HEAT LOSS ANALYSIS FOR AN OCEANAUT

by

GUL HIRANAND ADVANI

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Ralph G. Nevins
Major Professor

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INTRODUCTION

> "Knowledge of the ocean is more than a matter of curiosity;
> our very survival may hinge on it."
>
> ---- John F. Kennedy.

The mysteries of the ocean have long been as the sirens call to men endowed with scientific curiosity. They call forth the ingenuity, the imagination and the desire to meet and conquer challenges. For this is the Earth's last frontier - the inner space. The scientists and engineers of our times have been in the fore in quest for the scientific capability and technical mastery to meet the challenge offered by the wonderful world that lies under water.

History gives no record of the date when man's under water probe began or who the first divers may have been, but man's curiosity probably led him into the water at a very early stage. Like some of the native pearl divers who still continue the primitive art, the early divers probably used no equipment at all. But with the changing times he has learned to use the equipment that will allow him to stay under water for longer periods, and explore the world within. Many expeditions have been organized with several different objectives; one of them is to see how long a man can survive in the conditions that are encountered under water. A number of different types of underwater vessels have been constructed for underwater exploration and study. Captain Jacques-Yves Cousteau, President, World Underwater Confederation has organized many such expeditions (1)*. More expeditions are planned for the future. In 'Conshelf Two' in June 1963, two men lived at a depth of 99 feet in a vessel which Captain Costeau calls a 'Deep Cabin.'

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* Numbers in the parantheses designate the references at end of report.

They lived there for two weeks in an environment of 100 percent relative humidity.

In expeditions such as these it has been found necessary to control the environment so that the oceanauts can live in comfortable conditions for long periods of time and conduct the necessary studies with ease. In order to artificially condition the deep cabin environment the heat exchange between man and his environment must be analyzed. An attempt has been made in this report to analyze this heat exchange from a man in an Oceanographic Research Vessel stationed at a depth of 100 feet. A relationship between the mean radiant temperature and the ambient air temperature is determined for various average skin temperatures. The relationship is programmed for the digital computer to assist in the calculations. This program can be used for conditions other than those specified in this report by changing a few constants.

The Oceanographic Research Vessel described in this report is similar to the 'Deep Cabin' described by Captain Costeau as illustrated in Figure 1. It is a cylindrical vessel and is open at the bottom so that the oceanauts may come and go for exploration. The water is prevented from coming in by increasing the pressure of the air or gas inside the vessel. Thereby equalising the pressure of the water at that depth. It has been found that the pressure of the sea water at the depth of 99 feet is four atmospheres (2). The walls of the vessel do not have to be very thick in this case because the pressure inside and outside the vessel is the same.

The temperature of the surrounding water depends upon the depth and the geographical location of the vessel.

FIG·1. OCEANOGRAPHIC RESEARCH VESSEL

EFFECT OF HIGH PRESSURE ON HUMAN BODY

The human body can withstand tremendous pressures. High pressures do not affect blood pressure or circulation (3). If the pressure difference between the inside of an artery and the surrounding area is measured at any depth it will be found to be the same as that measured at sea level, even though the pressure at that depth is high. The artery pressure increases as the atmospheric pressure increases. One might wonder, for example, why the brain is not crushed by a collapse of its protective skull. This would be possible if the skull was full of air at a pressure lower than that of the surroundings. But it so happens that the solids and liquids of the brain and their covering occupy the entire space within the skull and they are subjected to the same compressive force as are the scalp and the skull itself. Almost the entire body, with the exception of a few air passages, is completely made up of fluids and solids which are virtually incompressible and which transmit pressure freely, equalizing the pressure very rapidly.

HUMAN COMFORT

In order for the oceanaut to work efficiently under water, an understanding of the relation of man to his environment is essential. Comfort is an intangible term, its meaning depending upon a combination of one's physical, physiological and psychological conditions. If the discussion is restricted to the thermal aspects the requirements for thermal comfort can be calculated by evaluating the heat exchange between the man and his environment.

The factors which affect human comfort are:

(1) Humidity.

(2) Dry bulb temperature.

(3) Air motion and distribution.

(4) Mean radiant temperature.

(5) Purity of air in conditioned space, which includes odors, dust, toxic gases and bacteria.

A complete air conditioning system calls for the control of all factors in order to provide satisfactory environment for human comfort. However, many air conditioning systems do not control all the above factors and yet are reasonably effective.

PHYSIOLOGICAL CONSIDERATIONS

To understand the effect of the above mentioned factors on an oceanaut working under water, in the environments encountered in an Oceanographic Research Vessel, it is necessary to study certain physiological responses of the human body.

The human body may be thought of as a low efficiency, constant temperature heat engine. This is justified by the fact that in both, man and the heat engine, it is possible to relate the initial and final energy content of the fuel to work done and heat dissipated. However, comparing both minutely, one can find several differences between the two. One of these being the ability of the human body to adjust itself to the environmental conditions. As the heat engine derives energy from its fuel, the human body receives its energy in form of food and this energy is converted to heat by certain exothermic chemical reactions. A part of this energy received from food may be converted to work and the remainder must be dissipated to the surroundings or stored in the body. From the heat transfer point of view, the objective of any cooling or heating system is merely to provide an environment in which an individual can easily dissipate metabolic heat at the same rate at which it is produced in the body. When environmental conditions are such that this rate is unbalanced, there will be a change in energy in the body resulting in a rise or fall of body temperature. The temperature of the body is essentially constant, however, it is known to vary in more or less uniform cycle during each twenty-four hours. McConnel and Houghton (4) state that minimum temperature of this cycle occurs during early hours of the morning (2:00 to 3:00 a.m.) followed by a marked early morning rate of rise which becomes less pronounced as the day progresses.

The temperature reaches a maximum about 5 p.m.

One of the main mechanisms for controlling skin and body temperatures is evaporative cooling. More or less amount of moisture is evaporated from the body surface in the form of perspiration, depending on whether skin temperature is rising or falling respectively.

A human being can control his heat production to a certain extent, whenever the environments demand. He may control his heat loss to some extent by adding or removing clothes, thereby increasing or decreasing the area of skin which is exposed to the surroundings and changing the insulating value of the skin. Although these measures are effective, they may not be sufficient for a man in extreme environments, such as encountered in the Oceanographic Research Vessel. If temperature and humidity are such that the heat produced by the body is dissipated too rapidly, the metabolic rate will be increased by involuntary exercise, that is shivering. If this is not sufficient, the metabolic rate can further be increased by willful exercise of physical exertion. However, if such environmental conditions persist for a long time, physical exhaustion will develop the body, temperature will fall, and death will ultimately occur.

Excessive adjustments to environmental conditions may be defined as thermal discomfort. On the other handthermal comfort may be defined as that set of environmental conditions under which the rate of heat loss from the body is equal to the rate of body heat production or metabolic rate. Since the conditions of thermal comfort are dependent on the environmental conditions, it is important to know the relationship among the various factors which influence the balance between the body heat loss and body heat production.

On psychological side of comfort, consideration may be given to those people who cannot feel comfortable unless they see that the windows are open, or their opposites who are extremely sensitive to draft, imaginary or otherwise, and many other individuals, each having his or her own pecularities. The psychological aspect will not be considered here.

HEAT BALANCE

In order to use existing data for predicting the desired environmental conditions in an Oceanographic Research Vessel, it is necessary to first separate the effects of the various modes of heat transfer from the human body. Body temperature depends upon the balance between heat production and heat losses. Under normal conditions, the heat resulting from oxidation of food elements in the body, namely metabolism, maintains the body temperature above that of the environments. At the same time heat is being dissipated to the environment by conduction, convection, radiation, and evaporation including respiratory heat loss. The fundamental thermodynamic processes governing the heat exchange between the human body and his environment can be expressed in the form of the following equation:

$$M = \pm S \pm K \pm R \pm C + E$$

where,

M - Rate of metabolic heat produced within the body, BTU per hour.

S - Rate of storage of heat in the body, BTU per hour.

K - Rate of conductive heat loss or gain, BTU per hour.

R - Rate of radiative heat loss or gain, BTU per hour.

C - Rate of convective heat loss or gain, BTU per hour.

E - Rate of evaporative heat loss, BTU per hour.

The metabolic rate M, is always positive since this heat is produced within the body. Rate of storage S, may be positive or negative depending on whether the heat is being lost from or stored in the body due to fall or rise of the body temperature. Rates of convective, radiative, and conductive heat exchange are positive if the body surface temperature is above that of the environments and negative if below. Heat loss due to evaporation and respiration is always positive.

Heat Production-Metabolism

The metabolic rate of an individual may vary over a very wide range, depending on the degree of physical or mental activity. Jennings and Lewis (5) have given the heat production rate of a man for various activities as shown in Table 1.

TABLE 1

Total Heat Dissipation from Individuals

Activity	BTU per hour, Room Temp. Between 60 Degrees F and 90 Degrees F
Adults at rest, seated	380
Adults at rest, standing	430
Moderately active worker	600
Metal worker	860
Walking, 2 mph	760
Restaurang worker, very busy	1000
Walking, 3 mph	1050
Walking, 4 mph, active dancing	1390
Slow run	2290
Maximum exertion	3000 to 4800

The thermal efficiency of a human body is in general low and most of the energy produced in the metabolic process must be dissipated as heat. When the individual performs no external work, the energy released is equal to the metabolic rate. Normally, the metabolic rate equals the sum of body heat dissipation and the work rate.

The wide variation in body heat production with various degrees of activity would require correspondingly large variations in environmental conditions from comfort point of view. However, in this report the oceanauts are considered from the following two points of view.

(1) 'Near sedentary'state: The oceanaut in a sitting position is engaged in a light activity. This situation may be taken as an intermediate between 'sitting at rest' and 'standing at rest.' From Table 1, the metabolic rate for this case is taken as 400 BTU per hour.

(2) 'Moderately active worker" The oceanauts are engaged in moderate activity. For this case, the heat dissipation may be taken as 600 BTU per hour, as seen from Table 1.

The heat loss calculations are given for metabolic rates of 400 BTU per hour and 600 BTU per hour but the relationship can always be obtained for other activity rates changing the value of M in the Fortran Program.

Conductive Heat Loss

The heat loss due to conduction depends on intimate contact between the body and a solid object with a temperature difference. If an oceanaut is sitting in a chair, the area of contact of the body and the chair would be relatively small. There would be no convection and radiation over the area that is in contact with the chair. The conduction heat transfer coefficient is perhaps not too different from the convection plus the radiation heat transfer coefficients (6). Hence, if the temperature of the chair or any solid object that is in contact with the oceanaut is at about the same temperature as that of the environment, the assumption of heat transfer by convection and radiation from the body areas which are actually conductive areas is probably not grossly in error. Hence, the conduction heat loss term in equation (1) may be conveniently eliminated.

Storage 'S'

If a man is to be comfortable in an Ocenaographic Research Vessel and perform his duties effectively he should not need to resort to the involuntary thermoregulatory activities of shivering or sweating or the voluntary activities of changing clothes or increasing activity. To do this the internal body temperature of an oceanaut must remain constant or almost so. Therefore, thermally comfortable conditions must be provided and the storage term 'S' in equation (1) must be reduced to zero.

Evaporative Heat Loss 'E'

The evaporative heat loss from the skin can be divided into two distinct processes that of insensible perspiration and sweating. Insensible perspiration is the evaporation of water which diffuses through the epidermis from the deeper layers of the skin and from the moist surfaces of the respiratory system. Under normal circumstances the evaporation takes place at the skin surface, the liquid sweat passing into vapor at about skin temperature and finally passing in the environments, resulting in the cooling of the body surface and increasing the relative humidity of the environments. According to Bazett (8), for a resting subject exposed to moderate or comfortable environments, this insensible heat loss amounts or approximately twenty-four percent of the total heat loss. But this insensible heat loss from the lungs and skin can vary from close to zero for an inactive person exposed to cold and damp environments to a high value of 3000 BTU per hour under the conditions of maximum exertion in hot environments. It may be noted that even though a person may perspire and wet the skin, the latent heat loss will be zero if no water is evaporated from the skin.

Houghton et.al. (7) calculated the heat losses from the respiratory tract from the volume of normal air a man would inhale and exhale for this rate of oxygen consumption and the temperature and moisture content of the air for each test condition. The loss of heat due to respiration was found to be small in comparison with the other losses at normal room temperature and atmospheric pressure.

In hot environments the evaporative heat loss is an important factor. As the air temperature increases, the circulatory system allows the blood to flow in greater quantities to the skin surfaces. This results in a rise in skin temperature, thus increasing the convective and radiative heat loss. At the same time perspiration causing skin wetting occurs and increases the evaporative heat loss. Winslow et.al.(9) have shown that in environments where the air temperature is above 85 degrees F and where perspiration causing skin wetting occurs, the relative humidity has a marked effect on evaporative heat loss. However, for air temperatures below 85 degrees F, the relative humidity has little or no effect, varying from twenty percent to seventy percent. Insensible perspiration and the resulting evaporative heat loss remaining essentially constant.

For calculating the heat loss due to evaporation, Gagge (10) introduced the following equation:

$$E = (W\mu)\ A\ (P_s - RH \times P_a) \qquad (2)$$

where,

W = Fraction of body area completely wet.

μ = Coefficient of heat transfer by evaporation, containing the constants for vaporization, air motion and direction, BTU per square foot - hour - inches Hg vapor pressure.

A = Total body area (Du Bois formula), square feet.

P_s = Saturated vapor pressure at skin temperature, inches Hg.

RH = Relative humidity, fraction.

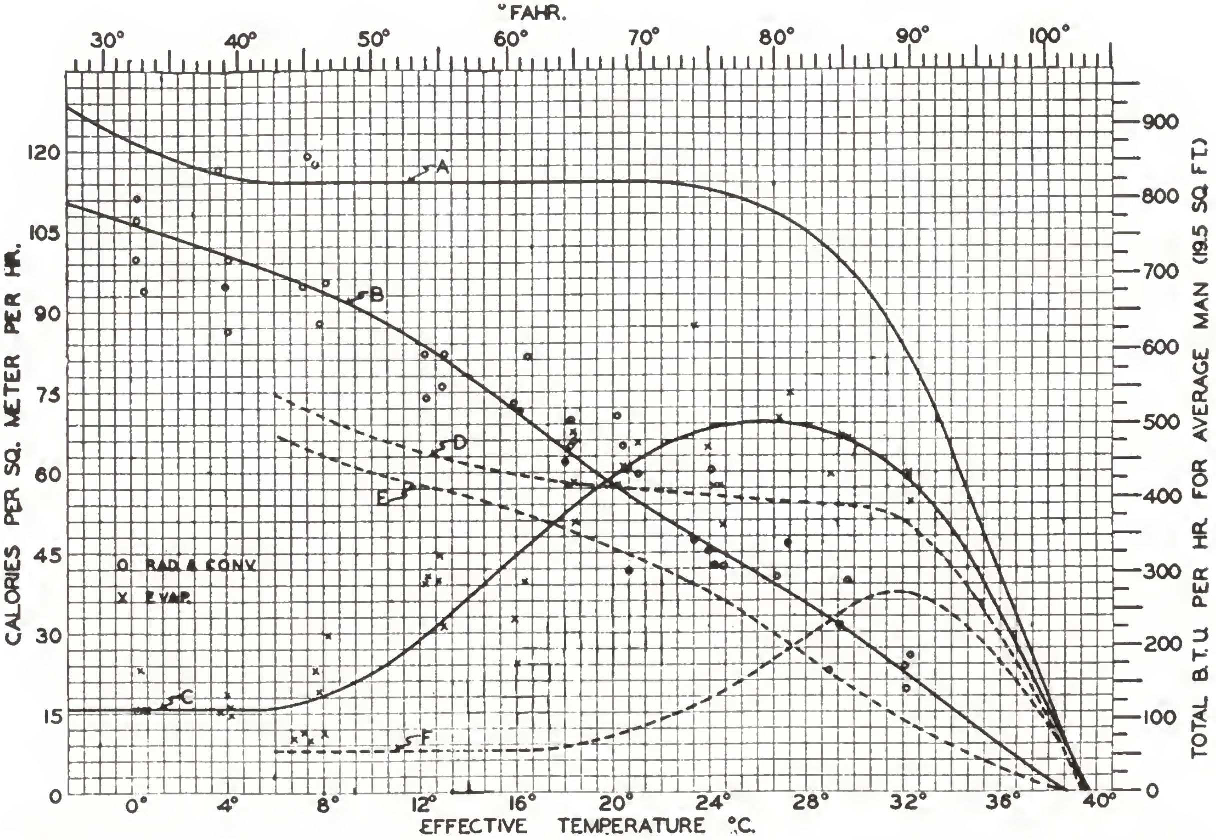
P_a = Saturated vapor pressure at air temperature, inches Hg.

