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PHYSIOLOGICAL DESIGN GOALS AND PROPOSED THERMAL LIMITS FOR U. S. NAVY THERMAL GARMENTS:

Proceedings of two conferences sponsored by the Naval Medical Research and Development Command

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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

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The proceedings of two conferences that were held to develop physiological limits and design goals for passive thermal garments are presented. These proceedings have not been archived in the literature, but were in the form of reports submitted to the Office of Naval Research and Naval Medical Research and Development Command. This technical report has been published solely to archive these proceedings, which are of historic value.

The first proceeding is entitled "Proposed Thermal Limits for Divers: A Guide for Designers of Thermally Protective Equipment," held in July 1976. This proceedings sets the physiologic limits for both cold and heat exposure within which protective gear must maintain individuals. Total body and respiratory heat loss, core temperature, skin temperature, and hand and foot limits are discussed. A section on performance factors is also given.

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The second proceedings is entitled "Physiological Design Goals for Thermal Protection of Divers," held in September 1980. This was an update of limits proposed in the first proceedings. Minimum net body heat loss, core temperature, mean skin temperature limits are given for cold and heat exposures. Minimum inspired gas limits are also proposed.

While many of the limits proposed in these two proceedings have been superceded, modern limits have been based on these initial working limits.

Foreword

In the course of developing physiologic limits for thermal exposures and design goals of passive thermal garments, the U.S. Navy funded research which produced documents that did not get published in the archival literature. The two proceedings contained in this report are such documents. In the course of writing papers describing modern thermal exposure limits, it became apparent that these proceedings had some historical value and needed to be published in archival for so they could be referenced. The purpose of this report is to accomplish this and the subject proceedings have been reproduced exactly from the original without editing or comment.

Edward D. Thalmann
Naval Medical Research Institute
Bethesda, Maryland
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PART A

PROPOSED THERMAL LIMITS FOR DIVERS:

A Guide for Designers of Thermally Protective Equipment

Paul Webb, E.L. Beckman, Philip Sexton, and W.S. Vaughan

July, 1976

This research was supported by the Office of Naval Research Contract N00014-72-0057 with funds provided by the Naval Medical Research and Development Command.

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Foreword

In recent months there have been a number of discussions among members of the diving community about the need for new equipment to protect divers and underwater swimmers from the effects of cold. Engineers who design such equipment have asked for guidelines from biomedical scientists so that they can know what are the permissible thermal states of such men -- that is, states other than thermal comfort which still would allow divers to perform their required tasks and stay free of medical risk.

In order to prepare such a guide, to be based on laboratory research and field investigation, a conference was held from 19-21 May in the Webb Associates laboratory, Yellow Springs, Ohio. The conference was sponsored by the Naval Medical Research and Development command through ONR contract N00014-72-C-0057. In attendance at the conference were:

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Professor of Physiology, University of Hawaii, Honolulu

Philip Sexton, M.S.M.E., Task Manager - Thermal Protection
Naval coastal Systems Laboratory, Panama City, Florida

William S. Vaughan, Jr., Ph.D., President
Oceanautics, Inc., Landover, Maryland

Paul Webb, M.D., Principal Associate
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This report is the result of that conference. It represents what the conferees felt were reasonable thermal limits for designers to work within, and it provides brief discussion of physiological and performance effects of cold, upon which the limits were based.

The guidelines provided here should be thought of as interim ones, subject to periodic revision as experience in cold water accumulates. Revisions should be planned at intervals of 12 to 18 months. Further, it is strongly recommended that designers, who might start from the information in this report, seek the advice of physiologists and behavioral scientists when designing and evaluating new equipment.

I. Introduction

The current stage of development of life support equipment for the diver is such that thermal protection is the limiting factor. The free swimmer, for example, has a choice of a number of breathing apparatuses that allow up to ten hours of very light underwater activity. Should the temperature of the water be 40 °F, however, the diver is thermally limited to something near half that time with the best available garment. There are many such thermally stressful diving situations in both shallow and deep water.

