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PROPOSED THERMAL LIMITS FOR DIVERS

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The thermal stress of cold water diving limits the amount of dive time available for the completion of mission tasks. Heat loss resulting from immersion in cold water also degrades progressively diver psychomotor performance before tolerance limits are reached that necessitate rewarming of the diver. This report is a review of current research efforts aimed at quantifying mechanisms of heat loss, the physiological and psychomotor responses to varying degrees of heat loss, and protective systems to extend diving times and performance under thermally adverse conditions.

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EXECUTIVE SUMMARY

The thermal stress of cold water diving limits the amount of dive time available for the completion of mission tasks. Immersion in cold water causes increased convective heat loss due to the large thermal conductivity, specific heat, and density of water compared to those same characteristics of air at the same temperature. The convective coefficient in water is 25 times that of air, causing the water temperature at which a thermally unprotected man may remain indefinitely to be higher than that of air: 33-34 °C for a man at rest, dropping to 26 °C for a subject exercising at three times his resting metabolic rate (Houdas, 1982).

The rapid rate of heat removal from the diver produces a fall in body temperature that is dependent upon immersion time, water temperature, and exertion level. A diver entering cold water with a normal body core temperature of 37 °C may lose heat at the rate of 400-1000 watts for each degree of temperature difference between his warm skin and the cold water. This rapid heat loss is reduced as the diver's skin cools and vasoconstriction reduces the flow of warm blood from the core of the body to the periphery. The extremities begin to cool, however, as the peripheral blood flow diminishes to conserve heat in the core of the body for optimal function of the central nervous system. The rate of this cooling depends upon the level of exercise the diver is performing during the mission. Low activity levels produce little heat; high levels can produce significant muscular release of heat in the limbs. As the heat loss in the limbs, especially the hands, continues, there is a progressive loss of feeling, dexterity, and strength that may compromise the mission.

Heat loss due to immersion in cold water also degrades progressively diver psychomotor performance before tolerance limits are reached that necessitate

rewarming of the diver. Quantifying the physical mechanisms of heat loss, and the physiological and psychomotor responses to varying degrees of heat loss are of current research interest. The current investigations will facilitate the establishment of guidelines for diver heat loss in adverse diving conditions and the prediction of the performance decrements likely to be encountered in specific diving mission scenarios. Design of protective systems to extend diving times and performance under thermally adverse conditions will be facilitated by the predictive engineering modeling made possible by current research data.

INTRODUCTION

The current stage of developing life support equipment for the diver is limited by the factor of thermal protection. For example, the free swimmer has a choice of many breathing apparatuses that allow up to 10 hr of very light underwater activity. Should the temperature of the water reach 40 °F, however, the diver's thermal protection is limited to nearly half that time with the best garment available. There are many diving situations in both shallow and deep water that induce thermal stress of this magnitude. An engineer concerned with the design and evaluation of thermal protective equipment for divers must have access to information on the thermal tolerance limits of man and his responses to thermal stress. He must have at least a rudimentary appreciation of the functional characteristics of the human body in addition to the quantitative information necessary for detailed design calculations. The need for this information is both crucial and immediate, as the frequency of diving in cold water is accelerating for both military and civilian purposes.

The emphasis of this report will be a description of the results of human exposure to cold water rather than of environmental parameters, types of clothing for cold-water diving, or various operational needs. Divers and underwater swimmers must be able to perform their mission while remaining within physiologically acceptable limits of heat loss. As a result, the physiological and behavioral descriptions of man subjected to cold stress are primary features of this report. Pertinent research information is presented in what is hopefully a useful format, but it is apparent that much of the information necessary for the designer is unavailable. Important areas of necessary research are identified at the end of this report. Because change in work performance and physiological detriment due to cold are not sufficiently understood, it is urged that designers not consider this report as either

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complete or universally applicable. Designers should, however, include information from experienced physiological and behavioral scientists in their analysis of a specific design problem.

This report begins with a summary of the most recent research on human thermal limits concerning permissible heat loss, namely the proposed thermal limits that designers should heed. (Note that these limits are not to be used operationally because the required measurements are not feasible for use in the field.) Included next is a condensed discussion of the physiological and behavioral effects of cold exposure in diving, followed by a list of measurements necessary to evaluate equipment to ensure that thermal protection meets the recommended limits. Also included are some additional factors that designers should consider: a list of additional research to aid the designer and a list of references, including both those cited in the text and those recommended for general reading.

THERMAL LIMITS

If producing a state of thermal comfort in all underwater situations is an unrealistic requirement for protective equipment, limits must be set on the amount of deviation from comfort that can be allowed. Based on our present knowledge of the physiological and performance effects of cold exposure, which are discussed in later sections of this report, a diver or underwater swimmer should be able to safely perform his assigned tasks if he is kept within the recommended limits. Because it is not practical to make the necessary measurements on a working diver, these limits must be satisfied by laboratory and field testing of newly designed equipment. The following limits are based on the weight of the average U.S. Navy diver, 81 Kg (Beatty and Berghage, 1972). These five limits apply concurrently:

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1. Maximum net body heat loss (change in enthalpy) of 200 kcal (3 kcal/kg), assuming a normothermic starting core temperature.

2. Core temperature not lower than 36 °C or no more than a 1 °C 'rop, whichever is lower. This allows a safety margin for the severe debilitation experienced at 35 °C.

3. Mean skin temperature not lower than 25 °C and no individual skin temperature lower than 20 °C, except that of the hand, which may fall as low as 15 °C. This will help prevent pain and possible cold stress during long dives.

4. Metabolic response to shivering no more than an incremental oxygen consumption rate of 0.5 L/min above the metabolic cost of the diver's activity.

5. Minimum inspired gas temperature as a function of depth, as specified in Fig. 1 (Braithwaite, 1972).

When applying heat to a man, either as supplemental heating in cold water or during rewarming of a previously chilled diver, the following limits apply:

1. Core temperature not higher than 38.5 °C.

2. Mean and individual skin temperatures not higher than 42 °C.

3. Maximum inspired gas temperature of 45 °C for exposures of 1 hr or less and 40 °C for long exposures of indefinite length.

