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THE PREDICTABLE EFFECTS OF COLD  
EXPOSURE ON WET AIRCRAFT PASSENGERS

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The incorporation of a cabin water spray system (CWSS) aboard commercial passenger aircraft has been suggested as a mechanism of reducing passenger death and injury from the fire and smoke commonly associated with aircraft accidents. A potential health risk associated with a CWSS is the physiological stress that would be imposed upon an individual by being wet from a CWSS activation in the aircraft cabin and then evacuated into a cold environment. The severity of this type of exposure would be proportional to the degree to which the individual was doused with water and the wind speed, and inversely proportionally to the ambient temperature. The physiological responses to partial wetting and subsequent exposure to cold environmental conditions have not been studied. The effects of cold exposure, as well as the degree of protection provided to the individual, particularly the cardiorespiratory system, would need to be fully investigated to determine if the survival benefits of a CWSS outweigh the potential health risks.

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## **Introduction**

Body heat balance is one of the most well regulated control systems of human physiology. In a dry environment at temperatures between 60 and 130°F, regulatory mechanisms are capable of maintaining normal body temperature of  $98.6 \pm 1.4^{\circ}\text{F}$  (1). To complement this control system, humans have developed behavior patterns allowing them to live in environments of extreme heat and cold. The purpose of this review is to consider the physiological responses of humans removed from a controlled environment, the interior of a passenger aircraft, and exposed to the elements after saturation with moisture from a cabin water spray system (CWSS), proposed for fighting onboard fires while improving passenger evacuation time.

To predict the responses of an individual, an understanding of the physiological response to thermal stress is required. These responses must be evaluated with respect to pertinent physiological and environmental conditions. Specifically, the focus is on an emergency situation aboard an aircraft in which a CWSS is activated. Other physiological questions that need to be addressed before the advantages and disadvantages of a CWSS can be fully assessed.

## **Control System for Body Temperature Homeostasis**

As is true for most physiological control systems, temperature regulation depends upon negative feedback mechanisms. A negative feedback control system is defined by the output of the system suppressing or inhibiting the activity of the system. For control of body temperature, this requires receptors at the

periphery to send signals back to the brain, which must integrate the information and evoke the appropriate response. For body temperature control, this system is complicated by the temperature at the body surface being lower than the internal core temperature. To reconcile this discrepancy, a particular area of the brain, the hypothalamus, integrates input from both central and peripheral sensors and evokes responses to maintain thermal balance.

The preoptic area of the hypothalamus has receptors that are sensitive to both heat and cold (2). This area of the brain is often referred to as "the body's thermostat". Activation of these receptors evokes intense thermoregulatory responses. Similarly, the peripheral receptors sense the presence of either heat or cold. These include receptors in the skin and some internal organs. The majority of peripheral temperature receptors are sensitive to cold. The hypothalamus integrates the input from both preoptic and peripheral receptors and transmits signals to the periphery to evoke the appropriate response to maintain heat balance.

#### **Mechanisms Involved in Body Temperature Homeostasis**

The human body is constantly undergoing heat flux. The control system for body heat balance functions so that body heat is lost or dissipated in warm environments and conserved in cold environments to keep internal core temperature relatively constant (3, 4). Temperature homeostasis occurs when heat loss equals heat gain. This relationship can be considered in the

following terms (5).

$$\Delta H = M \pm C_d \pm C_v \pm R - E \quad (\text{Equation 1})$$

where

$\Delta H$  = Change in body heat content

$M$  = Metabolism

$C_d$  = Conduction

$C_v$  = Convection

$R$  = Radiation

$E$  = Evaporation

Each of the variables on the right side of the above equation requires a gradient, over which energy can be exchanged. Each mechanism of heat transfer is briefly described below and discussed with respect to its contribution to heat exchange in body temperature regulation.

*Metabolism.* The body is constantly producing heat as a by-product of cellular metabolism. In a warm environment, excess metabolic heat is lost through a combination of radiation, conduction, convection, and evaporation. In a cool environment, metabolic heat can actually be increased by shivering, to help maintain body temperature at an appropriate level.

*Radiation.* Radiation refers to the loss or gain of heat by infrared heat waves. Normally, people exist in an environment in which the temperature is below their body temperature and therefore lose heat to the environment via radiation.