An engineer concerned with the design and evaluation of divers' protective equipment must have access to information on human thermal tolerance limits and man's responses to thermal stress. He must have at least a rudimentary appreciation of the functional characteristics of the body in addition to the quantitative information necessary for detailed design calculations. The need for this information is both immediate and crucial. Diving in cold water is being done at an accelerated rate for both military and civil purposes.

The emphasis in this report will be on descriptions of man exposed to cold water rather than on environmental parameters, types of clothing, or varied operational needs. Divers and underwater swimmers must be able to perform, and must stay within physiologically acceptable limits of cooling. Therefore, physiological and behavioral descriptions of man are primary features here.

We have tried to include pertinent information in a useful format, but it is apparent that much that the designer wants to know is not available. Important areas of needed research will be identified at the end of this report.

Precisely because performance change and physiological detriment from cold are insufficiently understood, it is urged that designers not take this report as either complete or universally applicable, but that they should include in their analysis of a specific design problem the participation of experienced behavioral and physiological scientists.

The report begins with conclusions reached at the conference -- namely, the proposed thermal limits that designers should heed. (Note that these limits are not intended to be used operationally, since measurements would be required which are not feasible for use in the field.) There follows a condensed discussion of physiological and behavioral effects of cold exposure in diving, then a list of measurements needed to evaluate equipment to insure that protection is adequate to meet the recommended limits. And we have included some additional factors that the conferees felt designers should consider, a listing of research needed to further aid the designer, and a list of references, including both those cited in the text and some suggested general reading.

II. 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 present knowledge of 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 perform his assigned tasks and be relatively safe if he is kept within the limits listed below. These limits must be satisfied by using testing of newly designed equipment, since it is not practical to make the necessary measurements on a working diver. The limits are scaled to the size of the average Navy diver, 81 kg (Beatty and Berghage, 1972).

The following five conditions apply concurrently:

1. Maximum net body heat loss (change in enthalpy) of 200 kcal.
2. Core temperature not lower than 36 °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 go as low as 15 °C.
4. Metabolic response from shivering no more than an incremental oxygen consumption rate of 0.5 liters/min above the metabolic cost of the diver's activity.
5. Minimum inspired gas temperature as a function of depth as specified by Figure 1 (Braithwaite, 1972). (Note: this recommendation has not been fully tested experimentally.)[1]

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 one hour or less, and 40 °C for indefinitely long exposures.

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[1] Current U.S. Navy minimum inspired gas limits have been documented in: Piantadosi, C.A. Respiratory Heat Loss Limits in Helium-Oxygen Saturation Diving. Navy Experimental Diving Unit Report 10-80 (Revision March 1982).

III. Physiological Factors

The physiological factors involved in tolerance to cold exposure are briefly described in this section. Starting with body heat loss and the separate areas from which losses are measured, the discussion 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, then the metabolic effects of shivering, then some important secondary effects of cold and water immersion -- diuresis and dehydration -- and the interaction of cold with decompression sickness. First, we present a brief narrative of the sequence of major events during cold exposure.

When a nude or under-protected person is submerged in cold water, the cold water causes a drop in skin temperature which produces vasoconstriction just beneath the skin; therefore the skin temperature drops more rapidly because it is no longer being warmed by full circulation. The end of this sequence is when skin temperature approaches water temperature, even though heat from the warm tissues in the center of the body continues to move from the deeper structures. In a resting man, the cooled shell of the body becomes larger while the relatively warm and stable core becomes smaller. The next response is an increase in muscle tension, leading to increased heat production, which is soon detected as visible shivering. If the vasoconstriction and increased heat production do not conserve enough heat to maintain thermal balance, the result is a fall in core temperature leading to the clinical condition of hypothermia.

In response to a strong cold stimulus, cutaneous vasoconstriction varies in different parts of the body. It is quite complete on the hands and feet, less on the arms and legs, possibly less on the torso, and apparently absent on the head. There is also a real difference in the rates of heat loss for thin and fat persons, since subcutaneous fat acts as insulation when the circulation to the skin has been cut off.