PHYSIOLOGICAL FACTORS

The physiological factors involved in tolerance to cold exposure are described briefly in this section. The discussion starts with body heat loss and the separate areas where losses are measured, and proceeds to temperature changes in deep body tissues, on the body surface, and in the hands and feet. The concept of body core and shell is described, as well as the metabolic effects of shivering, and some important secondary effects of cold and water
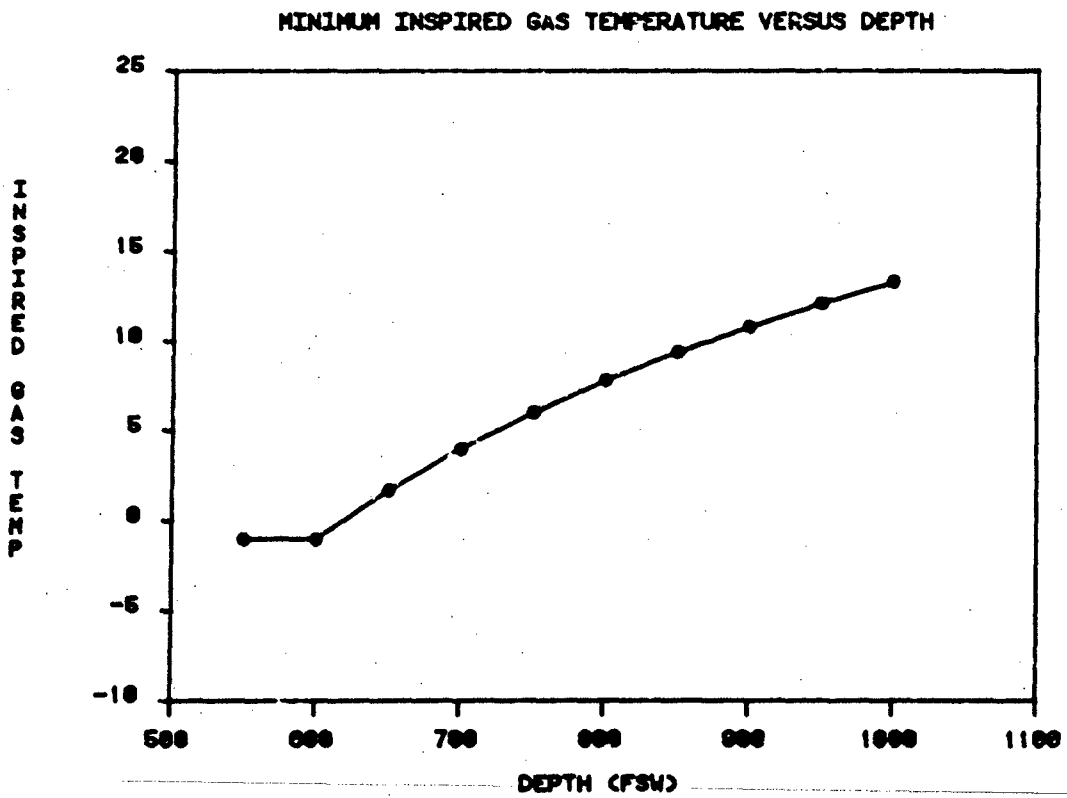
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MINIMUM INSPIRED GAS TEMPERATURE VERSUS DEPTH

Fig. 1. A recommended minimum inspired gas temperature as a function of depth,
or pressure of the respired gas. Braithwaite, 1972.

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immersion (diuresis and dehydration), including the interaction of cold with decompression sickness. First, a brief narrative is presented to cover the sequence of major physiological adjustments that occur during cold exposure.

When a nude or thermally underprotected person is submerged in cold water, the water causes a drop in skin temperature as heat flows from the warm skin to the cooler water. This decrease in skin temperature is sensed by temperature-sersitive neurons in the skin and transmitted to the central nervous system where it causes peripheral vasoconstriction to minimize peripheral blood flow. The diminished blood flow in the skin surface allows the skin temperature to drop more rapidly while heat is preserved in the center of the body. The skin temperature will approach the water temperature, but will be maintained at some level slightly above the water temperature due to conduction of heat from deeper body tissues and small levels of periodic blood flow to the skin to meet the metabolic requirements of the tissues.

This theoretical partition of heat stores in the body between a peripheral "shell" and a central "core" is useful in the physiological modeling of physical processes involved in thermoregulation. In resting man experiencing cold stress, the cooled "shell" of the body becomes larger (greater peripheral heat loss) while the relatively warm and stable "core" becomes smaller. When the combination of peripheral and central body temperatures is low enough, muscle tension increases, which increases heat production. If this increase in muscle tone fails to sufficiently offset heat losses, a pattern of gross muscle pair movements begins that is recognized as visible shivering. If the peripheral vasoconstriction and increased metabolic heat production do not respectively conserve and produce enough heat to maintain thermal balance, the result is a fall in body core temperature that leads to the clinical condition of hypothermia.

In response to a strong cold stimulus, the amount of cutaneous vasoconstriction varies in different parts of the body. It is quite complete in the hands and feet, less in the arms and legs, possibly less in the torso and apparently absent in the head. There are also differences in the rates of heat loss for underweight and overweight persons because subcutaneous fat is an effective insulator when circulation to the skin decreases greatly.

Total body heat loss

At first, body heat loss during cold exposure occurs at a high rate, then lessens with time. The curve is nearly exponential, as shown by Craig and Dvorak (1975), because the highest temperature gradient from skin to water occurs at the start and the lowest occurs when the body surface temperature has dropped to the lowest level. The tolerable quantity of heat loss in experimental subjects who determine their own limits for cold is between 180 and 300 kcal. Larger people tolerate more total heat loss and people with more body fat tolerate more heat loss than people of the same weight with a lower percentage of body fat. Experimental results suggest that people at rest tolerate less heat loss than subjects swimming (Craig and Dvorak, 1976; Webb, 1982).

Respiratory heat loss

Under ordinary conditions of air breathing at 1 ATA, the respiratory component of heat loss is only 10-20% of the metabolic heat production, and the majority of that heat loss is evaporative. When breathing hyperbaric air or heliox, however, the convective component of respiratory heat loss increases steadily with the density at a given inspired gas temperature. The evaporative component does not increase and thus becomes a minor part of respiratory loss.

At 19 ATA (600 fsw), respiratory heat loss can easily equal 100% of the metabolic heat production if the inspired gas temperature is 10 °C or lower.

The gas must be heated, both to reduce heat loss from the core and to prevent

local effects of breathing cold, dense gas, such as copious secretions of

sticky mucous. The minimum safe temperature recommended for hyperbaric

breathing gas at various depths is shown in Fig. 1. Figure 2 shows respiratory

heat loss or gain as a function of inspired gas (heliox) temperature at 15, 30,

and 45 ATA.

A thorough review of respiratory heat loss in diving, a related model, and

new data on the penetration of cold gas into the bronchial tree can be found in

a report by Johnson and Linderoth (1976). Hayward and Steinman (1975) reported

the successful rewarming of divers by breathing moistened oxygen at 50 °C. In

a study of isolated core temperature, cooling was produced by subjects

breathing cool hyperbaric helium-oxygen mixtures in a warm hyperbaric chamber

at pressures equivalent to 640-1800 fsw. Subject rectal temperatures fell by

0.43-0.98 °C after 60 min when they inspired gas at 14 °C. The rate of drop in

temperature was a direct function of the heat transfer characteristics of

inspired gas. The metabolic response consisted of an increased consumption of

oxygen that had no thermal benefit due to the greater respiratory heat loss

associated with increased pulmonary ventilation (Piantadosi et. al., 1981).

