Physiologic Mechanisms of Maintaining Thermal Balance in High-Pressure Environments

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This review of body-temperature control aims to define the optimal environment for deep submergence habitats, at pressures of 15–20 atm. Environmental factors demand major attention since they will largely dictate the physiologic adjustments which will be required. Inherent changes in gas composition and density indicate major increases in surface heat transfer, depending upon atmospheric temperature and movement. Habitat insulation and ocean temperature suggest that body-surface heat transfer will also be increased by radiation, but this may be modified by heating techniques, special insulation methods, or by treatment of cold habitat surfaces. Humidity may be an important determinant of comfort and skin hygiene. Psychrometric methods for hyperbaric atmospheres are discussed. Experimental data on body heat transfer in helium-rich environments are presented from simulation studies, showing a major increase in convective heat transfer from the skin, in helium at increased pressures. The implications of these findings upon physiologic and environmental aspects of deep submergence programs are discussed.

Introduction

To the adventurer, the adventure is its own reward. The unknown is viewed with the eyes of a Hillary contemplating Everest, and little is required to justify an expedition, except a challenge. In the public domain, however, such activities must be justified more by reason than by romance. For man to risk entry into an abnormal environment, there must be a purpose for his presence, a job he is to carry out. The Man in the Sea experiments of the U. S. Navy's Deep Submergence Systems Project (DSSP) are directed by the hypothesis that some underwater tasks are best done by man when he is free to traffic directly with the ocean from a habitat that is maintained at a pressure that is equivalent to its depth. To test this premise, information on the optimal conditions for human performance in pressurized underwater environments is being assembled.

Some answers are available from analogous programs. Regarding behavioral aspects of deep submergence, for example, experience from submarine cruises may be helpful. Medical and physiological questions may be partially answered by observations from less prolonged and shallower diving situations, and from hyperbaric-chamber experiments. But, in general, the gaps in our knowledge far exceed the areas of reliable information. One area in which additional knowledge is being assembled is body-temperature regulation.

A convenient means of discussing the thermal balance of the human body is to apply the first law of thermodynamics. In its simplest form, this states that input equals accumulation plus output. If one chooses, as a system, the energy balance of the resting human body in a steady state, the "accumulation" term is zero. The energy input from metabolic processes is, therefore, balanced by heat losses to the environment. These losses may be in the form of evaporation ($\dot{E}$), radiation ($\dot{R}$), convection ($\dot{C}$). Heat transfer by conduction is usually negligible. This relationship is described in Eq. (1), in which the metabolic rate is expressed in terms of oxygen consumption ($\dot{V}_{O_2}$),

$$\dot{V}_{O_2} = \dot{E} + \dot{R} + \dot{C} \tag{1}$$

The relative proportions of heat transfer by the various modes will largely be dictated by environmental conditions of temperature, humidity and atmospheric movement. Anatomic and physiologic characteristics of individuals will also influence the manner in which thermal balance is acccomplished. When the environment is too warm or too cool, thermal imbalance will cause "accumulation" of energy resulting in a rise or fall of mean body temperature. Increased metabolic activity may also compensate for excessive heat losses to the environment.

The present discussion is intended to examine the question of body-temperature regulation and metabolism under deep submergence conditions. It will be attempted to relate physiologic responses to the environmental variables. The results of experimental observations will also be presented.

I. Environmental Characteristics

Because the environment will largely control the extent and means of heat transfer from its occupants, it is desirable to devote attention to the specific environmental features that influence thermal balance. The most important ones are gaseous atmosphere, dry-bulb temperature, mean radiant temperature, humidity, and atmospheric movement. Each will be discussed individually.

A. Gaseous Atmosphere

To minimize the narcotic effects seen when air is breathed during deep diving, it is necessary to provide gas mixtures increasingly rich in helium as depth is increased. At the same time, it is necessary to limit the oxygen content of the breathing mixture to avoid oxygen toxicity. When prolonged exposures are involved[1] the oxygen partial pressure must be limited to something less than 0.6 atm absolute (ATA). For deep submergence habitats at depths of 450 ft or greater, therefore, it may be assumed for purposes of heat-transfer calculations that a pure helium atmosphere is present. The high thermal conductivity of helium, six times that of air, makes obvious the importance of this environmental substitution.

