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EFFECTS OF HAND AND FOOT HEATING ON DIVER THERMAL BALANCE

Robert P. Weinberg
Edward D. Thalmann

Naval Medical Research
and Development Command
Bethesda, Maryland 20814-5055

Department of the Navy
Naval Medical Command
Washington, DC 20372-5210

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TECHNICAL REVIEW AND APPROVAL
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The experiments reported herein were conducted according to the principles set forth in the current edition of the "Guide for the Care and Use of Laboratory Animals," Institute of Laboratory Animal Resources, National Research Council.

This technical report has been reviewed by the NMRI scientific and public affairs staff and is approved for publication. It is releasable to the National Technical Information Service where it will be available to the general public, including foreign nations.

LARRY W. LAUGHLIN
CAPT, MC, USN

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→ Divers at rest immersed in cold water for long durations wearing passive thermal protection garments are limited by low finger and toe temperatures, which cause pain and numbness before rectal temperatures fall to unsafe levels. It was reasoned that low levels of hand and foot heating might improve diver comfort. Supplemental heating of the hands and feet to maintain finger and toe temperatures between 12 and 18 °C (after passive cooling) was employed.

A total of 32 divers wearing a dry suit with M-600 Thinsulated undergarments were immersed for periods of up to 8 hours in 3 °C water. The divers wore electrical resistance heated gloves and socks over polypropylene liners and under the Thinsulated insulation, or warm-water-perfused gloves and socks over polypropylene liners and under foam neoprene insulation. Hands and feet remained dry by communication with the dry suit. Water perfusion rate or electrical power was adjusted to maintain desired digit temperatures.→

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Power required for warm-water heating averaged 211 W. The average electrical resistance heating power requirement was estimated as the product of dutycycle and continuous power available. The average electrical power delivered was 13.4 ± 3.4 watts/hand and 9.8 ± 2.4 watts/foot for 18 °C digit temperatures. Mean skin and rectal temperature decreased by 6 ± 2.2 °C and 1.2 ± 0.3 °C during the 4-hour immersion. Hand dexterity was improved by supplemental heating compared to the unheated group. No differences were observed in skin conductivity or whole body heat loss between groups.

Supplemental heating did not reduce the need for adequate passive whole body thermal insulation for long-duration immersions in cold water. Supplemental heating did reduce hand and foot discomfort at low energy cost, and reduced the decrement in manual dexterity compared to no heating. The low energy cost of resistance heating makes this feasible for immediate use by the Fleet.

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BACKGROUND

A diver's ability to safely complete a task in cold water is often limited by inadequate thermal protection. In such instances heat loss from the diver can exceed his metabolic heat production, which results in body cooling. As body temperature decreases, lower tissue temperatures will impair physical and mental performance and ultimately his safety. The rate and total amount of this net heat loss is a function of the water temperature, thermal protective garment, mission duration, and diver activity level. Since water temperature and mission duration are not generally subject to manipulation, selection of the optimal thermal protection garment is critical to safe mission completion.

Current passive insulation thermal garments, while able to maintain adequate levels of core temperature for several hours, may not provide adequate insulation for extremities. For example, Figure 1 illustrates finger and toe temperatures obtained previously in this laboratory during a 6-hour immersion in 5 °C water for a diver wearing a diver passive thermal protection system (DPTPS) dry suit and dry Thinsulate gloves. These cooling rates are similar to those reported by Thalmann (1987) and others for divers wearing dry Thinsulate gloves in 2-4 °C water. The digit temperatures fell rapidly during the first hour and reached a plateau of about 7-7.5 °C by the second hour. Currently, experimental limits for digit temperatures are 8 °C for 30 min or 6 °C at any time. These limits are designed to avoid any possibility of tissue injury and are equally applicable to operational dives. The dives shown in Figure 1 were just below these limits for the last 3 hours or so and should have been aborted by 4 hours using current criteria. These durations are typical with current gloves. Pain, discomfort, and loss of tactile sensation in the hands and feet are frequently observed during this type of exposure. Rectal temperature decreased an average of 1.9 ± 0.6 °C in this study, and achieved a plateau at this level indicating that core temperature was maintained. This type of study illustrates that the rate of endogenous metabolic heat production (of divers nearly at rest) will maintain core temperature, but the divers' are unable to maintain distal extremity temperatures with currently existing passive thermal protection. In fact, 22% of exposures in this study prematurely aborted were due to extreme peripheral cooling, resulting in pain and numbness of the hands and feet. Fingers and toes reached temperatures within a few degrees of water temperature. This condition can be damaging if continued for long periods of time in very cold water (Francis, 1984, and Leitch, 1978) and has been associated with decreased manual performance (Van Dilla, 1949). Additional passive insulation for hands and feet is impractical, as manual performance is already impaired due to the bulky insulation.

Supplemental external heating represents one possible means of maintaining adequate temperatures of distal extremities. The amount of externally applied heat does not by itself have to be sufficient to maintain the body in thermal balance but only sufficient to keep digits well above the zone of discomfort and in the zone of adequate manual dexterity.

By applying active heating in this way, improved levels of comfort and performance can be obtained at a significantly lower energy cost than whole body supplemental heating. In this way, extremity temperatures can be eliminated as the mission limiting factor. Mission length would be governed by core temperature drop, which would be less than 1 • C wearing a dry suit with a M-600 Thinsulate undergarment in 3 • C water at rest for 6-7 hours (Thalmann, 1987).

OBJECTIVES

The primary objective of this study was to measure the amount of power required to maintain finger and toe skin temperatures at either 12 or 18 • C and determine the feasibility of extremity heating. A temperature of 12 • C was chosen because it is reported to be the lower limit for onset of pain or discomfort (Francis, 1985). The value of 18 • C was chosen because insulative value of skin is still at a maximum (Wenger, 1985), yet tactile sensation is not notably impaired. The power required to maintain finger and toe temperatures at 12 or 18 • C was measured for both a warm-water-perfused system and a direct electrical resistance heating system. Immersions were conducted in 3 • C water while wearing a dry suit with a fixed amount of passive insulation.

Another question that had to be answered was whether the site of supplemental heat application would affect overall body thermal balance. Therefore, a secondary objective was to determine if active heating of the hands and feet produced a reactive decrease in body insulation in unheated areas, thereby producing an increased heat loss in passively insulated area's of the body. Manual performance was measured to assess any effects of extremity heating.

METHODS

A total of 32 male U.S. Navy divers volunteered to participate in the study after giving their informed consent. The divers were 29 ± 4 years old, 178 ± 12 cm tall and 75.2 ± 10 kg in weight. All subjects were told to refrain from vigorous exercise and consuming any caffeine, nicotine, or alcohol for a period of 8 h prior to each immersion. All dives were made in a 3500-gallon tank filled with 3 °C water. The divers were immersed in a seated position while resting in a semi-reclining web chair, which could be lowered into the immersion tank by an overhead hoist.

Three experimental series of immersions with supplemental heating were accomplished. Series I (Warm Water Heating, n=21 divers) was conducted using water-perfused gloves and socks (STRON, Redwood, CA) as shown in Figure 2. Three conditions were tested in series I: no supplemental heating (n=5), heating sufficient to maintain 12 °C (n=8), and heating sufficient to maintain 18 °C extremity digit temperatures (n=8). Manual dexterity and grip strength were measured during the immersion and subjects were asked to rate subjective discomfort. Series II (Constant Electric Heating, n=8) utilized electrical-resistance heated gloves and socks (Vacuum Reflex Ltd, England)(Figure 3) that were continually energized throughout the period of immersion, to determine if sufficient heating power was available to maintain 18 °C digit temperatures. During Series III (Intermittent Electric Heating, n=8) the gloves and socks were manually turned on and off to maintain digit temperatures between 17.5 and 18.5 °C.

Each diver donned a Hollister external penile catheter that conducted urine by tubing through a dry suit penetration for overboard dump into the immersion tank (Thalmann, 1987). Reflux was prevented by insertion of a one-way check valve in the tubing. This arrangement permitted the diver to remain submerged throughout the course of an immersion.

Heat flux and skin temperature sensors were attached at 12 regional sites and recorded by computer (Weinberg, 1984). Body core temperature was measured by a standard YSI rectal temperature sensor inserted 15 cm past the anal sphincter. Additional temperature sensors were attached with adhesive tape to the palmar surfaces on the distal phalanges of the third and fifth fingers and the first and fifth toes. Mean heat flows and temperatures were computed as a weighted average from 12 regional sites using weighing factors: forehead and foot 0.07 each; upper and lower back, chest, and abdomen 0.0875 each; dorsal and anterior thigh 0.095 each; calf and anterior leg 0.065 each; dorsal hand 0.05; and forearm 0.14 (Layton, 1983).

All immersions were conducted with the diver wearing a modified dry suit, which consisted of a TLS (trilaminate-butyl nylon) dry suit outergarment with a composite 600-weight Thinsulate and polypropylene undergarment (Diving Unlimited International, San Diego, CA). The one-piece Thinsulate garment was comprised of 400-weight Thinsulate in the knees, seat, shoulders, and elbows; and 600-weight Thinsulate in the calves, thighs, arms, and forearms. The trunk region was made of 800-weight Thinsulate. Divers wore polypropylene socks under both water-perfused and electrical-resistance heating socks.

The diver's head was insulated with a 400-weight Thinsulate hood worn underneath a 1/4" foam neoprene wet suit hood. Divers wore an AGA full face mask (Interspiro, Sweden) with weights to minimize the buoyancy of the mask. Two-way diver audio communications were used throughout the immersion to assess diver status.

Divers wore 40 kg of lead weight to provide slight negative buoyancy when the dry suit was inflated (to provide theoretically optimal insulation). These 40 kg of weight would permit up to 40 l of gas in the suit (neglecting diver buoyancy). The divers were instructed to adjust the amount of suit inflation gas to produce a slight negative buoyancy.

In Series I, air was breathed from a demand regulator connected to a heat exchanger that produced an inspired gas temperature within 2 °C of the water temperature. Divers in the electric heating Series II and Series III breathed chilled room air (5-10 °C) supplied from above the immersion tank through an AGA mask. Expired gas was collected for 5-minute intervals every 10 min in a Douglas bag and mixed. A sample was then analyzed for carbon dioxide and oxygen concentration using Applied Electrochemistry gas analyzers. The volume was measured by Tissot gasometer. Metabolic rate was calculated from oxygen consumption using standard equations (Hoke, 1976).

Immersions were terminated if the diver's core temperature declined by 2 °C from the pre-immersion value, or reached 35 °C. Dives were also terminated if a finger or toe temperature fell below 8 °C for a continuous period of 30 min, or if any digit temperature fell below 6 °C at anytime (Francis, 1985 and Thalmann, 1987).

Series I

In Series I, 21 divers were immersed for periods up to 8 h while wearing the hot-water-perfused gloves and socks. Five subjects were immersed while wearing the gloves and socks but without water flow; 8 subjects were immersed with extremity supplemental heating sufficient to maintain 12 °C digit temperatures, and 8 subjects were immersed with extremity supplemental heating sufficient to maintain 18 °C digit temperatures. There were no repeat exposures. The order of digit temperature assignment for each subject was random.

Hot water was provided by a closed-circuit system consisting of a pump and heater external to the immersion tank and an umbilical consisting of supply and return lines. The flow of water was independently adjusted to maintain finger and toe temperatures at the desired temperature. The warm water heating system consisted of thin-walled flexible plastic tubing woven in a cotton glove mesh for support, with separate manifolds for water distribution through each sock or glove (Figure 2). A heavy wool sock was worn over the heated socks, which, due to their bulk, prevented use of standard Thinsulate booties. For the gloves, the diver donned a polypropylene five-fingered glove that was worn next to the hand to minimize thermal gradients. The heated five-finger water-perfused glove was then covered by a 1/8" five-finger foam neoprene glove.