Examining equation (2) it can be seen that when relative humidity increases, the term (P_s - RH x P_a) decreases and thus the evaporative heat loss E, also decreases.

Now consider the environment encountered in an Oceanographic Research Vessel. Since the bottom of the vessel is open to the water, the air inside the vessel becomes saturated. This was also reported by Captain Costeau (1) in his Conshelf Two expedition. Hence, the air inside the vessel is expected to have 100 percent relative humidity.

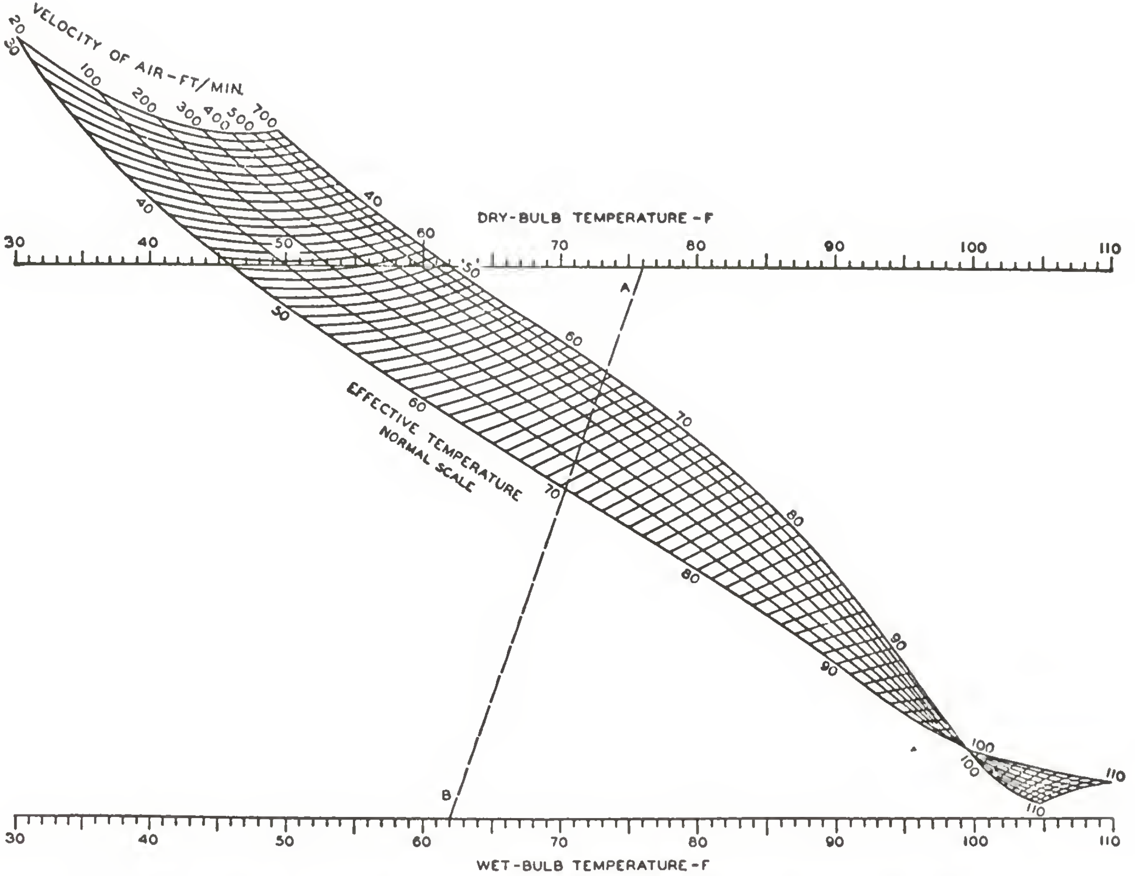
Putting this value of relative humidity in equation (2) it can be noted that the term (P_s - RH x P_a) is zero and consequently the evaporative heat loss is zero.

This conclusion is supported by the work of F. C. Houghton et.al. (11) at the ASHVE research laboratory. Heat losses from human subjects were determined with the relative humidity equal to twenty percent and 95 percent. Figure 2 is the reporduction of their work and shows the relation between the heat losses from the human body and the effective temperature. The effective temperature is defined as an empircal sensory index combining into a single value the thermal effect of temperature, humidity, and movement of air upon the human body (12). The effective temperature can be read from Figure 3, which is the reproduction from ASHRAE Guide and Data Book (12). Since the relative humidity in the Oceanographic Research Vessel is assumed to be 100 percent, the effective, dry bulb and wet bulb temperatures will all be the same, as can be seen from Effective Temperature chart. Examining Figure 2, we note that the evaporative heat losses for an individual seated



FIG·2. Relation Between Heat Loss from the Human Body and Effective Temperature at 95 Per Cent Relative Humidity *

* *A*—Total heat loss, at work. *B*—Loss by radiation and convection, at work. *C*—Loss by evaporation, at work. *D*—Total heat loss, seated at rest. *E*—Loss by radiation and convection, seated at rest. *F*—Loss by evaporation, seated at rest.



A. Clothing: Customary indoor clothing. B. Activity: Sedentary or light muscular work. C. Heating Methods: Convection type, i.e., warm air, direct steam or hot water radiators, plenum systems.

FIG· 3. .... Effective Temperature Chart Showing Normal Scale of Effective Temperature, Applicable to Inhabitants of the United States Under Conditions Stated at rest, for 95 percent humidity, are very low. Hence, for 100 percent relative humidity the losses can be expected to be still lower or none at all for all practical purposes.

Based on the foregoing discussion, it will be assumed that K = 0, S = 0, E = 0. Thus, equation (1) reduces to,

$$M = \pm R \pm C \qquad (3)$$

Radiative Heat Losses, 'R'

The net radiative heat exchange between an oceanaut and his environments in an Oceanographic Research Vessel is given by the following equation as obtained from literature (13).

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

σ = Stefan - Boltzman constant.

= 0.1713×10^{-8} BTU per square feet - hour - (degrees R)^4

(14, page 59)

A_r = Radiative surface area of the oceanaut, square feet.

ε_1 = Emissivity of the human skin.

ε_2 = Emissivity of the environments.

A_e = Surface area of environment, square feet.

T_s = Average skin temperature, degrees R.

T_{mrt} = Mean radiant temperature, degrees R.

Radiative Surface Area

Radiative surface area is that area of the body which is contributing to the heat loss by radiation. The skin areas between fingers, under the arms, between the legs, under the chin, etc. radiate to adjacent skin area, but do not 'see' the surfaces of the enclosure. Thus, for radiative heat transfer only a portion of total body surface area is to be considered as the effective radiative area. Eugene DuBois and Delafield DuBois (15) developed an equation for the total surface area of the human body, based on the known height and weight of the individual. The total DuBois surface area is given by,

$$A = (W)^{.425} (H)^{.725} (C) \qquad (5)$$

where,

A = Total surface area, square meters.

W = Weight of an individual, kilograms.

H = Height of an individual, centimeters.

C = DuBois constant.

= 71.84 square meters per $(\text{kgm.})^{.425} - (\text{cms.})^{.725}$

Equation (5) is graphed in Figure 4. If an average man is considered to weigh 150 pounds (68.18 Kg) and is 68 inches (172.72 cm) tall, the surface area is found to be 1.8 square meters or 19.5 square feet.

The effective radiation area also depends on the position of an individual. For example, when a man is curled up with knees drawn up against the chest, his radiative area is much less as compared to the fully extended, 'spead eagle,' configuration. It is assumed that the oceanaut an oceanographic research vessel is in a normal position and DuBois (16) has found that for normal positions the effective radiative area is about 80 percent of the total surface area.

For this case, the radiative area is, therefore, 15.5 square feet.

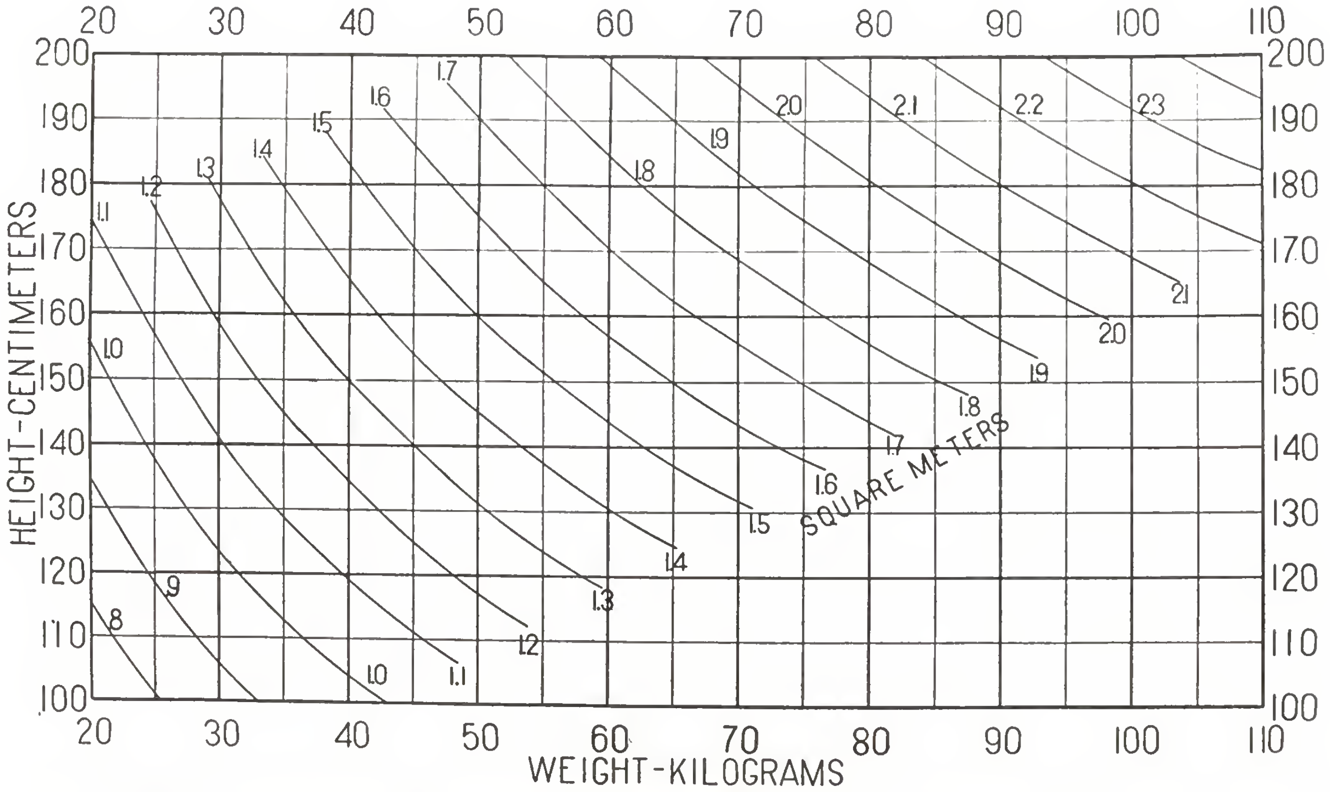


Fig. 4.—Chart for determining surface area of man in square meters from weight in kilograms (Wt.) and height in centimeters (Ht.) according to the formula: Area (Sq. Cm.) $=\text{Wt.}^{0.425} \times \text{Ht.}^{0.725} \times 71.84$.

Shape Factor

Since the oceanaut is completely enclosed in the oceanographic research vessel, the shape factor, F_{12}, from oceanaut to the environments is unity.

Emissivity of the Oceanaut and the Environments

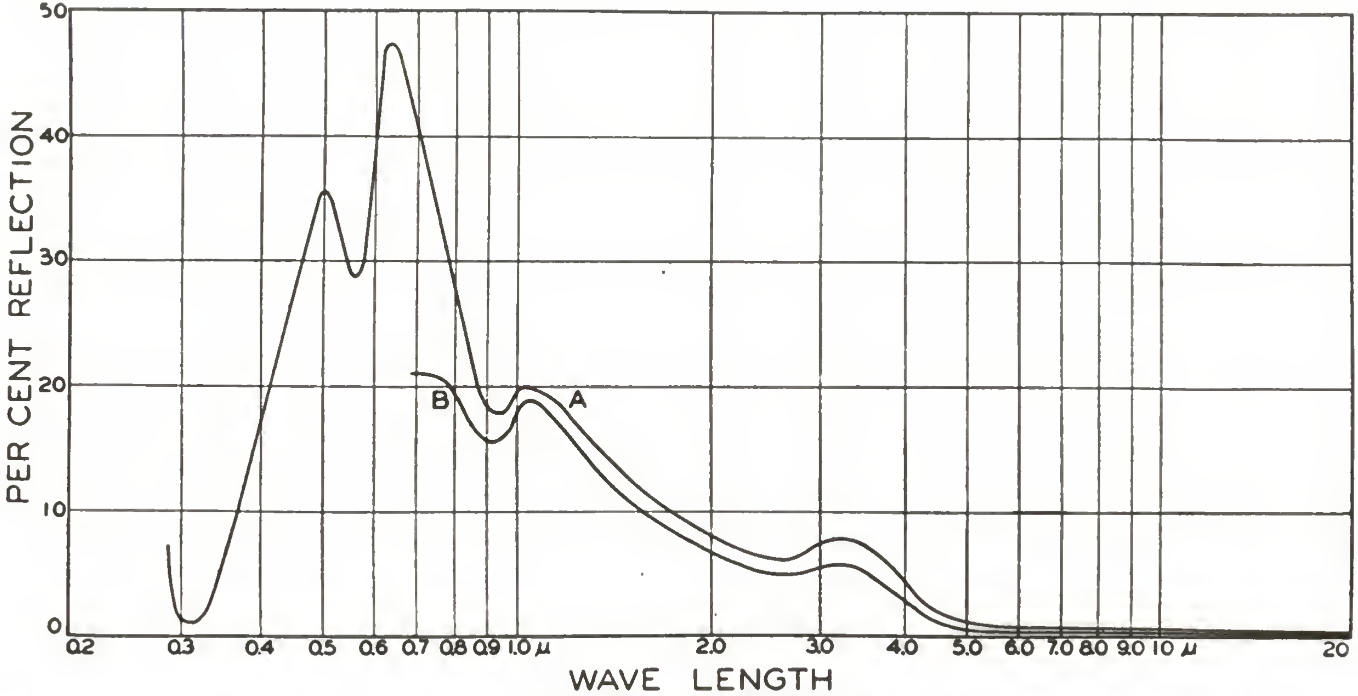
By definition, a black body is one which does not reflect any radiation . Most of the surfaces which are full are black bodies or almost so the human skin belongs to this class. The reflecting power of the human skin varies with wave length as shown in Figure 5, as taken from reference (17). It can be seen that human skin is a good reflector in the visible light spectrum but does not reflect in infra red region. It was shown by Hardy and Muschenchein (18), that in the infra red region and regardless of color, human skin approximates the black body. The emissivity of the human skin for this report is taken as 0.94 (6).

Another important factor that must be considered for the radiative heat loss is the emissivity of the environment. As can be seen in the literature (14) most dull surfaces have a high value of emissivity. It has been, therefore, assumed that the indoor environment of an Oceanographic Research Vessel is not composed of any shining surfaces and hence, the emissivity of the environment is close to unity. Emissivities of a few materials are given in Table II (17).

TABLE II

Emissivities of a Few Materials

Inside of a black cone	1.00
Roughned rubber	0.98
Black laquer (glossy)	0.95
White laquer (glossy)	0.95
Copper (polished)	0.10 - 0.15
Silver (polished)	0.02



FIG· 5 Reflecting power of white and Negro skin. *A*, white skin; *B*, Negro skin. (Modified from Büttner, K.: Strahlentherapie *58*, and Hardy, J. D.: J. Clin. Investigation, Vol. 13.)