Presented as Paper 66-715 at the AIAA/USN 2nd Marine Systems & ASW Conference, Los Angeles-Long Beach, Calif., August 8–10, 1966; submitted August 3, 1966. It is a pleasure to acknowledge the technical assistance of R. D. Edwards, Hospital Corpsman 2, U. S. Navy, in the conduct of these studies. The help of D. E. Evans, Lieutenant JG., U. S. Navy, and of C. H. Greenhalgh, Hospital Corpsman Chief, U. S. Navy, in improving the hyperbaric facilities are also gratefully recognized. The author wishes to acknowledge the secretarial assistance of C. A. Tamara. [12.15]

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It should be noted that the thermal conductivity of dry helium is relatively insensitive to changes in pressure, and can be assumed to be constant over the current range of DSSP interest.[2–4] For the condition of helium saturated with water vapor, the thermal conductivity should also be independent of pressure, since the mass of water vapor per unit volume of helium will be approximately the same for a given dew-point temperature, whatever the total pressure of the habitat. Unfortunately, numerical data on the effect of water-vapor content upon the thermal conductivity of gaseous helium do not appear to be available.

Increased density is a second feature of the high-pressure environment and its atmosphere, which leads to important changes in heat transfer. For example, a dry helium atmosphere at 450 ft (14.6 ATA) has a density about twice that of dry air at normal pressure. Expressions describing the process of convective heat transfer between a surface and a gas phase at a different temperature, indicate that both of the previous changes, thermal conductivity and density, will contribute to a major increase in convective conductance h_c.[5,6]† This coefficient defines the rate of heat flow from the surface to the surrounding gas. The relationship is shown in Eq. (2):

$$\dot{C} = h_c A \ (T_s - T)_a \tag{2}$$

in which $\dot{C}$ is the rate of convective heat transfer, and A is the area and $(T_s - T_a)$ is the difference between surface and atmospheric temperatures. Theoretical calculations, representing the body as a cylinder 6 ft tall and 1 ft in diameter, indicate that h_c is increased eight- to ten-fold in helium at 15 ATA, relative to air at 1 ATA.[7]

B. Dry-Bulb Temperature

The foregoing comments have attempted to show that a hallmark of the high-pressure atmosphere of DSSP habitats is its improved ability to transfer heat. To conserve body heat in such an atmosphere, it would be necessary to choose a dry-bulb temperature which would minimize the gradient between skin and ambient temperatures. This appears to have been the case in the Sealab II habitat, where the comfort zone was 88°F, plus or minus 2°F.[8] As greater depths are encountered, it is likely that a slightly higher temperature will be chosen, and that smaller deviations from it may produce discomfort. This effect would not be expected to create significant operational problems, except in the event of a prolonged absence of power to heat the habitat.

C. Mean Radiant Temperature

Heat transfer by radiation from the body surface will largely depend upon the wall temperature of the habitat, modified by the effects of radiant heaters and other sources of infrared radiation. Two factors which could lead to low values of mean radiant temperature in DSSP habitats are the low temperature of the ocean water at great depths and the impaired value of insulating materials in pressurized atmospheres. This impairment is due in part to a decrease in thickness upon compression, but permeation of the material by the highly conductive atmosphere is probably more important.[9] Mean radiant-temperature data from DSSP habitats will be valuable in determining whether body radiant heat losses can be controlled by reducing surface absorptivity by polishing or other means.

† For forced convection, convective conductance h_c may be calculated from the following relationships: $h_c = kC(Re)^n/D$ (cylinder), $h_c = 0.37k(Re)^{0.6}/D$ (sphere), where k is the thermal conductivity, and D is the diameter of the heat transfer surface. Reynolds number Re equals the product of gas density, velocity, and surface diameter, divided by the absolute viscosity. C and n are constants which derive their value from empirical correlations with the Reynolds number.

D. Humidity

The role of atmospheric humidity in body-temperature control should be no different in high-pressure environments than at normal pressure, provided enough dehumidifying capacity is available to handle the water-vapor load from cooking, drying out of diving gear, hot showers and other sources. Problems in measuring humidity may occur depending upon the technique employed, as well as the atmosphere and pressure. Psychrometric charts are available (Figs. 1 and 2) for use in air up to 10 ATA[10] and for helium at 15 ATA,[11] if wet-bulb techniques are used. The differences in heat-transfer properties of air at normal pressure, contrasted to air at 5.5 ATA or helium at 15 ATA, are reflected in the interpretation of identical psychrometric measurements under these conditions. In the example chosen, the assumed values of dry-bulb (95°F) and wet-bulb temperature (85°F) are the same in each of the three cases. In air at normal pressure, these values would indicate a vapor pressure of 1.11 in. Hg and a relative humidity of 67%. From Fig. 1, it is evident that the same data in air at 5.5 ATA would reflect a considerably lower vapor pressure (0.59 in. Hg) and relative humidity (35%). For a helium atmosphere (Fig. 2) at 15 ATA, the identical temperature data would indicate a very dry environment indeed (relative humidity well below 10%).

