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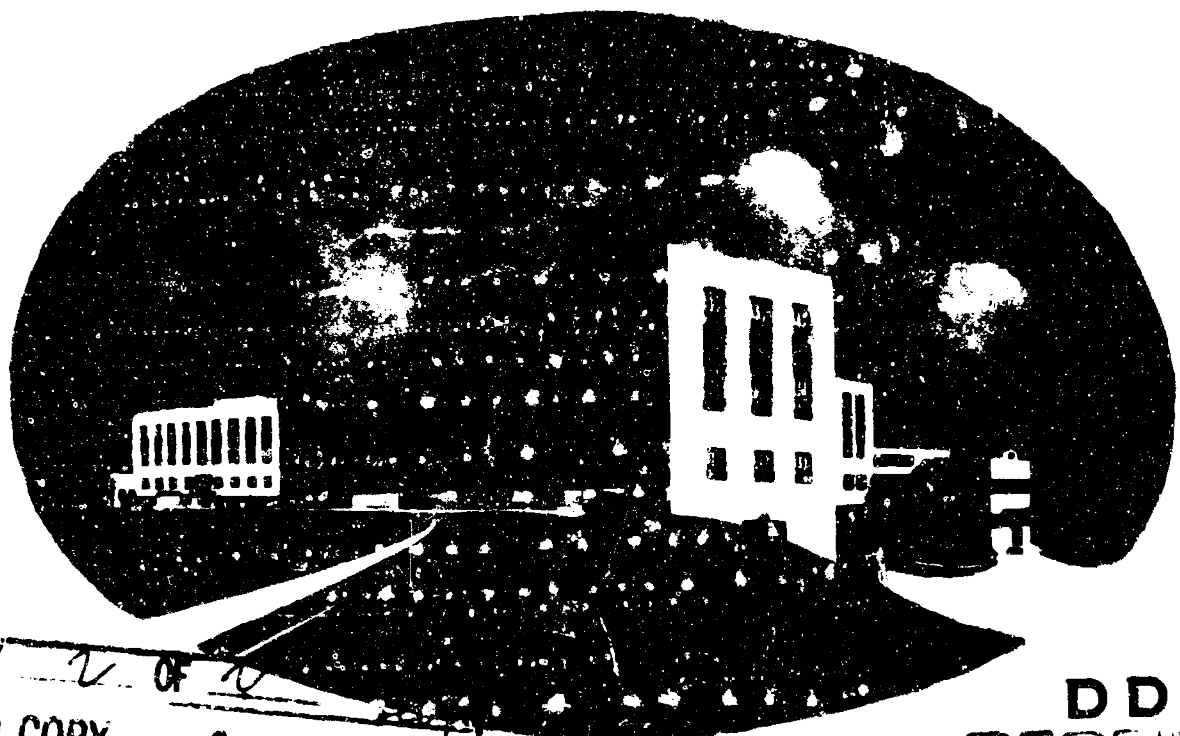

A REVIEW OF CURRENT CONCEPTS AND PRACTICES USED TO CONTROL BODY HEAT LOSS DURING WATER IMMERSION

RESEARCH REPORT

MR 005.13-4001.06 Report No. 3

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Presented to the: Aerospace Medical Panel
Fourteenth General Assembly of Advisory
Group for Aeronautical Research and
Development.

Lisbon, Portugal 12 September 1964

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NAVAL MEDICAL RESEARCH INSTITUTE
Bethesda, Maryland

From Bureau of Medicine and Surgery, Navy Department, Research Task No. MR005.13 - 4001.06. The opinions or assertions expressed herein are the private ones of the author and are not to be construed as official or reflecting the views of the Navy Department or the Naval service at large.

ABSTRACT

The problem of providing adequate clothing for personnel who either during normal operations or accidently are immersed in cold water has continued to challange clothing manufacturers. In the past decade the development of foamed plastics and other clothing materials has offered new possibilities. Likewise advances in energy conversion and storage systems offer new solutions to this critical operational problem.

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

A REVIEW OF CURRENT CONCEPTS AND PRACTICES USED TO CONTROL BODY HEAT LOSS DURING WATER IMMERSION

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Immersion in cold water is one of the most severe stresses which the military man may be forced to endure. To the naval aviator, it is a daily threat; to the Air Force pilot, a possible misfortune; and, to the underwater swimmer or reconnaissance team member, it is a way of life. Even daily immersion in cold water makes the experience no less unpleasant, and does little to change the rate at which heat is lost to the cold water.

If the unprotected human body is immersed in water at a temperature even as high as 30°C, a significant gradient of heat flow out of the body is established. Conductive heat loss from the immersed nude body occurs at all water temperatures below body temperature. When the temperature difference between the body and the water amounts to 15°C, body heat loss threatens life within a day. At temperature differences greater than this, failure of body thermal balance may become critical in a matter of hours or even minutes if the immersion is in freezing sea water.

The effects of body heat loss vary considerably throughout the animal kingdom. Man is particularly sensitive to decrease in body temperature. Although the deep body temperature at which given central nervous system changes occur varies with different individuals, McQueen,[1] on the basis of clinical experience in producing hypothermic anesthesia, found that when the core temperature decreased to 34°C, amnesia occurred for the period of cooling below that temperature. Below this temperature, the patients became dysarthric, and began to loose contact with their surroundings. Pain was generally appreciated down to about 30°C when the ability to recognize relatives or surroundings was also lost. Voluntary motion was lost at 27°C, as were pupillary light reflexes, deep tendon and skin reflexes. Virtue[2] 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.

