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**HEAT PRODUCTION AND OPTIMAL COOLING
FOR NAVY SPECIAL WARFARE DIVERS**

M. B. Beckett

J. A. Hodgdon

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NAVAL HEALTH RESEARCH CENTER
P.O. BOX 85122
SAN DIEGO, CALIFORNIA 92186-5122

NAVAL MEDICAL RESEARCH AND DEVELOPMENT COMMAND
BETHESDA, MARYLAND



Heat Production and Optimal Cooling for Navy Special Warfare Divers*

M. B. Beckett, M.A.

J. A. Hodgdon, Ph.D.

**Naval Health Research Center
P.O. Box 85122
San Diego, CA 92186-5122**

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Summary

Navy Special Warfare divers wearing insulated dry suits designed to keep them warm at rest in cold water may overheat during subsequent swimming. Naval Coastal Systems Center is developing a dry suit with variable heat transfer properties that would extend the range of diver activities that can be carried out in thermal comfort. The Naval Health Research Center has been tasked to assist in this effort by providing the human thermal data necessary for the design and construction of such a suit. This report is the product of the first phase of our investigation and it comprises a review of the scientific literature regarding 1) energy expenditure and heat production during underwater fin swimming; and 2) optimal body sites for cooling Navy Special Warfare divers.

In previous studies, divers fin swimming at paces sustainable for at least 20 min showed oxygen consumption rates ($\dot{V}O_2$) ranging from 1.25 to 2.3 l/min. During rapid swimming sustainable for 10 min, a $\dot{V}O_2$ of 3.1 l/min has been reported. The heat produced by these divers (estimated from $\dot{V}O_2$) ranged from 400 to 736 W for the longer duration swims (≥ 20 min) and up to 992 W during the 10-min swim.

Review of the literature regarding cooling of the human body revealed that the head, neck, and areas overlying active muscles are the body regions that can provide the greatest heat removal per skin surface area. Cooling the head has the added benefit of greatly enhancing thermal comfort. Areas providing lesser heat removal per skin surface area, such as the chest, abdomen and back, can still be quite effective for removal of excess body heat because of their large total surface area. Whole body liquid cooling garments are capable of removing 465 to 558 W of metabolic heat produced during sustained energy expenditure rates of 500 to 600 kcal/hr, respectively.

Based on the estimated heat production of fin swimming divers and the review of the body cooling literature, recommendations for optimal cooling sites on the diver were made. The diver will need to be cooled over a large portion of his body area in order to maintain thermal balance. Body regions overlying active muscle (i.e., the thighs, legs, and buttocks) should receive the highest priority for cooling. The head and neck should also be considered high priority areas for

cooling. Although the chest, abdomen, and back are areas of lower priority, the magnitude of metabolic heat generated will probably require some cooling at these sites. The lowest priority is given to cooling the arms.

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Introduction

Navy Special Warfare missions require divers to remain in a seated position for several hours in water of temperatures less than 5°C. Following this inactive period, the divers may be required to swim some distance to carry out their mission. The problem associated with such mission profiles is that the diver will overheat during the swimming portion of the mission if he wears a dry suit and undergarments of sufficient insulation to maintain body core temperature during the inactive portion of the mission. Conversely, if insulation is low enough to allow thermal comfort during swimming, it will not provide sufficient thermal protection for the diver during the inactive transit.

One approach to solving this problem is to design a suit with variable heat transfer properties. The incorporation of liquid crystals in the material of a dry suit has been proposed as a method of achieving this goal. The crystals vary their heat transfer properties as a function of the magnitude of an electric current passed through them. If such a suit can be constructed, it will extend the range of activities which can be carried out by Navy Special Warfare divers.

Naval Coastal Systems Center is considering the construction of such suits, and has tasked the Naval Health Research Center to assist by providing human thermal data necessary for the design and construction of the suit. This report is the product of the first phase of our investigation. An extensive review of the scientific literature was conducted to investigate 1) energy expenditure and heat production during underwater fin swimming; and 2) optimal body sites for cooling Navy Special Warfare divers. This report contains a summary of the pertinent literature and recommendations based on this information.