**Conduction.** Refers to the transfer of body heat directly to or from another object. Usually, the amount of heat lost or gained by the body in this manner is minimal.

**Convection.** Refers to the special case of heat conduction to air molecules at the body's surface. The air molecules are carried away from the body by air currents.

**Evaporation.** Evaporation of one milliliter (ml) of water results in a heat loss of 0.58 kilocalorie (kcal)<sup>1</sup>. Humans lose a minimum of 600 ml of water a day from the skin and lungs by evaporation, regardless of environmental conditions. As can be seen from Equation 1, evaporative mechanisms of thermal regulation are only effective as a means of heat dissipation. In a very hot environment, evaporative heat loss can be the only way in which the body can eliminate excess heat. However, evaporative heat loss decreases as relative humidity<sup>2</sup> increases. It is for this reason that a hot, humid environment is so dangerous when performing physical activity.

#### **Mechanisms Activated by Moderate Body Cooling**

When an individual is exposed to a cool or cold environment, specific physiological responses are evoked. Initially, cold induced stimulation of the cutaneous thermal receptors sends

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<sup>1</sup> A kilocalorie is defined as the amount of heat required to raise 1 kilogram of water 1°C.

<sup>2</sup> Relative humidity is defined as the ratio of the mol fraction of water vapor present in a volume of air to the mol fraction present in saturated air, both at the same temperature and pressure (6).

signals to central thermoregulatory areas, triggering responses to conserve body heat. In general, the body attempts to increase heat production, while trying to minimize heat loss. To minimize heat loss, cutaneous vasoconstriction reduces the amount of blood flow to the skin, thereby reducing the amount of heat that can be lost at the body's surface through radiation, convection, and conduction (7). Piloerection of body surface hair occurs to trap a layer of warm air next to the skin and provide insulation. This mechanism is an ineffective means of conserving body heat in humans.

For maintaining normal body core temperature, regulatory mechanisms for increased heat production are more numerous and more effective than mechanisms operating to minimize heat loss. Increases in body heat production are elicited by both indirect and direct means. Increased secretions of both epinephrine and norepinephrine results in an increased basal metabolism, thus increasing metabolic heat production (8, 9). The release of these catecholamines is characteristic of a generalized stress response. Furthermore, there is increased secretion of thyroid stimulating hormone (TSH) from the anterior pituitary. Increases in TSH result in increased activity of the thyroid gland and the accompanying release of thyroxine, which increases basal metabolic rate. Although not a completely conscious act, individuals have the tendency to increase motor activity when exposed to cold in order to enhance heat production. In response to a drop in body temperature, shivering occurs. Shivering is a



result of increased skeletal muscle tone and can multiply body heat production four to five times (10). Another mechanism of body heat conservation is the transfer of heat to deep veins in the limbs, which are parallel and in close proximity to arteries. This is referred to as counter-current heat exchange (11, 12). The extent to which the above responses would occur is dependent upon the intensity of the cold stimulus present. Figure 1 presents a simplified schematic of the negative feedback system controlling body temperature in a cold environment.