These charts have been prepared using the ideal gas laws and may not be accurate enough for applications in which molecular interactions introduce significant errors. Errors may also arise from the mechanical effect of pressure on mercury-in-glass thermometers.[7] Small inaccuracies in dry- and wet-bulb temperature measurements will produce large errors in vapor pressure and humidity data. Dew-point instruments and those employing hygroscopic salts whose resistance varies with ambient vapor pressure appear to be simpler and more reliable. Published data on their performance under pressure do not appear to be available.

E. Atmospheric Movement

It is recognized that the rate of heat transfer between a surface and a surrounding gas will depend greatly upon the movement of the gas, as long as a temperature gradient is maintained.[5] Evaporative heat loss is also velocity-dependent,[12] provided a gradient exists in vapor pressure between the skin surface and the ambient gas phase. The influence of velocity makes it desirable to include appropriate measurements of this environmental variable. Care must be exercised in calibrating instruments used for this determination, since their response will be altered greatly in a pressurized atmosphere.

II. Environmental Simulation Experiments

The possible physiologic implications of the environmental features discussed previously require that a better knowledge be obtained of their interactions, especially concerning body skin temperature and convection. Studies with copper manikins[13] and human subjects exposed to helium at 1 ATA indicate an increase in convective heat loss of about 13%, resulting in a decrease in skin temperature averaging 1° to 3°F.[14] In anticipation of DSSP chamber exposures and field operations at pressures up to 20 ATA, additional simulation studies and theoretical calculations have been made of convective heat transfer in a pressurized helium atmosphere.

A. Hyperbaric Chamber Methods

The experimental apparatus is shown in Fig. 3. The available pressure facility is a steel chamber with inside diameter of 18 in. and length of 36 in. and (Model 1836, Bethlehem Corp., Bethlehem, Pa.) a maximum working