Skin Temperature: The surface temperature of all parts of the human body is not the same and hence, an average temperature is used for the heat loss calculations. This average temperature is obtained by measuring the skin temperature of the various parts of the body and weighing these according to the proportion of the surface area of the part. Hardy and Du Bois (19) suggested the following weighing factors for the various parts of the body.

	TABLE III	
Part of the Body	Temperature	Weighing Factor
Head	T_1	.07
Arms	T_2	.14
Hands	T_3	.05
Feet	T_4	.07
Legs	T_5	.13
Thighs	T_6	.19
Trunk	T_7	.35
		1.00

The average skin temperature is thus given by the equation:

$$T_s = .07\ T_1 + .14\ T_2 + .05\ T_3 + .07\ T_4 + .13\ T_5 + .19\ T_6 + .35\ T_7$$

Mean Radiant Temperature: The radiative heat transfer depends on the difference between the fourth power of the weighed mean skin temperature (absolute) and the fourth power of a weighed mean temperature (absolute) of the surroundings, which may include the surface temperatures of furniture, walls, windows and other articles in the vessel. This average temperature which is used for calculating the radiative heat loss is known as mean radiant temperature and may be defined as the uniform surface temperature of a black body enclosure which would give rise to the same net radiant heat loss as that which occurs in the actual enclosure being investigated.

The area of the environments is considered to be very large as compared to the area of an oceanaut.

A summary of the physical and other data required for calculating the radiative heat loss is given in Table IV.

TABLE IV

Summary of Physical and Other Data Used in Calculating Radiative Heat Loss

Average weight	150 lbs.
Average height	68 inches
Du Bois Surface area	19.5 square feet
Average effective body area of radiation	15.5 square feet
Average body emissivity, ε_1 .	0.94
Emissivity of the environment, ε_2.	1.0
Shape factor, man to environment, F_{12}.	1.0

Substituting the values from Table IV in equation 4, the Radiative heat loss is given by ,

$$R = 2.49 \times 10^{-8} (T_s^4 - T_{mrt}^4) \quad (7)$$

Convective Heat Loss

Unlike radiation, the convective heat transfer depends upon the properties of the surrounding medium which in an Oceanographic Research Vessel may be air, or a mixture of oxygen and helium.

It is assumed from this report that the velocity of air entering the vessel is negligible and hence, conditions for free or natural convection prevail in the vessel.

The convective heat loss can be calculated from the equation,

$$C = h \ A_c (t_s - t_a) \quad (8)$$

where,

h = Convective heat transfer coefficient, BTU per hour - square feet - F.

A_c = A convective area of the oceanaut, square feet.

t_s = Average skin temperature, F.

t_a = Dry bulb temperature of ambient fluid, F.

Although equation (8) looks simple, in reality the convective heat loss is extremely difficult to evaluate because of the complicated nature of convective heat transfer coefficient ',h'.

'h' depends on the following factors.

(1) The composition and properties of the surrounding fluid, which in this case may air or a mixture of oxygen and helium.

(2) The geometry of the body.

(3) The temperature difference: For free convection, the film coefficient increases as the temperature difference between the body surface and the fluid increases. For forced convection, the film coefficient is practically independent of the temperature difference (14).

The coefficient of heat transfer may be expressed as,

$$h = f(L, \mu, \rho, k, C_p, \Delta t, \beta, g) \qquad (9)$$

where,

L = Characteristic geometrical dimension which in this case is height, feet.

μ = Viscosity of the fluid, pounds per hour - feet.

ρ = Density of the fluid, pounds per cubic feet.

k = Thermal conductivity of the fluid, BTU per hour - feet - deg. F.

C_p = Specific heat at constant pressure of the fluid, BTU per lb.-deg. F.

Δt = Temperature difference between body surface and ambient air, deg.F.

β = Coefficient of volumetric expansion, per degree F.

Very complicated geometrical shape of the human body makes it almost impossible to determine the value of the convective heat transfer coefficient accurately. Most of the work in the area of convective heat transfer has dealt with simple geometrical shapes such as spheres, cylinders, planes, etc. No attempt has been made to actually determine the convective heat transfer coefficient of the human body. The convective heat transfer coefficient h, may be estimated by approximating the human body by a simple geometrical shape for which a correlation equation for the convective heat transfer coefficient already exists. If the surface area of an average man is assumed to be 19.5 feet, the average human body can be approximated by a vertical cylinder having a diameter of 13 inches and height of 68 inches (20); which gives a surface area of 19.5 square feet.

McAdams (14) suggests the following equation for determination of the heat transfer coefficient for vertical cylinders with natural convection.

$$\frac{h\ L}{k} = 0.59\left[\frac{L^3\ \rho^2\ g}{\mu^2}\ \beta(\Delta t)\ \frac{C_p\ \mu}{k}\right]^{.25} \qquad (10)$$

where,

g = Acceleration due to gravity.

$= 4.17 \times 10^{-8}$ feet per $(\text{hour})^2$

The other terms are defined as before.

Property values for air were obtained from reference (21). The values for ρ, and k were evaluated at a pressure of four atmospheres and at different temperatures. The variation of viscosity with pressure was considered negligible hence, the viscotity was evaluated at a pressure of one atmosphere for the various temperatures. The values of all these variables were plotted as functions of temperature in the range of 62 degree F and 90 degree F and these plots are shown in Figures 13, 14, 15, and 16 in Appendix I.

It was noted that the specific heat C_p was essentially constant for the range of temperature and pressure considered. The specific heat at 62 degrees F is .241478 BTU per pound - F and that at 98 degrees F is 0.241485.

Determination of Convective Heat Transfer Coefficient at Different Temperatures

Rearranging and simplifying equation (10), we have

$$\frac{h}{(\Delta t)^{.25}} = C_c = (.059)\,(k)^{.75}\left[\frac{g\,C_p}{L}\quad\frac{\rho^2\beta}{\mu}\right]^{.25} \qquad (11)$$

where $C_c = \frac{h}{(\Delta t)^{.25}}$, BTU per hour (degree F)$^{1.25}$

Now substituting the values of factors which do not change within the temperature range considered, namely g, C_p, and L equation (11) reduces to,

$$C_c = (0.59)\,(k)^{.75}\left[17,\,734,\,700\,\frac{\rho^2\beta}{\mu}\right]^{.25} \qquad (12)$$

Using equation (12) C_c was determined for the temperature range, 62 to 90 degrees F, at intervals of two degrees. The values of C_c along with other variables are shown in Table V and variation of C_c with respect to temperature is plotted in Figure 17 in Appendix I.

As stated before, the convective surface area of an average human being is assumed to be 19.5 square feet. Now substituting C_c in place of 'h' in equation (8), we finally get,

$$C = C_c\,(19.5)\,(t_s - t_a)^{1.25}$$

The above equation can also be written in terms of absolute temperatures. Hence, the convective heat exchange is given by,

$$C = C_c\,(19.5)(T_s - T_a)^{1.25} \qquad (13)$$

where, T_a and T_s are in degrees Rankine.

DETERMINATION OF RELATIONSHIP BETWEEN MEAN RADIANT TEMPERATURE AND AMBIENT AIR TEMPERATURE

Combining equations (7) and (13) and substituting into equation (3) the relationship between mean radiant temperature and ambient air temperature can be obtained for an assumed value of 'M' and 'T_s'. Equation (3) reduces to,

$$M = 2.49 \times 10^{-8} (T_s^4 - T_{mrt}^4) + (19.5)\, C_c\, (T_s - T_a)^{1.25}$$

Rearranging and simplifying the above equation the relation between mean radiant temperature and ambient air temperature is obtained, namely

$$T_{mrt} = \left[T_s^4 - \frac{10^8}{2.49} \left\{ M - (19.5)\, C_c\, (T_s - T_a)^{1.25} \right\} \right]^{.25} \qquad (14)$$

From equation (14), the relationship between mean radiant temperature and the ambient air temperature can be obtained for various skin temperatures and metabolic rates. However, for this report, the oceanaut is considered to be 'near sedentary' and 'moderately active' for which the metabolic rate was shown to be 400 BTU per hour and 600 BTU per hour respectively. The average skin temperatures considered are in a range that are usually considered to be comfortable for a normal human being. It was shown by C.P. Yaglou and Anne Messer (22) that under comfortable conditions the mean skin temperature of men and women is 92 degrees F; hence, for this report the skin temperatures were taken in the range of 90 degrees F to 96 degrees F, since the oceanaut will generally be naked.

The relationships obtained for air for metabolic rates of 400 BTU per hour 600 BTU per hour are tabulated in Table VI and Table VII respectively. The values of C_c are taken at film temperatures, 'T_f,' which is defined as the mean of the skin temperature and the ambient air temperature.

The relationship between mean radiant temperature and ambient air temperature is plotted in Figure 6 for a metabolic rate of 400 BTU per hour and in Figure 7 for a metabolic rate of 600 BTU per hour.

TABLE VI

RELATIONSHIP BETWEEN AMBIENT AIR TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 400 BTU/HOUR

Pr. = 4atm., RH = 100%, E=K=0

T_s °F	T_a °F	T_f °F	C_c BTU/Hr.$(^oF)^{1.25}$	T_{mrt} °R
90	62	76	.40586278	556.50684
90	66	78	.40543991	551.20145
90	70	80	.40467279	545.95778
90	74	82	.40442920	540.86546
90	78	84	.40396514	535.94902
90	82	86	.40353988	531.31999
90	86	88	.40298751	527.16013
90	90	90	.40259738	524.08666
92	62	77	.40565134	561.04996
92	66	79	.40505595	555.76545
92	70	81	.40455099	550.55378
92	74	83	.40419717	545.45082
92	78	85	.40375251	540.49509
92	82	87	.40326369	535.76791
92	86	89	.40279244	531.40086
92	90	91	.40232119	527.67547
94	62	78	.40543991	565.54556
94	66	80	.40467279	560.28472
94	70	82	.40442920	555.11420
94	74	84	.40396514	550.01082
94	78	86	.40353988	545.03399
94	82	88	.40298751	540.23982
94	86	90	.40259738	535.73367
94	90	92	.40218900	531.68805
96	62	79	.40505595	569.97868
96	66	81	.40455099	564.77807
96	70	83	.40419717	559.62944
96	74	85	.40375251	554.54117
96	78	87	.40326369	549.55362
96	82	89	.40279244	544.72052
96	86	91	.40232119	540.11585
96	90	93	.40189800	535.86574

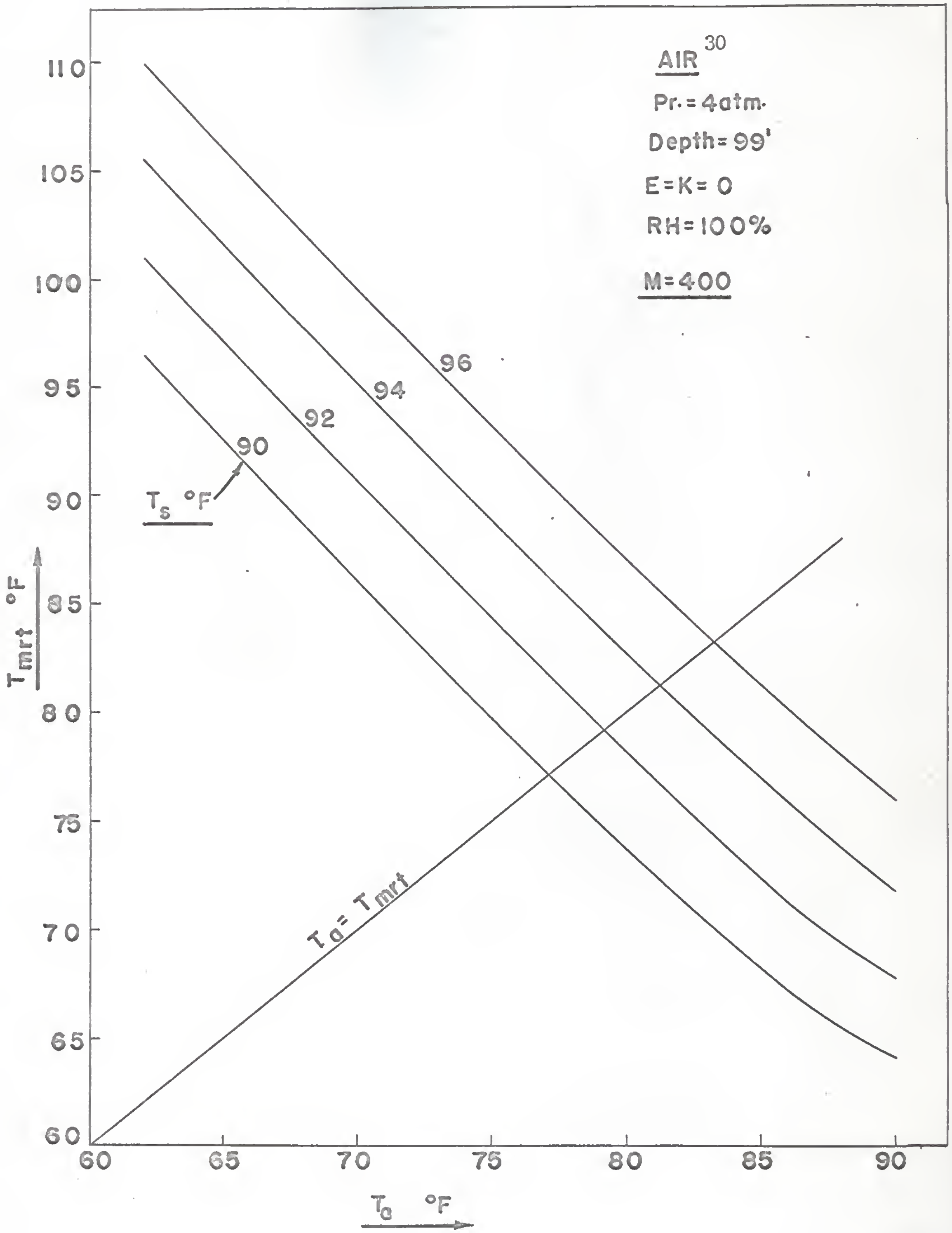


FIGURE 6

RELATION BETWEEN AMBIENT AIR TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 400 BTU/HOUR Pr.=4atm. RH = 100%, E=K=0

TABLE VIII

RELATIONSHIP BETWEEN AMBIENT AIR TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BUT/HOUR
Pr. = 4 atm., RH = 100%, E=K=0

T_s ^oF	T_a ^oF	T_f ^oF	C_c BTU/Hr.$(^oF)^{1.25}$	T_{mrt} ^oR
90	62	76	.40586278	544.47115
90	66	78	.40543991	538.79850
90	70	80	.40467279	533.17657
90	74	82	.40442920	527.70143
90	78	84	.40396514	522.40025
90	82	86	.40353988	517.39451
90	86	88	.40298751	512.83578
90	90	90	.40259738	509.54290
92	62	77	.40565134	549.31682
92	66	79	.40505595	543.67936
92	70	81	.40455099	538.10497
92	74	83	.40419717	532.63216
92	78	85	.40375251	527.30264
92	82	87	.40326369	522.20469
92	86	89	.40279244	517.48190
92	90	91	.40232119	513.44291
94	62	78	.40543991	554.10182
94	66	80	.40467279	548.50146
94	70	82	.40442920	542.98356
94	74	84	.40396514	537.52333
94	78	86	.40353988	532.18440
94	82	88	.40298751	527.02762
94	86	90	.40259738	522.16762
94	90	92	.40218900	517.79295
96	62	79	.40505595	558.81052
96	66	81	.40455099	553.28551
96	70	83	.40419717	547.80296
96	74	85	.40375251	542.37115
96	78	87	.40326369	537.03360
96	82	89	.40279244	531.84779
96	86	91	.40232119	526.89408
96	90	93	.40189800	522.31019