Both hands were supplied from one closed-circuit perfusion system, a second identical hot water supply system supplied both feet. The water flow rate was individually adjustable to each limb between 0-1000 ml/min. The inlet water temperature of the pump was fixed at 45 • C, but inlet temperatures measured at the gloves and socks varied, due to flow dependent heat loss in the umbilical distribution system in the cold tank. Digit temperatures were permitted to fall upon immersion until 0.5 • C below the target temperature before flow was initiated at a rate sufficient to maintain skin temperatures of the toes and fingers at either 12 or 18 • C.

Water temperature and flow rate at the inlet and outlet of each glove and sock were monitored continuously during the dive. The power requirement for each system was calculated from inlet and outlet water temperatures (Tin, Tout in • C), and flow rate (l/min) to the gloves/socks, according to the equation.

$$\text{Power (watts)} = 69.7 * (\text{Tin} - \text{Tout}) * \text{flow rate} * \text{Cp} \qquad (1)$$

where 69.7 converts Kcal/min to watts of power (Cp, specific heat of water is 1 Kcal/L • C). Both subjective rating of diver comfort and objective evaluation of diver performance as a function of thermal status were obtained. Divers were interrogated every 2 h as to their perceived thermal comfort using a modified Borg scale (rating of 5 denoting no discomfort, 4 cold, 3 very cold, 2 painful, 1 very painful, 0 numb) while underwater. Tests of manual dexterity (Minnesota rate of rapid turning) and handgrip strength were done during brief periods out of the water. Minnesota rate of rapid turning is a measure of finger and wrist dexterity, timing how long it takes to completely remove, invert, and reinsert a matrix of 1-inch- diameter by 2-inch-long pegs. Handgrip strength was measured using a hand dynamometer (Lafayette Instrument Co., Lafayette, IN) that was individually adjusted for each diver's optimal finger to palm distance while wearing the glove assembly.

Series II

Series II (Constant Electric Heating) was conducted using 8 subjects who wore the electrical-resistance heated gloves and socks that were continually energized for 8 h. At the full operating voltage of 28 VDC, each glove or sock drew 0.75 A for a delivered power of 21 W/limb, or a total supplemental heat delivery of 84 W. Measurements of skin temperature were made to determine if this level of continuous active heating could maintain the desired digit temperature of 18 °C. During initial testing of continuous electrical heating the gloves and socks were found to generate surface temperatures at the heating wires up to 40-42 °C, which produced local discomfort (and burning of the skin in one instance). The addition of a polypropylene liner under the heated glove/sock provided a more uniform heat distribution that was judged comfortable. Continuous electrical heating produced finger temperatures of 25 ± 3 °C and toe temperatures of 29 ± 2 °C. The more compact size of the electric socks (vice the water-perfused system) permitted wearing an 800-weight Thinsulate bootie during both Series II and III. During Series II and III a five-fingered polypropylene glove liner was worn under the heated glove, over which was worn an 1/8" five-finger M-200 Thinsulate glove. An outer latex rubber glove provided a waterproof environment that was contiguous with the dry suit.

Series III

In Series III (Intermittent Electric Heating), intermittent electrical heating of the socks and gloves worn by 8 subjects as described in Series II was used to estimate the continuous power requirement to maintain 18 °C digit temperatures. Immersions lasted 4 h. Control was done manually by supplying power when the digit temperature fell to 17.5 °C and turning it off when the digit temperature rose to 18.5 °C. To minimize wear (and possible failure) on the electric gloves, the manual dexterity and grip strength tests were omitted. It was reasoned that performance would be similar to that observed during earlier runs at similar digit temperatures.

In summary, the passive glove complement for each series was:

Series I - Polypropylene liner, 1/8" foam neoprene five-fingered outer glove

Series II and III - Polypropylene liner, M-200 Thinsulate five-fingered glove, latex outer glove

In all series, divers were instructed to maintain their hands at waist level to prevent excessive inflation with dry suit gas or hydrostatic compression.

Data were analyzed using a paired t-test corrected for repeated measure when necessary. Statistical analysis of the data was considered significant at the $p < 0.05$ level. Data are presented as means ± standard deviation (±SD).

RESULTS

A total of 29 successful immersions (out of 37 attempts) were made in the 3 experimental series. Of the unsuccessful attempts, 5 were due to equipment failure (leaks, lack of safety temperature readouts, and catheter not working). Subject requests (cold feet, cold hands) accounted for 2 aborts in Series I when 12 °C digit temperatures were investigated. Headache occurred in 1 subject.

The effective regional suit insulation for all immersions was calculated from the difference between the skin and ambient water temperature divided by the regional heat flux. This is a rearrangement of the heat flow equation

$$H = \frac{6.45(T_{sk} - T_{amb})}{I} \quad (2)$$

where H is heat flow and I is insulation. Torso insulation averaged 2.5 ± 0.4 clo as shown in Figure 4, the remainder of the garment averaged 1.2 ± 0.2 clo. Allowing an average of 5 kg negative buoyancy, this leaves 35 l of gas in the suit, which for an average diver with a surface area of 2 m^2 permits an average undergarment thickness of nearly 1.5 cm. Theoretically, this amount of gas, if uniformly distributed, would then provide nearly 3 CLO of insulation. Actual measurements were 1.75 ± 0.6 as the weighted average of 10 regional sites. This actual value is likely due to uneven gas distribution and less than ideal insulation of the undergarments. Insulation of the hands and feet could not be determined during active heating. The insulation for hand and foot was estimated from the known insulation values of Thinsulate (5 CLO/in) and the foam (3 CLO/in) neoprene. The theoretical value for total hand insulation based on 1/8" Thinsulate was 0.6 CLO, while 1/8" foam neoprene was estimated to provide 0.4 CLO. The boots had thicker Thinsulate resulting in a theoretical foot insulation value of 1.2 CLO.

Data presented in Figure 5 show that finger temperatures of all groups decreased rapidly in the first 30 min of immersion to 18 • C, except the continuously heated group which showed a prolonged fall over the first hour to 25 • C and remained constant thereafter. Toe temperature decreased during the first 60-90 min to 18 • C without heating, and in the continuously heated group reached 29 • C for the rest of the immersion. Supplemental heating was applied when the digit temperatures reached 0.5 • C below desired temperature for the 12 and 18 • C heated group. Finger and toe temperature then remained at the desired temperature for the duration of the immersion. Figure 5 shows digit temperature for all conditions. Active heating maintained digits at stable values as would be expected. Unheated digits fell to abort criteria in 1-2 hours.

Series I

In Series I, 5 immersions with no supplemental heating were attempted resulting in 3 aborts (2 due to equipment failures, 1 subject-requested due to painfully cold hands). Eight immersions were attempted with supplemental digit heating to 12 • C, resulting in 2 aborts (1 due to equipment failure, 1 subject-requested due to numb hands). All 8 immersions were successfully completed with supplemental digit heating to 18 • C.

Unheated finger and toe temperatures dropped rapidly during the first 1-2 hours of immersion to 10-15 • C, as shown in Figure 5, then continued to fall more slowly to a final value of 7-9 • C by 8 h. A similar response has been reported by Thalmann (1987) in divers wearing Thinsulate with rubber outermitts in 2-4 • C water. Supplemental heating was initiated between the 1st and 2nd hours of immersion for both the 12 °C and 18 °C supplemental heating digit temperatures.

Inlet water temperature to the hands for the 18 °C group averaged 35.0 ± 1.1 °C, with a mean outlet temperature of 28.0 ± 1 °C. Flow rate for both hands averaged 0.350 ± 0.023 l/min. The average energy requirement for heating the hands to produce a finger temperature of 18 °C was 171 ± 4 W. Flow to both feet averaged 0.237 ± 0.046 l/min, resulting in inlet and outlet temperatures of 33.0 ± 1.2 °C and 30.6 ± 0.8 °C, respectively. The power requirement to maintain a toe temperature of 18 °C was 40 ± 6 watts. Thus, an overall energy cost of nearly 211 W was made to maintain 18 °C digit temperatures by the warm-water heating system. Energy requirements to maintain 12 °C finger and toe temperatures averaged 100 ± 14 W for the hands and 28 ± 6 W for the feet, for an energy cost of nearly 130 W.

Mean skin temperatures for Series I (excluding hands and feet) are shown in Figure 6, and were not significantly different between divers whose finger and toe temperatures were unheated or heated to either 12 or 18 °C. Mean skin temperatures began at 33 °C and fell within the first two hours to stabilize at 27 ± 3 °C for all groups. Divers were instructed to remain at rest during the immersion, but removal from the immersion tank for performance testing in Series I resulted in transient 1-2 °C elevations in skin temperature.

Total body heat fluxes were not significantly different among the three groups in Series I (Figure 7). Whole body heat flux upon immersion was 125 ± 5 watts per square meter (W/m^2), and slowly decreased over the 8-hour period to 82 ± 6 W/m^2.

Heating the hands and feet did not result in any observed changes in body skin blood flow. Figure 8 shows conductivity (an index of skin blood flow) calculated as regional heat flux divided by the difference between rectal temperature and regional skin temperature during the last hour of immersion (Nadel, 1984). There was no difference between unheated and heated digits on regional skin conductivity. Values fall in the 14-22 $W/m^2 \cdot C$ range reported by Nadel (1984) to represent maximal vasoconstriction. Foot and hand conductivity were not calculated during supplemental heating: measured heat loss from the back of the hand fell within the first hour to 0.5 ± 1.8 W in the heated groups, and remained essentially zero for the duration of immersion.

Rectal temperature of all groups did not differ (Figure 9), beginning at 37.4 ± 0.2 • C and decreasing over the first 2-3 h to 36.2 ± 0.2 • C, where it remained constant for the rest of the 8-hour immersion.

Hand grip strength (Figure 10) was only measured in Series I and was reduced to 70 ± 6 % of dry control due to the subject wearing gloves. Immersion in 3 • C water reduced the maximal grip strength by an additional 31 ± 8% during the course of an 8-hour immersion in both unheated and heated digit groups. Forearm temperatures were not significantly different between unheated (22.7 ± 0.8 • C) and heated (23.1 ± 1.0 • C) groups. Data presented in Figure 10 were normalized to the pre-immersion grip strength wearing gloves. The grip strength of all groups fell during the first 4 h of immersion to approximately 80% of the pre-immersion value, with no significant differences between the unheated, 12 • C and 18 • C groups. As shown in Figure 11, fine finger and wrist dexterity (Minnesota Rate of Rapid Turning) showed progressive decrement in both heated digit groups. A 28% slower response occurred at 2 h, becoming 65% slower at 8 h. There was no significant difference between heated digit groups. Divers with unheated digits were significantly different from the heated groups when measured at 2 h of immersion, and were unable to complete the test at subsequent test intervals due to finger numbness.

Divers in the 12 and 18 • C groups had similar ratings of subjective whole body discomfort during the first 2 hour interval. Subjects with digit heating to 12 • C exhibited a progressive increase in discomfort that was significantly greater than the group with digit heating to 18 • C by 4 h (Figure 12). Divers in the 18 • C group uniformly reported minimal finger or toe discomfort, while 50% of divers in the 12 • C group reported discomfort or numbness by the end of the immersion. Unheated divers uniformly reported numbness by 2 h that continued for the duration of the dive.

