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# *THERMAL PROBLEMS IN DIVING*

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# THERMAL PROBLEMS IN DIVING

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# THERMAL PROBLEMS IN DIVING

## Introduction

Discussion of the effects of cold water exposure was lively and continuous for the two days of the conference, despite the fact that few important physiological findings have been added since the general review of the physiology of cold exposure in 1955 (Burton, A. C. and O. G. Edholm, Man in a Cold Environment, Edward Arnold, Ltd., London, 1955). Further, the effects of direct exposure to cold water have been admirably summarized by one of the conferees in his book, Survival in Cold Water (Keatinge, W. R., Blackwell Publishers, Oxford & Edinburgh, 1969), which includes updated discussions of hypothermia, rewarming, and survival from immersion following ship sinkings. The conference did focus the attention of people active in the cold exposure field on the particular problem of cold exposure in diving. About this, there is presently too little known.

There is no significant body of physiological and performance data from real diving experience. It is possible to say that divers routinely get cold, that they may be self-selected to be unusually tolerant of cold exposure, and that cold is a seriously limiting factor in many diving operations. And it is reasonable to speculate that occasionally hypothermia, with its insidious onset, has caused fatal diving accidents. But because cold exposure is routine in diving, it is accepted and its potential for harm discounted.

Much of the protective clothing a diver selects serves well, thermally speaking, so that he does not get in as much trouble as fast as the survivor of a ship sinking in the North Atlantic. But cold is a diver's constant companion, and a constant concern.

This summary report presents briefly the currently accepted knowledge of the effects of cold water exposure. Points that were especially useful, or new, are emphasized. Rewarming and thermal protection are separately treated, as are limits for experimental cold exposures and selection of subjects for such exposures. There are also brief sections on diver effectiveness in cold, and on the thermal problems of hyperbaric living.

## Effects of Exposure to Cold Water

The human body has only limited defenses against heat loss during immersion, and the consequences of hypothermia can be serious. The following discussion is aimed at the working diver, while a separate section is devoted to the special problem of accidental immersion in extremely cold water.

Unlike diving mammals, man has no significant passive insulation in the form of a fur or blubber layer, and depends primarily upon peripheral vasoconstriction for defense. On immersion, the temperature of unprotected skin rapidly approaches that of the surrounding water. This peripheral cooling has immediate consequences, including discomfort, loss of sensation, decreased muscle strength, and loss of manual dexterity.

Following the onset of exposure to cold water without adequate protection, there is an initial marked peripheral vasoconstriction accompanied by increasing arterial blood pressure and heart rate. Deep body temperature--rectal, for instance--does not fall immediately and may even rise slightly.

With continued cooling the defense mechanisms of peripheral constriction and shivering are unable to maintain thermal balance, and rectal temperature falls. A roughly linear relationship exists between rectal temperature and heart rate. This fall is most likely due to a direct effect of cooling on the cardiac pacemaker, and it is not influenced by blocking the vagus nerve by either atropine or section. Arterial blood pressure steadily falls. These changes are accompanied by a fluid shift from blood plasma into the tissues, resulting in hemoconcentration. In prolonged cooling this fluid shift can result in considerable reduction in blood volume, a matter to be considered during rewarming.

Once maximal vasoconstriction occurs, a steady state is established for heat flow from the body to water. Classically, the body is then visualized as consisting of two compartments, a chilled vasoconstricted shell and a warm core. The actual rate of heat loss depends upon a number of variables, including effective body insulation (tissue plus clothing), water temperature, and convective movement of water next to the skin.

The most serious consequences of cold immersion result when heat loss exceeds metabolic heat production for a prolonged period. In the face of continued negative heat balance, progressively greater portions of the body are relegated to the cold shell, and eventually core cooling occurs. There follows deterioration of rational thought and clinical hypothermia. Cold may also exaggerate inert gas narcosis and alter the circulation sufficiently to produce bends on normally conservative decompression schedules.

If the cold exposure continues to the stage of deep hypothermia, when deep body temperature reaches about 30 to 32°C (86 to 90°F), cardiac arrhythmias appear, and ventricular fibrillation occurs at temperatures between 25 and 30°C, causing death. The lethal temperature varies considerably, and it is worth noting that recovery of humans from cooling to a rectal temperature of 18°C (64°F) or lower has been known to occur.