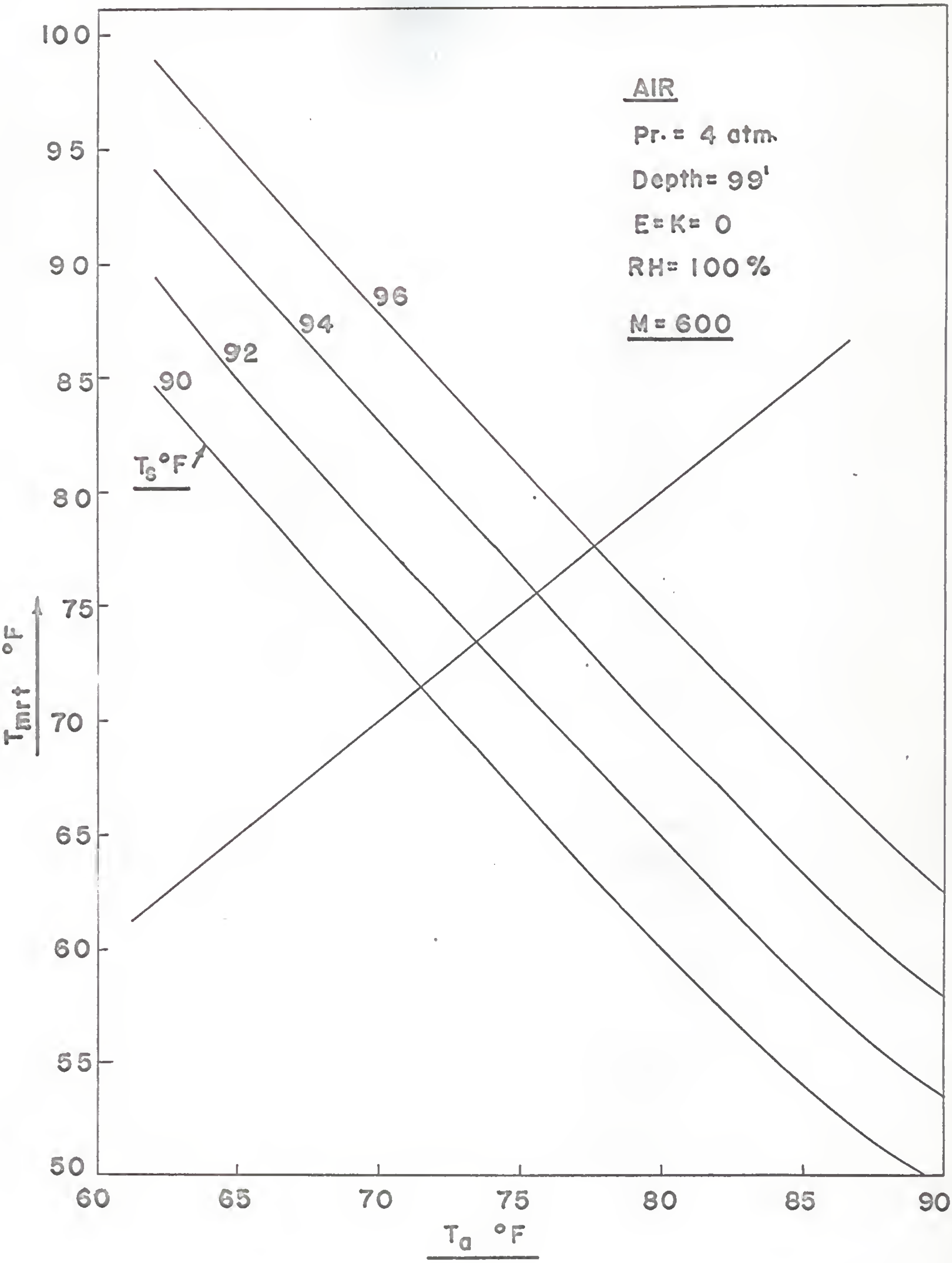


FIGURE 7

RELATION BETWEEN AMBIENT AIR TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HOUR Pr. = 4atm. RH = 100%, E=K=0

ENVIRONMENT OF OXYGEN AND HELIUM

An atmosphere of a mixture of oxygen and helium is necessary to avoid the nitrogen narcosis in deep waters. The heat loss analysis will be affected so that calculations were made for this atmosphere. It can be seen from equation (4) that the radiative heat loss is not affected by any change in the environmental medium, because the radiative heat loss does not depend on the properties of the surrounding fluid. The only factor that would be affected is the convective heat loss, since the convective heat transfer coefficient varies with the properties of the surrounding fluid.

The actual composition of the O_2-He environment is determined from a consideration of the amount of O_2 required for breathing. It is the partial pressure of the constituent gas which determines whether the amount of oxygen in the breathing medium is adequate. For example, atmospheric air contains about twenty-one percent oxygen and considering air to be an ideal gas, according to Dalton's law of partial pressures, this provides an oxygen partial pressure of 0.21 atmospheres. This is ample for human beings at sea level, but a drop to 0.16 atmospheres will cause the onset of anoxic symptoms (i.e. the condition in which the tissue cells fail to receive or utilize enough oxygen to maintain their life and normal function). If the partial pressure gets as low as 0.10 atmospheres, unconsciousness usually appears; permanent brain damage and death are only a matter of time (3).

It may not seem reasonable that the danger may arise due to 'too much oxygen' but this is an important factor in deep sea diving. Oxygen poisoning does not enter the picture unless the partial pressure of the oxygen is higher than that at the surface. If the partial pressure of oxygen gets high enough, it can cause convulsions (fits and seizures) which may lead to a number of mishaps under water, viz. muscular twitching, nausea, abnormalities of vision or hearing, difficulties in breathing, unusual fatigue, etc. It is known that the maximum partial pressure of oxygen that an individual can withstand is of the order of about 8 p.s.i. (24). This of course, is an extreme value; the partial pressure of oxygen for comfortable breathing is 0.21 atmospheres or 2.94 p.s.i. In an Oceanographic Research Vessel, a lower percentage of oxygen would suffice to maintain an adequate partial pressure of oxygen. At a depth of 100 feet, five percent oxygen should be enough because the partial pressure is given by,

$$P_o = C_o \times P_t \qquad (16)$$

where,

P_o = Partial pressure of oxygen.

C_o = Proportion of oxygen.

P_t = Total pressure of atmosphere.

Hence, $P_o = .05 \times 4$

$= .20$ atmospheres.

It can, therefore, be seen that for comfortable breathing conditions, the proportion of oxygen would be very low as compared to that of helium, and it will be quite reasonable to assume that the coefficient of heat transfer depends only on the properties of helium.

The properties of helium were obtained from reference (23). Again, it is noted that the viscosity of helium at one atmosphere is practically the same as that at four atmospheres. This confirms the view that viscosity is not a function of pressure, at least for the pressures considered in this report. Figures 18, 19, and 20 in Appendix I are the reproduction of the plots (22) for the properties of helium.

Substituting the various constants into equation (11), the heat transfer coefficient for helium is given by,

$$C_c = 0.59 \times (k)^{.75} \left[91.66 \times 10^6 \times \frac{\rho^2\beta}{\mu} \right]^{.25} \qquad (17)$$

Using equation (17) values of C_c are tabulated in Table VIII for a temperature range of 76 to 94 and a pressure of four atmospheres. Variation of C_c with respect to temperature is shown in Figure 21, in Appendix I.

Finally, equation (14) is solved for different values of C_c for helium and the relationship, between mean radiant temperature and ambient air temperature is plotted in Figure 8 for metabolic rate of 400 BTU per hour and skin temperatures of 90 degree F to 96 degree F. Relationship is also plotted for a metabolic rate of 600 BTU per hour in Figure 9.

TABLE IX

RELATIONSHIP BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 400 BTU/HOUR

Pr. = 4atm., RH = 100%, E=K=0

T_s °F	T_a °F	T_f °F	C_c BTU/Hr.(°F)$^{1.25}$	T_{mrt} oR
90	62	76	.80503804	583.66019
90	66	78	.80400507	574.44167
90	70	80	.80271797	565.17361
90	74	82	.80190908	555.96062
90	78	84	.80097144	546.88627
90	82	86	.79996224	538.14910
90	86	88	.79935768	530.13148
90	90	90	.79858657	524.08666
92	62	77	.80465843	589.81720
92	66	79	.80337619	580.70719
92	70	81	.80213708	571.54685
92	74	83	.80137892	562.40929
92	78	85	.80030420	553.34515
92	82	87	.79959036	544.52309
92	86	89	.79887214	536.18843
92	90	91	.79796591	528.92490
94	62	78	.80400507	595.85387
94	66	80	.80271797	586.87019
94	70	82	.80190908	577.84551
94	74	84	.80097144	568.78554
94	78	86	.79996224	559.76550
94	82	88	.79935768	550.91176
94	86	90	.79858657	542.39236
94	90	92	.79787322	534.57987
96	62	79	.80337619	601.79127
96	66	81	.80213708	592.93819
96	70	83	.80137892	584.03438
96	74	85	.80030420	575.06545
96	78	87	.79959036	566.12271
96	82	89	.79887214	557.27267
96	86	91	.79796591	548.65347
96	90	93	.79760042	540.53227

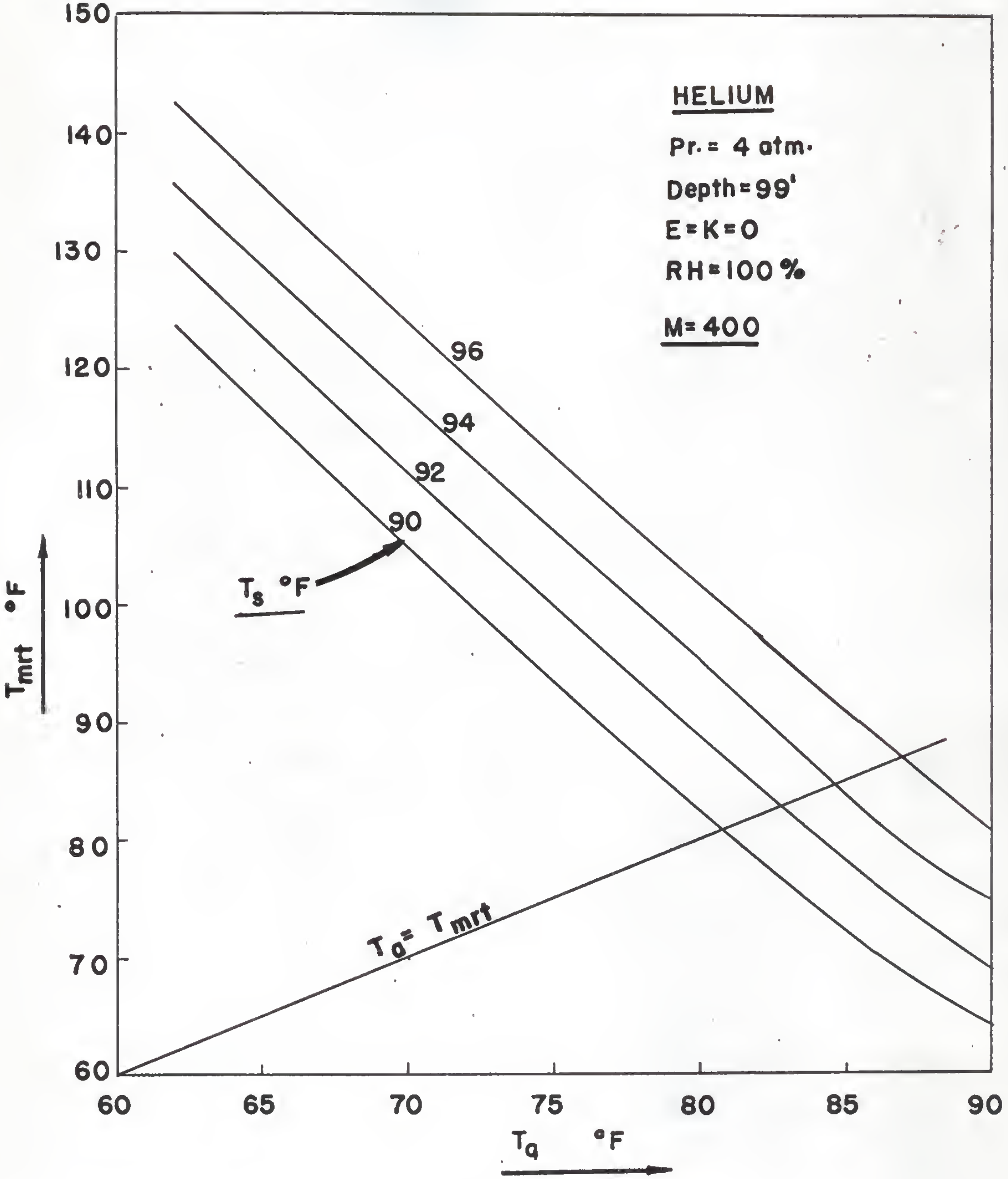


FIGURE 8

RELATION BETWEEN AMBIENT AIR TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 400 BTU/HOUR pr. = 4atm. RH = 100%, E=K=0

TALBE X

RELATIONSHIP BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HOUR

Pr. = 4atm., RH = 100%, E=K=0

T_s °F	T_a °F	T_f °F	C_c BTU/Hr.(°F)$^{1.25}$	T_{mrt} °F
90	62	76	.80503804	113.28768
90	66	78	.80400507	103.54200
90	70	80	.80271797	93.70611
90	74	82	.80190908	83.88773
90	78	84	.80097144	74.17321
90	82	86	.79996224	64.77435
90	86	88	.79935768	56.10692
90	90	90	.79858657	49.54290
92	62	77	.80465843	119.77747
92	66	79	.80337619	110.16976
92	70	81	.80213708	100.47417
92	74	83	.80137892	90.76480
92	78	85	.80030420	81.09245
92	82	87	.79959036	71.63569
92	86	89	.79887214	62.65864
92	90	91	.79796591	54.79870
94	62	78	.80400507	126.12633
94	66	80	.80271797	116.67310
94	70	82	.80190908	107.14480
94	74	84	.80097144	97.54407
94	78	86	.79996224	87.94787
94	82	88	.79935768	78.48840
94	86	90	.79858657	69.34476
94	90	92	.79787322	60.92108
96	62	79	.80337619	132.35798
96	66	81	.80213708	123.06143
96	70	83	.80137892	113.68252
96	74	85	.80030420	104.20262
96	78	87	.79959036	94.71533
96	82	89	.79887214	85.28874
96	86	91	.79796591	76.06871
96	90	93	.79760042	67.34261

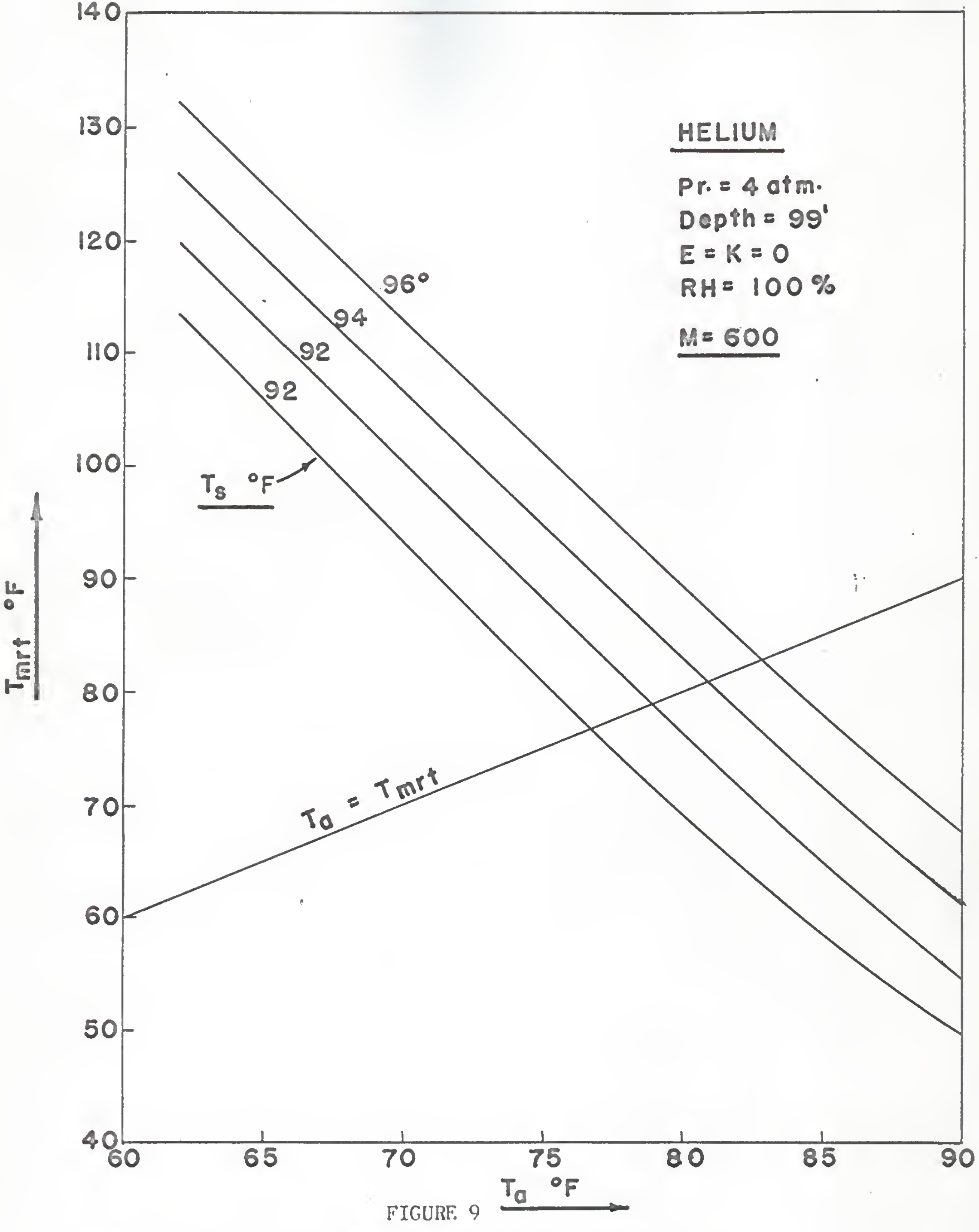


FIGURE 9

RELATION BETWEEN AMBIENT HELIUM TEMPERATURE AND
MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR
Pressure = 4 atm., RH = 100%, E=K=0

DISCUSSION AND CONCLUSIONS

In this analysis the heat losses from an oceanaut in an Oceanographic Research Vessel are considered for 'near sedentary' and 'moderately active' conditions. However, if other than those conditions are encountered, equation (14) can be used with the appropriate change in the values of M (see Appendix II for the Fortran Program).