Despite the serious effects of whole body hypothermia, the regional heat losses from the fingers, hands, and arms have been found to be the limiting factors in the effectiveness of many garments for protection against cooling during immersion. Provins and Clarke [3] demonstrated that as the fingers, hands, and arms cooled below 15.5°C, their subjects developed an increased reaction time, a decrease in tracking proficiency, 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 at 10°C, unprotected subjects demonstrated a decrease in grip strength down to 50% after one hour of immersion.

Because of the severe physiological effects of hypothermia, any situation, accidental or otherwise, in which personnel are immersed in cold water necessitates that some provision be made for controlling the body heat loss. Factors which can be used to limit the heat loss are:

(1) Controlling the duration of the period of immersion.

(2) Utilizing the body's own thermal protective mechanisms to maximum advantage.

(3) Use of adequate external body insulation to limit heat loss.

(4) Use of supplementary body heating to replace the heat loss.

Limiting the time of immersion is completely effective at all ranges of water temperature below body temperature. Immersion of an unprotected subject in freezing water is an excruciatingly painful but survivable experience and could even be regarded as pleasurable if judged by the widening popularity of Sauna baths. Military salvage divers must work in freezing water, but protect themsleves against critical cooling by limiting the period of submergence. Underwater demolition teams and reconnaissance teams cannot control the duration of their immersion during operations and thus become completely ineffective if their mission requires activities in water at low temperatures. The unfortunate "ditched" aviator must survive in the cold water until rescued. Obviously, protecting military personnel against the effects of cold water immersion by trying to control the duration of exposure has little operational value.

The need to utilize the body's own protective mechanisms to the maximum is a sine qua non. Enhancement of the body's tolerance to cold water immersion by training or conditioning is possible but has limited value. Admittedly, some long distance swimmers are capable of enduring prolonged immersion in cold water. They protect themselves against rapid heat loss to the water thickness of their subcutaneous fat layer and by training so as to be able to swim for long periods with a very high metabolic heat output. Carlson et al[(4)] studied one such swimmer who was able to swim for 14 hours in 4 - 8°C water. He had a body fat content of 33 percent and swam at a work rate of 550 Kcal/hr. Pugh and Edholm[(5)] studied English Channel swimmers and observed that they also utilized the same technique of increasing their subcutaneous fat to limit the rate of heat loss and then swimming vigorously to generate large amounts of heat by muscular work. The practice of developing a thick layer of body fat for thermal insulation is not, however, consistent with present concepts for limiting the occurrence of bends among aviators and divers. Training to improve the physical work capacity is possible, 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 military duty.

Only the last two of the thermal loss factors would seem to be useful 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 garments might be available. In addition, the newer technologies of direct energy conversion systems, 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 now be possible to maintain immersed personnel in thermal balance even in freezing water.

It would seem timely, therefore, to: (1) review the problem of heat loss and thermal balance during voluntary and involuntary immersion; (2) define the physical and physiological limitations of thermal balance during immersion; (3) evaluate the advances in insulation and heat replacement methods which would be useful in maintaining the thermal balance of immersed military personnel; and, (4) obtain a realistic understanding of what future developments should be undertaken in support of the serviceman who must be immersed in cold water.

In order to define a thermal protective system, it is necessary first to define the limits within which the protective system is expected to function. For immersion in cold water, the immersion problems of the downed aviator differ somewhat from those of the immersed reconnaissance team member and underwater swimmer. Their basic problems, however, remain the same, and only the duration of their immersions may be different. To the downed aviator, the period of immersion prior to rescue may last from 1 to even 36 hours in water at temperatures which may vary from that of freezing salt water, (-2°C) to that of the warm water of the Persian Gulf where the water in summer warms to 32°C. To the underwater swimmer or reconnaissance team member, the water temperatures in which he must operate may likewise vary from that of freezing sea water upwards to a comfort range of 32°C. The duration of his immersion may not be as long, but must be planned for 8 - 12 hours of immersion. Consequently, from the point of view of either a survival or a protective, thermobalance system, it is appropriate to consider an immersion of 12 - 24 hours in waters varying in temperature from -2°C to 30°C.

Before contemplating methods of preventing and replacing heat loss, it is first necessary to evaluate the ability of the body to protect itself. The ability of the human body to withstand immersion in cold water is limited by the duration of the exposure as well as the temperature of the water. The insulative value of the human tissue is also a significant factor. The insulation of the body may be described as both active and inactive. The active part of the body insulation is that part of the body tissue which becomes insulative as a result of severe peripheral vasoconstriction of blood vessels such as those in the skin. The inactive insulation is that of the relatively avascular subcutaneous fat. The thickness of the insulative layer, therefore, may be defined as being equal to that of the relatively inactive fat layer plus the thickness of the active insulative layer, which is produced by vasoconstriction of the peripheral vessels causing a relatively avascular layer of tissue about the body. Although many studies have been made to define the insulative value of these layers, it seems appropriate, for the purpose of this review to consider the thermal conductance of the external part of the body as being approximately equal to an equal thickness of natural rubber. This concept is substantiated by reference to the thermal conductivity chart, Table 3 Ref. 6.

TABLE I - Thermal Conductivity taken from proceedings of the second symposium on underwater physiology, Ref. 6.

	Thermal Conductivity ($Kcal/m^2/hr/deg\ C^o$)
Body surface* (rest, cold, not shivering)	9
Body surface, (rest, cold shivering)	13
Body surface, (Warm, exercising)	50
Water	53 For one cm. thickness
Still air	2.3 " " " "
Wool Clothing (normal)	8 " " " "
Wool Clothing (maximum)	3.4 " " " "
Foamed neoprene**	4.6 " " " "
Solid neoprene or rubber	16 " " " "
Rubber impregnated cloth	16 " " " "
Fat (in vitro)	14.4 " " " "
Muscle, wet (in vitro)	39.6 " " " "

* Area of normal body

** Calculated on basis of additive conductivity of neoprene and nitrogen gas. Density of neoprene taken as $1/8\ gm/cm^3$. 0.156 normal density.

