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NAVY EXPERIMENTAL DIVING UNIT

REPORT NO. 3-90

IOLOGICAL EVALUATION OF TWO DIVER ACTIVE THERMAL SYSTEMS (ATS): S-TRON AND ILC-DOVER

LCDR JOHN A. STERBA, MC, USNR

MARCH 1990

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PHYSIOLOGICAL EVALUATION OF TWO DIVER ACTIVE THERMAL SYSTEMS (ATS): S-TRON AND ILC-DOVER

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I. INTRODUCTION

In support of Naval Sea Systems Command (NAVSEA) Task #88-18A, Navy Experimental Diving Unit (NEDU) conducted a physiological and human factors evaluation of diver Active Thermal Systems (ATS). Diver ATS consist of the following: a tubulated undergarment with a closed circuit circulation of hot water, an undergarment of microfibrous batting for insulation, and a dry suit for waterproofing the ATS ensemble. This report will include the physiological results of the thermal protection of two ATS in 2°C (35°F) water studied in U.S. Navy (USN) divers at rest and free-swimming, simulating a Special Warfare (SPECWAR) Swimmer Delivery Vehicle (SDV) training mission.

II. METHODS

A. DIVER-SUBJECTS

Eight USN divers were used as diver-subjects in this physiological study. A total of ten divers were used in the human factors evaluation. All divers were specially trained and were very experienced in dry suit diving in near-freezing water. Prior to this study, all diver-subjects regularly swam in the NEDU cold water flume wearing dry suits in 2°C fresh water. The diver-subjects were medically screened by history and physical examination prior to voluntary participation in this study. These diver-subjects did not have a history of nonfreezing cold injury to the hands or feet from previous cold wet or dry exposure.

Anthropometric data on the eight, male diver subjects are listed in Table 1. Percent body fat was determined by four-site skin fold thickness using a skin fold caliper (1).

Table 1
Anthropometric Data
(mean ± SD)

Age: 32 ± 4 yrs
Weight: 80.4 ±9.5 kg
Height: 179.8 ± 5.8 cm
Body Surface Area: 2.04 ± 0.13 m^2
Body Fat: 20.1 ± 5.8%

B. DIVING EQUIPMENT

Two diver ATS were compared, the S-TRON (Redwood, CA) and the ILC-Dover (Diving Unlimited International (DUI), San Diego, CA). The S-TRON ATS tubes are arranged in series with thermal panels covering approximately 60% of the total surface area of the torso, abdomen, arms and legs with complete coverage of the hands, feet, and head. This leaves areas of the torso, abdomen, and extremities not actively heated, e.g. shoulders, armpits (axilla), elbows, wrists, lower abdomen, buttocks, groin, hips, knees, and from the mid-calf to the ankle. Figure 1 (front view) and Figure 2 (back view) illustrate the

S-TRON tube suit with the tube panels sewn on the outside of the thin polypropylene long underwear.

From the diver's skin outward, the following layers comprised the S-TRON ATS: S-TRON tube suit, single piece construction vapor barrier (DUI), M-400-weight Thinsulate undergarment (DUI) and a DUI trilaminate system (TLS) dry suit as one ensemble. The S-TRON tubulated glove was a mitt design with two compartments for a thumb and four fingers. The diver could keep his index finger in the mitt to keep it warm or extend it out into an unheated finger stall. The following figures illustrate various parts of this ensemble: Figure 3, M-400 Thinsulate undergarment, described below; Figure 4, Thinsulate head protection; Figure 5, latex hood, chest zippers, and low profile penetrator for physiological data collection through the outer garment; Figure 6, instrumented hand with surgical glove showing inner wrist ring; Figure 7, tube glove attached, held by small clip; Figure 8, diver fully dressed in S-TRON ATS, with tape required on wrist to prevent leaks and glove over-inflation.

The second ATS was the ILC Dover tube suit. This is a light weight, elastic and nylon undergarment with individual, water-filled tubes (0.16 cm, 1/16 inch outer diameter) approximately 2 cm apart. The ILC-Dover tube suit does not cover the hands, bottom of the feet, toes or head. It is worn over thin polypropylene long underwear (Capilene, mid-weight by Patagonia, distributed by Great Pacific Iron Works, Santa Barbara, CA). Next, a single piece construction vapor barrier prevents perspiration from reaching the M-400 Thinsulate (DUI) undergarment worn as the passive insulation. The inner surface of the undergarment was flannel to allow easy drying. The outer surface of the Thinsulate undergarment was neoprene coated nylon, acting as a water-proof barrier against dry suit leaks. This undergarment was used in both S-TRON and ILC-Dover ATS evaluations. Because of its better durability and diver preference, the dry suit chosen was the Viking dry suit. (model: Pro, military version, Viking America, Solon, OH). There is no appreciable difference in insulation between materials used in either DUI or Viking dry suits. Figure 9 shows the diver donning the ILC-Dover tube suit and Figure 10, a diver wearing the Viking dry suit and MK-15 UBA in the water.

Both S-TRON and ILC-Dover ATS had inlet and outlet water connectors inside the dry suit at one location.

For the ILC-Dover ATS, the hands were thermally protected with M-600 Thinsulate glove liners with finger stalls for the thumb, index/middle fingers, and ring/little fingers, hereafter called the T-2-2 combination. With the S-TRON ATS, the glove assembly was a mitt with insulation and water tubing. The thumb and four fingers were in separate compartments. With the ILC-Dover ATS, the outer glove was the Viking dry suit glove in the T-2-2 combination. The Viking dry suit glove had a flexible, rubber wrist skirt that is stretched tightly over the standard forearm ring assembly. The feet in both S-TRON and ILC-Dover ATS were thermally protected with M-800 Thinsulate booties (DUI). Both the Viking and DUI TLS dry suits had extra large, attached dry boots. The head was protected in both ATS by a Thinsulate cap (DUI) and a dry latex hood.

With both ATS, the following diving gear was used: one weight vest (model: Alpha, modified for NEDU by Zeagle, Zephyrhills, FL) with approximately 15.9 kg (35 lbs) of lead shot weight, one pair of cold water fins (model: Mares Power Plana, USA Sequest, Carlsbad, CA), and a MK-15 Mod 0 UBA. The full face mask (FFM) was the AGA (Interspiro, Branford, CT) with the reduced volume faceplate. Lead counter weights (total = 1.4 kg, 3 lbs) bolted along the sides of the FFM faceplate were needed to reduce the unwanted positive buoyancy of the AGA FFM using the MK-15 UBA (Figure 10). Since a modified Jack Brown harness did not improve the face and jaw discomfort common with the AGA FFM for prolonged dives, the standard AGA jocking harness was used.

C. EXPERIMENTAL DESIGN

In our study, the divers were instructed to dive the dry suits as they are operationally used by SPECWAR during SDV training missions (personal observation and communication, SDV Team One). After purging as much air as possible with the diver's head a few inches below the surface, only enough weight to remain neutrally buoyant was given to each diver in the prone position. Dry suit inflation gas was <u>not</u> added during descent to the SDV cockpit at 4.6 m (15 ft). This increase in the amount of dry suit squeeze, customary for SPECWAR SDV divers, was well tolerated by all eight divers in this study. Having sufficient dry suit gas to improve insulation of the hands and body is not desired close to the target area due to altering the buoyancy of the SDV and causing off-gassing during ascent, disclosing SDV or diver position (personal communications, SDV Team One, NCSC, NAVSEA 06Z).

To simulate SDV transit, a 3.5 hour rest period was used with two divers in a leaning forward (near-prone) position in an SDV cockpit (Figure 11). During this rest period, both ATS had surface supplied warm water pumped to the diver, controlled for inlet temperature and flow held at 0.5 gallons per min (gpm). Since the portable hot water heater (Conox, S-TRON) was not yet manufactured, no ATS could be tested under closed circuit conditions. The tube suit effluent water was discharged into the large cold water flume without affecting the 2°C water temperature. The tube suit ideal inlet temperature was predetermined to be 39°C (102°F) for long duration exposures in 2°C water using the ILC-Dover tube suit (2).

Following the initial 3.5 hour rest period, the speed of water flow in the flume was maintained at 0.5 knots (kns), the diver's hot water was secured and the diver began swimming with only passive thermal protection (Figure 12). The underwater swimming phase was 1.0 hr, which was a reasonable exercise stress test for the maximum amount of total time spent swimming to compare different ATS. Thereafter, the diver was to reenter the SDV cockpit, the hot water to the ATS turned on, and conduct another 3.5 hour rest period to simulate SDV transit. The dry phase of land exercise was excluded from this evaluation of diver ATS. We did not simulate carrying certain devices (weapons, cameras, escape and evasion gear) during the underwater swim.

The evaluation of the diver ATS included physiological measurement of mean skin temperature, core temperature (rectal), mean body temperature, mean fingertip and toe temperatures as well as individual finger and toe temperatures. For both ATS, mean heat flux, tube suit insulation, and body insulation were also calculated. Respiratory heat loss could not be measured in this study for technical reasons. Esophageal temperature could not be measured in all divers and will not be reported since it interfered with middle ear equalization to 4.6 m causing middle ear squeeze. The tube suit water inlet and outlet temperatures and water flow were used to calculate the total thermal power supplied to the tube suit. Unfortunately, this total power could not be subdivided into the power delivered to the man and the power lost to the cold environment.

D. TERMINATION CRITERIA

To avoid nonfreezing cold injury to the digits (3), the following termination criteria was used, first proposed by Thalmann, Schedlich, Broome, et al. (4). No digit (finger or toe) temperature was allowed to be at or below $8^{\circ}C$ for longer than 30 minutes. Also, if any digit temperature reached $6^{\circ}C$, the dive was aborted for that diver. Dives were also terminated if rectal core temperature fell below $35.0^{\circ}C$ ($95.0^{\circ}F$) even though the ATS design prerequisite for the U.S. Navy is a minimum of $36^{\circ}C$ ($96.8^{\circ}F$), rectal temperature. The dive was terminated if the scrubber effluent rose above 1.0% fraction inspired CO_2 (F_ICO_2) indicating failure of the CO_2 absorbent. Any diver could terminate, for whatever reason including pain or discomfort, without prejudice.

E. CONTROL OF CONFOUNDING VARIABLES

In a preliminary study, swimming at 0.7 kns at $2^{\circ}C$ water temperature, excessively high work rates were noted, reflected by maximal heart and respiratory rates, oxygen consumption, sweating, and elevated body core temperature using only *moderate thickness*, undergarment insulation (M-400 Thinsulate) (5-6). Based on further physiological study and U.S. Navy diver preference at NEDU as reported elsewhere (5-6), 0.5 kns was chosen as a reasonable speed to simulate long distance swimming.

The depth of the dive was 4.6 m (15 ft) while at rest simulating a training mission in an SDV and 3.0 m (10 ft) while free-swimming also simulating training swimming depths (personal communications, SDV Team One, NCSC and NAVSEA 06Z). The swimming depth of 3.0 m allowed the diver to adequately control his trim, keeping the center of buoyancy and center of gravity near each other. At 1.5 m (5 ft), there were exaggerated changes in buoyancy with small depth changes. Compared to 3.0 m, all eight diver-subjects reported that swimming at 1.5 m required more effort to swim straight and level due to dry suit gas moving into the feet, placing the diver in an inefficient, head-down swimming attitude. Occasionally, divers could not avoid kicking their fins on the surface while attempting to swim near the surface at 1.5 m. With the experienced diver fully purging his dry suit before descending and using appropriate weight in a weight vest, these buoyancy problems were not experienced at 3.0 m during free-swimming.

To control for any variation in drag underwater, only one type of commonly used UBA was used, the MK-15 MOD 0 closed circuit UBA. Since drag increases underwater while swimming close to any surface, each diver swam alone in the center of the cold water flume, at least 1.2 m (4 ft) from any surface at the

3.0 m level. This depth was also in a large area of constant flow in the cold water flume, controlled at 0.5 ± 0.1 kns.

Buoyancy, affecting body attitude and underwater drag, was controlled by using USN divers adequately trained and very proficient in cold water dry suit diving. Viking America, Inc. and Diving Unlimited International are two leading authorities in cold water diving. It has been their experience that following a dry suit training course, a minimum of 10 open-water cold water dives are needed before the diver is competent in diving dry suits, including using appropriate weight, controlling buoyancy, and preventing leaks (personal communications, Mr. Bob Chaplin (Viking) and Mr. Dick Long (DUI)). We selected eight U.S. Navy trained divers very experienced in cold water diving for this study. To control for varying diving experience in cold water, all eight divers were then formally trained in dry suits by Mr. Bob Chaplin of Viking America, Inc. and NEDU personnel. This training involved one week of didactic training on all types of dry suits along with dry suit diving in the ocean and a minimum of 10 dives in near-freezing cold water in the flume. Following this training, all divers maintained their competence in dry suit diving by frequent cold water swimming in the flume at NEDU. Controlling for the wide range of physical conditioning seen in civilian sport SCUBA divers, the divers in this study were physically conditioned with underwater swimming and routine, diver oriented physical training prior to this study.

Underwater swimming performance, thermal balance and energy cost may be affected by the comfort, fit and flexibility between dry suits and undergarments. Therefore, the selection of one dry suit undergarment, Thinsulate, and two dry suits (DUI, model: TLS and Viking, model: Pro) for our study was based on a formal survey of military cold water diving units and dry suit manufacturers (7), unmanned testing of undergarments (8-9) and preliminary manned evaluation of dry suits and undergarments at NEDU and during monitored dives under the ice in the Arctic Sea.

In the U.S. Navy, the selection of both dry suits and undergarments is by diver preference (10-11). Changes in fit between commonly shared dry suits, especially wrist and neck seals, can greatly affect diver comfort during free-swimming. In addition, anecdotal reports received by NEDU suggest that two-piece construction of undergarments may be less insulating compared to better fit of one-piece construction undergarments. Therefore, both Viking and DUI dry suits and one-piece construction undergarments (M-400, M-600, and M-800 Thinsulate (DUI)) were custom made for each diver-subject in this study.

Even though changes in kick frequency might affect the energy cost of underwater fin swimming, it was frequently mentioned among the U.S. Navy divers in our study that they could not change how they swam underwater without rigorous retraining. Kick frequency was not controlled, but was measured for future studies evaluating this interesting factor and is reported elsewhere (6).

Modifying muscle glycogen stores and controlling for diet was beyond the scope of this project. No attempt was be made to either carbohydrate or lipid load in this study. Diet was not modified beyond insuring an adequate breakfast prior to each cold water exposure. Caffeine consumption was kept to a minimum and could not be reliably eliminated in this sample of U.S. Navy divers. Alcohol consumption was limited and not allowed 24 hours prior to diving. Adequate hydration was controlled by having no diver exercise or dive leading to an increase in urination (immersion diuresis) within 24 hours of exposure.

All dives began at the same hour of the day to avoid any potential influence of circadian rhythm on metabolism.

It is highly unlikely that any cold acclimatization could occur during this study. All divers swam vigorously in the cold water flume during the training phase and never experienced any discomfort of the cold. A minimum of 48 hrs elapsed between cold water exposures for any subject during the ATS experimental phase. Each diver was allowed a maximum of three cold water exposures to termination criteria during the three weeks of experimentation. The warm weather of Panama City and routine exercise in the heat would have eliminated any cold acclimatization that may have occurred.

F. PHYSIOLOGICAL MEASUREMENTS

1. Pulmonary Physiology Variables

Ideal variables to evaluate diver performance during long duration fin swimming would include metabolic measurements of oxygen consumption ($\dot{V}O_2$) including maximum VO_2 ($\dot{V}O_2$ max) and carbon dioxide production ($\dot{V}CO_2$). This would allow a calculation of respiratory quotient (RQ) defined as the ratio $\dot{V}CO_2/\dot{V}O_2$. Other variables of respiratory function would include minute ventilation ($\dot{V}_E$), tidal volume (V_T), respiratory rate (RR), end-tidal CO_2 partial pressure ($P_{ET}CO2$) to monitor for CO_2 retention and the measurement of venous blood lactic acid, reflecting anerobic metabolism. Unfortunately, such a comprehensive physiological evaluation of the total energy cost, both aerobic and anerobic, of long duration dives with fin swimming was not possible for this study due to time constraints.