Series II

In Series II, 8 immersions were successfully completed without difficulty. This series focused on whether adequate power was available to maintain finger and toe temperatures of 18 • C using the electrical-resistance heated gloves and socks. Finger and toe temperatures averaged 25 ± 3 • C for fingers and 29 ± 2 • C for toes, with constant heating of 21 W/limb.

Mean skin temperatures were not significantly different between hot water heating of digits and electrical extremity heating. Heat flow measured at the back of the hand (-3 ± 1.3 W/m^2) and top of the foot (-5 ± 2.7 W/m^2) were in the direction of absorption into the body with the remainder of the heat applied presumably lost to the water. Heat flow on the rest of the body surface was not significantly elevated compared to unheated immersions.

The divers' metabolic rate averaged 91 ± 18 W/m^2 initially, and slowly rose during the 4-hour immersion to 108 ± 7 W/m^2. The respiratory exchange ratio averaged 0.82 ± 0.02.

The average net non-respiratory thermal balance is shown in Figure 13 and combines data from all series. During the first 2 h of immersion heat loss was greater than metabolic heat production, starting at a net heat loss of 46 ± 20 W/m^2 and then coming into a state of slight heat gain for 2-8 h. This does not include respiratory heat loss. One can calculate (Hoke, 1976), based on inspired gas temperatures of 5-10 °C and respiratory minute volumes of 15-30 L/min, a respiratory heat loss of 10-20 W/m^2. The respiratory heat loss offsets the positive balance shown in Figure 13 and accounts for the presumed state of thermal balance as indicated by the stable rectal temperatures.

Rectal temperature (Figure 9) decreased in both heated and unheated divers during the first 3 h of immersion from 37.4 ± 0.2 °C to 36.2 ± 0.2 °C and remained steady for the rest of the immersion independent of supplemental heating level.

Series III

Of 8 attempted immersions, 5 were successfully completed. Two immersions were aborted due to equipment difficulty (suit flooding and computer malfunction) and 1 immersion due to headache.

The duty cycle [ON time/(ON + OFF time)] required to maintain digit temperatures at 18 °C was 62 ± 5% for hands and 49 ± 3% for feet during the last 2 h of immersion. Heating requirements prior to two hours were more variable among the subjects. Since the duty cycle was constant after 2 h, the average power delivered was estimated as the simple product of the peak power available (21 W/limb) multiplied by the percentage of time energized. The average power requirement for heating each hand was 13.4 ± 3.4 W, and each foot 9.8 ± 2.4 W for a total of 46 W.

Rectal temperatures for intermittent electrical (and hot water) heating are shown in Figure 9, and show a decrease from 37.4 to 36.4 °C while resting in 3 °C water. The effect of supplemental heating on other skin temperatures is shown in Figure 6, where the extremity heating is seen to have little influence on diver mean skin temperatures.

DISCUSSION

The failure rate observed for all series was essentially due to research equipment problems; only one instance of a suit leak occurred. Requests for abort by the diver occurred primarily during unheated and 12 °C digit temperature immersions. The only instance of abort at 18 °C digit heating was due to headache. This headache may have been caused by the breathing mask straps being too tight, as the pain resolved within 30 minutes of removal from the water and initiation of rewarming.

The drysuit worn in this study adequately protected resting diver core temperature as rectal temperature did not drop below 36 °C after 8 h of immersion in 3 °C water. Non-respiratory heat loss (Figure 13) is positive 5-15 W/m^2, which should increase body temperature at 0.1 °C/h. This was not observed and may be accounted for by the estimated respiratory heat loss of 10-20 W/m^2 (Hoke, 1976). The effect of supplemental heating of the hands and feet did not appear to influence this overall total body net thermal balance.

Supplemental heating of digits to 12 • C was not satisfactory based on diver subjective evaluation. Greater thermal discomfort was reported by the divers at 12 • C versus 18 • C digit temperatures, but both levels of digit heating were judged to be more comfortable than the unheated condition. However, there was no measurable difference in hand grip strength or manual dexterity between the two levels of supplemental heating. Manual dexterity was improved by supplemental heating, the rate of impairment was slowed, as unheated subjects were unable to perform the test after 2 h of immersion due to numbness and pain. Grip strength, which is primarily a function of forearm muscle groups, was not influenced by any level of hand heating. Apparently, the amount of heat transferred from the hand via venous circulation is insufficient to affect forearm muscle temperature enough to prevent a decrease in handgrip strength. Although 3-5 W was measured as positive heat flow into the hand, no change was measured in forearm temperature. Previous work by Vincent (1988) showed that there is an average decrease of 16% in maximal voluntary grip strength produced by short term hand and forearm immersion in 5 • C water. This value is in agreement with the reduction in grip strength seen in the first 2 hours of immersion in this study.

The purpose of supplemental heating is to surround the hands and feet with a warm barrier, which reduces the temperature gradient for heat loss from the skin to the water. This effective insulation increase can be seen to follow from rearranging equation

(2). This reduction was essentially complete in this study, as net hand and foot heat loss fell to nearly zero. The amount of power required to minimize loss is a function of the overlying insulation and ambient water temperature.

Electrical resistance heating was much more energy efficient than warm-water heating. To maintain digits at 18 °C, approximately 50 W of electrical energy was supplied, while over four times that amount (211 W) was consumed by the hot water gloves. The reasons for this disparity are complex and not readily apparent from the data of this experiment. Hot water temperature was 35 °C at the inlet and 28 °C at the outlet for a mean temperature of 31.5 °C. If one applies the heat flow equation (2) assuming an insulative value for neoprene gloves of 0.4 CLO and water temperature of 5 °C one calculates that the energy lost to the water to be

$$\frac{H}{SA} = \frac{6.45(31.5-5.0)}{0.4} = 427\ W/m^2 \qquad (3)$$

A similar calculation for the amount of heat transmitted to the hand assuming a skin temperature of 18 °C would be 217 W/m^2. Assuming the effective surface area for heat transfer to the extremities and environment are the same, the effective surface area of the tubing in the gloves and boots to account for a total heat loss of 211 W would be 0.35 m^2 for all four extremities.

The situation for electrical resistance heating is more complex. As mentioned earlier, at full power local temperatures up to 40-42 °C were observed at digit temperatures ranging from 25-29 °C. Using methods similar to equation (2), assuming an insulative value of 0.6 CLO, a mean extremity temperature of 27 • C, and heating wire temperature of 41 • C, one calculates a heat loss at 387 W/m^2 to the environment and 150 W/m^2 to the extremities. Under these conditions the total power consumption was 84 W, so the effective surface area for heat transfer was 0.16 m^2. Thus, the increased efficiency of electrical heating is probably due not only to the increased insulative value at the boots and glove, but also to the electrical wires having a smaller effective radiative surface area than the water filled tubing in the water perfused system.

Whatever the reason, the lower energy consumption of the electric resistance heating combined with much lower bulk than the hot water glove makes this method preferable. In addition, the power requirement consists only of some batteries, which makes the entire system very simple from a mechanical standpoint. If digit temperatures of 18 • C are maintained, the 50-watt power supply is small enough that a diver could probably carry a 6- to 8-hour power supply with him.

Better insulation could reduce the energy costs, but only at the expense of further reductions in manual dexterity, which is already comprised by the thickness of the gloves. There is a trade-off between increasing insulation and further decreasing manual dexterity, which must be considered. Although manual dexterity was not measured during electrical heating, differences are not expected compared to water heating at similar digit temperatures, if the glove insulation and resultant flexibilities are similar.

In addition, because the warm water socks were bulky and prevented use of the Thinsulate booties, heavy wool socks were worn that provided less insulation. Due to the more compact design of the electrical socks, space was available in the dry suit to wear Thinsulate booties, increasing the passive insulation with a corresponding decrease in supplemental heating power required.

The energy required for extremity supplemental heating in this study (50 W for electrical, 211 W for warm water) is in the range of only 10-25% of the energy cost of whole body heating, which was calculated by Lippitt (1983) to be between 500 and 1000 W for a diver in 0-5 °C water temperature. However, Lippitt's calculations were based on no significant change in core temperature, while in this study core temperature decreased 1.2 ± 0.3 in 8 h. This is similar in magnitude to the observed fall in core temperature previously observed in divers without supplemental heating in this laboratory and reported by Thalmann (1987) for similarly insulated resting divers. The major advantage of extremity heating is the improvement in perceived comfort and manual dexterity, as there was no demonstrable effect on diver core temperature change during immersion in cold water.

Based on the results of this series of studies, application of modest amounts of supplemental heating to the extremities can maintain 18 °C finger and toe temperatures. The energy cost of approximately 50 W in 3 °C water could be readily supplied from a support ship or carried by a non-tethered diver for long-duration missions. Decrements in manual performance and dexterity do occur, but are not associated with the debilitating perception of unbearably cold (or numb) hands and feet. The possibility of non-freezing cold injury is also greatly reduced. Supplemental heating had no discernable effect on overall body thermal balance, since mean skin and rectal temperatures decreased at a rate similar to that exhibited by subjects in the unheated condition. There is no indication that supplemental heating of the digits to 18 °C produces an increased core to skin conductance of heat in other unheated regions of the body.

The method of heating hands and feet used in this study could probably be further reduced by a better designed system. Another simple method to improve electrical resistance heating would be to wear a bulky foam neoprene gauntlet/mitten over the hands when inactive, which could be removed or opened to expose a five-finger glove with less insulation but more suitable to performing fine hand tasks when needed. Heating of the forearm in addition to the hand might reduce the fall in grip strength by maintaining forearm temperatures at higher levels.

Supplemental heating does not appear to lessen the need for adequate passive whole body thermal insulation for long duration missions in cold water. Rectal temperatures continue to fall during immersion in cold water when hand and foot heating is provided, but at a rate similar to that seen in unheated divers in this study and similarly insulated divers in a study by Thalmann (1987). The benefits of low-level supplemental heating of the hands and feet are reduction in diver discomfort by keeping these extremities warm at low energy cost, and reduction in the likelihood of permanent injury due to low digit temperatures.

CONCLUSIONS

- Heating hands and feet is feasible without altering normal diver thermal regulation while wearing existing thermal protection garments.
- Energy costs for electrical resistance heating are modest and may be further reduced with improved glove design.
- Prototype development should include provision for forearm heating evaluation.
- Hand and foot heating using electrical resistance heating can solve a fleet problem using existing off-the-shelf hardware.

LAY LANGUAGE SUMMARY

Three series of immersions were conducted for periods of up to 8 h in a 3500-gallon tank of 3 °C water. In the first series, divers wore warm-water-perfused gloves and socks. The gloves and socks were heated to maintain finger and toe temperatures of 12 °C or 18 °C. The diver was questioned as to his comfort, and tested for grip strength and ability to do fine hand tasks every 2 h. In the second series, divers wore electrically heated socks and gloves, which continually delivered 21 W of heat to each extremity. Finger and toe temperatures ranged from 25-29 °C. A third series was conducted with intermittent energizing of the gloves and socks to maintain 18 °C finger and toe temperatures, which provide adequate heating at about 60% of the energy consumption.

During the first series the divers reported that 12 °C finger and toe temperatures were uncomfortably cold, with 50% reporting numbness by the end of an 8 hour-immersion. Heating finger and toe to 18 °C resulted in greater perceived comfort, with divers reporting some cold sensation but no discomfort or numbness. Hand grip strength was not better in the heated group than the unheated group, as forearm muscle groups that provide grip strength were presumably not affected by hand heating. (No measured increase in forearm skin temperature or heat flux.) Manual dexterity was not different between groups heated to 12 or 18 °C, but was improved over the unheated group, whose fingers became painfully cold or numb between 2 and 4 hours of immersion.

