Current Concepts and Practices Applicable to the Control of Body Heat Loss in Aircrew Subjected to Water Immersion

Capt. E. L. Beckman, MC, USN, Cdr. E. Reeves, MSC, USN, and R. F. Goldman, Ph.D.

The problem of providing adequate clothing for personnel who either accidentally or otherwise are immersed in cold water has continued to challenge clothing manufacturers for the past decade. The development of foamed plastics and other clothing materials offers new possibilities. Likewise new advances in energy conversion systems offer new solutions to this critical operational problem.

The basic physical and physiological concepts which pertain to the problem of limiting thermal loss from the immersed human are reviewed. The newer technical developments in insulative clothing and supplemental heating systems are reviewed and discussed with relation to these basic concepts.

IMMERSION IN COLD WATER is one of the major environmental hazards to which military personnel may be exposed. To the ground-based pilot and crew, it poses only a remote and little considered hazard, but to carrier-based flying personnel it is an ever present threat to existence. There is no conditioning program effective in altering the unpleasantness of the experience or in decreasing the lethal rate at which a warm body loses heat to the cold water. Conductive heat loss from the immersed nude body occurs at all water temperatures below that of the immersed body. When water temperature reaches 24° C, death from body heat loss for unprotected personnel must be anticipated within 24 hours. At lower water temperatures, critical failure of thermal balance will occur in a few hours or even in minutes if immersion occurs in freezing sea water. Thus, any situation, accidental or otherwise, in which personnel are immersed in cold water for any appreciable time requires provision for conserving body heat. The following methods for limiting the rate of heat loss from the immersed human body are presently practiced:

1—utilizing the body's own protective thermal mechanisms to maximum advantage;
2—limiting the duration of the period of immersion;
3—supplying insulative clothing to reduce heat loss;
4—providing supplementary heat to replace the

body's heat loss.

Utilizing the body's own protective mechanisms to the maximum is of primary importance. However, enhancement of the body's tolerance to cold water immersion by training or conditioning, while possible to a limited extent, is of little operational value. It has been established that some long distance swimmers can endure prolonged immersion in cold water as a result of the protection afforded against thermal loss by an increased thickness of their subcutaneous fat layer and also by a conditioning regimen that trains them to swim for long periods of time at a very high rate of metabolic heat production. Carlson, et al.,[1] studied one such swimmer who had spent as long as 14 hours swimming in water between 4 and 8°C; his body fat content was 33 percent of his total body weight and he swam at a heat production rate of 550 Kcal/hr. Pugh and Edholm,[2] studying English Channel swimmers, observed that they too had an increased subcutaneous fat which limited the rate of heat loss and they swam as vigorously as possible to maintain a high rate of heat production. Training to improve the physical work capacity is worthwhile but developing the capability of maintaining a 550 Kcal/hr work output for 8-12 hours can only be achieved after many years of training and is not likely to become a prerequisite for aviation duty. The deposition of excess body fat is contrary to our present military view of physical fitness.

Limiting the time of immersion can be completely effective at all subcorporeal ranges of water temperature. Immersion of an unprotected subject in freezing water is an excruciatingly painful but endurable experience and, judging by the practice of the many "Polar Bear" Clubs, even routine to some individuals. The water "ditched" airman, however, must cope with cold water until rescued, a period that may extend from minutes to hours. Obviously, protecting military personnel against the effects of accidental cold water immersion by controlling the duration of exposure has little operational meaning.

Only the remaining two methods of controlling thermal loss offer any promise of being rewarding from the military point of view. The advances in clothing and textile technology which have occurred within the past 10 years suggest that improved insulative fabrics could be provided. In addition, the newer technologies in energy conversion systems, i.e., thermoelectrics, electrochemistry, and thermionics, etc., suggest that

systems for replacement of body heat may be available at an acceptable weight penalty so that it may be possible to maintain immersed personnel in thermal balance for a significant period even in freezing water. It would, therefore, seem appropriate, to review the problem of heat loss and thermal balance of the immersed human; to define the physical and physiological limitations of thermal balance during immersion; to evaluate the advances in insulation and heat replacement methods which would be useful in maintaining the thermal balance of immersed military personnel; and, to attempt to derive a realtistic prediction of what developments should be undertaken in support of the servicemen who may be immersed in cold water.

Man appears to be acutely sensitive to any decrease in body temperature below 95°F (35°C). Although the deep body temperature at which given central nervous system changes occur varies between individuals, on the basis of clinical experience in producing hypothermic anesthesia, McQueen[3] has reported that when the core temperature is decreased to 34°C, amnesia occurs for the period of cooling below that temperature and the patients become dysarthric and begin to lose contact with their surroundings. Pain is generally appreciated down to a core temperature of 30°C at which point the ability to recognize relatives or surroundings is also lost. Voluntary motion is lost at 27°C, as are pupillary light reflexes and deep tendon and skin reflexes. Virtue[4] corroborated these findings and reported that cardiac irregularities such as atrial fibrillation, ventricular ectopic beats, and ventricular rhythms were to be expected at core temperatures of 32-30°C.

While there are these serious effects of whole body hypothermia, the regional heat losses from the fingers and hands have been found to be the practical limiting factor in the effectiveness of many of the garments designed for protection against cooling during immersion. Provins and Clark[5] demonstrated that as the fingers, hands, and arms were cooled below 15.5°C, subjects developed an increased reaction time, a decrease in tracking proficiency and a decrease in manual dexterity, with a loss of tactile discrimination and kinesthetic sensation as well as a decrease in muscle strength. In some of our immersion studies in 10°C water, unprotected subjects demonstrated a decrease in grip strength of 50 percent in less than one hour of immersion.[6]

In order to design a protective system, it is necessary to closely define the temperature limits within which the protective system is expected to function. Although the deep body temperature of 27°C is the critical vital temperature for the sedated, anesthetized patient, the unmedicated volunteer immersion subject appears to become thermally unstable below 34.4°C (94°F) and tends to become poikilothermic. Hence, it would seem to be necessary to limit the heat loss of cold water immersed victims so as to maintain the deep body temperature above 34.4°C if a survival/rescue operation is to be successful.