In our study, the MK-15, a closed circuit UBA allowed measurement of real-time changes in oxygen bottle pressure and an accurate and reproducible calculation of $\dot{V}O_2$ during free-swimming (5-6,12-13). A recently developed miniaturized hot wire anemometer (14) is currently being considered at NEDU to measure pulmonary physiology variables (V_T, RR, and $\dot{V}_E$) in various UBAs at NEDU but has not yet been sufficiently tested and could not be used.

2. Oxygen Consumption, $\dot{V}O_2$

Calculation of $\dot{V}O_2$ was based on changes in oxygen bottle pressure corrected for the temperature of the water and the exact internal (floodable) volume of the oxygen bottles in the MK-15 UBA. Oxygen consumption was calculated in units of ml/min, using equation 1, below (12-13), corrected to units of Standard Temperature Pressure Dry (STPD). The values of $\dot{V}O_2$ were also normalized for body weight (ml/min/kg) for each diver-subject.

$\dot{V}O_2$ - delta P/min * V_b/14.7 PSIG * 273/(T+73) Eqn 1

where:

$\dot{V}O_2$ - oxygen consumption, ml/min, STPD
delta P - change in oxygen bottle pressure corrected for depth
V_b - oxygen bottle's (floodable) volume, 2868 ml per NAVSEA drawing #6196009
PSIG - pounds per square inch, gauge.
T - water temperature, ^{o}C

Any small leaks from the full face mask or off-gassing from the MK-15 UBA did not affect the accuracy of $\dot{V}O_2$ calculation since oxygen is not added for lost volume in the breathing circuit. Oxygen is only added for a change in oxygen content below the set point of a PO_2 of 0.7 atmospheres absolute (ATA). The diluent bottle was filled with 55% O_2, 45% N_2, approximating 0.7 ATA PO_2 at 3 m. The MK-15 UBA breathing volume, oxygen partial pressure and oxygen cylinder temperature stabilized over the first 10 minutes in the water before the dive began. After the diver arrived at depth, the MK-15 UBA was purged with diluent and the diluent valve was secured. The MK-15 UBA stabilized its PO_2 within minutes before beginning 3.5 hours of resting bottle pressure measurements.

3. Thermisters, Heat Flux Disks and Body Sites Monitored

Figure 13 illustrates an instrumented diver prior to donning the ATS. Skin temperature was measured and heat flux was calculated from the same disk (Concept Engineering, Old Saybrook, CT). Body core temperature was recorded by rectal temperature (T_r) probe (model 400, Yellow Springs Instrument (YSI), Yellow Springs, OH), measured 15 cm into the rectum and taped into place. Esophageal temperature, measured 43 cm from the nose (model 90050, size: 9 Fr., Mallinckrodt Critical Care, Glens Falls, NY) was successfully measured, but since it interfered with middle ear equalization with the AGA FFM and caused two cases of mild middle ear barotrauma, data from all dives could not be collected. Finger tip and toe temperature was measured using specially adapted YSI thermisters (model 44033 adapted by YSI for NEDU), having extra electrical insulation on the lead wires for mechanical protection. These extra small digit thermisters conveniently fit beneath the tip of the nail. They were taped in place with tape (3-M, transpore tape, St. Paul, MN) on the nail and distal digit without circumferential restriction of digit blood flow. The following digits were monitored for temperature: thumb (first), index (second) and little (fifth) fingers on both hands and great (first) and little (fifth) toes on both feet. Latex surgical gloves helped to achieve a better air tight seal under the dry suit wrist seal with thermisters wires taped flat, beneath the surgical glove. Extra large latex gloves prevented unwanted restriction of finger blood flow and gave no appreciable increase in hand insulation. The same team of corpsmen instrumented each diver to ensure reproducible data. Data was collected using a computerized data acquisition system called the on-line Diver Monitoring System (DMS) designed and tested for accuracy at NEDU (15-16).

4. Thermal Measurements

Mean skin temperature (T_s) and mean heat flux from the skin (H_s) were calculated based on equations 2 and 3, below (17) with data recorded by the on-line DMS.

$$T_s = 0.07T_1 + 0.085T_2 + 0.065T_3 + 0.085T_4 + 0.14T_5 + 0.05T_6 + 0.095T_7 + 0.065T_8 + 0.07T_9 + 0.09T_{10} + 0.09T_{11} + 0.095T_{12} \quad \text{Eqn 2}$$

$$H_s = 0.07H_1 + 0.085H_2 + 0.065H_3 + 0.085H_4 + 0.14H_5 + 0.05H_6 \; 0.095H_7 + 0.065H_8 + 0.07H_9 + 0.09H_{10} + 0.09H_{11} + 0.095H_{12} \quad \text{Eqn 3}$$

where: T_{1-12} and H_{1-12} represent the 12-site measurements of skin temperature and heat flux.

Mean body temperature (MBT) was calculated from T_s and rectal temperature (T_r) according to equation 4, below (17).

$$MBT = (0.33 * T_s) + (0.67 * T_r) \quad \text{Eqn 4}$$

Insulation or thermal resistance provided by the dry suit and undergarment (R-suit), and by the physiological shell, (R-body) were calculated according to equations 5 and 6, respectively (17)

$$\text{R-suit} = (T_s - T_a)/H_s \quad \text{Eqn 5}$$

where: T_a = ambient water temperature.

$$\text{R-body} = (T_r - T_s)/H_s \quad \text{Eqn 6}$$

Total power delivered to the ATS was calculated from water inlet temperature (T_i), outlet temperature (T_o), water flow in gallons per minute (gpm) and the specific heat of water being 1 cal/gm/^oC per equation 7, below

$$\text{Power (watts)} = \text{water flow (gpm)} * (T_i - T_o) * 264.14 \quad \text{Eqn 7}$$

5. Accuracy of Measurements

The degree of accuracy of skin, esophageal, and rectal thermisters selected for use was within $\pm$ 0.1^oC, as compared to a calibrated quartz thermometer (Hewlett Packard, model 2804 A, Mountain View, CA) and calibrated electronic thermometer (Jofra Instruments, model D-50-PC, Farnum, Denmark). Both calibration thermometers were recently recalibrated and were traceable to the National Bureau of Standards for accuracy. A one-man immersion tank was used as a well-stirred water bath for temperature probe calibration at NEDU. Heat flow disks (Concept Engineering, Old Saybrook, CT) were also recalibrated prior to this study by using the Rapid-k Thermal Conductivity Instrument (Holometrics, Cambridge, MA). Oxygen bottle pressure was measured using a submersible, solid state pressure transducer (Druck, Inc., model PTX-160/D, Newfairfield, CT) with an accuracy of $\pm$ 0.1% full scale deflection. The calculated value of $\dot{V}O_2$ was determined by multiple measurements to have an uncertainty of ± 100ml/min. Water flow in the flume was measured using a Swoffer (model 2100, Seattle, WA) portable liquid flow meter with a reported degree of accuracy ± 0.04 kns. The water flow in the swimming area at 3 m and 1.5 m was repeatedly measured with an overall uncertainty of ± 0.1 kns for 0.5 and 0.7 kns. Turbulent water flow was predetermined to be well outside the swimming area.

G. PROTOCOL

Using the cold water flume, designed and tested at NEDU (18-19), the following protocol details the critical steps during the planned 8-hour manned exposure. Following physiological electrode placement with the on-line diver monitoring system, divers were promptly dressed into the ATS with the help of two tenders to minimize overheating and sweating. Divers entered the water, purged their MK-15 UBA with diluent and the O_2 bottle pressure stabilized over the first 10 minutes. Initial measurements of the thermal physiology variables were verified as accurate and recording began. Divers descended 4.6 m to the SDV, purged the MK-15 UBA again with diluent, secured the diluent valve and began hand strength and dexterity testing, repeated every hour during the dive. Physiological data was collected every 30 seconds during the planned 8 hour exposure of 3.5 hours of rest, 1.0 hour of free-swimming and 3.5 hours of rest. The MK-15 UBA CO_2 canister and O_2 bottle were replaced for each diver after the 3.5 hour rest period before beginning the 1.0 hour swim. Following the cold water exposure, divers rewarmed as necessary in a one-man immersion tank. The divers were also encouraged to eat and drink after rewarming. The divers were then medically evaluated before being released to go home.

H. DIVER SAFETY

Beyond the normal risks of diving in cold water with the MK-15 UBA, no additional risks were incurred. The F_ICO_2 never rose above 1.0% CO_2, avoiding canister failure and CO_2 narcosis. Extremity and core hypothermia was prevented by on-line, diver physiological monitoring. Respiratory and heart rates along with an EKG were continuously monitored by a corpsman for safety. All electrical equipment was connected to ground fault circuit interrupters, minimizing any electrical shock hazard. The water to the tube suits was controlled for both temperature and flow preventing any hot water scalding injury. A constant battery source (+ 13.5 V, -13.5 V) to the MK-15 UBA was used instead of MK-15 UBA batteries as a modification, which improved reliability of the MK-15 UBA during these long duration cold water dives at NEDU. Unconscious diver drills ensured appropriate diver recovery, airway management, and transport to a nearby hyperbaric chamber under 4 minutes.

This experimental protocol was approved by the NEDU Review Committee for the Protection of Diver Subjects.

I. DATA ANALYSIS

Temperature and heat flux data was collected every 30 sec. The mean ± standard deviation (SD) for T_s, T_r, H_s, MBT, R-suit and R-body were averaged for every 30 minutes for the eight diver-subjects. The difference in oxygen bottle pressure at one hour intervals was measured to calculate $\dot{V}O_2$. Results for all eight divers were tabulated for the two ATS and a paired Student's T-test was performed when data was compared with statistical significance accepted at $p < 0.05$.

III. RESULTS

A. DIVING EQUIPMENT FAILING PRELIMINARY TEST AND EVALUATION

1. Gloves

Both the DUI five-finger, electrician-type glove and the DUI T-1-1-2 combination, rubberized nylon glove were unsatisfactory for formal evaluation. The DUI five finger glove had such small finger stalls that only light weight wool liners could be used as insulation. The index finger of the wool liner is very tight, designed to allow greater dexterity on-land. This caused all fingers, especially the index finger to become compressed, resulting in rapid cooling to $4^{\circ}C$ in 30 minutes during monitored working dives under the ice in the Arctic (15). Five finger ski gloves were also restricting even when used with the T-2-2 Viking dry glove.

During preliminary tests in the Arctic and in the NEDU cold water swimming flume, the Viking double-locking, rubber ring wrist connection failed frequently with immediate flood-out of the hand. Also, the DUI wrist connection with double plastic rings and two internal O-rings also frequently failed at NEDU and in the Arctic. When the diver flexed the wrist, especially if the arm is over his head with glove inflated, both the Viking and DUI double rings separated. Therefore, these gloves and wrist rings were excluded from formal testing.

2. Dry Suit Undergarments

Free-swimming at 0.5 to 0.7 kns with M-600 Thinsulate and M-800 Thinsulate was reported by all divers to be much more restrictive plus required much more weight than using M-400 Thinsulate (6). Elevated rectal core temperature above $38.5^{\circ}C$, near maximal heart and respiratory rates, sweating and fatigue were common using these thicker undergarments. Controlling for proper buoyancy was more difficult with M-600 and M-800 Thinsulate. With underwater swimming using M-400 Thinsulate at 0.5 kns, there was no evidence of heat stress or excessively high $\dot{V}O_2$ during free-swimming determined by a small pilot study (5). With M-400 Thinsulate being standard issue for USN divers using dry suits and undergarments, called Passive Thermal Systems (PTS), it was chosen to prevent these problems of overheating, restrictive movement, and weight and balance found with heavier undergarments.

3. Prototype S-TRON ATS

During preliminary testing of the S-TRON ATS, 15 man-dives with 10 U.S. Navy divers were attempted. Due to numerous problems, the prototype S-TRON ATS was redesigned and modified by S-TRON for the formal evaluation at NEDU. Some of these initial problems were: miniature tubing connectors frequently separated or broke at the wrists, ankles and over the body; hood design prevented facemask sealing as well as attachment of hot water tubing connector for the head; the hood would over-inflate; main connectors for inlet and outlet water inside the suit disconnected inadvertently; tubing was degraded at flexed areas such as knees and elbows causing leaks; tubing to tubing junctions had leaks; glove design does not allow the thumb to oppose the index finger; swimming could not be performed, unless there was an exact fit, due to bulkiness in the upper body creating high buoyancy.

B. TUBE SUIT TEST AND EVALUATION

1. S-TRON ATS

The modified S-TRON ATS was evaluated in 13 man-dives with 10 divers, with eight divers used for physiological data collection. Unfortunately, there continued to be numerous problems in the modified S-TRON ATS including failure to reliably deliver warm water to the hands, feet and head; connector and tubing leaks; and wrist seal leaks of cold water. Despite these problems, leak-free dives allowed physiological data to be collected until finger temperature decreased to termination criteria or a major leak developed, aborting the dive. On one dive, a small warm water tube connector leak in one hand permitted the diver to continue with finger tip temperatures near termination criteria. No dives lasted longer than 2.5 hours which prevented any free-swimming evaluation following prolonged rest. Free-swimming testing was done during preliminary dives for human factors evaluation.

Notably, all divers complained of the many cold spots and warm spots with the S-TRON ATS, which were very uncomfortable and distracting. None of the eight divers could tolerate the predetermined 39°C (102°F) inlet water temperature. They complained of very uncomfortable sensations including scalding even though the inlet water temperature ranged from only 37 to 38°C (99 to 100°F). Scalding did not occur, and would not be seen below 45°C (113°F) water temperature (11). In two divers, nausea, salivation, and a sick feeling (malaise), and reduced heart rates to 60-66 beats/min developed at 38 to 39°C inlet temperature. This was immediately relieved by sending cooler water to the S-TRON tube suit. Other causes of these symptoms were eliminated, including hyperthermia, CO_2 narcosis, hypoxia, contaminated breathing gas, and uncomfortable dry suit squeeze.

2. ILC-Dover ATS

Initial training dives demonstrated high reliability of the ILC-Dover ATS to consistently deliver warm water to all the tubes. The ILC-Dover ATS was subjected to two months of hard use without tubes or connections breaking. No durability testing or simulating on-land heavy use (e.g. crawling, running) could be done, however.

The predetermined inlet water temperature of 39°C (2) was well tolerated by all divers using the ILC-Dover ATS, without complaint. The reasons for divers aborting the cold water exposure was due to fingertip temperatures reaching termination criteria, since the hands were not heated. The first subject was terminated due to low fingertip temperature at 78 minutes. Of the two divers that completed the 3.5 hour rest period, both divers voluntarily terminated at

25 and 45 minutes into the swim not due to the cold, but due to low back pain and foot cramping, respectively. Only one diver had data recorded at 240 minutes in the figures, although he terminated at 255 minutes, 4.25 hours. No divers completed the entire 1.0 hour swim or returned to the SDV for the second 3.5 hour rest period. Therefore, maximum exposure was 4.25 hours before voluntary termination using the ILC-Dover ATS.

C. DIVER THERMAL PROTECTION

In Figure 14, the mean fingertip temperature for both hands (first, second and fifth fingers) is shown for both the S-TRON ATS with hand heating and the ILC-Dover ATS without hand heating. The number of subjects is illustrated below the time scale. A significant difference occurred at 60 and 90 minutes between colder, mean fingertip temperature with the ILC-Dover ATS compared to the S-TRON ATS. Representing steady state, the average fingertip temperature from 0 to 2.5 hours for S-TRON ATS was 21.7 ± 0.7 (SE) °C, and from 1 to 3.5 hours for the ILC-Dover ATS, 14.4 ± 0.7 °C.