The energy supplied for warm water heating was 211 W for digit temperatures of

18 °C, but this value was felt to be higher than necessary due to two reasons. First, the water-perfused socks were bulky and prevented use of Thinsulate booties in the limited space of the dry suit, decreasing the insulation of the feet. Second, the water-perfused gloves were also bulky and, to provide some hand dexterity, only a five-finger neoprene glove was worn over them for insulation. Construction of more compact units may be possible, but a portable source of warm water is also required that likely require 1-2 years for design, fabrication, evaluation, and delivery.

Electrical resistance heating required only 50 W to maintain digit temperatures at 18 °C with the diver wearing Thinsulate booties in the dry suit and M-200 Thinsulate gloves covered by a latex rubber glove to keep the hands dry.

The divers rate of fall in mean skin or rectal temperature was not different from those of an unheated diver during the course of the immersion. Metabolic rate rose in response to falling body temperatures, and was sufficient to offset the rate of heat loss, resulting in rectal temperature plateau at 36 °C. Whole body heat fluxes were similar to those reported by Thalmann (1987) for resting divers immersed in 2-4 °C water wearing comparable amounts of dry suit insulation.

Supplemental heating of the hand and feet does provide increased comfort to the diver at low energy cost. However,it does not affect the loss of body heat during cold water immersion. The rate of body cooling remains a function of diver activity level, garment insulation, and water temperature duration determines the amount of heat loss, and resultant mental and performance decrement likely to occur.

This study has demonstrated that electrical resistance heating at the hands and feet has a much lower power consumption than the hot water perfused system that was tested. In addition, the entire electrical resistance system was assembled from off-the-shelf components that are readily available and easily adaptable for operational use. There is currently no hot water supply system available for the water perfused system that could be adopted for Fleet use. Also, the electrical resistance system allows for more passive insulation for a given amount of manual dexterity, thus attending more protection in the event of a power failure. It thus appears that an electrical resistance system suitable for operational evaluation could be rapidly (less than a year) constructed with minimal additional developments. It is recommended that operational prototypes based on the system described in this report be constructed and tested and be made available to Fleet operators as soon as possible. This will provide an immediate gain in operational capability, which will bridge the gap until further long term improvements in thermal protection are available.

RECOMMENDATIONS

- Construct diver-carried electrical resistance hands and feet heating prototype for operational evaluation using off-the-shelf hardware with appropriate human factors input.
- Increase energy efficiency using proportional heating controller and optimize insulation for needed manual dexterity.
- Investigate effects of exercise on energy costs of supplemental heating.
- Extend heating of hand to include forearm, and evaluate effect in grip strength and manual dexterity.
- Investigate effects of 18 °C vs. 25 °C digit temperatures on improved manual dexterity compared to power requirements.

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FIGURE LEGENDS

Figure 1. Finger and toe temperatures of a diver wearing a dry suit with dry M-200 Thinsulate gloves, under thin latex gloves, and outer 1/8" foam neoprene gauntlet mitts immersed in 5 • C water versus time.

Figure 2. Water-perfused glove and sock diagram.

Figure 3. Electric heated gloves and socks.

Figure 4. Regional dry suit insulation used during supplemental extremity heating for various body regions. Measurements taken without heating. UPBK = upper back, LOBK = lower back, CHST = chest, ABDM = abdomen, DTHI = dorsal thigh, ATHI = anterior thigh, DCAF = dorsal calf, ACAF = anterior calf, FOOT = top of foot, DHND = dorsal hand, FARM = forearm. (N=27)

Figure 5. Finger and toe temperatures obtained with and without supplemental heating versus time (10 minute averages). (18 • C digits N=18 of Series I for 8 h and N=5 of Series III for 4 h, no heating N=2 from Series I, continuous heating N=8 from Series II).

Figure 6. Mean skin temperature (excluding hands and feet) with and without extremity supplemental heating versus time (10 minute averages). (12 • C digits N=6, 18 • C digits N=13 / 0-4 h N=8 after 4-8 h, no heating N=2, continuous heating N=8).

Figure 7. Whole body heat flux versus time of immersion with and [illegible]nt supplemental heating. (12 • C digits N=6 from Series I, 18 • C digi[illegible] from Series I for 0-8 h and N=5 Series III for 0-4 h, no heating N=2 from Seri[illegible]inuous heating N=8 from Series III).

Figure 8. Regional skin conductivity with and without supplemental [illegible] for various body regions. UPBK = upper back, LOBK = lower back, CHST = cl[illegible]M = abdomen, DTHI = dorsal thigh, ATHI = anterior thigh, CALF = dors[illegible] SHIN = anterior calf, FARM = forearm. (No heating N=2 from Series I, 12/18 • [illegible]eating N=19 from Series I and III, continuous heating N=8 from Series II).

Figure 9. Rectal temperature with and without supplemental heating versus time (initial and final hourly values). (12 • C digits N=6 from Series I, 18 • C digits from Series II N=8 for 0-8 h and Series III N=5 for 0-4 h, not heated N=2 from Series I, continuous heating N=8 from Series II).

Figure 10. Hand grip strength during immersion with and without supplemental heating. (Not heated N=2 from Series I, 12 • C digits N=6 from Series I, 18 • C digits N=8 from Series I).

Figure 11. Percent change in Minnesota Rate of Rapid Turning test versus time of immersion with and without supplemental heating. (12 °C digits N=6 from Series I, 18 °C digits N=8 from Series I, no heating N=2 from Series I).

Figure 12. Subjective cold perception using modified Borg scale during time of immersion with and [5 = comfortable, 4 = cool, 3 = cold, 2 = painful, 1 = very painful, 0 = numb] without supplemental heating. (18 °C digits N=8 from Series I, 12 °C digits N=6 from Series I, no heating N=2 from Series I).

Figure 13. Whole body non-respiratory thermal balance versus time of immersion with 18 °C digit supplemental heating. N=5 for 0-4 h (Series I and III) and N=2 for 4-8 h (Series I).

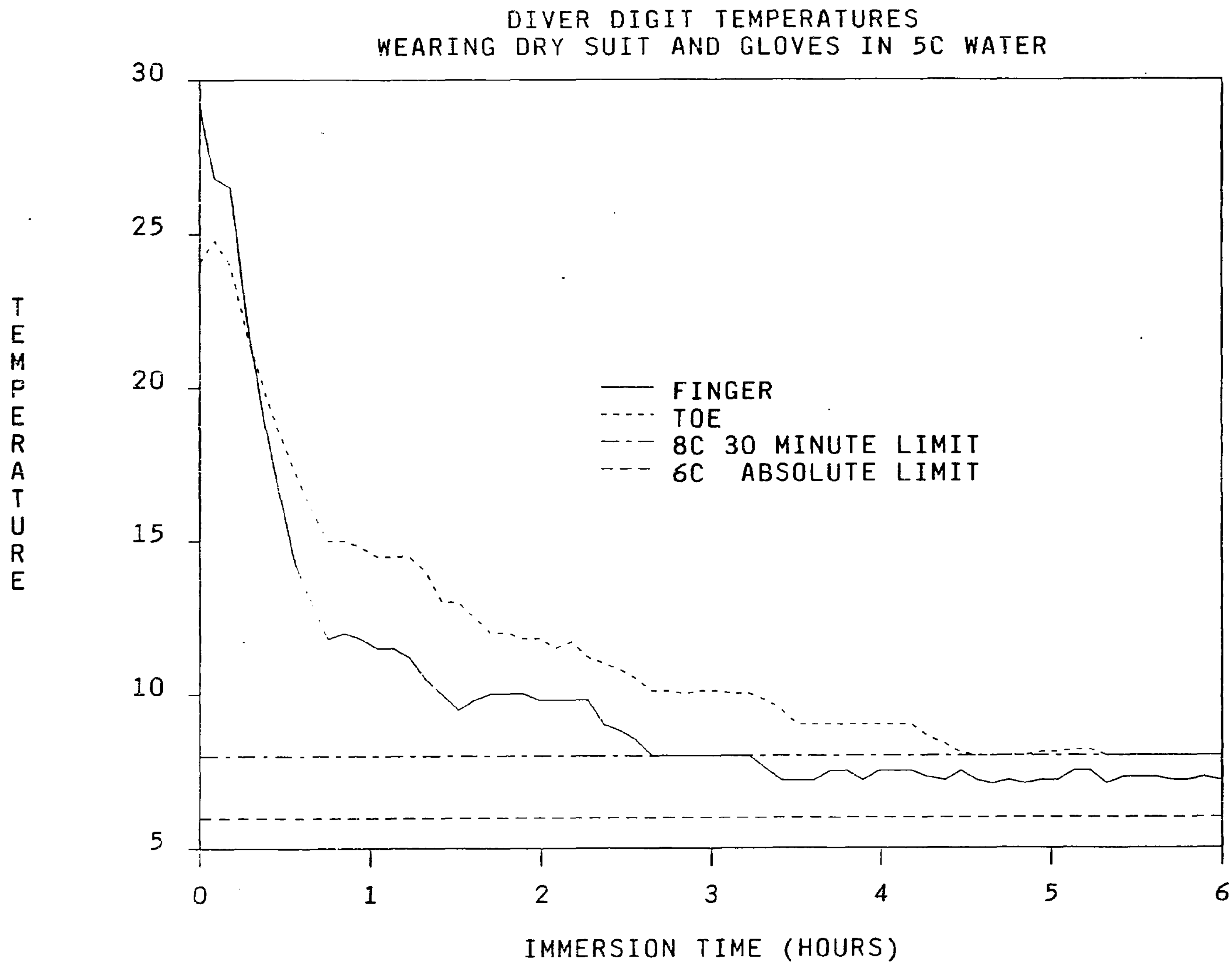

DIVER DIGIT TEMPERATURES
WEARING DRY SUIT AND GLOVES IN 5C WATER
TEMPERATURE
30
25
20
15
10
5
FINGER
TOE
8C 30 MINUTE LIMIT
6C ABSOLUTE LIMIT
0
1
2
3
4
5
6
IMMERSION TIME (HOURS)