Total body heat loss

Body heat loss during cold exposure occurs at a high rate at first, then lessens as time goes on. The curve is roughly exponential, as shown by Craig and Dvorak (1975), since the highest temperature gradient from skin to water exists at the start, and is least when the body surface temperature has fallen furthest. The tolerable quantity of heat loss in experimental subjects who determine their own limits for being cold lies between 180 and 300 kcal. Larger people tolerate more total heat loss; fatter people can lose more than thin ones of the same weight; and experimental results suggest that resting people tolerate less heat loss than actively swimming subjects (Craig and Dvorak, 1975; Webb, 1975).

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 a majority of that heat loss is evaporative. In hyperbaric air or heliox, the convective component of respiratory heat loss steadily increases 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 about 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 spicy mucous. Recommended minimum safe temperature for hyperbaric breathing gas at various depthd was shown in Figure 1. Figure 2 shows respiratory heat loss or gain as a function of inspired gas temperature (heliox) at 15, 30, and 45 ATA.

A thorough review of respiratory heat loss in diving, a model, and new data on the penetration of cold gas into the bronchial tree can be found in the report of Johnson and Linderoth (1976). Hayward and Steinman (1975) report the successful rewarming of divers through having them breathe moistened oxygen at 50 °C.

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, gut and related structures) by allowing the shell to cool, and by limiting blood circulation to the skin, sufficient total heat loss eventually causes the deep body temperature to fall. From many and varied experiences, we can say that core temperature as measured in the rectum (T_{re}) 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 compartment (T_{bl}) measured by passing a sensor on a catheter down the venous tree into the entrance to the right side of the heart, but this is rarely done even in the laboratory. The next best place to measure is in the esophagus (T_{es}) at heart level, since this is close thermally to the central blood compartment. The temperature of the ear drum, being influenced by a major artery to the brain, has also been recommended for monitoring core temperature, but since the ear drum is quite sensitive to pain, most people prefer to measure the temperature of the auditory canal (T_{ac}). T_{ac} is, however, influenced by heating and cooling of adjacent areas of the scalp. Another possibility is a temperature-sensitive radio piil. It can be swallowed and will give readings of gut temperatures as it passes along; if the portion of bowel is near the surface, its temperature would be lower than that of a loop of 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 (T_{ex}), but one has to be aware of the heat conserving mechanism present in the upper airway, which causes T_{ex} to be lower than either T_{re}, T_{es}, or T_{ac} by an increment progressively greater as the inspired gas is colder.

Surface temperature change

The temperature of skin falls rapidly when it is exposed without protection to cold water, and in fact approaches that of the water, to within 0.5 to 2 °C. There is extensive data on mean skin temperature ($\bar{T}_{sk}$) during nude immersions, but it is very difficult to make such data applicable to the thermal state of a clothed diver. Any clothing layer will keep skin temperature from reaching that of the water. As mentioned above, the skin on the hands and feet cools most quickly since blood flows there reduce most quickly on exposure to cold, while the scalp cools more slowly since blood flow there stays high despite chilling. A good display of the distribution of skin temperature over the body following immersion to the neck in water at 7.5 °C for 15 minutes is given in the report of Hayward, et al. (1973). These authors show by thermograms taken right after immersion that the groin and the lateral portions of the chest stay hot, hence have continuing high heat losses, while the hands, feet, arms, and legs cool the fastest and the most. If the subject swam in the cold water, the upper arms and shoulders stayed warm. One expects greater heat losses over active muscle masses.

A useful thermal description of man was given by Kerslake (1964), but only for a thermally comfortable man at rest. Comfortable surface temperatures and area heat losses are shown in the following table.

			Heat Loss	
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

One can design heated suits from this information. As an example, during the Sealab II and III era, electrically heated suits were made and found satisfactory for working in water at 4 °C, with the following proportioning 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

Hands and feet

Even though hands and feet cool quickly, thus limiting their later heat losses, they are important because they become painful, thus making it difficult to move about on the feet or to manipulate tools with the hands. They must be preferentially protected and warmed to keep a diver effective.