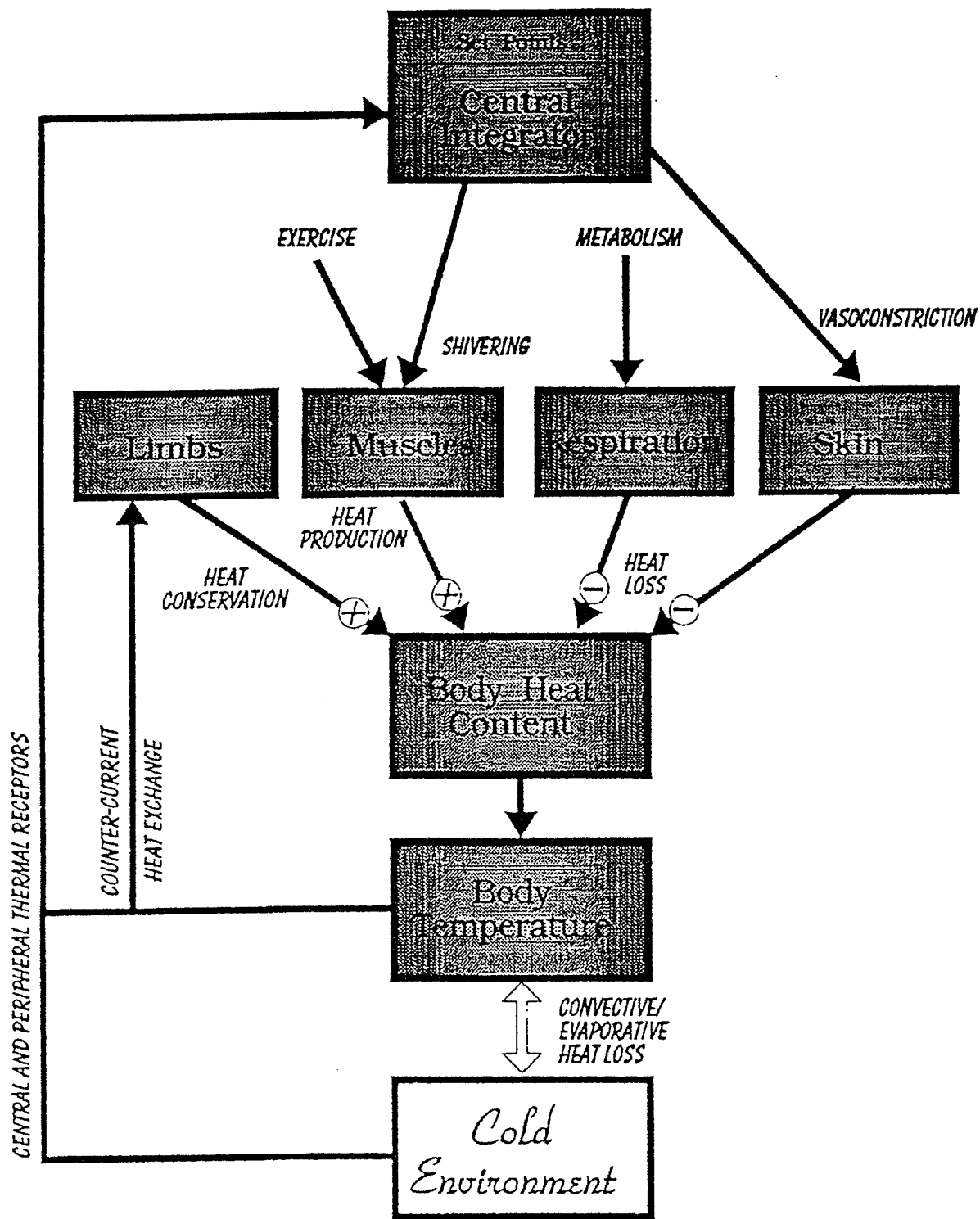


Figure 1. Simplified schematic of the negative feedback system which attempts to regulate body temperature during exposure to a cold environment. For an individual sprayed with water, it is important to note that the degree of convective and evaporative heat loss occurring will depend upon the water saturation level and environmental factors, such as temperature and wind speed.

## **Impact of CWSS on Aircraft Passengers**

In assessing the affect of a CWSS on aircraft passengers it should be realized that no two individuals, crashes, or crash environments are identical. Therefore, certain assumptions must be made to evaluate and predict the thermoregulatory challenge individuals would face after exposure to a CWSS. The impact of a CWSS must be considered with respect to individual differences in passengers, the emergency situation triggering the activation of the CWSS, and the environment that passengers will be exposed to after evacuation from the aircraft. Each of these variables is discussed below.

*The Passenger.* For the purposes of this review, the airline passengers are considered to be healthy adult individuals who have no significant physiological impairments and will respond to cold exposure consistently with the physiological responses previously described . However, it should be recognized that aboard any given passenger flight there will be a heterogeneous population of individuals whose individual characteristics will influence the physiological responses to cold exposure. Factors influencing an individual's response to a cold environment include: age, sex, ethnic background, body frame size and body composition, physical conditioning, and basal metabolic rate. The person's food, fluid, and alcohol consumption will also help determine the response to cold. In addition to these influences, persons suffering from any type of disease or physical handicap need their response to a cold environment to be considered with

respect to the particular pathology or impairment from which they suffer.