In another study the hyperbaric chamber was maintained at 15-20 °C (20.7

ATA) and the subjects breathed warm heliox for 60-120 min. Under these

conditions the increased metabolic heat production balanced cutaneous heat

losses but not respiratory losses. There was a correlation between respiratory

heat loss and fall in rectal temperature (Piantadosi, 1980). Compared to the

current U.S. Navy guidelines for divers, a set of more conservative values

based on the above findings concerning respiratory heat loss have been proposed

and are presented in Fig. 3 (Piantadosi, 1980). These new limits are based on

a diver wearing a hot-water suit with a maximum convective respiratory heat
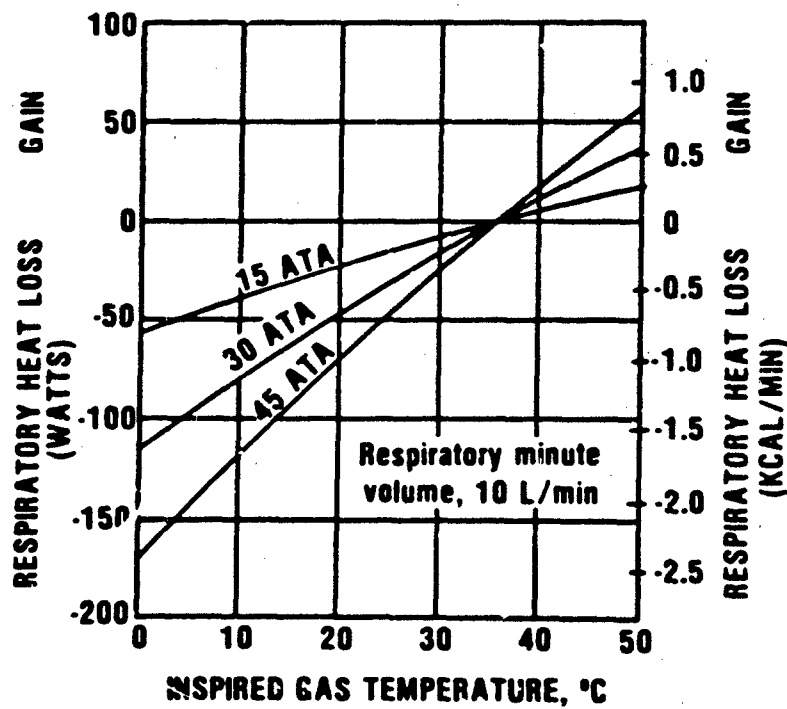
2. Respiratory heat loss or gain when breathing normoxic He-O_2 at three hyperbaric pres res. The curves are calculated for a resting man whose respiratory minute volume is 10 L/min. If he were working and had a minute volume of 30 L/min, the heat losses or gains would be three times as great. From Webb, 1982.
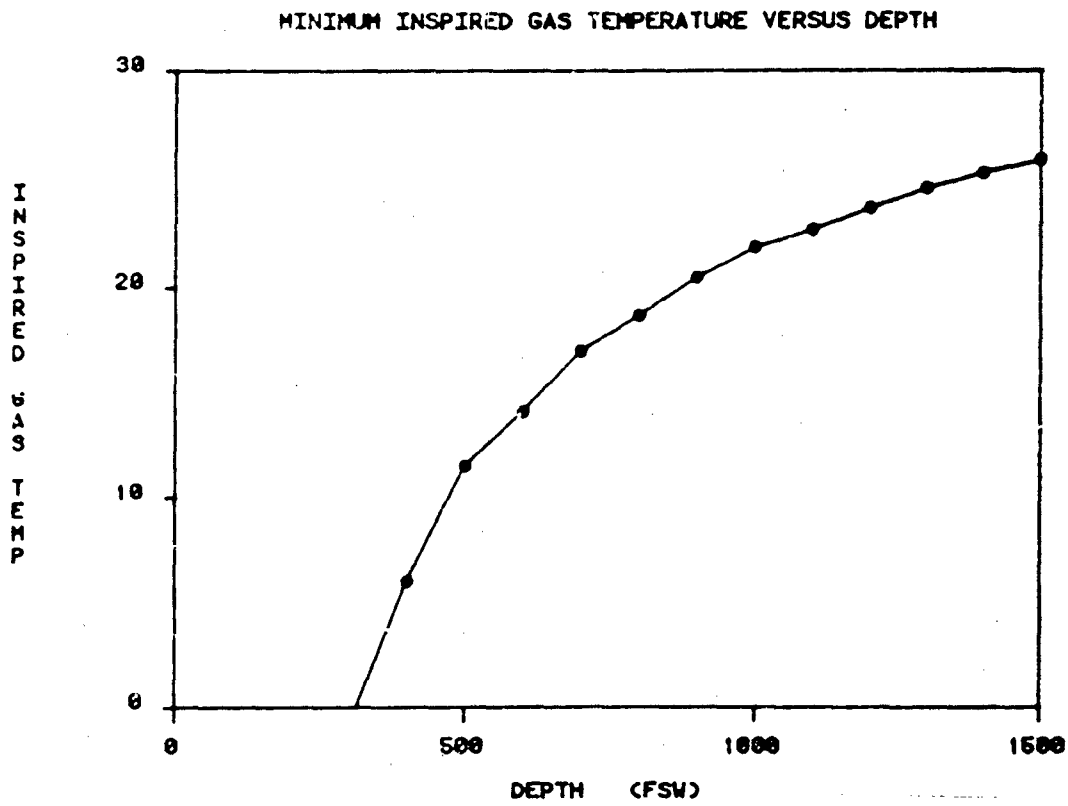
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MINIMUM INSPIRED GAS TEMPERATURE VERSUS DEPTH

Fig. 3. Proposed minimum inspired He-O$_2$ temperatures for saturation depths between 300 and 1500 fsw.

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loss of 20 Watts/meter^2 (W/m^2), and are calculated to limit core temperature

changes to a maximum of 1 °C during a 4-hr mission.

Change in core temperature

Despite the body's attempts to preserve its normal 37 °C temperature at

the core (central blood, heart, lungs, liver, kidneys, brain, and

gastrointestinal and related structures) by allowing the shell to cool and by

limiting blood circulation to the skin, peripheral heat loss may eventually

cause the deep body temperature to fall. Based on a variety of research and

clinical studies, it has been observed that core temperature as measured in the

rectum (Tre) must not reach 35 °C or the disabling symptoms of clinical

hypothermia will begin.

The ideal measurement of deep body (core) temperature is that of the

central blood compartments (Tbl), measured by passing a sensor on a catheter

down the venous tree into the entrance to the right side of the heart. This is

rarely done, however, even in the laboratory. The next best place to measure

core temperature is in the esophagus (Tes) at the heart level because this is

similar thermally to the central blood compartment. The temperature of the ear

drum, which is influenced by a major artery to the brain, has also been

recommended for monitoring core temperature. Because the ear drum is quite

sensitive to pain, however, most people prefer to measure the temperature of

the auditory canal (Tac). On the other hand, the auditory canal is influenced

by heating and cooling of adjacent areas of the scalp. Another possibility is

a temperature-sensitive radio pill. When swallowed, it will give readings of

gastrointestinal temperature as it passes through the body. If, however, the

portion of the bowel contacted by the pill is near the surface, its temperature

would be lower than that of a loop of the bowel next to the liver, which is a

heat source. A final possibility for measuring core temperature is to monitor

the temperature of the expired air (Tex), but one has to be aware of the heat-conserving mechanism present in the upper airway. This mechanism causes Tex to be lower than either Tre, Tes, or Tac by an increment that rises progressively as the inspired gas becomes colder.