Hands become uncomfortably cold when their skin temperatures reach 20 °C, and painful as temperatures progress downward to 15 or 10 °C. Functional decrement begins at about 15 °C, as described below in the section on performance factors. At 10 °C the skin is numb. but pain persists because its origin is from constricted blood vessels. Feet become uncomfortably cold at 23 °C, painful by 18 °C, and begin to numb at 13 °C.

Surface temperature measurement on hands and feet is useful, as opposed to the uselessness of trying to measure mean skin temperature for the whole body. Much of the experimental data on psychomotor performance in cold cites hand or finger skin temperature.

Shell and core relationships

Just as heat is transferred by the respiratory gases to the exterior of the body, so too is heat passed from the interior of the body through the skin to the layer of water surrounding the immersed diver. The amount of heat lost obviously depends upon the temperature difference between the body tissue and the surrounding water. This gradient 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, in that order. As the surface vessels of arms and legs shut down, blood must return through the deep veins which parallel and lie close to the arteries entering the limbs. A heat exchange occurs which may reduce arterial blood temperature to as low as 23 °C at the wrist.

Thus a temperature gradient is established from the maximally cooled skin and subcutaneous tissue to the tissues of the core of the body, which are maintained at near 37 °C 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 tissue of the body, whose temperatures approach 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 the water, and the suit will become the outer temperature shell and the adjacent layer of skin an inner temperature shell. These temperature shells might usefully be considered as isothermal shells which can be used to describe temperature gradients throughout the various parts of the body.

These isothermal shells are not uniform in either outline or depth, since they are modified both by the body geometry and by heat generators within the body mass -- the muscles, liver, kidneys, heart, and brain (Aschoff and Wever, 1958; Carlson and Hsieh, 1965). These isothermal shells would 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 Figure 3, which shows isotherms for a man at rest in comfortable temperatures and after exposure to cold air. It would be useful to have similar diagrams made for men in cold water, both a[illegible]st and active, nude and variously clothed. Such an analysis has not been undertaken yet.

During strong body cooling, the cooled shell increases in size while the core decreases in size. It is as if the shell is discarded, thermally speaking, in order to protect the core, and the amount of cooled shell grows until the most central parts of the core are threatened.

Metabolic Effects

Shivering is a major response to body cooling. 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 electromyograms. 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 be a linear relationship, as shown on Figure 4. It is possible that $\dot{V}O_2$ could be used as an index of heat loss, if the data of Figure 4 are confirmed and extended.

Shivering starts as sporadic bursts, which become frequent as the subject cools more. Finally it becomes continuous. In the early stages shivering can be suppressed by swimming and other muscular activity, but there is still an increased oxygen cost to swimming in cold water, as reported by Nadel et al. (1974). In later stages, Nadel's very cold subjects swam and shivered simultaneously.

Continuous hard shivering is fatiguing. As with any tiring and sustained muscular activity, carbohydrate reserves are soon consumed and the fat store is called upon to supply fuel. Thus the R.Q. decreases from 0.9 toward 0.7. There should also be a decrease in blood glucose, an increase in free fatty acids, and increased blood lactates. One would also expect indicators of generalized stress change, such as corticoids in blood and urine.

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.

Under conditions of diving in which decompression tables are used, such blood temperature changes may significantly increase the required decompression, simply from 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 is dependent upon the temperature of the tissues, being inversely proportional to the absolute temperature. Using handbook values, Figure 5 was constructed to show that a decrease in temperature from 38 to 18 °C would increase the amount of O_2 and N_2 which would be dissolved in a given amount of tissue by approximately 40%. This implies that for a given pressure the amount of air which would dissolve in watery tissues at 18 °C would be 40% greater than that which would be 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, which would thus 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. Gas bubble formation would be exacerbated during decompression and reestablishment of normal tissue temperature gradients. Experimental evidence supports the probable interaction between thermal state and decompression sickness, as reported by Hempleman (1967) and Balldin (1973).