Assuming that a significant majority of individuals on a passenger aircraft that crashes would consider the experience highly stressful, the physiological responses associated with the generalized stress response of this situation include many of the responses that are elicited by exposure to cold (13). Catecholamine levels and metabolic rates would increase, and also motor activity levels, associated with bracing for impact and evacuation, would also be elevated. This is important because much of the "reserve" of the thermoregulatory control system is already activated. Furthermore, the impact of crash induced injury on thermoregulatory mechanisms should be considered. Injuries such as burns, broken bones, blood loss, etc., can markedly influence an individual's physiological response to a given stimulus.

*The Emergency Situation.* Cabin water spray systems are relevant to passenger survival in postcrash fire situations. Even in accidents in which a severe impact occurs, fire and smoke are a major cause of passenger death (13). People are killed by burning fuel and aircraft structure, in addition to the associated smoke and toxic fumes. Conceptually, a postcrash cabin water spray system would retard the spread of fire in the aircraft cabin, thus allowing greater opportunity for passenger evacuation (14). The passengers may become wet from the water spray system during this time period. The impact of this wetting

on body temperature regulation would depend upon a number of factors, including: 1) the degree of wetting, 2) clothing, 3) the ambient temperature and wind speed of the environment into which the individuals were evacuated, and 4) the length of time they remained in the hostile environment before being placed in safe, thermo-regulated surroundings.

*The Evacuation Environment.* Seasonal variations of the ambient temperature influence the rate of body heat loss. In spring, summer, and early autumn, or in areas where temperatures remain warm, body heat loss resulting from exposure to a CWSS would not appear to pose a significant problem. For the purposes of this discussion, it is assumed that the passengers will be evacuated from the aircraft cabin into a cool or cold environment. An outline of the factors influencing the magnitude of the physiological response to cold water immersion, cold dry conditions, and the hypothetical situation of being sprayed and introduced into a cold environment is presented, in Table 1.

Influences	Dry	Water Immersion	Spray
Behavioral			
Exercise	X	X	X
Environmental			
Air Temperature	X		X
Humidity	X		X
Water Temperature		X	X
Wind Velocity	X		X
Individual			
Basal Metabolism	X	X	X
Body Composition	X	X	X
Body Somatotype	X	X	X
Pathological Conditions	X	X	X
Physical Condition (Fitness)	X	X	X
Situational			
Clothing	X		X
Exposure Time	X	X	X

Table 1. A listing of some of the factors that will influence an individual's response to cold exposure. Behavioral and situational influences can be manipulated so that probability of injuries, such as frostbite, can be reduced when exposed to a cold environment.

The colder the ambient temperature, the greater the body heat loss. Potentially, even relatively brief exposure to extremely cold environment may result in cold injury, frostbite or hypothermia (Appendix I). The reason is that in extremely cold air the rate of heat loss by convection becomes very large since the cold air is capable of removing all the heat that can diffuse through the subcutaneous insulation of the skin. Furthermore, the physiological stress of the cold environment will be increased by exposure moisture from a CWSS. If an

individual's clothing becomes wet, it is no longer an effective means of preventing heat loss from the body, due to the high heat conductivity of the water. In fact, wet clothing may actually enhance the rate at which heat is lost from the body. Body heat loss would be further augmented by any air flow present in the evacuation environment. The influence of wind speed on heat loss from the body has been well characterized and is defined as windchill (Appendix II). For these reasons, passenger evacuation from the aircraft cabin into a cold environment after exposure to a CWSS poses a potential threat to the individual's well-being. The extent to which this is a problem depends a great deal upon the availability of appropriate rescue services and medical facilities.

If the aircraft CWSS activation occurs during takeoff or landing at an airport that had rescue facilities immediately available, the health risk resulting from exposure can be considered minimal. Exposed individuals could be taken directly to health care facilities, be treated, and monitored. If activation, like that associated with an emergency landing, occurs in a more remote area, the chances of clinical problems arising from exposure would be greatly increased. Clinical manifestations of exposure such as above-freezing cold injury, frostbite, and hypothermia could be expected to be positively correlated with the amount of time required to deliver rescue personnel to the crash site, the ambient temperature, and the wind speed at the evacuation site.