Surface temperature change

The temperature of the skin falls rapidly when it is exposed without protection to cold water, approaching within 0.5-2 °C of the water. There are extensive data on mean skin temperature (Tsk) during nude immersions, but it is very difficult to apply these data to the thermal state of a clothed diver. Any layer of clothing will keep skin temperature from reaching that of the water. As mentioned previously, the skin on the hands and feet cools most quickly because blood flow in these areas decreases quickly during exposure to cold. The scalp cools more slowly, however, because blood flow there remains high despite chilling. A good display of the distribution of skin temperature over the body after immersion to the neck in water at 7.5 °C for 15 min is provided in a report by Hayward et al. (1973). These researchers used thermograms taken right after immersion to show that the groin and the lateral portions of the chest stay hot, and thus have continuous high losses of heat, while the hands, feet, arms, and legs cool more efficiently and quickly. Because the upper arms and shoulders of a swimmer stay warm in cold water, we might expect greater heat losses in active muscle masses.

A useful thermal description of man was detailed by Kerslake (1964), but only for a thermally comfortable man at rest. Comfortable skin surface temperatures and area heat losses are shown in Table 1. An extension of these data to hyperbaric environments has indicated even larger heat losses of up to 250 W/m^2 for the hands (Hayes and Padbury, 1980). From this theoretical information, one can design heated suits. As an example, during the Sealab II

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TABLE 1. Heat Losses of Thermally Comfortable Man at Rest

Region	Area (m^2)	Temp (°C)	kcal/hr	kcal/m^2/hr
Head	0.20	34.6	8	41
Trunk	0.70	34.6	29	41
Thighs	0.33	33.0	12	36
Calves	0.20	30.8	15	75
Feet	0.12	28.6	10	83
Arms	0.10	33.0	8	80
Forearms	0.08	30.8	9	113
Hands	0.07	28.6	8	114

and III era, electrically heated suits were designed and used satisfactorily for working in water at 4 °C, with the following proportions of a total power of 500 W (Beckman, unpublished data):

	Area Power (W)	Fraction of Total (%)
Head	40	8
Torso	200	40
Legs	100	20
Feet	60	12
Arms	50	10
Hands	50	10
	500	100

An analysis of the heating requirements for both active and passive divers was determined recently from a combination of physical heat transfer principles and thermal diving research. Lippitt (1983) proposed that a 1000-W diver heater would allow deep dives and a 500-W heater would suffice for shallow water operations in water as cold as 5 °C. Sufficient heat necessary to achieve thermal balance may not be required in all diving situations. A torso heating system, consisting of sachets of iron and magnesium in sea water producing exothermically less than 50% of the heat required for thermal balance, increased significantly both dive duration and perceived comfort by the diver (Burton, 1983).

Hands and feet

Even though hands and feet cool quickly (thus limiting their later heat losses), cold in these areas is painful and makes it difficult to move the legs and feet or to manipulate tools with the hands. Preferably, hands and feet must be protected and warmed to maintain a diver's effectiveness. Hands become uncomfortably cold when skin temperature reaches 20 °C, and pain begins as temperatures progress downward to 15 or 10 °C. Functional decrement begins at about 15 °C, as described later in the section on performance factors. At 10 °C the skin is numb, but pain persists because its origin is from constricted

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blood vessels. Feet become uncomfortably cold at 23 °C, painful at 18 °C, and begin to numb at 13 °C.

The surface temperature measurement of hands and feet is useful and can be combined, using appropriate weighting factors of surface area, into an estimate of the total body measure of mean skin temperature for use in thermal heat-transfer models. Temperature measurement of hands and feet is useful as much of the experimental data on psychomotor performance in cold cite the skin temperature of only one hand or finger.

Shell and core relationships

Just as heat is transferred by the respiratory gases to the exterior of the body, heat is also passed from the interior of the body through the skin to the layer of water surrounding the immersed diver. The amount of heat loss depends upon the temperature difference between the body tissue and the surrounding water, and the thermal insulation of the body tissues and any garments. The actual heat loss is altered by the insulative effect of subcutaneous adipose tissue and the limitation of blood flow and heat transfer caused by constriction of the vasculature of the skin, subcutaneous tissue, muscle, and bone.

As the surface vessels of arms and legs constrict, the blood is forced to return through deep veins. Some of these deep veins anatomically parallel and approximate the arteries entering the limbs. A countercurrent heat exchange occurs between warm arterial blood from the core and cool venous blood from the periphery that may further reduce heat loss by reducing arterial blood temperature to as low as 23 °C at the wrist.

During cold water immersion, a temperature gradient is established across the maximally cooled skin with associated peripheral subcutaneous tissue and the deep tissues of the core of the body. The deep tissues are thereby

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maintained as close to 37 °C for as long as possible through this mechanism of preferential cooling at the surface and by increased heat production as a response to cooling. The outer layers of body tissue, with temperatures approaching that of the surrounding water, comprise the thermal shell of the body. In the case of a diver wearing an insulating diving suit, the outside of the suit will approximate the temperature of water, and the suit can be considered an outer temperature shell and the adjacent layer of skin an inner temperature shell. These temperature shells might usefully be considered as isothermal shells that can be used to describe temperature gradients throughout the various parts of the body for modeling purposes.

These isothermal shells should not be considered uniform in either outline or depth because they are modified both by the body geometry and by local heat generators within the body mass, such as active muscles, the liver, kidneys, the heart, and the brain (Aschoff and Wever, 1958; Carlson and Hsieh, 1965). The shells change locale with the amount and duration of muscle activity, as well as with the depth of tissue vasoconstriction and the temperature of the outermost isothermal shell. The concept of changing core and shell is illustrated in Fig. 4, which shows isotherms for a man at rest in comfortable temperatures and after exposure to cold air. It would be useful to make similar diagrams for men in cold water, both at rest and active, and nude and variously clothed. Such an analysis has not been undertaken yet.