Energy Expenditure and Heat Production During Underwater Fin Swimming

Measurement of oxygen consumption ($\dot{V}O_2$) during underwater fin swimming has been carried out by only a few investigators (Donald & Davidson, 1954; Goff et al., 1956; Hunt et al., 1964; Lanphier, 1954; Morrison, 1973; Sterba, 1990; Titcombe, 1973). Pertinent information and results from these seven studies are presented in Table 1. Conditions such as type of diving suit worn, breathing apparatus used, and swimming speed and intensity are variable across the studies. $\dot{V}O_2$ ranges from 0.93 l/min for a 27-hr swim (Hunt et al., 1964) to 3.1 l/min for a "fast" 10-min swim (Donald & Davidson, 1954). Swimming at a pace considered normal, moderate, or average for 20 min or more resulted in $\dot{V}O_2$ ranging from 1.25 to 2.3 l/min (Donald & Davidson, 1954; Sterba, 1990).

Energy expenditure values shown in Table 1 were calculated from $\dot{V}O_2$ assuming the relationship: 4.83 kcal/l O_2 (Mathews & Fox, 1976). Conversion of kcal/hr to watt was accomplished via 1.1628 watt per kcal/hr (Åstrand & Rodahl, 1977). The work efficiency of the human body swimming underwater with fins is reported to range from 1 to 8% (Goff et al., 1957; Lanphier, 1954; Specht et al., 1957). For the purposes of this report, a 5% work efficiency was assumed and heat production was estimated as 95% of total energy expenditure. Based on these calculations, fin swimmers produce 400 to 736 W of heat while swimming at sustained speeds for extended periods (≥ 20 min), and up to 992 W during short bursts (10 min) of higher speed swimming.

Table 1. Oxygen consumption, energy expenditure, and heat production during underwater fin swimming.

Study	n	Suit Type	Swimming Speed (km/hr)	Swimming Intensity	$\dot{V}O_2$ (l/min)	Energy Expenditure ^a (kcal/hr)	Heat Production (W) ^b
Sterba (1990)	8	dry	0.93	normal long-distance pace	1.25	362	421
			1.30	max. sustainable/20 min	1.86	539	627
Morrison (1973)	7	dry	--	max. sustainable/10 min	2.6	753	876
							832
Titcombe (1973)	--	--	.93	slow or light work	0.8	232	270
			1.57	average or moderate	1.4	406	472
			1.85	heavy work	1.8	522	607
			2.22	severe work	2.5	725	842
							800
Lanphier (1954)	15	none	1.67	normal long-distance pace	1.3	377	438
							416
Hunt et al. (1964)	1	wet	1.77	average pace for 27-hr continuous swim	0.93	270	313
							297
Goff et al. (1956)	27	wool	1.21 to 1.45	normal pace, sustainable for extended periods	1.3 to 1.9	377 to 551	438 to 640
							416 to 608
Donald & Davidson (1954)	11	wet	1.3 to 1.7	medium pace/20 min	2.3	667	775
			1.7 to 2.3	fast pace/10 min	3.1	898	1044
							736 to 992

^a Energy expenditure calculations: kcal/hr = $\dot{V}O_2$ (l/min) x 4.83 (kcal/l) x 60 (min/hr) (Mathevs & Fox 1976); 1 kcal/hr = 1.1628 watt (Astrand & Rodahl, 1977).

^b Heat production calculated assuming work efficiency during underwater swimming is 5% (Specht et al., 1957).

Cooling the Human Body

Heat Transfer and Effect of Local Cooling.

Heat stress is the sum of metabolic and environmental heat loads placed on the body, and heat strain is the effect on the body of the heat stress (Hales & Richards, 1987). Some indices of heat strain are body core temperature (rectal, esophageal or aural), mean skin temperature, heart rate, sweat rate, and subjective state. When the body is subjected to a heat stress, either from the environment and/or produced internally through muscle activity, mechanisms are evoked to dissipate heat and maintain thermal equilibrium (Åstrand & Rodahl, 1977). The normal pathways for heat transfer are radiation to and from the environment, convection by motion of air or water around the body, conduction by contact with a solid, and evaporation of sweat (Åstrand & Rodahl, 1977).

