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16. Abstract
The purpose of this study was to develop a prototype life preserver that included provisions for: (1) increased thermal protection in the event of accidental immersion in cold water, (2) 35 pounds of buoyancy, (3) a donning time of 15 s for an adult, (4) not weighing more nor requiring more storage space than currently used life preservers, (5) fitting individuals from the 5th percentile of adult females to the 95th percentile of adult males in the U.S. adult population, and (6) self-righting the wearer in 5 s. Evaluations were made to ensure that the prototype life preserver met goals of items (2) through (6). However, the focus of the study was the assessment of thermal response characteristics. To assess the thermal response of subjects wearing the prototype life preserver and a currently used standard personal flotation device, a laboratory study with 10 subjects was conducted. Two subjects, one wearing the prototype and the other a standard vest, were immersed during each experiment in 12.8 $^{\circ}$C (55 $^{\circ}$F) water in the Civil Aeromedical Institute survival tank for 2 hours. Rectal temperature, heart rate, and EKG were measured continuously. Eight of ten subjects, while wearing the prototype life preserver, showed a decrease in the rate of cooling when compared to the cooling rate when wearing the standard vest. The mean cooling rate with the prototype life preserver was 1.15 $^{\circ}$C/h and 1.72 $^{\circ}$C/h with the standard device. Differences were statistically significant at the 0.05 level. Differences in heart rate were also shown to be statistically significant. After 20 min of immersion, subjects wearing the prototype life preserver experienced lower heart rates than when they wore the standard personal flotation device.

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INTRODUCTION

The Federal Aviation Administration (FAA) requires that all commercial extended over water flights must carry life preservers and other safety flotation devices for civilian passengers and crews. However, no provisions are made to protect immersed victims from cold water. Boutelier (1) states that 47 percent of the ocean waters have a temperature of less than 20 °C. The ocean waters off the coasts of the northern United States and Canada range from 0 °C to 15 °C during the winter. In the United States, 215 airports have large bodies of water near the airport departure and approach areas. A representative of the Air Line Pilots Association reports that 78 percent of airliner accidents occur during takeoff, climb, approach, and landing (2).

The problem of providing thermal protection for individuals accidentally submerged in cold water is acknowledged by the military, offshore oil industries, and fishing fleets. However, with an increase in overwater air traffic, the safety of civilian passengers who are being exposed to the potential of accidental immersion in cold water also becomes a concern. If this type accident occurs in water below 18 °C, special protection is needed if victims are to survive until rescue efforts are successful (1). Currently, a personal flotation device (PFD) is provided for civilian passengers; however, this device is designed only to prevent drowning. Three commonly criticized design features of the currently used PFD's are: (i) they encompass only the neck area and no thermal protection is provided to the rest of the body; (ii) the mean donning time ranges from 28.0 to 37.6 s (3); and (iii) when inflated, the cells form a "V" which channels the water directly to the face, increasing the possibility of drowning.

If a life preserver provides a measure of thermal protection, not only are the chances of death caused by hypothermia decreased, but also the chances of death caused by drowning decrease. For example, Golden (4) reported the problem of drowning in cold water as:

> Normally if you keep your back to the wave, the wave goes over the head, but when you stop making that physical effort to keep your back to the waves your legs act as a sea anchor, the top of the body is buoyant, the next wave that comes pushes the top of the body around and you are facing the oncoming wave; you quickly drown in that situation when you lose control of respiration. It depends very much on the frequency of the waves and how much you are able to control your respiration and judge when the next wave is coming. The

small scurring wave going across the big wave is difficult to judge. The minute you inhale a bit of water you start a cough reflex and you have lost all control of respiration at that stage and you very quickly drown. It may well be that the fifty percent survival time figure that we have looked at in the graphs is related to that; it is the time when consciousness is impaired to a degree when drowning occurs and that just occurs when you lose about 2 or 3 degrees in body temperature.

Thus, when determining the degree of thermal protection required, the deep body temperature before the time when consciousness is impaired should be considered. According to Beckman, Reeves, and Goldman (5) conscious muscular activity is lost at 34.4 °C core temperature.

The following accidents demonstrate the necessity of a thermal protective life preserver (6):

SS Lakonia, December 1963, Ship fire with evacuation:

1) Two hundred passengers and crew, all wearing life preservers, were immersed.
2) The rescue operation was effected in approximately 3 h.
3) All passengers and crew survived.
4) The water temperature was 18 °C (64 °F) and was a potential problem.

SS Prinsendam, October 1980, Ship fire with evacuation:

1) Five hundred and nineteen passengers and crew entered life boats.
2) Though less than 100 miles from land, the rescue operation, using ships and helicopters, required 12 h.
3) All passengers and crew survived.
4) The water temperature of 14 °C (57 °F) was a potential problem.

Shetland Islands, HS-748, July 1981, Unsuccessful aircraft takeoff with water impact 50 meters from land:

1) Most passengers were not able to obtain life preservers from under the seats.
2) Airport ground rescue equipment was near the site in 2 min but was not effective.
3) Two helicopters were over the site within 4 min but were not effective due to the weather conditions.
4) Of 47 aboard, 17 drowned, 10 outside the aircraft.
5) The water temperature of 11 °C (52 °F) was a problem.

Washington, D.C., B-737, January 1982, Unanticipated aircraft crash into the Potomac River

1) Of 79 aboard, 73 died of impact injuries, 1 drowned, and 5 were rescued.
2) A Park Police helicopter arrived at the site 21 min after impact.
3) The one drowning probably did involve the effects of immersion hypothermia. The water temperature of near 0 °C (32 °F) was a factor.

The time it took for an effective rescue operation and the cold water temperatures in the above accidents indicate a need for a thermal protective life preserver.

In July 1981, as part of an FAA Water Survival Program, the Director, Office of Airworthiness, requested that the Office of Aviation Medicine (OAM) conduct research in the area of survivability in unplanned crash landings in water for transport and commuter aircraft. The Federal Air Surgeon (OAM), requested that the Civil Aeromedical Institute (CAMI) develop the content and resource requirements for a Water Survival Research Program. The protocol for the program was prepared by the Protection and Survival Laboratory. The protocol was approved, and funding for the program was received in April 1982.

The approved protocol divided the Program into eight work areas. One of these eight areas dealt with concepts for improved types of life preservers. In response to this work area of the approved protocol, the development of prototype life preservers was initiated.

In June 1982, the Supervisor, Survival Research Unit, conferred with the Chairperson, Department of Clothing, Textiles and Merchandising of the Oklahoma State University (OSU) concerning the possibility of cooperative work on pattern development using universal sizing techniques for a vest-style life preserver which also provides thermal protection. Goals for the prototype were to:

1) Provide increased thermal protection in the event of accidental submersion in cold waters.
2) Provide at least 35 pounds buoyancy.
3) Be capable of being donned by an adult in 15 s.
4) Weigh no more and require no more storage space than currently used personal flotation devices.
5) Fit individuals from the 5th percentile of adult females to the 95th percentile of adult males in the United States population.
6) Self-right the wearer in 5 s.

In September 1982, another conference was held with faculty members and graduate students. In December, the project was accepted by a graduate student, Ms. Karla Knoepfli, under the supervision of her Major Professor, Dr. Donna Branson.

Ms. Knoepfli's work and the initial work of the Survival Research Unit were reported in a Protection and Survival Laboratory Memorandum in October 1983 (6). In the early stages of life preserver development, it was advantageous to develop as many prototypes as possible. As the work progressed, it was clear that some ideas should be discarded while others should be pursued further. Among those discarded were the use of a closed-cell flotation foam, hoods, slipover styles, D-rings with snaps, buckles, and crotch straps. Some ideas retained for further investigation included the use of Gore-Tex covered Thinsulate as insulation, zippered fronts, high collars, pull-type cinching straps, and expansion panels. Ms. Knoepfli's subsequent work dealt primarily with universal sizing techniques.

In December of 1983, the senior author accepted further work on life preserver development with renewed emphasis on thermal protection. The senior author accepted the project as an OSU graduate student and subsequently as a member of the Survival Research Unit, CAMI. Three prototypes were developed; however, this report gives results of the evaluation of the final prototype, which most closely met the original goals.

DESIGN DEVELOPMENT

In the development of the design for the prototype life preserver, consideration was given to all the goals stated above, although the primary goal was to provide increased thermal protection.

To be able to keep the weight and storage size at or below those of currently used PFD's, any consideration of a full protection suit was eliminated. To allow for ease and speed of donning and yet provide thermal protection, attention was focused on a life preserver that covered the upper torso. Because of the limited weight, consideration was given to lightweight materials and closure devices which had the ability to be folded compactly, yet provide thermal protection. Polyurethane-coated nylon was used for the air bladder portion of the prototype life preserver. Heat sealing equipment was used to bond the polyurethane film together for an airtight bladder. A light weight conventional zipper was used for closure and one-eighth inch closed cell neoprene was used in the lower back region. A jacket-style air bladder was designed so that the major heat loss areas of the upper torso were protected. Studies using infrared pictures (7) have indicated that the upper chest and back, sides of the chest, and groin area are the major heat loss areas during immersion. Protection for the groin area was not considered due to the additional weight and storage space and the extra time that would be required to don a life preserver that covered the groin area. The air within the bladder appeared to be a practical way of providing insulation without adding additional weight or storage space.

The currently used PFD's are dual-chamber air bladders that are U-shaped and encompass only the neck area. Complicated retention harnesses are used to secure the life preserver to the body (Figures 1 through 3). The current PFD's do not provide thermal protection or allow for ease or speed of donning. The study by Rasmussen and Steen (3) found that the mean donning time for the currently used PFD's ranged from 28.0 to 37.8 s. The same study found that the mean donning time of experimental models (sleeveless jacket-style boating vests) ranged from 15.8 to 16.8 s. Therefore, to take advantage of this rapid donning characteristic, an air bladder was designed as a jacket-style (Figures 4 through 6) with a conventional wide-toothed zipper positioned down the center front for closure. This jacket-style design provides for simplicity and familiarity so that passengers could readily understand how to don the life preserver.

Universal sizing was achieved by the currently used PFD's. However, to enhance thermal protection and retain fit for a majority of the wearers, additional considerations had to be made. Studies by Reins and Shampine (8) found that thermal protection was significantly increased when a suit provided a close fit to the wearer's body. To assist in providing universal sizing, while retaining closeness of fit, one-eighth inch closed cell neoprene was attached to the air bladder in the lower back region (Figure 6). The neoprene allows for 300 percent stretch. It also provides 60 pounds/square inch tensile strength which, reduces the possibility of tearing when stretched.

Another technique for providing closeness of fit involves the proper location of the heat-sealed areas of the bladder (Figures 4 and 6). By heat-sealing the polyurethane-coated nylon in the proper locations, the inflation assists in holding the vest close to the body where desired. Extensive design modifications were made to configure the air bladder so that the life preserver would remain close to the body in the areas of the neck and armholes, thereby restricting water entry and water movement between the preserver and the subject.

Guidelines for determining fit were obtained from anthropometric data (9) for males and females at certain critical measurements. The chest measurement for the prototype vest (uninflated) was the 95th percentile male chest measurement. Although it is 10.8 inches greater than the 5th percentile chest measurement for females, a good fit

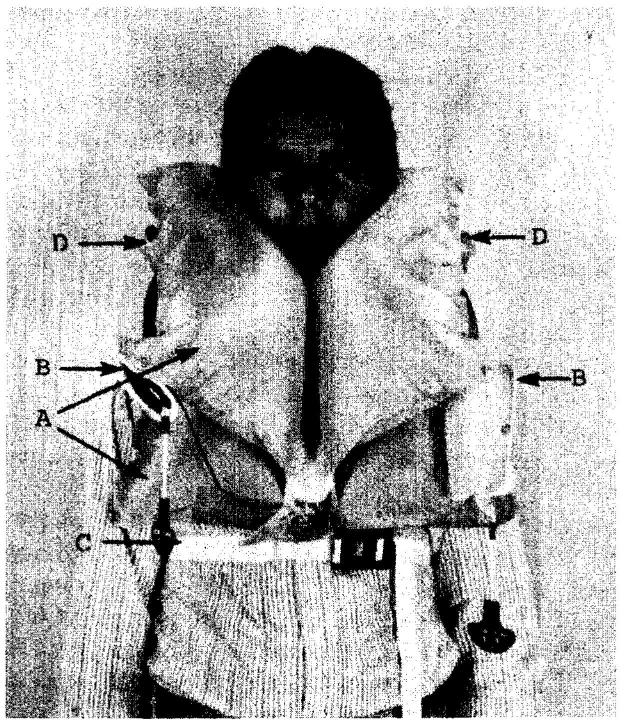

Figure 1. Standard Personal Flotation Device (Front View).
A. Dual-chamber air bladder
B. 16-g CO_2 cylinders
C. Adjustable waist strap
D. Oral inflation tubes

Figure 2. Standard Personal Flotation Device (Side View).
A. 16-g CO_2 cylinder
B. Oral inflation tube

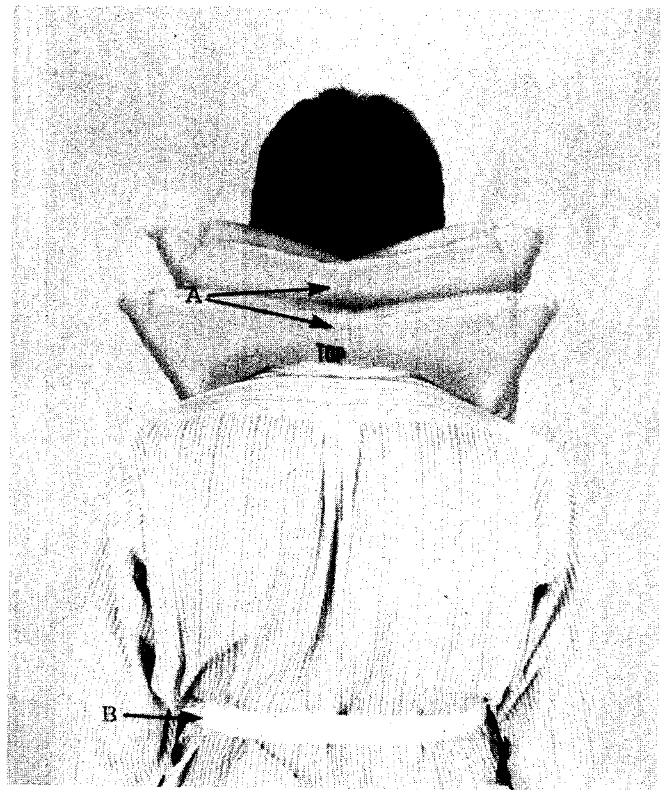

Figure 3. Standard Personal Flotation Device (Back View).
A. High inflatable collar for support of head and neck
B. Waist strap

Figure 4. Prototype Life Preserver (Front View).
A. Single-chamber air bladder
B. One 28-g CO_2 cylinder
C. Oral inflation tube
D. Front zipper
E. Heat-sealed areas
F. Belt

Figure 5. Prototype Life Preserver (Side View).

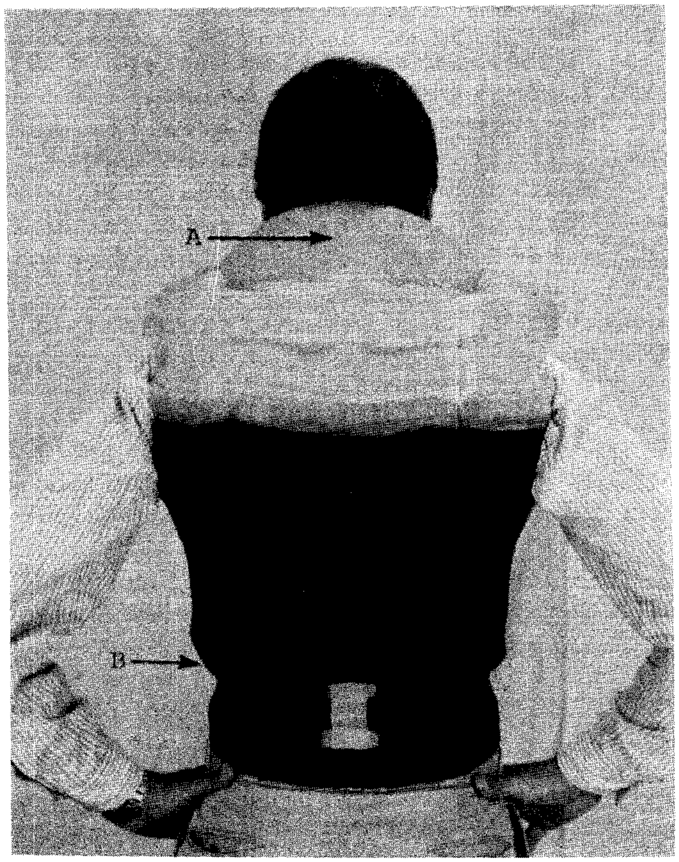

Figure 6. Prototype Life Preserver (Back View).
A. High inflatable collar for support of head and neck
B.. Closed-cell neoprene

for small females is attained when the vest is inflated. Another guideline for sizing was the waist measurement. Thirty-eight inches was selected. This is 14.6 inches larger than the 5th percentile adult female waist and 1.6 inches smaller than the 95th percentile male waist. The large waist measurement was chosen primarily to enhance the ease of donning for the large individuals. When inflated, the prototype life preserver contracted approximately 3 inches in the waist. To provide a better fit and to restrict water entry for smaller adults, a belt that could be cinched was attached to the lower part of the prototype. The belt is also needed to maintain the bladder tightly against the body during immersion. The closed-cell neoprene in the back provided ample stretch for the larger individuals.