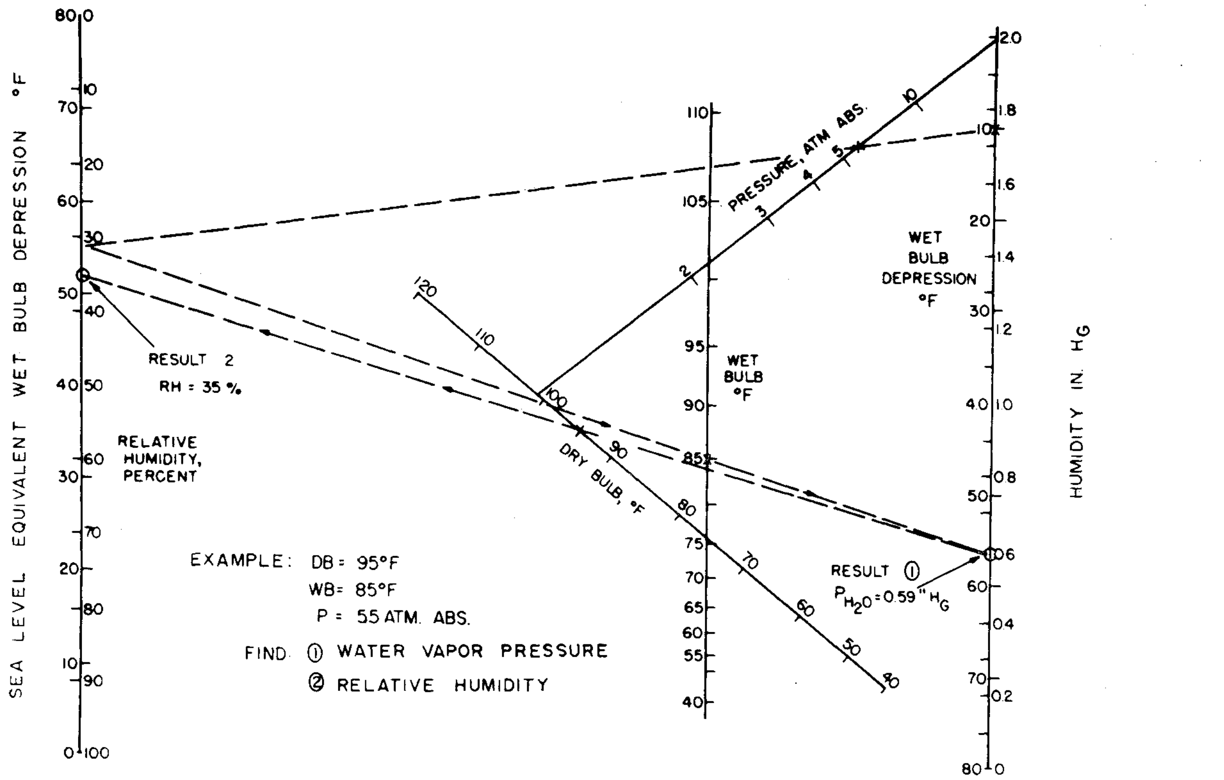

Fig. 1 Psychrometric nomograph for air at pressures of 1 to 10 ATA (D. B. Brooks).

pressure of 11.2 ATA. Temperatures were measured with matched thermistors (Yellow Springs Instrument Co., Yellow Springs, Ohio) whose electrical outputs were transmitted from within the chamber by soldered connections to a pressure-tight electrical system (Deutsch Components Div., Banning, Calif.) and read with a matching tele-thermometer. The accuracy of the temperature measuring system was checked to within 0.1°F against two mercury-in-glass thermometers certified by the National Bureau of Standards (NBS) for the range of interest. Pressure stability was checked by imposing an axial mechanical stress of 1000 psi upon the thermistors, which were again compared against the NBS thermometers while all were immersed in a water bath. Readings remained within 0.1–0.2°F of the NBS instruments. The thermistor designated to measure atmospheric temperature (t_a) was shielded from radiation by a thin layer of tin foil.

A pair of thin-walled copper spheres (diam = 6 in., wt = 0.722 lb) were selected and coated with a flat black enamel. One was fitted with a thermistor in its center, to measure the mean radiant temperature (t_r) within the pressure chamber. The other was fitted with a 10-w power resistor in its center, and a thermistor cemented to its surface to measure surface temperature t_s. Power was supplied from outside the chamber through the Deutsch fitting by a transistor power supply. Voltage and amperage output were selected

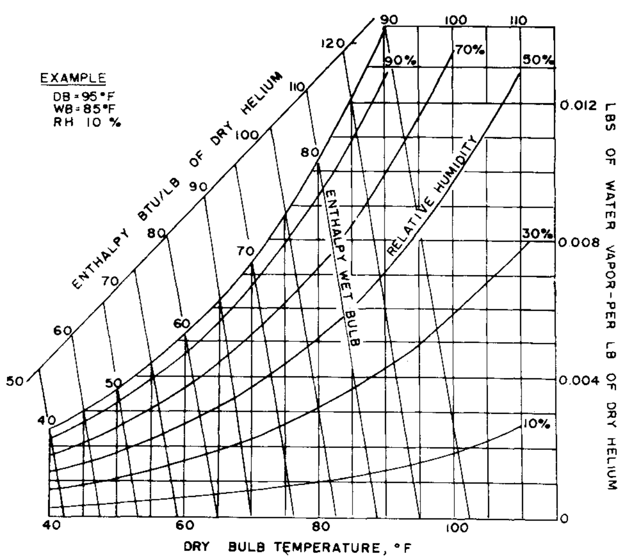

Fig. 2 Psychrometric chart for helium atmospheres at 15 ATA.

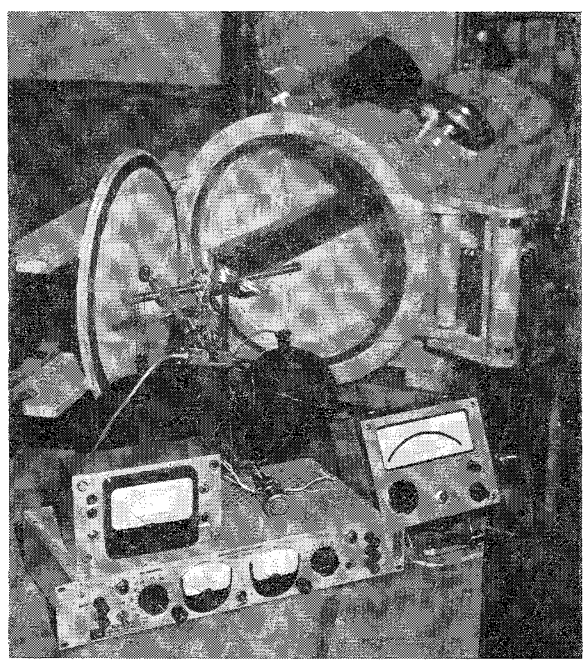

Fig. 3 Apparatus for thermal balance model studies in helium at increased pressures.