During intensive body cooling, the cooled shell increases in size while the core decreases in size. In thermal terms, it is as if the shell is thermally sacrificed in order to protect the core heat. The size of the cooled shell grows until the most central parts of the core are threatened. This may explain the observation that rectal temperatures do not change significantly

WARM COMFORT   COLD EXPOSURE IN AIR
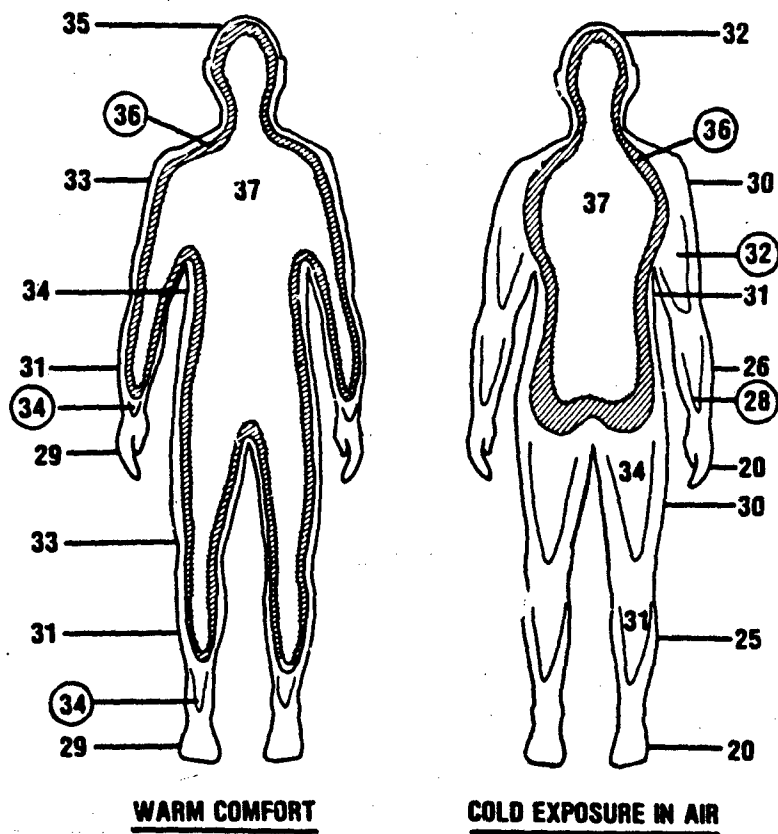
Fig. 4. Core and shell variation in resting man who is comfortably warm, at
left, and exposed to cold air, at right. Not only is there quite a
different set of surface temperatures, but also in the cold man the
core at 37 °C is much smaller, comprising only the brain and the
contents of the chest and abdomen. Between the warm core and the
cooler surface is a shell with isothermal outlines approximately as
shown. During activity, muscle layers in the shell would radically
change the isotherms shown. Adapted from Aschoff and Wever, 1958.

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during cold exposure, which is known to remove significant amounts of heat from the body.

Metabolic effects

Shivering is a major response to body cooling, but even before gross visible shivering begins there is increasing tension in skeletal muscle. This tension and the soon-to-follow tremor of shivering are detectable by electromyography. Shivering, whose purpose is to generate metabolic heat, is best measured from the oxygen consumption rate ($\dot{V}O_2$), or less accurately, by monitoring respiratory minute volume. Increasing $\dot{V}O_2$ with increasing total body heat loss appears to follow a linear relationship, as shown in Fig. 5. It is possible that $\dot{V}O_2$ could be used as an index of heat loss if the data of Fig. 5 are confirmed and extended.

Shivering starts as sporadic bursts that become more frequent as the subject cools. Finally, shivering is continuous. In the early stages, shivering can be suppressed by swimming and other muscular activity, but there is still an increased oxygen cost for swimming in cold water, as reported by Nadel (1974). In later stages, Nadel's very cold subjects swam and shivered simultaneously. Exercise in a cold (10 °C) environment on a bicycle ergometer suppressed shivering; the decrement observed in shivering was proportional to the intensity of the exercise (Hong and Nadel, 1979).

Continuous hard shivering is fatiguing. As with any tiring and sustained muscular activity, fat stores are soon mobilized to supply metabolic requirements, as carbohydrate reserves used by muscle are quickly depleted. Thus, the respiratory quotient (RQ) decreases from 0.9 to 0.7. There may also be a transient decrease in blood glucose followed by increased insulin release, an increase in plasma free fatty acids, and an increase in blood lactate, depending upon the level of shivering. One would see a general increase in the
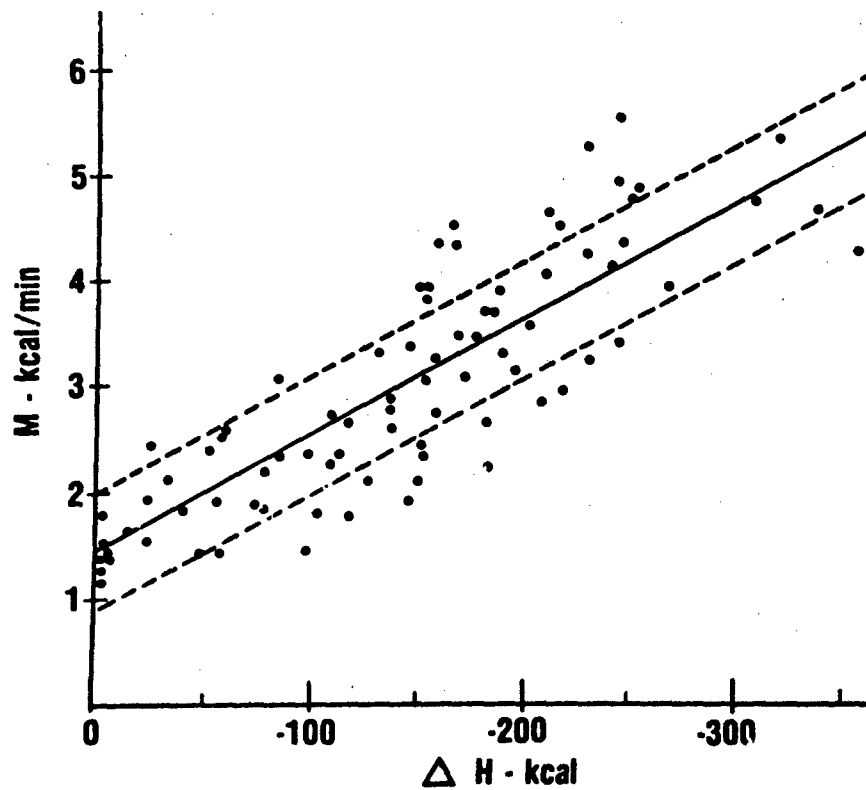
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Fig. 5. Preliminary data from direct and indirect calorimetry showing the apparently linear relationship between metabolic heat production (M), based on O_2 consumption, and enthalpy change (ΔH) during strong cooling. Each point is a 10-min average for M at a given level of ΔH. From Webb, 1976.

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levels of indicators of generalized stress, such as corticoids and catecholamines in blood and a greater urine content of such substances or their metabolites.

Secondary effects of exposure to cold

1. Effects of cooling of tissues on the incidence of decompression sickness.

The submergence of divers in cold water may reduce blood temperatures by 20 °C, from 38 °C central blood temperature to 18 °C peripheral blood temperature. In diving conditions where decompression tables are used such changes in blood temperature may increase significantly the required decompression simply because of the difference in solubility of gases at various temperatures.