After the onset of exercise (210 minutes) with two subjects swimming at 0.5 kns, all finger tip temperatures rose without active heating. This was illustrated in one subject at 240 minutes with all other subjects having been terminated by 30 minutes into exercise. In Figure 15, there was no significant difference between the mean foot temperature for both feet (great and little toes) for either S-TRON and ILC-Dover ATS. By 90 minutes, mean toe temperature for S-TRON and ILC-Dover ATS had stabilized at 18.5 ± 1.2 (SE) °C representing steady state. Recall that the ILC-Dover ATS supplied heat to the upper (dorsal) surface of the feet, but not the toes or lower (plantar) surface.

Figure 16 illustrates rectal temperature for both the ILC-Dover and S-TRON ATS. Although it appears that rectal temperature with the S-TRON ATS becomes less than with the ILC-Dover ATS, this was not statistically significant. Statistical analysis is not possible if there is only one value for comparison. The steady state rectal body core temperature averaged 37.1 ± 0.1 (SE) °C for the 3.5 hour rest period for the ILC-Dover ATS.

Due to short duration dives or recurrent tubing connector leaks in the modified S-TRON tube suit, useful data could not be collected to calculate mean skin temperature (T_s), mean body temperature (MBT), mean heat flux from the skin (H_s) or the thermal insulation of the suit and body (R-suit, R-body). These variables were calculated for the ILC-Dover ATS and are illustrated in Figures 17 to 21. Although comparisons could not be made with the S-TRON ATS, this data may be useful for others investigating the predicted value of these variables and to calculate net thermal balance. For ILC-Dover, the steady state values during the entire 3.5 hour rest period were as shown in Figures 17-21. Mean skin temperature in Figure 17 is 33.8 ± 0.1 (SE) °C. The mean body temperature in Figure 18 is 36.0 ± 0.1 (SE) °C. The mean heat flux in Figure 19 is 598.3 ± 60.5 (SE) watts/m^2 with an average body surface area of 2.04 m^2 giving 1220.5 watts, the mean thermal insulation of the suit in Figure 20 is 0.066 ± 0.006 (SE) clo, and thermal insulation of the body in Figure 21 is 0.007 ± 0.0005 (SE) clo.

D. COLD INDUCED TISSUE EFFECTS

For all divers terminated due to low temperature of the fingers, there was no evidence of nonfreezing cold injury (NCI) such as red (erythema), swollen (edema), painful or itching (pruritis) hands or feet during rewarming (3). Four divers did experience reduced tactile sensation (hypesthesia) and mild pins and needles sensations (paresthesia) of the fingers, lasting a few hours to eight hours. There was no increased sensitivity to cold in subsequent exposures in these four divers. These transient signs and symptoms were attributed to fingertip ischemia from the direct effect of cold plus vasoconstriction and dry glove squeeze.

The two divers who completed 3.5 hours of exposure in the ILC-Dover ATS experienced edema of the face which was noted upon surfacing, lasting two to three hours. In the absence of pain with rewarming in room air and no subsequent sensitivity to cold water exposure, nonfreezing cold injury to the face did not occur. This tissue edema was attributed to the effect of cold caused by little insulation from the AGA FFM, venous congestion due to facemask compression, and negative facemask pressure in the near-prone position.

E. FULL FACEMASK DISCOMFORT AND RISKS

Using counter weights, a reduced volume faceplate and releasing the straps as much as possible on the bottom did not improve severe jaw pain during dives longer than two hours. Following two to four hour dives, the lower teeth on the jaw (mandible) did not match to the upper teeth (maxilla) during chewing for up to 6 hours. Pain in the temporomandibular joint, especially with chewing, lasted as long as 24 hours.

Preliminary testing demonstrated that upon relaxing the jaw underwater simulating unconsciousness, the AGA FFM jocking harnesses would pull the jaw in, causing the tongue to occlude the airway of the diver. With no neck ring with an AGA FFM, the head would flex forward, worsening this airway obstruction. This problem of the jaw being pulled into the face by the AGA jocking harness was made worse with a modified Jack Brown harness.

F. OXYGEN CONSUMPTION, $\dot{V}O_2$

Figure 22 is the drop in O_2 bottle pressure in one subject at rest, representative of all subjects. The initial drop in pressure is associated with immersion in 2°C water, followed by a gradual decline in pressure reflecting VO_2. The slope of the decline in O_2 bottle pressure, measured by best fit at the top of the tracing, was measured over one hour intervals to calculate $\dot{V}O_2$. The downward spikes are low pressure recordings when the O_2 bottle valve is temporarily opened. These spikes were not used in calculating the $\dot{V}O_2$. At two hours, the mean VO_2 at rest for the five divers remaining was 457.1 ± 69.2 (SD) ml/min (STPD) or normalized by body weight, 5.8 ± 0.6 ml/min/kg.

Although measured in only two subjects during exercise, the $\dot{V}O_2$ was 1,936.8 ± 273.9 ml/min or 23.1 ± 1.7 ml/min/kg . This can be compared to a separate study of the same eight divers wearing the same fin (Mares, Power Plana) and swimming for 40 mins in the same dry suit at 0.5 kns, but <u>not</u> wearing the ILC Dover tube suit and no preceeding 3.5 hour rest period. The $\dot{V}O_2$ was 1,336.4 ± 198.2 (SD) ml/min or 16.7 ± 2.3 ml/min/kg (5,6).

To summarize, adding the ILC-Dover tube suit and swimming after 3.5 hours of rest increased $\dot{V}O_2$ by approximately 45% in these two divers using the same fin.

G. THERMAL POWER DELIVERED TO S-TRON AND ILC-DOVER ATS

The water flow to both ATS was kept as close to 0.5 gpm as possible, as shown by Figure 23. Steady state values averaged 0.49 ± 0.01 (SE) gpm for ILC-Dover for 0 to 3 hours and 0.51 ± 0.01 (SE) gpm for S-TRON for 0 to 2.5 hours. The average inlet water temperature for the ILC-Dover ATS from 0 to 3 hours was 38.7 ± 0.1 (SE) °C (101.7 °F) and for the S-TRON ATS from 0 to 1.5 hours, 36.9 ± 0.2 (SE) °C (98.4 °F). Based on the temperature difference between inlet and outlet water temperature for S-TRON and ILC-Dover ATS (Figures 24 and 25, respectively), the power delivered to both ATS in thermal units of watts is illustrated in Figure 26. At two hours, the mean power delivered to the ILC-Dover ATS was 624.0 ± 178.4 (SD) watts. This is power to heat the body but not the hands or head. The variability in this number is primarily due to the unavoidable fluctuation in water flow of approximately ± 0.1 gpm (Figure 23). The power delivered to the S-TRON ATS heating both hands, feet, head and body was approximately 650 watts.

H. PORTABLE AND ON-LINE DIVER MONITORING SYSTEMS (DMS)

During five man-dives with the ILC-Dover ATS, the portable DMS (Science/Electronics, model 1299, Dayton, OH) was used along with the on-line DMS on the same fingers to compare fingertip temperatures for accuracy (15-16). Comparable values between the calibrated on-line DMS and portable DMS were within ± 0.3°C, providing all digit thermisters (YSI, model 44033) were pre-selected to be accurate and within 0.1°C of each other. Degree of accuracy of using only the portable DMS was ± 0.3°C for skin temperature and ± 0.06°C for core temperature, determined by unmanned evaluation (15). Special design characteristics included a reduction in thickness of this modified data recorder (60 mm to 40 mm). With a low profile umbilical connector and water-proof bag, the portable DMS was used under dry suits while diving under the ice in the Arctic and in the NEDU cold water flume without affecting diver comfort.

The portable DMS has 10 channels for skin (e.g. fingertip, toe or skin) temperature, two channels for core temperature (rectal or esophageal), ECG for heart rate, and an analog channel useful to measure depth or O_2 bottle pressure for VO_2 measurement from a closed circuit UBA. A new feature allowed multiple runs to be stored up to 12 hours. This unit can also be specially ordered to measure heat flux, but would increase the thickness 50% (40 mm to 60 mm).

IV. DISCUSSION

A. HAND THERMAL PROTECTION

Although the S-TRON ATS had frequent failures, it did provide better hand thermal protection beyond 60 minutes of immersion compared to the ILC-Dover ATS with heat on the forearm but unheated hands. The variability in fingertip temperature with either S-TRON or ILC-Dover ATS was due to varying degrees of dry glove squeeze, affected by hand position. In preliminary testing, glove liners and dry gloves that were too tight also caused rapid cooling of fingertips. Operating SDV controls or conducting dexterity tests in the near-prone position, the hands were squeezed below the collapse plane observed to be at the chest level. This caused a rapid reduction in fingertip temperature with the ILC-Dover ATS, aborting the first diver at 78 minutes due to termination criteria. This diver's fingers were also painful and with little dexterity 30 minutes prior to termination. If the ILC-Dover ATS is used with the dry gloves below the collapse plane, active heating of the hands will be required for dives longer than one hour.

It was observed in the two divers who completed 3.5 hours of exposure in the ILC-Dover ATS that their gloves were inflated, above the collapse plane, when not conducting dexterity and SDV controls testing. The other six divers followed the protocol keeping their gloves below the collapse plane and were terminated during the initial 3.5 hour rest priod. If the SDV can be modified to allow divers to inflate their gloves, then this will have to be studied at 4.6 m in 2°C water, simulating an SDV training mission.

In two laboratory studies of diver passive thermal systems (PTS) evaluating British made dry suits and undergarments in 2 to 5°C water, it was reported that divers achieved exposures as long as 408 minutes (4) and 242 minutes (20). However, low fingertip temperature caused divers to abort due to termination criteria as early as 48 minutes (4) and 62 minutes (20), respectively. No comment was made whether glove inflation was controlled or if nonfreezing cold injury occurred during these dives. These studies, done at rest in an immersion tank, used an undergarment called Flectalon (Arktis Outdoor Products, Exeter, England) of similar thickness and insulation to the heavier weight M-600 Thinsulate (8-9). Flectalon also restricts divers during long distance free-swimming (personal communication, Major Clifford, Royal Marines). These studies suggest active heating of only the hands would be needed for dives longer than 30 minutes to avoid hands from becoming numb.

In a recent laboratory study of diver PTS at the Naval Medical Research Institute (NMRI), the successful completion of 6 hour exposures in divers wearing dry suits in 5°C (41°F) water may have been due to divers having dry gloves inflated while sitting upright on a chair (personal communication, Dr. Weinberg). This study, soon to be published, was conducted at a shallow depth (1.8 m, 6 ft) with a greater amount of dry suit gas compared to our study at 4.6 m (15 ft). There were no measurements of fingertip temperature in this NMRI study for comparison to our study and no instances of nonfreezing cold injury were noted. In this NMRI study, divers used M-800 weight Thinsulate on the torso and M-600 weight Thinsulate on the rest of the body with approximately 40 kg (88 lbs) of weight across the lap. In our study, M-400 weight Thinsulate was used which is 50% the insulation of M-800 and 67% of

M-600 Thinsulate. Using M-400 Thinsulate in our study required only 15.9 kg (35 lbs) of lead shot in a weight vest. As discussed, the M-400 weight Thinsulate was preferred over M-600 and M-800 Thinsulate undergarments by our cold water dive team due to less restriction during swimming, less weight carried and no over-heating (hyperthermia) or exhaustion during free-swimming at 0.5 kns (6). Although conditions differed in the NMRI study to ours, glove inflation was responsible in part for extended exposures in 5°C water at NMRI.

Preliminary data from NMRI (personal communication, Dr. R. Weinberg) indicates that active heating of the hands and feet of divers wearing dry suits supported divers in 2°C for up to eight hours. These tests were also done in shallow water (1.8 m) and used M-800 weight Thinsulate on the torso and M-600 weight Thinsulate on the rest of the body with a 40 kg lap weight belt. The gloves were also allowed to inflate at upper chest level with the divers in a sitting position. This was much more insulation and dry suit gas than used in our study testing thinner undergarment insulation at a greater depth of 4.6 m with our diver's hands more compressed. Approximately 100 watts of power was required to thermally protect the hands in the inflated gloves (personal communication, Dr. R. Weinberg). What remains to be evaluated is the benefit of active hand heating and the power requirement with the same degree of glove and suit squeeze experienced operationally by SPECWAR SDV divers.

As suggested by Mr. Dudinsky of the Naval Coastal Systems Center (NCSC), moving the SDV control panel up would allow the hands to remain warmer due to less dry glove squeeze. With many of the divers in our study complaining of low back discomfort in the near-prone position, the body position would also have to change to support the diver working with hands above the chest level. As suggested by Mr. Richard Roesch of NCSC, possibly a kneeling position would eliminate low back pain. This position would also reduce the uncomfortable negative facemask squeeze of being near-prone with the MK-15 UBA and AGA FFM.

Although it is difficult to sustain work on dry land with hands raised above the heart level, while immersed the arms and hands are neutral or positively buoyant requiring less effort. Also, with less dry glove squeeze, capillary blood flow would not be restricted adding more warmth to the hands. With an elevated instrument position and more comfortable body position, passive or active hand thermal protection must be tested with the same degree of dry suit squeeze experienced during SDV transit. The NEDU cold water flume is an ideal facility to allow a complete physiological and human factors evaluation of divers in an SDV cockpit at 4.6 m in salt water to -2°C (28°F) or fresh water to 2°C (35°F).

The critical test of thermal protection of the hands would be to compare active vs. passive hand protection in conditions relevant to SPECWAR diving simulating the proper depth plus body and hand position of SDV transit and free-swimming. If the core temperature, plus hand dexterity and comfortable skin temperature can be maintained passively, active heating of the hands would not be needed for shorter duration dives in 2°C water. It is doubtful, however, that the preferred M-400 Thinsulate could passively protect the diver for a total of 8 hours of immersion. With inadequate undergarment insulation, there would be cold skin and a dropping core temperature causing cutaneous vasoconstriction. This would also lead to reduced finger blood flow and cause very cold hands even if the gloves were inflated.

If glove inflation is going to be tested further, volume restriction and a method to retain the gloves near the fingertips (e.g. cinching straps) are needed to prevent loss of dexterity. Dry suit gas easily escapes under the wrist seal and will overinflate most gloves away from the fingers. This has lead to gloves popping off or preventing the diver from adjusting his equipment during Arctic diving operations and SDV training missions. One-way valves on the back of the hand should be avoided due to observations of leaks and a complete purge of dry suit gas during testing at NEDU.

Active heat applied to only the hands of a diver that is otherwise passively protected has recently been investigated at NMRI (personal communication, Dr. Weinberg). Although this is an attractive alternative by reducing hardware design and equipment carried by the diver, heating only the hands may lead to increased heat loss of a diver. Warming the hands of a cold diver may override the body's attempt to conserve heat by causing unwanted dilation of the body's skin blood vessels (reflexive vasodilation). This effect, documented one study of hand blood flow, is reviewed elsewhere (21). Increasing warm blood flow to the skin might feel warm to the diver, but it would increase heat loss and may cause hypothermia. Warming the hands with a subject having a cold core temperature has never been investigated for any influence on skin blood flow and heat loss. This must be resolved before any conclusion is made that active heating of the hands would not require active body heating.

B. NONFREEZING COLD INJURY

With thermal conductivity of water 26 times greater than air (3), hypothermia of the finger and toes, called extremity hypothermia, is a frequent occurrence during cold water diving. The limits of thermal protection are becoming more dependent on avoiding extremity hypothermia due to intolerable hand and foot pain and the loss of hand dexterity (22). In our study using ATS at 2°C and during monitored dives using passive thermal systems (PTS) in the Arctic at -2°C, the finger tip temperature dropped to the pain threshold of 10° to 12°C in 45-60 minutes if the diver was at rest, not generating sufficient heat by swimming or vigorous underwater work (15-16). This occurred hours before the core temperature would have fallen to hypothermic levels. Going beyond finger pain, into numbness (8° to 10°C), increases the risk of inducing nonfreezing cold injury, NCI (3). The mechanism of NCI is unclear, but prolonged cold exposure and restriction of digit blood flow may permanently alter the normal blood flow response to tissue rewarming and subsequent cold exposure (3,23). Following nonfreezing cold exposure, the rewarming process is accompanied by swelling, redness, pain and itching, which is similar to rewarming frostbitten tissue. The treatment of prolonged cold exposure leading to numbness would be the same as for frostbite; immersion in 40-42°C (104-108°F) water for quick rewarming to limit tissue damage from the cold (24-25). Pain medication (narcotic analgesia) may also be needed. The treatment of hypothermia and NCI during diving is extensively reviewed elsewhere (26-27).

