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DEVELOPMENT OF EXPOSURE GUIDANCE FOR WARM WATER DIVING:

Volume 1 — Physiology and Endurance

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Navy Experimental Diving Unit

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19. ABSTRACT (Continue on reverse if necessary and identify by block number). Objective. To provide guidance for conducting diving operations in warm water environments and investigate diver endurance, physiologic change, and physiological and cognitive effects of water temperatures (T_w) from 94 to 101.5 °F (34.4 to 38.6 °C) on divers. Method. This study was conducted in three phases. In Phase 1, 16 divers conducted 458 dives in T_w from 94 to 101.5 °F. In Phase 2, 21 divers in either of two forms of diving dress, dry suits and "dive skins," conducted 522 dives in T_w of 96.5 and 99 °F (35.8 and 37.2 °C), respectively. In Phase 3, 24 divers in different forms of USN diving dress completed 784 dives in T_w between 90 and 101.5 °F (32.2 and 38.6 °C). Results. Developing and maintaining warm water tolerance may require repeating warm water dives more than once or twice a week. Decreasing endurance with increasing T_w appears to be significant, whether the diver is exercising or at rest. Once the T_w is greater than normal body temperature, diver tolerance to warm water diving decreases markedly. In resting and exercise dives, rectal temperature (T_{rec}) increase rate during the first 30 minutes is rapid, endurance decreases as T_w approaches and then exceeds body temperature. The report suggests guidelines and recommendations to be used for warm water diving planning. However, the maximum recommended dive times should not be regarded as absolute safe limits. This study's divers received lengthy acclimation and rigorous preconditioning. Maximum limits are appropriate only for maximally conditioned divers. Some divers may tolerate high temperatures better than other divers due to individual variability. Dive supervisors should consider this variability in diver selection and dive planning.

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INTRODUCTION

GENERAL

Throughout the history of diving, operational planners have lacked guidelines for conducting operations in warm water environments. The graph on page 6-16 of the *U.S. Navy Diving Manual*[1] shows that a working diver overheats at 88 °F (31.1 °C) and a resting diver overheats at 94 °F (34.4 °C). These forecasts implicitly establish maximum temperatures for a moderately working diver and a diver at rest. Yet since operational divers are never completely at rest, this graph — although it is not normally so interpreted — could be construed as forbidding diving in water warmer than 88 °F (31.1 °C). Its guidance does imply that overheating might occur but says nothing about when that might happen, how high body temperature might be, or whether that overheating could be dangerous to the diver.

Events of the Gulf War, and contingency operations since then, have increased sustained diving operations by U.S. military units in the warm waters of the Persian Gulf. Divers there have suffered various problems attributed to high water and air temperatures,[2] problems that have affected their abilities to perform missions and have revealed needs for accurate information about the physiological effects, and limitations, that this environment imposes on missions.

Therefore, Naval Sea Systems Command (NAVSEA) tasked the Navy Experimental Diving Unit (NEDU) to conduct manned studies to develop exposure guidance for diving in warm waters.[3] The purpose was to determine the physiological and cognitive effects of water temperatures (T_w) from 94 to 101.5 °F (34.4 to 38.6 °C) on divers. Specifically, the manned diver testing was to determine the effects of

1) T_w on diver endurance;
2) T_w on diver performance (cognitive and physical);
3) T_w and diver dress on diver endurance; and
4) T_w and diver dress on diver performance (cognitive and physical).

Due to the concern for diver-subject safety under the proposed conditions, this study was conducted in phases spanning three years: Phase 1 (1999), Phase 2 (2000), and Phase 3 (2001). Phase 1 was designed to determine how warm water affected the endurance and performance of swimsuited diver-subjects in water temperatures from 94 to 101.5 °F (34.4 to 38.6 °C). One series of dives was limited to a maximum of four hours of exercise, as this approximates a combat swimmer's mission profile. The exercise rate chosen was one reasonably sustainable by combat divers: 1.5 liters/minute (L/min) of oxygen consumption ($\dot{V}O_2$).[4] A second series of dives, using swimsuited diver-subjects exposed to the same range of water temperatures but for a maximum of eight hours and resting rather than exercising, was conducted to approximate a swimmer delivery vehicle (SDV) scenario. These exercise and duration limits were also felt to cover fleet divers. During dives conducting ships husbandry and shallow water salvage diving operations, for instance, work rates might exceed 1.5

L/min $\dot{V}O_2$ for short times, but the rates should average out between these resting and continuous work levels of activity. In addition, a continuously working combat swimmer is considered to be in a worst-case situation, because his physiological and psychological condition receives no topside monitoring.

The objective of Phase 2 was to determine the effect of warm water on endurance and performance for diver-subjects wearing different forms of U.S. Navy (USN) diver dress during exercise. These dives were limited to a maximum of four hours' exercise at the same workload as that during Phase 1. Diver-subjects in either of the two forms of diving dress, dry suits and "dive skins," were tested in water temperatures of 96.5 °F (35.8 °C) and 99 °F (37.2 °C), respectively.

Phase 3 of this study was to determine the physiologic response of diver-subjects in different forms of USN diving dress at a reduced exercise rate. This phase determined whether a decreased work rate could mitigate some effects of warm water and, as a result, could increase diver endurance. Phase 3 dives were in water temperatures between 90 and 101.5 °F (32.2 and 38.6 °C). Fin-swimming versus underwater cycling was also compared.

Cognitive and performance effects of diving in warm water were investigated. The submersible System for the Investigation of Divers Behavior at Depth (SINDBAD) was used to perform cognitive testing with the immersed diver-subjects. The Special Operations Forces (SOF) Mission-Related Performance Measures (MRPM) testing was used to investigate diver-subject postdive performance, and results from this testing are presented in a separate report.[5]

Volume 1 of this report presents results from the investigation of diver endurance and physiologic changes during dives performed in warm water. Recommendations provided in this volume also summarize all results obtained during this study and include those from Volume 2 of this report.