Individual characteristics have some bearing on immersion hypothermia. Training or acclimatization may improve tolerance to sudden peripheral cooling, both by decreasing its subjective effects and by increasing the promptness and degree of vasoconstriction. Obese individuals derive added tissue insulation from subcutaneous fat, but are likely to be otherwise less fit. Cardiovascular fitness seems to correlate with improved response to cold immersion and certainly increases ability to maintain elevated metabolic rates over long periods. Tolerance of cooling varies among individuals, and divers naturally tend to belong to a highly tolerant group.

Because even moderate hypothermia is potentially dangerous to the working diver, improved methods of estimating heat loss and more realistic models of human thermoregulation are of great practical importance. Using modern technology, it is possible to measure temperature continuously at multiple skin sites, in the esophagus or rectum, and at the tympanic membrane, but there is no agreement on the interpretation of these temperatures in terms of body heat content. Classically, heat content is estimated by dividing the body mass between shell and core compartments, assuming a specific heat for each, and monitoring the temperature of each compartment at selected sites under various thermal conditions. Recent experiments cast doubt on this approach, since the shell-to-core ratio appears to vary widely with environmental conditions and with the degree of hypothermia.

### Metabolism and respiration

Shortly after cooling commences, there is intense shivering. This response can be quite marked in man, increases as the early phase of cooling proceeds, and can result in an increase in metabolic rate up to five or six times.

Despite the increase in heat production, heat loss in severe exposure in cold water is often greater, and a generally declining deep body temperature ensues.

As rectal temperature falls below 35°C, shivering steadily declines. It ceases below about 30 to 32°C and is replaced by muscular rigidity. Shivering recommences during rewarming at a rectal temperature above 30°C. Prolonged intense shivering depletes glycogen reserves.

Respiration increases at the onset of cooling, and the hyperventilation produces a decline in alveolar $P_{CO_2}$. As cooling continues past the stage accompanied by shivering, $CO_2$ rises and $O_2$ gradually falls. With very severe cooling to about 25°C, circulatory transport of sufficient oxygen to support metabolism is no longer dependent upon the presence of hemoglobin, but simply upon that in physical solution in blood. Consequently $CO_2$ rises. $CO_2$ is a depressant at those temperatures. It is important therefore to avoid oxygen therapy in hypothermia. It has been shown experimentally that animals breathing oxygen died at higher temperatures than those breathing air.

Although the oxygen-hemoglobin curve is shifted to the left by lowered temperature, a progressive shift of pH toward increasing acidity also occurs. The declining pH appears to roughly compensate for the temperature change, with the result that the dissociation curve is little changed during cold exposure.

### Body fat

The variability in rate of cooling during cold exposure in water is mostly dependent upon the thickness of subcutaneous fat, which is a generally constant fraction of the total body fat. Therefore the fatter subject has a thermal advantage in cold water exposure. However, this is not the whole story. Survival is attributable to a variety of conditions, including physical fitness and aquatic skill.

Long distance swimmers such as channel competitors demonstrate the characteristics likely to favor long survival in cold water. They have thick subcutaneous fat, endurance for long sustained high energy expenditure, and familiarity with exposure.

## Quantification of body heat loss

Recent studies in two laboratories have begun to establish how much heat the body actually loses in cold water. At the University of Rochester, A. B. Craig immerses nearly nude subjects to the neck in a bath calorimeter, while at Webb Associates a water cooled suit is used as a calorimeter. In both laboratories, heat losses of 200-300 kcals in an hour caused strong cold discomfort, heavy shivering, and voluntary termination of the exposure, yet decreases in deep body temperature were small: 0.2 to 1.0°C.

The connection between heat loss in kilocalories, or similar units, and change in body temperature has not yet been established.

Without calorimetry this vital relationship cannot be known. It is clear that one cannot reliably find from weighting coefficients for surface and deep temperatures what the loss of heat has been. Nevertheless, the accepted concept of a core of nearly constant temperature and a shell of varying temperature is useful, if elusive of quantification.

Calorimetry during exercise combined with cold exposure is still in its infancy. There would appear to be a large difference between the regional rates of heat loss in rest and exercise. Certainly the circulation to the limbs is driven to higher levels, thus overcoming the reduction in limb blood flow of the cold resting man.

The process of rewarming has been partially described calorimetrically. Rewarming is said to be complete when the lost calories have all been restored, and the normal processes of vasomotor thermal regulation in comfort have reappeared. This state does not, unfortunately, coincide with predictable temperature levels.