FIGURE 1

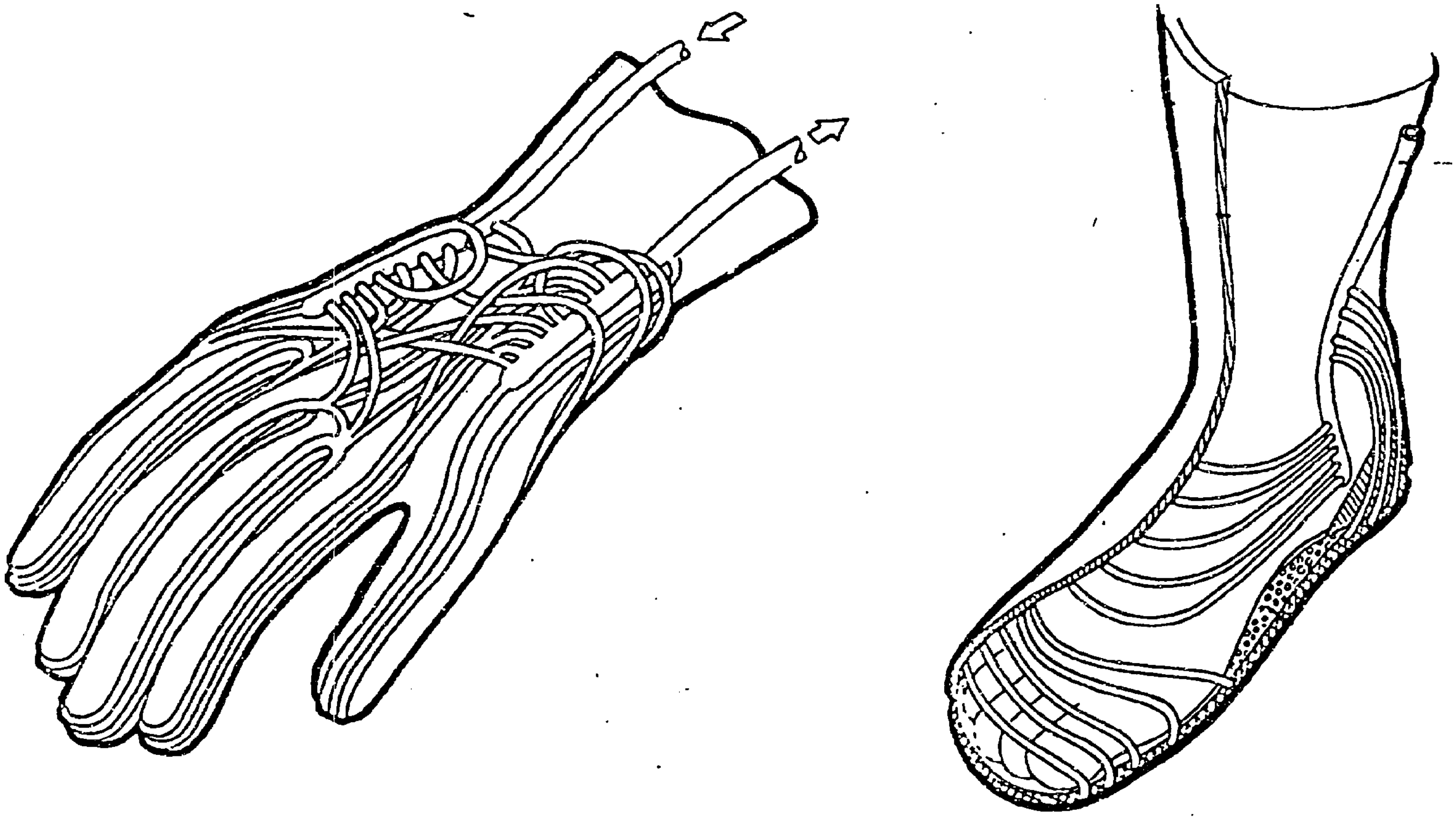
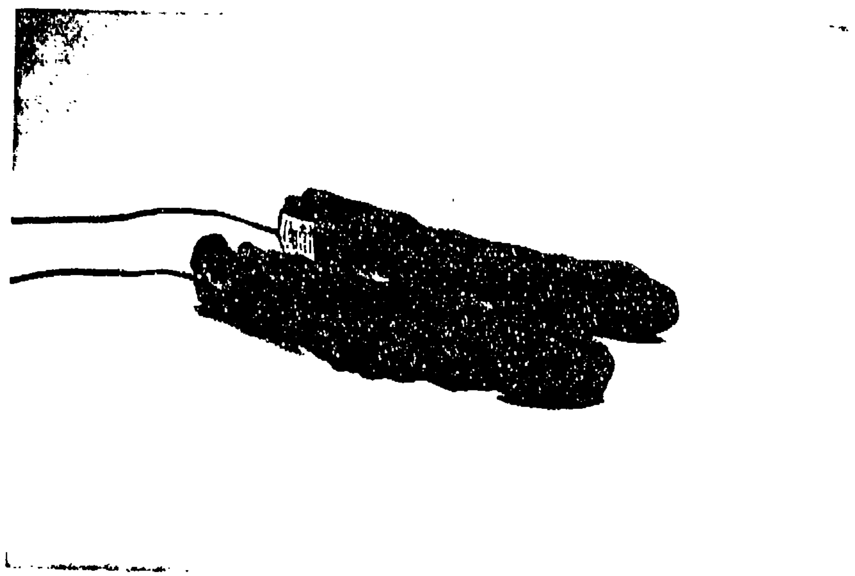


FIGURE 2

ELECTRIC GLOVES



ELECTRIC SOCKS

FIGURE 3

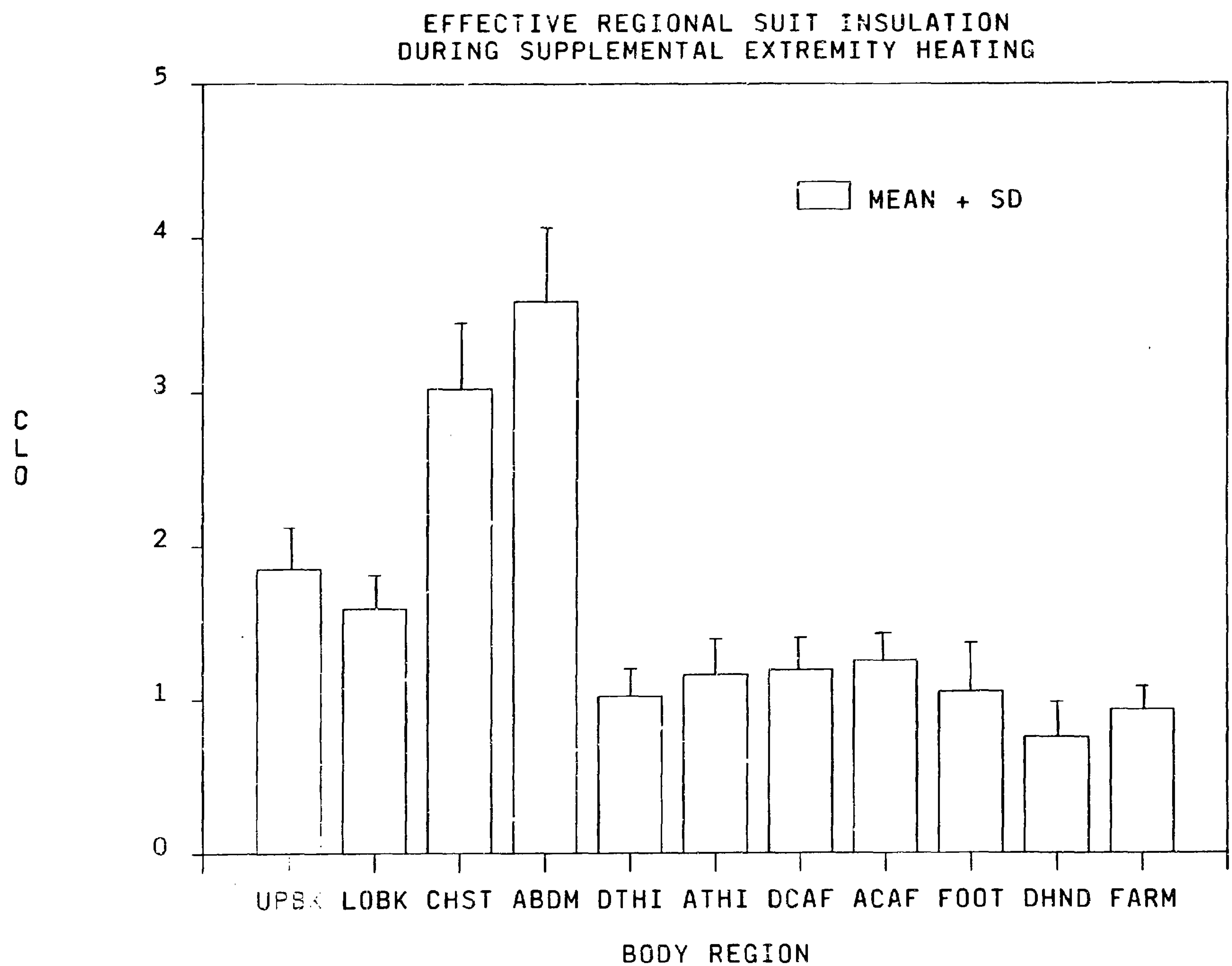

EFFECTIVE REGIONAL SUIT INSULATION
DURING SUPPLEMENTAL EXTREMITY HEATING
MEAN + SD
CLO
0
1
2
3
4
5
UPBK LOBK CHST ABDM DTHI ATHI DCAF ACAF FOOT DHND FARM
BODY REGION

FIGURE 4

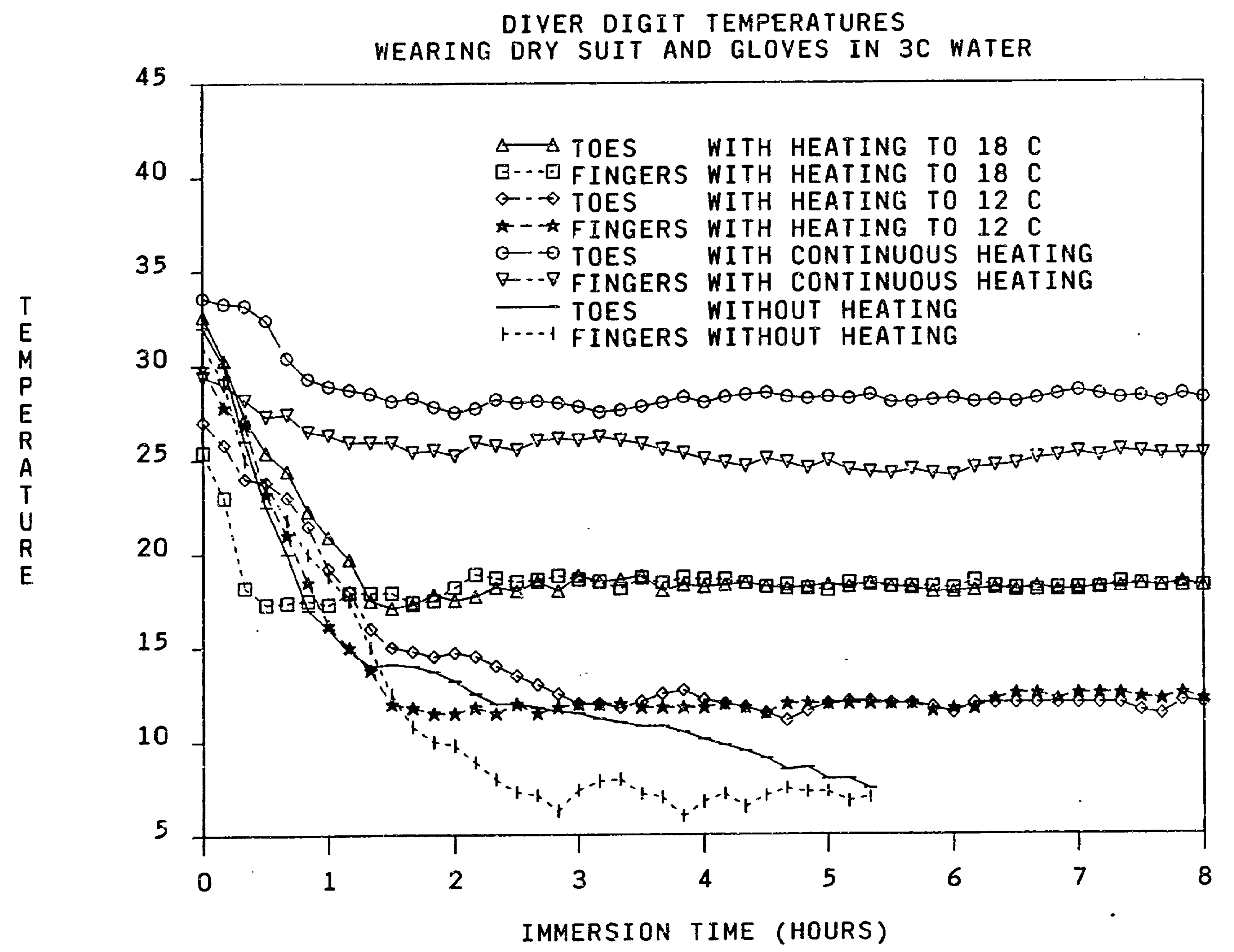

DIVER DIGIT TEMPERATURES
WEARING DRY SUIT AND GLOVES IN 3C WATER
TEMPERATURE
45
40
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
TOES WITH HEATING TO 18 C
FINGERS WITH HEATING TO 18 C
TOES WITH HEATING TO 12 C
FINGERS WITH HEATING TO 12 C
TOES WITH CONTINUOUS HEATING
FINGERS WITH CONTINUOUS HEATING
TOES WITHOUT HEATING
FINGERS WITHOUT HEATING
IMMERSION TIME (HOURS)