METHODS

GENERAL

Specific testing protocols were developed for each of the three phases of this study.[6,7,8]

SUBJECTS

A minimum of 16 Navy-trained diver-subjects from NEDU and the Navy Diving and Salvage Training Center (NDSTC) were given training, including familiarization dives, with both the MK 25 UBA and the OXY-LUNG UBA (Aqua Lung America, Inc.; Vista, CA) in the NEDU test pool. These diver-subjects were then used for all subsequent testing during particular phases (1, 2, or 3) of the study.

EQUIPMENT

Underwater Breathing Apparatus (UBA)

Two different closed-circuit 100% O_2 UBAs were used during this study. The USN MK 25 was used during Phase 1 resting dives at 94 °F (34.4 °C). However, after this series of dives the OXY-LUNG was used for the remainder of Phase 1 and for all diving in Phases 2 and 3. For testing purposes, this UBA was selected rather than the USN MK 25 because of cost, manufacturer technical support, and diver-subject preference.

Underwater Cycle Ergometers

Four (4) modified Collins Pedal-Mate[9] (Collins Medical; Braintree, MA), cycle ergometers were staged within the NEDU test pool. The cycle ergometer frames were set at zero inclination and were on a platform approximately three feet deep.

Exercycles (dry)

A commercial-grade Precor Model C846 (Precor USA; Woodinville, WA), recumbent exercycle was used for all dry cycle conditioning. These same cycles were used for the dry acclimation portion of Phase 2; they were believed to approximate the underwater cycle ergometers that were used for all nonfinning exercise dives. These exercycles allowed diver-subjects to monitor their heart rates during conditioning and to record those heart rates, as these exercycles interfaced with the Polar Accurex Plus™ heart rate monitor (Polar Electro Inc.; Woodbury, NY).

Test Pool and Ocean Simulation Facility (OSF)

All dives were conducted in either the NEDU test pool or the OSF, the latter of which was used only during acclimation dives because of the physical effort required to exit that facility. All testing dives were conducted in the test pool, where cycle ergometers were mounted on a three-foot deep platform, a setup that allowed easy access to a diver-subject if either a physiological or a UBA problem occurred.

Trolling Motors

To avoid stratifying T_w and thereby to ensure a well-stirred pool temperature, two MotorGuide (Minnekota, WI) trolling motors were used to stir the water column in the test pool.

Maximum Oxygen Consumption ($\dot{V}O_2$ Max) Testing

Maximum $\dot{V}O_2$ testing was performed on all diver-subjects who participated in this study. For Phase 1 and 2 a continuous, progressive intensity treadmill test with a Collins Model Plus/GSM and Plus/CPX/M (Collins Medical Inc; Braintree, MA) metabolic cart was used to determine oxygen uptake and carbon dioxide production ($\dot{V}CO_2$). For

Phase 3 a continuous, progressive intensity treadmill test with a Quinton Model Q-Stress (Quinton Cardiology Systems Inc., Bothell, WA) treadmill and a Collins Model Plus/CPL (Collins Medical Inc; Braintree, MA) metabolic cart was used.

Dry Suits

The Trelleborg Viking dry suit (Trelleborg Viking, Inc; Portsmouth, NH), a heavy-duty vulcanized rubber dry suit that comprises the diving dress for the U.S. Navy's contaminated water diving system, was chosen for use during Phases 2 and 3.[10,11] Since the only reason to wear a dry suit in warm water is for protection from a contaminated environment, this contaminated diving dry suit was used during testing.

Dive Skins

The dive skins used for Phase 2 and Phase 3 dives are identical to those used by Navy Special Warfare (SEAL) and VSW Mine Countermeasure (MCM) divers.

Cooling Suits

During the Phase 2 proof of concept (POC) dives, a commercially available active cooling suit was used to determine whether "cooling" the diver could enhance his endurance. These suits were provided by Delta T-Max (Med-Eng System; Pembroke, Ontario).

Phase Change Material (PCM) Vests

Cool-Vest (50-Degree Company; Melbourne, FL) PCM vests are used by Explosive Ordnance Disposal (EOD) personnel, firemen, and National Aeronautical and Space Administration (NASA) rocket fuel handlers. Although different types of PCM garments are available, many are large and cumbersome, and they severely restrict diver movement. To minimize these problems, the Cool-Vest system was chosen. In addition, this vest can be "charged" via a simple ice bath and reused an unlimited number of times. During Phase 3 POC dives a commercially available passive cooling suit was used to determine whether a diver's endurance could be enhanced by cooling him and thereby preventing him from overheating.

Dry Suit Dryer

During Phase 3 a commercially available dryer was used to dry the suits so that, if needed, they could be used the following day. Using this dryer not only prevented mildew damage to the suits but also ensured that diver-subjects started their test dives with "dry" dry suits. MisoSolutions (Montrose, CO) provided the system gratis to NEDU.

INSTRUMENTATION

Rectal Temperature (T_{rec})

A YSI 700 series thermistor probe (YSI, Inc; Yellow Springs, OH) was used to measure T_{rec} of diver-subjects during all phases of the study. This probe was inserted 15 cm past the anal verge and was retained there by a ¼-inch (6.4 mm) diameter button. This instrumentation was combined with the diver-subjects' safety umbilicals, which included a safety line, gas sampling line, and temperature probe wiring.

Pool Temperature

Another YSI 700 series thermistor probe was used to monitor the test pool temperature at the same depth as that of the diver-subjects. Pool temperature was maintained within ±0.5 °F (±0.28 °C) of the stated test temperature. To ensure a well-mixed pool temperature, trolling motors were mounted and run continuously (see **EQUIPMENT:** Trolling Motors).