2. Maceration of the skin.

During prolonged immersion in water -- from 12 to 24 hours -- 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 becomes a limit for prolonged wear of wet suits that might otherwise be thermally satisfactory.

3. Dehydration

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

Diuresis, or increased urinary output, is initiated 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 increased pressure differential, which results from external hydrostatic pressure and the decreased pressures of respiration when using an underwater breathing apparatus. Whatever the mechanism, the process may cause an increase in urinary production of up to 2 liters within 2 hours. This amount of urinary loss (2.5% of body weight for an 80 kg diver) produces a dehydration which is eventually deleterious to maintaining 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 and hour. And further, in long underwater missions it will become 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 most effectively where skin circulation is highest; thus the head and the trunk would be the most likely areas for warming. But, as already noted, hands and feet must be warmed in order to keep them effective and free from distracting pain.

A limit to surface heating is the point at which skin becomes painful -- 43 °C and higher. At 45 °C, pain is severe, and if that temperature is maintained burns will result.

Heat can be added to the core by heating the inspired gas; the quantity of heat so added is determined by the gas volume exchanged and its heat capacity. There is no experimental data on respiratory heating by hyperbaric gases, so at present a safe high temperature limit 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. Such considerations as possible injury to ciliary lining of the respiratory tree, or the effect of keeping the upper tract constantly wet condensation, must be taken into account.

When body heat content rises above the level it has at comfort, blood vessels in the skin open, cardiac output increases, and sweating begins. Core temperatures rise if these responses are insufficient to prevent body heat storage. When T_{re} in a resting subject reaches 39 °C, a tolerance limit appears in a condition called impending heat stroke. However, it is unlikely that the warming or rewarming of a diver would be carried to such a point.

IV. Performance Factors

Man's performance characteristics range from 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. Tactile discrimination, manual dexterity, and reaction time are examples of well determined abilities, easily understood and reliably tested. The higher order perceptual-cognitive abilities are far less precise attributes such as memory, problem solving, vigilance, and reasoning. Tests of these abilities, in contrast to the psychomotor, are not well standardized and tend to be "home-made" tests of unknown technical characteristics. Part of the problem of determining the performance consequences of cold water exposure lies in the lack of a strong structure on perceptual-cognitive abilities. 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 shown this view to be oversimplified, and a more sophisticated, time-dependent pattern of performance effects can be formulated in four stages.

The first stage, upon initial exposure to very cold water, causes distraction effects lasting for perhaps as long as an hour. Many investigators have found that, at the beginning of a cold exposure, the diver's attentional capacities appear to be narrowed, and performance in a wide variety of tasks becomes inferior to performance in moderate or warm water. The next stage is that, as the body protects the cor , at the expense of the shell, the diver's hands and arms become cold and therefore less sensitive, less strong and less dexterous. These peripheral effects of cold significantly degrade performance of a wide range of tasks involving sensory sensitivity and psychomotor abilities. If the exposure is of long duration, leading to deep body cooling, there may be deleterious effects on perceptual and cognitive performance, but this has not been proven by the various studies done so far. What is known is that in such situations cold stress becomes only one of many factors, including fatigue and boredom, that contribute to performance degradation. At the extreme end of the time scale, a few diver performance studies have extended to six hours 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 categories follow.

1. Distraction effects.

This term applies when performance degradation occurs in the absence of significant physiological cooling. It is presumably a psychological phenomenon that occurs in response to extreme environmental conditions and not in response to change in physiological state. Tasks that have been found 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 directly tied to the temperature of the skin or muscle. The main areas of performance affected 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 at a maximum at a skin temperature of 37 °C. Vibrating sensitivity degrades at an accelerating rate as skin temperature is decreased to 21 °C (Weitz, 1941).

b. Two-edged discrimination and skin temperature.