In this Table, various materials are compared with respect to their thermal conductivity rather than their insulative value. It is important, therefore, to remember that the insulative value, Ki, is the reciprocal of the thermal conductivity described in $Kcal/m^2/hr/^oC$. It should be noted here that the thermal conductivity of solid neoprene rubber is 16 $Kcal/m^2/hr/1^oC$, with a thickness of the material of 1 cm. Foamed neoprene is seen to have approximately one-fourth of this thermal conductivity. The thermal conductivity of the surface of the body is seen in the upper three lines under three conditions of the body surface: (1) when the body is at rest, cold, and not shivering, the thermal conductivity is 9 $Kcal/m^2/hr/1^oC$; (2) when the body is at rest, cold, but shivering, the thermal conductivity is increased by 4 Kcal; (3) when the body is warm and exercising, the thermal conductivity of the skin is 50 $Kcal/m^2/hr/^oC$. The lower two values in Table I show the thermal conductivity of fresh human tissue. Measurements made on excised fat tissue showed that the thermal conductivity of fatty tissue 1 cm. in thickness was equal to 14.4 $Kcal/m^2/hr/^oC$. This value is significantly less than that of muscle, which had a thermal conductivity of 39.6 $Kcal/m^2/hr/^oC/cm$ thickness. The thermal conductivity of the skin and subcutaneous tissues of the human body have also been described as varying from 2.2 $Kcal/m^2/hr/^oC$ for an obese human resting in 36°C water; and, (4) between these two values, there are determinations on both obese and thin subjects resting in cold and warm water and at various degrees of activity. These extremes in insulative values reflect the skinfold thickness, the depth of chilling and the degree of vasoconstriction due to the cold stimulus. It is, therefore, only proper to make estimates of effective thermal insulation of the human surface tissue based upon measurements of the thermal loss through that tissue under ths specific conditions being considered.

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 the body immersed in cold water is based upon both active and passive thermogenesis. Passive thermogenesis may be described as the sum of the heat output due to involuntary shivering, to the non-shivering thermogeneis subsequent to a cold stimulus and to the heat output of basal metabolism. The oxygen consumption rate of nude subjects immersed in 10°C water varied from 2.2 times their resting metabolic rate up to a maximum of 9 times their resting rate.[6] Active thermogenesis, which may be described as the active or voluntary muscular work, is likewise varied, depending upon the muscular ability and fitness of the individual. The energy requirements of various physical activities have been enumerated by Morehouse and Miller.[7]

TABLE II - Energy Required by 70 Kgm Man for Various Physical Activities. (From Physiology of Exercise, Morehouse and Miller)[7]

Activity	Energy Expended Kcal/hr
Sitting	100
Walking 2 MPH	170
Swimming, Breast Stroke 1 MPH	410
Swimming, Crawl Stroke 1 MPH	420
Swimming, Breast Stroke 1.6 MPH	490
Swimming, Crawl Stroke 1.6 MPH	700
Swimming, Crawl Stroke 2.2 MPH	1600
Swimming, Breast Stroke 2.2 MPH	1850

In this data taken primarily from studies at the Harvard Fatigue Laboratory, it would seem that the energy expenditure and consequently the heat production of exercise would be most useful in maintaining body heat in cold water. However, Morehouse and Miller[8] further point out that work which results in an energy expenditure of over 700 Kcal/hr. cannot be continued for much longer than one hour by the average man.

Trained frogmen while swimming are expected to maintain a work rate of only 200 Kcal/m^2/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[9] expended 135-140 Kcal/m^2/hr or 256-266 Kcal/hr while swimming with swim fins at a speed of 1.1 MPH during a 5 hour underwater swim. Beckman and Reeves [10] studied the physiological effects of immersion of nude subjects in 24°C water for 12 hours and found that although the experiment on only 2 of 24 subjects had to be terminated because of a decrease in core temperature to less than 35°C, 16 subjects failed to complete the immersion period because of severe muscle cramps and other effects attributable to physical exhaustion. Their subjects consumed a mean value of 90 Kcal/m^2/hr or 160 Kcal/hr by shivering, passive thermogenesis, and light exercise which was sustained for a mean immersion period of 8.5 hours. Thus, it would seem that the capacity for heat generation in these subjects was limited to a mean value of 160 Kcal/hr for 8.5 hours or 1,280 Kcal while exercising and while immersed in cold water.

Beckman and Reeves[10] also calculated the rates of heat loss for their subjects and related these rates to the specific gravities of their subjects. The rates of heat loss in Figure 1 can be seen to vary from 60-180 Kcal/m^2/hr for subjects immersed in 24°C water. The subjects who were forced to limit the duration of their immersion because of severe body heat loss are represented by the upper two dots on the graph. The subjects who were able to endure the longest period of immersion are represented by the dots nearest the intersection of the ordinate and the abscissa. It would appear from this graph that the ability to endure long periods of immersion could be related to a low, body specific gravity. Since body specific gravity is inversely related to body fat content and, therefore,