Inhalation UBA Gas Temperature

A YSI 700 series thermistor probe was placed in the inhalation breathing hose to monitor inhalation gas temperatures just upstream from the one-way flapper valve in the UBA.

O_2 Bottle Pressure

Oxygen bottle pressure was continuously monitored with a Druck pressure transducer (Druck, Inc; Braintree, MA) and was logged every 30 seconds. Oxygen consumption was calculated from changes in O_2 bottle pressure (see **METHODS**: Oxygen Consumption).

Data Recording

The following parameters were recorded with LabVIEW (National Instruments; Austin, TX) software and an NEDU data acquisition system (DAS) computer on the test pool medical deck:

(1) T_w (logged every 30 seconds);
(2) zero time, actual time (logged every 30 seconds);
(3) rectal temperature (T_{rec}), continuously monitored and logged every 30 seconds; and
(4) inhalation UBA gas temperature (logged every 30 seconds).

Calibrations

Oxygen pressure gauges and thermistor calibrations were checked at the beginning of each day and again after the last run of the day.

Heart Rate

Heart rate was continuously monitored with Quinton Q-Tel Rehab ECG telemetry (Quinton Cardiology Systems, Inc; Bothell, WA) and manually logged every five minutes. Additionally, diver heart rate was logged every 15 seconds with a Polar Accurex Plus™ heart rate monitor, which was downloaded at the end of each diver-subject's test run.

Electrocardiograph (ECG)

ECG was observed on a monitor with Quinton Q-Tel Rehab ECG telemetry for diver-subject safety, but only heart rate from this telemetry was recorded.

O_2 and CO_2 Monitoring

During all dives using the OXY-LUNG UBA, both inspired O_2 and CO_2 concentrations were monitored for diver-subject safety. These measurements were made with an Extrel Mass Spectrometer Model GS (ABB Extrel; Pittsburgh, PA).

PHYSIOLOGICAL PARAMETERS

Urinalysis

The baseline urinalysis was made on the first morning void on the day of immersion testing. A second urine sample was required from diver-subjects before they entered the water for a test dive. This second sample was collected after they had eaten and drunk according to the predive protocol. During test-run dives, all male diver-subjects wore external urinary catheter systems to collect urine. Because no noninvasive urine collection system exists for females, urine was not collected from these diver-subjects during immersion portions of this study. Throughout the dive, this collection system was emptied as needed. Postdive urine also was collected and analyzed, but because these samples were acquired after diver-subjects had hydrated ad lib, these postdive samples were used only to fulfill postdive release criteria before diver-subjects left NEDU. Specific urine analyses consisted of the following:

a. Specific gravity (Phases 1, 2, and 3)
b. Myoglobin (Phase 1 only)
c. Osmolality (Phase 1 only)
d. Ketones (Phase 1 only)

Blood analysis

Baseline measurements were made on fasting blood samples drawn from diver-subjects before they ate breakfast and hydrated on the mornings of their test dives. The following hematological measurements were made predive and then repeated postdive, before diver-subjects hydrated and began postdive performance testing:

a. Hematocrit
b. Hemoglobin
c. Osmolality
d. Electrolytes (sodium, chloride, potassium, calcium, magnesium, phosphorous)
e. pH
f. Bicarbonate
g. Glucose
h. Lactate
i. BUN
j. Creatinine
k. LDH (Phase 1 only)
l. AST (Phase 1 only)
m. ALT (Phase 1 only)
n. CPK, fractionated for MM, MB, and BB isoforms when CPK was appropriately elevated (Phase 1 only)

Weight

All diver-subjects were weighed on the morning of immersion testing, after their first morning voids but before they had eaten breakfast or drunk. Before diver-subjects entered the water, they were also reweighed — a predive weight taken after they had eaten one Meals Ready to Eat (MRE), drunk 0.5 L of fluid, and been instrumented for their dives. All diver-subjects were also weighed immediately postdive.

Diver-Subject Vital Signs

All diver-subjects had blood pressures and pulse rates taken while they were seated and then one minute after standing during the morning predive weigh-in and blood draw. These measurements were also performed as soon as the divers exited the water postdive.

Visual Acuity

During Phase 1 testing, a Snellen Chart was used to measure the visual acuity of the diver-subject at 20 feet. Visual acuity was measured both pre- and postdive because of concern for hyperoxic myopia. This testing was discontinued for Phases 2 and 3, because no effect was seen during Phase 1 testing.

Daily Diver Routine

All diver-subjects were required to follow the standard predive routine outlined in Appendix A and provided to diver-subjects the afternoon before their scheduled dives.

DIVER-SUBJECT SYMPTOMS

During Phase 1 dives at water temperatures of 78, 94, and 96.5 °F (25.6, 34.4, and 35.8 °C), diver-subjects were asked a series of questions (see Appendix C) approximately every 60 minutes. This interval was shortened to approximately every 30 minutes during all dives at 94 and 96.5 °F (34.4 and 35.8 °C). During Phases 2 and 3 this same questionnaire was used, with questions again asked every 60 minutes, or every 30 minutes for short-duration dives. This questionnaire afforded a subjective evaluation of the diver-subjects' symptoms associated with O_2 toxicity and heat stress; its results were recorded manually on a data collection sheet and later manually entered into a database.

OXYGEN CONSUMPTION

Maximum Oxygen Consumption

All diver-subjects completed a progressive intensity $\dot{V}O_2$ max test [see **Equipment:** Maximum Oxygen Consumption ($\dot{V}O_2$ Max) Testing] before they started test dives. The only exception occurred during Phase 3, when this testing was conducted late in the diving phase because of equipment problems. For Phase 3 the diver-subjects' most recent USN Physical Readiness Test (PRT) results were used to divide the diver-subject pool into two balanced groups, with groupings based on sorted results from the PRT. These two groups were then used as diver-subjects for heat acclimation. Use of these PRT results was necessary because of equipment problems associated with $\dot{V}O_2$ max testing.