The solubility of breathing gases (O_2, N_2, CO_2, and He) in water, body fluids, and watery tissues depends upon the temperature of the tissues, which is inversely proportional to the absolute temperature. Based on handbook values, Fig. 6 shows that a decrease in temperature from 38 °C to 18 °C would increase the amount of O_2 and N_2 that would be dissolved in a given amount of tissue by approximately 40%. This implies that for a given pressure the amount of air that would dissolve in watery tissues at 18 °C would be 40% greater than that dissolved at 38 °C. Therefore, even with no change in pressure, the cooled blood would contain 40% more gas than could be held in solution at normal deep body temperature; this would then permit bubbles to form on the basis of temperature change alone. Thus, the cooling of body tissues during diving at increased pressure may precipitate the onset of decompression sickness while the diver is still chilled at depth. The formation of gas bubbles would be exacerbated during decompression and the reestablishment of normal temperature gradients of tissue. Experimental evidence supports the
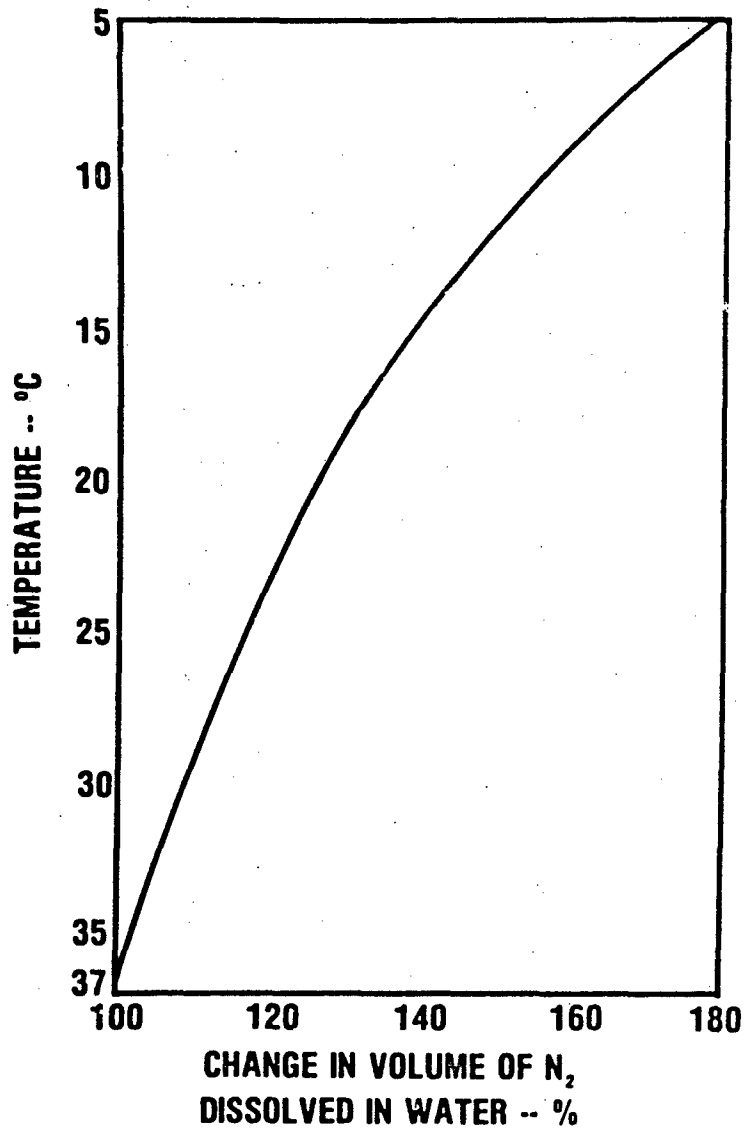
Fig. 6. The increasing volume of gaseous N_2 at 760 mm Hg that dissolves in water as the water becomes colder than 37 °C, expressed as percent of the volume dissolved at 37 °C. Based on tabulated data in Forsythe, 1954.

probable interaction between thermal state and decompression sickness, as reported by Hempleman (1982) and Balldin (1973).

2. Maceration of the skin.

During prolonged immersion in water -- from 12 to 24 hr -- skin swells, softens, and loses its barrier capability. Cracking and bleeding occur and there is pain, especially around joints. The skin becomes porous to both water and electrolytes. This skin maceration limits the prolonged wearing of wet suits that might otherwise provide adequate thermal protection.

3. Dehydration.

Dehydration is another physiological stress that can be limiting in underwater operations. It may be produced by diuresis, by a lack of ingest water, or by a loss of water through evaporation from respiration of dry air.

Diuresis, or increased urinary output, begins in underwater work by two factors: 1) chilling, with vasoconstriction and secondary increase in central blood volume, and 2) increase of central blood volume from an increased pressure differential, which results from external hydrostatic pressure and decreased respiration pressures during use of an underwater breathing apparatus. Whatever the mechanism, the process may cause an increase in urinary production of up to 2 L within two hr. This amount of urinary loss (2.5% of body weight for an 80-kg diver) produces dehydration that is eventually deleterious to the maintenance of circulation. In addition to the physiological decrement, diuresis causes serious problems to the "dry" suited diver; a urine-collection device becomes a necessary component of dry suits that are worn for more than an hour. Furthermore, in long underwater missions it is necessary to provide equipment to allow the diver (or swimmer) to drink and possibly to eat solid food.

Heating the body

Heat can be added to the body through its surface and is most effective where blood circulation of the skin is highest. Thus, the head and the trunk would be the most likely areas for warming. As already noted, the hands and feet must be warmed in order to maintain work performance and free these appendages from distracting pain. Selective warming of the head sufficient to produce a rise in tympanic temperature of 1 °C has been shown to increase the efficient performance of simple mental tasks. Heating the head increased the rate of mental addition without significantly affecting the error rate in subjects under thermoneutral conditions (Hancock, 1983). The investigators also discussed previous work that showed that reactions to both central and peripheral visual stimuli were slower but more accurate under the heating conditions. Further research is needed in this area of cognitive and psychomotor performance in diving. The limit to surface heating is the point at which skin becomes painful: 43 °C and above. At 45 °C pain is severe and if this temperature is maintained burns will result.

Heat can be added to the core by heating the inspired gas; the quantity of heat added is determined by the gas-volume exchange and its heat capacity. In hypothermic subjects, breathing warmed, humidified gas (43-48°C) minimized the rectal temperature afterdrop but produced a recovery time of the tympanic temperature longer than that produced by immersion in hot water (Collis, 1977). A later study by Marcus (1978) confirmed these findings but could not support the idea that breathing warmed, humidified gas was significantly better than spontaneous rewarming. In a study using anesthetized dogs cooled to 29°C by cold-water immersion, warm water immersion produced the most rapid core temperature increases. To examine the relative contributions of shivering and rewarming by inhalation (45-50°C), a group of dogs was anesthetized and

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artificially respirated. That group required 12 hr to reach the same core temperature reached by the shivering group in 2 hr. It was concluded that the amount of heat transferred across the respiratory tract was very small (Auld, 1979). Examination of inhalation rewarming rates, and physiologic and anthropomorphic measures allowed predictive equations to be formulated and reduced some of the variability between previous experiments (Morrison, 1980). Unfortunately, there are very few experimental data concerning inhalation rewarming by hyperbaric gases, so a safe maximum temperature can only be estimated. At 1 ATA, gas at 50 °C and saturated with water vapor (PH_2O = 92 mm Hg) is uncomfortably warm to breathe. Considerations such as possible injury to the ciliary lining of the respiratory tree or the effect of keeping the upper tract constantly wet from condensation must be taken into account.