to represent the metabolic rate of a human engaging in light activity, but scaled down by a ratio of surface areas of copper sphere to human equalling 0.785 to 20 ft² (thus an input power of 5.7 w to the sphere represents a metabolic rate of 480 btu/hr for a human, or about 60 kg-cal/m²/hr). In experiments involving forced convection, atmospheric motion was provided by a miniature battery-operated centrifugal/ blower, arranged to create a tangential velocity of 90 ft/min in air at 1 ATA, at the edge of the heated sphere which was normal to the direction of flow. In natural-convection experiments, the velocity was measured with an Alnor Thermoanemometer (Alnor Instrument Co., Chicago, Ill.) whose sensing element was placed normal to the direction of flow. It was not possible to calibrate this instrument in helium under pressure, so it is not known whether the blower maintained a 90-ft/min velocity throughout the experimental periods.

After the apparatus was sealed inside the chamber, a 30-min period was required for equilibration, after which the values of t_s, t_a, and t_r were within 0.1°F of one another. Power was then switched on in the heated sphere, and the chamber pressurized with water-pumped helium (Southern Oxygen Co., Washington, D. C.) to 11.2 ATA, where ventilation with helium was continued until the residual nitrogen content of the chamber was less than 3%. Samples of the chamber atmosphere were analyzed periodically by gas chromatography using a type I molecular sieve column and Vapor Fractometer Model 154L (Perkin Elmer Corp., Norwalk, Conn.) standardized with atmospheric air. After 10 to 30 min, a steady state of heat exchange between the heated sphere and the helium atmosphere developed, and 1-min observations of t_s, t_a and t_r were made over the ensuing 10 to 20 min. Chamber pressure was then lowered, and observations were repeated at 5.1, 2.0 and 1.0 ATA. The value of h_c was also determined in air at 1.0 ATA.

B. Method of Calculation

To compute convective heat transfer $\dot{C}$, it is necessary to subtract the radiative portion $\dot{R}$ from the total power supplied to the heated sphere Equation (3) gives the method of calculation of $\dot{R}$, in Btu/hr

$$\dot{R} = 1.22 \times 10^{-9} (t_s^4 - t_r^4) \quad (3)$$

Values of t_s and t_r are in degrees Rankine, and the coefficient $(1.22 \times 10)^{-9}$ is obtained from the product of the Stefan-Boltzmann constant and the sphere's effective radiant area (85%), assuming an emissivity of 0.97. With $\dot{R}$ known, $\dot{C}$ is obtained by difference and h_c computed from Eq. (2).

C. Results

The experimental data are presented in Tables 1 and 2, and in Fig. 4. The units used throughout are h_c = Btu/hr ft°F, pressure = ATA, temperatures = °F. Each value represents the mean of four observations. Figure 4 also presents the theoretical values of h_c in forced convection, predicted by a conventional relationship.[5] For the sake of comparison, experimental values of h_c in natural convection are plotted on the same graph, although it is recognized that distinct mechanisms are involved.

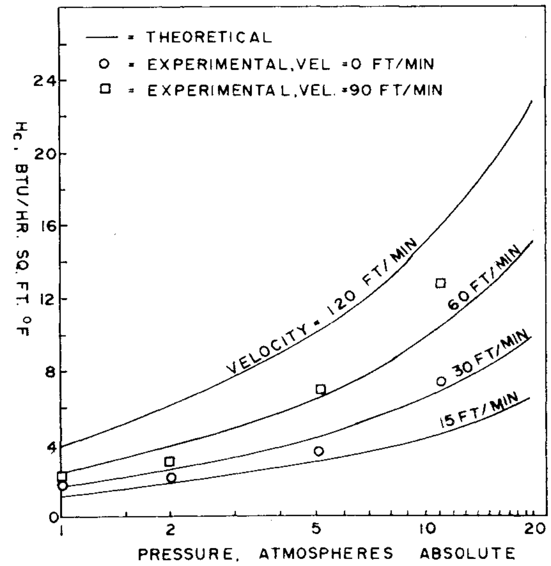

Fig. 4 Calculated and observed values of convective conductance h_c as a function of pressure in a helium atmosphere.