So that it would self-right the wearer in 5 s, the vest was designed to place the majority of the buoyancy in the upper chest portion of the prototype life preserver.

Early in the development, a waterproof zipper (open at both ends) was considered. However, this design concept was deleted because the zipper was difficult to close and was expensive. Unlike conventional zippers, the waterproof zipper had to be turned to the inside before it could be fastened at the bottom.

Another discarded design concept was the use of goose down feathers placed inside the air bladder. The feathers were considered due to their high insulating value and compressibility. However, from a manufacturing standpoint, it was impractical because of the difficulty in keeping the feathers inside the bladder during the production process. They also increased the cost significantly.

One other design feature tried, but discarded, was the placement of closed-cell neoprene around the armholes and at the waist to increase sealing and prevent movement of water inside the vest. It was found, however, that this design feature slowed donning efficiency.

<u>Achievement of Goals Other Than Thermal Protection</u>

<u>Goal 2</u>: Provide at least 35 pounds buoyancy

The final prototype life preserver was tested for buoyancy using an Instron Universal Testing Instrument (Model 1123). The initial buoyancy was measured at 38 pounds. Buoyancy was measured at three consecutive 30-min periods following the initial measurement and was unchanged.

Goal 3: Be capable of being donned by an adult in 15 s.

Donning tests were conducted for the prototype life preserver, and the results are presented in Table I. The mean donning time was found to be 17.5 s, and 12 of 26 naive subjects were able to don the life preserver in 15 s or less. Acquisition time is also shown in the table. Acquisition time is the interval from the time both hands are on the unopened package until the time the life preserver is clear of the storage package. Donning time is the interval from the time the life preserver is clear of the storage package until donning is complete.

Goal 4: Weigh no more and require no more storage space than currently used personal flotation devices.

One of the currently used personal flotation devices weighs approximately 1 pound 8 ounces. Typical airline storage space for one life preserver is approximately 5.5 inches wide, 7 inches high, and 3.25 inches deep. The prototype life preserver weighs 1 pound 7 ounces and can be packaged to fit in the required space. Figure 7 illustrates the comparison in packaging for the prototype life preserver and the standard PFD.

Goal 5: Fit individuals from the 5th percentile of adult females to the 95th percentile of adult males in the United States population.

Not enough data were collected to ensure compliance with this goal. However, during the donning test, the prototype vest was donned properly by all 26 naive subjects, and a good fit was achieved by the smallest female (5'1/4" tall and 90.25 lb, clothed), the largest female (5'4" tall and 254 lb, clothed), and the largest male (5'8 1/2" tall and 235 lb, clothed). Subjective observations indicated that it would fit an even wider range of sizes.

Goal 6: Self-right the wearer in 5 s.

Self-righting tests were conducted with FAA personnel in the CAMI survival tank and with OSU students at the OSU indoor pool. Each of 12 subjects donned and inflated the prototype life preserver, assumed a facedown position in the water, and simulated unconsciousness. All were righted to the face-up position in 5 s or less. The smallest individual was a female who was 4'10" tall and weighed 90 lb. The largest individual was a male who was 6'1" tall and weighed 215 lb.

TABLE I

Acquisition and Donning Times of
the Prototype Life Preserver

Subject Number	Age (yr)	Acquisition Time (s)	Donning Time (s)	Total Time (s)
006	22	6.8	12.8	19.6
008	56	4.7	18.9	23.6
010	27	5.3	13.6	18.9
019	34	7.6	23.1	30.7
022	34	4.8	16.4	21.2
024	31	7.5	14.8	22.3
031	29	*	30.9	*
048	22	5.0	20.3	25.3
051	33	*	13.8	*
052	46	*	12.3	*
063	47	5.7	24.9	30.6
069	59	*	12.6	*
081	60	*	28.4	*
084	45	*	12.5	*
087	66	15.4	21.6	37.0
090	43	*	18.0	*
092	21	*	11.1	*
098	59	9.3	12.0	21.3
100	35	4.7	11.2	15.9
104	42	*	13.0	*
112	55	5.3	16.0	21.3
116	61	11.2	13.6	24.8
119	63	9.7	25.9	35.6
122	56	22.5	24.6	47.1
126	47	*	16.4	*
130	61	*	17.5	*
Mean	44.4	8.4	17.5	26.3

*Could not determine beginning of acquisition time because subject's body position blocked the view from preset camera angle.

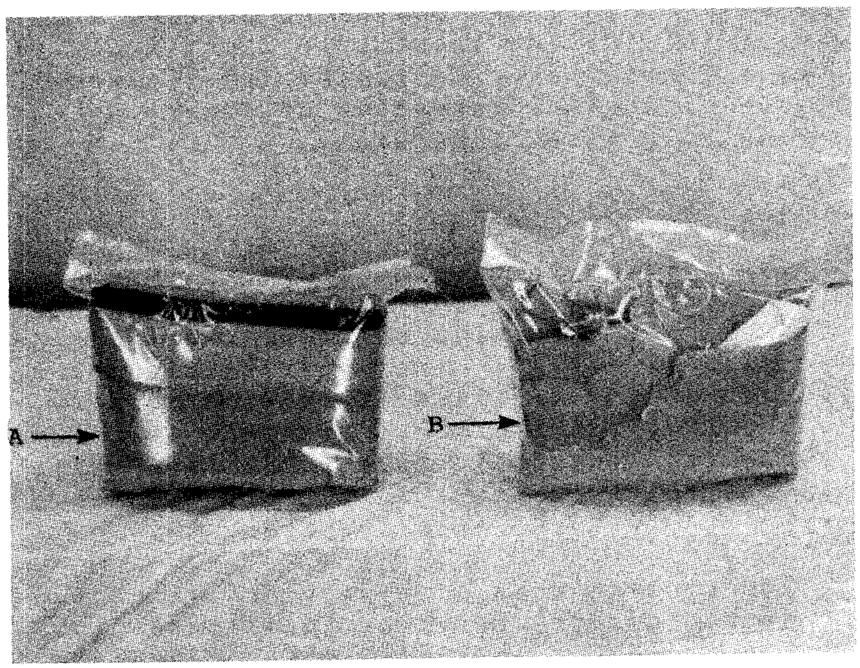

Figure 7. Package comparison.
A. Prototype life preserver
B. Standard personal flotation device

EVALUATION OF THERMAL PROTECTIVE CHARACTERISTICS

Physiology of Immersion Hypothermia

The human body loses heat much more rapidly in water than in air. The thermal conductivity of water is approximately 26 times greater than that of air. Thus, during immersion heat is conducted away from the body to the surrounding water at 26 times the rate it is in air (4). An unclothed man immersed in cold water becomes largely dependent on internal mechanisms to limit this loss of body heat. The following section reviews the internal mechanisms and other physiological responses of humans in the defensive phase during cold water immersion.

Respiratory Responses

The initial shock of cold water immersion will produce hyperventilation with respiratory rates increasing to approximately five times the level of pre-immersion rest (10). The hyperventilation response is greatest during the first couple of minutes, and by 5 min the respiratory rate is reduced to a level more dependent on metabolic rate (10). This response starts from the cold receptors in the skin, which act directly on the respiratory control center.

The consequences of hyperventilation can be serious. The inital gasping response facilitates the breathing of water and, thus, the possibility of drowning. Hyperventilation also reduces the carbon dioxide of arterial blood, which can lead to reduced cerebral blood flow resulting in clouding of consciousness and reduced swimming ability (10).

Cardiovascular Responses

The primary physiological defense during exposure of the body to cold is peripheral vasoconstriction. This causes a reduction in the circulation of blood in the skin and, as a result, heat loss to the environment is reduced. Boutelier (1) reports that peripheral vasoconstriction is proportional to the intensity of cooling and

> ...affects one, two, or all three arteriolar plexi; if cooling is more intense, even some of the muscular blood vessels are involved, particularly in such extremities as the hands, forearms, feet and legs (p. 34).

The effectiveness of peripheral vasoconstriction in reducing heat loss is further increased by counter-current exchange of heat between the arteries and veins that run side by side in the limbs. Boutelier (1) states the effectiveness of counter-current heat exchange as:

> This veritable thermal "shunt" is a particularly effective mechanism; on the one hand, the arterial blood reaches the extremities at a low temperature, so that the heat loss in the extremities is limited by the fact that the temperature difference between the environment is reduced and, on the other hand, the gradual rewarming of the venous blood from the periphery reduces the cooling of the central parts of the organism.

Most of the heat loss from the body in moderately cold water therefore takes place from the trunk and not the limbs (11).

In very cold water (less than 10 °C), cold-induced vasoconstriction may be replaced by cold-induced vasodilation due to the cold paralysis of the vascular smooth muscle (10). This reaction is generally confined to the extremities and involves sudden bursts of vasodilation, which brings a flow of warm blood to the extremities (1). However, this condition may be insignificant to increases in core cooling rate. Hayward (10) explains the possible effects of cold-induced vasodilation as:

> This condition is very obvious from the reddening of the skin of subjects during prolonged immersion in cold water. However, this author has not observed sudden increases in core cooling rate commensurate with skin vasodilation. It is probable that constriction of deeper vessels in warmer tissues is being maintained such that skin blood flow is negligible despite skin dilation.

This rewarming of the skin appears to be considered a protective mechanism in the prevention of cold injuries to the skin.

In regard to other cardiovascular responses to cold water immersion, the heart rate, blood pressure, and cardiac output are also affected. In the initial stimulatory phase, the heart rate increases dramatically and there is an increase in arterial pressure and cardiac output, accompanied by intense peripheral vasoconstriction (1). As hypothermia becomes established, the heart rate and the cardiac output decrease simultaneously with the drop in body temperature (1). This cardiac response appears to have no consistent relationship to peripheral vasoconstriction. Boutelier (1) stated:

> Peripheral resistance shows an opposite change from that of the cardiac output, increasing as the body gets colder. However, if the rectal temperature falls below 25 °C it decreases, showing that there has been failure of vasomotor tone.

Not only is there a failure of the vasomotor tone, but death due to cardiac arrest may also occur. Golden (4) stated, "In humans, death due to cardiac arrest appears to occur between 24 °C and 26 °C, but there have been cases of accidental hypothermia surviving core temperatures of 18 °C."

Metabolic Heat Production

Under basal conditions when no work is being done, all the metabolic energy appears as heat. During physical exertion, more than 75 percent of the increased metabolism appears as heat within the body, while the remainder of energy is converted to work (12).

If an unclothed man is exposed to an environmental temperature below 28 °C, a rise in heat production occurs. This rise in metabolic rate occurs primarily in the skeletal muscles, even before shivering is initiated (12). During cold water immersion when shivering reaches its maximum at a core temperature of 35 °C (4), the overall heat production may be as much as 4.5 times the resting rate (10). Although shivering increases heat production, it also presents problems in conserving heat. Boutelier (1) explains this phenomenon as;

> This production of heat by shivering is not entirely beneficial. Indeed, rapid muscular shaking has the effect of disturbing the boundary layer of still water in the vicinity of the skin and, consequently, leads to an increase in the coefficient of heat exchange in water. In addition, shivering helps to maintain a higher temperature difference between the skin and the water than in the case of passive cooling and increases the losses by convection. Finally, the increased oxygen consumption leads to an increase in ventilation and in the heat losses through the respiratory tract.

When core temperature is between 27 °C and 30 °C, the metabolic rate returns to a resting level (4).

Cooling Rate

If protection is not provided in water temperatures below 25 °C, heat loss overcomes heat production and core cooling results (10). The cooling rate of humans immersed in cold water is largely dependent on individual variation. The major factors that influence cooling rate are human differences (body size, body build, subcutaneous fatness, and shivering response) and behavioral effects (activity and posture). The following outline describes these factors (10):

Individual Differences

Body Size: Small body size has a greater surface area relative to volume. The greater relative surface area has an increased effect on core cooling rate. Thus, children tend to cool much faster than adults.

Body Build: For any one body weight and fatness, ectomorphs have a greater surface area relative to volume and, thus, cool faster than mesomorphs.

Subcutaneous Fatness: Extra amounts of subcutaneous fatness decrease core cooling rate.

Shivering Response: There are considerable differences (intensity and ability of maintaining a high metabolic level) among individuals in their shivering response to cold water. Good shiverers tend to cool more slowly.

Behavioral Effects

Activity: During physical activity, blood circulation is increased to the arms, legs, and skin. This causes core cooling to be 35 percent faster than when the individual is holding still.

Posture: In a curled-up position (arms against the chest and the thighs against the chest), the core cooling rate can be reduced by a significant amount.

Objectives

The objectives of this study were to (i) test and evaluate the thermal response characteristics of human subjects wearing the prototype life preserver and a currently used standard PFD, and (ii) estimate a predicted survival time for these subjects wearing the prototype life preserver and the standard PFD.

Selection of the Sample

Because of the nature of the exposures during these tests, no attempt was made to obtain a cross-sectional sample of subjects. The sample consisted of 10 paid volunteer male subjects, aged 18 to 35 years, in good health. Subjects were selected who would be at minimal risk when exposed to cold water. Table II describes subjects' characteristics. Because the experiment design required subjects to be tested on two occasions, the selection of subjects was focused on individuals who would have a personal interest in the study. Three subjects were solicited from the Oklahoma City Fire Department Water Rescue Team, four subjects from the Oklahoma State University Scuba Club, and three from the general public, including one pilot and one individual with prior scuba diving experience. All subjects were acquired through a CAMI subject contractor.

TABLE II

Subject Characteristics

Subject	Age (yr)	Weight (kg)	Height (cm)
JA	31	97.7	180.3
PP	18	90.0	180.3
MS	30	87.7	177.8
KB	25	93.6	180.3
OB	26	75.0	167.6
BP	24	74.5	177.8
MJ	22	74.1	188.0
AR	23	63.2	175.3
KT	23	65.9	167.6
GR	33	72.7	182.9

Each subject gave his informed consent to participate after being familiarized with all the procedures and purposes of the experiment. The safety criteria required that no subject be using any medication. In addition, subjects were required to pass a medical examination. This examination required a medical history, a physical examination given by an FAA physician, and the donation of blood and urine for analysis.

After acceptance by the physician, the subject proceeded to the survival tank to participate in a trial test. The subject placed a flexible rectal thermistor probe approximately 10 cm (4") beyond the anal sphincter for the measurement of internal body temperature. The subject was also instrumented with adhesive chest electrodes (Figure 8) to which wires were connected for the recording of heart rate and electrocardiogram (EKG). After instrumentation was completed, the subject donned the standard PFD or the prototype life preserver and entered the water for a 15-min period. This trial test gave the subjects an opportunity to become familiar with test procedures and to determine whether or not they were willing to participate in the study. If the subject passed the medical examination and was willing to participate, the tests were then scheduled.

Experiment Design

Table III outlines the experiment design for this study. Two subjects were tested at one time. Two positions in the pool were selected to ensure that both subjects were equal distances from the water current generated by the inlet ports. The prototype life preserver was assigned to position 1 and the standard PFD was assigned to position 2. Each subject wore the prototype in one experiment and the standard PFD in the other experiment. At least 48 hours separated the two experimental tests. The prototype life preserver and the standard PFD were tested on the same day. All subjects wore standard cotton shorts and athletic supporters during the tests.