Oxygen Consumption ($\dot{V}O_2$)

The diver-subjects' in-water oxygen consumption during acclimation, resting, and exercise dives was calculated from changes in recorded UBA O_2 bottle pressure during the dive. This delta P was then used to calculate oxygen consumption per the following equation:

$$\dot{V}O_2 = [(P_{START} - P_{FINISH}) / t] \times [V_b / 14.7 \text{ psig}] \times 273 / (T + 273),$$

where

$\dot{V}O_2$ = oxygen consumption (L/min STPD),
P_{START} = O_2 bottle starting pressure (psig),
P_{FINISH} = O_2 bottle finish pressure (psig),
t = time interval (min) for which $\dot{V}O_2$ is being calculated,

V_b = floodable volume of O_2 bottle in liters (L), and
T = temperature (°C).

CONDITIONING

Cycling

All diver-subjects underwent predive exercise conditioning by riding a stationary exercycle. During Phase 1 these cycles were placed in the NEDU environmental chamber (EC), where temperature was 94 °F (34.4 °C) and relative humidity was 50%. During cycling conditioning, all diver-subjects were provided their own personal hydration systems to ensure adequate hydration during those extended cycle training periods. The tapered increase in required cycling was the same for all three phases (see Appendix D). During subsequent phases, cycle conditioning was conducted in the NEDU physiology lab, an air-conditioned facility with an average ambient temperature of 78 °F (25.6 °C). This conditioning temperature was used because two different heat acclimation strategies were employed during Phases 2 and 3 [see **CONDITIONING:** Heat Conditioning (Acclimation)].

Fin Conditioning

Fin conditioning was scheduled three times per week, but diver-subjects were required to participate in only two of the three sessions. These sessions were arranged to accommodate NEDU work schedules and to allow diver-subjects to continue to fin swim even after the start of underwater cycle ergometer testing. Fin conditioning entailed finning sessions of increasing duration in St. Andrew Bay, Panama City, FL, at ambient T_w. Diver-subjects used dive fins of their choice for the first three weeks, but then were provided with either Apollo Bio-Fins (Apollo Sports USA Inc; Everett, WA) or ScubaPro TwinJet (ScubaPro/Uwatec; El Cajon, CA) fins for these sessions. Diver-subjects were instructed not to use their arms during these sessions. To maintain the achieved level of conditioning, diver-subjects continued this fin conditioning through the cycling portion of the protocol.

Heat Conditioning (Acclimation)

Heat acclimation for diver-subjects was conducted in two different ways. The first was natural heat acclimation, which occurs with diver-subjects doing nothing and was the main reason that study dates were set to be as similar as possible during the different years. Panama City, FL, is located on the Gulf of Mexico and has an average summertime temperature of 76.8 °F (24.9 °C) from May through October.[12] The average high for these months is 86.6 °F (30.3 °C), and the average low is 71.2 °F (21.8 °C). Because NEDU has mandatory outdoor physical training three days a week (from 0700 until 0830 hours), all diver-subjects were exposed to natural heat acclimation from living, working, and exercising in Panama City.

However, to ensure that all diver-subjects were heat acclimated at the beginning of testing, a second means of heat acclimation was required of them. As described for each phase, this acclimation consisted of being exposed to a hot environment, either wet or dry. Selection of these heat acclimation strategies was based on current NEDU research to determine optimum acclimating strategy,[13] and the results are not presented here. It is generally agreed that most acclimation to heat occurs within the first seven days' exposure; there is no sharp end to improvement.[14] Consequently, regardless of the second heat acclimation strategy used, ten days of heat exposure was felt to be sufficient to acclimate all diver-subjects.[13] To ensure that natural acclimation was as consistent as possible, Phase 1, 2, and 3 were all conducted during the months of May through October 1999, 2000, and 2001 respectively.

All Phase 1 cycle conditioning was performed in the NEDU environmental chamber (see **CONDITIONING**: Cycling) at constant conditions.

During Phase 2 two different heat acclimation strategies were used. Following $\dot{V}O_2$ max testing, diver-subjects were sorted by $\dot{V}O_2$ max scores and evenly divided into one of two groups for heat acclimation. This sorting was done so that each heat acclimation group was representative of the entire diver-subject pool for a particular phase. Then for two weeks,

1) 50% of the diver-subjects exercised on underwater cycle ergometers at 50 watts for one hour in 94 °F (34.4 °C) water, and

2) 50% of the diver-subjects exercised on the recumbent exercycles at 125—150 watts for one hour in the EC (where they were dry) at 94 °F (34.4 °C) and 50% relative humidity.

During Phase 3 all heat acclimation was conducted on underwater cycle ergometers. Due to equipment problems with the $\dot{V}O_2$ max testing equipment, diver-subjects were sorted by their last USN PRT scores and then evenly divided into one of two groups for heat acclimation. This procedure was used so that each heat acclimation group would represent the entire diver-subject pool for a particular phase. Then for two weeks,

1) 50% of the diver-subjects exercised at 50 watts for two hours in 94 °F (34.4 °C) water, and

2) 50% of the diver-subjects exercised at 0 watts for one hour in 98 °F (36.7 °C) water.

Because of difficulties with the computer that set the workload for the cycle ergometers, the 98 °F (36.7 °C) group performed with a different workload (watts) from that of the 94 °F (34.4 °C) group.

COGNITIVE AND PHYSICAL PERFORMANCE MEASURES

SINDBAD In-Water Testing

In-water testing was conducted with the System for Investigation of Divers' Behavior at Depth (SINDBAD),[15] which consists of a computer and a submersible response panel.