Once NCI occurs, upon subsequent exposure to cold water, the diver would experience intense cold and pain very quickly. This is possibly due to early vasoconstriction in the digit blood vessels (3,23). The duration of cold exposure that will develop NCI is not known. With slow cooling of the hands, the diver may never realize his hands have become numb. In fact, some divers in our studies at NEDU and in the Arctic have noted that their hands developed an unusual partial numbness but also warm sensation subsequent to varying levels of pain. It was also difficult to check for numbness with negative glove pressure reducing tactile sensation. The digit temperatures of these divers of only 6-8°C were within the numbness range for most divers (15-16). Relying on severe pain as the only voluntary termination criteria is not reliable or advised to avoid NCI during laboratory or operational dives.

Only four divers in our study complained of transient mild pins and needles (paresthesia) and reduced sensation (hypesthesia). There was no evidence of tissue damage or increased susceptibility to cold exposure in these diver-subjects. With adequate physiological monitoring and follow-up medical evaluation in our study, the digit temperature termination criteria of 8°C for 30 mins or 6°C at anytime (4) has now been sufficiently evaluated. This termination criteria should be considered as a safe exposure limit (SEL) to prevent NCI during monitored diving in near-freezing water.

Based only on anecdotal reports from military cold water diving units, we would estimate that 60 mins of digit numbness would probably develop NCI in most divers. There appears to be great inter-subject variability in susceptibility to NCI. The prevention of this disabling problem, which can prevent a diver from diving in cold water, is being investigated by scientists who are now monitoring digit temperature during open-ocean dives in near-freezing cold water (15-16) and experimental dives in the laboratory (4,20). Safe exposure limits for cold water diving can then be determined using various factors including water temperature, levels of underwater exercise, diving suit garment, hand position and body type.

C. WHOLE BODY THERMAL PROTECTION

Recently, Lockheed (San Diego, CA) documented the results of three man-dives conducted in shallow water (1.8 m, 6 ft) also at 2°C (35°F) water with the same ILC-Dover ATS (2). It was reported that inlet water temperature of 102 F (39°C) at 0.5 gpm allowed rectal temperature to remain within 0.5°C of normal control values. The approximate power requirement to supply heat from a thermoelectric heat pump to the ILC-Dover ATS was 275-300 watts. This was less than half the power delivered to the same ILC-Dover ATS tested at NEDU (624 watts). Our testing was at three times the depth (4.6 m) with much more suit squeeze and less insulation, which may account for an increased power consumption during testing at NEDU.

Many of the conclusions from the above Lockheed study were based on one of three dives which lasted 2 hours with considerable dry suit leaking from the waist down. The diver's rectal temperature never reached a steady state over the 2-hour dive. Exercise was allowed but was not measured or controlled. Exercise would have increased heat production but also heat loss to the skin

(28) which helps to explain why there was less of a drop in water temperature through the tube suit (2.4°C) compared to our study (6.0°C). Although one comparison dive at Lockheed was successfully done without any dry suit leaks, it only lasted 90 minutes which is too short to predict steady state rectal core temperatures for long duration dives.

In the third Lockheed dive at 2 hours, 45 minutes, the diver began 50 minutes of uncontrolled moderate exercise. Mid-way through the exercise period rectal core temperature began to rapidly fall, reaching 36.15°C at the four-hour mark. The dive was then terminated due to this unexplained drop in core temperature (personal communication, Mr. Tom Schmidt). It would appear that peripheral vasodilation and exercise increased heat loss which lead to the fall in rectal core temperature (28).

In a recent diver PTS study at NMRI (29) with no active heating, exercise was shown to increase heat loss as reflected by elevations in mean skin temperature and heat flux. At rest after two hours, mean skin temperature was 27.8°C and heat flux was 126 watts/m^2. In our study of divers actively heated at rest, we observed very high mean skin temperatures (33.8°C) and heat flux (598 watts/m^2) from the potentially vasodilated skin caused by active heating with the ILC-Dover ATS. In our study after 3.5 hours of active heating at rest, one passively protected diver completed 30 minutes of free-swimming, but showed a near doubling of heat flux (1200 watts/m^2) compared to resting values with active heat.

The values of power supplied to the tube suit (624) watts is much less than the total of 1220 watts of heat flux (598 watts/m^2 * 2.04 m^2 - 1220 watts) from the diver. This discrepancy is unexplained. The values of heat flux were predetermined to be accurate and in the correct direction of heat loss from the diver. The sporadic surface heating of heat flux disks by the hot water tubes may affect the accuracy of these transducers which already have an inherent uncertainty of 20-30 % (personal communication, Dr. M.L. Nuckols).

In summary, our results have documented a negative effect of active body heat at rest increasing heat loss and possibly increasing heat flux during subsequent exercise with passive protection. Lockheed's results suggest increased heat loss with exercise and active heating and NMRI has documented increased heat loss with exercise in passively protected divers.

This unwanted high loss of body heat with peripheral vasodilation caused by skin warming from the ATS additionally being aggravated by exercise must be studied more thoroughly. If active heat is required during extra vehicular activity (EVA) from the SDV with man-carried heat sources, it cannot be assumed safe to thermally protect the diver until studied further simulating operational conditions.

If a passively heated, free-swimming diver returns to the SDV and active heating is restarted for hands or whole body, continued high heat loss from skin of the now resting diver could cause hypothermia. The fatigued, dehydrated and nutritionally depleted diver would not generate much heat at rest with active skin heating suppressing any heat production from either shivering or non-shivering thermogenesis. Hypothermia could insidiously occur during the second SDV transit if the skin temperature is kept warm and vasodilated by active heating, preventing symptoms of shivering or uncomfortably cold skin if insufficient calories of heat are delivered to the diver.

D. FULL FACEMASK USE DURING PROLONGED COLD WATER DIVING

Due to inadequate thermal protection, face discomfort during diving, jaw pain following diving, and the risk of the AGA FFM closing off the airway of an unconscious diver, a full helmet is strongly recommended for prolonged dives in near-freezing cold water.

E. OXYGEN CONSUMPTION

Resting values of $\dot{V}O_2$ (457 ml/min) indicate that the ILC-Dover ATS thermally protected divers since these values are very close to resting values of $\dot{V}O_2$ (11). For comparison, shivering, which never occurred using the ILC-Dover, is known to increase resting $\dot{V}O_2$ three to five times (30). Compared to free-swimming in the same dry suit without the ILC-Dover tubulated undergarment, the two divers who completed 3.5 hours of rest and began swimming with the ILC-Dover ATS had a 45% increase in $\dot{V}O_2$. This indicates more effort was needed to swim with the addition of the ILC-Dover tube suit following the 3.5 hour exposure at rest. In this study, values of $\dot{V}O_2$ in the Results section should be useful to calculate realistic values of carbon dioxide (CO_2) production for the unmanned evaluation of CO_2 canister duration at rest and free-swimming.

Further research in the total energy cost of underwater fin swimming is being investigated by Dr. David Pendergast, Professor of Physiology, Department of Physiology, State University of New York at Buffalo.

F. HUMAN FACTORS SUMMARY

The human factors analysis, published as a separate report (29), will include the evaluation of dry gloves, dry hoods and other dry suit accessories, e.g., weight vests, two urinary overboard dump systems and compatibility of the two ATS with the MK-15 Mod 0 underwater breathing apparatus (UBA). Hand dexterity and strength measures during the simulated SPECWAR mission will also be reported in the human factors report.

The evaluations of S-TRON and ILC-Dover ATS and urinary overboard dump systems are summarized below.

1. S-TRON and ILC-Dover ATS

The eight divers who dove both the S-TRON and ILC-Dover ATS unanimously preferred the ILC-Dover due to ease of dressing, comfort and flexibility in the water, design simplicity, and to reliably deliver warm water and not leak. The S-TRON ATS had increased bulkiness with dressing which restricted underwater swimming. The panel design of the tubes in the S-TRON resulted in hot and cold spots which was perceived as highly uncomfortable. The tube suit glove, although favorably evaluated for warmth, did not allow the index finger to be withdrawn back into the warm mitt, nor could the thumb oppose with the index finger during controls manipulation. The poor reliability of the prototype S-TRON ATS resulted in leaks during 15 out of 15 man-dives. Out of 13 additional man-dives with the modified S-TRON, only three dives lasted 60 mins and one dive, 150 minutes before leaks or restriction of hot water flow developed. Failures causing termination were the following in decreasing order: dry wrist seal flooding (cold water), tube suit connector failures, hot water inlet/outlet coupling failures, and tube kinking with restriction of water flow.

The S-TRON is not recommended for full scale engineering development due to patchy distribution of hot and cold causing scalding sensation and nausea, plus poor reliability and bulkiness during underwater evaluation. The ILC-Dover ATS is recommended due to the uniform distribution of heat being well tolerated, high reliability, and reasonable flexibility during underwater evaluation.

Actively heated gloves will be needed for dives lasting longer than one hour to avoid NCI and prevent reductions in reduced hand strength and dexterity with cold fingers if the gloves are below the collapse plane.

2. Urinary overboard dump systems

Eight divers evaluated the standard issue urinary overboard dump systems (UODS) having a condom, catheter and one-way check valve. We also modified this UODS by simply adding another check valve to prevent the low air pressure from developing between the one-way check valve and the penis. This was done to prevent ruptured blood vessels (ecchymosis and hematoma) and swelling on the tip of the penis which has occurred with the original version of the UODS. All eight divers at NEDU and divers at SDV Team One unanimously agreed that it was unreasonable to require the diver to urinate in the standard UODS before diving begins to prevent low air pressure developing in the UODS. Adding another one-way valve between the condom and overboard one-way valve with a Y connector allowed incoming dry suit gas to prevent this squeeze. No discomfort was found with descent or urination to depths of 4.6 m. The tubing must be stiff and custom cut to not kink to avoid restriction of urination and intense pain. An ideal suit penetrator with a stiff tube is the oral inflator (part #27200) by SI TECH AB of Sweden, distributed by High Tech Diving (Port Charlotte, FL). The point of contact regarding installation and use of the UODS is T. J. Doubt, Ph.D. at NMRI, (202) 295-5912, or A/V 295-5912.

V. CONCLUSIONS AND RECOMMENDATIONS

1. The S-TRON ATS provides poor thermal protection to the body of the diver and should not be considered for further engineering development. The actively heated glove is adequate to thermally protect the hands compared to the unheated glove in the ILC-Dover ATS. Factors known to cause rapid cooling of the fingers are underwater glove compression and liners/dry gloves fitting too tight.

2. The ILC-Dover ATS thermally protects the body core for 3.5 hours at rest providing the hands have not reached termination criteria. Active heating of the hands will be required for dives longer than one hour in near-freezing

water. Reliable active heating of the hands with a water-proof wrist seal must be solved before further evaluations are undertaken. Durability testing of the ILC-Dover tube suit should also be evaluated under simulated on-land conditions (e.g., crawling, running).

3. Power required for heating the hands would be approximately 100 watts using inflated gloves (personal communication, Dr. Weinberg) and 624 watts for the heating the body from our study, totalling 724 watts. With deflated gloves and adding heat to the head, power required would be higher and should be investigated.

4. The digit temperature termination criteria (4) used in this study was physiologically evaluated, and should be used as a safe exposure limit (SEL) during future monitored cold water diving to prevent nonfreezing cold injury.

5. The portable Diver Monitoring System (DMS) has been favorably evaluated at NEDU and during operational dives in the Arctic (15-16). It can be reliably used in the field during training dives to help collect data to generate dive tables of thermal safe exposure limits (SEL) for operational dives to avoid nonfreezing cold injury (NCI) and hypothermia.

6. Dive tables of thermal SELs must be determined for specific diving conditions (e.g. water temperature, diving garment, rest/swim scenario, hand position and body type) based on field and laboratory data including digit and core temperature. Until these maximum exposure times can be determined, operational diving should be suspended if the diver has any degree of pain or numbness of the digits (fingers or toes) for 30 minutes or longer to avoid NCI unless operational considerations warrant assuming the risk of inducing NCI.

7. Undergarments thicker than M-400 Thinsulate should not be used with ATS development due to problems encountered during free-swimming at moderate speeds with over-heating, buoyancy control, and too much weight carried by the diver.

8. Single piece construction vapor barrier prevented perspiration from reaching the Thinsulate undergarment. The outer surface of the Thinsulate was also water-proof which prevented small dry suit leaks from saturating the Thinsulate undergarment. This layering system should be used in ATS development and operational dry suit diving to maximize thermal protection of the dry undergarments.

9. For dives longer than two hours in near-freezing water, the AGA full facemask should be replaced with a helmet for better thermal protection, less jaw pain during and following diving and to prevent airway obstruction with unconsciousness.

10. The urinary over-board dump system (UODS) must be modified with another one-way valve to prevent tissue injury to the tip of the penis.

11. Further evaluation of diver Active Thermal Systems (ATS) must include the operational body position, depth and suit squeeze, manual tasks of SDV operation, and free-swimming during a simulated eight-hour SPECWAR SDV training mission. The expertise of a Ph.D. physiologist to insure accurate and

reproducible data with appropriate physiological interpretation when using the NEDU cold water flume is strongly recommended for future evaluation of diver ATS.

12. In future studies, a minimum of six subjects for physiological data should be required before conclusions are made on ATS evaluation due to a high variability between subjects in thermal physiology performance.

13. For both experimental evaluation of diver ATS and operational use of standard dry suits, a formal dry suit training course with a minimum of ten open-water dives is strongly recommended.

14. Summarizing the unanswered questions for future ATS evaluation:

(a) If the SDV instruments can be elevated with a better body position, what is the maximum duration of exposure at rest with inflated gloves, passively or actively heated, using M-400 Thinsulate with passive or active body thermal protection with the ILC-Dover ATS? This evaluation should be conducted at 4.6 m at 2^{o}C water temperature at NEDU.

(b) If active body heating is required in (a), what is the minimum inlet temperature, and power delivered to the ILC-Dover ATS that will thermally support a diver's hands and core temperature for the initial and final 3.5 hour transit periods in the appropriate SDV instrument and body position configuration?

(c) At rest, does active heating of the hands of a diver that has a cold core temperature increase heat loss and cause hypothermia due to dilating blood vessels in the skin (reflexive vasodilation)?

(d) Data only exists from two divers swimming at 0.5 kns following 3.5 hours of rest in our study. More research is needed to determine if: (i) O_2 consumption and therefore CO_2 production is much higher than anticipated, and (ii) if active hand or body heating is required for extra vehicular activity (EVA) from the SDV. Does the diver require active hand or body heating during EVA if there is rest in between periods of free-swimming? Is there potential harmful effects of inducing hypothermia in this scenario by increasing heat loss caused by reflexive vasodilation from hand or body heating?