Instrumentation

The subjects were fitted with three adhesive chest electrodes (Beckman well electrodes, Ag/AgCl, Beckman Instruments, Inc., Fullerton, CA 77036) to which wires were connected for the recording of heart rate and EKG. The CM5 single lead was used to monitor EKG function. The EKG cable was connected to remote monitoring and recording equipment. The EKG was monitored on an electrocardiograph (Burdick EK-5A, The Burdick Corp., Milton, WI) and simultaneously was continuously recorded on a polygraph (Grass Instrument Co., Quincy, MA). The heart rate was also monitored on a heart rate meter that continuously averaged the preceding four beats (Burdick CSS-61, The Burdick Corp., Milton, WI).

TABLE III

Experiment Design

Experiment Number	Tank Position 1	Tank Position 2
1	S-2/V-2	S-1/V-1
2	S-1/V-2	S-2/V-1
3	S-4/V-2	S-3/V-1
4	S-3/V-2	S-4/V-1
5	S-6/V-2	S-5/V-1
6	S-5/V-2	S-6/V-1
7	S-8/V-2	S-7/V-1
8	S-7/V-2	S-8/V-1
9	S-10/V-2	S-9/V-1
10	S-9/V-2	S-10/V-1

Legend: S-1 represents subject 1, S-2 represents subject 2, etc.; V-1 represents the standard personal flotation device, V-2 represents the prototype life preserver.

Figure 8. Subject instrumented with adhesive chest electrodes.

A BIO-TEK analyser (BIO-TEK Instruments Inc., Burlington, VT) was used to check the equipment to ensure that the hazard of electrical shock to the subject was within acceptable limits.

Each rectal thermistor probe was calibrated with its designated recorder via a constant temperature water bath (Haake, Polyscience Corp., Evanston, IL) and a National Bureau of Standards thermometer. Correction factors ranged from -0.13 to +0.05 °F.

Experiment Protocol

Subjects were instructed to refrain from eating between midnight of the preceding day to the end of the test period. Subjects reported for their test session at 8:15 a.m. The tests began at approximately 9:00 a.m. Performing the tests at the same time each day minimized the differential effects on body temperature caused by diurnal variation.

When the subjects reported, they were examined briefly by a physician to ensure that their physical condition had not changed. Blood pressure, pulse, and oral temperature were taken. If no changes were detected, they then proceeded to the survival tank where they were instrumented as during the trial test. Prior to instrumentation subjects emptied their bladders as completely as they could.

After instrumentation was complete, the subjects entered the water. Each test exposure lasted for 2 h or until any of the following conditions occurred: (i) internal body temperature reached 35 °C (95 °F); (ii) an electrocardiographic abnormality was detected; (iii) the subject requested termination of the test; (iv) the attending physician requested termination; or (v) physiological monitoring was lost. The physical activity during exposure was kept to a minimum. The subjects adopted a face-up flotation position (Figures 9 and 10).

While in the pool, the subjects were tethered and each had his own individual observer. A physician, a lifeguard and a video technician were always in attendance during the tests. A team of support personnel was also in attendance to monitor and record heart rate, EKG, and rectal temperature. When the tests were complete, the subjects were brought out of the water on a stretcher. The vests were quickly removed and then the subjects were taken to an adjacent room where assistance was provided to remove the wet shorts and to put on a sweat suit. During the changing of the garments, the rectal thermistor probe remained inserted and EKG electrodes remained attached to allow postexposure monitoring of the subjects. When the changes were completed, the subjects were taken to a warm room where they remained until their internal body temperature reached 36.5 °C. At this time, urine was

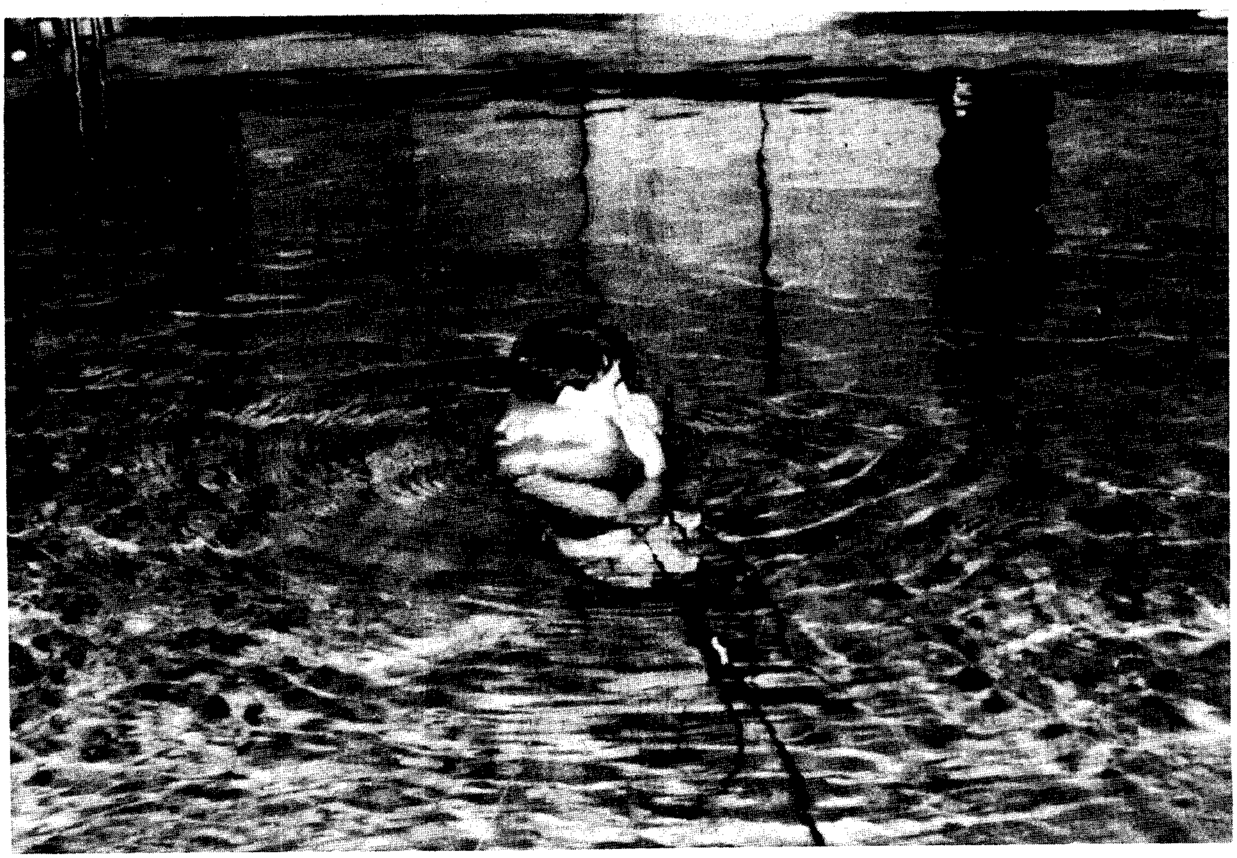

Figure 9. Subject demonstrating a face-up flotation position while wearing the prototype life preserver.

Figure 10. Subject demonstrating a face-up flotation position while wearing the standard personal flotation device.

collected and measured. During the rewarming phase, subjects were provided Gatorade* to drink for rehydration. When internal body temperature reached 36.5 °C, subjects were allowed to take a warm shower, then dress.

Test Conditions

During the period of the study, the water temperature was maintained at 12.8 °C (55.0 °F) +- 0.5 °C and the air temperature was 21.1 °C (70.0 °F) +- 1.7 °C. Water temperature was measured at various locations around the tank, on all four sides and at varying depths. It was measured with a rectal thermistor probe (Yellow Springs Instrument 701). The range of water temperature measured varied only 0.75 °F.

Data Analysis

The subject's rectal temperature, while wearing each vest, was graphed over time. Rectal temperature was measured and recorded every 2 min. Least squares regression was used to fit the data to a straight line for determining the slope from which a cooling rate was established. A paired t-test was used to determine significant differences between cooling rates for subjects wearing the two vests. Differences were accepted as significant at the 0.05 level of confidence.

To determine the rate of cooling, a "linear model" was adopted for this study, which involves two parameters: the time (t) that internal body cooling was established at a fairly uniform rate for all subjects (20 min) and the rate of cooling (r) following this time. The rate of cooling was the slope of the regression line, which was determined from the datum point obtained at t to the last datum point recorded.

Hayward and Eckerson's formula (13) was used with the cooling rate data to estimate predicted survival time (pst). It must be noted that the pst estimates are based on the assumption that the linear cooling rates established during the experimental tests would continue until a lethal level is reached. In this study, estimates of pst for two rectal temperatures (Tr) were determined: 34.4 °C, which is the critical temperature as defined by Beckman *et al.* (5), and 30.0 °C, the critical temperature as defined by Hayward and Eckerson (13). The same formula was used for both determinations:

pst = (Tr at 20 min - lethal Tr)/cooling rate + 20 min

Each subject's heart rate was recorded continuously. Recorded heart rates were counted from the EKG polygraph at

*Registered Trademark

5, 10, 20, 30, and 40 min after immersion began. The rates were also counted during the last 4 min of each subject's immersion test when the rectal temperature was expected to be at its lowest. A paired t-test was used to determine significant differences between subjects' heart rates while wearing the two vests. Differences were accepted as significant at the 0.05 level of confidence.

Results

The complete rectal temperature/immersion time profiles are shown graphically for each subject in Figures 11 through 20. These graphs illustrate the changes in rectal temperature as a function of elapsed immersion time. Figures 21 through 30 present the absolute rectal temperatures over time. Each graph includes the two experimental tests completed by each subject. The standard PFD is labeled as vest 1 and the prototype life preserver as vest 2. Of the 20 immersion tests, five were terminated early due to cramps, gastrointestinal discomfort, or the subject's request. One had to be terminated early due to loss of EKG signal.

The results of the cold water immersion tests are summarized, in terms of cooling rate per hour, in Table IV. The means and standard deviations are shown for each design. Regression correlation coefficients are presented for each subject's cooling rate by vest design. Percentage of improvement in reduction of cooling rate of the prototype life preserver over the standard PFD is presented for each subject. As data show, the mean cooling rate for subjects wearing the prototype life preserver (1.15 °C/h) was less than when the same subjects wore the standard PFD (1.72 °C/h). Differences in cooling rate were statistically significant. The regression analysis shows that there is a high degree of correlation between the immersion time and the change in rectal temperature. This indicates that the assumption of a linear decline used to predict survival times was probably a valid assumption. While wearing the prototype life preserver, 8 of 10 subjects showed a decrease in the rate of cooling over the rate while wearing the standard PFD.

In order to further evaluate the practical significance of increased thermal protection, the cooling rate data of the present study were used to estimate durations to "lethal" levels of hypothermia if immersed in water near 12.8 °C. What constitutes a "lethal" level of hypothermia has been a matter of controversy among researchers. Hayward and Eckerson (13) used a rectal temperature of 30.0 °C as a definition of "incipient death." According to Beckman et al. (5), a rectal temperature of 34.4 °C is the time when conscious muscular activity is lost, which can result in death by drowning. Thus, for this study, the two rectal temperatures (34.4 and 30.0 °C) were used to estimate survival times. These are summarized in Table V.

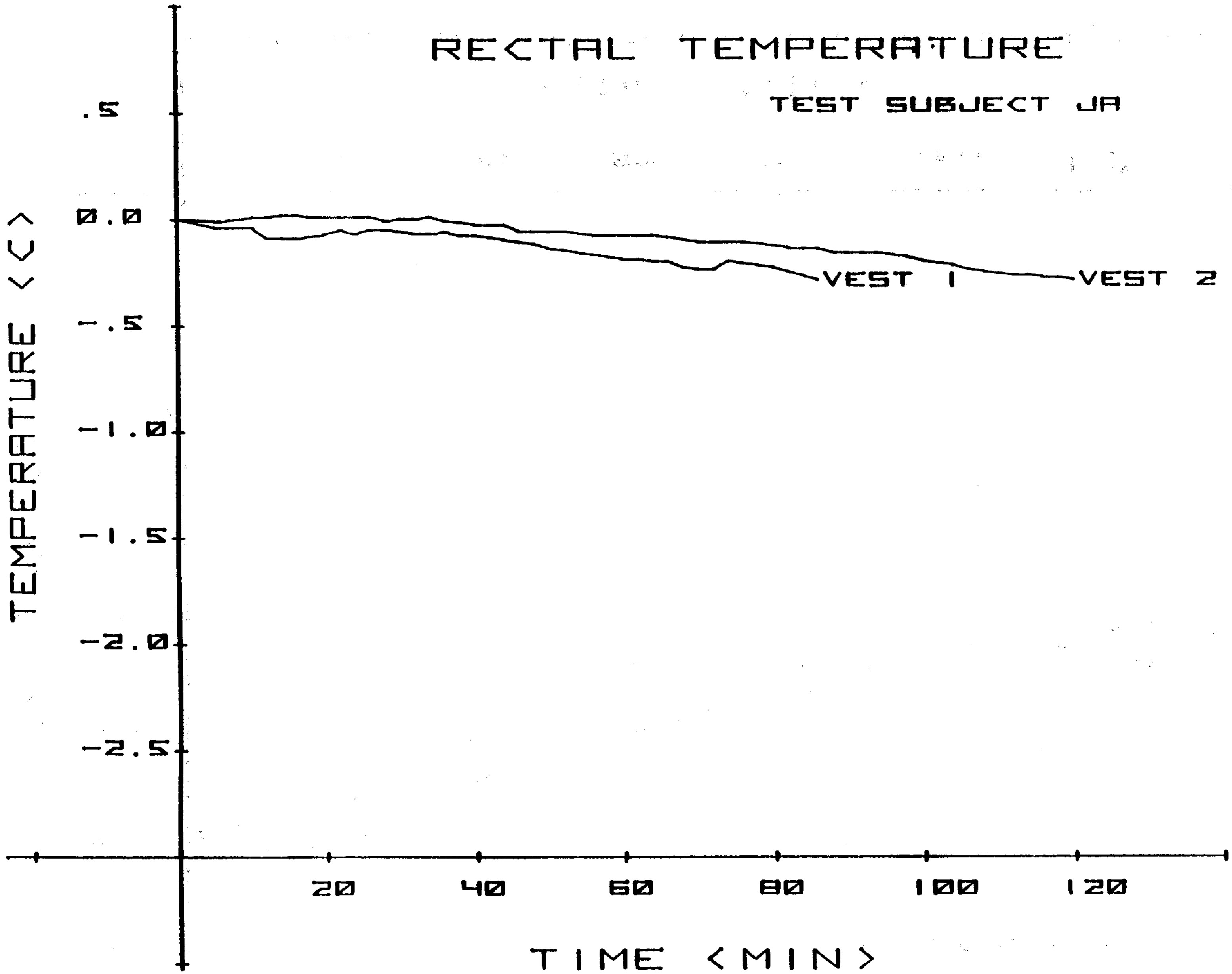

Figure 11. Change from initial rectal temperature (^{o}C) over time during immersion.