The SINDBAD system was used during this study to assess changes in diver performance during water dives. The in-water SINDBAD assessment was conducted at repeated intervals from the time the diver entered the water until the dive was terminated. While the SINDBAD system consists of 30 different tests of perceptual, memory, cognitive, and psychomotor abilities, only five tests designed for in-water testing were used during this study.

Key Insertion Test — This test was designed to measure fine motor coordination. Using only the preferred hand, the diver alternately inserted the round and the square ends of a 1-inch long key device into a round and a square cell on the display-response panel. The test lasted for 60 seconds. The score represents the number of responses completed minus the number of failures to alternate.

Stylus Test — This test measured tapping coordination. The diver inserted the stylus into a display-response panel cell as many times as possible during a 30-second test. The score represents the number of responses completed minus the number of irrelevant responses.

Visual Reaction Time Test — This test measured reaction speed to a simple, discrete stimulus. The diver was to remove the stylus from the asterisk cell as rapidly as possible when the numeric group at the top of the panel went on and showed all zeroes. In each of 20 trials, a delay of from one to three seconds was inserted between the diver's ready response (inserting the stylus into the asterisk cell) and the onset of the stimulus, with delays being randomly ordered over trials. The score is the mean reaction time in seconds.

Visual Digit Span Test — This test measured span memory, the ability to reproduce material very recently studied. The diver was to accurately reproduce a numeral series immediately after the series was presented. Numerals in the series were presented at the rate of 1/sec on a numeric display at the top of the display-response panel. The score is number of correct responses.

Operation Test — This test measured general reasoning and numerical ability. The diver was given two numerals and a solution; the task was to select one of the simple arithmetic operations (addition, subtraction, multiplication, or division) that would produce the solution for the numerals. Instructions emphasized speed to discourage actual computation. Test time was two minutes. The score is the number of correct responses minus the number of incorrect responses divided by three.

For Phase 1, to avoid having a training effect on diver-subjects during data collection runs, training with the SINDBAD was conducted in a dry environment. Wet training with SINDBAD and reaction time testing with a mask and snorkel in a hot tub at 78 °F (25.6 °C) also was conducted for in-water baseline proficiency and familiarization. Training was conducted until diver-subjects reached ±5% baseline stability for the SINDBAD in a dry environment. In addition during this phase, the first SINDBAD test of each day was done predive (dry).

During Phases 2 and 3 all training and testing was conducted while diver-subjects were submerged. During acclimation and familiarization dives no testing was done, although diver-subjects practiced with the SINDBAD. The SINDBAD testing in each phase was performed as follows:

Phase 1	pre- and postdive (dry = air), and either every 30 minutes (exercise) or every hour (rest) during in-water periods;
Phases 2 and 3	only in the water and every hour, or at 30-minute intervals when, based on Phase 1 testing results, diver endurance was expected to be less than two hours.

During Phases 2 and 3, in-water SINDBAD testing occurred immediately after the diver-subject was settled in the water, and then every 60 minutes until dive termination. During Phase 1 dives at T_w of 78, 94, and 96.5 °F (25.6, 34.4, and 35.8 °C), SINDBAD testing was conducted every 60 minutes. However, this interval was shortened to approximately every 30 minutes during Phase 1 dives with temperatures greater than 96.5 °F (35.8 °C). The testing interval was also shortened to 30 minutes during Phases 2 and 3 dives, when diver endurance was expected to be less than two hours.

Special Operations Forces (SOF) Mission-Related Performance Measures (MRPM)

This performance battery was used to assess diver-subject ability to perform mission-related tasks following a warm water dive exposure. All MRPM testing was postdive and conducted in a dry air-testing environment. A complete description of this series of tests used during Phases 2 and 3 is provided as Appendix B. Since this system was not available for testing during Phase 1, a scaled down or modified variant of it was used during that phase, and a complete description of this modified MRPM is provided as Appendix A. All phases of this testing were conducted in the NEDU physiology lab at ambient air temperature, approximately 78 °F (25.6 °C).

TERMINATION CRITERIA

Significant concern for the safety of diver-subjects was expressed not only by the Institutional Review Committee [(IRB), formerly known as the Committee for the Protection of Human Subjects (CPHS)], but also by the researchers. Therefore, a detailed list of involuntary termination criteria was developed and followed throughout all three phases of this study. Any diver meeting one or more of these criteria exited the water and, if his condition was deemed to be safe by the Medical Monitor and Diving Medical Officer, he then completed the remainder of the protocol. Diver-subjects always had the option of voluntarily terminating dives. The criteria are shown in Table 1.

Table 1.

TERMINATION CRITERIA
1. When the diver-subject requests termination, for any reason.
2. When the diver-subject is unable to maintain the minimum watt load setting (10 watts) on the cycle ergometer.
3. When the rectal temperature is >104 °F (>40 °C) continuously for 5 min or >104.9 °F (>40.5 °C) at any time.
4. When significant ECG abnormalities (6 PVC/minute or more; also couplets, bigeminy, or trigeminy) are present.
5. When the diver-subject's cognitive performance on any SINDBAD test cycle decreases 50% from the initial in-water test results for that particular dive.
6. When the exercising diver-subject has completed the maximum scheduled dive duration.

PHASE-SPECIFIC DESCRIPTIONS

PHASE 1

Participants

A total of 21 U.S. Navy divers carried out the dives in Phase 1.

Acclimation

Heat acclimation was accomplished by requiring diver-subjects to perform all aerobic cycle conditioning (Appendix D) in the EC at NEDU, with temperature set at 94 °F (34.4 °C) and relative humidity at 50%. Diver-subjects also cycled an additional two hours three times per week in the EC to maintain overall cycling conditioning once testing had started.