The water temperature in which the downed aviator must survive varies with the geographical location of

TABLE I. TEMPERATURE VARIATIONS IN THE OCEANS

Percentage of Ocean Surface with Temperature Below	Atlantic	Indian	Pacific	Mean
25°C (77°F)	77.6	62.0	59.9	66.7
20°C (68°F)	49.9	48.3	41.6	46.6
Annual Variation Tropical Latitudes		—1°	— 2°C	
Annual Variation Higher Latitudes		—1°	—17°C	
Diurnal Variations		—0.1°	— 0.4°C	

the accident, the weather, time of year, and time of day as shown in Table I. Studies in progress at the Naval Medical Research Institute indicate that heat loss is not a critical limiting factor in experimental immersions of 24 hours (nude) in 85°F water, but that it becomes critical for many subjects immersed nude in 75°F water in less than 12 hours.[6] The mean voluntary tolerance time of 24 subjects immersed in 75°F water was 8.3 hours. This is substantially the tolerance time found in actual survival experiences. Therefore, some form of protection is needed for prolonged immersion in water of 75°F and below. From Table I, it can be seen that on the basis of the geographical distribution of ocean areas having a surface temperature below 77°F, there is a 67 per cent probability of an accidental immersion occurring in water requiring some thermal protective garment. In the past the time required for rescue varied from less than 1 to 36 hours. The thermal protection required obviously varies with the duration of the exposure. The temperatures of the oceans of the world vary from that of freezing salt water (—2°C) to the 32°C summer water temperature of the Persian Gulf. Consequently, from the point of view of either a survival or a protective thermobalance system, it is necessary to consider an immersion of 1 to 36 hours in waters varying in temperatures from —2° to 30°C with weather conditions varying from sunshine to storm and in sea states from flat calm to typhoon. Solar radiation is very beneficial in warming the cold water immersed victim whereas the rougher the sea state the greater will be the heat lost to the water moving past the immersed victim and the greater will be his rate of cooling.

Since weight and space are limiting factors in the design of aircrew equipment, it is necessary to consider the weight and cube of any survival system. The present anti-exposure garments for aircrew weigh 7.5 kg (16.5 lbs); this then should be an acceptable upper limit for any replacement system.

Before considering methods of prevention of heat loss by insulation or replacement of heat loss by supplementary heat, it is first necessary to evaluate the insulative and heat-generating capacity of the body itself. The insulative capacity of the body may be described as both active and passive, e.g.: the active phase of tissue insulation results from the variable peripheral vasoconstriction of blood vessels in the skin and the passive insulation is provided by the thickness of the relatively avascular subcutaneous fat layer. In other words, the insulative effectiveness of the surface of the body is equal to the insulative value of the relatively constant fat layer plus the thickness of the

actively vasoconstricted, and thus insulative layer.

Thermal conductivity measurements made on freshly excised human tissue show that the heat loss through a layer of fatty tissue 1 cm. in thickness is equal to 14.4 K/cal/m²/hr/°C. Similar measurements on excised fresh muscle, revealed a thermal conductivity of 39.6 Kcal/m²/hr/°C/cm thickness. The heat losses of the surface tissue of the body measured *in vivo* at three conditions of body metabolism yielded the following results: (1) when the body is cold, at rest, and not shivering, the heat loss is 9 Kcal/m²/hr/°C; (2) when the body is cold, at rest, but shivering, the heat loss is increased to 13 Kcal/m²/hr/°C; (3) when the body is warm and exercising, the heat loss from the skin is 50 Kcal/m²/hr/°C. The thermal transfers of the skin and subcutaneous tissues of an obese long distance swimmer have been observed to vary from 2.2 Kcal/m²/hr/°C for the resting condition in 10°C water, up to 33 Kcal/m²/hr/°C in 36°C water.[7] These extremes in insulative values reflect the skinfold thickness and the variation in depth of chilling and degree of vasoconstriction due to the cold stimulus. The difference between the measurements obtained on excised tissue and those obtained *in vivo* primarily represents the effects of blood flow. It may be assumed that the thermal conductivity of the combined skin, subcutaneous and fat tissues cannot be less than that of the fat layer, i.e., 14 Kcal/m²/hr/°C/cm. Observed values of heat loss from the intact body less than this, i.e., 2.2 to 9 Kcal/m²/hr/°C imply a mean thickness of the insulative layer greater than 1 cm. These data indicate that: (1) the fat man will be better protected than his thin counterpart; (2) the thermal conductivity and thus the insulative value of the body surface layer may vary 20 fold* for different persons; and, (3) the highest insulative value will be provided by a cold, vasoconstricted skin with a thick subcutaneous fat layer. From these data it may further be inferred that a fat and a thin man will require different amounts of external insulation to protect them equally. Furthermore, it appears that the protective system should be designed to keep the skin cold and vasoconstricted for optimal efficiency of the insulative and heating systems of the body.