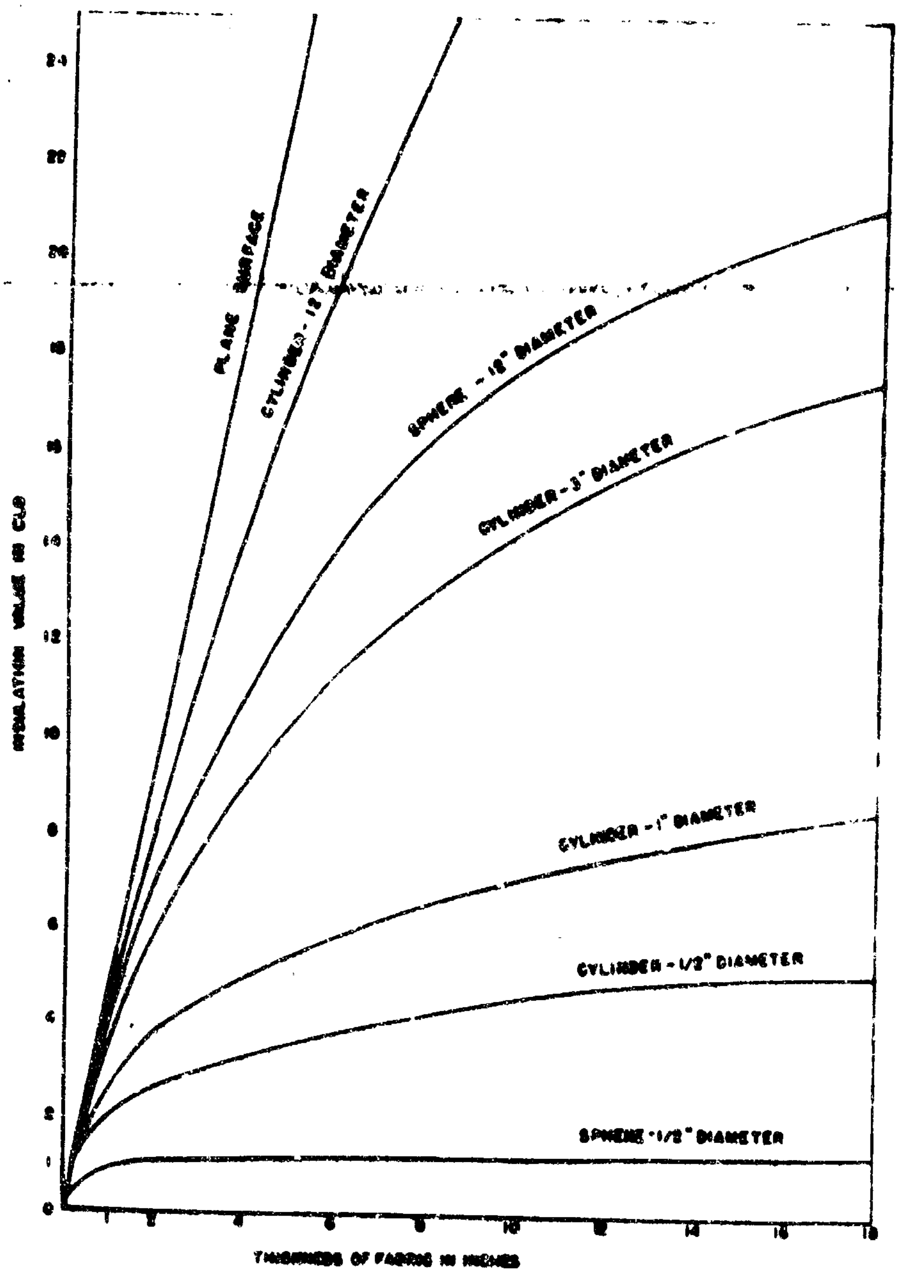

Fig. 74. Insulation of ideal fabric on a plane, cylinders, and spheres.

FIGURE I

to body insulation, it is apparent that the ability to endure cold water immersion is related to body fat content and the amount of body thermal insulation. Only six of these subjects could generate sufficient heat from exercise and passive thermogenesis to maintain their body temperature for 12 hours.

From the foregoing, it can be seen that both the insulation of the skin of the body and the heat production of the body vary many-fold within the individual and between individuals. It, therefore, would seem futile to depend upon these variable values for protection against thermal heat loss during immersion. It would be more appropriate to consider the use of external insulative systems to control the loss of the heat which is produced by the body. The value of any insulative system depends upon: (1) the heat output of the body; (2) the temperature difference between the body surface and the surrounding water; (3) the insulative value of the external insulation plus the insulation of the body surface; and, (4) the geometry of the body to be insulated. It has been pointed out in the previous paragraph that the ability of the body to generate a significant duration is limited. The maximum temperature difference at which the survival insulative system must be effective may be defined as that temperature which would exist between the temperature of freezing sea water (-2°C) and the temperature of the thermally sensitive, deep tissues of the body, i. e., brain, heart, liver, adrenals, etc. The thermal insulation provided by the tissue of the body surface (skin, subcutaneous and adipose tissues) must maintain the thermal gradient between the body core temperature and that of the skin surface. In order to maintain thermal comfort, the mean skin temperature of the body should be maintained at above 28°C. The external insulative garment must then provide sufficient insulation to maintain a temperature gradient between the skin surface at 28°C and the water at -2°C.

In general, the insulative effectiveness of a substance has been compared to that of an equal thickness of uncompressed wool. A vacuum layer, or a still air layer would provide better thermal insulation, but these layers are difficult to provide in flexible garments. Consequently, something less than ideal must be accepted. The optimal clothing material, represented by uncompressed wool or by foamed neoprene provides approximately 1.6 CLO* [11] of insulation/1 cm thickness, or 4 CLO/inch.