## Acute Reactions to Extremely Cold Water

Immersion of unprotected man in extremely cold water (less than 10°C) is a life-threatening event. The initial shock of entry seems to saturate all sensory pathways, making rational thought difficult if not impossible. There is an immediate reflex gasp, and it is possible that cardiac arrest occurs in a few cases.

If a person survives entry, other problems arise. There is an uncontrollable hyperventilation which increases the likelihood of water inhalation and blows off body $CO_2$ stores, sometimes to the point of tetany. Normally the body conserves heat by cutaneous vasoconstriction, but in extremely cold water a paradoxical vasodilation occurs, virtually eliminating tissue insulation, dumping core heat rapidly into the water so that clinical hypothermia develops more rapidly than usual. The cold also causes increased salivation which adds to the danger of aspiration.

Under these conditions, self-rescue is very unlikely. The victim's mental processes are affected to the extent that he is unable to obey shouted instructions. Swimming causes rapid exhaustion, both because chilled muscles function poorly and because water at less than 10°C has a significantly increased viscosity which adds resistance to movement. This may explain certain drownings where the victim is seen swimming and then simply disappears from sight.

Rescue from water at these temperatures must be fast, and of those pulled conscious from the water, many (20%) die suddenly within the next few minutes, due to cardiac arrest. The mechanism is not entirely clear, but may involve arrival at the heart of a bolus of chilled, chemically abnormal blood or development of a sudden relative insufficiency of coronary perfusion. The victim should therefore receive immediate aggressive rewarming while a close watch is kept for cardiac arrest.

## Rewarming

Given a thoroughly cold diver, what situations require aggressive action, and what are best treated conservatively? Aggressive action means active rewarming, using a tub of hot water for immersion. (Even more aggressive but generally impractical for diving operations would be internal rewarming by heating blood in an extra-corporeal circuit, or by peritoneal lavage with warm saline.) Conservative therapy, or passive rewarming by allowing the patient's metabolic heat to accumulate, means stopping further cooling (e. g. by removing wet clothes, or by getting the person out of the wind); conserving body heat with dry clothing or blankets; and psychological support with hot showers and hot, non-alcoholic drinks.)

The consensus is that a man who is conscious and communicative and able to move about should be treated conservatively. If there is regular pulse and respiration, don't interfere; let him rewarm himself. An unconscious person, or one who is severely depressed physiologically, which usually means that his rectal temperature is below 33°C, should be treated at once by active rewarming.

History is important. If the patient has developed severe hypothermia ($T_{re}$ of 33°C or lower) acutely, meaning within one or two hours, then rapid rewarming in a hot bath should be started immediately. If the hypothermia has developed gradually over many hours, then he should be warmed gently and slowly and carefully watched.

In any event, one must avoid procedures which can harm the patient. Many of the common emergency procedures used on people who appear to be dead must not be used in profound hypothermia. Closed chest massage, intubation and forced pulmonary ventilation, electrical defibrillation, and even passing an esophageal temperature probe are all potentially dangerous. The cold heart is especially irritable, and these procedures are apt to initiate ventricular fibrillation. It is much wiser to start rewarming, monitor temperature and heart action, and otherwise keep hands off.

A particular problem in patients with slowly developed hypothermia is the danger of sudden hypotension during rewarming. Circulatory blood volume decreases during the slow development of hypothermia, and as rewarming progresses, peripheral vasodilation can so aggravate the hypervolemia that hypotension and collapse ensue. This is one of several reasons for not rewarming a person with slowly developed hypothermia in a hot bath. If a diver has been in the water for several hours, or if he has dived several times and may not have rewarmed adequately between dives, he may be hypovolemic.

A further set of problems in slowly developed hypothermia is revealed by blood chemistry procedures for electrolytes, glucose, pH, and carbon dioxide. But a caution is necessary here. Venous blood samples can be highly misleading. The circulation in the limbs is greatly slowed in hypothermia, and the levels of glucose or $CO_2$ may not represent those of the patient as a whole. What is recommended is the taking of arterial blood for such determinations, and then only after slow rewarming is well under way. A patient in profound hypothermia of the slow onset variety may have been rewarmed to a rectal temperature of 33°C without incident, then develop severe acidosis, with unconsciousness and deterioration. Arterial blood samples are useful here in guiding intravenous therapy. Intravenous glucose therapy is seldom needed; during the hypothermic state sugar is not used as rapidly as usual, although peripheral venous blood samples may show low glucose levels. Adding glucose may raise general glucose levels enormously, so care is needed.