FIGURE 5

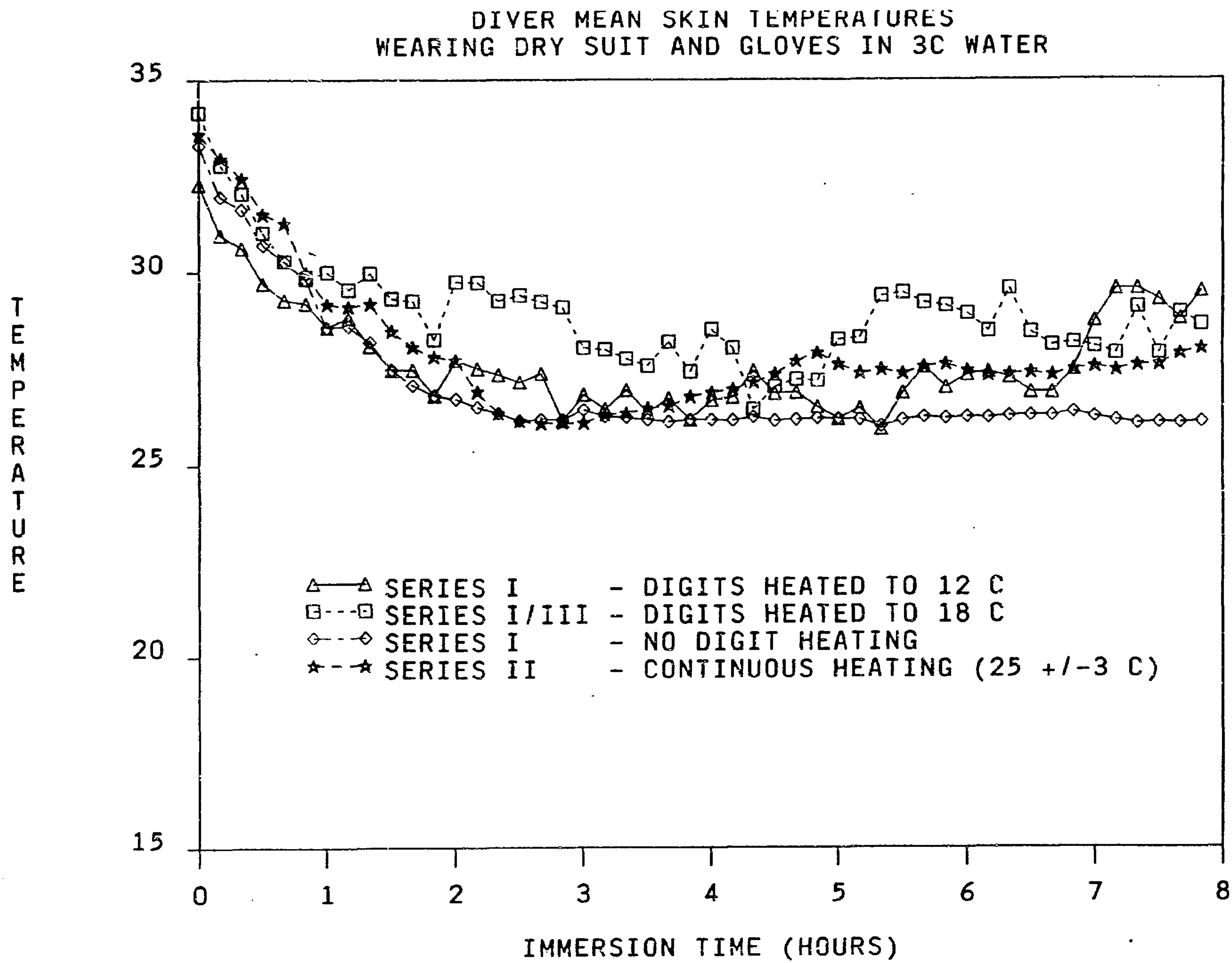
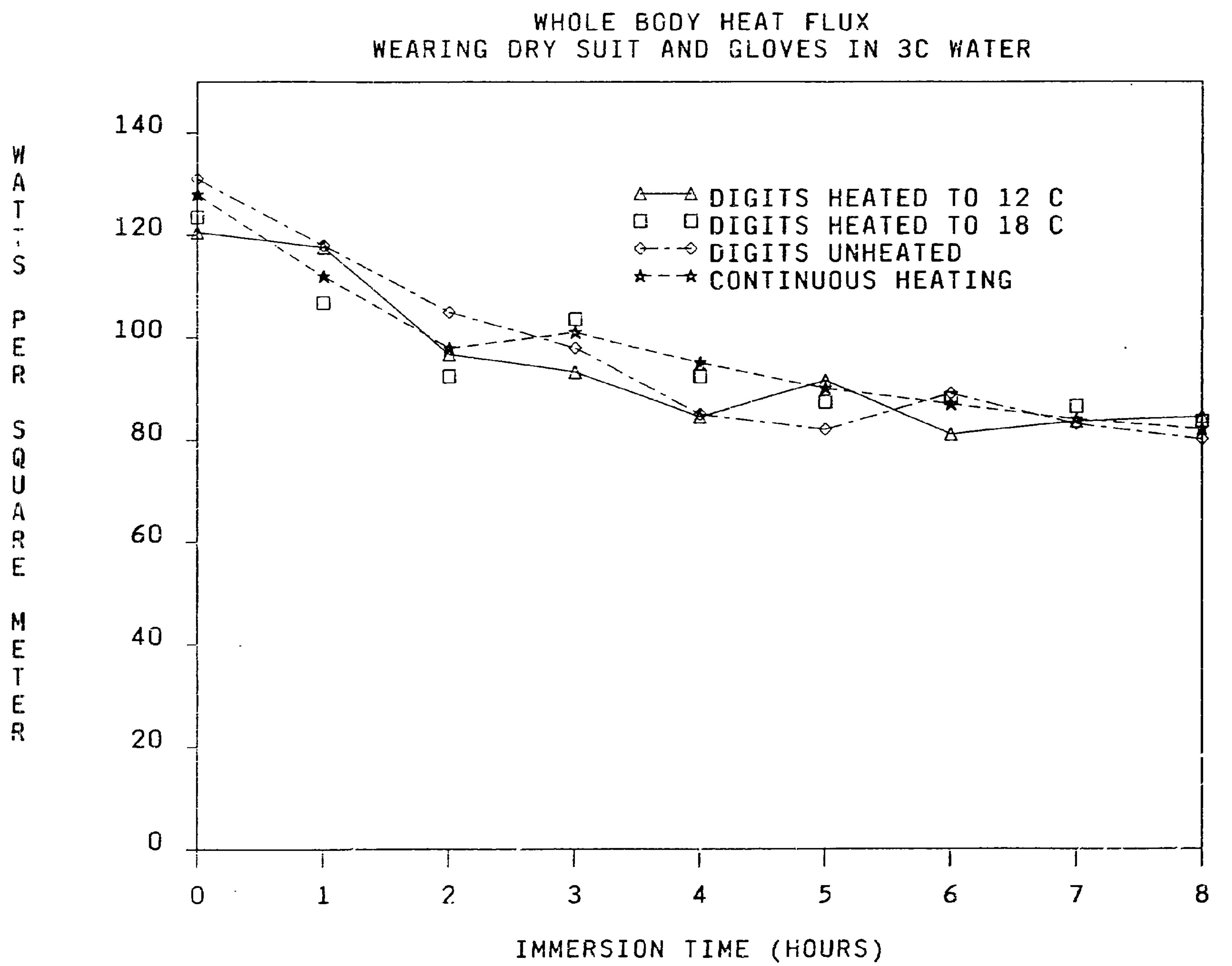

DIVER MEAN SKIN TEMPERATURES
WEARING DRY SUIT AND GLOVES IN 3C WATER
35
30
25
20
15
TEMPERATURE
0
1
2
3
4
5
6
7
8
IMMERSION TIME (HOURS)
SERIES I - DIGITS HEATED TO 12 C
SERIES I/III - DIGITS HEATED TO 18 C
SERIES I - NO DIGIT HEATING
SERIES II - CONTINUOUS HEATING (25 +/-3 C)

FIGURE 6



WHOLE BODY HEAT FLUX
WEARING DRY SUIT AND GLOVES IN 3C WATER
DIGITS HEATED TO 12 C
DIGITS HEATED TO 18 C
DIGITS UNHEATED
CONTINUOUS HEATING
WATTS PER SQUARE METER
140
120
100
80
60
40
20
0
0
1
2
3
4
5
6
7
8
IMMERSION TIME (HOURS)