In the case of the diver dressed in an insulated, impermeable, dry suit, the primary avenue of heat loss will be conduction between the diver and the suit. The diver will also lose some heat through respiration. A frequently assumed value for respiratory heat loss is 8% of total metabolic heat. With exercise, this may increase to 14% (Doubt, 1991). Bradner (1985), however, speculated that respiratory heat loss in divers using a rebreathing apparatus would be minimal. Because of uncertainty about its value, respiratory heat loss will be ignored in this report.

Conduction between the diver and suit will be a function of the skin temperature (T_{sk}) and the temperature of the suit's inner surface. The greater the difference between these two temperatures, the greater the heat transfer to the suit. The temperature of the suit's inner surface is dictated by the temperature of the surrounding water and the thermal resistance of the suit. T_{sk} is a function of the skin blood flow and of the heat content of the tissues underlying the skin (Brück, 1983). Heat content of underlying tissues is determined by their blood perfusion and metabolism. Skin blood flow is regulated both locally and centrally as a function of T_{sk} and body core temperature (T_c). T_{sk} affects vascular smooth muscle directly, and T_c and T_{sk} elsewhere affect skin blood flow by reflexes operating through the sympathetic nervous system (Sawka & Wenger, 1988). In response to rising T_c or increased heating of the skin, the

vessels of the skin dilate and skin blood flow increases. In response to falling T_c or cooling of the skin, the skin vessels constrict and skin blood flow is reduced (Åstrand & Rodahl, 1977). T_c appears to have a greater impact on skin blood flow than T_{sk} as evidenced by the experiments of Ferretti et al. (1989) which showed T_c (rectal) to have a 7- to 9-fold stronger effect on thigh vasodilation and heat flux than T_{sk} .

The proposed use of liquid crystals in the dry suit is designed to facilitate heat transfer by enhancing conduction between the diver's skin and the water surrounding the dry suit. However, contact with the liquid crystals will also enhance the cold stimulus to thermal receptors in the skin. An important point for consideration is how this cold stimulus will effect skin blood flow and heat transfer from the body of the swimming diver.

Although cutaneous vasoconstriction is a normal response to local cooling in the resting human, different regions of the body have different vasomotor characteristics which affect this response (Sawka & Wenger, 1988). The skin of the head, neck, and upper chest has little vasoconstrictive capacity and remains well perfused even during cold exposure (Fox et al., 1962). In addition, active vasoconstriction is believed to play only a minor role in controlling skin blood flow in the trunk (Sawka & Wenger, 1988). In the arms, legs, and thighs, both active vasoconstriction and active vasodilation are important in skin blood flow control; whereas in the hands and feet, active vasoconstriction is the predominant controller (Sawka & Wenger, 1988). In regions with the potential for vasoconstriction, however, there appears to be a different response when the body is hot or working (both of which conditions may elevate T_c). Webb et al. (1972) found no evidence of vasoconstriction when local cooling was applied during exercise to various body regions including the upper and lower limbs and extremities. Spealman (1945) showed that vasoconstriction of the hand in response to immersion in cold water was greatly reduced when the body was uncomfortably warm versus in a thermoneutral state. Other experiments have shown significant heat loss to occur through hand immersion in cold water for subjects at rest in the heat (Hill, 1921) and exercising in an impermeable garment (Livingstone et al., 1989).

In addition to raising T_c , exercise may exert an effect on the vasoconstrictor response through the conductance of metabolic heat between

working muscle and overlying skin. In her review article, Nunneley (1970) concluded that cutaneous vessels of the limbs constrict on exposure to cold, except over areas of working muscle. This conclusion has been supported by numerous studies including those finding significant heat transfer and reduction of heat strain when cooling is applied to the thighs and legs during lower body exercise (Sagawa et al., 1988; Shitzer et al., 1973; Young et al., 1987), and to the upper torso during upper body exercise (Young et al., 1987). In summary, it appears that despite the potential for cutaneous vasoconstriction, appreciable heat transfer can be obtained via local cooling applied to a hot or working body.

Whole Body Cooling.