This is the ability to sense the presence of two separated points or edges. As the skin cools, the separation must be widened in order to be perceived as other than a single point. The maximum sensitivity is 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

Grip strength is at a maximum when the brachioradialis muscle is at a temperature between 25 and 30 °C (Clarke et al., 1958). It has been shown to be significantly degraded from 56 to 47 kg of force when upper arm skin temperature is reduced to 21 °C (Vaughan and Andersen, 1973). Grip strength in water is significantly reduced by wearing neoprene rubber gloves, whatever the temperature -- from 63 kg barehanded to 49 kg with a glove (Egstrom et al., 1973). Torquing strength (grasp and twist) is significantly reduced in water (53 inch pounds) from what it is in air (60 inch pounds). These data were taken with a gloved hand by McGinnis et al. (1972).

C. Hand-arm steadiness.

Lockhart (1968) found that when skin temperature is reduced from 25 to 21 °C, aiming steadiness is significantly degraded.

D. Manual dexterity.

Hunter et al. (1952) found significant stiffening of the finger joints occurring at 10 °C skin temperature. Criterion levels of performance in tasks requiring finger dexterity can be maintained to a skin temperature of 15 °C, but degradation becomes significant at between 12 and 10 °C (Clark, 1961; Gaydos, 1958).

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

A reasonably long list of higher order tasks has been studied as potentially sensitive to the effects of cold. These include 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 showed significant decrements in task performance. Exposure temperatures were low enough -- 4.5 to 8.5 °C -- but exposure durations were relatively short, and body heat loss was estimated from rectal and skin temperatures, which is a method that is felt to be suspect.

Memory could be an exception to this conclusion. Memory, and in particular recall, has consistently shown a performance decrement in cold water studies, although the several authors suggest their results may be attributable 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 the material and recalling it, as seen in the following Table.

4. Dysfunction effects.

Probably the most severe exposure condition reported in the performance-oriented cold effects literature is six hours in 6 °C water (Vaughan, 1975). Divers experienced 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 persevered in recording errors that ordinarily would have been apparent as errors. Evidence of response blocking or the omission of required responses has also been reported by Bowen (1968) and by Vaughan and

Andersen (1973).

V. 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.

Such testing could be done at the SINBAD test facility (System for Investigation of Diver Behavior at Depth) located at the Naval Experimental Diving Unit, NCSL, Panama City, Florida. At the SINBAD facility, well established, standardized psychomotor and perceptual-cognitive tests have been incorporated into a hardware system capable of operation in a wet chamber at pressures to 445 psi (1000 FSW). SINBAD is capable of presenting 22 separate tests, which represents the range of basic human abilities as determined by factor analytic studies and which were 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 identified as sensitive to temperature, such as: arm-hand steadiness; finger dexterity; manual dexterity; multi-limb coordination; reaction time; speed of arm movement; vigilance; associative memory; memory span.

Physiological evaluation of prototype suits can be done by choosing to make some of the following measurements on a man wearing the protective garment. The intent is to insure that the subject being exposed to cold conditions is maintained by the equipment within the thermal limits proposed in section II.

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 based on metabolic response to cold. N.B. Both techniques require further development and validation.

Temperature measurements

1. Core temperature measured in the esophagus or rectum. Gut temperature and auditory canal temperature are second choices because of limitations discussed above.
2. Hand and foot skin temperatures.
3. Skin temperatures, various locations.
4. Temperatures of inspired and expired gas.

Metabolic measurements

1. Oxygen consumption rate, or respiratory minute volume.
2. Shivering by electromyography.
3. Respiratory quotient ($\dot{V}CO_2/\dot{V}O_2$), blood glucose, lactates, and free fatty acids.

General monitoring of the suit's effectiveness can be done by listening to the subject's comments or reports of cold, discomfort, and fatigue, and by visual observation of his condition.

VI. Further Thoughts

Encumbrance of a diver or underwater swimmer is already a problem with today's respiratory and thermal equipment. If better thermal protection can be achieved only by equipment which further hampers the wearer, it will not be accepted. Mobility must be preserved -- for swimming, walking, sitting, exiting through small hatches, and all the other activities of these men. Similarly, hands must be kept dexterous and fingers allowed to feel.

Increased pressure with depth affects thermal protection in several obvious 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.