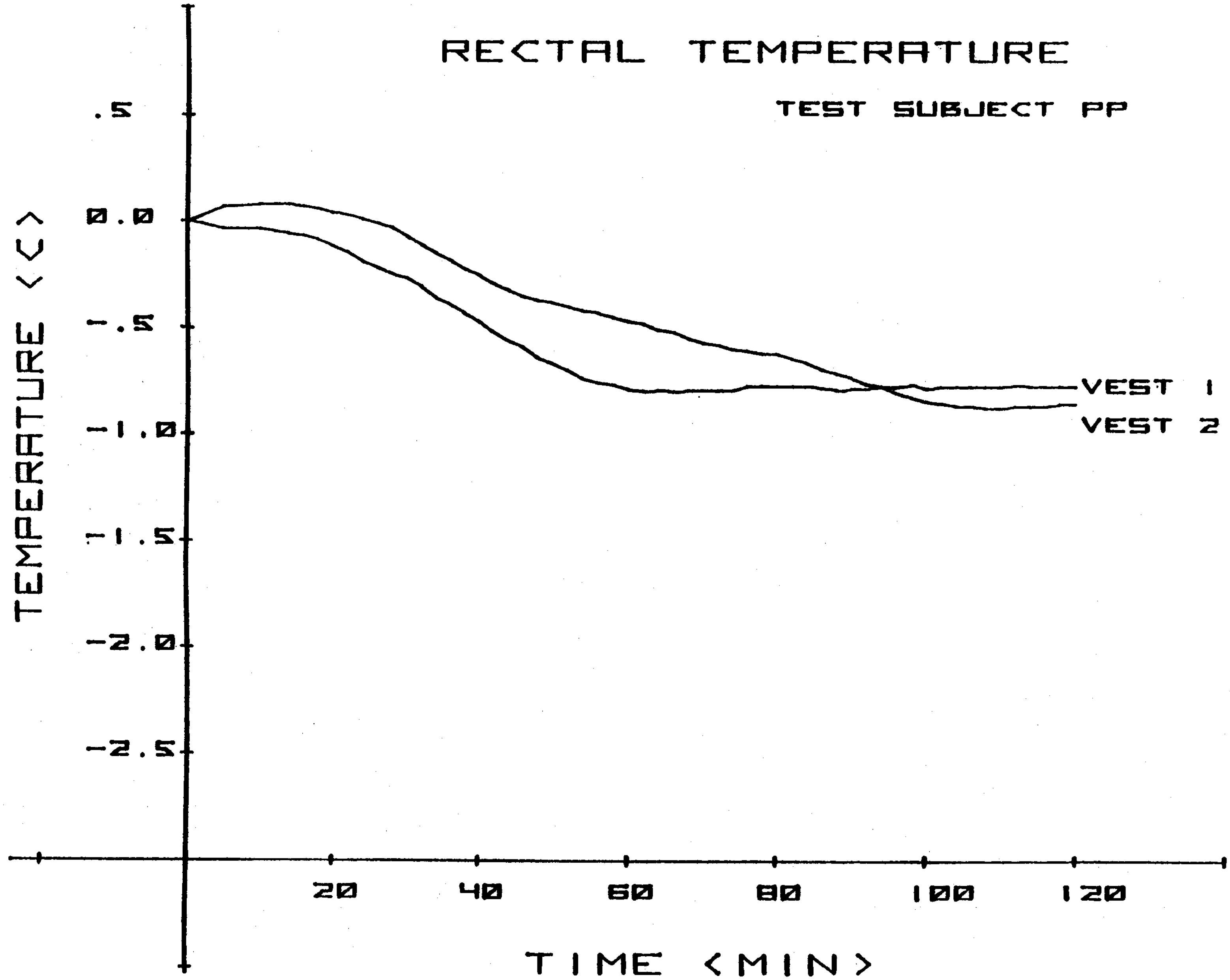

Figure 12. Change from initial rectal temperature (°C) over time during immersion.

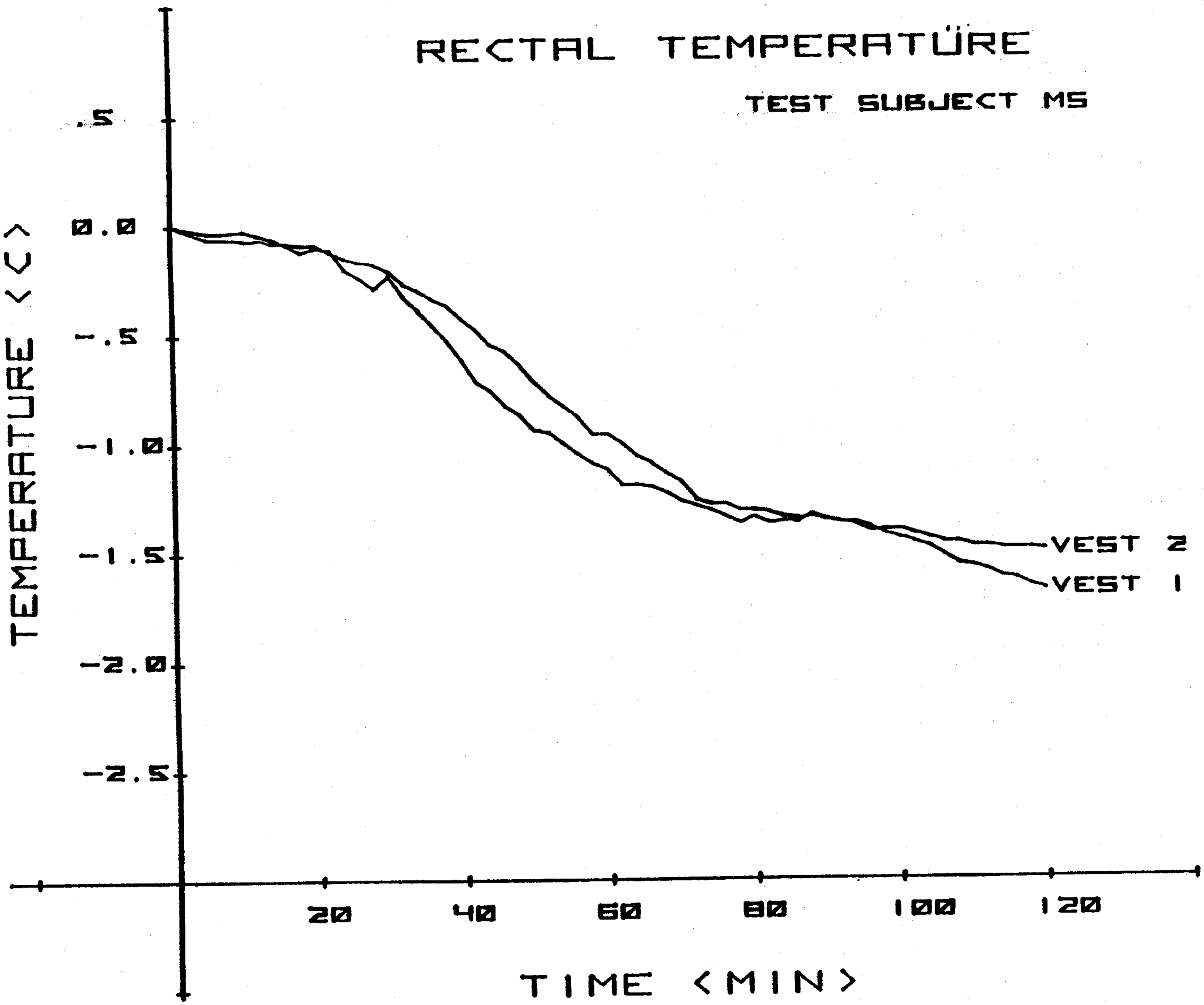

Figure 13. Change from initial rectal temperature (^oC) over time during immersion.

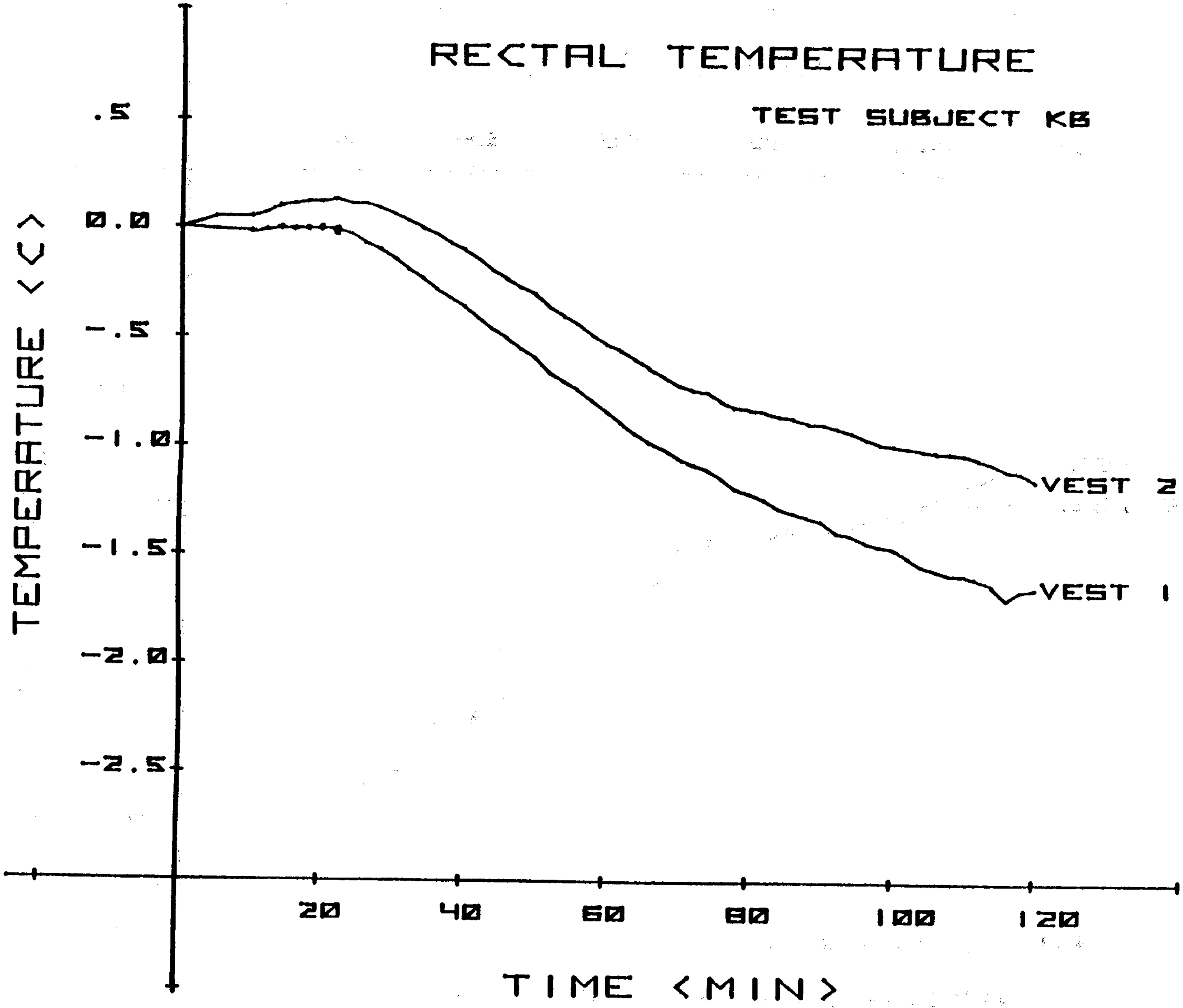

Figure 14. Change from initial rectal temperature (^{0}C) over time during immersion.

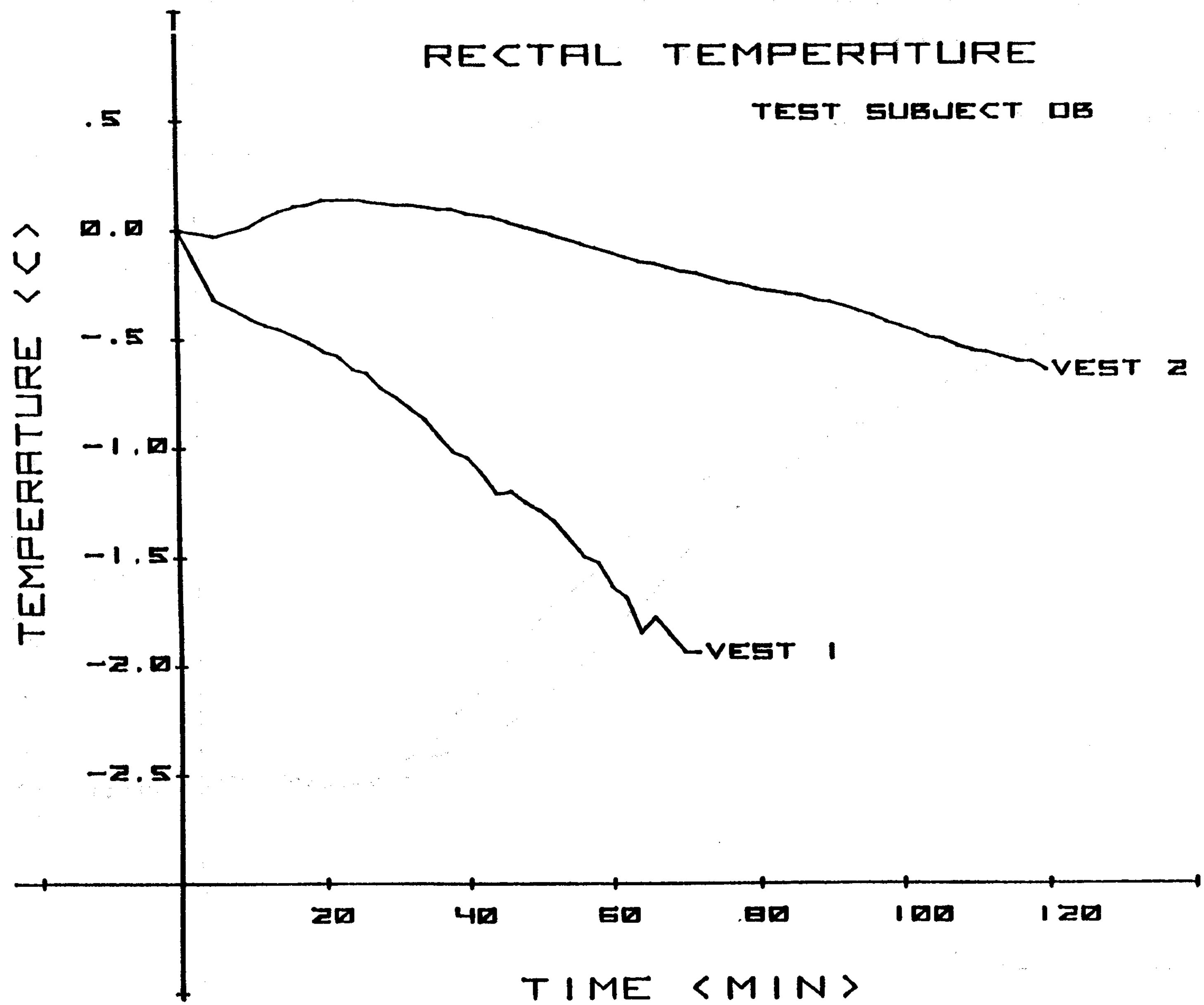

Figure 15. Change from initial rectal temperature (^{o}C) over time during immersion.

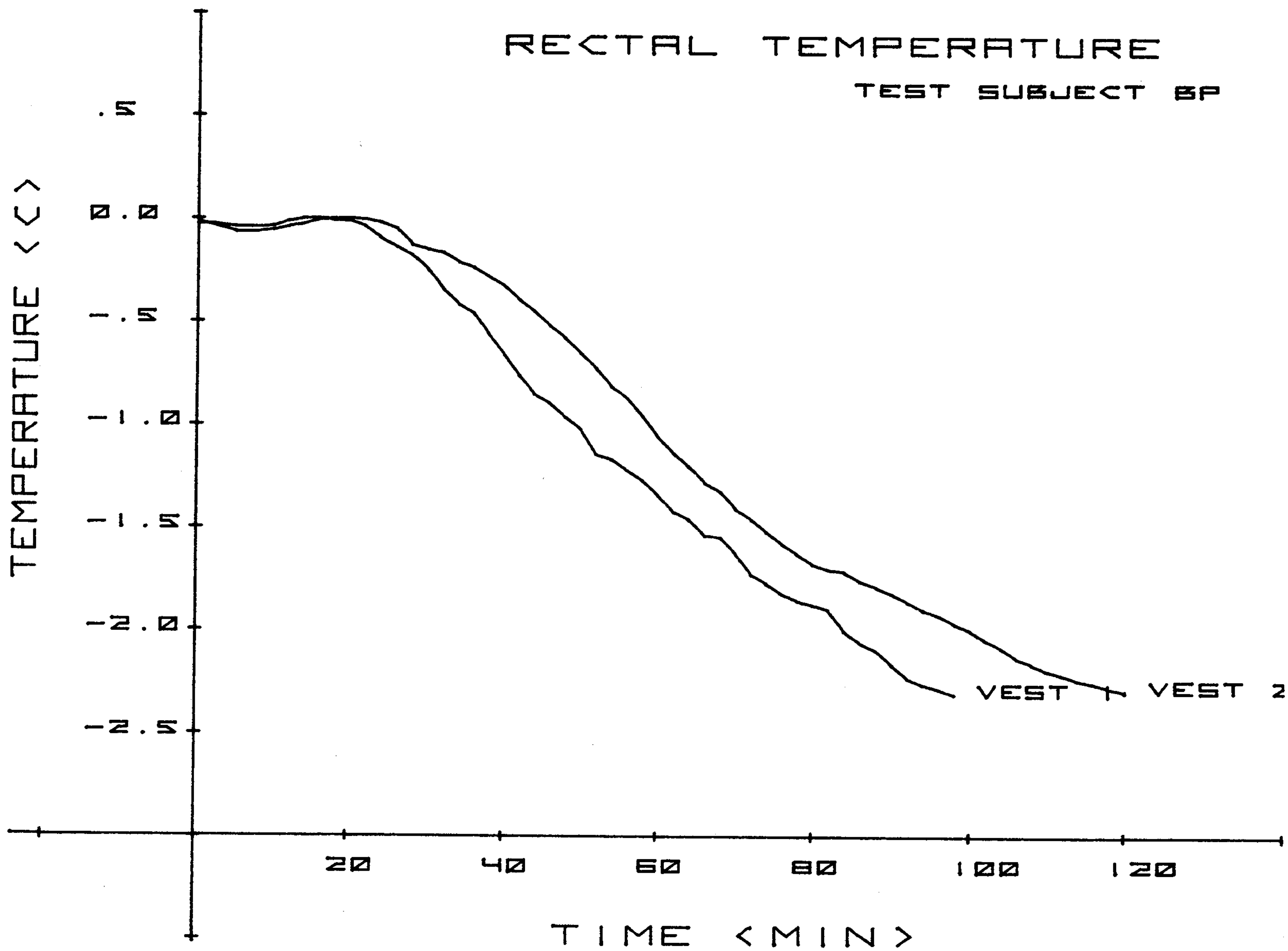

Figure 16. Change from initial rectal temperature (°C) over time during immersion.