In cooling the human body, maximal effectiveness is accomplished with cooling of the entire body surface (Shvartz, 1972). Most of the work with whole body cooling has been carried out using liquid cooled garments (LCG). LCGs are composed of lengths of narrow tubing, arranged in a net-like fashion, through which a coolant (usually water) flows. The most effective LCGs cover all parts of the body except for the face, ears, hands and feet, however, the cooling tubes are only in direct contact with about 10 to 22% of the body's total surface area (Burton, 1966; Waligora & Michel, 1968; Webb & Annis, 1967 & 1968). The lowest water temperatures used in these LCGs range from 6 to 12°C. Temperature preference varies by region, however, with colder temperatures preferred on the head, neck and over the working muscles of exercising subjects (Shitzer et al., 1973). LCGs have been shown to be quite effective in reducing or eliminating heat strain in men walking on a treadmill in hot ambient conditions (Gold and Zornitzer, 1968; Shvartz, 1970; Shvartz and Benor, 1971). In studies that have measured energy expenditure, LCGs have been shown to remove the body heat produced at work rates of 500 to 600 kcal/hr during uphill walking sustained for one hour or more (Waligora & Michel, 1968; Webb & Annis, 1967 & 1968). Assuming a 20% work efficiency for uphill walking (Åstrand & Rodahl, 1977), the metabolic heat produced at these workloads is 465 to 558 W.

In summary, whole body cooling has been shown to be effective in eliminating heat strain during exercise in the heat and to be capable of removing up to 558 W of metabolic heat. Since the fin swimming diver is expected to produce from 400 to 736 W for sustained periods of time (≥ 20 min), complete heat removal may

require cooling of much of the body surface. For the diver swimming in cold water, however, this cooling requirement will be reduced to some extent because some body heat will be lost through heat leakage into the cold water and via respiration.

Regional Body Cooling.

When whole body cooling is not practical or is not required due to the level of heat stress imposed, cooling of specific body regions can be used to reduce heat strain (Nunneley, 1970). Researchers have commonly measured either regional heat loss or indices of heat strain in order to evaluate the cooling effectiveness of different body regions.

Head and Neck. On an area-adjusted basis, head and neck cooling is more effective in reducing heat strain than the cooling of any other part of the body (Kissen et al., 1971; Riggs et al., 1981; Shvartz, 1970 & 1972, Shvartz et al., 1974). The head has the highest T_{sk} and heat flux of any part of the body except working muscle (Nunneley et al., 1971). Head cooling removes about 30% of the metabolic heat during rest and 19% during exercise (Fonesca, 1971; Nunneley et al., 1982; Shvartz, 1970). Cooling the head has a profound positive effect on thermal comfort (Brown & Williams, 1982; Frim, 1989; Nunneley et al., 1982; Shitzer et al., 1973). None of these researchers observed any detrimental effects of head cooling, however, headaches have been reported by subjects wearing a cooling cap and vest during rest and exercise in the heat (Cadarette et al., 1990). Gordon et al. (1990) reported that neck cooling reduced T_c (rectal) and sweat rate in men running at a strenuous pace for 45 min. Katsuura et al. (1989 & 1990) showed that cooling the head alone reduced heat strain during light exercise in a hot environment, but for moderate exercise in the heat it resulted in a higher T_c (rectal). Williams and Shitzer (1974) found that a water-cooled helmet liner reduced heat strain by 50% and removed 10 to 30% of the metabolic heat produced while sitting in a hot, humid environment. Moderate head cooling has been shown to improve exercise performance in the heat (Greenleaf et al., 1980). In summary, a majority of the studies suggest that cooling the head and neck reduces heat strain substantially, and contributes significantly to thermal comfort.

Torso and Limbs. Researchers have examined both the heat loss from the torso and limbs and the effects of cooling these areas. Although at rest maximum surface heat generation occurs at the head and thorax, with exercise this expands to include the active muscles of the exercising limbs (Crocker et al., 1964; Nunneley et al., 1985). Heat loss from the torso and limbs is equivalent in men at rest in cool water (Ferretti et al., 1988). With arm or leg exercise in the water, however, greater heat loss occurs in regions overlying the active muscles (Ferretti et al., 1988; Sagawa et al., 1988; Wade & Veghte, 1977). In both cool and warm air, arm cycling exercise elicits greater radiative heat loss from the torso than lower body exercise and this is consistent with greater heat loss over the active muscles (back and chest) involved in arm cycling (Sawka et al., 1984).