From Fig. 4, it is seen that the observed increases in forced convective heat transport with this experimental model are similar to those predicted. Values of h_c are increased several fold in hyperbaric helium atmospheres, and the increase is magnified when forced convection exists. Even with natural (unstirred) convection, large increases in h_c occur. Reference to Tables 1 and 2 calls attention to the practical significance of this somewhat abstract finding. That is, if h_c increases and power input is constant, the experimental model cannot maintain a "skin temperature" much higher than the atmospheric temperature. To put the matter differently, the atmosphere drains heat away from the model's surface so rapidly that skin temperature is reduced close to the ambient level. The physiologic consequences of a reduced t_s in man will be discussed in Sec. III, Physiologic Responses.

Like most models, the apparatus used in this series of observations imitates man most imperfectly. As an inexpensive and unbending means of estimating the changes in one vulnerable avenue of energy loss, however, it seems a useful analog.

III. Physiologic Responses

The discussion, so far, has emphasized the environmental changes to be expected in pressurized atmospheres. The physiologic correlates of these physical changes have not as yet been measured. They can, however, be predicted to some extent from physiologic observations in synthetic atmospheres at normal pressure. It is possible also to extrapolate from direct measurements in hyperbaric chambers with laboratory animals and physical models, such as those discussed previously. Another method is the application of theoretical relationships of heat transfer to the man-environment system. Each of these three approaches requires that

Table 1 Natural convection

Atmosphere	t_s	t_a	t_r	h_c
Air, 1 ATA	93.0	81.8	81.3	1.08
He, 1 ATA	89.0	80.0	79.8	1.70
He, 2 ATA	87.1	79.7	79.4	2.05
He, 5. 1 ATA	82.4	77.2	76.5	3.50
He, 11. 2 ATA	82.2	79.5	76.6	7.34

Table 2 Forced convection

Atmosphere	t_s	t_a	t_r	h_c
Air, 1 ATA	86.4	74.5	73.3	0.92
He, 1 ATA	81.8	75.4	73.0	2.36
He, 2 ATA	79.9	73.7	73.1	2.79
He, 5.1 ATA	76.1	73.1	72.9	7.00
He, 11. 2 ATA	75.8	74.1	74.0	12.85

the environmental conditions be clearly defined. They offer the advantage that these conditions can be carefully controlled or specified. The information obtained with these approaches, and its application question of thermal balance in hyperbaric environments, will be discussed in detail.

A. Oxygen Consumption

Chilling during exposures to helium was reported by Behnke and Yarborough[15] in 1938, in both diving and chamber experiments. Systematic studies of thermal physiology in helium atmospheres have been limited to normal or reduced pressures, however, The mechanism of increased oxygen consumption ($\dot{V}_{O_2}$) of rats observed in a helium-oxygen environment at 1 ATA was studied by Leon and Cook.[16] They showed that the effect could be prevented by providing an ambient temperature close to the normal skin temperature of their experimental animals. For example, the $\dot{V}_{O_2}$ of animals exposed to a helium-oxygen mixture averaged 46% above that of their control group in air, when the ambient temperature was 67°F. The increase in $\dot{V}_{O_2}$ was reduced to 22% when the ambient temperature was 77°F, and was only 5% when the temperature was 86°F. These workers expressed doubt that a significant degree of hypermetabolism due to chilling would occur in helium-oxygen divers, if suit gas temperature is kept above 70°F.

This view is favored by data on the oxygen consumption of man in helium-oxygen at normal pressure and at 0.5 ATA, maintaining a temperature of 79°F and a low relative humidity.[17] Although there was no increase in metabolic rate, a significant increase in convective heat transfer occurred, which was compensated by reduced rates of radiative and evaporative heat transfer. Under environmental conditions producing still greater convective heat transfer,[7,18] it is likely that reductions in body temperature would stimulate a significant metabolic response. Either a lower environmental temperature, increased atmospheric motion, or a higher pressure of helium might provide such conditions.