A garment is made wearable through proper fit. Clothing terms like "drape" and "hand" also apply to wearability and affect the acceptability of the garment.

Men come in many sizes and shapes, which have been usefully described by physical 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, and there are missions where equipment will have to protect a resting man from cold water, and the same man while he is being quite active in air. Thus the thermal protection may have to be variable.

Human skin is sensitive to certain materials. plasticizers, dyes, and so forth. There are other possibilities for harm, from noise, or radiation, or other environmental hazards which attend the use of today's technology.

These ideas arose during the course of the conference on thermal limits. While not central to our purpose, they have been mentioned here as a reminder, if one is needed, that a good piece of equipment results from considering a whole range of human and environmental factors.

VII. Research Needs

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

First priority

a. Define physiological measures which correlate with net body heat loss (enthalpy change), e.g., some body temperature or combination of temperatures, regional heat flow state, or oxygen consumption, and validate them 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, e.g., complex tasks involving problem solving, decision making, following procedures, and memory.

Second priority

a. Measure gloved hand performance in cold water.

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

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

Third priority

a. Describe heat loss by body region, e.g., head, limbs, and torso.

b. Determine best areas for the application of supplemental heat.

c. Investigate body heating via warmed respiratory gas.

Fourth priority

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

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

c. Investigate skin maceration in prolonged submersion.

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PART B

PHYSIOLOGICAL DESIGN GOALS FOR THERMAL PROTECTION OF DIVERS

Prepared at a conference on
September 5, 1980
at
Bethesda, Maryland

Prepared for the Naval Medical Research and Development command by Webb Associates, Yellow Springs, Ohio, under contract N00014-80-C-0193

Foreword

The predecessor of this document was a report entitled "PROPOSED THERMAL LIMITS FOR DIVERS: A Guide for Designers of Thermally Protective Equipment," which was written in July 1976 and circulated informally. During the past four years, there has been considerable progress in physiological research and an increased interest in diver thermal protection. Therefore, under the auspices of the Naval Medical Research and Development Command, a conference was arranged to consider revisions of the original document. A two-day workshop of the Undersea Medical Society on thermal physiology in diving and its effect on equipment design had served to update many of the conferees. The revision took place the following day, September 5, 1980, in a meeting room of the Federated American Societies for Experimental Biology, Bethesda, Maryland (arranged by the Undersea Medical Society). Those in attendance were chosen to represent not only the scientists active in research, but also the potential users of the revised document.

List of Attendees:

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PHYSIOLOGICAL DESIGN GOALS FOR THERMAL PROTECTION OF DIVERS

If producing a state of complete 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 present knowledge of physiological and performance effects of cold exposure, a diver or underwater swimmer should be able to perform his assigned tasks and be relatively safe if the following conditions are met. Newly designed equipment should be tested by methods generally accepted in thermal physiology. It is to be emphasized that the purpose of this guidance is to set goals for the design of equipment. It is not intended as an acceptance standard or military specification.

The following four conditions apply concurrently:

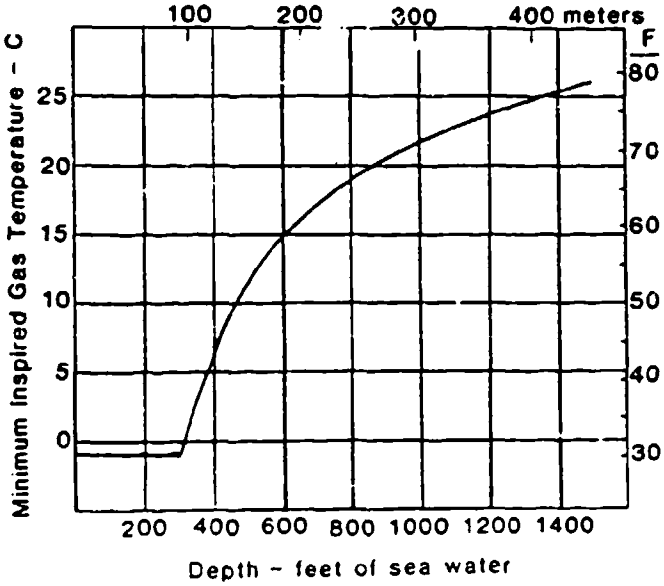
1. Maximum net body heat loss (change in enthalpy) of 3 kcal/kg of body weight.
2. Core temperature not lower than 36 °C, or a decrease of 1 °C, whichever is lower.
3. Mean skin temperature not lower than 25 °C, and no individual skin temperature lower than 20 ° C, except that of the hand, which may go as low as 15 °C.
4. Minimum inspired gas temperature as a function of depth specified by the figure and table below.