In his review of LCGs, Shvartz (1972) suggests that a significant amount of heat may be removed from the arms when only the arms and torso are cooled. In contrast, Young et al. (1987) showed that cooling the arms and torso during upper body exercise removed no more heat than cooling the torso alone. During lower body exercise, however, cooling the thighs and torso provided more heat removal than cooling the torso alone. During uphill treadmill walking in an LCG, calf T_{sk} remained high, suggesting a need for increased cooling over active muscles (Webb and Annis, 1968). When thermally isolated men wearing LCGs and walking on a treadmill at 4.8 km/hr were allowed to control coolant temperature by region to maintain thermal comfort, they selected the lowest coolant temperatures over the thighs, legs, and head (Shitzer et al., 1973). Over half (56%) of their excess body heat was removed at cooling sites on the lower limbs, while only 30% of body heat was removed from the torso. Somewhat different results were reported by Shvartz et al. (1974) studying men performing leg exercise in the heat. These investigators found that more body heat could be removed by cooling the torso alone than by cooling either the upper or lower limbs. Differences in methodology may account for this discrepancy. Shvartz et al. cooled each region by itself, in separate experiments. The other investigators cooled several regions simultaneously while measuring heat removal at specific sites. It seems likely that interactions occur when several regions are cooled and these influence the relative amount of heat extraction at each region.

Cooling vests covering parts of the chest, abdomen, and back have been shown to help relieve heat strain at low levels of work (≤ 215 kcal/hr) (Holmer, 1989;

Shapiro et al., 1982) and at rest (Kaufman & Pittman, 1966) in hot environments. Cadarette et al. (1990) evaluated three commercially available cooling vests and found they could remove up to 244 W of heat but were not capable of preventing heat storage in men exercising at 440 W in the heat. At moderate to high levels of work or heat, cooling vests appear to be inadequate for complete removal of excess heat (Cadarette et al., 1990; Shapiro et al., 1982). In summary, studies have shown both the torso and areas overlying active muscles to be effective cooling sites, although the latter appear to have the potential for extraction of a larger portion of total body heat.

Optimal Cooling Configurations and Implications for the Swimming Diver.

Based on his review of LCGs, Shvartz (1972) ranked body cooling configurations in order of greatest effectiveness at removing body heat as follows: 1) whole body; 2) whole body except head; 3) head, torso, upper arms, thighs; 4) torso, upper arms; 5) head, neck; and 6) torso. He believed maximal removal of body heat could be achieved by cooling the entire body surface, with an emphasis on the upper body, especially the head. He recommended an LCG tube distribution of 30, 25, 25, and 20% over the torso, head/neck, thighs/legs, and arms, respectively. In a later study in which body regions were cooled separately, however, Shvartz et al. (1974) recommended a modified tube distribution: 38, 15, 32, and 15% over the torso, head/neck, thighs/legs/feet, and arms/hands, respectively. In both of these suit designs, the torso receives a higher proportion of the tubing than other body regions.

In contrast, the LCG designs of Burton (1966) and Webb et al. (1972) have greater emphasis on the lower limbs. In Burton's design, 48% of the cooling tubes were distributed over the legs/thighs/buttocks, 26% over the arms, and 26% over the torso. Webb et al. (1972) used an LCG in which the thighs/legs/feet received 50% of the cooling tubes, the arms/hands 23%, the torso 19%, and the head/neck 8%.

The optimal cooling configuration suggested by the work of Shitzer et al. (1973) also emphasizes cooling of the lower limbs and it holds special significance for the problem at hand - cooling the swimming divers. In this study, men wore LCGs and insulating outer garments which isolated them from

temperate ambient conditions and then walked on a treadmill at a moderate pace (4.8 km/hr) for 45 minutes. Regional heat removal expressed as a percentage of total body heat removed was 42% at the thighs, 17% at the abdomen and lower back, 14% at the legs, 13% at the chest and upper back, 10% at the head, and 4% at the arms. This study's conditions are similar to what we might expect for the swimming diver wearing a liquid crystal dry suit in two important respects: 1) the microclimate inside an insulated suit in which local cooling has been incorporated (cooling tubes versus liquid crystals); and 2) lower limb exercise that generates heat in the same general body regions (walking versus fin kicking). Although a literature review did not reveal a muscle action analysis for fin kicking, the movement appears similar to the flutter kick used in the front crawl swimming stroke. The major muscle groups involved in the flutter kick are the flexors and extensors of the hip, knee and ankle (Clarys, 1988; Hay, 1978; Rasch & Burke, 1978). These same muscle groups are involved in walking uphill (Rasch & Burke, 1978).