If the Oceanographic Research Vessel is to be air conditioned for comfort of oceanauts, various combinations of mean radiant temperature and ambient air temperature can be utilized for comfortable skin temperature, which according to Yaglou and Messer (22) is 92 degrees F. This skin temperature, however, varies according to individuals and hence, the value may be chosen to suit the individuals. The mean radiant temperature will depend mostly on the temperature of the walls which in turn would depend upon the temperature of the water surrounding the vessel, because as explained before, the walls of the vessel need not be very thick due to pressure equalization. The temperature of water varies with the geographical location, time of the year, and the depth.

We may examine the conditions for which the mean radiant temperature and the ambient air temperature are equal. Taking the value of skin temperatures as 92 degrees F, which is normal for a nude individual, the following observations may be made from Figures 6, 7, 8, and 9.

(1) For 'near sedentary' conditions, an air environment and a pressure of four atmospheres, $T_a = T_{mrt} = 79$ degree F. For the same conditions with a helium environment, $T_a = T_{mrt} = 82.9$ degree F.

(2) For 'moderately active' condition, an air environment and a pressure of four atmospheres, $T_a = T_{mrt} = 73.5$ degree F. For the same conditions, with a helium environment, $T_a = T_{mrt} = 78.9$ degree F.

As given in ASHRAE Guide and Data Book (12, page 116), the comfortable mean temperature (with an air environment, press.=1atm.) for winter and summer conditions, is 77.5 degree F, which is in reasonably good agreement with the results obtained for air. Edwin A. Link (25) reported that in an atmosphere of helium-oxygen mixture, the comfortable temperature was 86 degree F and the results obtained here are also in good agreement with this.

The relationship between mean radiant temperature and dry bulb temperature for oxygen-helium mixtures at pressures of 13 atmospheres (396 feet), 31 atmospheres (990 feet) and 61 atmospheres (1980 feet) are shown in Figures 10, 11, and 12. At these depths, the water is expected to be very cold (25), hence an oceanaut would wear some type of diving suit. Due to the insulating value of the suit, the average surface temperature T_s, is of the order of about 82^oF. A summary of results for $T_a = T_{mrt}$ is given in Table IX.

TABLE XI

Pressure Atmospheres	Depth Feet	M BTU/HR	Medium	T_s ^oF	$T_a = T_{mrt}$ ^oF
4	99		Air	92	79
4	99	400	Helium	92	82.9
4	99	600	Air	92	73.5
4	99	600	Helium	92	78.9
13	396	600	Helium	82	73.4
13	396	600	Helium	92	83.2
31	990	600	Helium	82	75.6
31	990	600	Helium	92	85.7
61	1880	600	Helium	82	76.4
61	1880	600	Helium	92	86.8

TABLE XII

RELATIONSHIP BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR
Pressure = 13 atm., RH = 100%, E=K=0

T_s °F	T_a °F	C_c BTU/Hr(°F)$^{1.25}$	T_{mrt} °F
82.00	62.00	1.5820	121.8307
82.00	64.00	1.5820	113.4442
82.00	66.00	1.5820	104.9188
82.00	68.00	1.5820	96.2709
82.00	70.00	1.5820	87.5268
82.00	72.00	1.5820	78.7279
82.00	74.00	1.5820	69.9408
82.00	76.00	1.5820	61.2731
82.00	78.00	1.5820	52.9097
82.00	80.00	1.5820	45.2129
86.00	62.00	1.5820	141.1410
86.00	64.00	1.5820	133.1787
86.00	66.00	1.5820	125.0729
86.00	68.00	1.5820	116.8290
86.00	70.00	1.5820	108.4573
86.00	72.00	1.5820	99.9750
86.00	74.00	1.5820	91.4085
86.00	76.00	1.5820	82.8002
86.00	78.00	1.5820	74.2158
86.00	80.00	1.5820	65.7611
92.00	62.00	1.5820	168.1958
92.00	64.00	1.5820	160.8186
92.00	66.00	1.5820	153.3070
92.00	68.00	1.5820	145.6601
92.00	70.00	1.5820	137.8796
92.00	72.00	1.5820	129.9684
92.00	74.00	1.5820	121.9339
92.00	76.00	1.5820	113.7869
92.00	78.00	1.5820	105.5455
92.00	80.00	1.5820	97.2374
94.00	62.00	1.5820	176.7534
94.00	64.00	1.5820	169.5555
94.00	66.00	1.5820	162.2275
94.00	68.00	1.5820	154.7679
94.00	70.00	1.5820	147.1768
94.00	72.00	1.5820	139.4558
94.00	74.00	1.5820	131.6087
94.00	76.00	1.5820	123.6426
94.00	78.00	1.5820	115.5690
94.00	80.00	1.5820	107.4061

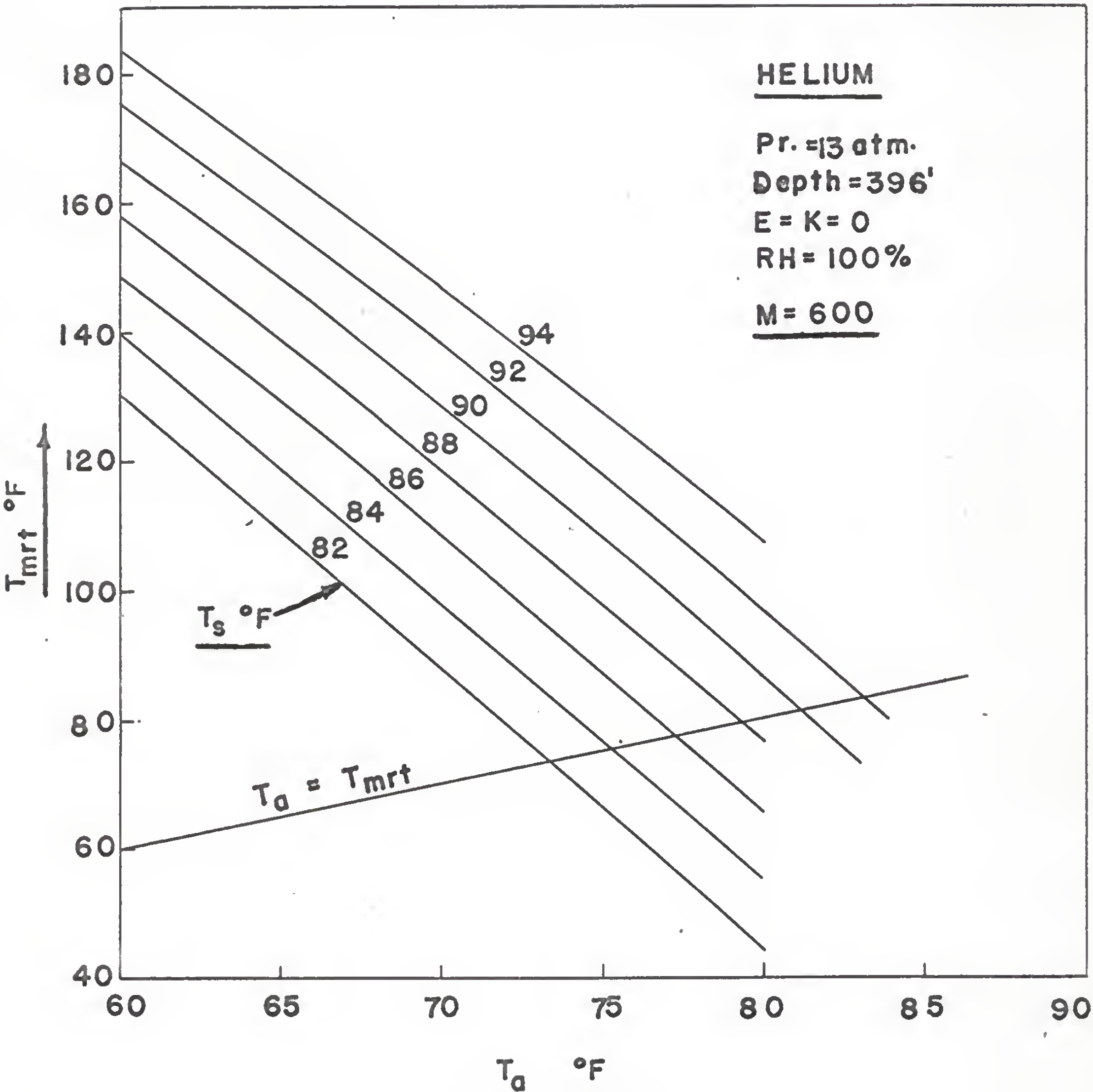


FIGURE 10

RELATION BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR Pressure = 13 atm., RH = 100%, E=K=0

TABLE XIII

RELATIONSHIP BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR
Pressure = 31 atm., RH = 100%, E=K=0

T_s ^oF	T_a ^oF	C_c BTU/Hr$(^oF)^{1.25}$	T_{mrt} ^oF
82.00	62.00	2.4837	156.5129
82.00	64.00	2.4837	145.3850
82.00	66.00	2.4837	133.9398
82.00	68.00	2.4837	122.1781
82.00	70.00	2.4837	110.1119
82.00	72.00	2.4837	97.7724
82.00	74.00	2.4837	85.2261
82.00	76.00	2.4837	72.6023
82.00	78.00	2.4837	60.1556
82.00	80.00	2.4837	48.4380
86.00	62.00	2.4837	180.3123
86.00	64.00	2.4837	169.9219
86.00	66.00	2.4837	159.2428
86.00	68.00	2.4837	148.2668
86.00	70.00	2.4837	136.9898
86.00	72.00	2.4837	125.4146
86.00	74.00	2.4837	113.5557
86.00	76.00	2.4837	101.4469
86.00	78.00	2.4837	89.1566
86.00	80.00	2.4837	76.8145
92.00	62.00	2.4837	213.1369
92.00	64.00	2.4837	203.6913
92.00	66.00	2.4837	194.0026
92.00	68.00	2.4837	184.0611
92.00	70.00	2.4837	173.8570
92.00	72.00	2.4837	163.3824
92.00	74.00	2.4837	152.6312
92.00	76.00	2.4837	141.6025
92.00	78.00	2.4837	130.3019
92.00	80.00	2.4837	118.7467
94.00	62.00	2.4837	223.4126
94.00	64.00	2.4837	214.2431
94.00	66.00	2.4837	204.8451
94.00	68.00	2.4837	195.2084
94.00	70.00	2.4837	185.3234
94.00	72.00	2.4837	175.1810
94.00	74.00	2.4837	164.7738
94.00	76.00	2.4837	154.0970
94.00	78.00	2.4837	143.1498
94.00	80.00	2.4837	131.9392

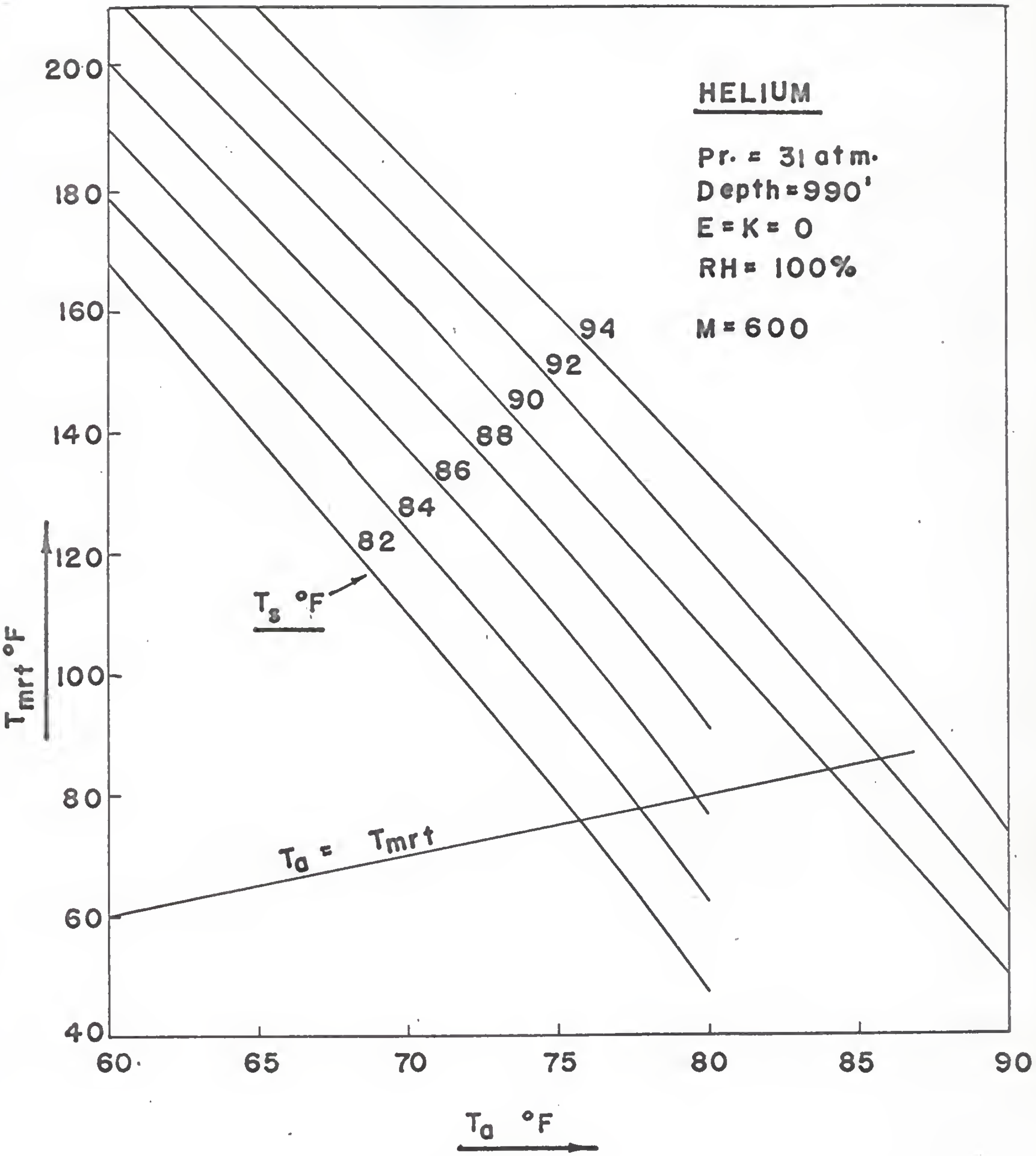


FIGURE 11

RELATION BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR Pressure = 31 atm. RH = 100%, E=K=0