When the body heat content increases, the core will expand and the shell will decrease to allow greater heat transfer from the surface of the body to the environment. Progressively greater heat storage will be sensed as an increase in body temperature and cause blood vessels in the skin to open, cardiac output to increase, and sweating to begin. Core temperature rise if these responses are insufficient to balance body heat production, absorption, and losses. When the core temperature in a resting subject reaches 39 °C, a condition of impending heat stroke is likely. It is unlikely that the warming or rewarming of a diver would be carried to this point.

PERFORMANCE FACTORS

Man's performance characteristics range from simple sensory and motor skills to more complex perceptual and cognitive abilities. In general, the simpler sensory-psychomotor abilities are better defined and understood than the perceptual-cognitive abilities. Tactile discrimination, manual dexterity, and reaction time are examples of well determined abilities that are understood

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easily and tested reliably. The perceptual-cognitive abilities of a higher

order are far less precise attributes, such as memory, problem solving,

vigilance, and reasoning.

Tests of these perceptive-cognitive abilities, in contrast to the

psychomotor abilities, are not well standardized and tend to be "homemade"

tests of unknown technical characteristics. Part of the problem of determining

the consequences of cold water exposure on performance is the lack of a strong

measurement technique for perceptual-cognitive abilities. Several examples are

given in Table II. The general conception of how cold water exposure affects

performance has been that peripheral cooling degrades skin sensitivity and

motor performance, while deep body cooling degrades the higher-order abilities

such as problem solving. Recent attempts to quantify the relationships between

indices of deep body cooling and perceptual-cognitive task performance,

however, have demonstrated that this view is oversimplified. A more

sophisticated, time-dependent pattern of performance effects can be formulated

in four stages.

The first stage is an initial exposure to very cold water that causes

distraction effects lasting for perhaps as long as an hour. Many investigators

found that at the beginning of cold exposure the diver's ability to pay

attention decreases, and his performance in a wide variety of tasks is inferior

when compared to performance of the same tasks in moderate or warm water. In

the next stage, the body protects the core at the expense of the shell; the

diver's hands and arms become cold and therefore less sensitive, weaker, and

less dextrous. These peripheral effects of cold significantly degrade

performance of a wide range of tasks involving sensory sensitivity and

psychomotor abilities. If the exposure is long, leading to deep body cooling,

there may be deleterious effects on perceptual and cognitive performance, but

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TABLE 2. Studies of Higher-Order Task Performance in Cold Water With Moderate Water Exposure as a Control

Authors	Control Exposure (°C)	Cold Exposure			Task Areas	Cold Effects: Physiological (°C)	Performance Decrements
		(°C)	Time (mins)	Depth (m)			
Baddeley et al., 1975	25.5	4.5	50	4.9	Vigilance Reasoning Memory	Rectal Δ0.72 (Δonly was reported; no values)	Decrement in recall memory only. Caution re: distraction effect.
Davis et al., 1975	20.0	5.0	40	9.0	Digit span Arithmetic Reasoning Memory	Rectal Δ1.1 pre: 37.9 post: 36.8	Decrement in recall and recognition memory. Recall decrement correlated with body temperature change.
Vaughan and Anderson, 1975	15.5	4.5	180	2.5	Vigilance Problem solving	Rectal Δ0.6 pre: 37.4 post: 36.8	Decrement in 1st hour only for both tasks. No significant differences from control in 2nd & 3rd hour performances. No correlation with change in BHC.
Egstrom et al., 1972, 1973	25.5	4.5	45		Vigilance Memory	None measured	Decrement in recall memory only. Caution re: contextual learning effort.
Bowen, 1968	16.6	8.4	20		Memory Reasoning Symbol processing	None measured	Decrement in memory only.

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this has not been proven by various studies completed so far. What is known is that in such situations cold stress is only one of many factors, including fatigue and boredom, that contribute to degradation of performance. At the extreme end of the time scale, a few studies of diver performance have extended to 6 hr of continuously submerged operations. From these and other research studies, there is evidence of two dysfunction effects that characterize the extremely cold diver: response blocking and preservation of inappropriate responses. Further descriptions of each of these four stages follow.

1. Distraction effects.

This term applies when performance degradation occurs in the absence of significant physiological cooling. It is presumedly a psychological phenomenon that occurs in response to extreme environmental conditions and not in response to change in physiological state. Tasks that are susceptible to the distraction effect of cold water include reaction time (Teichner, 1958), symbol processing (Bowen, 1968), target-detection time (Vaughan and Andersen, 1973), navigation problem solving (Vaughan and Andersen, 1973), and memory (Baddeley et al., 1975; Davis et al., 1975).

2. Peripheral cooling effects on sensory and psychomotor performance.

Peripheral cooling affects the tactile sensitivity of the skin, the flexibility of the finger joints, the strength of the muscles of the arms, hands, and fingers, and the performance of a wide variety of tasks dependent on finger and hand dexterity. These effects appear to be related directly to the temperature of the skin or muscle. The main areas of affected performance and the temperatures at which the effects occur are as follows:

A. Tactile sensitivity

    a. Vibratory sensitivity and skin temperature.

    Sensitivity to a vibrating stimulus is maximal at a skin temperature of

37 °C. Vibrational sensitivity degrades at an accelerating rate as skin temperature decreases to 21 °C (Weitz, 1941).

   b. Two-edge discrimination and skin temperature.

   This is the ability to sense the presence of two separated points or edges. As the skin cools, the separation distance must be widened in order to perceive more than a single point. The maximum sensitivity occurs at a skin temperature of 30 °C, where a separation of 1 mm can be detected. As the skin cools, the separation interval must be progressively larger. At 10 °C skin temperature, the rate of decrease in sensitivity accelerates sharply (Mills, 1956).

B. Hand-grip strength.

   Hand-grip strength is maximal when the musculus brachioradialis is at a temperature between 25 and 38 °C (Clarke et al., 1958). It has been shown to decrease significantly from 56 to 47 kg of force when skin temperatures of the upper arm drop to 21 °C (Vaughan and Anderson, 1973; Coppin et al., 1978). Grip strength in water drops significantly from 63 kg barehanded to 49 kg when wearing neoprene gloves, regardless of temperature (Egstrom et al., 1973). Torquing strength (grasp and twist) decreases significantly in water (53 inch-pounds) when compared to that in air (60 inch-pounds). These data were obtained from a gloved hand (McGinnis et al., 1972).

C. Hand-arm steadiness.

   Lockhart (1968) found that when skin temperature decreases from 25 to 21 °C, steadiness in aim decreases significantly.