In the case of the swimming diver, it may not be possible to cool the entire body, therefore, examination of the relative (area-adjusted) heat removal at the different regions is useful in identifying which regions should have the highest priority. From the data given by Shitzer et al. (1973), we were able to calculate the heat extracted per skin surface area (W/m^2) in each body region during uphill treadmill walking. These are presented in Figure 1. The greatest relative heat removal occurred at the thighs; the legs, head, lower torso and upper torso were next; and the arms last. Figure 2 is another representation of the same data. In this figure, the regions of the body have been shaded to indicate relative heat removal.

In summary, the cooling configurations recommended in the literature are similar in that 1) they include the same general body regions - the head and neck, the torso, and the limbs; and 2) the greatest proportion of cooling is applied to the torso and lower limbs, with the head/neck and arms receiving lesser amounts. There is some controversy over the proportion of cooling to be assigned to the limbs versus the torso. A majority of the studies suggest that cooling the lower limbs during lower body exercise removes more body heat than cooling the torso.

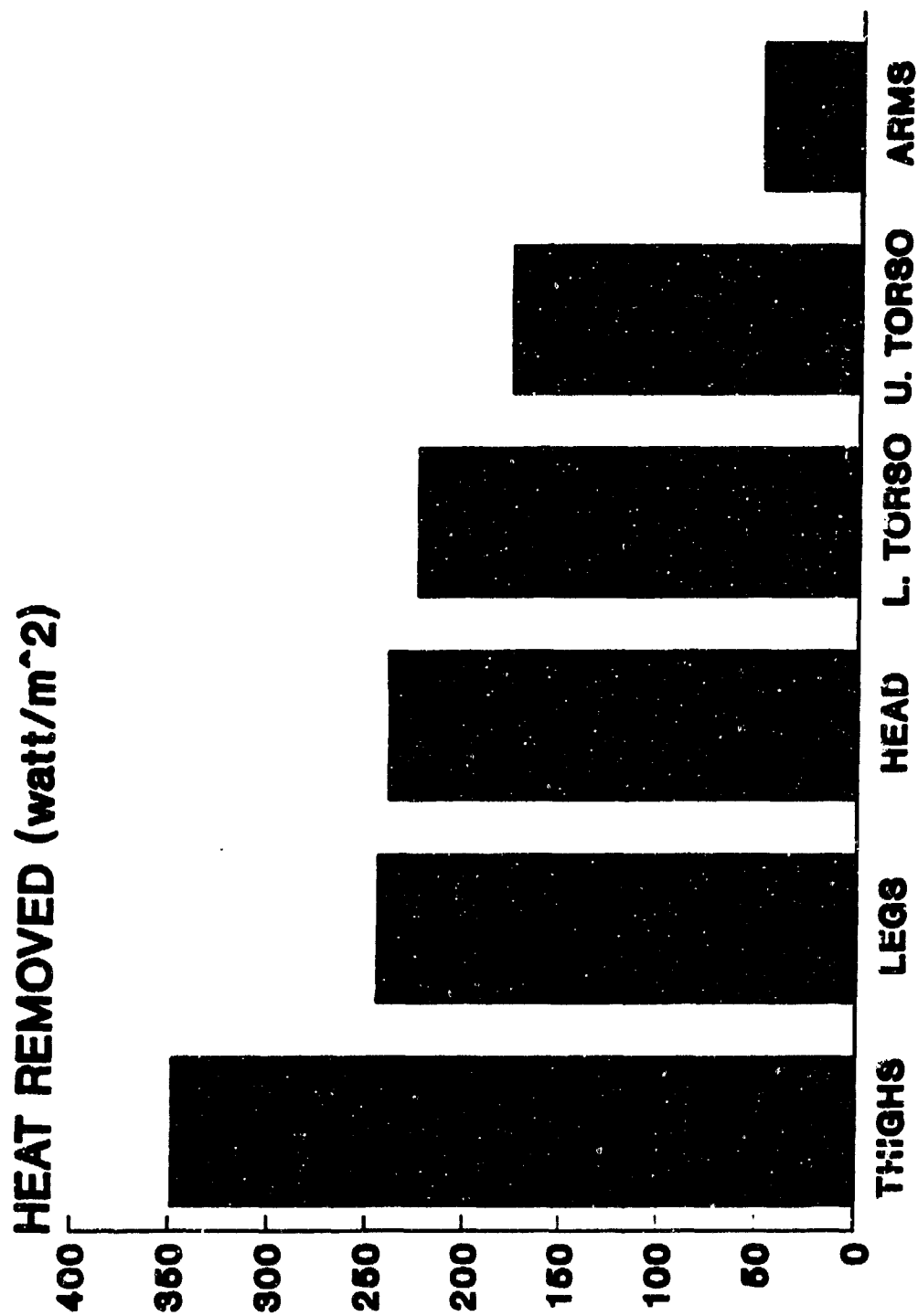


Figure 1. Heat removed per surface area (W/m^2) in six body regions in men walking at 4.8 km/hr. Derived from data of Shitzer et al. (1973).