Increased pressure, spanning a range from 0.7 to 15 ATA, was employed in a recent study of the $\dot{V}_{O_2}$ of the rabbit in synthetic atmospheres. A significant increase in $\dot{V}_{O_2}$ occurred when helium was substituted for nitrogen, atmospheric oxygen content being maintained at 0.2 ATA. Values of $\dot{V}_{O_2}$ less than control were seen when argon was substituted. Differences in convective heat transfer might easily account for the observed changes, especially since open-circuit ventilation was employed under hyperbaric conditions. The data for argon would be in line with its low thermal conductivity. This hypothesis cannot be analyzed without temperature and gas velocity data, however, which are not included in the published abstract.[19] The authors attribute the differences in $\dot{V}_{O_2}$ to inhibitory effects of nitrogen and argon upon metabolic processes. To distinguish between the alternative mechanism, it would be necessary to compare $\dot{V}_{O_2}$ under increasing pressures of nitrogen, argon, and helium, at 70° and again at 90°F.

B. Effect of Skin Temperature

The previous comments have focused attention on the most gross physiologic effect of the increased convective heat-transfer properties of the hyperbaric helium atmosphere, that is, increased metabolic rate. A second physiologic factor, intimately related to both convective heat transfer and metabolic rate, is the skin temperature. The relationship of skin temperature (t_s) to the rate of convective heat flow $\dot{C}$ from skin to atmosphere has been given earlier in Eq. (2). In an environment where the value of h_c is increased, several changes are likely to take place. If the atmospheric temperature is appreciably below a comfortable skin temperature (90°F), the high value of h_c will lead to a more rapid drain of heat from the skin,[13] causing t_s to fall.[14] By lowering t_s, the body reduces the gradient for surface heat transfer to the cold atmosphere and cold walls. Constriction of blood vessels supplying the skin occurs in response to decreased t_s, and the resulting improvement in insulation further tends to limit heat loss. The metabolic consequences of a reduced t_s, simply referred to earlier as increased $\dot{V}_{O_2}$, represent a complex interaction of central and peripheral nervous responses with hormonal ones.[20] Both shivering and nonshivering forms of heat production contribute to the increase in metabolic rate, which Hart[21] has shown to respond quite sensitively to reduction in t_s regardless of the manner of cooling. The neurohumoral mechanisms involved include increased secretion of adrenal medullary and cortical substances and of thyroid hormone, increased turnover of blood glucose, and increased utilization of body fat. A higher setting of the central thermoregulatory mechanism may also occur.

It should also be noted that a low t_s may also initiate behavioral and environmental changes such as addition of clothing, increased voluntary muscular activity, adjustment of heating and ventilating devices, complaints, and other steps that may serve to limit heat loss.

Although the emphasis in the foregoing has been placed upon body cooling, the enhanced heat-transfer properties of the hyperbaric helium atmosphere apply to body heating as well. It would be possible experimentally to impose severe heat stresses by maintaining a high ambient temperature in such an environment, especially under humid conditions. The tremendous heat sink provided by the ocean makes it most unlikely that such conditions would occur in DSSP habitats, except in case of fire. It is likely that the combination of high ambient temperature, humidity, and h_c may increase the scrotal temperature enough to alter testicular function in some individuals.

C. Immersion Effects

In discussing thermal balance in high-pressure environments, it must also be recognized that the occupants of DSSP habitats will be subjected to other physical and emotional stresses, which may be expected to create departures in their physiologic responses, as compared to other normal subjects. Not the least of these potential stresses stem from excursions in the extremely cold waters beyond the habitat. In spite of efforts to provide optimal thermal protective systems, it is likely that some individuals will re-enter the habitat with a considerable heat deficit. The effects of these sorties upon body thermoregulation and adaptation to the habitat conditions may be considerable. The rewarming process following them also requires more study.

IV. Summary

Although many environmental and behavioral variables bear on the problem of human thermal balance in DSSP habitats and other hyperbaric environments, optimal function will probably be assured by providing the following environmental characteristics: 1) ambient temperature close to desired skin temperature, i.e., 90° ±1°F; 2) minimal atmospheric movement, especially in bunk areas and other sites of low metabolism; 3) improved insulation and distributed radiant heating to provide mean radiant temperatures of 85°–90°F; 4) relative humidity of 40–80%. If optimal environmental conditions and thermal protective devices can be provided for DSSP conditions, body temperature regulation may be changed from a problem to a physiologic curiosity.

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