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FIGURE 1. S-TRON TUBULATED UNDERGARMENT, FRONT VIEW

FIGURE 2. S-TRON TUBULATED UNDERGARMENT, BACK VIEW

FIGURE 3. M-400 THINSULATE UNDERGARMENT OVER S-TRON TUBULATED UNDERGARMENT

FIGURE 4. THINSULATE HEAD PROTECTION

FIGURE 5. S-TRON ATS: LATEX HOOD, CHEST ZIPPERS

FIGURE 6. S-TRON ATS: INSTRUMENTED HAND WITH SURGICAL GLOVE SHOWING INNER WRIST RING

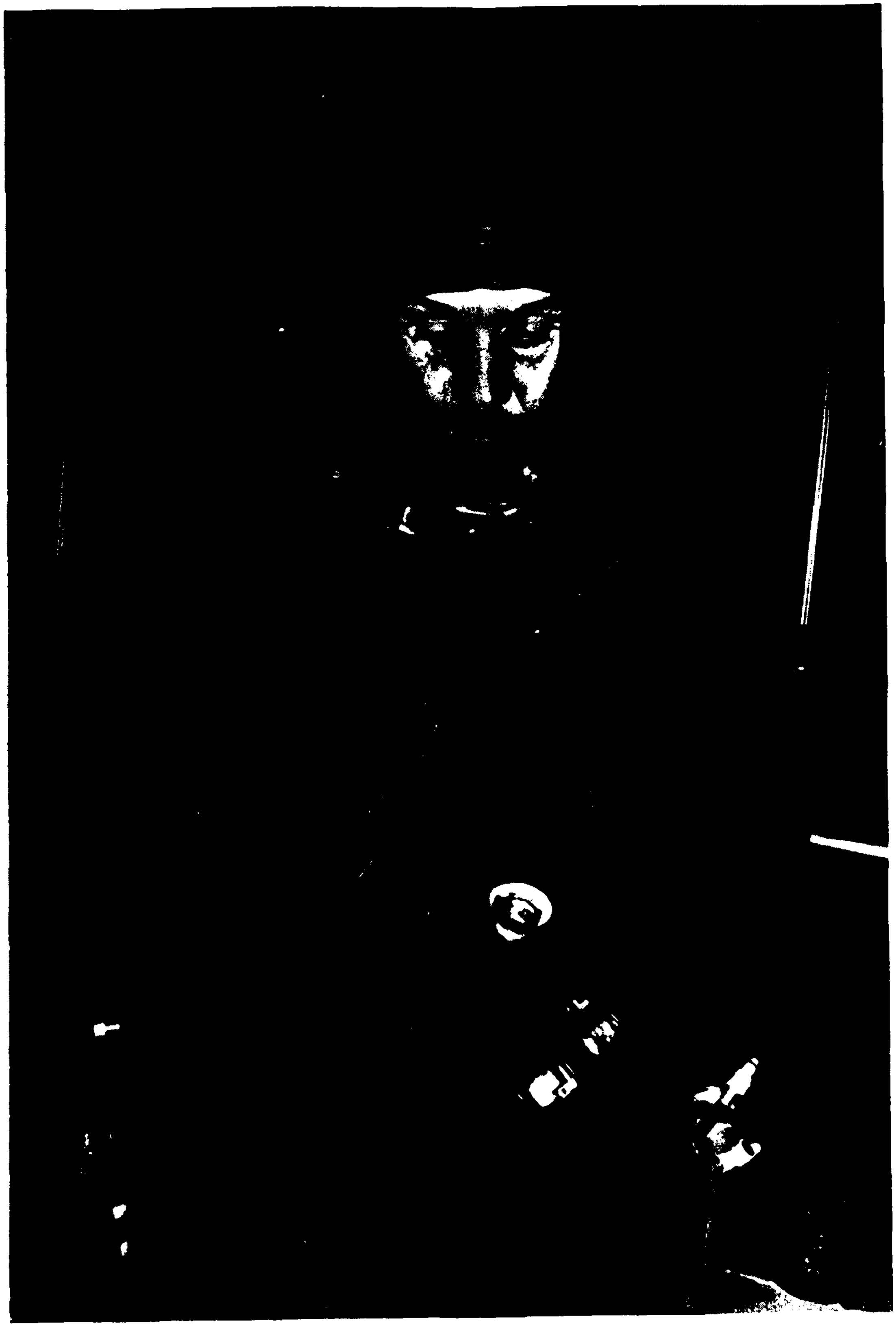


FIGURE 7. S-TRON ATS: TUBE GLOVE ATTACHED, HELD BY SMALL CLIP

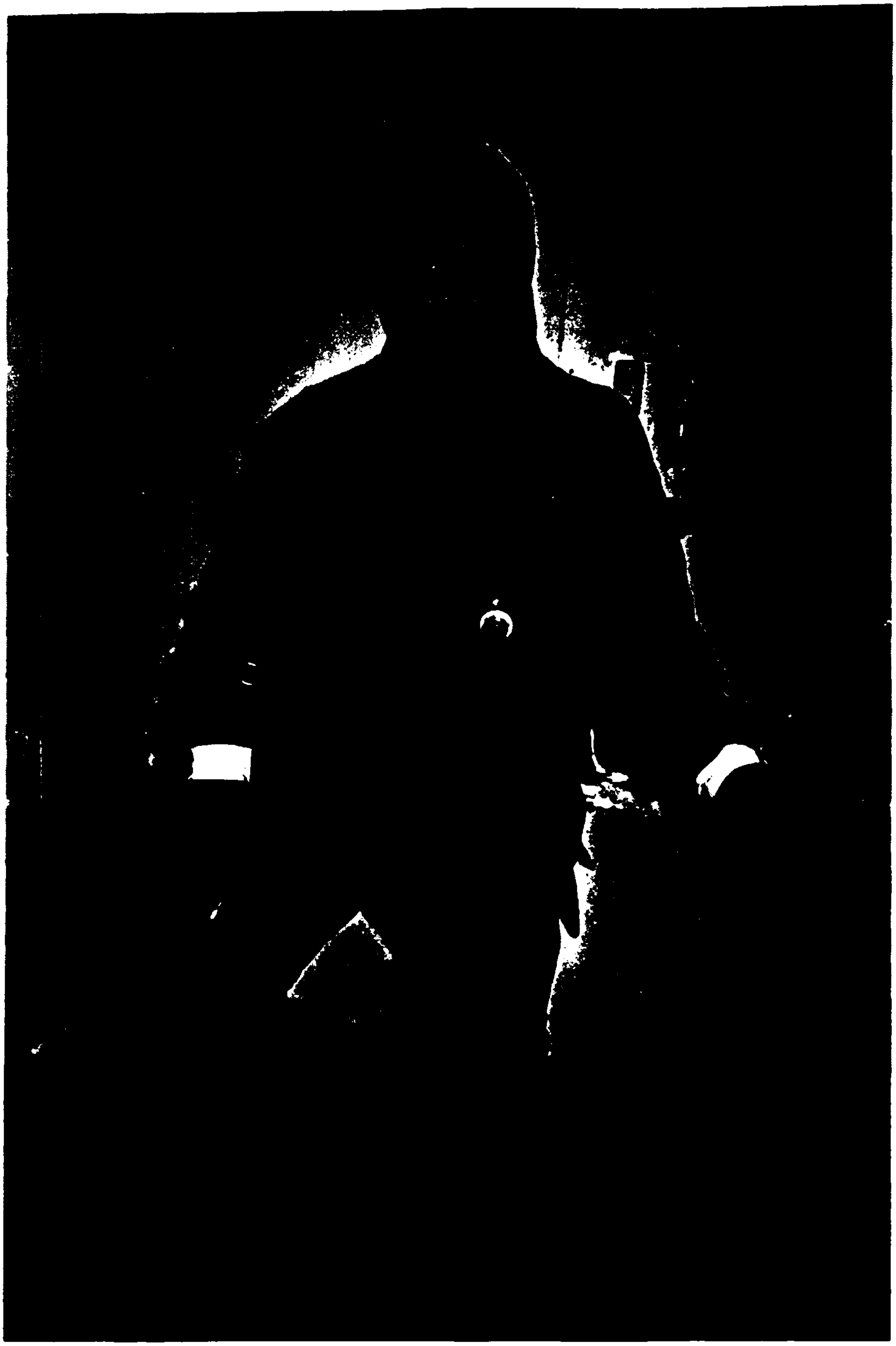


FIGURE 8. DIVER FULLY DRESSED IN S-TRON ATS WITH TAPE ON WRIST TO PREVENT LEAKS AND GLOVE OVER-INFLATION

FIGURE 9. ILC-DOVER TUBULATED UNDERGARMENT

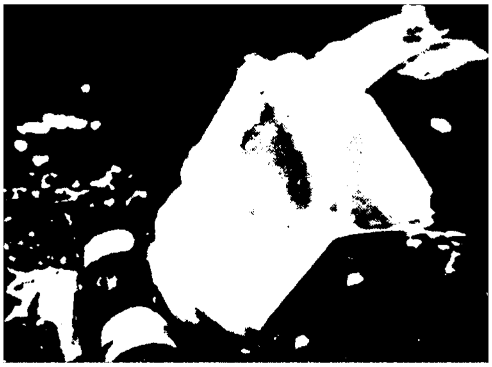


FIGURE 11. DIVERS AT 4.6 M, IN NEAR-PRONE POSITION IN SDV COCKPIT

FIGURE 12. FREE-SWIMMING DIVER IN NEDU COLD WATER FLUME

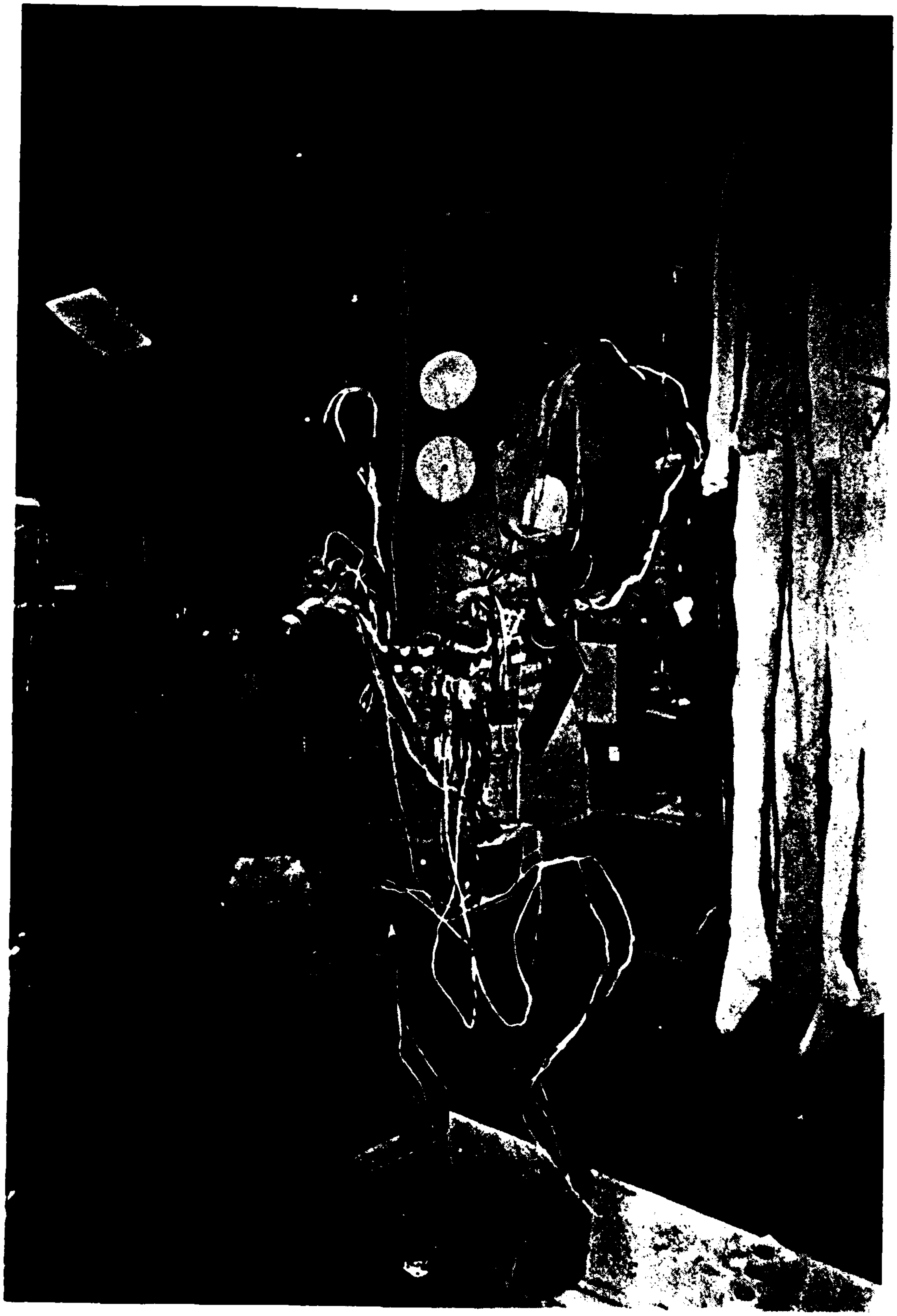
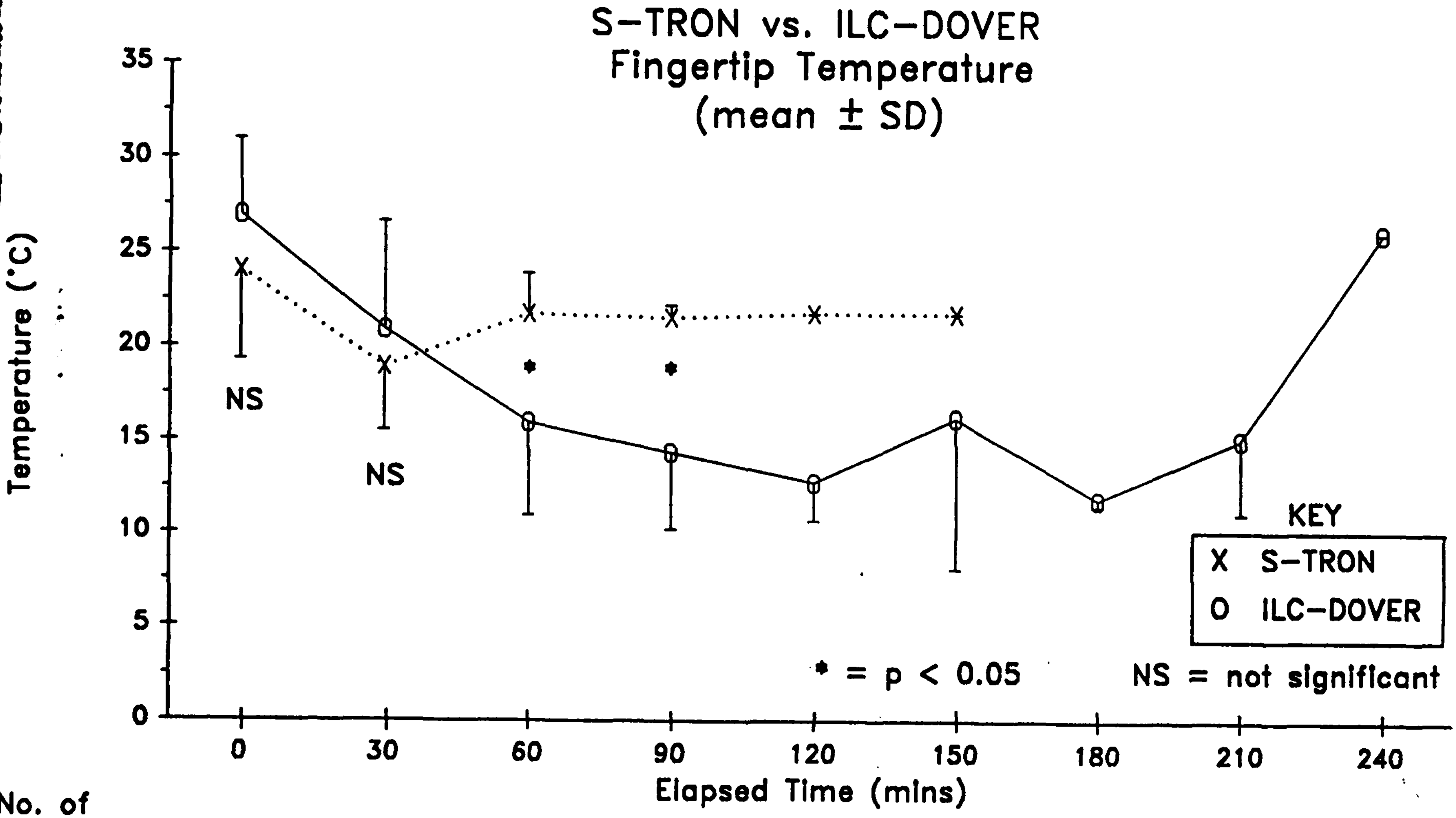