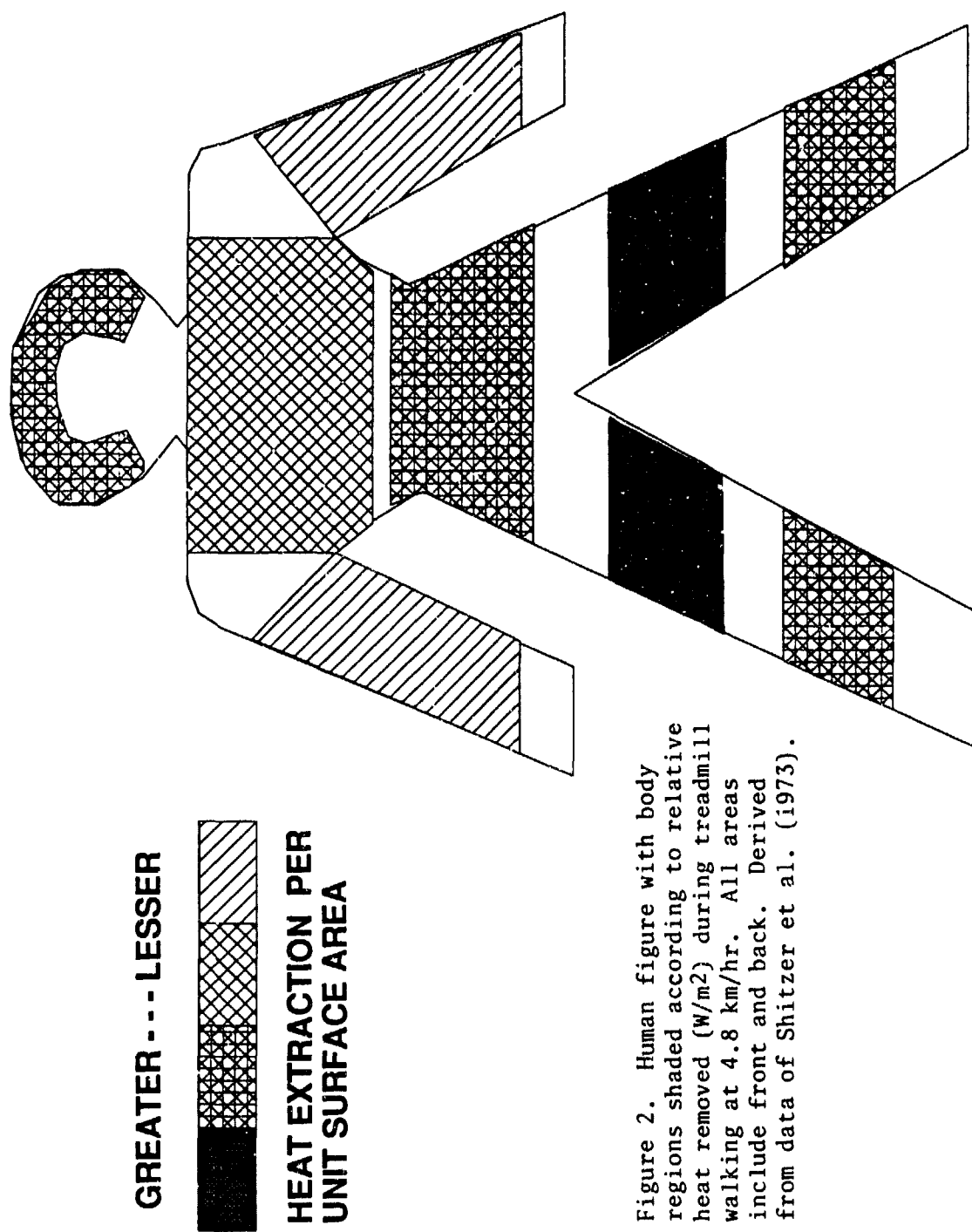


Figure 2. Human figure with body regions shaded according to relative heat removed (W/m^2) during treadmill walking at 4.8 km/hr. All areas include front and back. Derived from data of Shitzer et al. (1973).

Conclusions.

Review of the body cooling literature has led to the following conclusions:

- 1) The head, neck, and areas overlying active muscles are the body regions that can provide the greatest heat removal per skin surface area.
- 2) Cooling the head has the added benefit of greatly enhancing thermal comfort.
- 3) Regions providing lesser heat removal per skin surface area, such as the chest, abdomen and back, can still be quite effective for removing excess body heat because of their large total surface area.
- 4) Cooling only the torso or head can reduce or relieve heat strain during low levels of work; but at moderate to high levels of work more of the body must be cooled in order to minimize heat strain.
- 5) Whole body LCGs offer the most effective cooling and can remove the metabolic heat (465 to 558 W) produced with sustained energy expenditure rates of 500 to 600 kcal/hr.

Table 2. Recommended cooling site priorities for Navy Special Warfare divers fin swimming in dry suits.

Priority	Cooling Site
First	Thighs, Buttocks, Legs Head, Neck
Second	Chest, Abdomen, Back
Third	Arms

Recommendations for Cooling Sites in Navy Special Warfare Divers

From the literature on energy expenditure during underwater fin swimming, a heat production in the range of 400 to 736 W for extended periods (≥ 20 min) and 992 W for short periods (10 min) is expected. Given the reported cooling power (465 to 558 W) of whole body LCGs, we believe that the swimming diver will need to be cooled over much of the body surface. Our recommendations for optimal distribution of cooling in the swimming diver are largely consistent with the relative (area-adjusted) heat