During World War II, considerable effort was expended in investigation of the problems of clothing for Arctic based troops.[12] It was found that clothing with a thermal insulation of 4 CLO was necessary for protection but weighed 20-30 pounds. Even this thickness of heavy clothing did not provide adequate protection for the hands and feet in Arctic winters.

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.[13]

Insulative values of materials are normally described in terms of flat surface insulation. Although the insulative value of an insulator on a flat surface is directly related to its thickness, this does not pertain to insulators 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 around a 1/2 inch sphere is linearly increased, the

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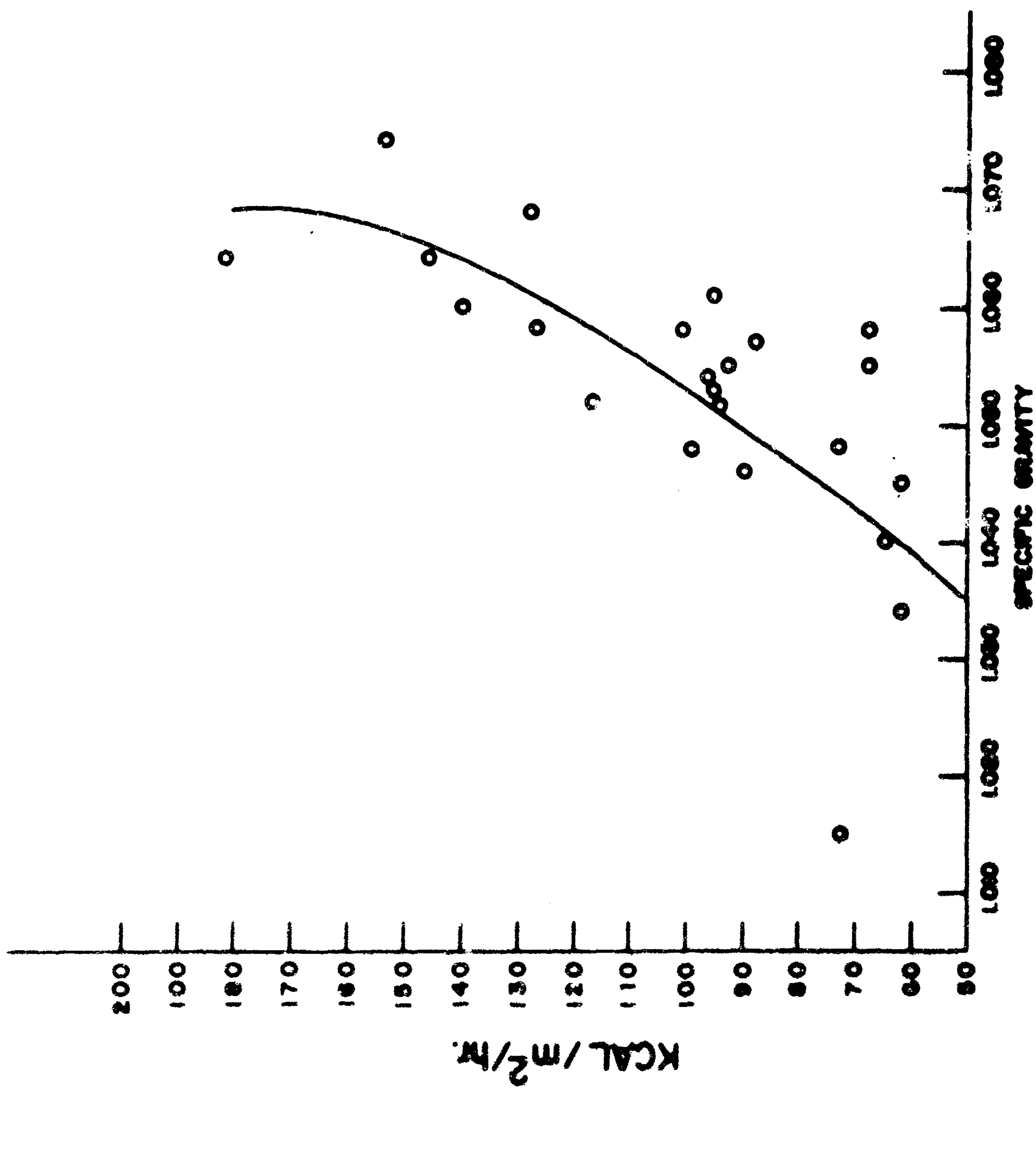
*CLO: The CLO is an arbitrary unit of insulation and is the amount of insulation necessary to maintain comfort and a mean skin temperature of 33.3°C in a room at 21°C with an air movement not over 10 ft/min., humidity not over 50%, and a body metabolism of 50 Kcal/m^2/hr. On the assumption that 76% of 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/m^2/hr with a temperature gradient of 0.18°C between the two surfaces.[11]

FIGURE 2



RELATIONSHIP OF RATE OF HEAT LOSS VS. BODY SPECIFIC GRAVITY IN 23 NUDE SUBJECTS IMMERSED TO NECK LEVEL IN 75° F. WATER.

insulative value increases only slightly and there is no significant increase in insulative value above a fabric thickness of 1 inch. The insulative effect of increasing the thickness of the insulative fabric around a 1/2 inch diameter cylinder is only slightly better than on a sphere. This figure illustrates why it is difficult, if not impossible, to provide 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 forms of gloves for the fingers and hands in extremely cold Arctic weather. For this reason, mittens have been devised so that the fingers and hands may be made into a large ball so as to improve their geometric shape.