TABLE IXV

RELATIONSHIP BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR

Pressure = 61 atm., RH = 100%, E=K=0

T_s °F	T_a °F	C_c BTU/Hr(°F)$^{1.25}$	T_{mrt} °F
82.00	62.00	3.0430	175.3922
82.00	64.00	3.0430	162.9078
82.00	66.00	3.0430	150.0007
82.00	68.00	3.0430	136.6574
82.00	70.00	3.0430	122.8751
82.00	72.00	3.0430	108.6703
82.00	74.00	3.0430	94.0971
82.00	76.00	3.0430	79.2817
82.00	78.00	3.0430	64.5023
82.00	80.00	3.0430	50.4080
86.00	62.00	3.0430	201.4040
86.00	64.00	3.0430	189.8311
86.00	66.00	3.0430	177.8877
86.00	68.00	3.0430	165.5552
86.00	70.00	3.0430	152.8182
86.00	72.00	3.0430	139.6663
86.00	74.00	3.0430	126.1001
86.00	76.00	3.0430	112.1401
86.00	78.00	3.0430	97.8441
86.00	80.00	3.0430	83.3416
92.00	62.00	3.0430	237.0398
92.00	64.00	3.0430	226.6024
92.00	66.00	3.0430	215.8643
92.00	68.00	3.0430	204.8091
92.00	70.00	3.0430	193.4195
92.00	72.00	3.0430	181.6789
92.00	74.00	3.0430	169.5722
92.00	76.00	3.0430	157.0873
92.00	78.00	3.0430	144.2183
92.00	80.00	3.0430	130.9703
94.00	62.00	3.0430	248.1471
94.00	64.00	3.0430	238.0362
94.00	66.00	3.0430	227.6449
94.00	68.00	3.0430	216.9572
94.00	70.00	3.0430	205.9572
94.00	72.00	3.0430	194.6285
94.00	74.00	3.0430	182.9552
94.00	76.00	3.0430	170.9234
94.00	78.00	3.0430	158.5217
94.00	80.00	3.0430	145.7458

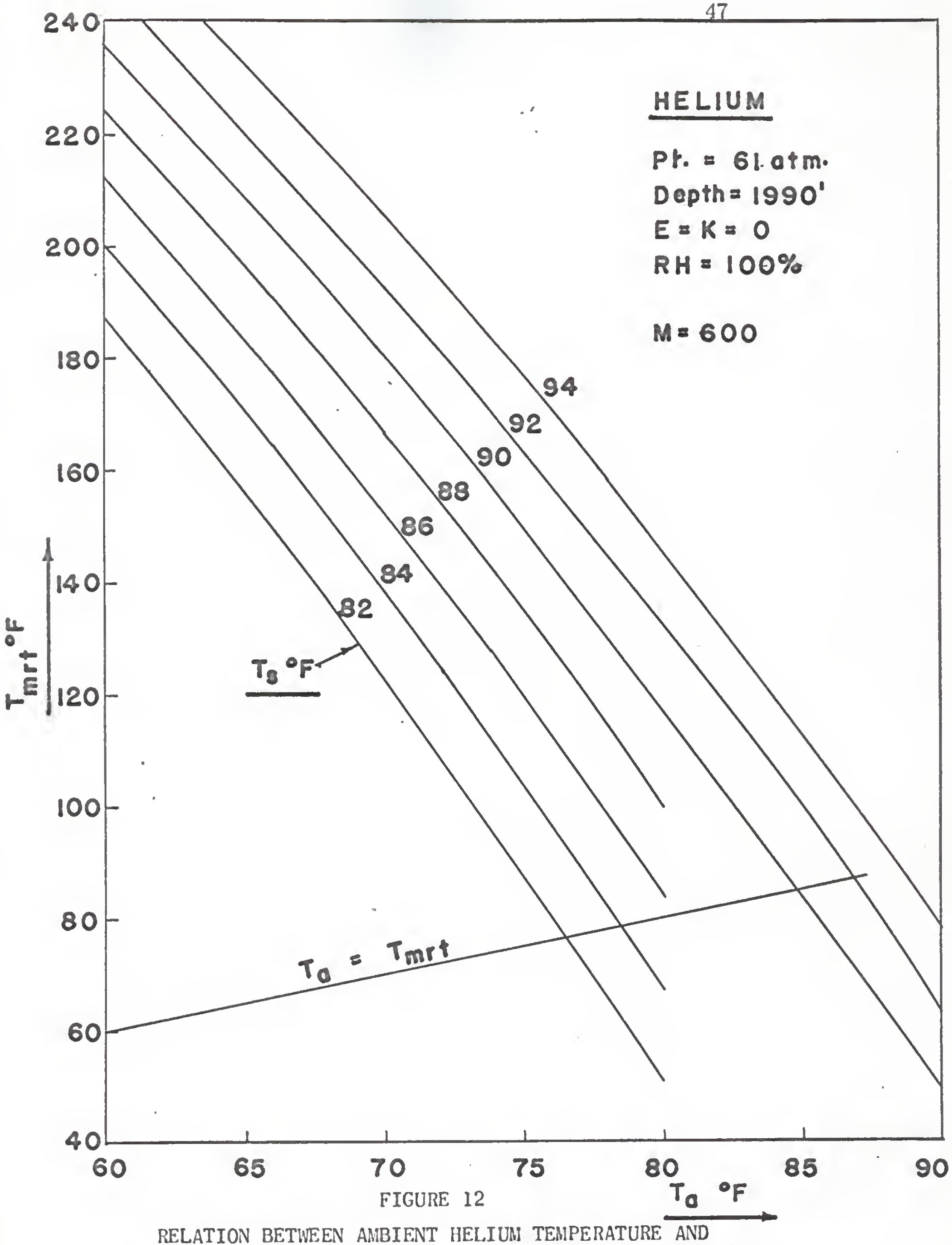


FIGURE 12

RELATION BETWEEN AMBIENT HELIUM TEMPERATURE AND MEAN RADIANT TEMPERATURE: METABOLIC RATE = 600 BTU/HR Pressure = 61 atm., RH = 100%, E=K=0

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Gratitude is also extended to the many authors from whose books and papers information has been so freely drawn.