FIGURE 13. PHYSIOLOGICALLY INSTRUMENTED DIVER

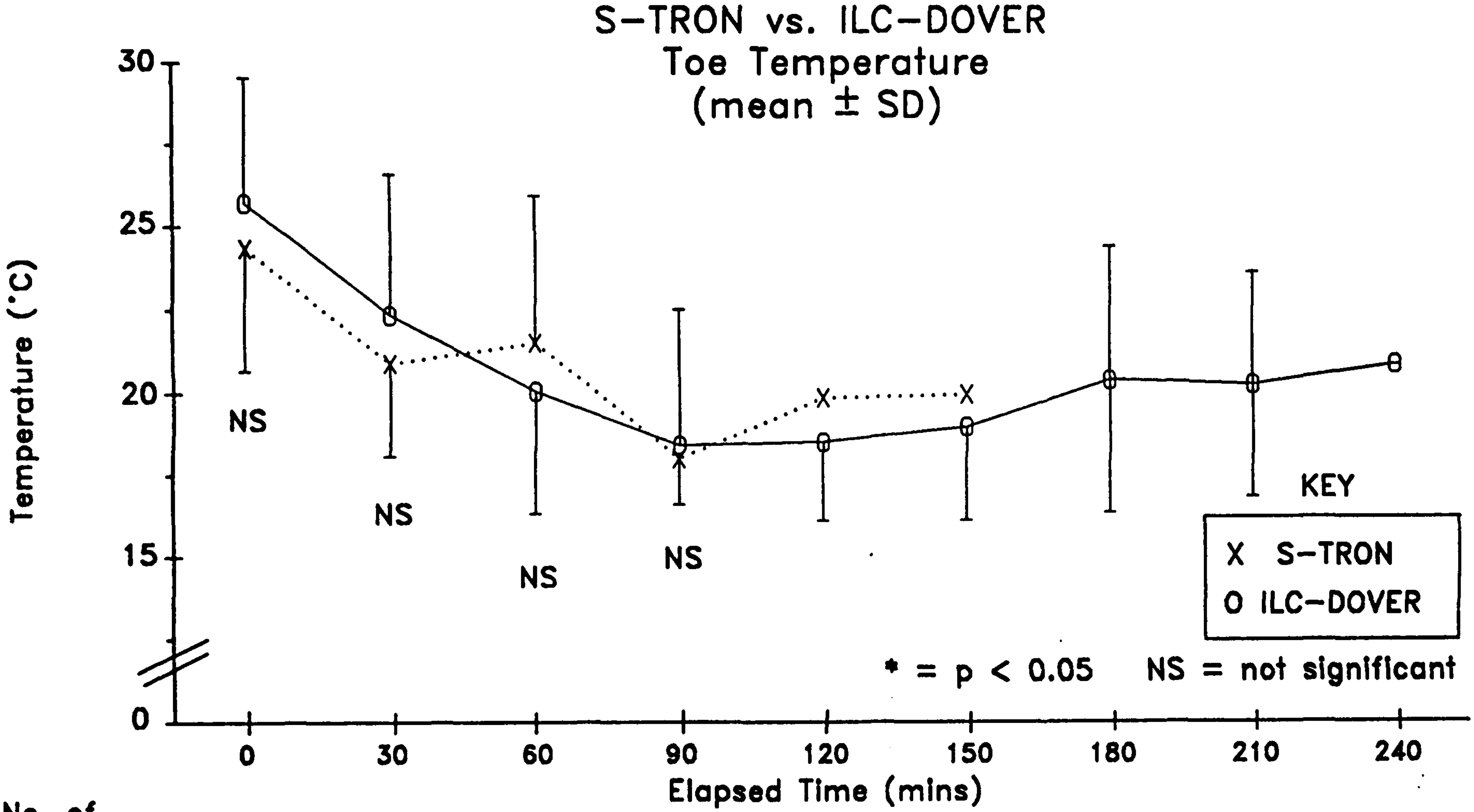


No. of Subjects

S-TRON	8	5	3	2	1	1	0	0	0
ILC-DOVER	8	8	8	7	5	3	2	2	1

[redacted]

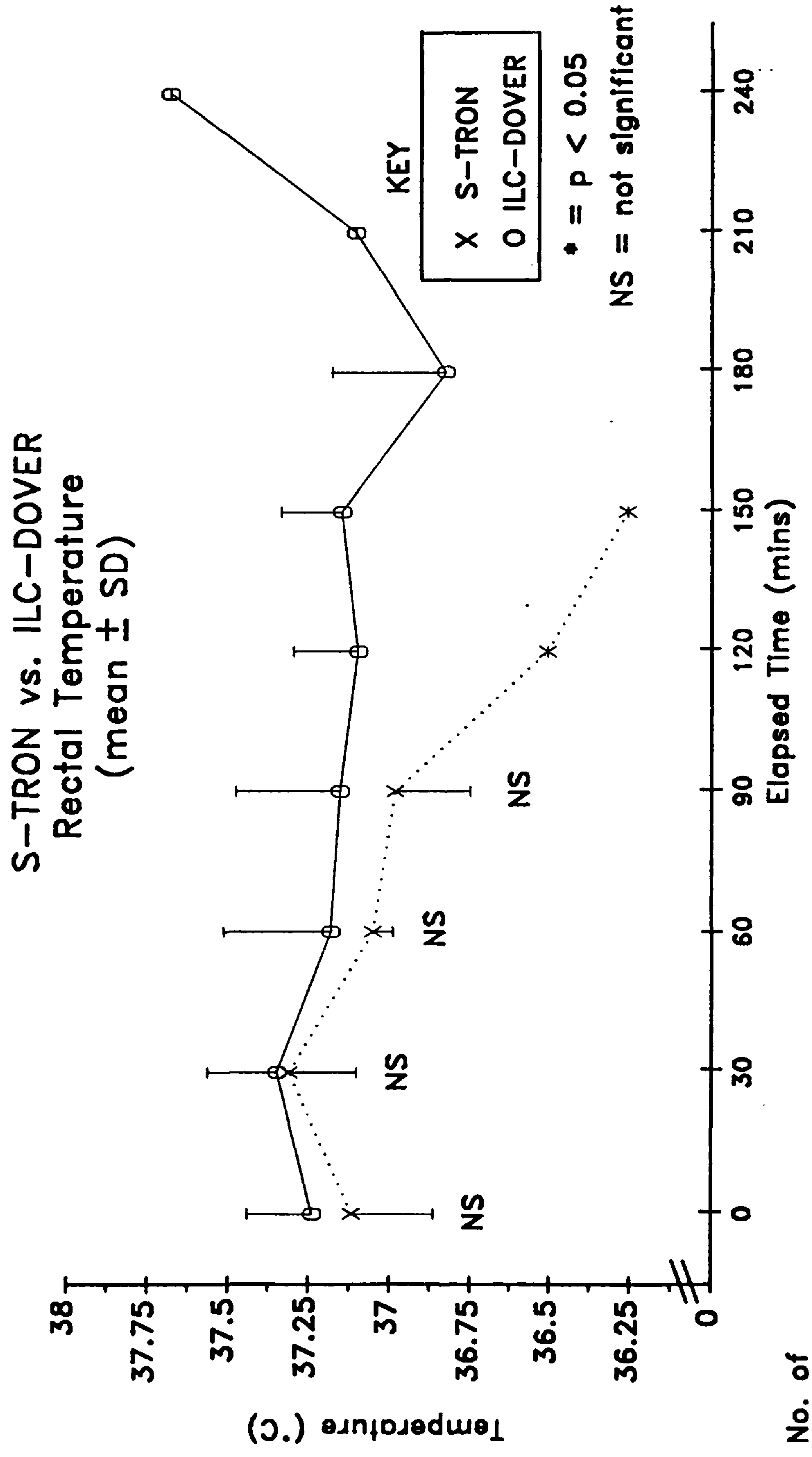
FIGURE 14.



No. of Subjects

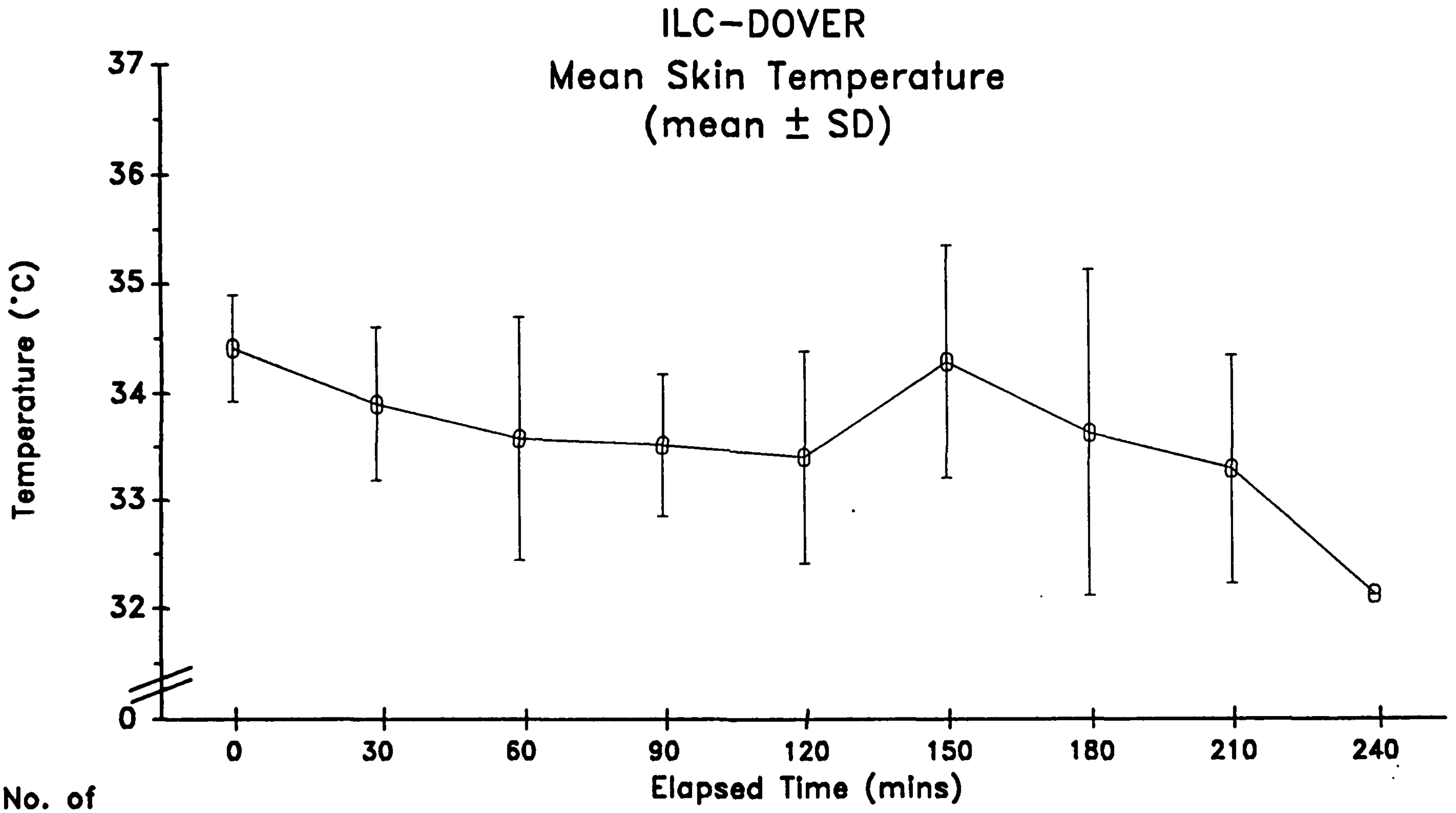
S-TRON	8	5	3	2	1	1	0	0	0
ILC-DOVER	8	8	8	7	5	3	2	2	1

FIGURE 15.



No. of Subjects	0	30	60	90	120	150	180	210	240
S–TRON	8	5	3	2	1	1	0	0	0
ILC–DOVER	8	8	8	7	5	3	2	2	1

FIGURE 16.



No. of Subjects

ILC–DOVER	8	8	8	7	5	3	2	2	1

FIGURE 17.

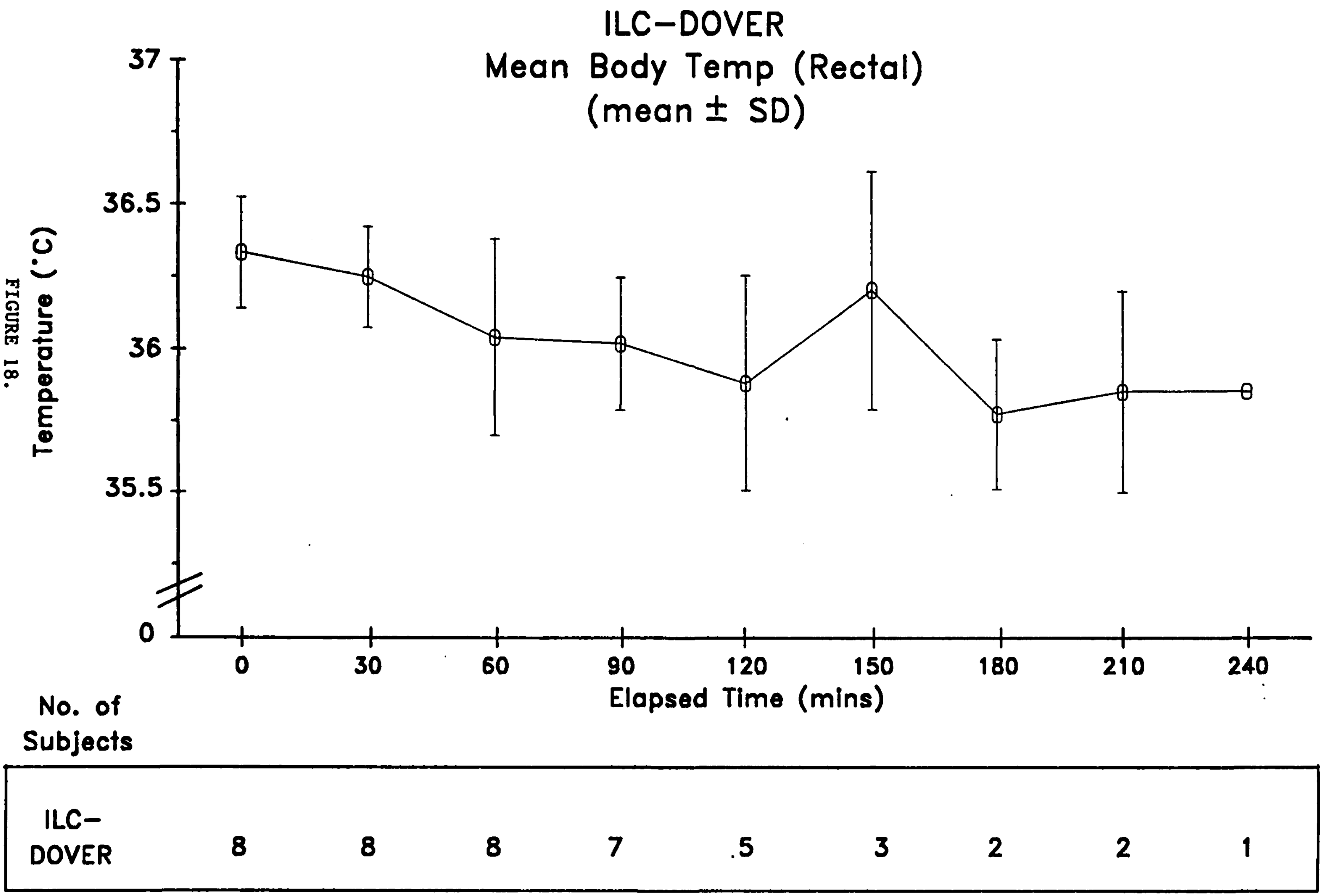

ILC–DOVER
Mean Body Temp (Rectal)
(mean ± SD)
Temperature (°C)
37
36.5
36
35.5
0
0
30
60
90
120
150
180
210
240
Elapsed Time (mins)
No. of Subjects
ILC–DOVER
8
8
8
7
.5
3
2
2
1

FIGURE 18.