D. Manual dexterity.

   Hunter et al. (1952) found significant stiffening of the finger joints at 10 °C skin temperature. Criterion levels of performance in tasks requiring

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finger dexterity can be distinguished to a skin temperature of 15 °C, but degradation becomes significant between 10 and 12 °C (Clark, 1961; Gaydos, 1958).

3. Deep body cooling effects on perceptual and cognitive performance.

A list of higher-order tasks that are potentially sensitive to the effects of cold have been studied. This long list includes vigilance, reasoning, digit-span problem solving, arithmetic computation, and symbol processing (Bowen, 1968; Egstrom et al., 1972; Vaughan and Andersen, 1973; Baddeley et al., 1975; Davis et al., 1975). None of these studies revealed significant decrement in task performance. Exposure temperatures were low enough (4.5-8.5 °C), but durations of exposure were relatively short, and body heat loss was estimated from rectal and skin temperatures, a questionable method.

Memory could be an exception to this conclusion. Memory, particularly recall, consistently showed a decrement in performance in cold water studies. Several authors suggest, however, that their results may be attributed to aspects of the experiment other than deep body cooling (Bowen, 1968; Egstrom et al., 1972; Baddeley et al., 1975; Davis et al., 1975). Alternate explanations include the distraction effect and the change in context between learning and recall of material.

In a series of recent experiments Coleshaw et. al. (1983) lowered body temperatures of individuals by immersing the subjects in 15 °C water. Cognitive function tests were administered during the progressive fall in core temperature. The results demonstrated a 70% decrease in the memory retention of data presented at core temperatures from 34-35 °C when compared to the amount of information retained at normal core temperatures. Recall of data learned previously was not impaired. These investigators rewarmed the subjects

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by immersing them in 41 °C water and th. subjects reported feeling comfortable even when their body core temperatures remained low (Coleshaw et. al., 1983).

4. Dysfunction effects.

Probably the most severe condition of exposure reported in the literature on cold effects and performance lasted 6 hr in 6 °C water (Vaughan, 1975). Divers had rectal temperatures of 35.5-36.0 °C and mean skin temperatures of 22 °C. Divers well trained in the operation of sonar equipment not only omitted required procedural steps, but also consistently made recording errors that ordinarily would have been recognized as errors and would not have been committed. Evidence of blocking of responses or ommitting required responses has also been reported by Bowen (1968) and by Vaughan and Andersen (1973).

Evaluation of Protective Equipment

Performance evaluation of prototype suits designed to meet thermal criteria could be conducted using standardized tests of those psychomotor and higher-order abilities affected by cooling. Eventually, of course, the suit should be tested against operational task requirements in cold environments. Operational testing could be performed at the test facility for the System for Investigation of Diver Behavior at Depth (SINBAD) located at the Naval Experimental Diving Unit, Naval Coastal Systems Laboratory (NCSL), Panama City, FL. At the SINBAD facility, well established, standardized psychomotor and perceptual-cognitive tests have been incorporated into a hardware system capable of operating in a wet chamber at pressures to 445 psi (1000 fsw). The SINBAD facility is able to facilitate 22 separate tests that represent the range of basic human abilities as determined by factor analytic studies and selected on the basis of technical criteria such as factor purity, test-retest reliability, and sensitivity to individual differences and environmental changes. Some of the factors that can be tested in the SINBAD facility include

those sensitive to temperature, such as arm-hand steadiness, finger dexterity, manual dexterity, multilimb coordination, reaction time, speed of arm movement, vigilance, associative memory, and memory span.

Physiological evaluation of prototype suits can be completed by making some of the following measurements on a man wearing the protective garment. The intent is to ensure that the equipment maintains the thermal limits proposed in section II for the subject exposed to cold conditions.

Heat loss measurements

1. Direct calorimetry in a bath calorimeter.

2. Direct calorimetry using heat-flow sensors for sampling area heat flows.

3. Estimates of body heat loss based on body temperature changes or metabolic response to cold. Both techniques require further development and validation.

Temperature measurements

1. Core temperature measured in the esophagus or rectum. Gastrointestinal temperature and auditory canal temperature are second choices because of limitations discussed previously.

2. Skin temperatures of the hand and foot.

3. Skin temperatures at various locations.

4. Temperatures of inspired and expired gas.

Metabolic measurements

1. Oxygen consumption rate or respiratory minute volume.

2. Shivering as measured by electromyography.

3. Respiratory quotient ($\dot{V}CO_2/\dot{V}O_2$), blood glucose, lactates, and free fatty acids.

Also evaluate the effectiveness of the suit by listening to the subject's

comments or reports of cold, discomfort and fatigue, and by observing his
condition.

Further Thoughts

Encumbrance of a diver or underwater swimmer is a major problem with today's respiratory and thermal equipment. If better thermal protection can only be achieved by designing equipment that further hampers the wearer, it is not acceptable. Mobility must be preserved for swimming, walking, sitting, exiting through small hatches, and all other activities of the underwater worker. Similarly, hands and fingers must be dextrous. Increased pressure with depth affects thermal protection in several ways. Gas-filled foams become compressed and lose insulation. Thermal transfer in hyperbaric gas increases dramatically. Many materials lose flexibility with both pressure and cold. Thermal protection must be adapted to pressure and depth changes.

A garment is considered wearable through proper fit. Clothing terms like "drape" and "hand" also apply to wearability and affect the acceptability of the garmet. Because man comes in many sizes and shapes as noted by anthropologists, sizing and tariffs of sizes should be based on accurate descriptions of the population of users.

Heat production varies with the diver's activity. Some missions require equipment that will first have to protect a resting man in cold water, and then protect the same man when active in an air environment. Thus, the same form of thermal protection may have to adapt to various environmental conditions.

Human skin is sensitive to certain materials, plasticizers, and dyes used in thermal equipment. Other potential areas of harm, such as noise, radiation, or other environmental hazards, are also being analyzed in the current design and technology of thermal equipment.

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RESEARCH NEEDS

To make the thermal limits of equipment more precise and inclusive for designers, and to improve current descriptions of performance decrement and physiological change, the following research is essential:

First priority

a. Define physiological measures that correlate with net body heat loss (enthalpy change). For example, define a body temperature or combination of temperatures, regional heat-flow state, and oxygen consumption level, and validate each factor in the type of cold exposure characteristic of diving.

b. Determine the relationship between body enthalpy change and performance of those higher-order tasks required of divers (problem solving, decision making, following procedures, and memory).

Second priority

a. Measure gloved-hand performance in cold water.

b. Reexamine thermal tolerance limits for the effects of long exposure times, varied activity levels, and various end points of performance.

c. Investigate the interaction of body cooling with decompression sickness.

Third priority

a. Describe heat loss by body region, such as head, limbs, and torso.

b. Determine the best areas for applying supplemental heat.

c. Investigate the benefits of body heating by warmed respiratory gas.

Fourth priority

a. Explore the concept of varying core and shell, establishing isotherms during body cooling.

b. Investigate diuresis and the limits of dehydration in cold.

c. Investigate skin maceration in prolonged submersion.

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