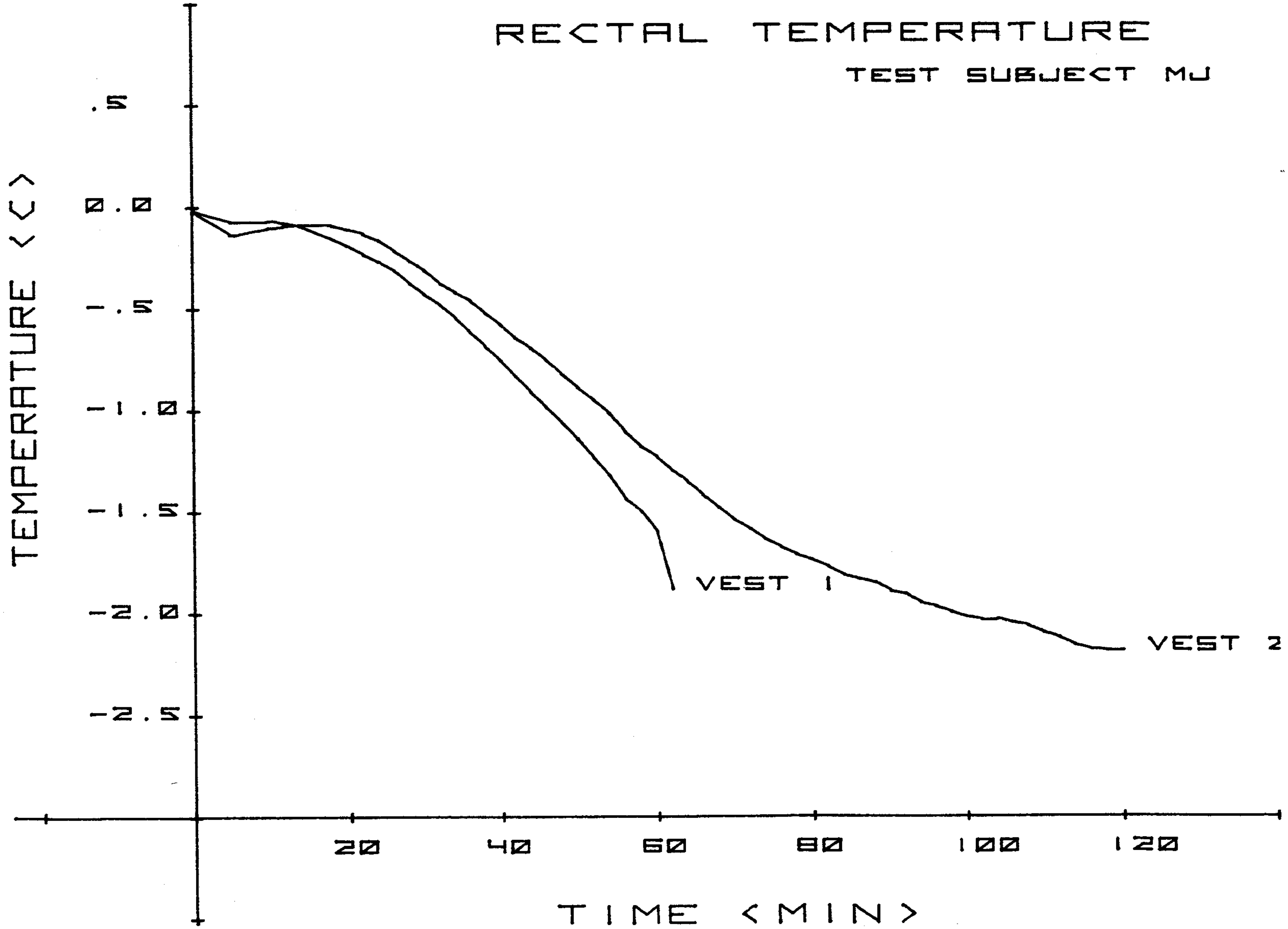

Figure 17. Change from initial rectal temperature (°C) over time during immersion.

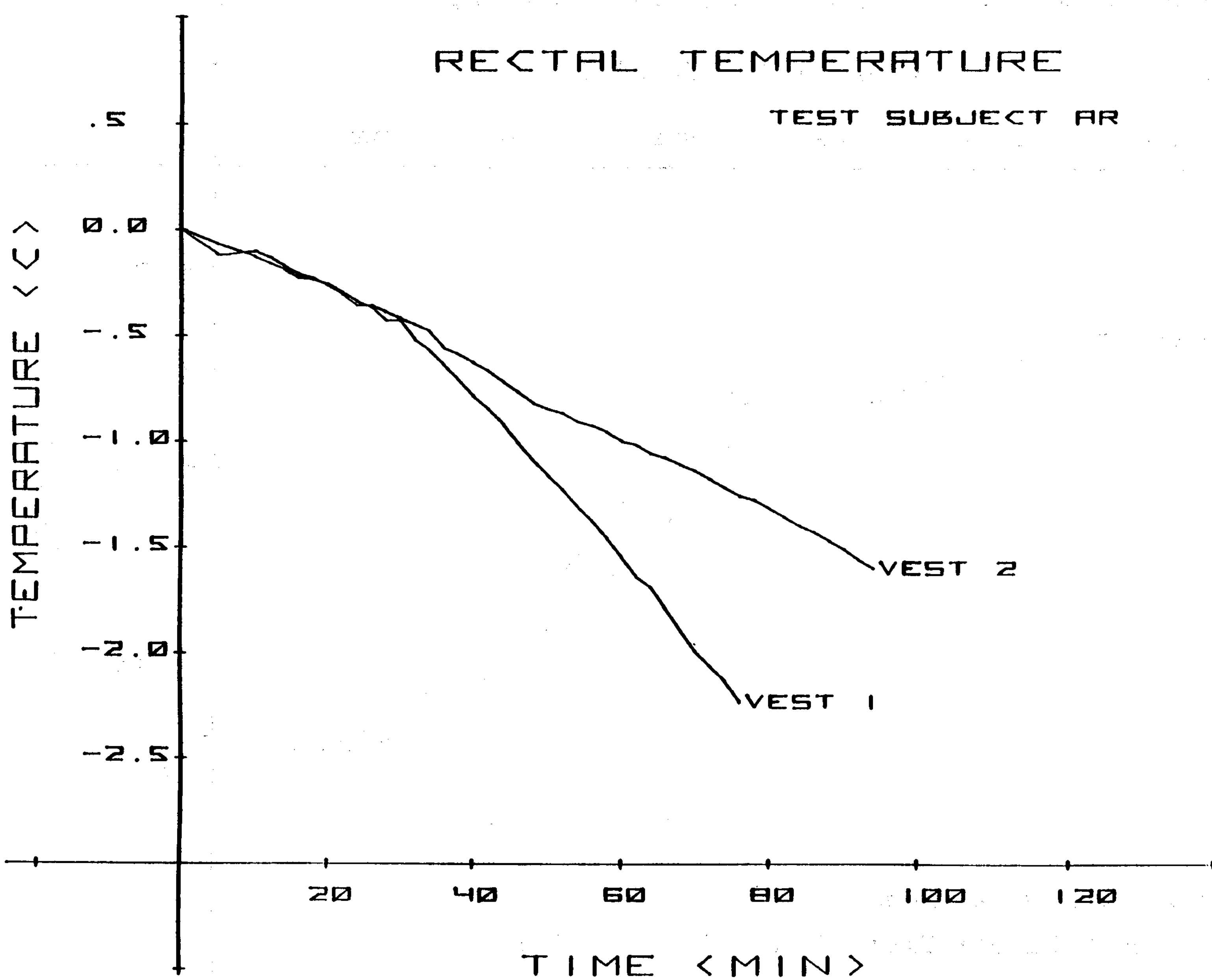

Figure 18. Change from initial rectal temperature (^{o}C) over time during immersion.

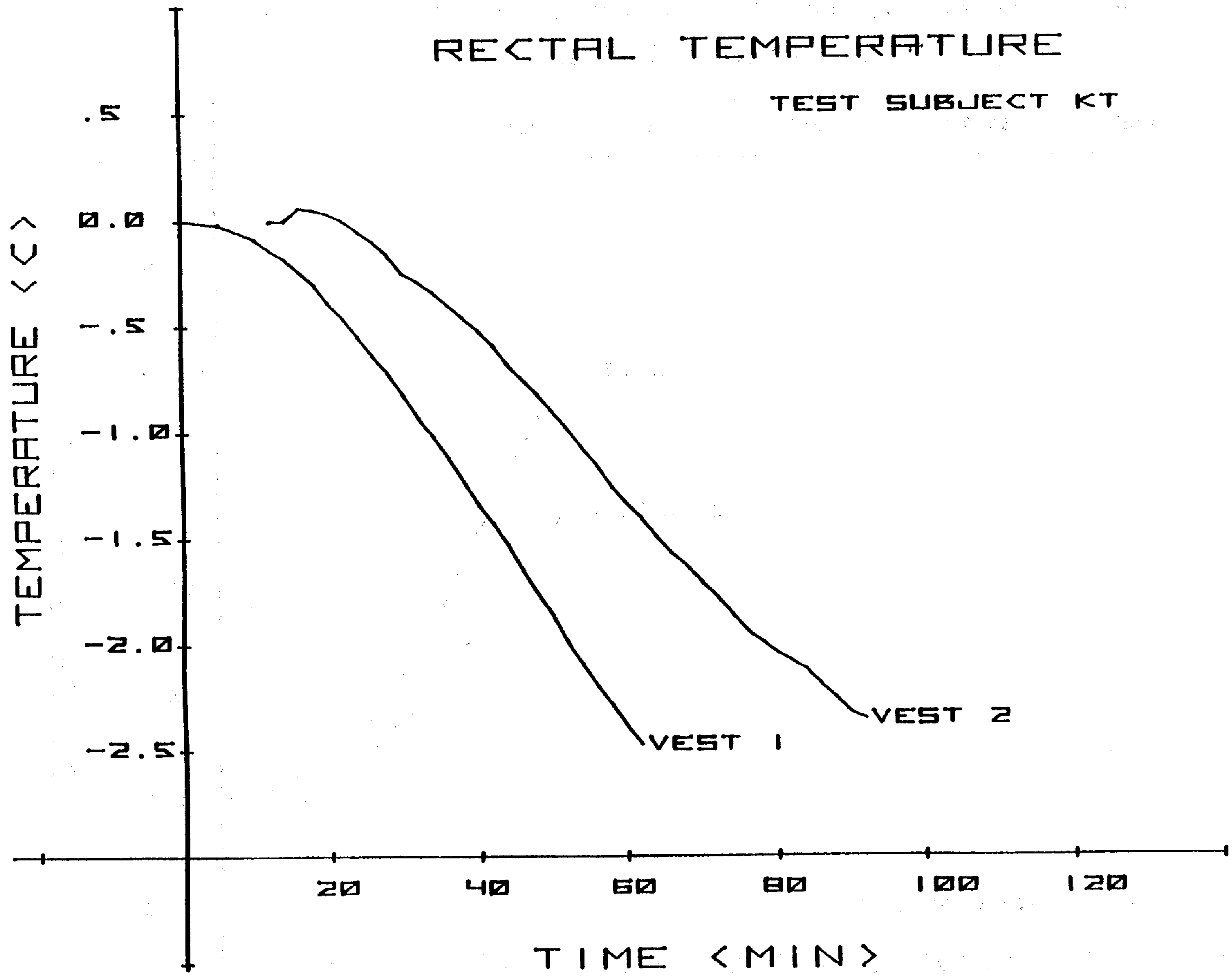

Figure 19. Change from initial rectal temperature (^{o}C) over time during immersion.

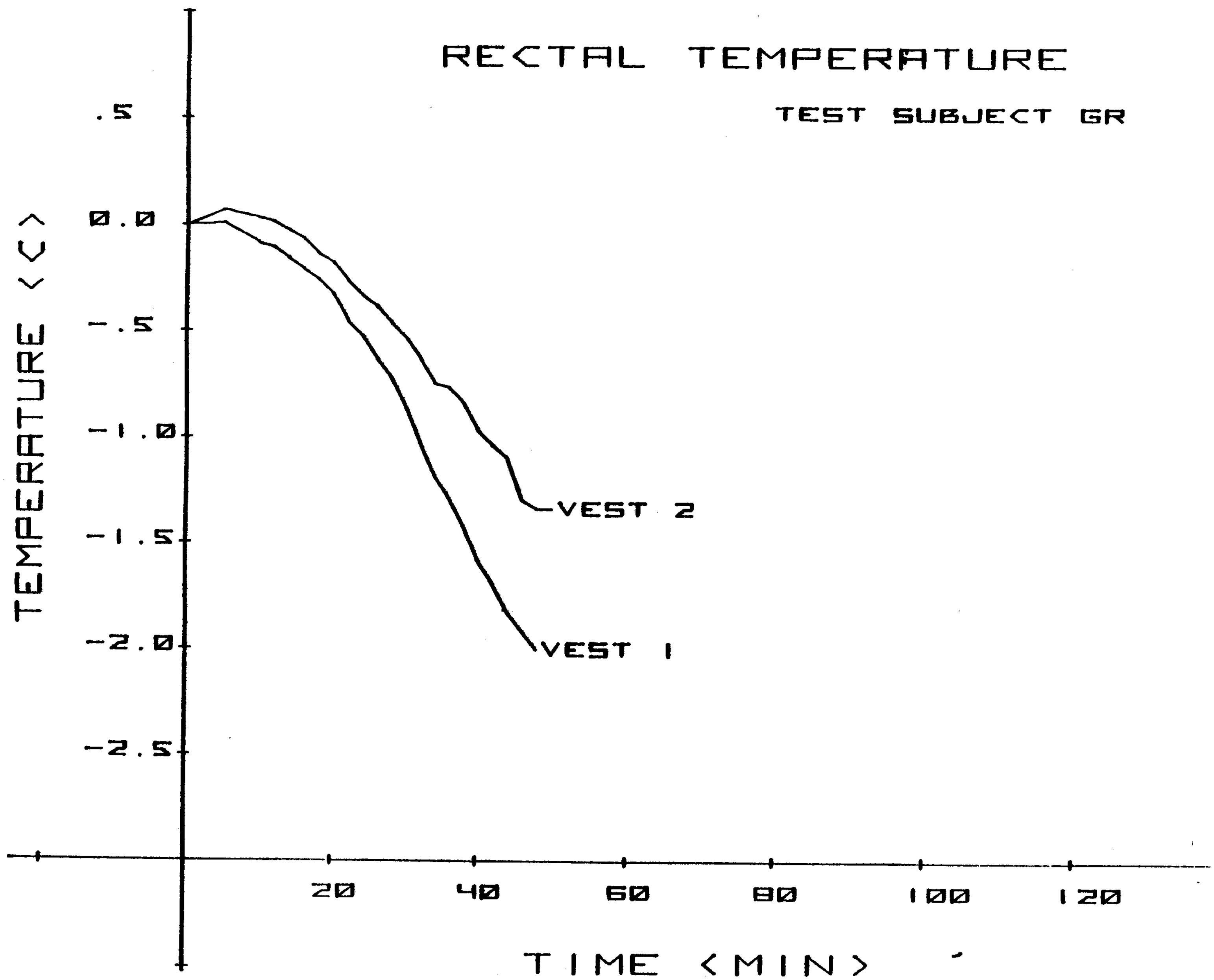

Figure 20. Change from initial rectal temperature (^{o}C) over time during immersion.