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

1. No individual skin temperature higher than 41 °C.
2. Maximum inspired gas temperature of 45 °C for up to one hour and 40 °C for indefinitely long exposures.

TABLE 1.

DEPTH fsw	MINIMUM INSPIRED GAS TEMPERATURE °C	 °F
300	-1.0	30.2
400	6.0	42.8
500	11.5	52.7
600	14.1	57.9
700	17.0	62.6
800	18.7	65.7
900	20.5	68.9
1000	21.9	71.4
1100	22.7	72.9
1200	23.7	74.7
1300	24.6	76.3
1400	25.3	77.5
1500	25.9	78.6



See Footnote 1, Part A

DISCUSSION

Briefly, the design goals are based on the following considerations:

A net heat loss of 3 kcal per kilogram of body weight is tolerable if not incurred as rapidly as, for example, in the sudden immersion of nude men in cold water. A diver wearing inadequate thermal protection might lose this amount of body heat in 1 to 1.5 hours, feel quite cold and shiver strongly. He is warned by these symptoms and terminates the exposure voluntarily. However, 3 kcal/kg lost over three to eight hours causes rather mild core and surface temperature decreases, a mild sense of cold, and little shivering, but this may be the beginning of behavioral changes which could be potentially dangerous. Normalizing the heat loss by body weight is consistent with the observation that large people tolerate far more heat loss than small ones. While net heat loss (heat loss minus heat production) is not a feasible measurement except in special laboratories, it is nevertheless a useful datum for engineering calculations.

A core temperature of 36 °C is a conservative low limit for design purposes. Divers whose deep temperatures are no lower than this are not in hypothermia. Medically speaking, hypothermia of significant degree is defined as a core temperature lower than 35 °C. The added definition "or a decrease of 1 °C, whichever is lower" is included because during the normal circadian rhythm of body temperature it is common for core temperature to fall to 36.5 °C overnight. A diver who happens to begin a dive when his core temperature is below 37 °C is safe if he loses only 1 °C in core temperature - provided, of course, that the low starting temperature was not low as the result of an immediately preceding cold dive.

Skin temperature limits derive from many laboratory and field measurements during various kinds of cold air and water exposures. When the general skin surface is 25 °C, there is a strong sensation of cold. Specific areas colder than 20 °C are painfully cold, except for the fingers and hands which can usually stay pain-free down to 15 °C.

The minimum temperatures of breathing gas at depths below 300 fsw, shown in the figure, are based on new experiments from the Navy Experimental Diving Unit.[2] They are temperatures which will produce a drop in core temperature of 1 °C in an hour, when surface heat loss has been minimized. These gas temperatures are far higher than those previously recommended (the Braithwaite curve), and may thus be conservative. They should nevertheless be achievable with respiratory gas heaters.

When designing equipment to heat a diver, the goal is to warm the skin, but not to the point of pain or damage. 41 °C is a conservative upper limit. Similarly, when heat is applied via the respired gas, a temperature of 45 °C for up to an hour (at any vapor pressure up to saturation at sea level pressure) avoids discomfort and damage to the lining of the respiratory tract. A lower limit of 40 °C for longer times is chosen to prevent damage to the cilia of the respiratory tract.

The design goals represent compromises between medical conservatism and freedom for the designer. These goals should be revised as new evidence accumulates.

[2] See Footnote 1, Part A