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. Divers who work in the "standard" hard hat diving costume have been unable to solve the insulation problem after 100 years of diving. 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, the dry suit is almost impossible to achieve in practice. When waterproof suits for immersion protection of Navy fliers were developed after World War II, they were bulky, hot, humid, and unpopular, but effective. The insulative value of these garments could be easily varied by varying the thickness of the insulative layer worn beneath the suit. The most serious disadvantage of this type of garment is that if it is torn or leaks because of fabric age or wear it has no insulative value whatsoever.

During World War II, C. R. Spealman of the Naval Medical Research

Institute, developed the concept of using "sponge" neoprene for an insulative, water-proof boot.[14] The insulative value of such boots were established by laboratory experiments and recommended for use in preventing the "immersion foot" of immersed shipwrecked survivors. The most significant advance in thermal insulative garments for immersed personnel was achieved in 1951 when Dr. Hugh Bradner[15] reported on his experiments with unicellular foamed neoprene garments for thermal insulation of immersed subjects and recommended the use of tailored suits of unicellular foamed neoprene for underwater swimmers Since then, such unicellular 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. Since these unicellular foams are compressed under pressure, their insulative effectiveness is decreased to approximately that of the solid neoprene at depths greater than 50 feet of 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 neoprene foamed suit for thermal insulation protection for downed aviators. In general, it may be said that subjects immersed to neck level in 10°C water and wearing 3/16 inch neoprene foamed trousers, 1/4 inch jacket, and 3/16 inch boots and gloves, were able to tolerate the immersion for approximately 4 hours at which time their great toe temperatures had decreased to close to water temperature. When the subjects were exposed to 4.4°C water, they in general were 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 fingers of the hands with subsequent pain and temperature decrease down to 7-8°C limited the exposure times in most of these experiments. In only a few subjects did the decrease in body core temperature to critical levels (35°C) occur before the extremities cooled to the critical level of 8°C.

The theorectical flat surface thermal insulation of unicellular foamed neoprene is 1 CLO for 1/4" thickness of fabric. Experiments on the effective insulation of a 1/4" foamed neoprene "wetsuit" worn on an electrically heated manikin(16) in stirred water determined that the effective thermal insulation of such a suit was 0.77 CLO*.

Theoretically, a 1 inch thick boot and glove and once inch thick suit of foamed neoprene would be adequate to protect the immersed survivor, swimmer, or diver, indefinitely in 0°C water. However, when subjects were equipped with 1 inch thick insulative unicellular foamed neoprene suit, boots and mittens, it was found that subjects increased their voluntary immersion time to 5 hours in the water at the temperature of 4.4°C. Although the resulting 3.5 CLO garment was so bulky as to severely restrict the motion of the subject, heat loss from the hands and feet was again the limiting factor. The toe and heel temperatures reached 10°C in some cases. These findings indicate that the concept of increasing the insulation of foamed neoprene suiting to decrease the heat loss of immersed personnel is limited by the geometry of the hands and feet in the same way that the insulative effectiveness of Arctic clothing is limited by the hands and feet.

Therefore, it becomes necessary to consider some method of replacing heat in order to provide thermal stability to the subjects immersed in cold

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*Carried out at the U.S.A. Quartermaster Climatic Research Lab., Natick Mass.

water. It is obviously not practical to rely solely only 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. Since the advent of the space era, there has been an ever-increasing need for more efficient power conversion systems fo. 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 a much more useful power:weight ratio, to the point that these systems now may be considered for use as a primary power source for personnel replacement heating systems.

Energy conversion systems can be compared on the basis of several important factors, i. e., theoretical energy/weight ratio, system energy/weight ratio, system power/weight ratio, shelf life, cost in terms of power delivered, 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 use. Thus, both a useful energy conversion system and a useful energy distribution system which can be used together are required to meet the needs of replacement 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-wire so that area heating can readily be controlled. The resistance-wired 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, Arctic troops have used electrically heated gloves and boots, but the battery packs are so heavy (20-30 lbs.) that their popularity is limited.

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 with the synthetic fiber threads into a stretchable garment. Figure 3 shows a glove woven with the white insulation of the wires showing in the fabric. Gloves, socks and a coverall type garment were developed by the R.A.F. for supplying heat to aircrew of inadequately heated aircraft. These same types of garments when constructed with waterproofing techniques could be used to provide supplemental heat to underwater swimmers or aircrew of ditched aircraft. Inactive subjects wearing such a garment under a 1/4" underwater swimmer's wetsuit in tests at the Naval Medical Research Institute required approximately 320-340 watts to maintain a comfortable body temperature in 5°C water. On the basis of the previously described experiments on the use of 1 inch unicellular foamed neoprene suit, it would seem that supplemental heat supplied only to the feet and hands would

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*Vacuum Reflex Limited, 2 C Hanbury Road, Tottenham, London, N. 17, England.

FIGURE 3 Resistance wire heating glove with waterproof connector

significantly increase the tolerance time to immersion. On the basis of the calculations described above and the basis of the experiments, it seems probable that the thick foamed neoprene suit with the 4 CLO thick foamed neoprene boots and gloves could be successfully incorporated with resistance-wire woven boots and gloves and a subsidiary battery power source to provide comfort and wearability to a suit which would protect the immersed victim in waters at a temperature of freezing sea water for a period of 12 hours or more.