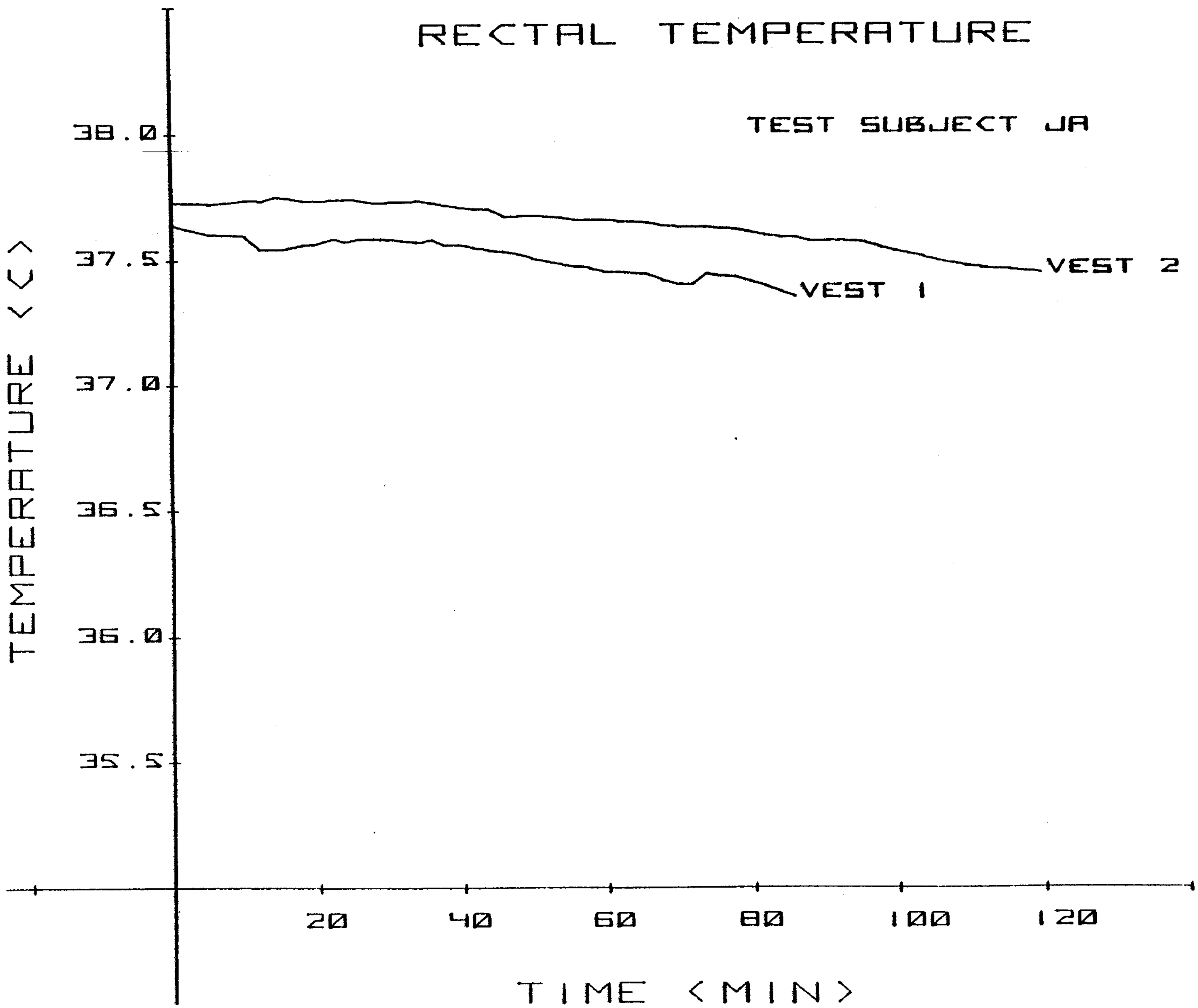

Figure 21. Rectal temperature vs. time during immersion.

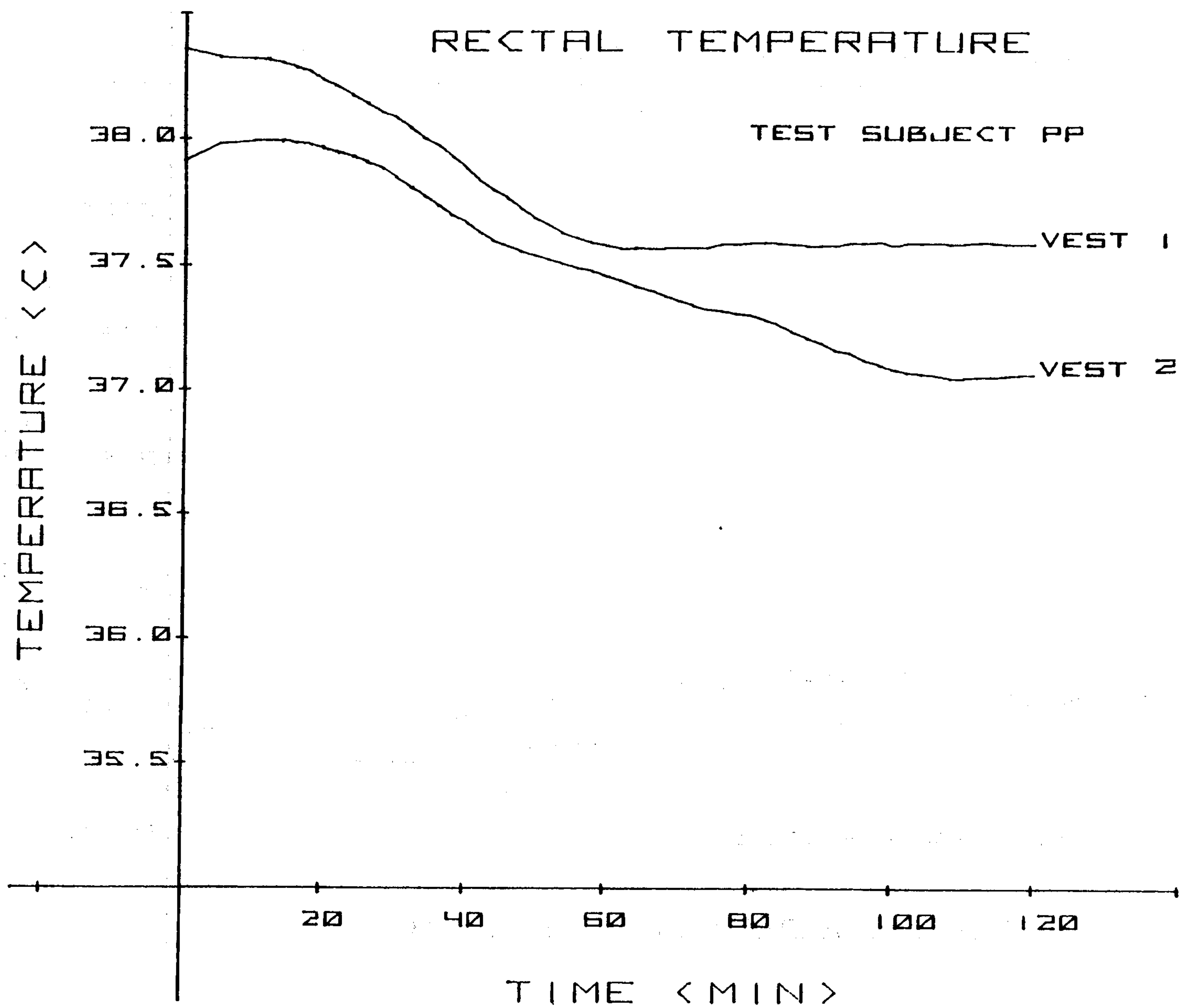

Figure 22. Rectal temperature vs. time during immersion.

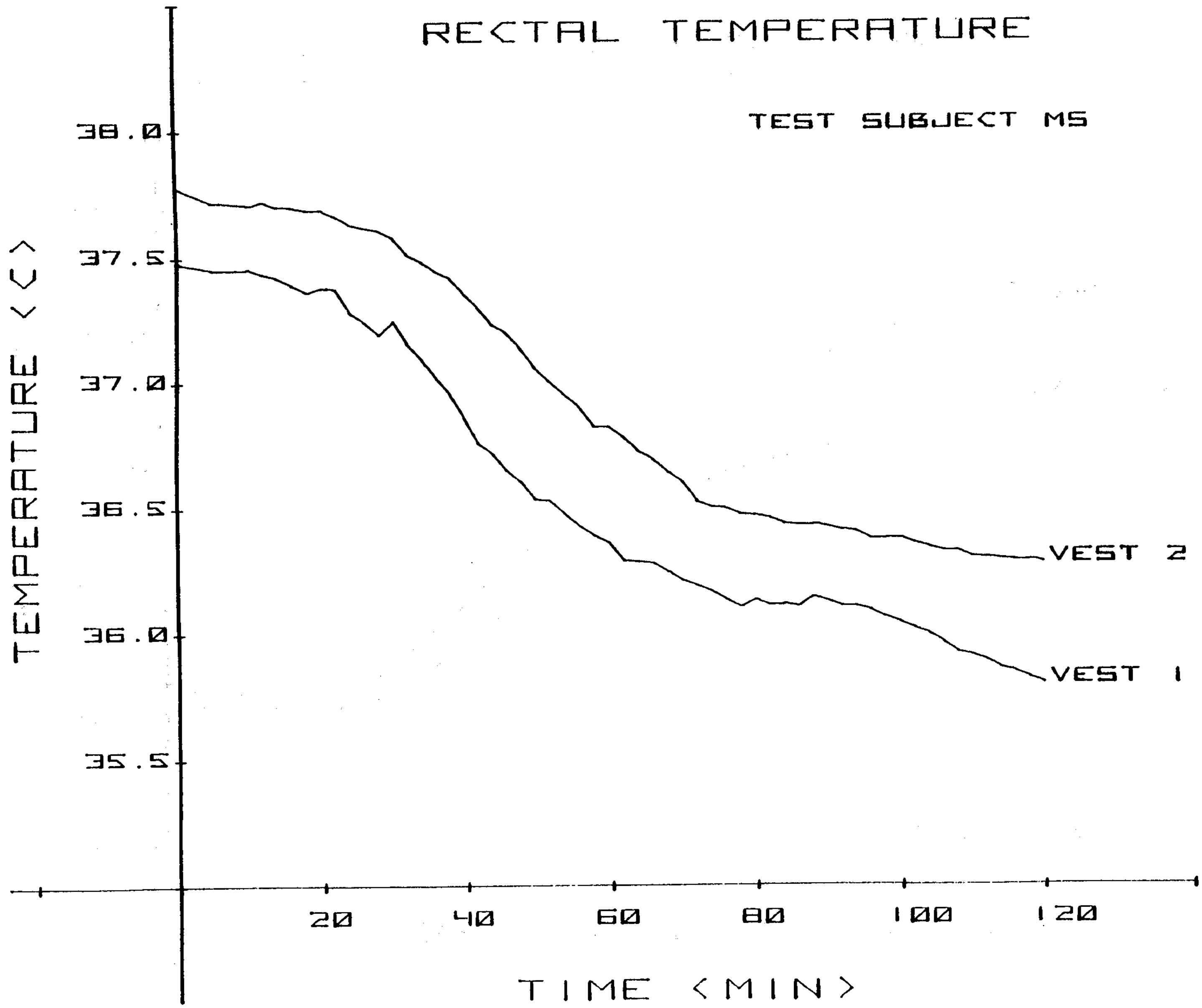

Figure 23. Rectal temperature vs. time during immersion.

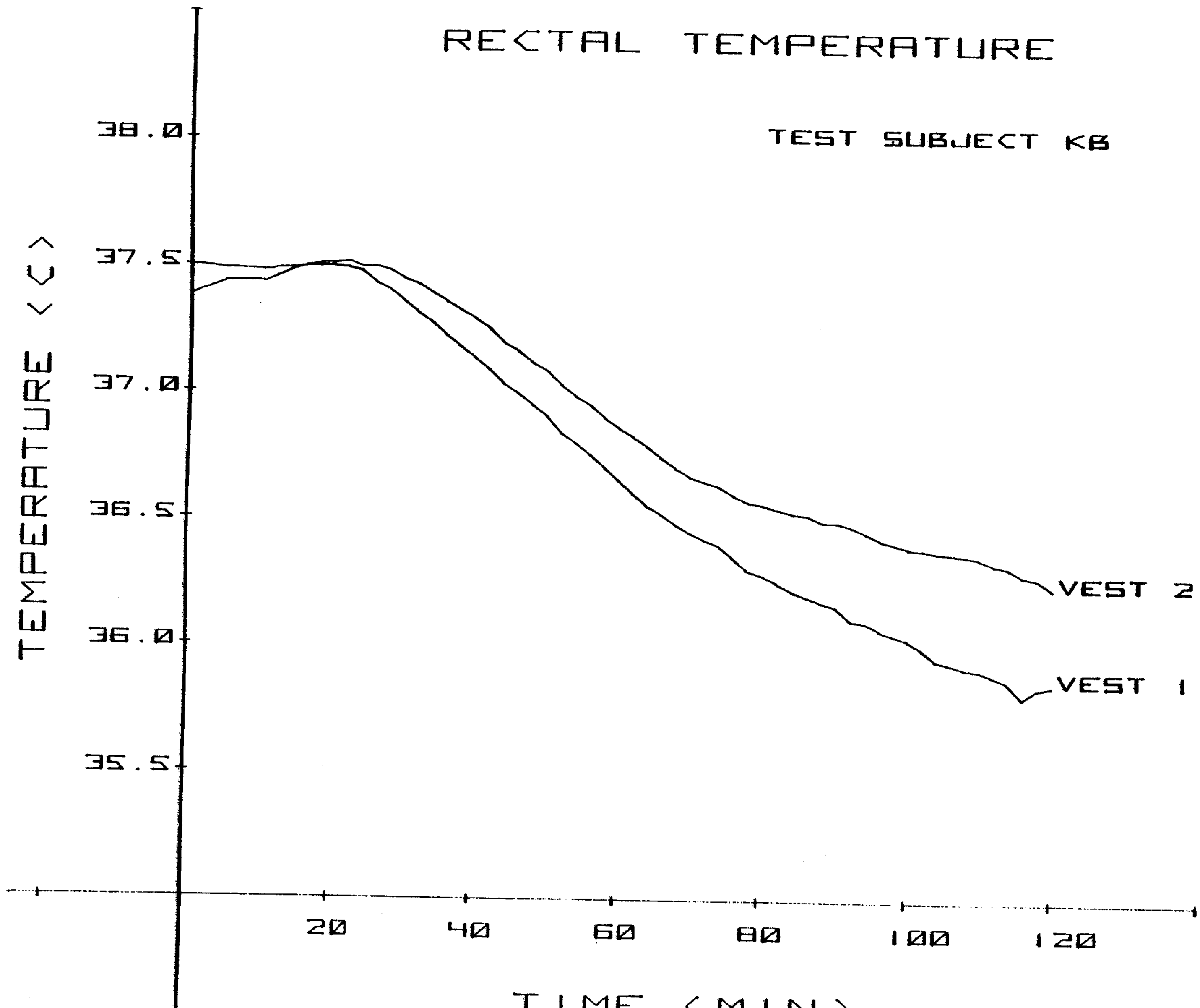

Figure 24. Rectal temperature vs. time during immersion.