To repeat, in any hypothermia where the person is conscious, breathing, and has a regular pulse, rewarming is done conservatively by preventing further heat loss and allowing the subject to warm himself. In deep hypothermia where vital signs are depressed or absent, the history of the event (slow or acute onset) and the present condition determine how to proceed. If rectal temperature is falling, active rewarming is called for. If the temperature is rising, and especially if the patient has been out of the cold for 30 minutes or more, conservative treatment is indicated. The general rule of "acute hypothermia--active rewarming; slow hypothermia--passive rewarming" should be tempered with a judgment of whether or not aggressive rewarming is needed to stabilize and reverse a deteriorating condition. And two general instructions are important: 1) don't do heroic resuscitation for hypothermia; and 2) monitor vital signs and interfere as little as possible.

Active rewarming is best done in a hot bath (42-44°C, or water as hot as the observer can comfortably leave his arm in). Active rewarming is to be started at once in a person in deep hypothermia ($T_{re}$ 33°C or lower) which developed quickly. Rewarming in the bath is continued until the rectal temperature reaches 36°C. The patient should be able to care for himself thereafter.

Passive rewarming is done by the patient himself, through accumulation of his own metabolic heat. The observer should make sure that body heat loss is minimized, i.e. that wet clothing is removed, dry warm clothing provided, a warm room used, and, if available, impermeable clothing employed.

During rewarming, monitoring of body temperature is essential, as is monitoring of heart action by pulse counts, ECG if available, and blood pressure. Monitoring of arterial $pCO_2$ and pH is useful after rewarming is underway, and then principally in the hypothermia of slow onset.

Finally, there are field situations that are less than ideal for the treatment of hypothermia. Some lack such items as bathtubs, although some sort of container for hot water can often be rigged. A useful method of rewarming, at least in the less severe cases, is to run hot water from a hose into the diver's clothing, whether wet or dry suit. It may even be possible to warm the torso preferentially, which should help to minimize the after-drop of body temperature.

A dangerous situation for a hypothermic man is air transport from a dive site. A cold and drafty airplane at 10,000 feet is designed to aggravate hypothermia, since evaporative cooling from wet clothing and skin is greatly enhanced by the low barometric pressure and high air motion. Similarly, a breezy helicopter ride would hasten evaporative cooling. The best plan, if at all possible, would be to carry out rewarming at the dive site, even with less than ideal equipment, then transport the diver. If this is not possible, the diver's clothing should be dried before the trip, or warm clothing put on, or he should be wrapped in impermeable film, like the polyethylene bag that is being tried in the U. K.

## Thermal Protection

Next to decompression considerations, thermal problems arising from exposure to cold water or to cold helium-oxygen often pose the major consideration in operational dive planning and the major consideration in equipment selection. The use of deck decompression chambers, bells, personnel transfer capsules, breathing gases, bottom time, electrical power, heated water, monitoring, diver's garments, and many other items of equipment or diving procedures are predicated on expected water temperatures.

The diver's garments protect against abrasion and other minor trauma, but are primarily designed for thermal protection. The insulation between the body core and the environment normally has three components for the diver in the water. The first is the surface layer of the body, including subcutaneous fat. The next is a layer of air, helium-oxygen, or water trapped on the surface of the skin. Next is a layer of clothing--in the diver's case, thermal underwear, foamed neoprene, or rubberized canvas. Unless heat is supplied to the garment, nearly all practical forms of external insulation depend upon air, which, with its low specific heat and heat capacity approaches the ideal, provided it is immobilized. The function of protective garments or suits to protect the diver is thus to trap gas in the fabric and between layers.

## Wetsuits

Foamed neoprene wetsuits are the most commonly used thermal protection. The air trapped in the closed cells provides excellent insulation for shallow diving. Wetsuits are relatively inexpensive, although personal tailoring is required to achieve the best immobilization of the water next to the skin. The disadvantages are that the neoprene foam is compressible and loses its insulation qualities as the diver goes deeper. Also, the neoprene foam is altered if stored in a helium atmosphere and then used in the water. In the helium atmosphere, helium diffuses into the closed cells. When the diver enters the water, the helium diffuses out of the neoprene into the water, collapsing the foam cells. The wetsuits then have the appearance of elephant skin and retain little insulating quality.