Diver Dress

Diver dress for Phase 1 consisted of cotton T-shirt, swim trunks, and diver booties. The testing schedules for exercise state (rest versus exercise) and T_W were not randomized during this phase because of concern for diver safety based on studies completed at the Naval Medical Research Center (NMRC), formerly known as Navy Medical Research Institute (NMRI).[16] Although 94 °F (34.4 °C) was felt to be a safe temperature to start exercise dives, resting dives were completed before exercise dives at each study temperature.

Temperature

Two sets of test dives were conducted: the first, with the diver at rest; the second, with the diver exercising on an underwater cycle ergometer. Initially the exercise rate was intended to be approximately 60% of each diver's $\dot{V}O_2$ maximum as determined from a progressive intensity, continuous effort treadmill protocol. However, this was determined to be impractical, and therefore during Phase 1 testing the exercise work rate was fixed at 50 watts for all diver-subjects. This wattage was used because previous testing at NEDU has determined that this approximates an oxygen consumption of 1.5 L/min, a standard combat swimmer pace.[4]

A baseline 4-hour exercise dive was conducted at 78 °F (25.6 °C) to ensure that an appropriate level of cycle training had been reached and that any decrement in performance at the study temperatures could be attributed to thermal conditions rather than to insufficient training. Test dives were conducted at 94, 96.5, 99, and 101.5 °F (34.4, 35.8, 37.2, and 38.6 °C).

Test Repetition

SINDBAD tests were performed predive, postdive, and at repeated intervals during each dive. All diver-subjects completed the pre- and postdive tests. In-water assessments were conducted at one-hour intervals for all resting dives. Assessments during the exercise dives were conducted at one-hour intervals at 78 °F (25.6 °C) and 94 °F (34.4 °C) and at 30-minute intervals during the 96.5, 99, and 101.5 °F (35.8, 37.2, and 38.6 °C) dives. Test dives continued until the diver met any one of the termination criteria listed in Table 1. Maximum test dive duration for resting dives was eight hours, and maximum duration for exercise dives was four hours. The number of in-water repetitions of the SINDBAD tests completed before dive termination varied greatly among diver-subjects and across conditions: from 1 to 7 at 94 °F (34.4 °C), and from 1 to 3 at 101.5 °F (38.6 °C). Therefore, the analysis of in-water performance for each SINDBAD test was limited to comparing the first in-water score at the start of the dive to the score on the last test completed before the dive terminated. Diver-subjects who completed only one in-water SINDBAD assessment were not included in this analysis.

PHASE 2

Participants

A total of 21 U.S. Navy divers carried out the dives in Phase 2.

Different conditions were varied in Phase 2 of the experiment: method of acclimation, diver dress, and T_w.

Acclimation

Following the end of the nonheat aerobic conditioning period, diver-subjects were randomized by their $\dot{V}O_2$ max levels into two groups for heat acclimation. Acclimation Group 1 (N = 11) underwent a two-week period of "wet" heat exposure in the NEDU test pool: one hour of underwater cycling five days per week, with water temperature maintained at 94 °F (34.4 °C). Diver-subjects also cycled an additional two hours three times per week in a nonheat environment to maintain overall cycling conditioning. Acclimation Group 2 (N = 10) underwent a two-week period of "dry" heat exposure in the NEDU environmental chamber, with temperature set at 94 °F (34.4 °C) and relative humidity at 50%. This heat exposure consisted of one hour of cycling five days per week. In addition, each diver was required to cycle for an additional two hours three times per week in a nonheat environment to maintain overall cycling conditioning.

Diver Dress

Three different diver dress configurations were used during the test dives: "dive skin," "dry suit," and "dry suit with MK 21." The testing schedule for diver dress and T_w was randomized.

Temperature

A baseline four-hour exercise dive was conducted at 94 °F (34.4 °C) to ensure that an appropriate level of cycle conditioning had been reached and that any decrement in performance at the study temperatures and with the diver dress could be attributed to thermal conditions rather than to insufficient training. No 78 °F (25.6 °C), four-hour exercise baseline dives were required, since no differences had been noted between 78 and 94 °F (25.6 and 34.4 °C) baseline dive endurance during Phase 1 testing. Test dives were conducted at 90, 94, 96.5, and 99 °F (32.2, 34.4, 35.8, and 37.2 °C). The temperatures varied among the diver dress configurations: dive skin dives were conducted at 96.5 and 99 °F (35.8 and 37.2 °C); dry suit dives were conducted at 90, 94, and 96.5 °F (32.2, 34.4, and 35.8 °C). Dry suit with MK 21 dives were conducted only at 96.5 °F (35.8 °C).

Test Repetition

SINDBAD tests were performed at 30-minute intervals during each dive, beginning immediately after the diver got settled in the water and continuing until the dive terminated. Dives began at a workload of 50 watts. As the diver fatigued and was no longer able to maintain 60 ± 5 rpm on the cycle ergometer, workload was decreased in 10-watt increments. The dive continued until the diver was unable to maintain the 10-watt rate, the lowest wattage setting on the cycle ergometer, or until the diver met other termination criteria. The maximum dive duration was four hours. The number of in-water repetitions of the SINDBAD tests completed before dive termination varied between 2 and 5 for the 94 °F (34.4 °C) baseline dive and between 1 and 5 for the various test dives. The in-water performance analysis for each SINDBAD test was limited to comparing the first in-water score at the start of the dive to the score on the last test completed before dive termination. Diver-subjects who completed only one in-water SINDBAD assessment were not included in this analysis.

PHASE 3

Participants

A total of 24 U.S. Navy divers participated in Phase 3.