APPENDIX I

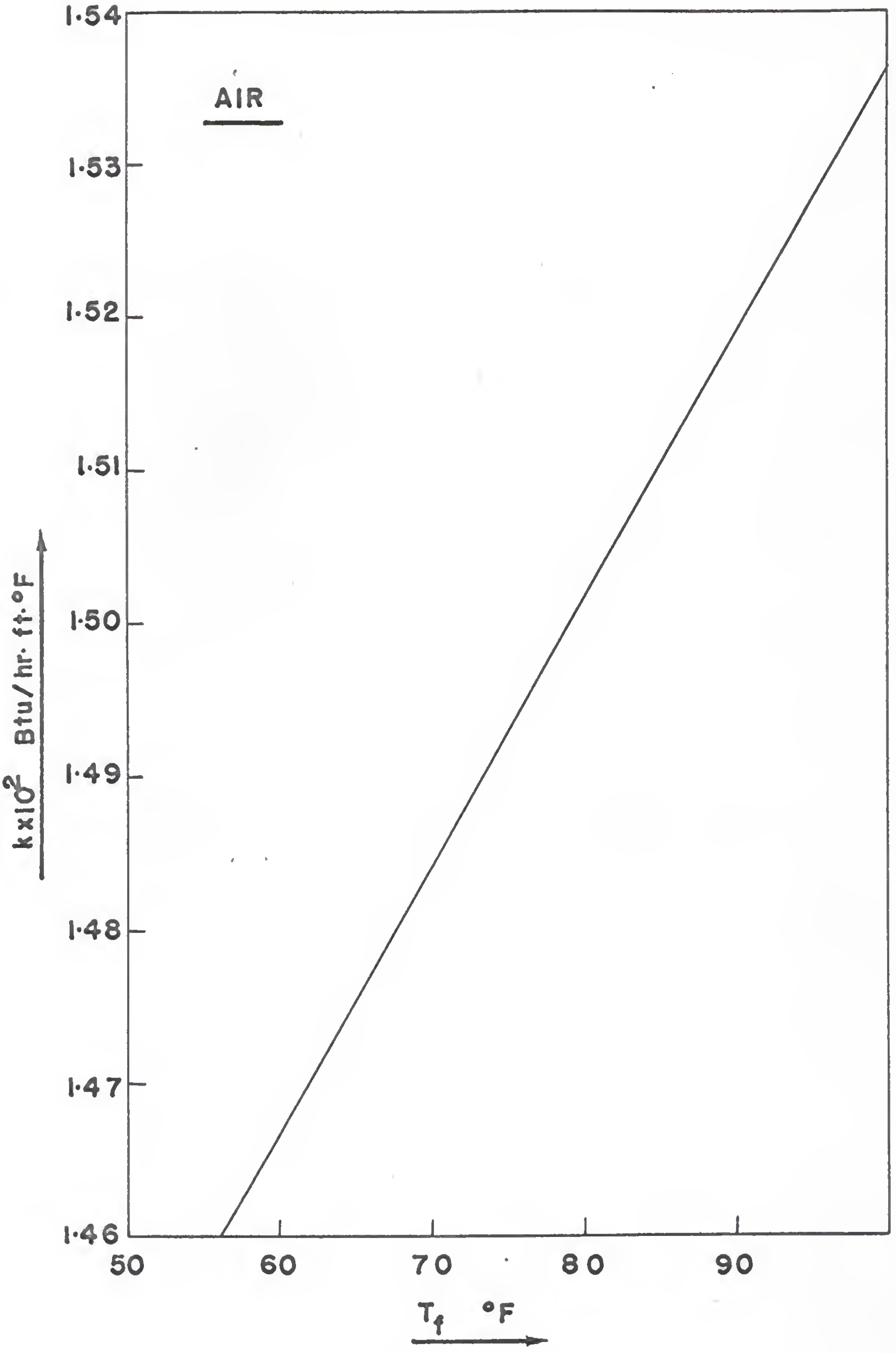

FIGURE 13

VARIATION OF THERMAL CONDUCTIVITY OF AIR AT A PRESSURE OF 4atm. WITH RESPECT TO FILM TEMPERATURE

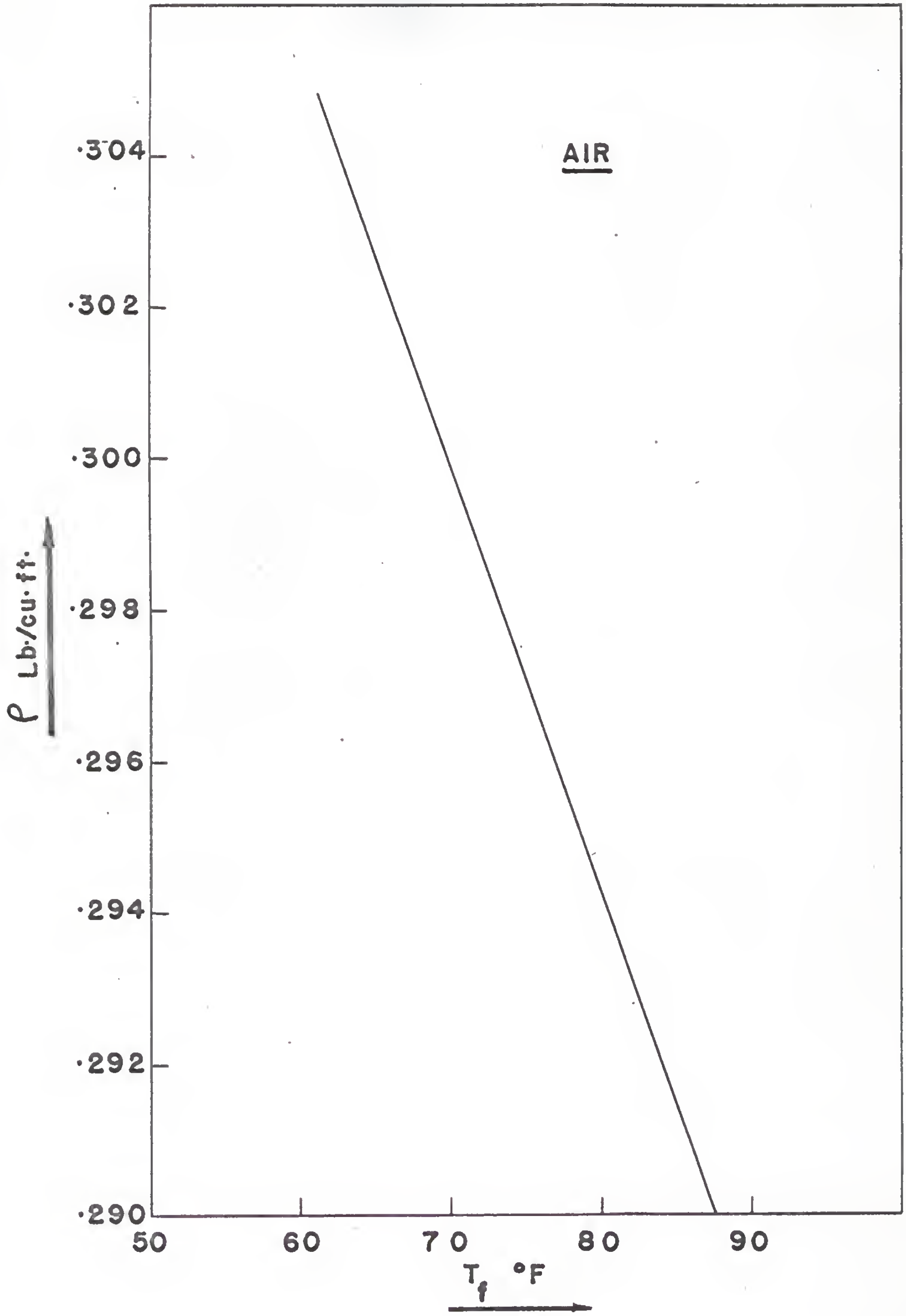

FIGURE 14

VARIATION OF DENSITY OF AIR AT A PRESSURE OF 4atm. WITH RESPECT TO FILM TERPERATURE

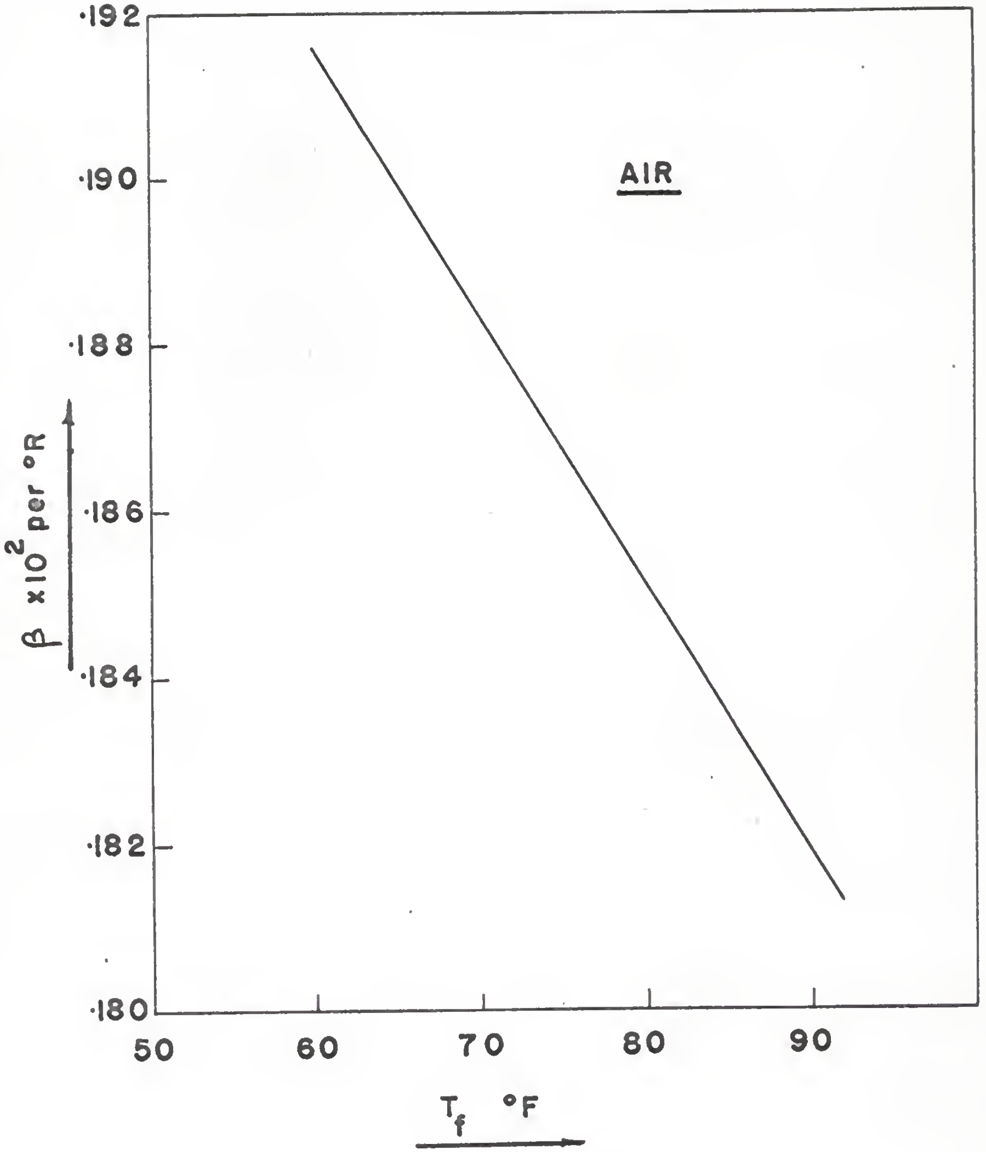

FIGURE 15

VARIATION OF COEFFICIENT OF VOLUMETRIC EXPANSION OF AIR AT A PRESSURE OF 4 atm. WITH RESPECT TO FILM TEMPERATURE

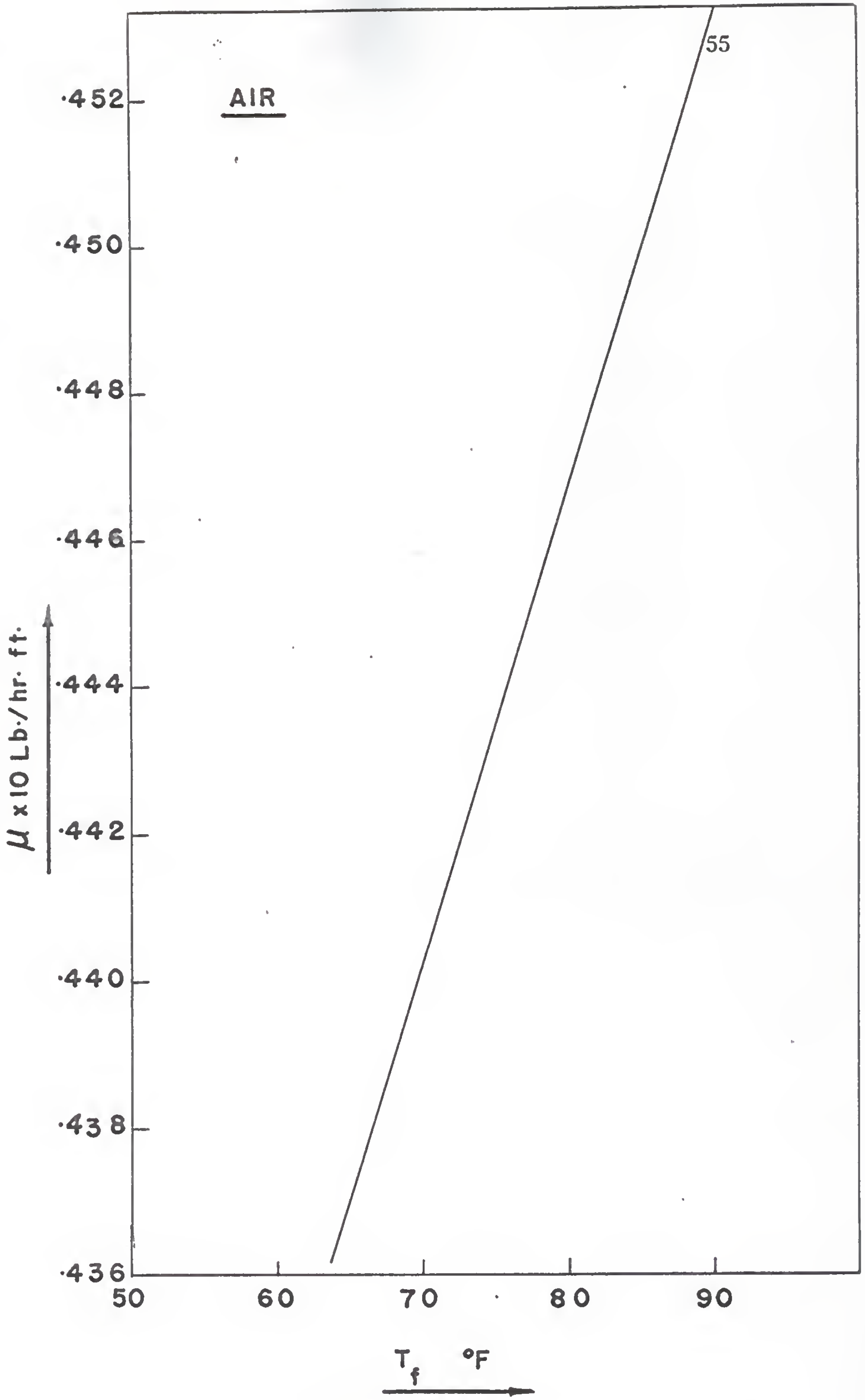

FIGURE 16

VARIATION OF VISCOSITY OF AIR AT A
PRESSURE OF 4atm WITH RESPECT TO FILM TEMPERATURE

TABLE V

VARIATION OF PROPERTIES AND MODIFIED CONVECTIVE HEAT TRANSFER COEFFICIENT OF AIR WITH RESPECT TO FILM TEMPERATURE

Pressure 4 atm.

T_f ^oF	k $BTU/Hr.^oF.ft.$	ρ lb/cu.ft.	β per ^oR	μ lb/ft.hr.	C_c $BTU/Hr.(^oF)^{1.25}$
62	.01471	.3044	.001916	.04350	.40886213
64	.01476	.3033	.001909	.04363	.40848331
66	.01481	.3022	.001902	.04376	.40808818
68	.01486	.3010	.001895	.04389	.40753610
70	.01491	.2998	.001888	.04402	.40707072
72	.01496	.2987	.001881	.04424	.40668970
74	.01501	.2976	.001874	.04427	.40627947
76	.01506	.2965	.001867	.04440	.40586278
78	.01511	.2954	.001860	.04453	.40543991
80	.01515	.2941	.001853	.04466	.40467279
82	.01520	.2931	.001846	.04478	.40442920
84	.01525	.2920	.001839	.04492	.40396514
86	.01530	.2909	.001832	.04504	.40353988
88	.01535	.2898	.001825	.04517	.40298751
90	.01540	.2888	.001818	.04530	.40259738

