. 12. The convective heat loss, C, is calculated in the subroutine named C CALC. The radiation term has not been calculated separately. Instead, equation 13 has been solved for T_{mrt} as is shown in statement 13 of the program.

If the program is used on the IBM 1410 using the PR-155 system, the only cards needed are the data cards.

The first data contains M, metabolic rate in Btu/hr, P, pressure in psia and L, a floating point number which when a 1 designates helium and a 2 designates air. The next data card contains the skin temperature (T_s) in degrees F. The third data card contains the ambient temperatures in degrees F. The fourth data card lists the values for Gagge's wetted area in KCal/cm hr-m^2 and the fifth values for relative humidity. The constants A listed on the sixth data card are used to generate values of vapor pressure in psia from values of temperature in degrees F: $A(1) = -0.7321633 \cdot 10^{-5}$, A(2) =

0.0604572, A(3) = 0.0021633962, A(4) = $-0.7321633 \cdot 10^{-5}$, A(5) = $0.84661484 \cdot 10^{-11}$. On the seventh data card are contained values for: the constant listed as C1, dimensionless, the significant dimension L,ft, the Prandtl number, dimensionless, the total body surface area, square feet and the acceleration of gravity in ft/hr^2. In the text the values for C1 and L are combined in one number but when the program was written a value of C1 was selected as 0.555 and the value of L altered to fit selected values for $\phi = C1/L^{0.25}$. The final data card contains the values of the Stefan Boltzman Constant, the radiation area and emissivity of the skin, and the conversion factor 1.90633 Btu-cm Hg-m^2/KCal-psia-ft^2.

HEAT TRANSFER FROM THE HUMAN BODY TO A ONE ATMOSPHERE HELIUM ENVIRONMENT

by

NORMAN EUGENE SMITH

B. S., Kansas State University, 1965

AN ABSTRACT OF A MASTER'S THESIS

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas

1967

ABSTRACT

Six tests were conducted involving a seated nude subject exposed to a helium environment using the equipment and techniques described in the body of this report. In addition, a test was run in the test cell used to contain helium with air as the ambient gas and two tests were run in air using the same equipment with the exception of the polyethylene bag. During these tests the subject recorded his subjective thermal comfort. Also the parameters necessary to determine the subject's heat balance were measured and calculations were made according to heat transfer theory.

For the conditions of this test, the subject was comfortable with ambient helium temperatures of 82-86 F.

The mean skin temperature in a helium atmosphere at 85 F was 0.6 F lower than the skin temperature in 85 F air.

The evaporative heat loss was found to vary with the skin temperature and is independent of the ambient gas for a given skin temperature.

A theoretical analysis was made for the heat transfer from the human body according to heat transfer theory. The theory determines a mathematical equation for heat transfer and heat balance in the zone of thermal equilibrium and comfort. The results of the equation are plotted on a graph of mean radiant temperature versus ambient temperature at pressures of one and twenty atmospheres and experimental points are compared with theoretical predictions for one atmosphere pressure.

VITA

Norman E. Smith

Candidate for the Degree of

Master of Science

Thesis: HEAT TRANSFER FROM THE HUMAN BODY TO A ONE ATMOSPHERE HELIUM ENVIRONMENT

Major Field: Mechanical Engineering

Biographical:

Personal Data: Born in Neodesha, Kansas, November 15, 1941, the son of Norman C. and Marjorie A. Smith

Education: Graduated from Parsons High School, Parsons, Kansas in 1959; received the Bachelor of Science degree from the Kansas State University, with a major in Mechanical Engineering in February, 1965, completed requirements for the Master of Science degree in December 1966.

Professional experience: Worked part-time in the Mechanical Engineering Department, Kansas State University for three years as an undergraduate; worked as an engineer at the NASA Manned Spacecraft Center, Houston, Texas during the summer of 1965.

Honors, Honor and Professional Societies: Received a Public Health Service Traineeship, a Western Electric Scholarship and a Henry E. Trembly Scholarship. Student member AIAA and ASHRAE and member Sigma Tau and Pi Tau Sigma.