Heat Acclimation Group

Following the end of the aerobic conditioning phase, diver-subjects were randomized by their $\dot{V}O_2$ max into two groups for heat acclimation. Acclimation Group 1 (N = 12) underwent two weeks of "wet" heat exposure in the NEDU test pool. These exposures consisted of two-hour underwater cycling periods five days per week, with the water temperature maintained at 94 ± 0.5 °F. Acclimation Group 2 (N = 12) underwent two weeks of "wet" heat exposure in the NEDU OSF, with water temperature set at 98 ± 0.5 °F. These exposures consisted of one hour of underwater cycling five days per week. Acclimation Group 2 diver-subjects also cycled for an additional hour, two times per week in a nonheat environment.

Diver Dress

Two different diver dress configurations were used during the test dives: "dive skin" and "dry suit."

Exercise Type

Two different types of exercise — cycling and finning — were used during the test dives. During the cycling test dives, workload was set at 30 watts and was not decreased or increased during the dive. During the fin-swim exercise dives, workload was set at 50 watts, as based on strain gauge calibrations.

Temperature

A 4-hour baseline verification exercise dive was conducted in swimsuits at 94 ± 0.5 °F to ensure that an appropriate level of cycle conditioning had been reached. Thereafter, any decrement in performance could be attributed to thermal conditions and, at the study temperatures, to diver dress and/or to exercise conditions rather than to insufficient training. Test dives were conducted at 90, 96.5, 98, 99, and 101.5 °F (32.2, 35.8, 36.7, 37.2, and 38.6 °C). The temperatures varied among the diver dress and exercise configurations. Cycling dive skin dives were conducted at 96.5, 99, and 101.5 °F (35.8, 37.2, and 38.6 °C). Fin-swim dive skin dives were conducted at 98 and 99 °F (36.7 and 37.2 °C), while fin-swim dry suit dives were conducted at 90 and 96.5 °F (32.2 and 35.8 °C).

Test Repetition

The baseline verification dive began with a workload of 50 watts. As the diver fatigued and was no longer able to maintain 60 ± 5 rpm on the cycle ergometer, workload was decreased in 10-watt increments. The dive continued until the diver was unable to maintain the 10-watt rate, the lowest wattage setting on the cycle ergometer, or until the diver met other termination criteria. The maximum dive duration for the exercise test dives was four hours. SINDBAD tests, beginning immediately after the diver got settled in the water and continuing until dive termination, were performed at 30-minute intervals during each dive. The number of in-water repetitions of the SINDBAD tests completed before dive termination varied between 3 and 5 for the 94 °F (34.4 °C) baseline verification dive and between 1 and 5 for the various test dives. Therefore, the in-water performance analysis for each SINDBAD test was limited to comparing the first in-water score at the start of the dive to the score on the last test completed before dive termination. Diver-subjects who completed only one in-water SINDBAD assessment were not included in this analysis. In this study, this small sample size therefore excluded analysis of the test repetition variable for all but the baseline verification dive and the 96.5 °F (35.8 °C) cycling dive skin dive.

RESULTS

Using Navy divers as research subjects for multiyear studies limits the statistical analysis of the resulting data, because many divers transfer over the course of the study.

The power of a statistical test lies in its ability to detect a difference between two or more observed means.[17] In studies with low power, insignificant results do not necessarily mean that no effect is present. In fact, an effect may be present, but because of the low power of the analysis, the presence of this effect is not illustrated by a statistically significant result. Low power results from a small size of a sample and/or of an effect (a result indicating the extent to which the groups differ on the dependent variable). Both low power and small sample size affected the statistical analysis of this study. Therefore, to ensure that the sample sizes were as large as possible, the statistical analyses had to assume that the dives were independent.

In the context of this study, *independence* means that the outcome of one dive is not related to that of any other. Arguably, this is not actually the situation: the same diver participated in multiple dives and thereby violated the assumption of independence. Thus, a repeated measures design is the "correct" method for analyzing the data. However, such a design requires each individual in the analysis to have participated in every level of the experiment. For example, in Phase 1 the participant must have completed each of the dives at 94, 96.5, 99, and 101.5 °F (34.4, 35.8, 37.2, and 38.6 °C) in both the resting and exercise conditions. If one of these dives has not been completed, then the individual cannot be included in the statistical analysis. Therefore, to keep the sample size as high as possible for the analysis, we decided to treat the dives as independent.

Results are reported separately for each of the three phases of the experiment. Although the data are generally analyzed independently for each study, data from the different studies are combined on some occasions to allow certain comparisons to be made.

PHASE 1

A total of 21 U.S. Navy divers carried out the dives in Phase 1, and results collected from the physiological measures are summarized in Table 2. Table 1 shows that dive durations decrease as water temperatures increase, and, as expected, the mean $\dot{V}O_2$ for the exercise dives is higher than for the resting dives (see Table 2). However, water temperature does not seem to affect this dependent variable. Table 2 shows that the core body temperature rate increase in the first 30 minutes is higher for the exercise than for the resting dives, a rate that also increases with the temperature of the water. The maximum core temperature in the water was also higher for the exercise than for the resting dives, except for those conducted in 101.5 °F (38.6 °C) water. Furthermore, the maximum core temperature in the water increased with the T_w of the dive.