## Application of Available Data

The physiological responses and dangers of passengers doused by a CWSS during evacuation from an aircraft cabin can be approximated for a given set of environmental variables by applying what is presently known about cold exposure to this specific situation.

For example, a sprayed person who evacuates into a 32°F environment with a wind of 15 miles per hour will face a severe thermoregulatory challenge. In this situation, the effective ambient temperature is 13°F.

A 15°F ambient temperature with a 15 mph wind results in an effective ambient temperature of -14°F. Frostbite occurs at a tissue temperature of about -2°F. If protective measures are not taken, the chance for frostbite injury is very real, particularly to the body extremities or exposed skin. If emergency medical attention is not forthcoming, core body temperatures could decline to hypothermic levels.

If an evacuation were to occur into an environment below -5°F at a wind speed of 15 mph, mechanisms for survival in the cold would have to be available. This combination of temperature and wind speed results in an effective ambient temperature of -37°F; exposed flesh freezes in less than one minute. Therefore, unless rescue personnel are at the crash site immediately, severe cases of frostbite and hypothermia would occur.

In each of these situations, the effective ambient temperature would be further lowered by any evaporation of CWSS



water from the skin and clothes. It is difficult to estimate how severe an effect this, and other levels of exposure, would have on the average person.

### **Conclusions and Recommendations**

The focus of this paper has been the effect of cold exposure on individuals that have been doused by a CWSS. Research studies have not adequately addressed the effect of conductive and evaporative heat loss due to a person being doused with water and then introduced into a cool or cold environment. The possibility of cold injury occurring during this type of exposure is substantial. Since it would be inappropriate to expose individuals to conditions that could actually induce cold injury, experiments need to be designed to develop models to help predict the severity of cold injury expected under variable environmental conditions and levels of passenger clothing water saturation. These efforts are important because the potential for enhanced accident survivability provided by a CWSS probably outweighs the risk of serious harm from environmental exposure. Currently, however, it is not possible to quantify this risk comparison.

There are a number of other questions pertinent to physiological issues that should be assessed in evaluating the advantages and disadvantages of a CWSS in protecting aircraft passengers from fire and smoke. The degree of protection a CWSS actually offers the respiratory system should be determined. Specifically, the impact of a CWSS should be evaluated in terms of the degree of protection it provides to the pulmonary

surfactant system and structural integrity of the lung.

Consideration should also be given to what other physiological challenges are presented by the CWSS itself, e.g., inhalation of dissolved toxins, superheated water vapor, etc. This research would allow assessment of both the short term and long term benefits offered by a CWSS to an individual's respiratory function.

## APPENDIX I

### Clinical Manifestations of Cold Exposure Frostbite

Frostbite occurs when the skin temperature approaches the freezing point of water. The areas most readily affected by frostbite are the apical areas of the body: hands, fingers, toes, ears, nose, and chin. Mild cases produce numbness, prickling and itching. As the condition worsens, paresthesia and stiffness occur. The first clinical sign of frostbite is pale tissue color. If untreated, tissue coloration progresses to a red-violet hue and eventually turns black, as the tissue dies. After recovery from severe frostbite, the skin and nails of an affected extremity may grow back, but permanent loss of motion may result. In the most severe cases, amputation of the affected area may be required. Although frostbite is usually regarded as an external problem, in cases of extreme exposure it can occur in the lungs and nasal passageways.

The factors that affect the development of frostbite are temperature, windchill, humidity, duration of exposure, and, to some extent, altitude. Frostbite can occur without an associated drop in core temperature of the organism. The duration and type of cold exposure are the most important factors to be considered. Coming into direct contact with certain materials can cause almost instantaneous frostbite injury. Touching cold wood or fabrics is not as dangerous as direct contact with cold metal, especially if the skin is wet or damp. This fact may be particularly relevant during evacuation from an aircraft and

subsequent environmental exposure after being doused by a CWSS.