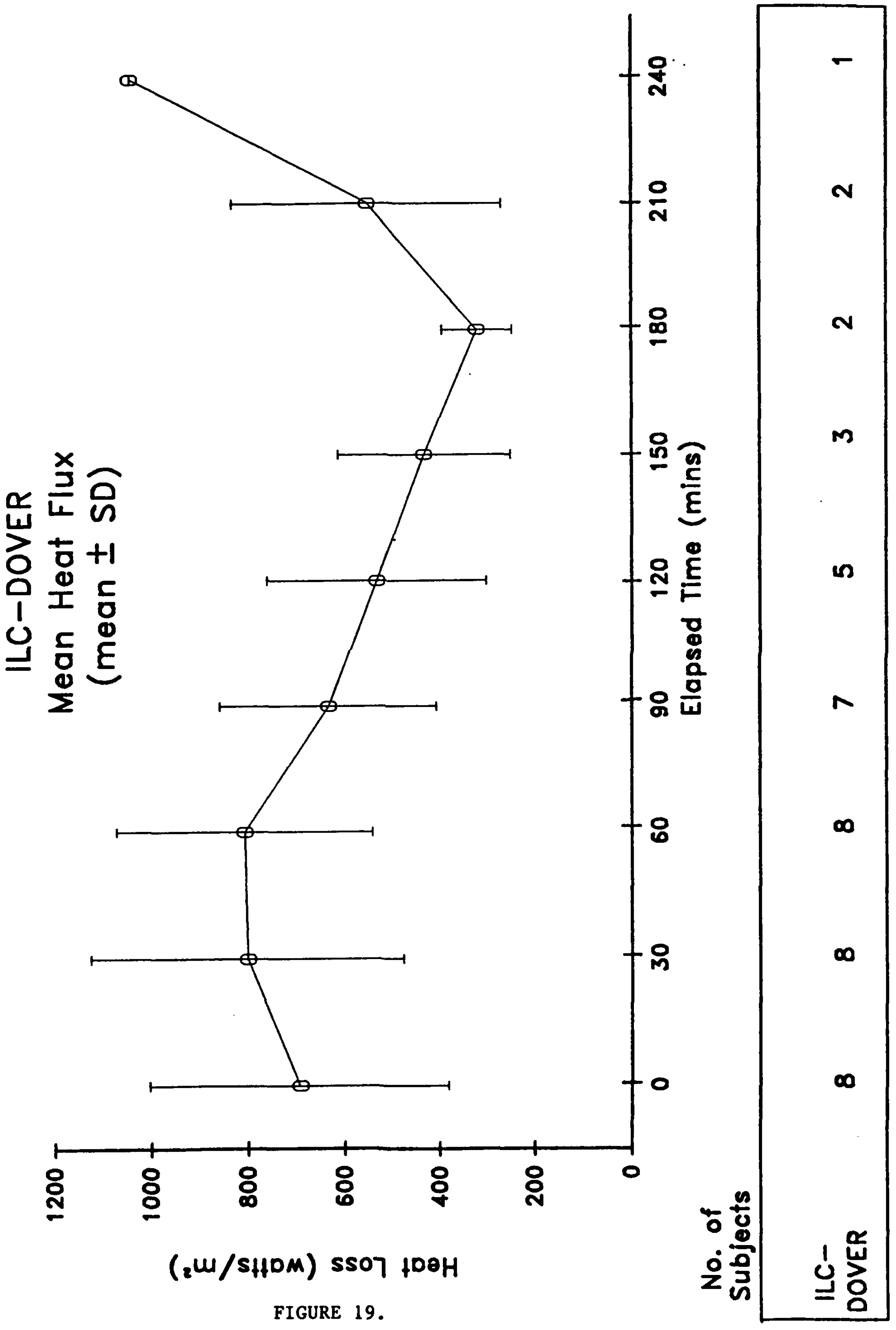
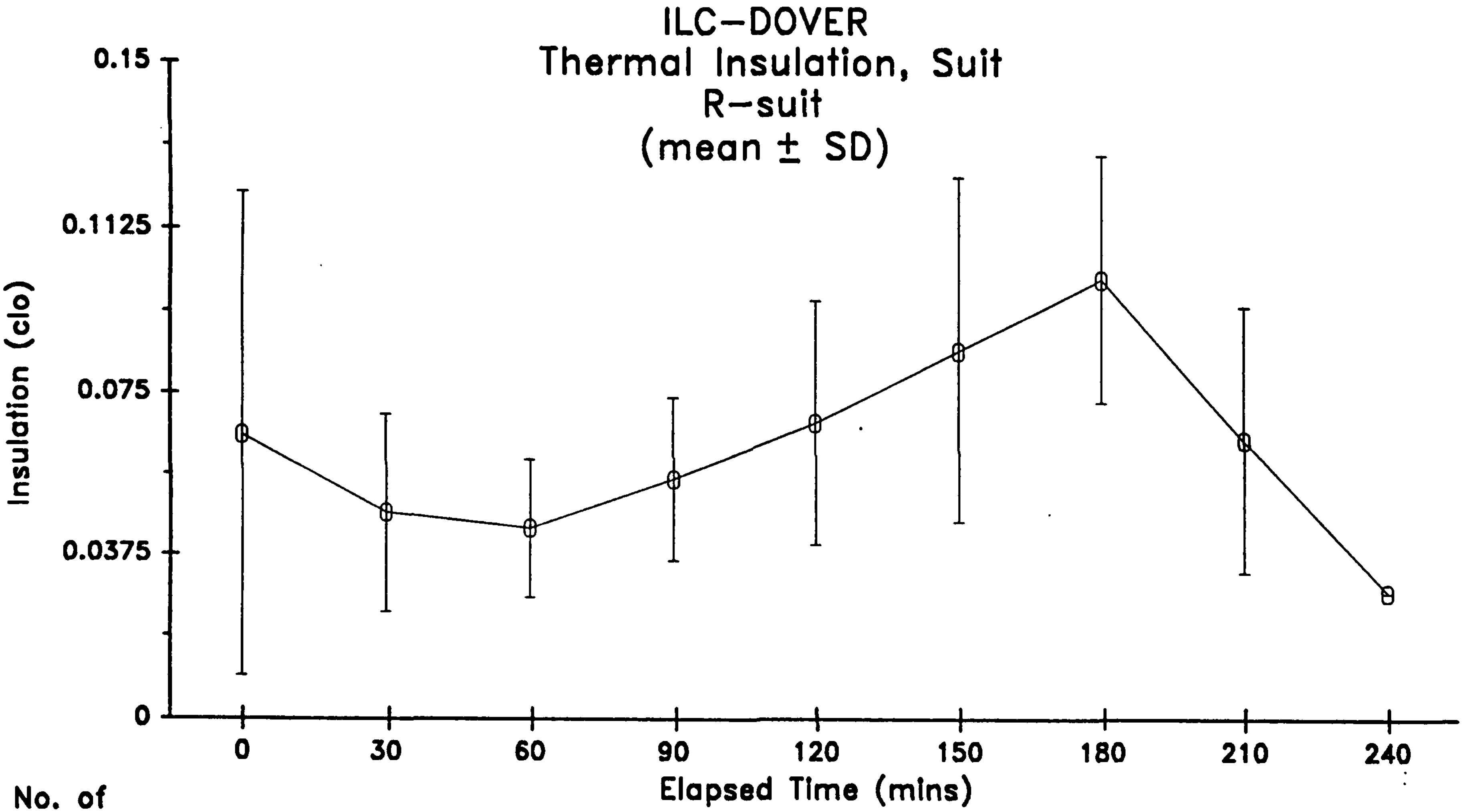
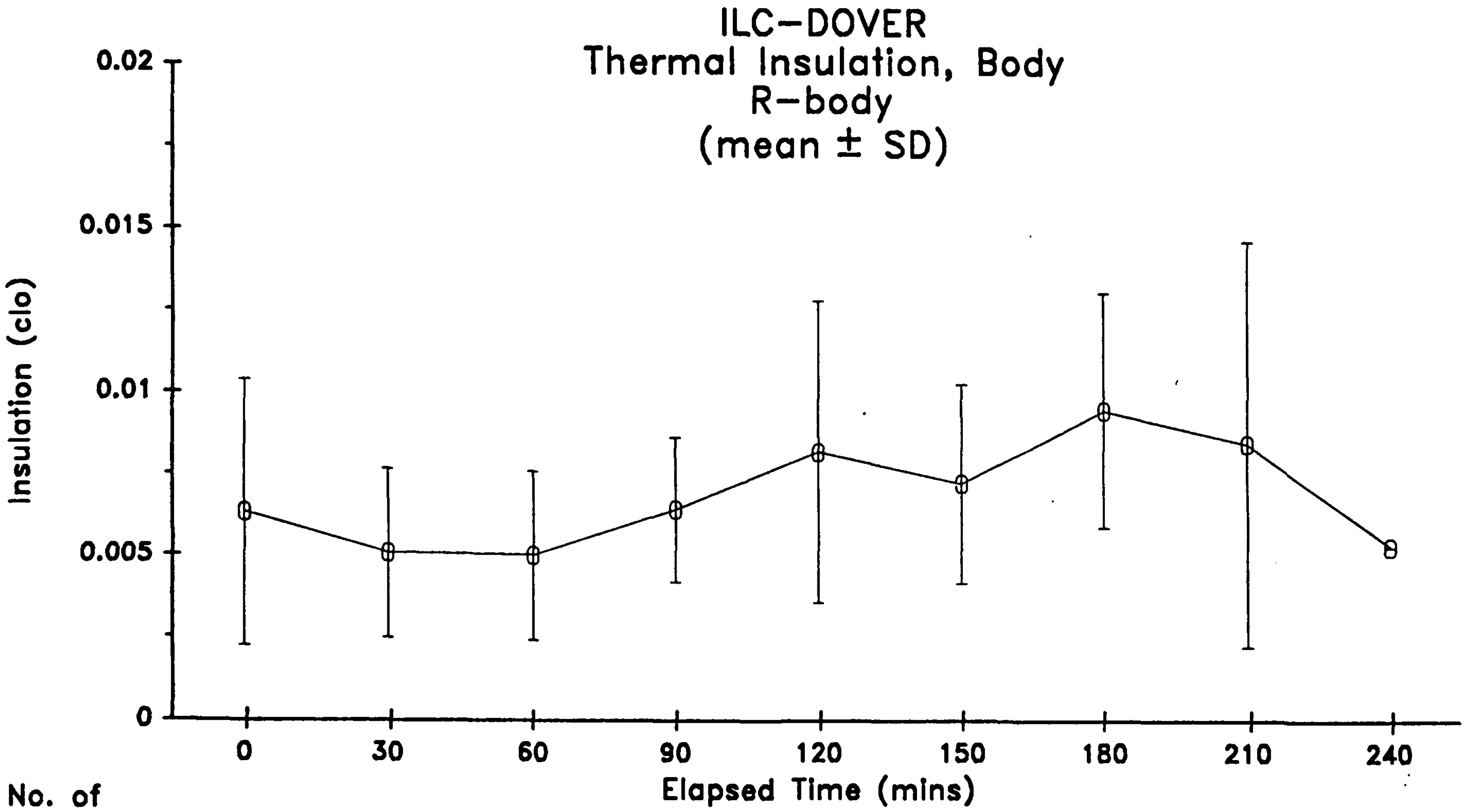

ILC–DOVER
Mean Heat Flux
(mean ± SD)
Heat Loss (watts/m²)
1200
1000
800
600
400
200
0
0
30
60
90
120
150
180
210
240
Elapsed Time (mins)
No. of Subjects
ILC–DOVER
8
8
8
7
5
3
2
2
1

FIGURE 19.



No. of Subjects									
ILC-DOVER	8	8	8	7	5	3	2	2	1

FIGURE 20.



No. of Subjects

ILC—DOVER	8	8	8	7	5	3	2	2	1

FIGURE 21.

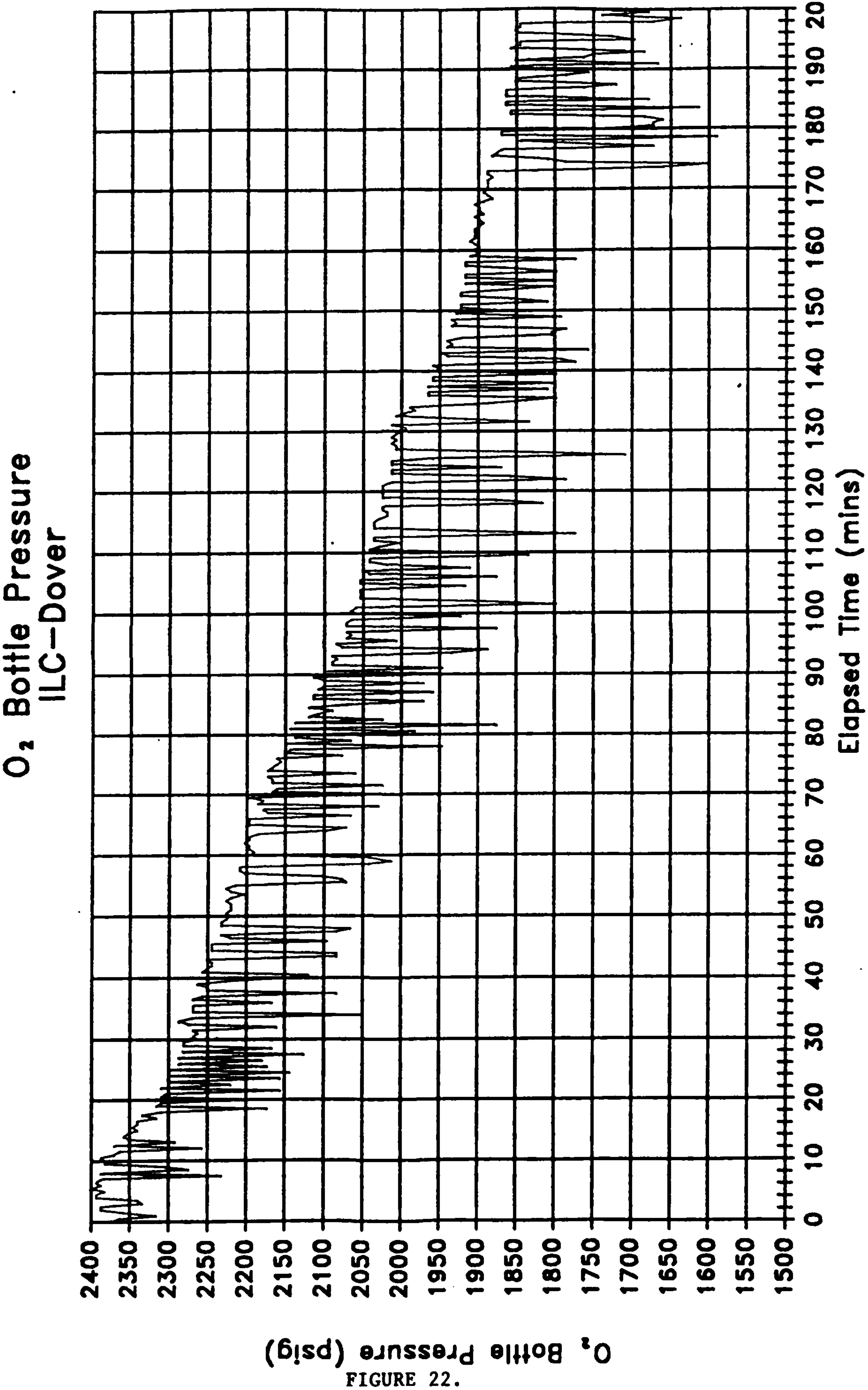
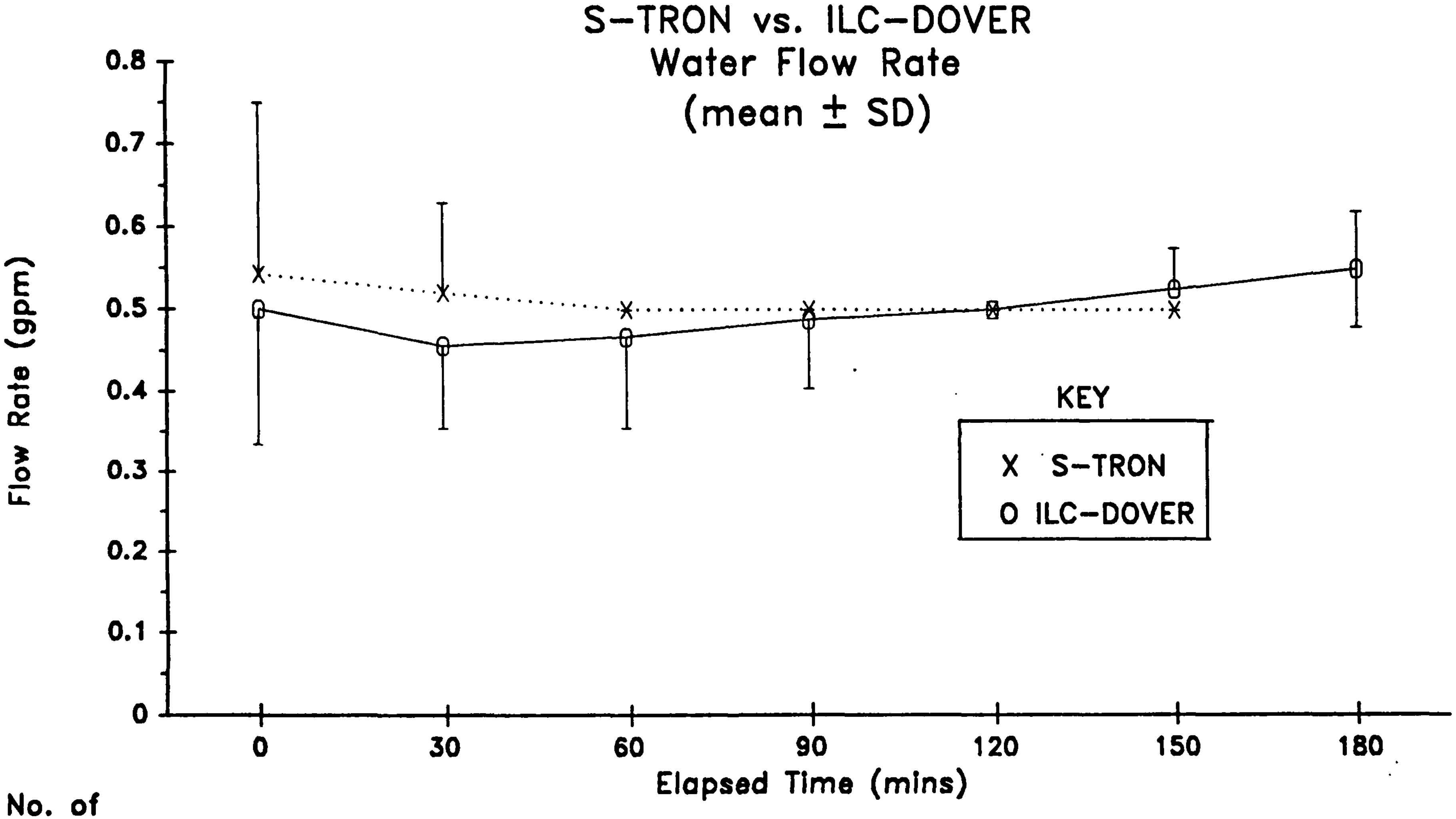