removal data presented in Figures 1 and 2, and are summarized in Table 2. Body regions overlying active muscle should receive a high priority for cooling. Hence, cooling should be applied to the front and back of the thighs and legs, and to the buttocks, as these sites overlie the active muscles in fin swimming. Cooling the head and neck should receive a high priority, not only because of relative heat removal, but due to the positive impact on thermal comfort. Cooling could also be applied to the chest, abdomen and back as much as is practically possible. The lowest priority area is the arms.

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13. ABSTRACT (Maximum 200 words) This report is a review of the literature regarding heat production and optimal cooling of divers swimming underwater. In previous studies, divers fin swimming at paces sustainable for at least 20 min showed oxygen consumption rates ($\dot{V}O_2$) ranging from 1.25 to 2.3 l/min. During rapid swimming sustainable for 10 min, a $\dot{V}O_2$ of 3.1 l/min has been reported. The heat produced by these divers (estimated from $\dot{V}O_2$) ranged from 400 to 736 W for the longer duration swims (≥ 20 min) and up to 992 W during the 10-min swim. The literature regarding cooling of the human body revealed whole body liquid cooling garments are capable of removing 465 to 558 W metabolic heat produced during sustained energy expenditure rates of 500 to 600 kcal/hr, respectively. The head, neck and areas overlying active muscles are the body regions that can provide the greatest heat removal per skin surface area. Cooling the head has the added benefit of greatly enhancing thermal comfort. Areas providing lesser heat removal per skin surface area, i.e., chest, abdomen and back, can still be quite effective for removal of excess body heat because of their large (cont on reverse)					
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