Thermal balance in the unprotected man is controlled not only by the rate of heat transfer through the externally cooled tissue, but also by the ability of the body to produce heat. Increase in the heat production of a body immersed in cold water is based upon both involuntary and voluntary thermogenesis where involuntary thermogenesis is the heat produced by involuntary shivering, increased muscle tonus, and by non-shivering thermogenesis subsequent to cold acclimatization; active thermogenesis is voluntary muscular effort. The oxygen consumption rate of nude subjects immersed in 10°C water varies from 2.2 times his resting metabolic rate for the obese subject up to a maximum of 9 times his resting rate for the tall lean subject.[6]

The energy requirements of a 70 kilogram man for various activities have been enumerated by Morehouse and Miller.[5] Such a subject, swimming the crawl stroke at 1 MPH, would expend 410 Kcal/hr; he would expend 420 Kcal/hr while swimming the breast stroke at the same rate. This heat production would certainly be useful in maintaining body temperature if it could be maintained. However, this amount of physical activity cannot be continued for an 8 to 10 hr. period by any but the most practiced swimmer. Trained frogmen, while swimming, are expected to maintain a work rate of only 200 Kcal/m²/hr which would be about 380 Kcal/hr for the 70 Kgm. man. The trained, long distance underwater swimmer, studied by Hunt, Reeves, and Beckman[8] produced only 260 Kcal/hr while swimming with swim fins at a speed of 1.1 MPH during a 5-hour underwater swim.

The practical value of increased energy expenditure with respect to the ability to endure prolonged immersion has been investigated by Beckman and Reeves,[10] who studied the physiological effects of immersion of 24 nude subjects in 24°C (75°F) water for up to 12 hours. Although only 2 of their experiments had to be terminated because of a decrease in core temperature to below 35°C (95°F), 16 subjects failed to complete the 12-hour immersion owing to severe, persistent muscle cramps and other effects attributable to physical exhaustion. Thus the practical solution appears to be in increasing the insulation. These investigators also related the specific gravity of their subjects, and as a corollary, total body fat (estimated with respect to a 14% standard reference body) to mean energy expenditure during the period of immersion. As shown in Figure 1, the short fat subject with the lowest specific gravity expended only 70 Kcal/m²/hr during a 12-hour immersion. However, the tall thin subject with the
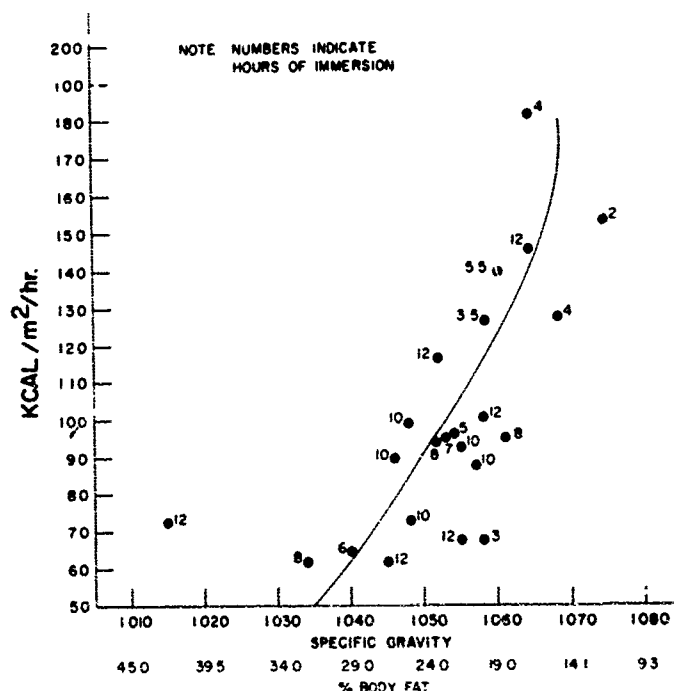

Fig. 1. Relationship of rate of heat loss vs. body specific gravity in 23 nude subjects immersed to neck level in 75°F. water.

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*The insulative value, K_i, is the reciprocal of the thermal conductivity described in Kcal/m²/hr/°C.

highest specific gravity while producing 137 Kcal/m²/hr during the two hours he remained in the water experienced a drop of deep body temperature to below 95°F. The uppermost data point on the line of best-fit represents a subject who also had to be taken from the pool within 4 hours owing to a decline of core temperature below 95°F. Between the extremes of the man with the thick, insulative, adipose layer and the two thin men with high specific gravities are data points representing the other subjects. A few of these subjects with high specific gravities were athletic by habit, and were able to maintain their body heat by continuous exercise for a twelve-hour period, even though they had a relatively thin adipose layer.

Some subjects in this series developed circulating blood glucose levels of 50-60 mgm percent and experienced a typical hypoglycemic episode. Some of these subjects were given brandy or hot coffee containing much sugar after they had declared that they could no longer endure the experiment. In most cases, these subjects then continued and were able to extend their tolerance times by one or two hours. Although no critical studies have been carried out, it is our impression that most subjects who had been given nothing by mouth during the immersion tests, extended their tolerance times when given food or brandy. The judicious use of food to increase metabolism by the "specific dynamic action of food"[11] and of brandy to decrease muscular rigidity, cramps and discomfort warrant further experimentation.

It is apparent that the inherent insulation of the body and the capacity of the body to produce heat both vary widely between individuals. It would be futile to depend upon such uncertain devices for protection against thermal heat loss during immersion. Even maximum values of both parameters are inadequate to protect the individual in 40-50°F (4-10°C) water. It is therefore necessary to consider the use of external insulative systems to limit the loss of any heat which is produced by the body.

The value of an insulative system depends upon: (1) the insulative value of the external insulation plus the insulation of any still layer at the body surface; (2) the geometry of the body to be insulated; (3) the temperature difference between the body surface and the surrounding water; and (4) the rate of flow of the water.