FIGURE 7

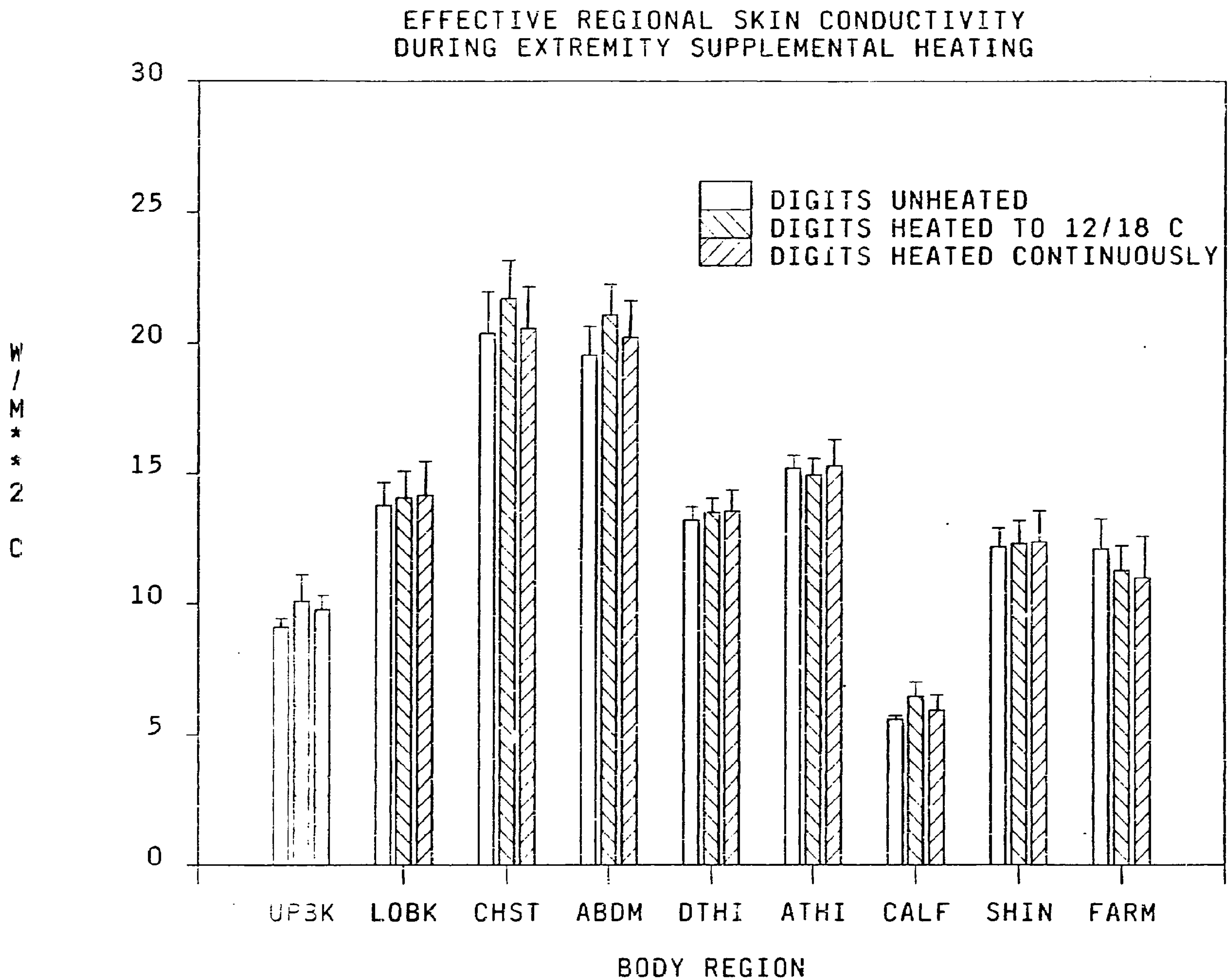
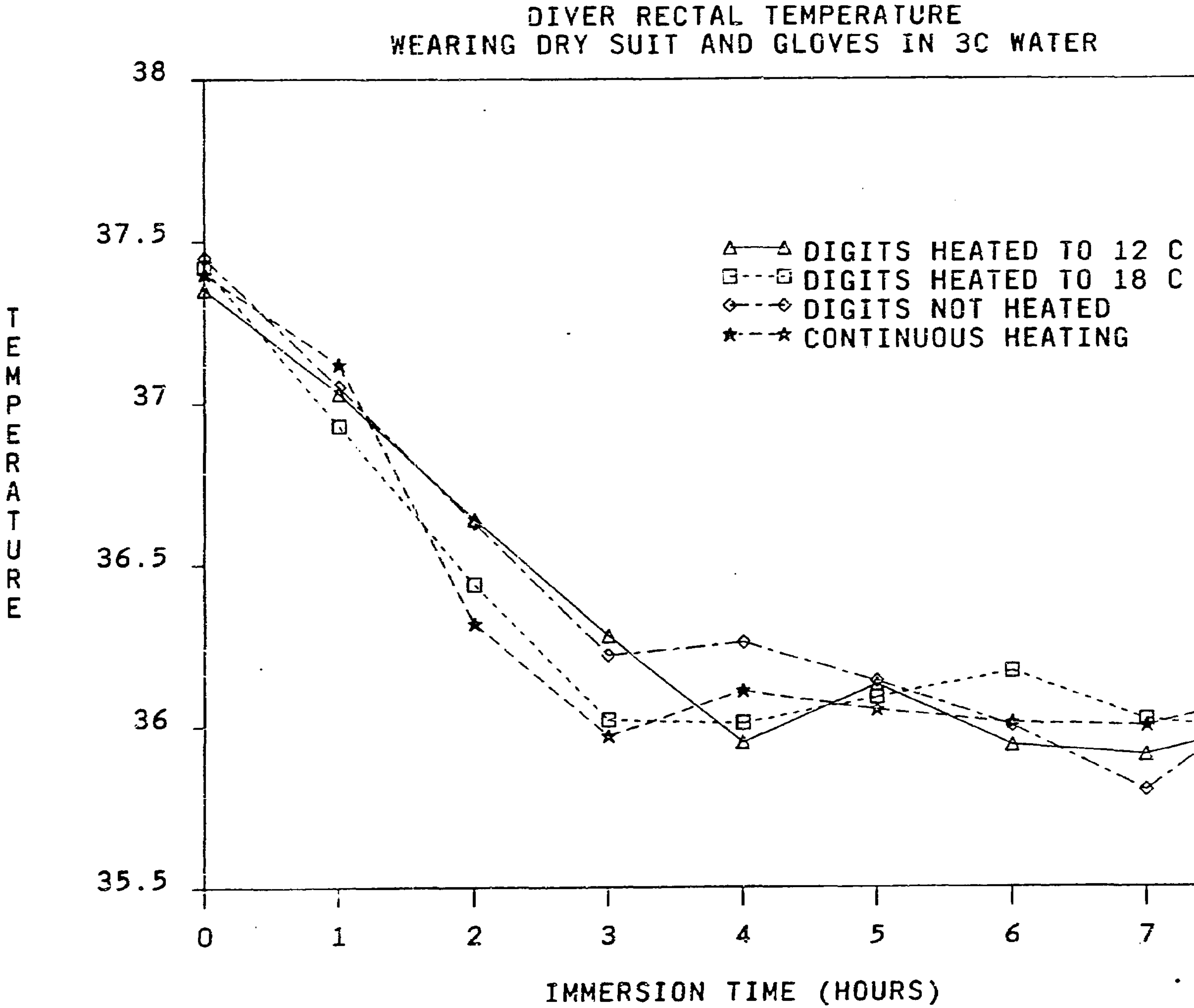

EFFECTIVE REGIONAL SKIN CONDUCTIVITY
DURING EXTREMITY SUPPLEMENTAL HEATING
DIGITS UNHEATED
DIGITS HEATED TO 12/18 C
DIGITS HEATED CONTINUOUSLY
W/M**2 C
30
25
20
15
10
5
0
UP3K
LOBK
CHST
ABDM
DTHI
ATHI
CALF
SHIN
FARM
BODY REGION

FIGURE 8



DIVER RECTAL TEMPERATURE
WEARING DRY SUIT AND GLOVES IN 3C WATER
38
37.5
37
36.5
36
35.5
TEMPERATURE
DIGITS HEATED TO 12 C
DIGITS HEATED TO 18 C
DIGITS NOT HEATED
CONTINUOUS HEATING
0
1
2
3
4
5
6
7
8
IMMERSION TIME (HOURS)

FIGURE 9

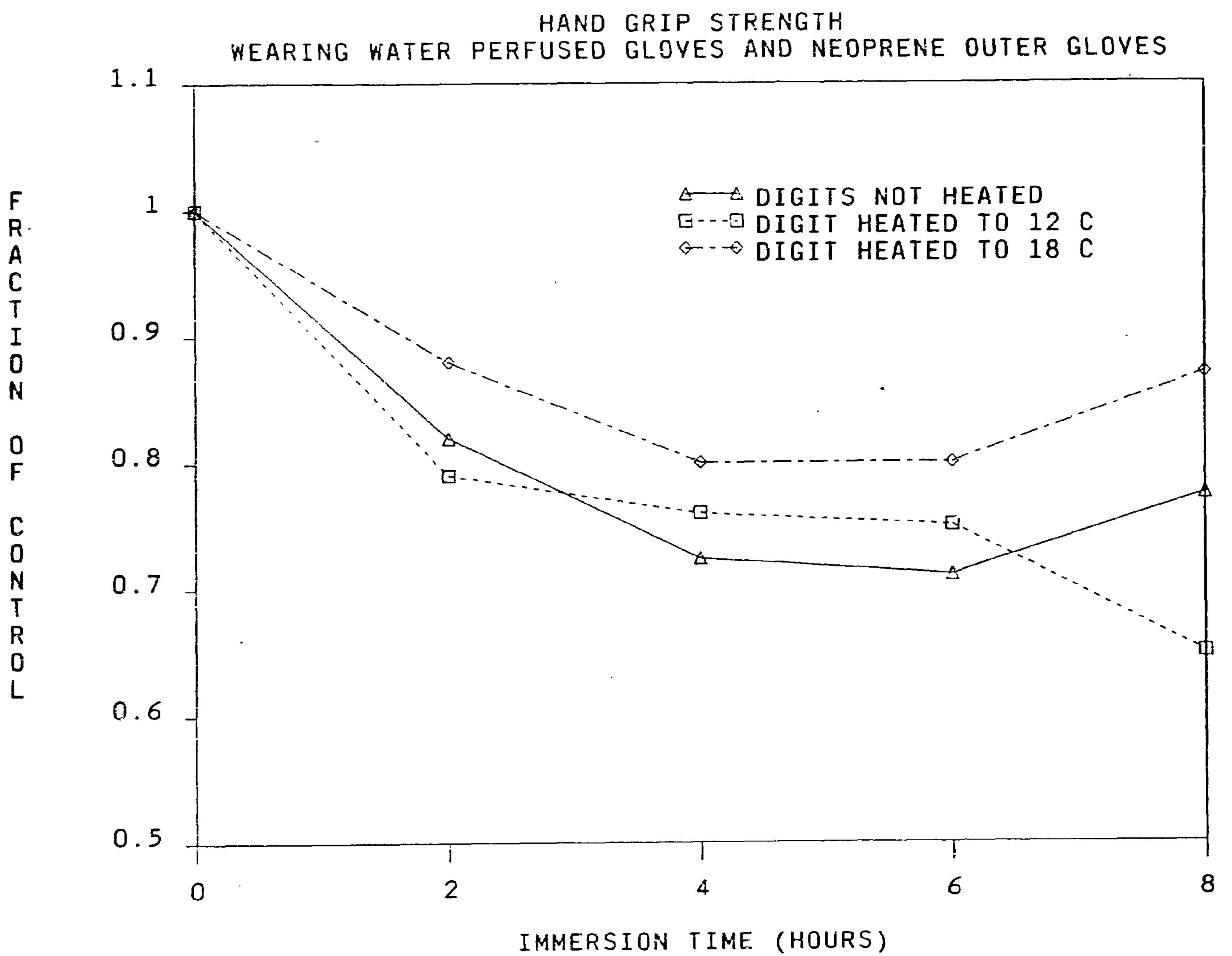

HAND GRIP STRENGTH
WEARING WATER PERFUSED GLOVES AND NEOPRENE OUTER GLOVES
DIGITS NOT HEATED
DIGIT HEATED TO 12 C
DIGIT HEATED TO 18 C
FRACTION OF CONTROL
1.1
1
0.9
0.8
0.7
0.6
0.5
0
2
4
6
8
IMMERSION TIME (HOURS)