## Constant volume drysuit

By sealing the foamed neoprene suit at the wrists, neck, and face, the diver's skin is kept dry. Pile underwear can then be worn to provide an added insulating layer. This insulating space is kept at a constant volume by providing compressed air inflation for descent and exhausts for the air during ascent. The constant volume drysuit is superior to the wetsuit and extends the diving duration and depth in cold water. Protecting the hands remains a problem. Also, if the breathing medium is helium-oxygen, the suit must be supplied with a separate air supply if it is to retain its insulating quality.

## Electrical heating

Electrically heated undergarments to be worn under a constant volume drysuit are available, but there remain problems of unreliability, hot spots, shock hazards, and relatively high cost.

## Hot water heating

Closed-circuit hot water heated garments, using a network of tubes next to the skin, have been developed, but generally suffer from problems similar to the electrically heated garments. However, by supplying approximately three gallons per minute of warm water to flush through a wetsuit, a reliable diver heating system has been developed and marketed. The water is supplied from topside heaters through low pressure hose with the diver's umbilical. By a simple tube array, the warm water is distributed throughout the suit and to the hands and feet. The system is open-circuit and wasteful of hot water but eminently reliable because of its simplicity. The hot water can also be supplied to the underwater breathing apparatus to heat the carbon dioxide absorbent and the breathing gas.

## Heating of breathing gases

Studies have shown that divers who breathe helium-oxygen mixtures at depths greater than 600 feet in cold water are exposed to severe thermal stress. Minimum safe inspired gas temperatures for use in deep diving have been specified in the U. S. Navy Diving Manual. These establish the limit for minimum safe inspired gas temperatures for use in operational dive planning and underwater breathing apparatus certification.

At present, hot water is used to heat the inspired gas or the entire underwater breathing apparatus may be flushed with hot water to heat the breathing gas and the carbon dioxide absorbent cannister.

## Safe Limits for Experimental Cold Exposure

In either experimental studies or field work in cold water, the maximum cooling permissible is one that produces a deep body temperature of 35°C. Actually, in experimental work, once a linear decrease in deep body temperature has been clearly established, there is little point in continuing. It is true that young people training for competitive swimming often reach deep temperatures of 35°C and lower, but this is considered an unsafe level of cooling in divers whose critical functions would be impaired, and who have a more difficult escape route ahead of them.

Deep body temperature is most commonly taken with a rectal temperature probe inserted to 10 cm beyond the anal sphincter. Esophageal temperature at the level of the cardiac atria is another excellent measurement. Ear canal temperature, or that of the tympanic membrane, is useful, but if there is cooling of the scalp above the ear, this temperature will be too low to represent deep body temperature.

In field work, a more important criterion is maintenance of diver function--including a margin of exposure time needed for safe return. Divers are often stoic about being cold, and they are well motivated to keep working. Being interested in the job makes cold exposure more tolerable by diverting attention from discomfort. All of these make it likely that a diver will permit himself to become cold, perhaps too cold, since one of the early effects of hypothermia is impairment of judgment. Monitoring of some sort from topside is strongly recommended. One cannot rely completely on the buddy system, since both divers may be affected.

After a cold exposure, the deep body temperature will fall further during rewarming, often by 1°C. Thus by terminating at a temperature of 35°C or higher, the after drop is not likely to carry the deep temperature lower than 34°C, and this is important since cardiac irregularities can appear at a deep temperature of 33°C.

Experimenters must not put pressure on subjects to continue cold exposure, or use bribery. When a man wants to stop, he stops. One should also avoid any kind of cold injury, even reversible injury.

## Screening Subjects for Experiments in Cold Exposure

A thorough history and physical examination should be used to screen out people with disease of more than transient nature (e. g. infections of the upper respiratory tract). People with marked varicose veins should be excluded, since thrombophlebitis has followed severe cold exposure, either from circulatory slowing or from cold injury to the veins. Laboratory work should include a chest X-ray, and resting and exercise EKG's. Fit people are wanted for experiments in cold water, since the cold stress is severe.

In taking the history, be sure to ask for any special reactions to cold. One would immediately exclude anyone with Raynaud's phenomenon, people who have angina pectoris on cold exposure, or those with cold allergies (urticaria, asthma, unusual swellings). One might also guard against using a subject who, on laboratory examination, had a sickling tendency, since the stasis of cold exposure could mean local hypoxia and the possibility of precipitating a crisis.