In general, a vacuum layer, or a still air layer, would provide the best thermal protection but these layers are difficult to provide in flexible garments. Consequently, something less than ideal must be accepted. Theoretically, optimal clothing material, represented by uncompressed wool or by foamed neoprene, provides approximately 1.6 CLO* of insulation/cm

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'CLO: The CLO is an arbitrary unit of insulation and is the amount of insulation necessary to maintain comfort at a mean skin temperature of 33.3°C in a room at 21 C with air movement not over 10 ft/min., humidity not over 50 per cent, and a body metabolism of 50 Kcal/m²/hr On the assumption that 76 per cent of the heat is lost through the clothing, a CLO may be defined as the amount of insulation that will allow the passage of 1 Kcal/m²/hr with a temperature gradient of 0.18°C between the two surfaces.

thickness, or 4 CLO/inch. During World War II, considerable effort was expended in investigation of the problems of clothing for Arctic based troops.[13] It was found that clothing with a thermal insulation of 4 CLO was necessary for protection but weighed 30 pounds. This amount of insulation could not be provided to the hands and feet and thus even this very thick, heavy clothing did not provide adequate protection. The difficulty in providing adequate thermal protection for the hands and feet relates to the geometry of the part to be insulated. The importance of this factor in insulation is summarized by van Dilla, Day, and Siple.[14] Insulative values of materials are normally described in terms of flat surface insulation. Although the insulative value of material on a flat surface is directly related to its thickness, the relationship is not as simple on shapes like cylinders and spheres. The relationship of thickness of fabric in inches to the effective insulation in CLO is seen in Figure 2. On the bottom line of this graph it is seen that as the thickness of the insulative fabric surrounding a ½ inch sphere is linearly increased, the insulative value increases only slightly and no significant increase in insulative value is provided by increasing fabric thickness beyond 1 inch. The insulative effect of increasing the thickness of the insulative fabric around a cylinder of ½-inch diameter is only slightly better than for a sphere. This figure illustrates why it is difficult, if not impossible to pro-
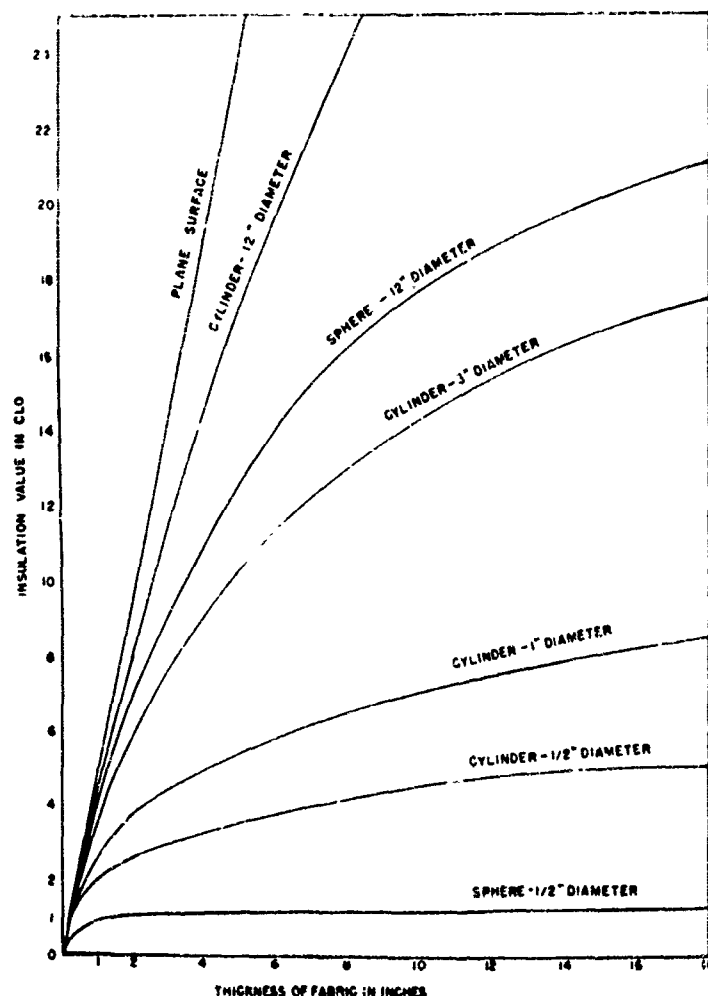

Fig. 2. Insulation of ideal fabric on a plane, cylinders and spheres.

vide adequate insulation for thin cylinders such as fingers and toes. It has long been known that it is almost impossible to provide adequate insulation in the form of gloves for the fingers and hands in extremely cold Arctic weather. For this reason, mittens rather than gloves have been provided so that the fingers and hands may be made into a ball to improve their surface to mass ratio. A theoretical solution proposed by van Dilla, et al.[13] to the problem of providing adequate insulation for Arctic troops is shown in Figure 3. The problems which must be solved to provide adequate thermal insulation for Arctic troops in —50°C weather with a 30 knot wind are equal in magnitude to those of providing adequate thermal insulation for personnel immersed in freezing water.