Mechanistically, frostbite damage is caused by the freezing of cellular cytoplasm. As the cell water crystallizes, cellular enzymes and membranes are damaged or destroyed. More importantly, this freezing obstructs the blood supply to the tissue. The endothelial cells lining the capillaries and small veins in frostbitten tissues are damaged by the cold in such a manner that they allow the blood serum to leak into the surrounding tissues. Loss of this fluid diminishes blood flow, and the red blood cells cannot remain suspended in the small, slowly moving volume of the cooling serum. As the red blood cells settle in the vessels, clotting occurs, further obstructing the flow of blood. Eventually, these processes totally halt circulation to the exposed tissue.

### **Hypothermia**

Hypothermia is defined as a body core temperature at or below 95°F. Figure 2 graphically depicts the physiological responses associated with exposure to a severely cold environment. The time required for each response to manifest itself will vary with the environmental variables, such as temperature, windchill, water immersion, etc.

Shivering starts when the core temperature starts to drop from the normal temperature of 98.6°F. When the body temperature drops to approximately 95°F, an individual begins to feel confused and disorientated. If core temperature continues to

fall, amnesia may occur. At a core temperature of approximately 91.5°F, shivering ceases and the skeletal muscles may become rigid. Cardiac arrhythmias may also become manifest at this point. It is important to note that when shivering stops, the body has lost the battle to maintain its internal temperature and the person will need medical assistance to recover.

At a core temperature below 91.5°F, the person becomes semi-conscious and loses awareness of the surroundings. The pupils of the eyes usually dilate. Unconsciousness occurs at a body core temperature of 86°F. Tendon reflexes are greatly diminished and will completely disappear if the core temperature continues to drop. Further reduction in core temperature to 82.5°F induces ventricular fibrillation and death soon follows. As illustrated in Figure 2, an unabated drop in core temperature results in death from cardiovascular failure. However, reports exist of individuals being resuscitated after their body core temperature fell to 68°F. Therefore, even a person with no visible signs of life should not be pronounced dead until vital signs are not evident at an increased body temperature.

Both immersion and dry conditions have been used to study hypothermia. In immersion studies, the primary focus has been the interaction of temperature and exposure time. To evaluate hypothermia in dry conditions, wind speed, air temperature, and humidity are varied and the impact on core temperature monitored. There has been a lack of research examining the effects of a cold, windy environment on a wet individual. Unfortunately, this

scenario is most pertinent to possible deleterious effects of a CWSS on body temperature regulation.