Before any experiment it is wise to ask subjects if they have any current illness, if they are hung over, or if they are taking medications. Not everyone volunteers this sort of information.

It is desirable to use divers as subjects if possible, since they are pre-screened, both in that they are fit and that they have been cold in cold water before. Divers are often rather stoic about being cold, which should be kept in mind when doing experiments with them.

For non-divers, try an initial mild cold stress first, in order to eliminate "over-reactors" and hyperventilators.

## Diver Effectiveness

The working diver commonly experiences continuous heat loss during immersion and often expects to be uncomfortably chilled at the end of a dive. This expectation of chilling is often paramount in dive planning, the planned bottom times being more determined by the diver's cold tolerance than by decompression considerations. Loss of dexterity and finger strength are also routinely expected. The consumption of breathing gas may be considerably more than the diver consumes in warm water because of the higher oxygen needs of a shivering diver. Therefore, water temperature and thermal protection often determine the expected effectiveness of divers to complete an underwater task.

Entry into cold water is itself a shock that can distract the diver, and the same is true whenever he experiences a sudden drop in skin temperature, such as when movements bring cold water under a wetsuit or when drysuits leak. Studies of divers in swimmer delivery vehicles have indicated degradations in performance immediately upon entrance into the water and before any fall in core temperature.

Peripheral chilling causes loss of dexterity as well as decreasing isometric strength. Even when divers wear protective clothing, the hands are frequently left exposed to the cold. Simple tasks that are familiar and well known are least affected by cold exposure. More difficult and complex tasks are more affected, especially if training and experience in the task are lacking. Similarly, tasks involving gross movements are less affected than tasks involving complex fine manipulation.

Divers tend to be task oriented and try to work even with progressive chilling. They often persist, aware of discomfort, but perhaps unaware of inefficiency and possibly deterioration of rational thought. The diver's thinking ability and the use of his hands and other motor functions may prevent him from choosing and executing the best procedures to enable him to complete his task, or in some cases to return safely to base.

Many diving incidents with injuries or fatalities attributed to diver error might be the result of depressed motor and cognitive function secondary to early hypothermia. Some incidents have been publicized, such as the death of Cannon during the SeaLab III dives. His direct cause of death remains controversial, but there is no doubt about the severe thermal stress involved in an excursion from an unheated personnel transfer capsule at 600 feet protected only by a wetsuit.

In June 1970, six men in the habitat Aegir spent five days at 516 feet in a helium-oxygen atmosphere with temperatures ranging from 72 to 77°F. The water temperature was 67-70°F, and the habitat heaters proved inadequate. The men were constantly cold, and were unable to do nearly as much excursion diving as originally planned. The real danger arose when the habitat could not be deballasted and floated from the bottom. Not all the divers were able to remain functional and carry out the in-water work necessary for their rescue. Fortunately, the habitat was surfaced in time.

The Johnson Sea-Link submersible tragedy with the loss of two divers also illustrates the hazards of thermal stress. The submersible was trapped in approximately 360 feet of water. Two divers in the lockout chamber were forced to breathe from emergency masks because of poor carbon dioxide absorbent function in the 40-45°F temperature of the chamber. Each breath increased the chamber pressure until they had compressed to the ambient 360 feet. Although carbon dioxide buildup in the aluminum chamber occupied by the two divers was probable because of poor carbon dioxide absorbent efficiency in cold, the cause of death in these two unclad and thermally unprotected divers was certainly the extreme exposure and heat draining conditions created by the helium atmosphere in an aluminum chamber surrounded by 40-45°F water at great depth.

These diving incidents were publicized. Other incidents have occurred in commercial diving, and many accidents attributed to other causes may have been thermal in origin.

## Hyperbaric Environments

### Respiratory heat loss

Every diver breathes hyperbaric gas, and the convective component of respiratory heat loss grows linearly with depth, hence with density of the gas mixture. If the breathing gas is not warmed, heat is lost directly from the core in this fashion, quite independent of what is done to prevent heat loss from the body surface. A number of studies have established the numbers needed for calculating respiratory heat loss as a function of gas temperature, density, and specific heat. In general, helium-oxygen mixtures at pressures equivalent to 600 FSW and greater require heating of gas respired to prevent serious drain of body heat.