During World War II, many types of thermal insulative garments were developed for protection against heat loss during immersion. These garments all utilized the "dry suit" concept of wrapping the subject in a waterproof bag. Although sound in principle, this is almost impossible to achieve in practice. When waterproof suits for immersion protection of Navy fliers were developed after World War II, they were effective but were also hot, humid, bulky, and unpopular. The insulative value of these garments in air can be easily controlled by varying the thickness of the insulation worn beneath the suit. However, when the insulative layers of such suits are compressed by the water pressure during immersion, the insulative value of the garment is significantly reduced. The MK5A anti-exposure suit for Naval aviators, consisting of a rubberized outer garment and insulative inner layer, is a "dry-suit" of this type with an effective insulation, in air of 2 CLO.[11] When the garment assembly was tested in water the effective insulation was only 0.57 CLO (See Table II). A most serious disadvan-

Any exposure, at rest

6 hour exposure, at rest

Best possible mitten, good for 2-3 hours, at rest
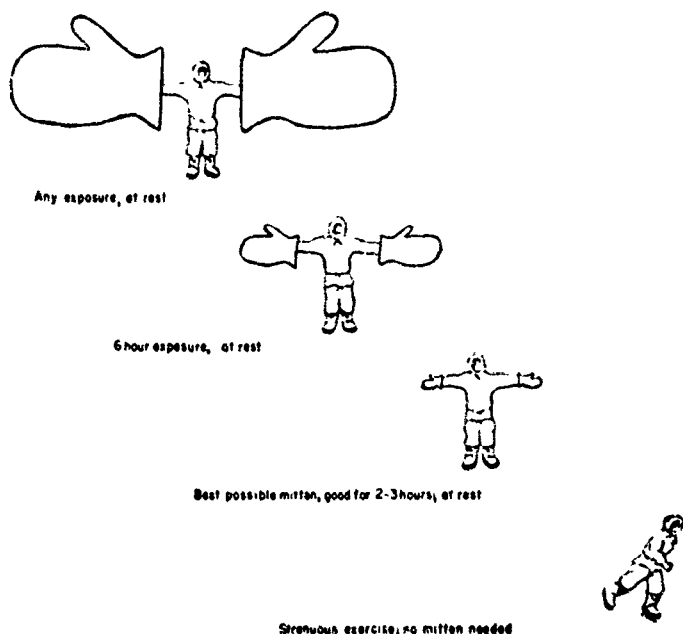

Strenuous exercise, no mitten needed

Fig. 3. Relative size of mittens needed for different exposure times at –20°F.

From Van Dilla, M., R. Day and P. A. Siple, p. 384 'Special Problem of the Hands," "Physiology of Heat Regulation and the Science of Clothing," L. H. Newburgh, W. B. Saunders Co., Philadelphia, 1949.

TABLE II. TOTAL INSULATING VALUES OF CLOTHING ASSEMBLIES MEASURED ON A COPPER MAN[19] IN AIR AND WATER (CLO UNITS)

Suit	Air	Still Water	Water Flow 1gpm/250gal	Stirred Water
Nude Copper Manikin	0.62	0.14	- -	0.11
MK5A Anti-Exposure Suit	2.05	0.56	0.57	
Underwater Swimmers Wetsuit (1/4" Foamed Neoprene)	1.49	0.76	0.77	0.71
Underwater Swimmers Wetsuit (3/16" Foamed Neoprene)	1.32	----	0.78	----

tage of this type of garment is that if it is torn or leaks because of fabric age or wear, the insulative value then approaches that of still water. An even more serious drawback to the "dry" type of anti-exposure garment results from the normal physiological processes of the body. Immersion in water up to the neck level has been shown by Beckman and DeForest[15] to produce a profound and continuing diuresis of such urgency as to rapidly convert the so-called drysuit to a very wet one.

During World War II, C. R. Spealman of the Naval Medical Research Institute developed the concept of using "spongy" neoprene for insulation in a waterproof boot.[16] The insulative value of such boots were established by laboratory experiment and recommended for use in preventing the "immersion foot" of immersed shipwrecked survivors. Subsequently, an equally significant advance in thermal insulative garments for immersed personnel was achieved when Dr. Hugh Bradner[17] in 1951 reported on his experiments with *unicellular foamed neoprene* garments for thermal insulation of immersed subjects and recommended the use of a tailored suit of unicellular foamed neoprene for underwater swimmers. Since then, such unicellar foamed neoprene "wetsuits" have been adopted by underwater swimmers and "scuba" divers throughout the world. They have proved to be entirely effective for use in water of moderate temperature but less effective in freezing water.

Experiments have been conducted at the Naval Medical Research Institute to evaluate the use of a 3/16 and 1/4 inch thick unicellular foamed neoprene suit for thermal insulation and protection for downed aviators.[18] In general, it was found that subjects immersed to neck nevel in 10°C water and wearing 3/16 inch neoprene foamed trousers, jacket, boots, and gloves, were able to tolerate the immersion for approximately 4 hours at which time their great toe temperatures had decreased to near water temperature. When the subjects were exposed to 4.4°C water while wearing the same garments, they were, in general, only able to tolerate 2 hours of immersion. When the subjects were immersed in freezing salt water at a temperature of —2°C, the immersion periods were decreased to 1.3-1.5 hours. Loss of heat from the toes and heels of the feet and from the fingers of the hands, with subsequent pain at temperature levels of 7-8°C limited the exposure

times in most of these experiments. In only a few subjects did body core temperature decrease to a critical level (35°C) before the extremities cooled to the critical level of 8°C.

The theoretical, flat surface thermal insulation of unicellular foamed neoprene is 1 CLO for a ¼-inch thickness of fabric. Experiments on the effective insulation of such a suit was 0.77 CLO.[*][14] (See Table II). The effect of increasing the velocity of the water past the manikin is also demonstrated by the data in Table II where it is shown that the effective insulation on the ¼-inch neoprene wetsuit was decreased from 0.77 CLO to 0.71 by slightly increasing the rate of flow of the water. Theoretically, a one-inch thick suit of foamed neoprene with an equal thickness of boots and gloves would be adequate to protect the immersed survivor or swimmer indefinitely in 0°C water. When subjects were clothed in such a bulky suit, it was found that they increased their voluntary immersion time in 4.4°C water to 5 hrs as compared to 2 hours when clothed in a 3/16-inch neoprene garment. While this garment, which weighed 40 lbs and severely restricted the motion of the subject, adequately protected the deep body temperature of the subject, the hands and feet cooled to pain temperatures and constituted the limiting parameters. These experimental results suggest that the required insulation for the extremities had not been achieved and that, within an 8 hour period, heat loss from the extremities will be such as to limit safe exposure to water at temperatures below 12°C at which temperature tissue damage is produced.[13] Therefore, it becomes necessary to consider some method of replacing heat in order to provide thermal protection to the subjects immersed in cold water. It is obviously not possible to rely solely on a thermal replacement system. It is necessary both to insulate the body against the external cold environment and to provide additional replacement heat over the critical areas where the geometry of the body tissues is contrary to the best interest of heat conservation. Goldman[19] came to a similar conclusion as a result of investigation on protective garments for inactive Arctic troops.