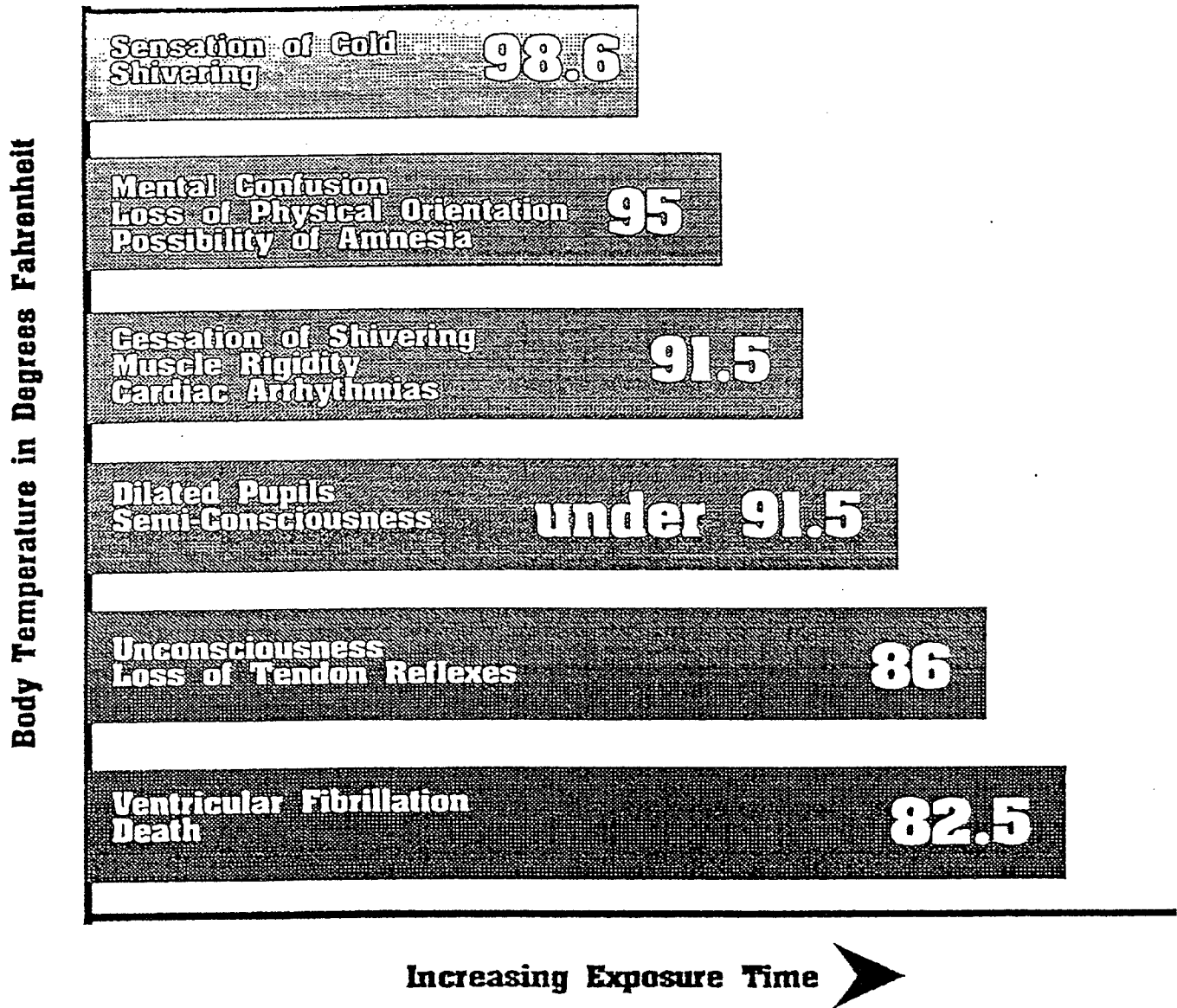


Figure 2. Progression of physiological responses when exposed to cold conditions for an extended period of time. The time required for each set of responses to occur will depend upon the severity of the environmental conditions.

## Appendix II

### Windchill

Windchill is a term used for the additional cooling effect produced by the wind. Air around a person is warmed by coming into contact with the skin through the process of convection. When the newly-warmed air is moved away, cool air moves in to take its place and begins the process of removing heat from the skin. For this reason, a mild temperature with a high wind speed can have the same effect on body temperature as a cold environmental temperature with no air movement. For example, a temperature of 23°F with a 25 mph wind is equivalent to a temperature of -10°F in the amount of heat that will be lost from the body. Figure 3 is a graph showing how wind speed and actual air temperature combine to produce an equivalent temperature.

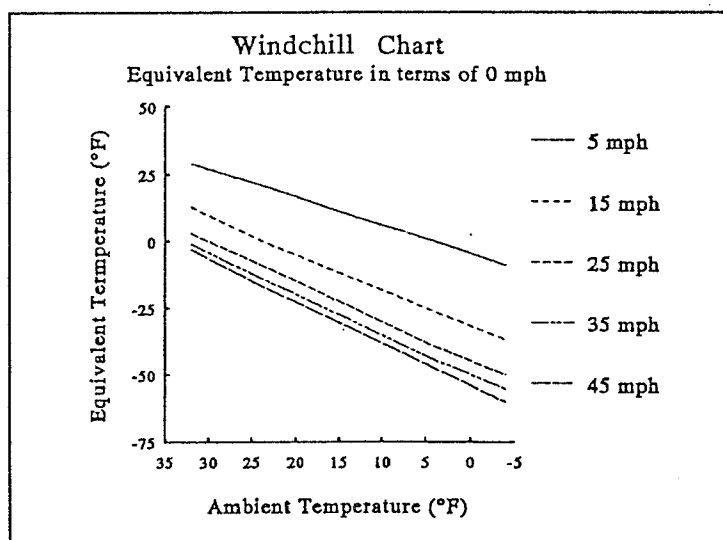


Figure 3: Impact of wind speed on equivalent temperature at ambient temperatures from 0 to 35°F. The most drastic reduction in equivalent temperature is elicited by a breeze of only 15 mph. Reduction of equivalent temperature at higher wind speeds is not as profound.

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