### Comfort temperatures

In undersea habitats, diving bells, and personnel transfer capsules, divers dwell in hyperbaric gas, the temperature of which must be regulated carefully to avoid excessive surface heat loss. Of course, duration of the exposure is a governing condition. For continuous exposure, the higher the pressure, the higher the temperature must be and the narrower the acceptable range of temperature. Thus at 1000 FSW in the helium-oxygen environment, a temperature of 32 ± 0.5°C (90 ± 1°F) is required. A number of laboratory studies have produced a recommended set of temperatures down to 1600 FSW equivalent pressure.

### Unexplained weight loss

Men who live in hyperbaric environments for some days lose weight despite evidently adequate to high food intake. It appears that despite comfortably warm temperatures, there is a metabolic drain, possibly thermal in origin. Experimental studies are needed to define and explain this observation.

## Research Plans

The research areas in the list below were identified by the conferees. Many, but not all, were to be pursued during the coming months and years.

In cold water immersion:

- arterial and venous $P_{O_2}$ and $P_{CO_2}$
- hand blood flows by venous plethysmography
- brain blood flow changes
- regional heat loss (hands, head, feet)
- hypoglycemia
- regulation of body fluid volume
- habituation to exposure
- reflex hyperventilation
- visco-elastic properties of muscle
- body temperature change in children
- levels of serotonin, prostaglandins, and various metabolites
- alcohol and other drugs

Effects of cold on cardiac function.

Conduction velocity in Purkinje fibres, which are near the internal surface of the myocardium.

Neural control of temperature regulation in seals.

Swimming in liquids of different viscosities.

Excessive secretions in the upper respiratory tract when breathing cold hyperbaric gas.

Penetration of cold hyperbaric gas into the airways.

Models of heat loss in cold water;core and shell compartments of the body; predictions of survival times; psychomotor motor performance and heat loss.

Further study of electrically heated suits.

Saturation dives to study energy balance and fluid balance.

Rewarming techniques; avoidance of afterdrop.

Cumulative thermal effects of repetitive dives.

Objective performance monitoring during diving.

The following remarks, slightly cut and edited, are from one of the group who felt impelled to present his own view. They are included here because they lead to two lines of research that are not conventionally considered.

The cliches relating the needs for closer cooperation between laboratory, shop, and consumer came to life and became the realistic focus and dominant theme of the meeting at Yellow Springs. A serious lack of new approaches and associated new information was made clear through presentations and discussions of both theory and practice in temperature regulation of men in long and deep dives. We rely, for example, for some of our most useful physiological data on the oft-quoted results of barbaric experiments carried out thirty years ago at Dachau. It is now clear that new work, both of an experimental and fundamental nature as well as new events in the technology of thermal protection will be required to resolve long standing problems of temperature regulation during diving. Such new work must not necessarily be extravagant and costly, but what is required is some new thinking by both physiologists and designers of environmental protective equipment.

While man is at a distinct disadvantage thermally and in other respects during water immersion, many species of marine mammals living throughout the world's oceans, in especially great concentrations in polar regions, manage to survive and to thrive throughout lifetimes in cold water. We would do well to examine some of the simple physiological and morphological adaptations which permit such accomodation in a hostile environment for mammalian temperature regulation. All but a very few of the marine mammals of the world depend upon a thick layer of relatively fixed fat subcutaneous insulation to protect their deep body cores from heat loss to cool water. These marine mammal species vary enormously in body size from a few pounds of certain newborn seals to the biggest living creature, the blue whale, of sixty or more tons. Some very few marine mammals, notably the polar bear and sea otter, do not possess a well developed blubber layer and must depend upon air trapped in their thick fur. Since air is readily compressible, the hydrostatic pressure of moderately deep dives profoundly reduces this layer of insulation and drastically interferes with both diving depth and duration. The situation of SCUBA diving man is very similar to that of the fur-protected mammal. The typical wet suit, while providing suitable protection at the surface, contains air cells which are readily compressed and thereby suffers considerable reduction in insulating quality.