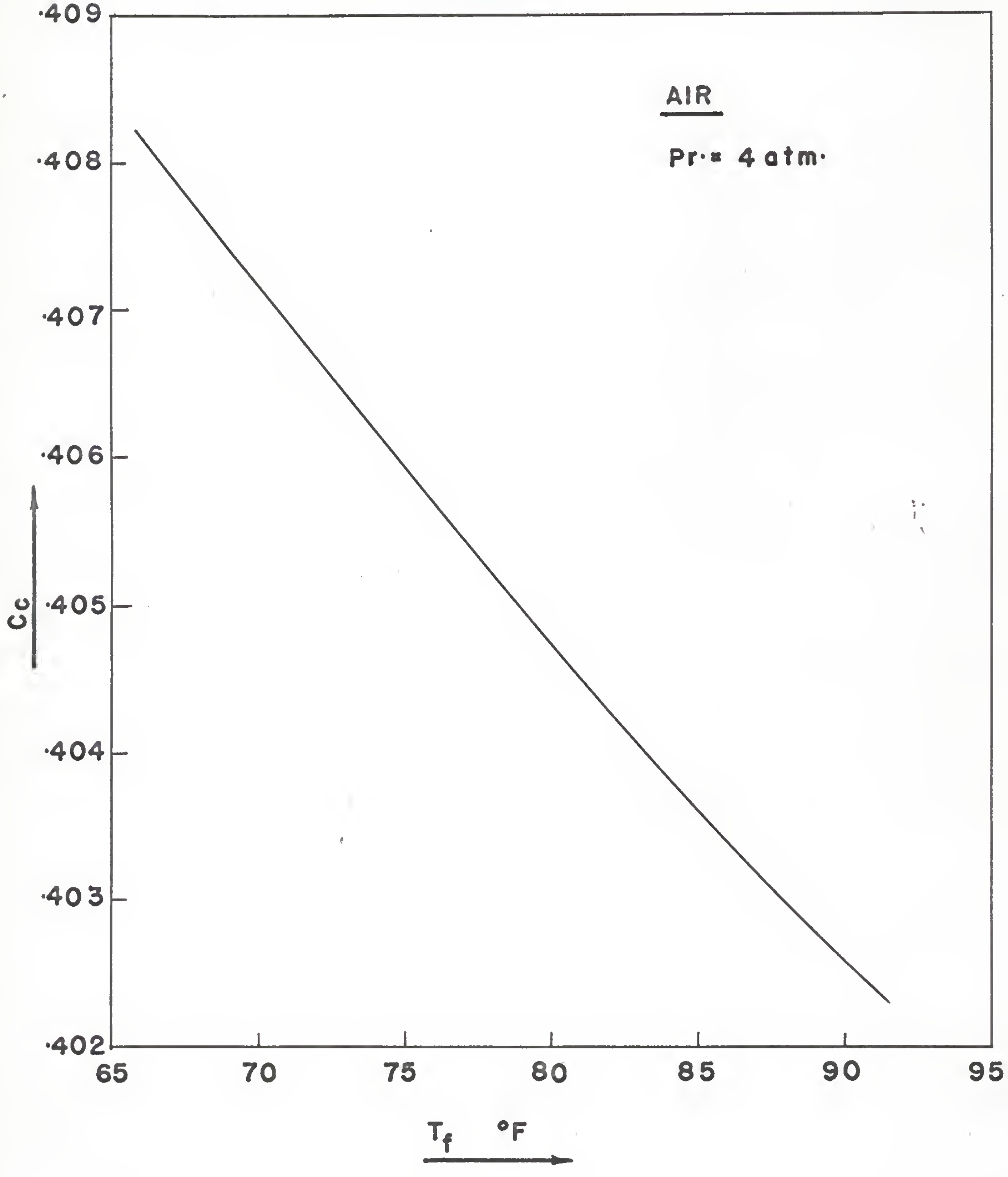

FIGURE 17

VARIATION OF MODIFIED COEFFICIENT OF CONVECTIVE HEAT TRANSFER AT
A PRESSURE OF 4atm WITH RESPECT TO FILM TEMPERATURE

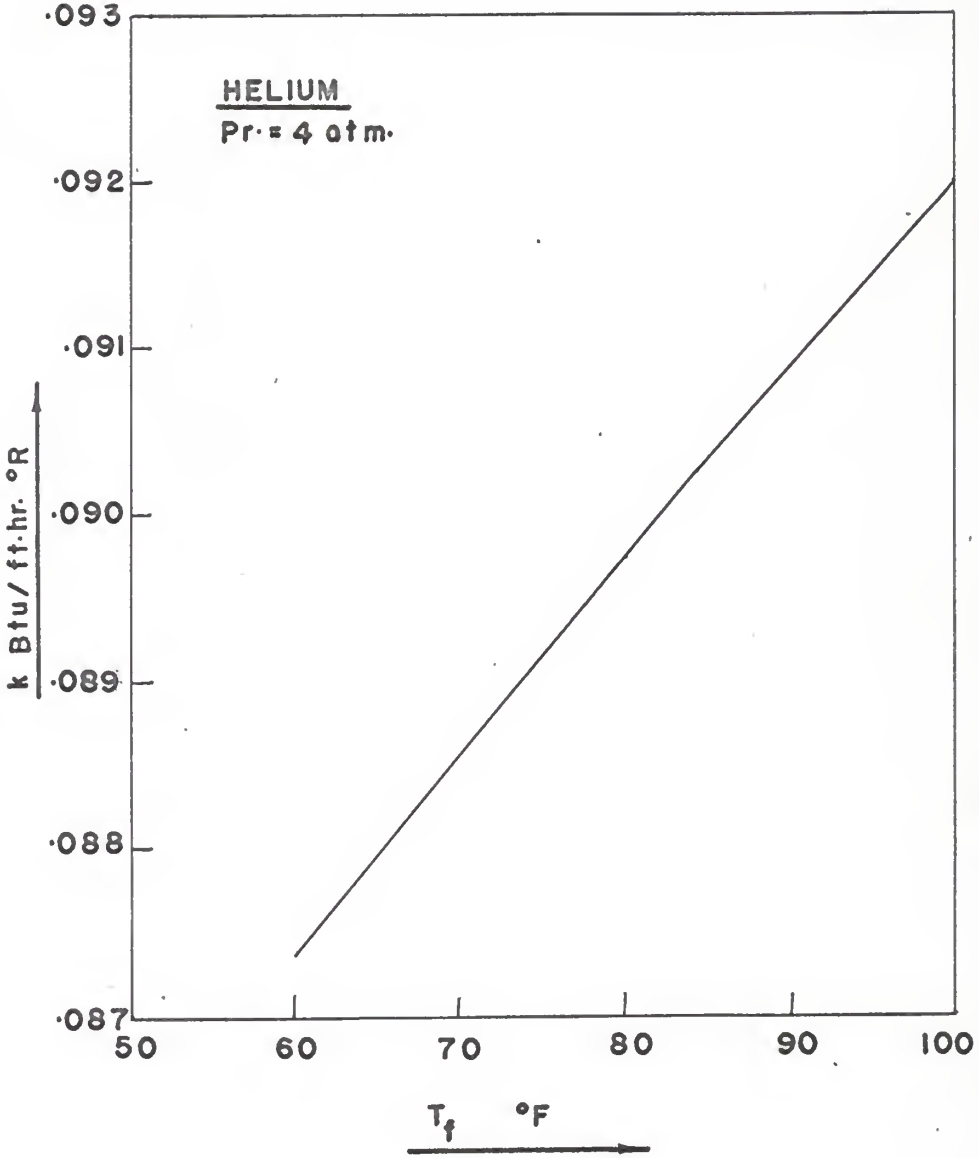

FIGURE 18

VARIATION OF THERMAL CONDUCTIVITY OF HELIUM AT
A PRESSURE OF 4atm. WITH RESPECT TO FILM TEMPERATURE

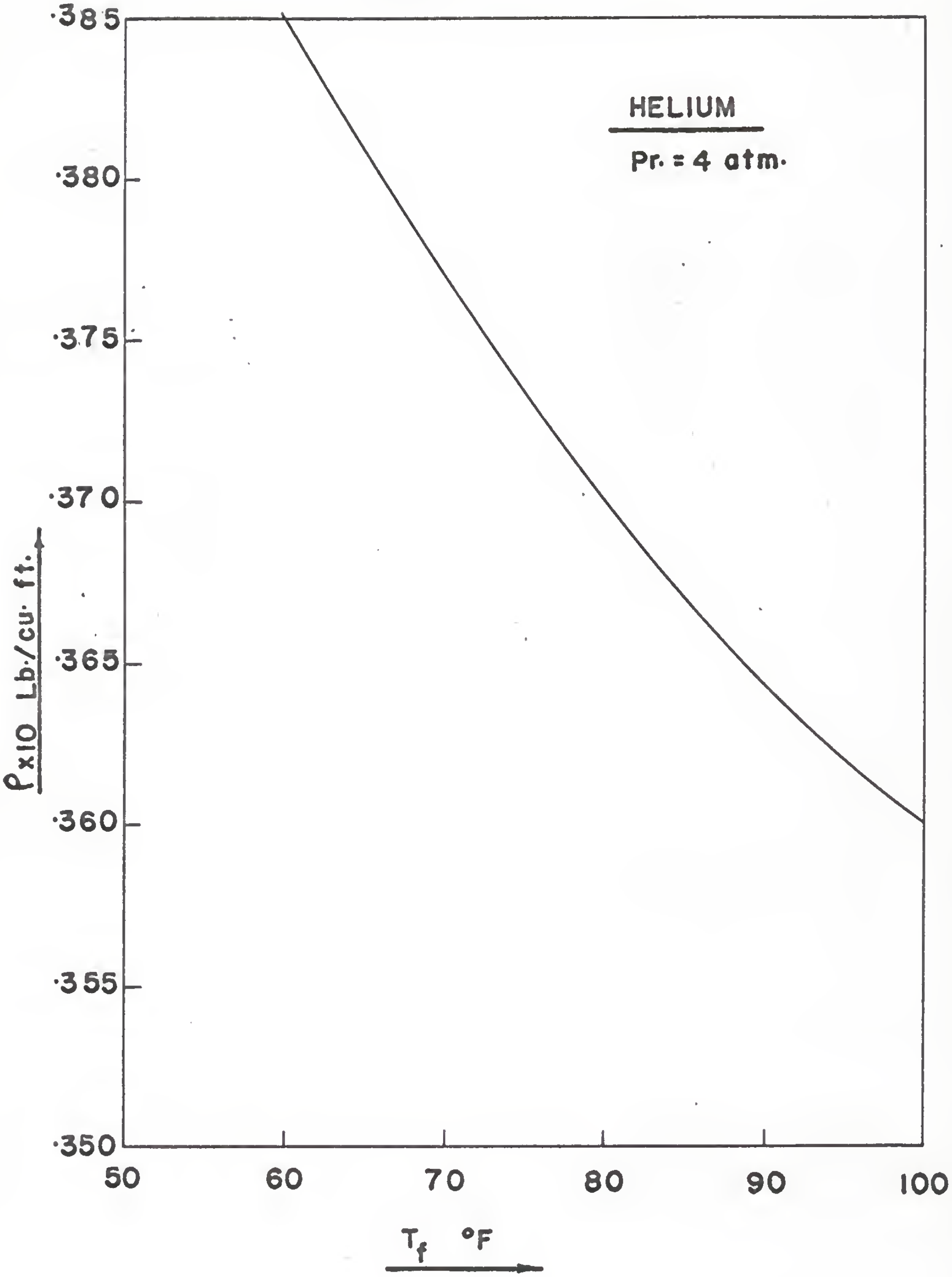

FIGURE 19

VARIATION OF DENSITY OF HELIUM AT A PRESSURE OF 4atm. WITH RESPECT TO FILM TEMPERATURE

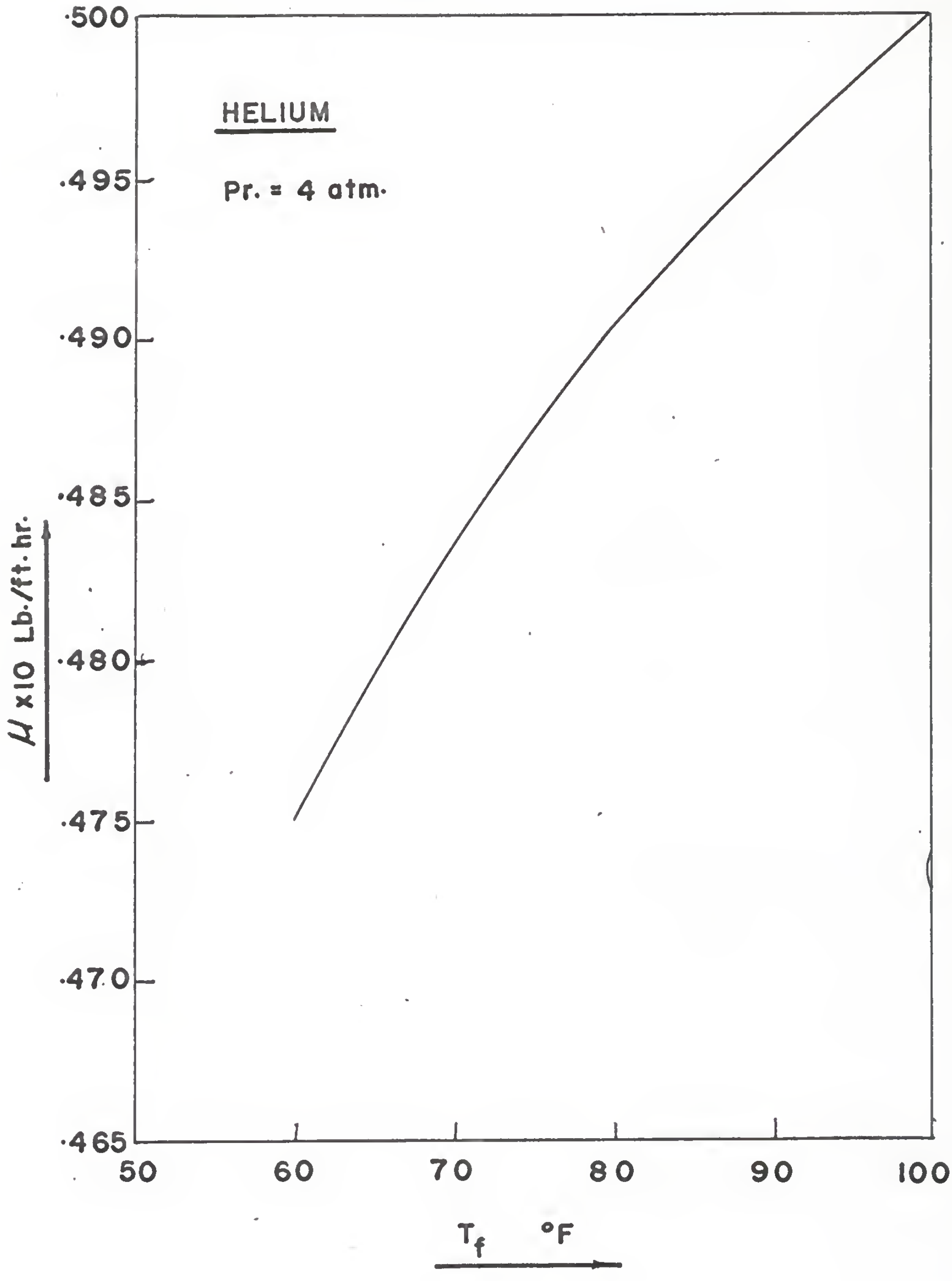

FIGURE 20

VARIATION OF VISCOSITY OF HELIUM AT A PRESSURE OF 4atm. WITH RESPECT TO FILM TEMPERATURE

TABLE VIII

VARIATION OF PROPERTIES AND MODIFIED CONVECTIVE HEAT TRANSFER COEFFICIENT OF HELIUM, WITH RESPECT TO FILM TEMPERATURE

Pressure = 4 atm.

T_f	k	ρ	β	μ	C_c
^{o}F	BTU/Hr.^{o}F ft.	lb/cu.ft.	per ^{o}R	lb/ft.hr.	BTU/Hr.$(^{o}F)^{1.25}$
76	.08925	.03731	.001867	.04880	.80503804
77	.08940	.03725	.001862	.04885	.80465843
78	.08950	.03717	.001860	.04891	.80400507
79	.08962	.03709	.001857	.04897	.80337619
80	.08975	.03700	.001853	.04900	.80271797
81	.08987	.03695	.001849	.04910	.80213708
82	.08998	.03691	.001846	.04915	.80190908
83	.09010	.03686	.001841	.04921	.80137892
84	.09020	.03680	.001839	.04926	.80097144
85	.09030	.03675	.001834	.04932	.80030420
86	.09040	.03670	.001832	.04938	.79996224
87	.09050	.03665	.001829	.04942	.79959036
88	.09065	.03660	.001825	.04948	.79935768
89	.09075	.03655	.001821	.04952	.79887214
90	.09087	.03650	.001818	.04957	.79858657
91	.09095	.03645	.001814	.04961	.79796591
92	.09110	.03640	.001811	.04966	.79787322
93	.09120	.03635	.001809	.04970	.79760042
94	.09130	.03630	.001805	.04974	.79710556

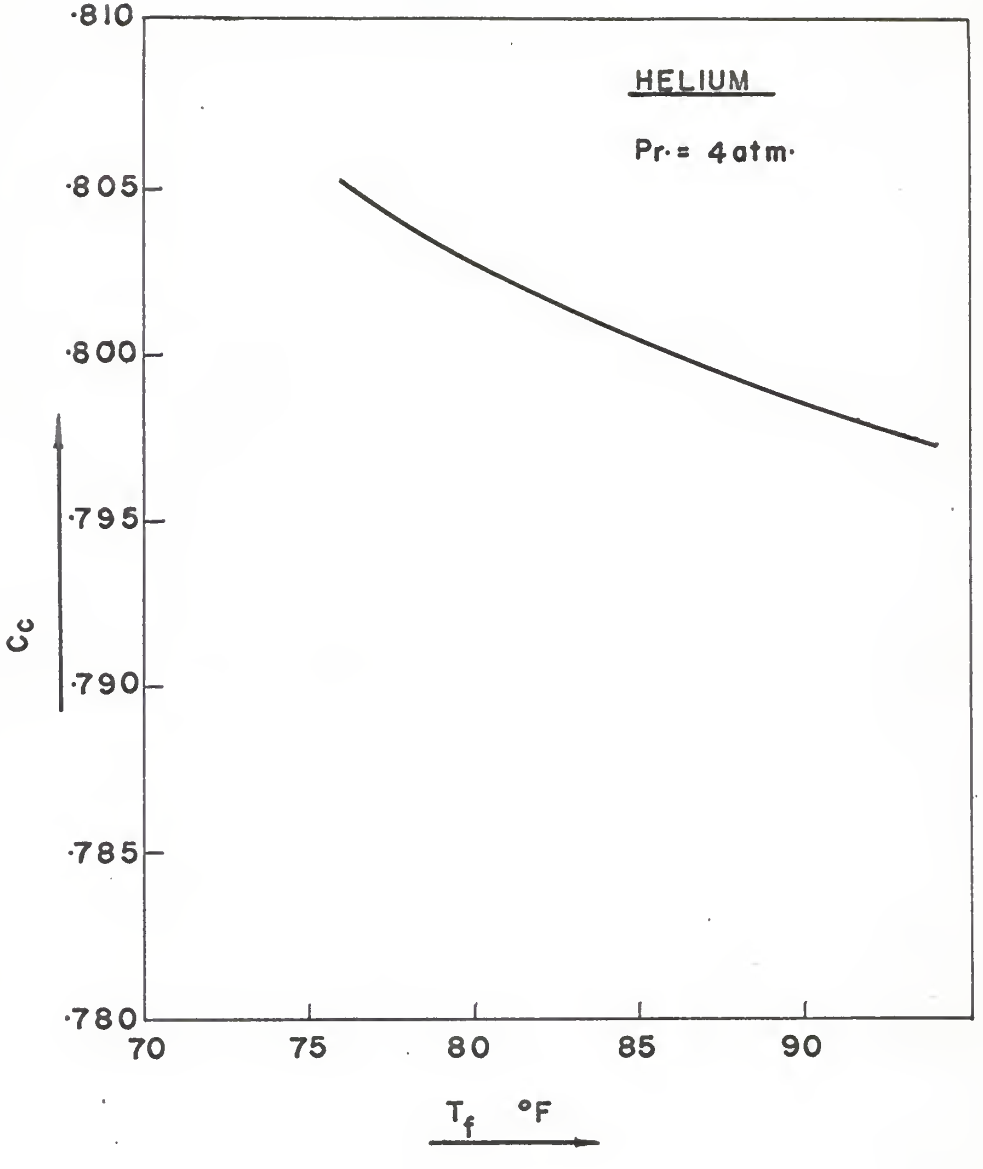

FIGURE 21

VARIATION OF MODIFIED COEFFICIENT OF CONVECTIVE HEAT TRANSFER AT A PRESSURE OF 4atm WITH RESPECT TO FILM TEMPERATURE

APPENDIX II

```
C     DETERMINATION OF HEAT TRANSFER COEFFICIENT FOR AIR

      DIMENSION AK(15), RHO(15), BETA(15), AM(15)
    1 FORMAT(5E16.8)
      DO 5 I=1,15
    5 READ (1,1) AK(I),RHO(I),BETA(I),AM(I)
      DO 10 I=1,15
      HC=.59*(AK(I)**.75)*((17734700.*RHO(I)*RHO(I)*BETA(I)/AM(I))**.25)
   10 WRITE (3,1) AK(I),RHO(I),BETA(I),AM(I),HC
      STOP
      END
```

```
.14715000E-01    .30440000E 00    .19160000E-02    .43500000E-01
.14765000E-01    .30330000E 00    .19090000E-02    .43630000E-01
.14815000E-01    .30220000E 00    .19020000E-02    .43760000E-01
.14860000E-01    .30100000E 00    .18950000E-02    .43890000E-01
.14910000E-01    .29980000E 00    .18880000E-02    .44020000E-01
.14960000E-01    .29870000E 00    .18810000E-02    .44140000E-01
.15010000E-01    .29760000E 00    .18740000E-02    .44270000E-01
.15060000E-01    .29650000E 00    .18670000E-02    .44400000E-01
.15110000E-01    .29540000E 00    .18600000E-02    .44530000E-01
.15150000E-01    .29410000E 00    .18530000E-02    .44660000E-01
.15205000E-01    .29310000E 00    .18460000E-02    .44780000E-01
.15255000E-01    .29200000E 00    .18390000E-02    .44920000E-01
.15305000E-01    .29090000E 00    .18320000E-02    .45040000E-01
.15350000E-01    .28980000E 00    .18250000E-02    .45170000E-01
.15400000E-01    .28880000E 00    .18180000E-02    .45300000E-01
```

```
C     DETERMINATION OF MRT FOR AIR, METABOLIC RATE = 600 BTU/HOUR

      DIMENSION CC(4,8)
    1 FORMAT (4E16.8)
      M=600
      DO 5 I=1,4
      DO 5 J=1,8
    5 READ (1,1) CC(I,J)
      DO 20 I=1,4
      DO 20 J=1,8
      AI=I
      AJ=J
      TS=548.+2.*AI
      TA=518.+4.*AJ
      TMRT=((TS*TS*TS*TS)-(100000000./2.49)*( M  -19.5*CC(I,J)*((TS-TA)*
     1*1.25)))**.25
   20 WRITE(3,1) TS,TA,CC(I,J),TMRT
      STOP
      END
```

```
C      DETERMINATION OF MRT,HELIUM,M=600 BTU/HR, PR.=31 ATM.
     1 FORMAT (2F18.2,F18.4,F18.4)
       CC=2.4837
       DO 20 I=1,8
       DO 20 J=1,11
       AI=I
       AJ=J
       TS=540.+2.*AI
       TA=518.+2.*AJ
       TMRT=((TS*TS*TS*TS)-(100000000./2.49)*(600.-19.5*CC*((TS-TA)**1.25
      1)))**.25
       TS=TS-460.
       TA=TA-460.
       TMRT=TMRT-460.
       WRITE (3,1) TS,TA,CC,TMRT
    20 WRITE(2,1) TS,TA,CC,TMRT
       STOP
       END
```

HEAT LOSS ANALYSIS FOR AN OCEANAUT

by

GUL HIRANAND ADVANI

B. S. (ME), Maharaja Sayajirao University of Baroda, 1962

AN ABSTRACT OF A MASTER'S REPORT

submitted in partial fulfillment of the

requirements for the degree

MASTER OF SCIENCE

Department of Mechanical Engineering

KANSAS STATE UNIVERSITY
Manhattan, Kansas
1965

Major Professor

The heat losses are analyzed for a man enclosed in an underwater research vessel. Convective, radiative, evaporative and conductive heat losses are studied in details. The relation between mean radiant temperature and ambient environmental temperature is obtained for environments of air and helium.

The relationships obtained can be used when the vessel is to have controlled environments.