Since the advent of the space era, there has been an ever-increasing need for more efficient power conversion systems for space vehicles with the result that there have been many significant developments in these technical fields over the past few years. These developments have resulted in systems with more advantageous power/weight ratios, to a point where they may now be considered for use as a primary power source for personnel heating systems. Energy conversion systems can be compared on the basis of several important factors: theoretical energy/weight ratio; system energy/weight ratio; system power/weight ratio; shelf life; cost in terms of power delivery; availability; and, controllability. Collectively, these factors determine the usefulness of the system.

A satisfactory energy conversion system is only one part of the problem of replacement heating. Not only must energy be provided, but the energy must be converted into heat and this heat must be distributed from the area where it is generated to the area of need. Thus, both a useful energy conversion system and a compatible energy distribution system are required to provide supplementary heating. The resistance-wire, electrically heated garment represents the most readily available system of heat generation and distribution. In this system, the energy is converted into heat throughout the distribution of the resistance elements so that area heating can readily be controlled. The resistance-wire electrically heated suit has had several periods of popularity in the military services. An electric-wire heating garment was developed for use by helium-oxygen divers even before World War II. Similar garments were adapted for use by flight crews during World War II. These systems met the need for replacement heating, but the techniques of manufacture left much to be desired and short circuits and "hot spots" were common experiences so that the use of these garments was discontinued after the operational urgency was ended.

More recently, scientists at the R.A.F. Institute of Aviation Medicine, Farnborough, England, together with an engineering firm,[*] have developed a technique for weaving a fabric in which the resistance-wires are woven between the synthetic fiber threads to form a stretchable garment. Figure 4 shows a glove woven

Fig. 4. A heated glove woven with the white insulated wires showing in the fabric.

with the white insulation of the wires showing in the fabric. Gloves, socks, and a coverall type garment of this material were developed for supplying heat to aircrew of inadequately heated aircraft.

Electrically heated Arctic thermal boots and gloves have been developed by the U. S. Army and provide supplemental heating at a power rate of 10 Watts for each boot and glove. The 6-8 hour battery packs used weigh 7 lbs. and are designed to provide protection at —40°C for the inactive Arctic soldier.[21] When constructed with waterproofing techniques, such garments could be used to provide supplemental heat to underwater swimmers or to aircrew of ditched aircraft. On

the basis of the previously described experiments on the use of a 1-inch unicellular foam neoprene suit, it would seem that supplemental heat supplied only to the feet and hands would significantly increase the tolerance time to immersion. On the basis of the experiments described above, it seems probable that the most effective type of immersion suit could be achieved by a one inch thick, foamed neoprene suit with the thick neoprene boots and gloves incorporating resistance-wire woven socks and gloves and supplied with a battery power source to provide local heat. Although such a suit might protect the immersed victim in waters at the temperature of freezing sea water for a period of 12 hours, it would weigh 52 lbs!

The advances in manufacturing techniques in resistance-wire garments have been paralleled by recent advances in high energy battery developments. Electro-chemical primary and secondary cells have been developed that will provide power supplies for supplemental heating devices. The increase in the power/weight ratio of both silver-zinc and silver-cadmium batteries makes both battery types usable. Silver zinc batteries provide from 40-80 watthours (whr) per pound, whereas the silver cadmium batteries provide 30-60 watthours (whr) per pound. The cost of these batteries is likewise high, i.e., approximately $1/whr for silver zinc and $1.3/whr for silver cadmium.

Sea water activated batteries of the silver chloride/magnesium type offer the highest power factor for this battery type. With such a system, it would be possible to provide 40 watts of heat to boots and gloves for 6 hours at a battery weight of 7 lbs. The electric resistance-wire and battery system is an immediately available, workable system and offers the greatest advantages, i.e., variable heat control, both as to amount and area supplied, a thermostatically controlled on/off cycle, and an evenly distributed supply of heat. One experimental Army Arctic glove and boot system (Figure 5) is thermostatically controlled and supplies 10-20 W to each glove and each boot. This assembly has been tested with a ¼ inch neoprene wetsuit and protected

the hands and feet effectively, more than doubling the voluntary immersion time of subjects in 40°F water. This thermal protective system when used with 350 whr AgCl-Mg sea water batteries would weigh a total of 22 lbs., and would protect the body and extremities for over 4 hours in 40°F water.