Men operating in submersible vehicles usually take with them a modified environment sufficient to provide adequate protection while they are inside the vehicle. The most extreme situation and the one with which we will deal is that pertaining to the diver operating without protection of a submersible vehicle for a long period and at relatively great depth. During the discussions at Yellow Springs, it became apparent that the free diver was the object of most concern. In the opinion of this reporter modern technology could do well by taking a lesson from the marine mammals. The possibilities for a practical system which would permit the free diver to be enclosed within a streamlined cover of fixed insulation similar to that of the marine mammal would have noteworthy beneficial features. Such a covering would provide for both practical heat conservation and in addition would provide other benefits to the diver. The enclosure of the diver within a fixed and therefore relatively rigid cocoon of streamlined insulation would suggest the need for a modification of the usual swim fin means of propulsion. There are several alternate systems which could readily be explored. Some devices have been experimentally tested which provide for the use of the major counter-gravity muscles of the lower limbs. The streamlining would be a very great advantage for the reduction of work required for propulsion through water. Great strides in improving technology can be made in this area.

But our major concern here is that of heat conservation. It frequently happens that a free swimming individual diver is required to do more than simply transport himself from one point to another. Therefore, he would be likely to need both the protection afforded by the insulating case and the mobility needed for performing work and doing other exploratory activities involving manual manipulations, and so forth. He would therefore like to be able to shed his insulating and propulsive enclosure and park it in a suitable place while he performed a task that was required of him. He could then, upon completion of the task, retire once more to the protective case. Judging very roughly from the experience with wet suits and the dimensions of tissues in marine mammals of similar size to man, one might estimate that the insulation, consisting of a substance having a thermal conductance similar to that of animal fat, should be approximately one inch thick. The entire enclosure would be required to be neutrally buoyant. Conceivably it could contain the diver's air supply in the form of tanks incorporated into the structure. The tank could either be detached or an auxillary could be employed during excursions from the casing. What is being suggested is a radical departure from the conventional configuration of wet suit, swim fins, and gas supply tanks. However, it is apparent that radical departures are required if simple thermal protection is to be provided for the free swimming SCUBA diver.

The subject of rewarming the already cooled and rescued swimmer received considerable attention at the Yellow Springs workshop. The participants agreed that the rescue of hypothermic swimmers involved very great risk and that the results were neither predictable nor generally satisfactory. Rewarming techniques that involve the application of heat to the external surface of the body are generally employed, and these involve plunging into warm baths and other means of applying heat to the surface. Such technique is almost universally followed by a further rapid and sometimes profound fall in deep body temperature as the peripheral circulation is once more opened up and the cold superficial blood is circulated to the interior of the body. This so called afterdrop of deep body temperature is probably the greatest single hazard to the rescue of severely chilled subjects. The conducting mechanism in cardiac tissue appears to be especially vulnerable to a low temperature generally and perhaps more so to the sudden change in temperature which is occasioned by the use of external rewarming techniques. Prospects resulting from the application of these techniques to a subject whose core temperature has been lowered below 32°C are not good.

Notably absent from the discussions at the workshop was consideration of internal rewarming as a technique for reviving chilled divers. This topic has been given some recent study, and the results have been remarkably successful. While there are too few cases to provide detailed statistical study, what results are available have indicated that techniques of internal rewarming have resulted in a much higher rate of recovery. Such recoveries have been swift and uneventful. Somewhat more is required than the simple hot bath that is usually used, but the techniques can be made safe and simple when employed by persons trained in first aid and medical practice.

The success of internal rewarming strongly indicates the desirability of further work with experimental animals to explore the various features of the techniques which provide safe and rapid recovery. Two general techniques have been used. These are the rewarming and circulation of blood and the use of peritoneal dialysis with warm solutions. The use of warmed blood leads to the very rapid warming of cardiac tissue and the conversion of cardiac rhythm to normal rate and characteristics. Peritoneal dialysis, while achieving the same result at a somewhat slower rate, is still vastly more rapid and apparently superior to all forms of external rewarming which have been used. Furthermore, this latter technique is far simpler to apply and less hazardous than rewarming through the circulation.

While it cannot be expected that in every situation in which a severely chilled diver or swimmer is encountered there will be ready at hand the techniques and trained personnel for the application of internal rewarming, such facilities and technicians should be made available in situations in which the revival of cold water victims may be anticipated. These would include applications in military and industrial activities in which cold water operation is expected to be frequent and of long duration.

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This report presents the proceedings of the Sixth Undersea Medical Society Workshop which was on "Thermal Problems in Diving", held at Webb Associates, Yellow Springs, Ohio on 2-3 May 1974. The following areas were discussed: Effects of exposure to cold water - Acute reactions to extremely cold water - Rewarming - Thermal protection - Safe limits for experimental cold exposure - Screening subjects for experimental cold exposure - Diver effectiveness - Hyperbaric environments

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