FIGURE 10

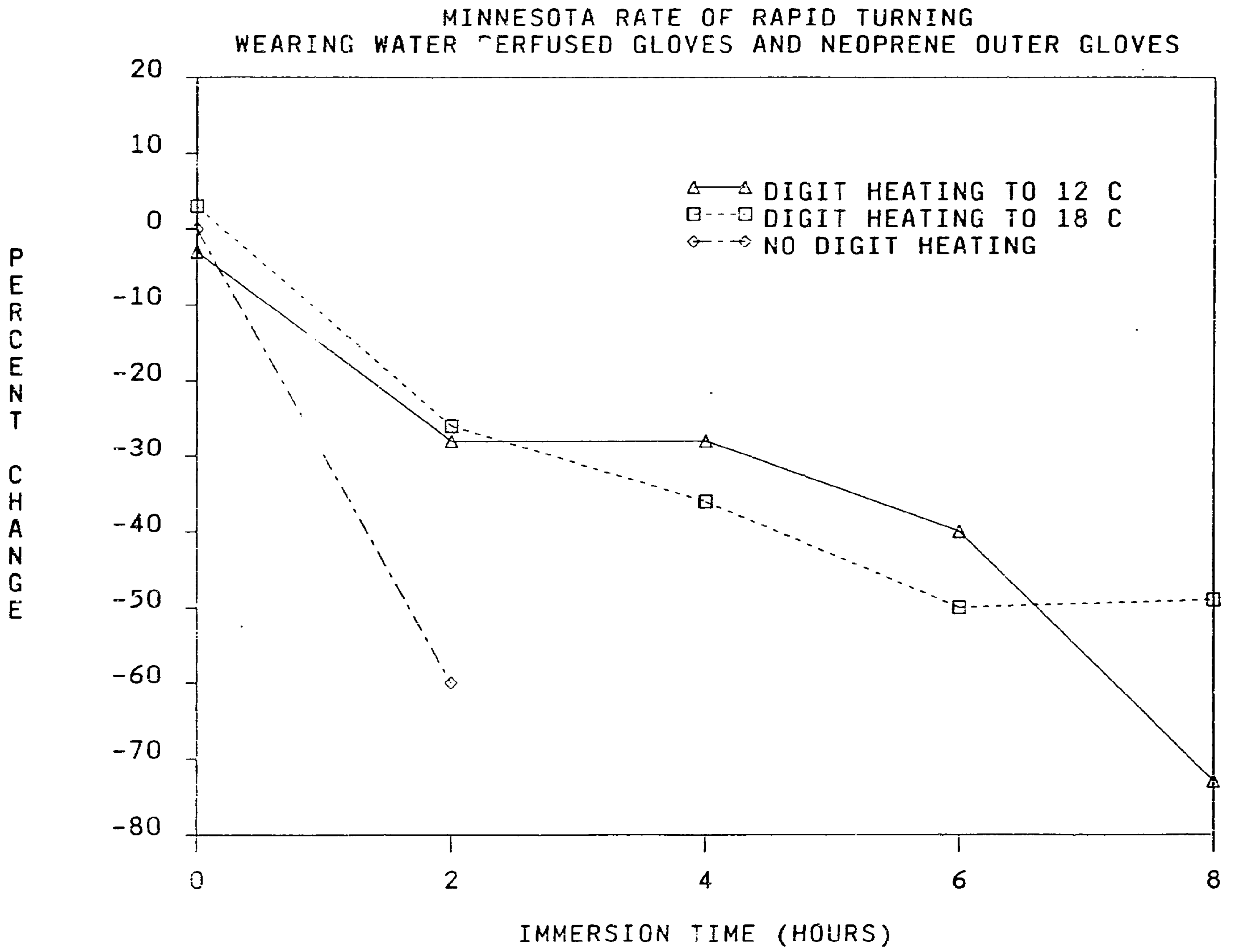

MINNESOTA RATE OF RAPID TURNING
WEARING WATER PERFUSED GLOVES AND NEOPRENE OUTER GLOVES
DIGIT HEATING TO 12 C
DIGIT HEATING TO 18 C
NO DIGIT HEATING
PERCENT CHANGE
20
10
0
-10
-20
-30
-40
-50
-60
-70
-80
0
2
4
6
8
IMMERSION TIME (HOURS)

FIGURE 11

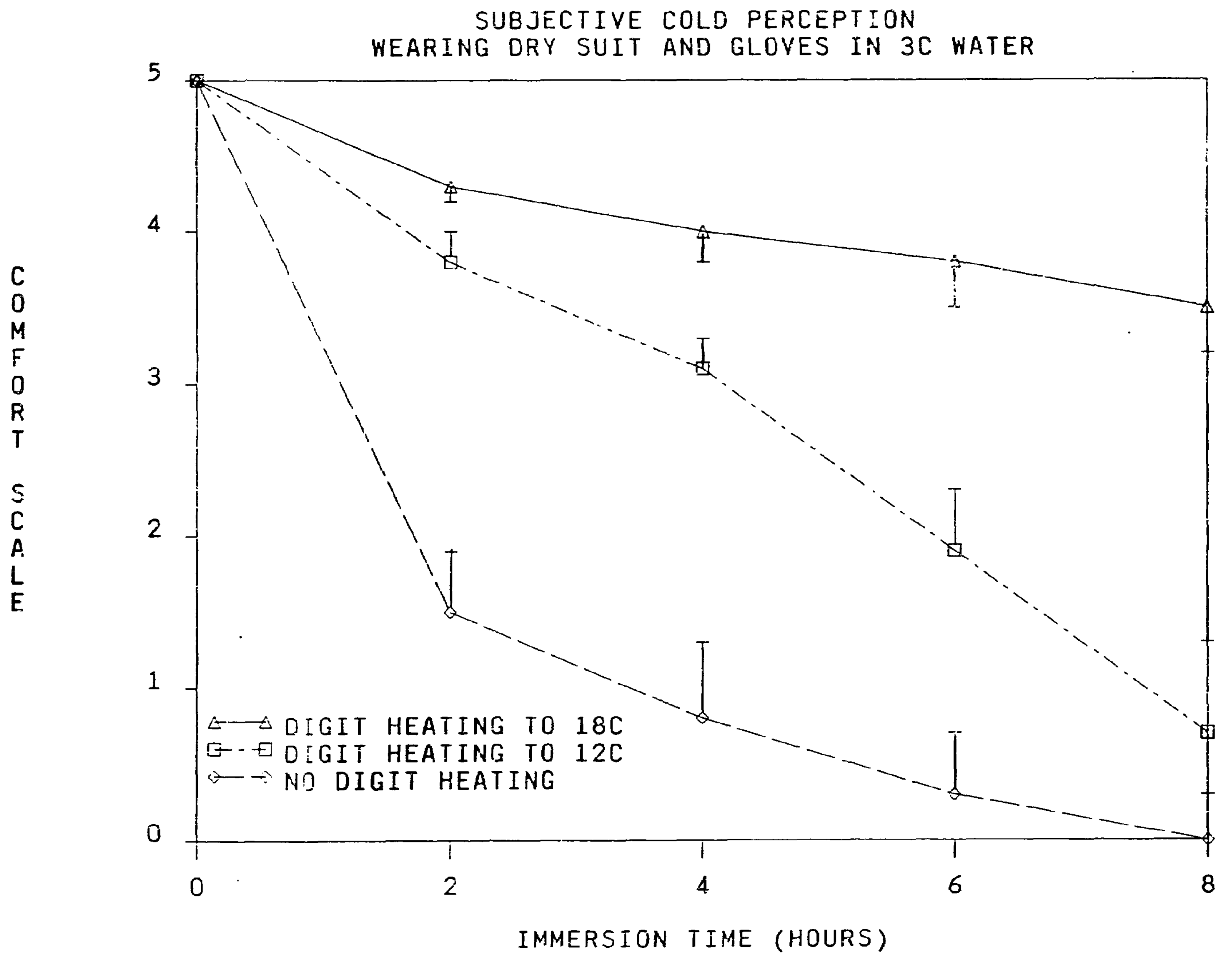

SUBJECTIVE COLD PERCEPTION
WEARING DRY SUIT AND GLOVES IN 3C WATER
COMFORT SCALE
5
4
3
2
1
0
DIGIT HEATING TO 18C
DIGIT HEATING TO 12C
NO DIGIT HEATING
0
2
4
6
8
IMMERSION TIME (HOURS)

FIGURE 12

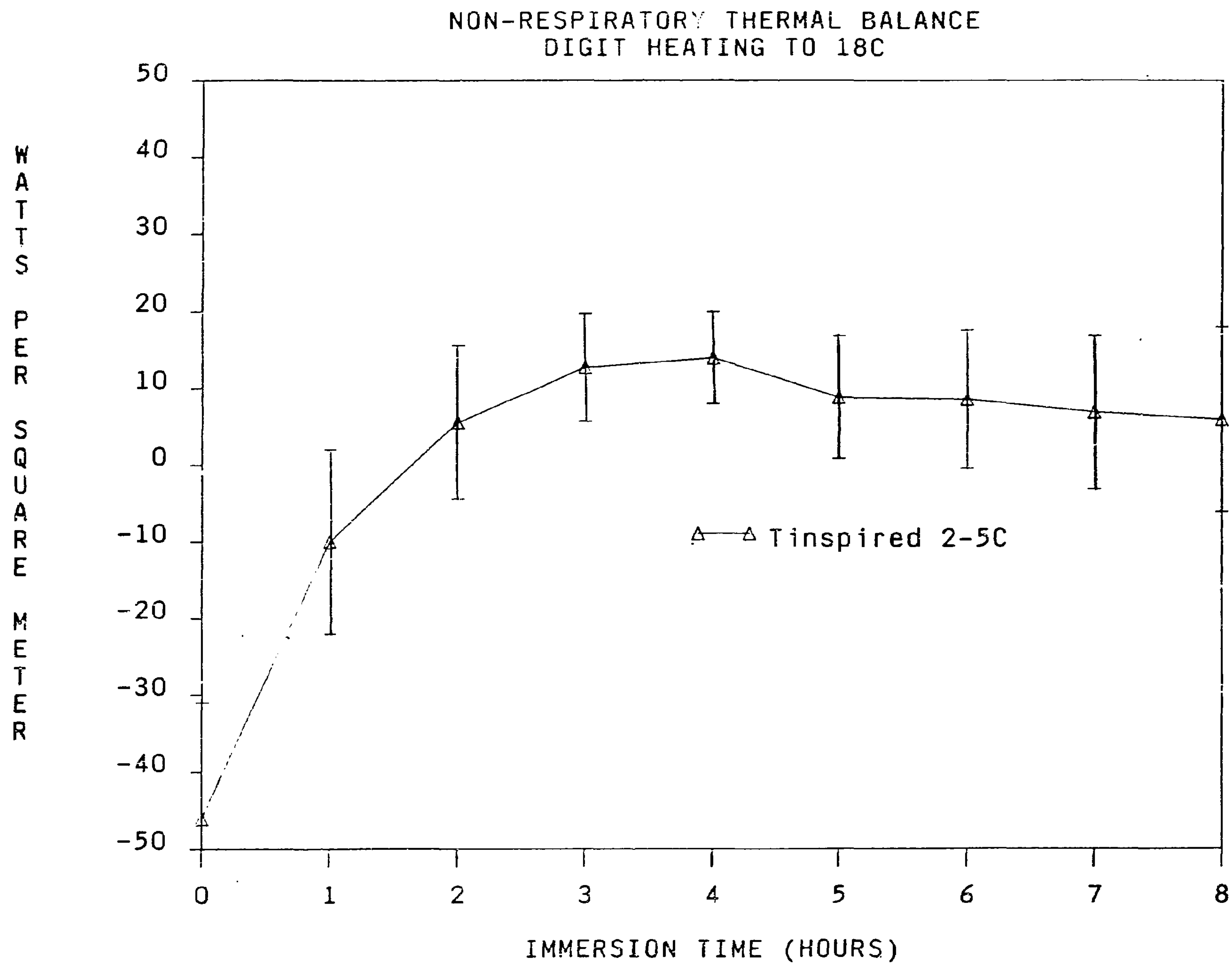

NON-RESPIRATORY THERMAL BALANCE
DIGIT HEATING TO 18C
WATTS PER SQUARE METER
50
40
30
20
10
0
-10
-20
-30
-40
-50
0
1
2
3
4
5
6
7
8
IMMERSION TIME (HOURS)
Tinspired 2-5C

FIGURE 13