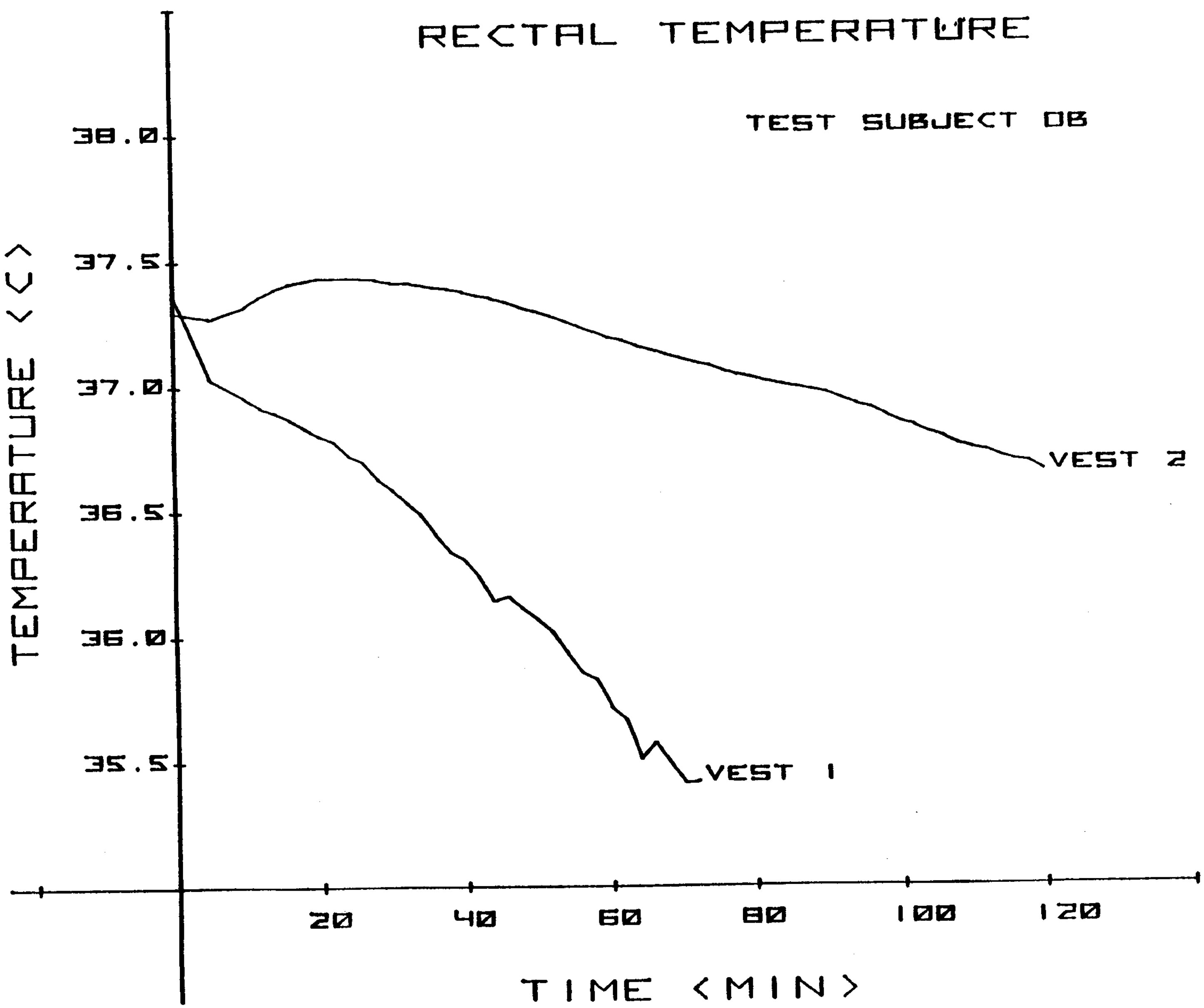

Figure 25. Rectal temperature vs. time during immersion.

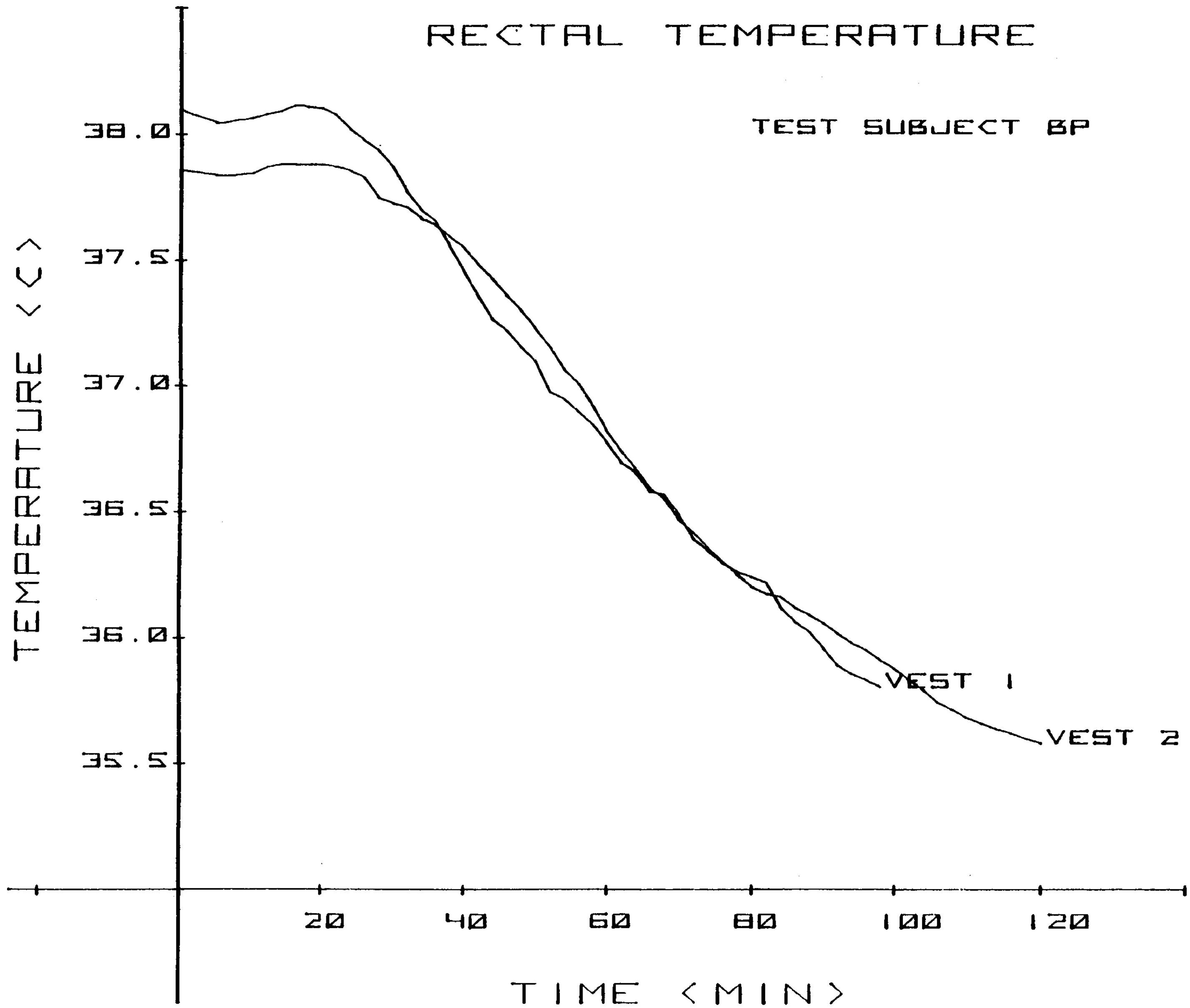

Figure 26. Rectal temperature vs. time during immersion.

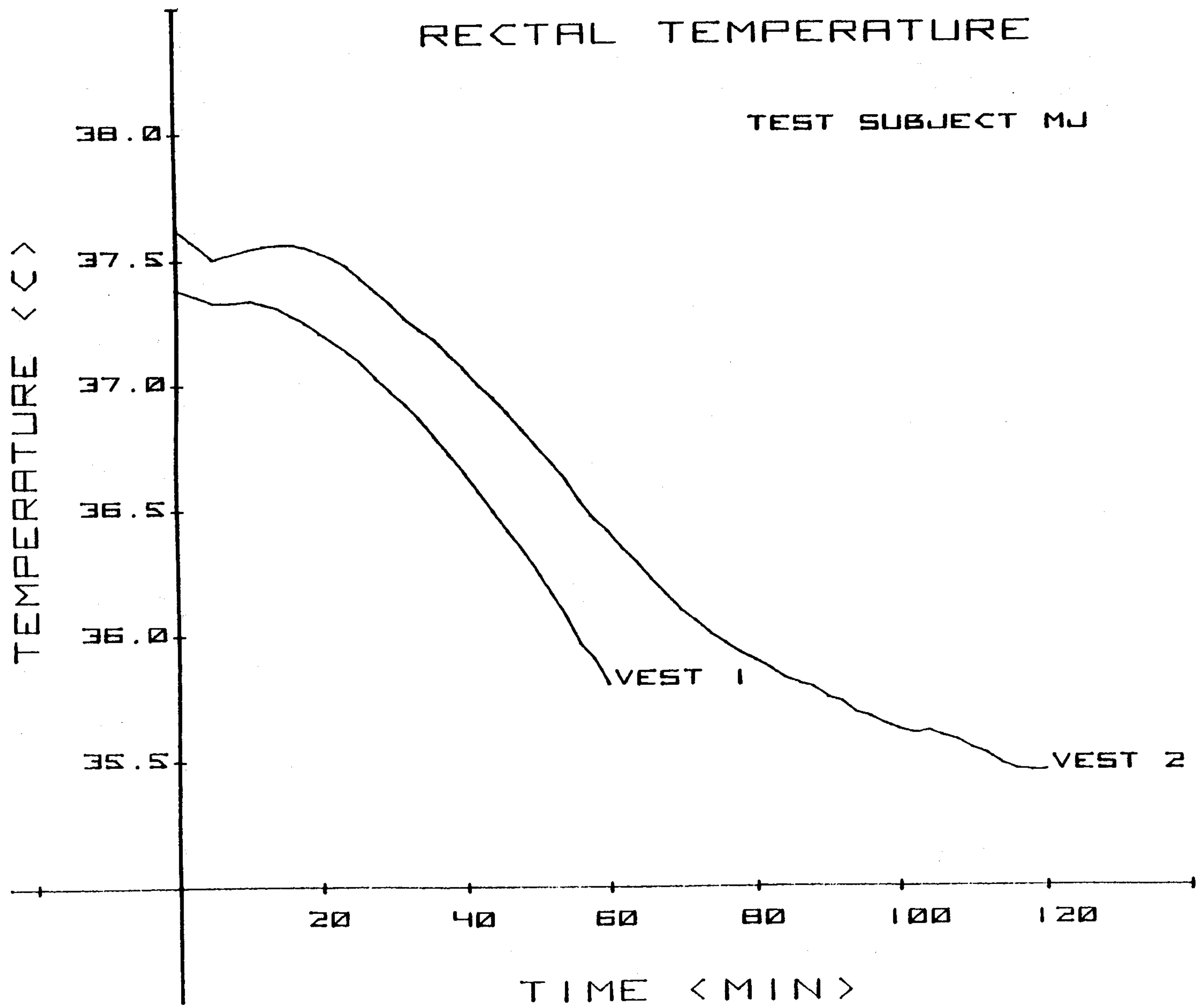

Figure 27. Rectal temperature vs. time during immersion.

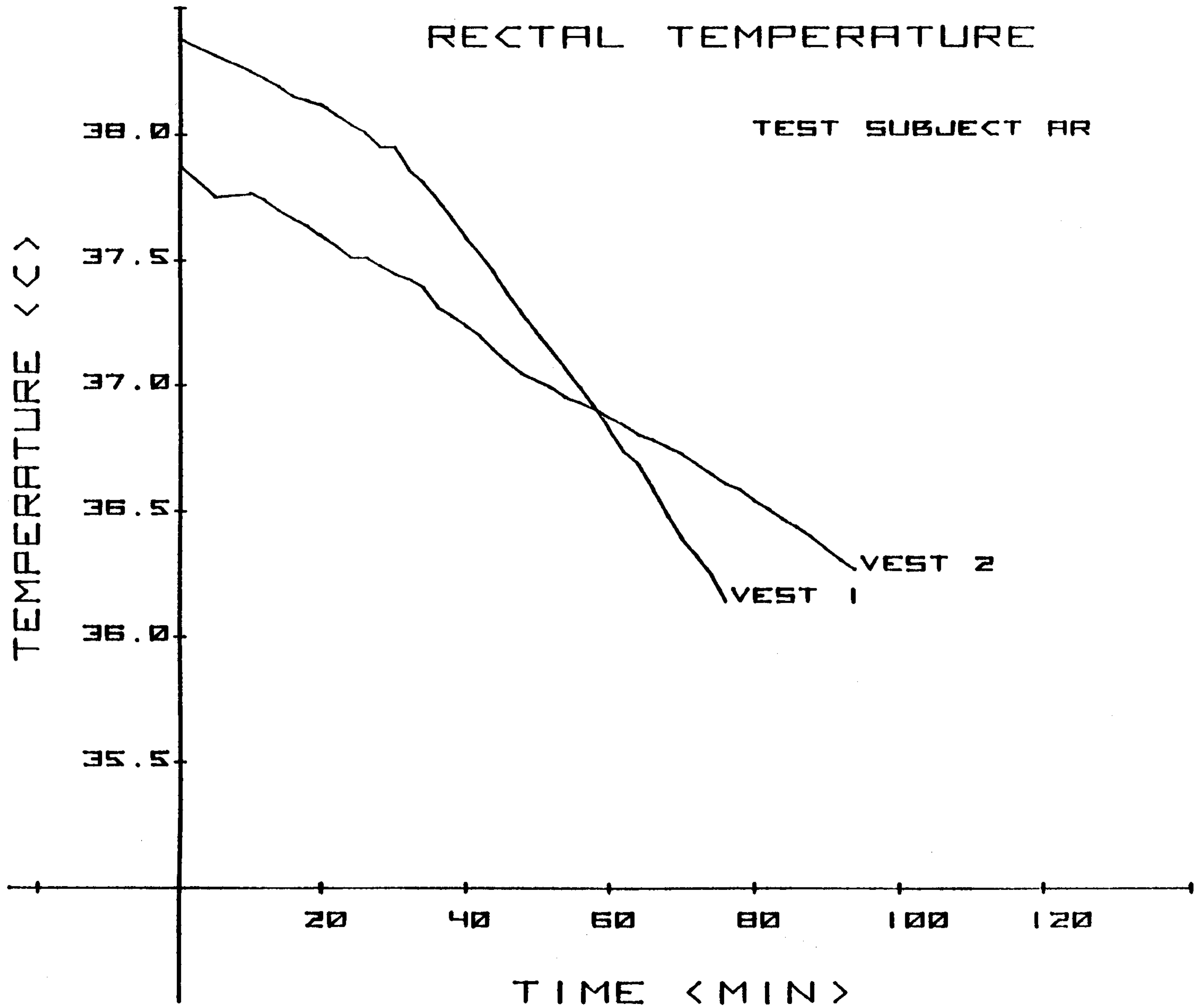

Figure 28. Rectal temperature vs. time during immersion.

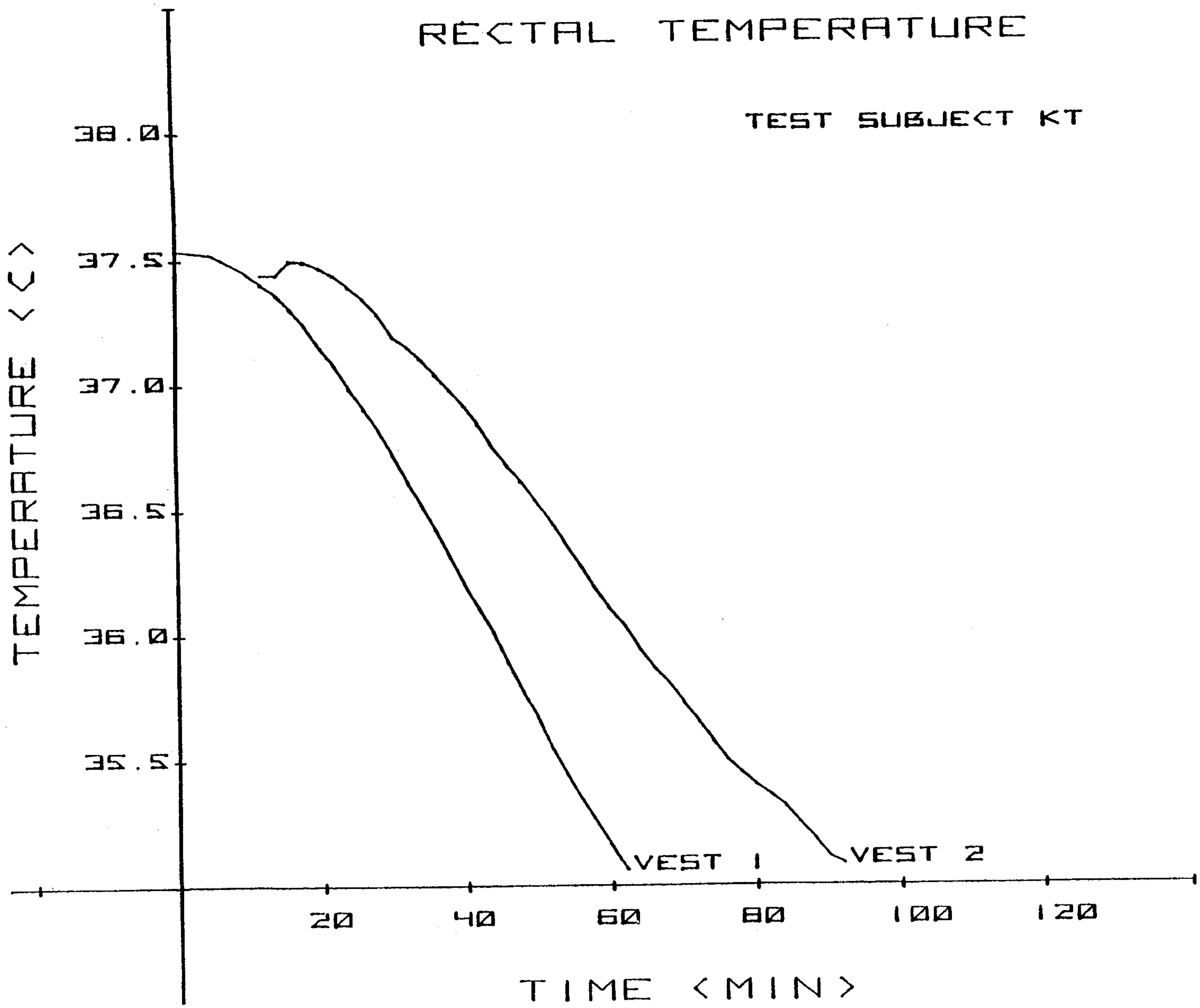

Figure 29. Rectal temperature vs. time during immersion.