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 so that power supplies for supplemental heating are now available. The increase in the energy/weight ratio of both silver-zinc and silver-cadmium batteries makes both battery types useful. Silver zinc batteries provide from 40-80 watt hours per pound, whereas the silver cadmium batteries provide 30-60 watt hours per pound. These batteries may be either primary or secondary (i. e., rechargeable). The cycle life varies from 10-30 cycles for silver zinc up to the order of 300-1,000 cycles for silver cadmium. The cost of these batteries is likewise high, i. e., approximately $1/w-hr. for silver zinc and $1.3/w-hr. for silver cadmium. For underwater swimming in cold water, the use of the buoyant wetsuit requires the use of weights of 25-30 lbs. This weight of silver zinc batteries would provide 350 watts for 3 hours. 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 66 watts of heat for 3 hours at a battery weight of 4.8 lbs. for heating boots and gloves. The electric resistance wire-battery system at present is a workable system and offers the greatest advantages, i. e., variable heat control, both as to amount and area supplied, a repeated on/off cycle, and an evenly distributed supply of heat. Its greatest disadvantage remains the weight of the energy source.

In addition to the resistance wire heating system, used with high power density batteries, recent advances in thermionics, thermoelectric generators, catalytic fuel cells and exothermic chemical reactions offer a wide range of selection for heat generation which may be of value for replacement heating to the immersed aviator or underwater swimmer.

The isotope power generators provide the highest power to weight ratio of any system. Polonium-210 has the power density of 140 thermal watts/gm, and Strontium-90, 0.9 watts/gm. If the fuel alone was considered, it would only require 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. It costs about $25 per watt, and also has decay emissions which make shielding a problem. Strontium-90 has a longer half-life (28 yrs). The weight of fuel to provide 350 watts would be only 470 gms., or slightly more than a pound. Strontium-90 is primarily a beta emitter but also emits troublesome, gamma rays which require heavy shielding. A comparative tabulation of the various isotopic power generators is shown in Table III.[17] When the calculation of power density includes the weight of the shielding, these isotopic power units are seen to be less desirable.

Heating systems employing the flameless surface combustion of hydrocarbons in the presence of specific catalysts are also efficient. Hand warmers for hunters are of this type and are marketed*. The temperature of the

*Therm-X and Whamo

TABLE III. Radioisotopes for Thermal Power Sources from "Power from Isotopes" (Ref. 17)

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	0.26	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

combustion varies from 316°C upward which would be dangerous for body heating in a survival situation.

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

$$NaAlH_4 + 2\,H_2O \longrightarrow NaAlO_2 + 4\,H_2 \uparrow$$

Since both air and water are available in excess in a surface survival

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Ethyl Corporation Research Lab., Detroit, Michigan situation, this chemical reaction has bertain advantages. However, the mixture of oxygen and hydrogen must be carefully controlled to limit the O_2/H_2 ratio to more than 20/1 by volume to prevent the mixture from being explosive. The practical efficiency 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 copper also gives a relatively high energy:weight ratio, likewise, in the order of 300 watt hours per pound, (.8WH/gm). Such a heating unit would have an indefinite shelf life and would cost relatively little, something in the order of 10¢ per w/hr. 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. This reaction, however, could not be used to heat the body directly. Similar exothermic chemical reactions could likewise be used, such as the heat generation provided by the hydrolysis of sodium. A summary of the various thermal energy generation systems is assembled in Table IV. 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. Air ventilated suits are not feasible for immersed personnel. The electric resistance-wire distribution system has obvious advantages which explains its long popularity. However,

*Aerospace Crew Equipment Laboratory, Naval Air Engineering Center, Phila., Pa.

recent developments of a liquid distribution system along the lines recommended by Siple [18] 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 liquid) to distribute heat to or transfer heat from the various areas of the body as required. In the model under development for NASA (Figures 4 and 5), thin (2mm) plastic water pipes are incorporated into Brynje type undergarments so as to have heating and cooling tubes covering the skin about 2 cm apart. [19,20,21] 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 jumping the heated water over the trunk first and then to the extremities. Dr. John Billingham, of NASA, 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. This suit uses a miniature electric pump which, with its battery and gearbox, weighs only 340 gms. The previously described thermal generators could be readily adapted to heat exchangers for use with this garment.

The water conditioned suit holds considerable promise for use not only for cooling astronauts but for supplying heat to immersed 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 in terms of power/weight ratio only supply heat. The chemical heating system has a high efficiency and would provide an excellent heat exchanger for use with the water conditioned suit.

POWER SYSTEM	REACTANTS	PRODUCTS	THEORETICAL POWER OR ENERGY DENSITY	DURATION OF POWER CYCLE	ESTIMATED WT OF 300W POWER UNIT IN KG.	STAGE OF DEVELOPMENT	ESTIMATED COST OF POWER UNIT IN $ (EXCLUDING DEVELOPMENT COSTS)
Primary Battery	$AgCl_2$+ Seawater	Electricity	.1-.2 Wh/gm	3-9 hrs.	4.0	Evaluation	$ 500.00
Secondary Battery	Silver Zinc	"	.1-.2 Wh/gm	3-9 hrs.	3.5	"	450.00
	Silver-Cadmium	"	.08-.16 Wh/gm	2-6 hrs.	5.0	"	600.00
Radio Isotope	Cesium-137	Heat	.26 W/gm	30 yrs.	20.	Research	20,000.00
"	Promethium-147	"	.36 W/gm	2.5 yrs.	15.	"	50,000.00
"	Plutonium-238	"	.55 W/gm	89 yrs.	5.0	Development	Astronomical
"	Strontium-90	"	.93 W/gm	28 yrs.	100.	Research	70,000.00
"	Curium-242	"	121.0 W/gm	0.4 yrs.	100.	"	30,000.00
"	Polonium-210	"	141.0 W/gm	0.4 yrs.	15.	"	20,000.00
Thermo-Chemical	$Mg+H_2O \rightarrow M_gO + H_2$	"	2.7 Wh/gm	3-4 hrs.	1.0	Development	10.00
Fuel Cell	$2H_2+O_2 \rightarrow H_2O$ H $NaALH2+2H20 \rightarrow NaALO_2 + 4H_2$	"	4.7 Wh/gm	3-4 hrs.	4.0	"	25.00