Recent advances in thermionics, thermoelectric generators, catalytic fuel cells and exothermic chemical reactions offer a wide range of selection for heat generation which potentially may be developed into useful systems for replacement heating of immersed survivors, in addition to the resistance-wire heating system used with high power/density batteries. Isotopic power generators provide the highest power to weight ratio of any system. Alpha emitting isotopes require the least shielding. Polonium-210 has a high power density, 140 thermal watts/gm. If the fuels alone are considered, it would require only 10 gms. of Polonium to provide enough heat to keep an immersed human warm without any added external insulation! However, Polonium has a half-life of 138 days which limits its shelf life. Although the present cost is about $800.00/watt, future development should decrease the cost to about $25.00/watt. Polonium also has decay emissions which introduce serious shielding problems. A comparative tabulation of the various isotopic power generators is

TABLE III. RADIOISOTOPES FOR THERMAL POWER SOURCES

Radioisotope Fuel	Half-life (years)	Initial Power Density (watts/gram)	Cost $/W	Major Radiations
Strontium—90	28	0.93	19.00	Beta, a few gammas
Cesium—137	30	0.20	21.00	Beta, a few gammas
Cerium—144	0.78	25.0	1.00	Beta, a few gammas
Promethium—147	2.5	0.36	91.00	Beta, a few gammas
Polonium—210	0.38	141.0	20.00	Alpha
Plutonium—238	89	0.55	1,000.00	Alpha
Curium—242	0.45	121.0	17.00	Alpha + Neutrons
Curium—244	18	2.8	357.00	Alpha + Neutrons

shown in Table III.[21] When the cost and the weight of the shielding are considered, these isotopic power units seem to have less value for present survival systems.

Heating systems employing the flameless surface combustion of hydrocarbons in the presence of specific catalysts are also efficient heat sources (13 whr/gm). Hand warmers for hunters are of this type and are marketed.* The temperature of the combustion varies from 316°C upward so that this system could not be used for direct heating, but would have to use an intermediary heat transfer system.

A new type of catalytic heating device which utilizes the combustion of hydrogen in the presence of a proprietary catalyst** at a temperature of 38°C offers
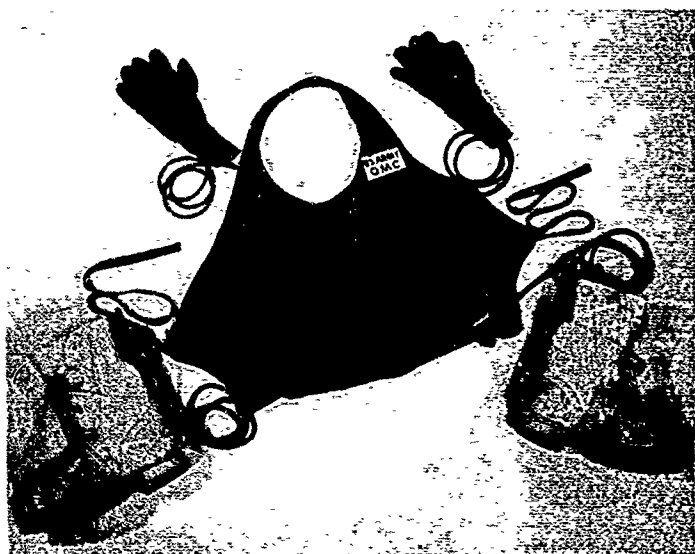

Fig. 5   U. S Army electrically heated gloves and boots with battery pack.

*Therm-X and Whamo.
**Ethyl Corporation Research Laboratory, Detroit, Michigan.

TABLE IV. COMPARISON OF VARIOUS HEAT GENERATING SYSTEMS

| Thermal System	Reactants	Product	Power or Energy Density	Estimated Wt of 100 W/Hr Power Unit in Kg	Duration of Power Cycle	Stage of Development	Estimate Cost of Power Unit in $ (Exhaling Development Costs)
Primary Battery	$AgCl$ + Seawater	Electricity	.1-.2 whr/gm*	3.0	5 hrs.	Evaluation	$ 300.00+
				3.0	5 hrs.	Evaluation	250.0+
Secondary Battery	Silver-Zinc	Electricity	.1-.2 whr/gm	4.0	5 hrs.	Evaluation	400.00+
	Silver-Cadmium	Electricity	.08-.16 whr/gm*	3.0	89 yrs.	Development	250,000.00+
Radio Isotope	Plutonium-238	Heat	.55 W/gm**	10.0	0.4 yrs.	Research	20,000.00+
Radio Isotope	Polonium-210	Heat	141.0 W/gm**				
Thermo-Chemical	$Mg + H_2O \xrightarrow{FE} MgO + H_2 + [H]$	Heat	3.8 whr/gm*	2.0	5 hrs.	Development	5.00--
Fuel Cell	$NaAlH_2 + 2H_2O \rightarrow NaAlO_2 + 4H_2$; $2H_2 + O_2 \rightarrow H_2O + [H]$	Heat	4.7 whr/gm*	3.0	5 hrs.	Development	15.00++
Wet Suit	Unicellular Foamed Neoprene	Insulation	.05 W/gm*	4.0		IN USE	25.00
Food	$CHO + O_2 \rightarrow CO_2 + H_2O$ [H]	Heat	4.6 whr/gm	0.5	5-10 hrs.	IN USE	0.50

*Measured

**Theoretical

+Requires use of Resistance Heating Suit Wt = 2Kg

++Requires use of water conditioned suit Wt = 3Kg

promise. The theoretical efficiency of such a thermal generator would be high with an energy density of 8 whr/gm. In this system, hydrogen would be generated by reacting sodium aluminum hydride with water according to the equation:

$$Na\ AlH_4 + 2H_2O \rightarrow Na\ AlO_2 + 4H_2$$
$$2H_2 + O_2 \rightarrow 2H_2O\ [H]$$
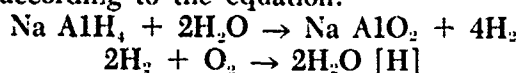
Since both air and water are available in excess in a surface survival situation, this chemical reaction has certain advantages. However, the mixture of oxygen and hydrogen must be carefully controlled to limit the O_2/H_2 ratio to more than 21/1 by volume to prevent the mixture being explosive. The practical energy of this system should be in the order of 10 pounds of equipment to provide 350 thermal watts for four hours. This system is currently under development for the U. S. Navy.*