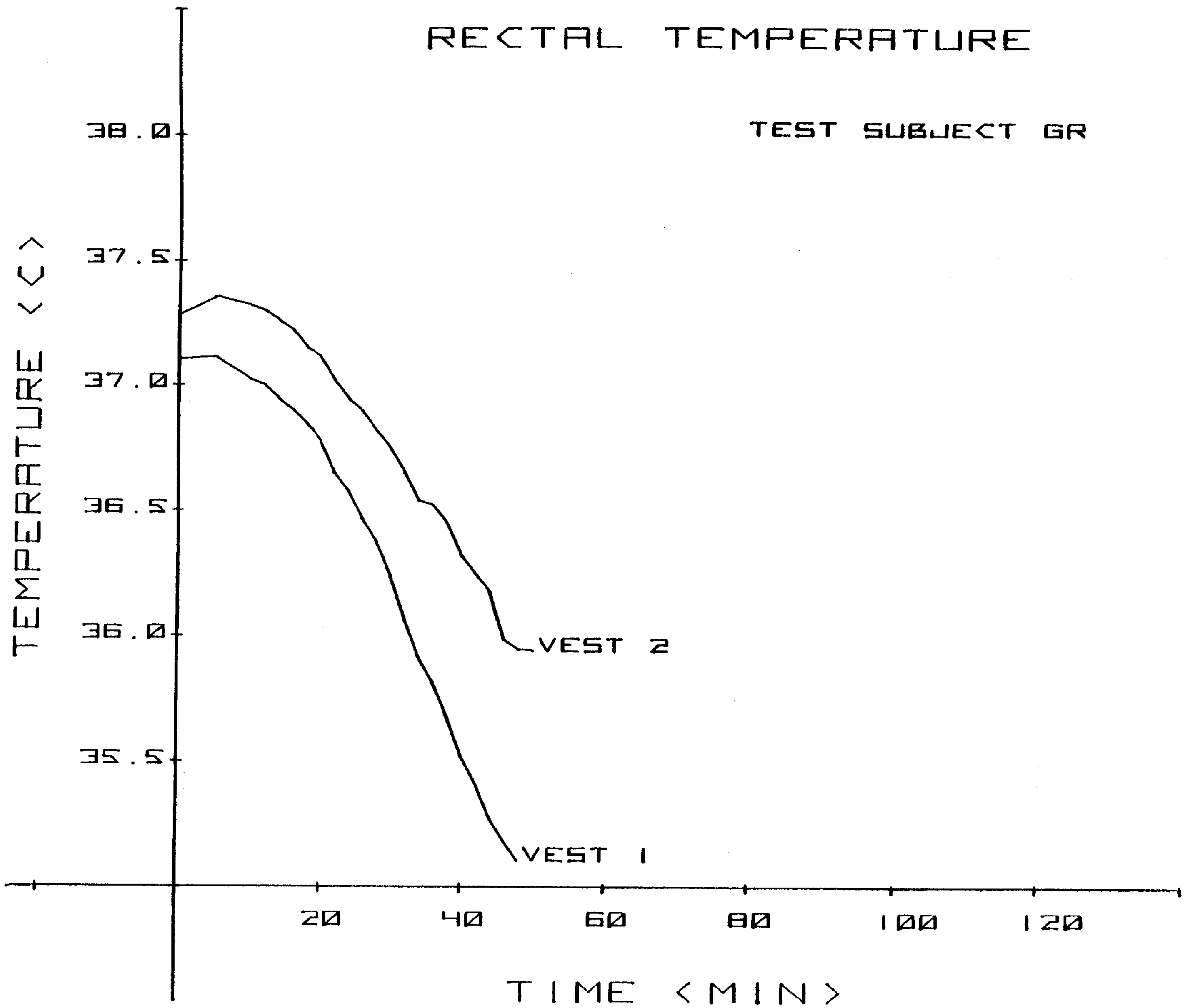

Figure 30. Rectal temperature vs. time during immersion.

TABLE IV

Results of Cold Water Immersion Experiments

Subject	Core Cooling Rates (°C/h)		Regression Correlation Coefficient		Percentage of Improvement of Vest 2 over Vest 1
	Vest 1	Vest 2	Vest 1	Vest 2	
JA	0.22	0.18	-0.97	-0.98	18
PP	0.33	0.57	-0.79	-0.98	-42
MS	0.89	0.93	-0.95	-0.96	- 4
KB	1.08	0.83	-0.99	-0.98	23
OB	1.68	0.50	-1.00	-1.00	70
BP	1.86	1.55	-1.00	-0.99	17
MJ	2.13	1.35	-0.99	-0.98	37
AR	2.18	1.06	-1.00	-1.00	51
KT	3.06	2.13	-1.00	-1.00	30
GR	3.74	2.43	-1.00	-1.00	35
Mean	1.72	1.15			
Standard Deviation	1.13	0.72			
Level of Significance		0.012			

TABLE V

Estimated Times to Reach Two Predicted Lethal Rectal Temperatures

Subject	Time (h) to 34.4 °C		Time (h) to 30.0 °C	
	Vest 1	Vest 2	Vest 1	Vest 2
JA	14.7	19.0	34.5	43.4
PP	12.0	6.6	25.4	14.3
MS	3.7	3.9	8.7	8.6
KB	3.2	4.1	7.3	9.4
OB	1.8	6.4	4.4	15.3
BP	2.3	2.6	4.7	5.4
MJ	1.7	2.7	3.7	5.9
AR	2.1	3.4	4.1	7.5
KT	1.2	1.8	2.7	3.9
GR	1.0	1.5	2.2	3.3
Mean	4.4	6.5	9.8	11.7
Standard Deviation	4.9	6.9	11.0	11.8

The means and standard deviations for the two rectal temperatures are given for each type of design in Table V. For a lethal rectal temperature of 34.4 °C, the mean estimated pst was 6.5 h for subjects wearing the prototype life preserver and 4.4 h if the same subjects wore the standard PFD. For a lethal rectal temperature of 30.0 °C, the mean estimated pst was 11.7 h for subjects wearing the prototype life preserver and 9.8 h if the same subjects wore the standard PFD. For both rectal temperatures, the mean estimated pst was greater for subjects wearing the prototpye life preserver than if the same subjects wore the standard PFD.

Heart rate data are given in Table VI for selected times after immersion. On entry into the cold water, all the subjects had an initial large increase in heart rate. Within the first minute of immersion the subjects' heart rates were 35 percent and 33 percent above preimmersion levels while wearing vest 1 and vest 2 respectively. By 5 min, heart rates fell to levels slightly less than preimmersion levels. Thereafter, heart rates increased gradually in either test condition.

At 5 and 10 min of immersion, the type of design worn did not significantly affect heart rates. However, beginning at 20 min of immersion, the mean heart rate for subjects wearing the prototype was 81 bpm and was 87 bpm in those wearing the standard PFD. At 30 min, the mean heart rate for subjects wearing the prototype life preserver was 82 bpm and was 91 bpm when the subjects were wearing the standard PFD. At 40 min, the mean heart rate for subjects wearing the prototype life preserver was 84 bpm and 92 bpm when wearing the standard PFD. During the last 4 min of immersion, the mean heart rate for subjects wearing the prototype life preserver was 87 bpm and 99 bpm when wearing the standard PFD. These differences in heart rate were statistically significant for 20, 30, and 40 min of immersion and during the last 4 min of immersion. These differences suggest that the prototype life preserver may have aided in conserving energy, since heart rate is directly affected by both level of physical activity and metabolic rate.

In a study by Bynum, Goldman, and Stewart (14), it was found that the mean increase in metabolic heat production for subjects wearing neoprene-insulated suits (15 W/m^2) was lower than when the same subjects were nude (130 W/m^2). This suggests that an important effect of additional insulation is to conserve metabolic energy which is associated with maintaining a given level of rectal temperature (14). This study was conducted in 20 °C water over a 60-min period.

TABLE VI

Heart Rates

Subject	Heart Rate (bpm) Given at Five Timed Intervals (min) and at Exit											
	5		10		20		30		40		Exit Water	
	V1	V2	V1	V2	V1	V2	V1	V2	V1	V2	V1	V2
JA	91	79	84	84	85	85	85	82	88	78	94	87
PP	82	89	78	84	71	79	72	79	79	86	100	62
MS	62	67	70	77	77	70	88	77	84	82	102	90
KB	90	82	88	76	80	67	86	71	87	74	103	86
OB	78	93	82	86	82	79	79	78	76	79	83	91
BP	83	78	81	70	76	70	81	73	80	75	88	81
MJ	107	106	104	92	104	93	120	92	122	94	120	111
AR	103	94	102	96	107	94	107	97	107	96	102	86
KT	106	108	110	105	107	99	107	101	105	102	106	103
GR	65	74	68	74	77	72	84	74	89	74	89	70
Mean	87	87	87	84	87	81	91	82	92	84	99	87
SD	16	14	14	11	14	11	15	11	15	10	11	14
Level of Significance	.917		.378		.019		.017		.038		.012	

Legend: V1 represents the standard personal flotation device; V2 represents the prototype life preserver.

This conservation of metabolic energy appears to be a possible explanation as to why subject PP did not show a lower cooling rate when wearing the prototype life preserver than while wearing the standard PFD. From visual observation, subject PP appeared to have significantly more total body fat than any of the other subjects. It is, therefore, hypothesized that this subject's own tissue insulation plus the insulation provided by the prototype life preserver may have decreased stimulation of deep thermoreceptors. This may have reduced the intensity of the response to a change in external temperature. As indicated in Figure 12, the subject's rectal temperature appeared to level off at approximately 60 min when wearing the standard PFD and at approximately 100 min when wearing the prototype life preserver. Thus, a longer exposure time may have resulted in a lower rate of cooling when the subject was wearing the prototype life preserver than when wearing the standard PFD. More work would have to be done to verify this.

Another subject (MS) also did not show a lower rate of cooling when wearing the prototype life preserver than when wearing the standard PFD. A possible explanation relates to the amount of urine produced during the tests. When subject MS was wearing the standard PFD he had a urine volume of 830 cc. When he was wearing the prototype life preserver he had a urine volume of 330 cc. As can be seen in Table VII, no other subject produced as large a volume of urine, nor demonstrated as great a difference between the two tests. The subject reported that, while wearing the standard PFD, he had a strong urge to urinate. Each time he tried to relax, the urge to urinate would return which would cause him to "tighten up and shiver." However, when the subject was wearing the prototype life preserver, he reported that he could relax and abstain from shivering for short periods of time. Thus, it is hypothesized that if the subject had shivered equally during each experiment, he may have shown a small decrease in the rate of cooling when wearing the prototype life preserver over the standard PFD. Again, more work would have to be done to verify this. Subject MS was also one of the heavier subjects with a greater body mass.

Based on weight and height alone, it also appears that the heavier subjects (JA, PP, MS, and KB) would need a longer exposure time for significant differences in cooling rate to occur. As can be calculated from Table IV, the mean cooling rate for these four subjects was 0.63 °C/h for vest 1 while the remaining subjects had a mean cooling rate of 2.44 °C/h. For vest 2, these four subjects had a mean cooling rate of 0.63 °C/h and the remaining subjects had a mean cooling rate of 2.26 °C/h.

TABLE VII

Urine Volumes (in Cubic Centimeters)
for Subjects During Cold Water Immersion Tests

Subject	Wearing Vest 1	Wearing Vest 2
JA	510	540
PP	720	730
MS	830	330
KB	400	670
OB	230	260
BP	300	485
MJ	200	535
AR	170	500
KT	230	200
GR	375	540
Mean	397	479
Standard Deviation	226	169

SUMMARY

A review of literature focused on physiological responses to cold water immersion and various design concepts previously developed and evaluated for protection against hypothermia. The review of literature was a source of design ideas for the development of the prototype thermal protective life preserver.

In the development of the prototype life preserver, goals established by the Survival Research Unit, CAMI, were used as guidelines. The requirements for self-righting, donning time, universal sizing and weight, and storage space limited the amount of thermal protection that could be provided. In order to meet the donning time and weight and storage goals, a single-chamber air bladder that covers the major heat loss areas of the upper torso was designed. To allow for ease of donning, the air bladder was developed into a jacket-style with a front zipper closure. In comparison, the current standard PFD is a dual-chamber air bladder that is U-shaped, encompasses only the neck area, and has complicated retention harnesses that prolong donning time.

Since thermal protection is significantly increased when a suit provides a close fit, means of accommodating the need for universal sizing and a close fit were sought.

Anthropometric data for male and female chest and waist sizes were used to determine key measurements. A material search resulted in the use of one-eighth inch closed-cell neoprene in the lower back region of the prototype. The 300 percent stretch provided universal sizing and allowed for a close fit for a wide range of subject sizes.

To test and evaluate the thermal response characteristics of the prototype life preserver and a currently used standard PFD, a laboratory experiment with 10 subjects immersed in 12.8 °C water was conducted. Each subject's rectal temperature was measured and recorded every 2 min. A cooling rate for each subject in each design was determined by least squares regression. A paired t-test was used to determine significant differences between cooling rates for the two vests.

The mean cooling rate estimate of subjects wearing the prototype life preserver (1.15 °C/h) was lower than when the same subjects wore the standard PFD (1.72 °C/h). Differences in cooling rate were statistically significant at the 0.05 level. Regression analysis showed that there was a high degree of linear correlation between the immersion time and the change in rectal temperature. Eight of ten subjects while wearing the prototype life preserver showed a decrease in cooling rate over the same subjects when wearing the standard PFD.

In order to further evaluate the practical significance of increased thermal protection, the cooling rate data of the present study were used to predict time to reach two rectal temperatures (34.4 and 30.0 °C) in 12.8 °C water. Hayward and Eckerson's formula (13) was used with the cooling rate data to estimate predicted survival time. For both rectal temperatures, the mean estimated predicted survival time was greater for subjects wearing the prototype life preserver than when the same subjects wore the standard PFD.

Each subject's heart rate for each vest was recorded continuously on an EKG polygraph. Recorded heart rates were counted at 5, 10, 20, 30, and 40 min of immersion and again during the last 4 min of each subject's immersion test when the rectal temperature was expected to be at its lowest. A paired t-test was used to determine significant differences between heart rate with the two vests.

At 5 and 10 min of immersion, the type of design worn did not significantly affect heart rate. However, beginning at 20 min of immersion, the mean heart rate for subjects wearing the prototype life preserver was significantly lower than for subjects wearing the standard PFD. The significance became greater with time of immersion.

CONCLUSIONS

The following general conclusions were drawn from the study:

1) Under the conditions of the test, the prototype life preserver provided additional thermal protection for 8 of 10 subjects.

2) The prototype life preserver provided greater than 35 pounds of buoyancy.

3) The prototype life preserver was able to self-right the wearer in 5 seconds.

4) The prototype life preserver provided a satisfactory fit for a wide range of adult sizes.

5) The prototype life preserver provided an average donning time of 17.5 seconds, with 60 percent of the subjects able to accomplish donning in 15 seconds or less.

6) The prototype life preserver weighed no more and required no more storage space than currently used personal flotation devices.

Based on these findings, the prototype life preserver has features that indicate an improvement in protection for aircraft passengers in the event of accidental submersion in cold water compared to currently used designs.

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