O₂ Bottle Pressure
ILC-Dover
O₂ Bottle Pressure (psig)
Elapsed Time (mins)
2400
2350
2300
2250
2200
2150
2100
2050
2000
1950
1900
1850
1800
1750
1700
1650
1600
1550
1500
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200

FIGURE 22.



No. of Subjects

S–TRON	8	5	3	2	1	1	0
ILC–DOVER	8	8	8	7	5	3	2

FIGURE 23.

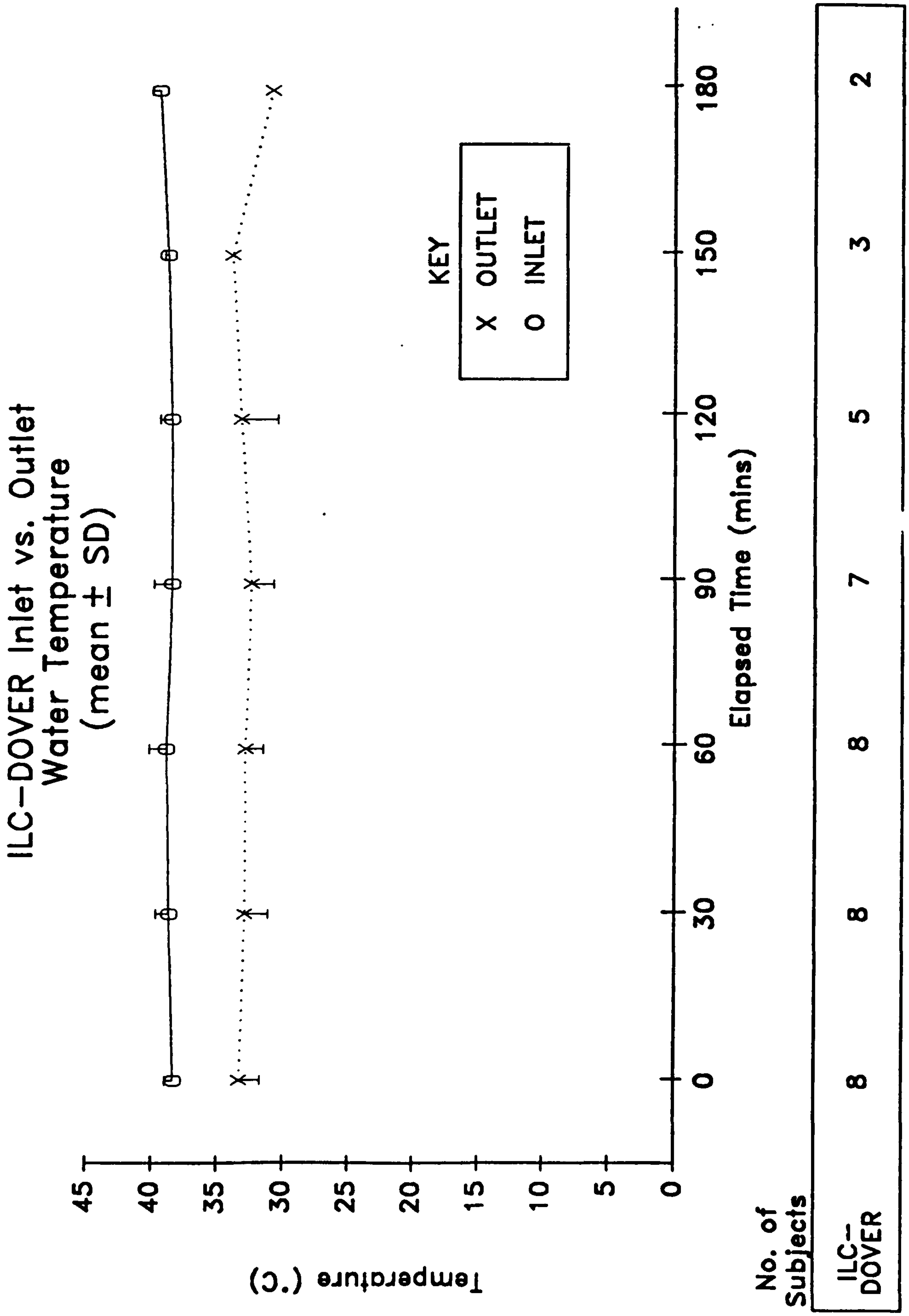

ILC–DOVER Inlet vs. Outlet
Water Temperature
(mean ± SD)
Temperature (°C)
45
40
35
30
25
20
15
10
5
0
0
30
60
90
120
150
180
Elapsed Time (mins)
KEY
X OUTLET
O INLET
No. of Subjects
ILC–DOVER
8
8
8
7
5
3
2

FIGURE 24.

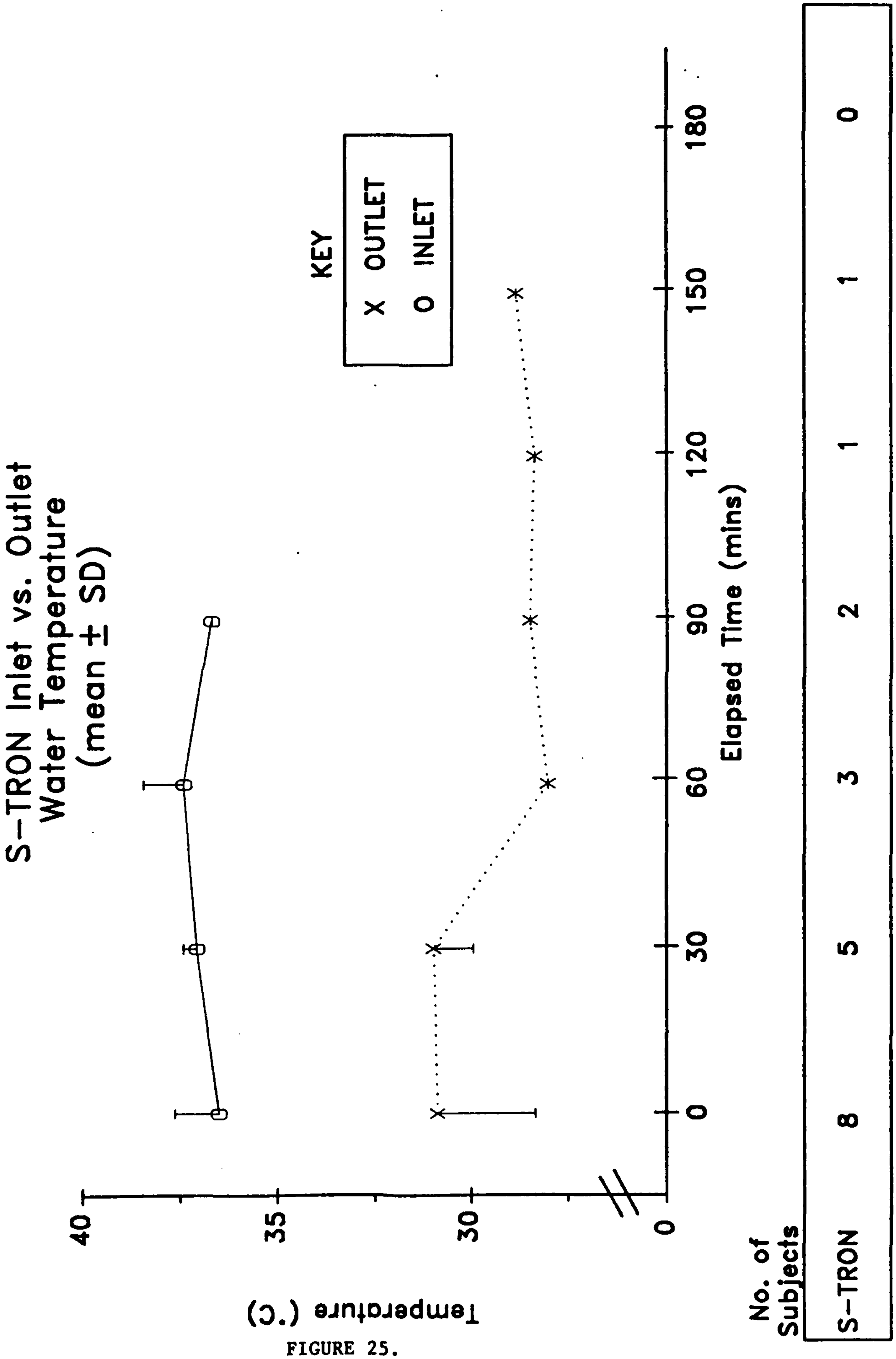
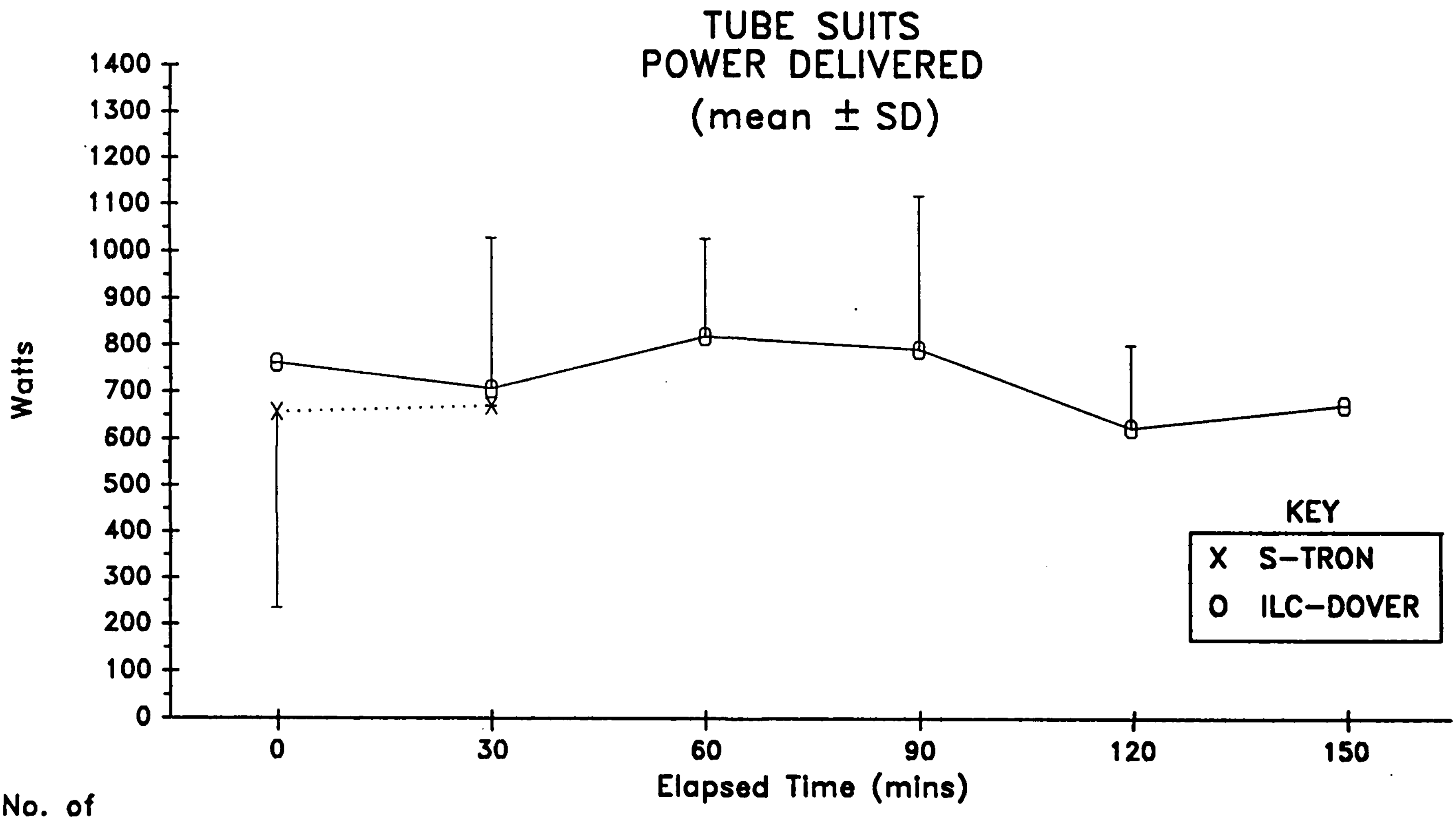

S–TRON Inlet vs. Outlet
Water Temperature
(mean ± SD)
KEY
X OUTLET
O INLET
Temperature (°C)
40
35
30
0
Elapsed Time (mins)
0
30
60
90
120
150
180
No. of Subjects
S–TRON
8
5
3
2
1
1
0

FIGURE 25.



No. of Subjects

S–TRON	8	5	3	2	1	1
ILC–DOVER	8	8	8	7	5	3

FIGURE 26.