Thermochemical systems such as the combination of magnesium and water in the presence of iron also give a relatively high theoretical energy, on the order of 1.5 KWH per pound (4.0 whr/gm). Such a unit would have an indefinite shelf life and would cost relatively little, perhaps 10c per watt. The basic ingredients are readily available and a simple and suitable heat generator could easily be provided. Unfortunately, this is the type of reaction that is very difficult to control once it has been initiated although the gas that is generated could possibly be utilized to quench the reaction. Similar exothermic chemical reactions could be employed, such as the heat generation provided by the hydrolysis of sodium. However, these types of

reactions could not be used to heat the body directly. A summary of the various power conversion systems is set out in Table IV, where it is shown that there are several conversion systems available which would provide sufficient heat to significantly prolong survival and operating times during immersion in cold water if the heat could be properly distributed. Recent developments of a liquid distribution system along the lines recommended by Siple[22] show considerable promise. The principle of the "water conditioned" suit for heating and cooling the body is essentially simple, and utilizes the high specific heat of water (or other high specific heat liquid) to distribute heat to or transfer heat from the various areas of the body as required. Pioneer work on this type of suit has been carried out at the Royal Aircraft Establishment, Farnborough, England,[23] and is being pursued at the Manned Spacecraft Center, NASA, Houston.[24,25]

In the model under development for NASA by Dr. J. Billingham (Figures 6 and 7), thin (2mm) plastic water pipes are incorporated into Brynje type (fishnet) undergarments so as to have heat exchange tubes covering the skin about 2 cm apart. By taking advantage of the normal skin temperature gradient from the central body toward the extremities, cooling water is pumped over the extremities toward the central body to provide a progressive heat transfer gradient. Heating is accomplished by pumping the heated water first over the trunk and then to the extremities. Dr. Billingham tested one of these suits under a 3/16-inch unicellular foamed diver's wetsuit. He was immersed in 4°C water for 70 minutes and maintained his body temperature by using an inlet water temperature of 45°C and a mean flow of 3.8 liters of water per hour.

Space News Roundup, Page 6, August 5, 1964.

Fig. 6. Water cooled garment.
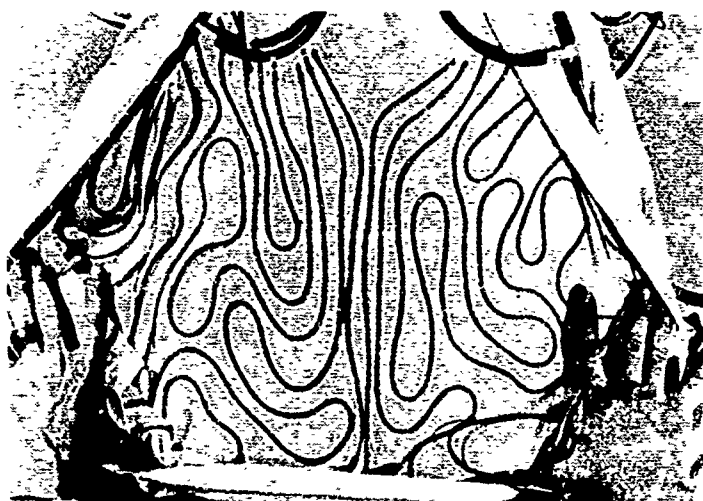
Space News Roundup, Page 7, June 24, 1964.

Fig. 7. Plastic water pipes sewn into the material of long underwear.

This suit uses a miniature electric pump which, with its battery and gearbox, weighs only 340 gms. The suit itself weighs only 2 kilograms.

The water conditioned suit holds considerable promise for use not only for supplying heat to immersed personnel but for cooling flight personnel as well. Because the liquid is incompressible and the tubes are relatively rigid, the pressure drop in the tubing is not affected by immersion as occurs in the air conditioned suit. Reference to the power conversion Table IV shows that the most efficient systems supply only heat. The chemical heating system has a high efficiency and would provide an excellent heat exchanger for use with the water conditioned suit. An isotopic power conversion unit would likewise by adaptable for use with the water conditioned suit.

In order to meet present needs for thermal protective anti-immersion clothing, it therefore seems advantageous to incorporate unicellular foamed neoprene with supplemental resistance heating systems into anti-exposure garments. The neoprene foamed suits are

desirable as protective garments because of the following advantages: (1) they provide effective, reliable, and adequate insulation for use in a cold, wet environment; (2) they provide positive buoyancy at all times, (3) they provide mechanical protection against external moving objects; and, (4) they are relatively inexpensive. An electric resistance-wire supplementary heating system consisting of boots and gloves, powered by a silver chloride-magnesium sea water battery would provide adequate protection for an operation immersion of useful duration when used with a 3/16-inch unicellular neoprene wetsuit.

For future development, the water conditioned suit might be exploited for use beneath the unicellular foamed outer garment. The development of low temperature oxidation and thermochemical cells should provide a significant improvement over the efficiency and power density of the battery systems. The development of such a heating system should be of use not only by aircrew, but also by divers, underwater swimmers, reconnaissance teams, and the Army Corps of Engineers.

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13. ABSTRACT

The problem of providing adequate clothing for personnel who either accidentally or otherwise are immersed in cold water has continued to challenge clothing manufacturers for the past decade. The development of foamed plastics and other clothing materials offers new possibilities. Likewise new advances in energy conversion systems offer new solutions to this critical operational problem.

The basic physical and physiological concepts which pertain to the problem of limiting thermal loss from the immersed human are reviewed. The newer technical developments in insulative clothing and supplemental heating systems are reviewed. The newer technical developments in insulative clothing and supplemental heating systems are reviewed and discussed with relation to these basic concepts.

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