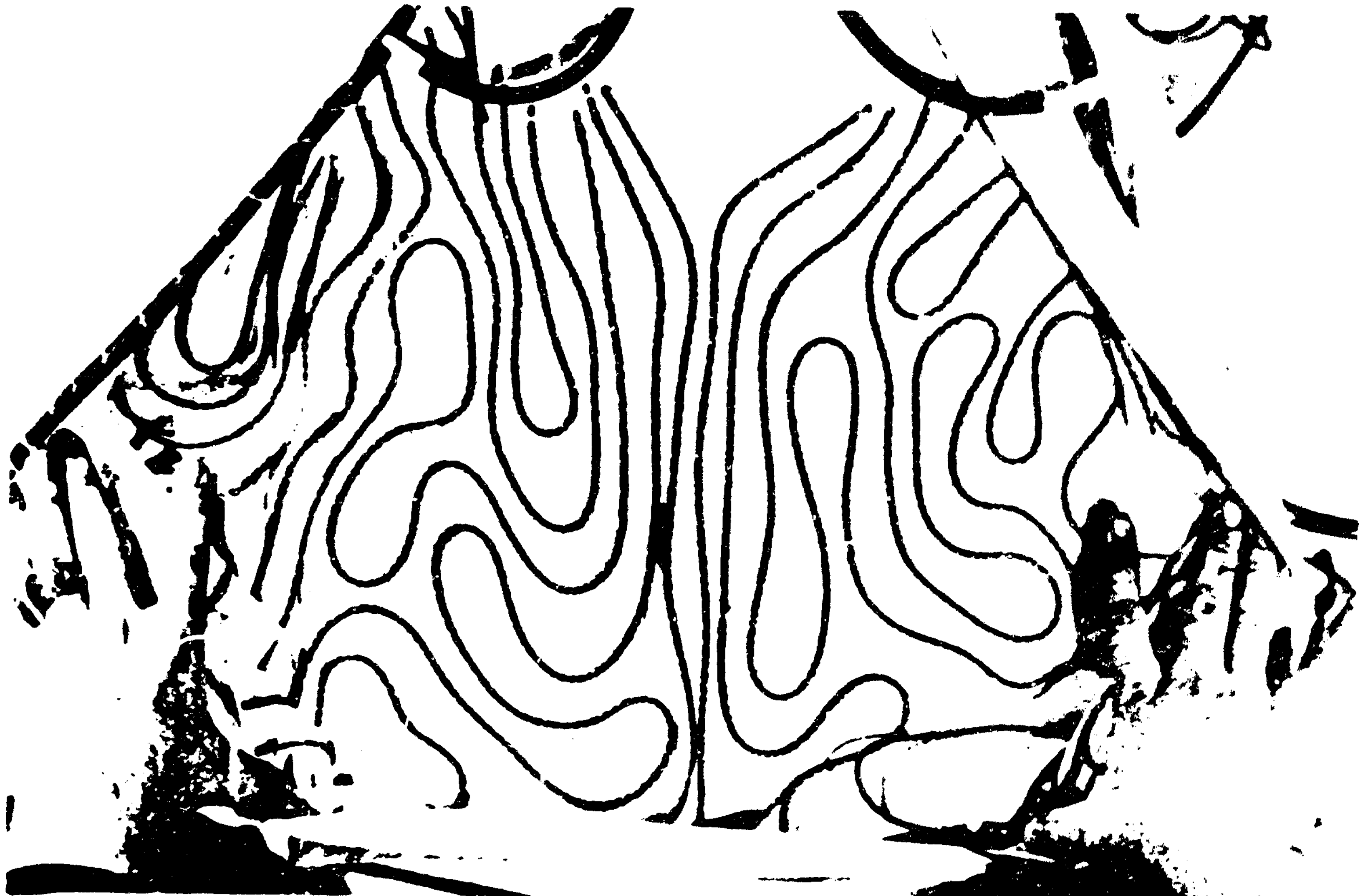
COMPARISON OF VARIOUS HEAT GENERATING SYSTEMS

TABLE IV

FIGURE 4

WATER COOLED GARMENT—An experimental garmet designed to cool space-suit-clad astronauts by water-filled tubes sewn to its fabric has been delivered to the Crew Systems Division here at the Manned Spacecraft Center for evaluation. The garment which promises to allow astronauts to work harder and perform more tasks that originally expected, is being developed by the Hamilton Standard division of United Aircraft Corporation.

SPACE NEWS ROUNDUP PAGE 6 AUGUST 5, 1964



PLASTIC WATER PIPES, sewn into the material of the long underwear and worn next to the skin, will keep space travelers cool as cold water is circulated through the pipes.

SPACE NEWS ROUNDUP JUNE 24, 1964 PAGE 7

FIGURE 5

The isotopic power conversion units would likewise be adaptable to this system.

It would, therefore, seem probable that future developments in protective garments for personnel who may be immersed in cold water will be toward incorporating the unicellular neoprene foamed wetsuit with a supplemental heating system. 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. A waterproof, supplementary electric resistance-wire heating system consisting of boots and gloves and powered by a silver chloride-magnesium sea water cell battery pack will provide adequate protection for an operational immersion of useful duration when used for extremity heating under the foamed suit or an equivalent dry type immersion suit.

For future developments, it would seem most promising to exploit the water conditioned suit for use beneath the unicellular foamed outer garment. The development of isotopic thermal cells 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 find use by aircrew, divers, underwater swimmers, reconnaissance teams and even the Army Corp of Engineers.

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