Table 2.
Phase 1 Physiological Data Summary

Water temp (°F)		Length of dive (min)	Mean $\dot{V} O_2$ of dive (L/min)	Temp rate increase in first 30 min (.001 °C/min)	Max core temp in water (°C)
78 °F					
Exercise	**Mean**	**193.1**	**1.7**	**9.7**	**38.1**
	No. of dives	18	14	18	18
	Std. Dev	46.8	0.2	14.0	0.6
94 °F					
Resting	**Mean**	**432.5**	**0.4**	**-0.3**	**37.4**
	No. of dives	19	17	19	19
	Std. Dev	117.1	0.1	4.2	.43
Exercise	**Mean**	**170.8**	**1.6**	**12.1**	**38.2**
	No. of dives	19	16	19	19
	Std. Dev	77.9	0.2	8.5	0.5
96.5 °F					
Resting	**Mean**	**403.3**	**0.6**	**5.4**	**37.9**
	No. of dives	8	7	8	8
	Std. Dev	154.1	0.1	3.0	0.2
Exercise	**Mean**	**116.6**	**1.5**	**17.3**	**38.9**
	No. of dives	13	11	16	16
	Std. Dev	64.9	0.2	5.0	0.5
99 °F					
Resting	**Mean**	**123.4**	**0.7**	**18.6**	**38.5**
	No. of dives	7	5	7	7
	Std. Dev	102.3	0.2	3.7	0.6
Exercise	**Mean**	**66.9**	**1.6**	**33.4**	**39.0**
	No. of dives	13	12	14	14
	Std. Dev	35.5	.37	7.6	0.9
101.5 °F					
Resting	**Mean**	**69.8**	**0.7**	**36.4**	**39.3**
	No. of dives	5	4	4	4
	Std. Dev	20.5	0.2	2.5	0.5
Exercise	**Mean**	**45.5**	**1.6**	**48.4**	**39.1**
	No. of dives	14	11	13	13
	Std. Dev	23.0	0.2	18.3	0.8

After examining the data in Phase 1, we decided to collapse the cells to reduce the number of conditions to allow meaningful statistical analysis of the data by increasing the sample size of each cell and thus providing increased power to the test. The 94 and 96.5 °F (34.4 and 35.8 °C) dives as well as the 99 and 101.5 °F (37.2 and 38.6 °C) dives were collapsed (see Table 3). The rationale for these groupings was that at 94 and 96.5 °F (34.4 and 35.8 °C) the mean maximum core body temperature was below 102.2 °F (39 °C),[18] which is the upper limit for the least serious phase of heat stress. However, at 99 and 101.5 °F (37.2 and 38.6 °C) this threshold was exceeded, at least during the exercise condition.

Table 3.
Phase 1 Physiological Collapsed Data Summary

Water temp (°F)		Length of dive (min)	Mean $\dot{V}O_2$ of dive (L/min)	Temp rate increase in first 30 min (.001 °C/min)	Max core temp in water (°C)
94 and 96.5 °F dives					
Resting	**Mean**	423.8	0.42	1.38	37.5
	No. of dives	27	25	27	27
	Std. Dev	126.8	0.2	4.6	0.4
Exercise	**Mean**	148.8	1.5	14.4	38.5
	No. of dives	32	28	35	35
	Std. Dev	76.7	0.4	7.5	0.6
99 and 101.5 °F dives					
Resting	**Mean**	101.1	0.7	25.1	38.8
	No. of dives	12	9	11	11
	Std. Dev	81.4	0.2	9.5	0.6
Exercise	**Mean**	55.8	1.6	40.6	39.1
	No. of dives	27	23	27	27
	Std. Dev	31.1	0.3	16.4	0.8

Test 1.1. A two-way between-subjects ANOVA was used to compare the exercise and resting conditions at the two temperature ranges for each of the four dependent variables.

Results 1.1. The length of the dive was found to be significantly longer in the resting than in the exercise condition ($F[1,94] = 56.4$, $p < 0.05$; see Table 3). The lower temperature dives were found to be significantly longer than the higher temperature dives ($F[1,94] = 110.2$, $p < 0.05$). The interaction was also significant ($F[1,94] = 18.3$, $p < 0.05$), and the data indicate that this results from a larger difference in the lengths of the dives at the lower temperatures than at the higher ones (see Table 3).

The exercise dives resulted in a significantly higher mean $\dot{V}O_2$ than did the resting dives ($F[1,81] = 206.5$, $p < 0.05$). In addition, the higher temperature dives revealed a $\dot{V}O_2$ significantly higher than that for the dives at the lower temperatures ($F[1,81] = 6.8$, $p < 0.05$). The interaction effect was not significant.

The rate of increase in body temperature during the first 30 minutes was higher for the exercise than for the resting dives ($F[1,96] = 40.1$, $p < 0.05$). That temperature rate increase was also higher in the warmer water ($F[1,96] = 108.0$, $p < 0.05$). Furthermore, the interaction effect was also significant ($F[1,96] = 8.8$, $p < 0.05$), because the difference in the temperature rate increase is smaller between the exercise and resting conditions at the higher temperatures than it is at the lower temperatures.

The maximum core temperature in the water was higher in the exercise dives than the resting dives ($F [1,96] = 20.6$, $p < 0.05$) and higher in the 99 and 101.5 °F (37.2 and 38.6 °C) dives than the 94 and 96.5 °F (34.4 and 35.8 °C) dives ($F [1,96] = 41.3$, $p < 0.05$). The interaction between exercising/resting and water temperature was also significant ($F [1,96] = 7.0$, $p < 0.05$). This is because the difference in the maximum core temperatures of the exercise and resting conditions is smaller at the higher temperatures than it is at the lower ones.

PHASE 2

A total of 21 U.S. Navy divers carried out dives in Phase 2. The physiological data obtained during this phase is summarized in Table 4. The dive duration data indicate that the time of the dry suit dives decreases as temperature increases. A large decrease can also be seen in dive duration when the skin dives at 96.5 and 99 °F (35.8 and 37.2 °C) are compared. Phase 2 dives show that the rate of increase in body temperature during the first 30 minutes is greater at higher T_w and for the dry suit dives than in other dive dress configurations and for lower T_w. In addition, the MK 21 and the dry suit (with cooling) dives seem to reduce both the temperature rate increase in the first 30 minutes and the maximum core temperature in the water (see Table 4).

Table 4.
Phase 2 Physiological Data Summary

Water temp (°F)		Length of dive (min)	Mean $\dot{V}O_2$ of dive (L/min)	Temp rate increase in first 30 min (.001 °C/min)	Max core temp in water (°C)
90 °F					
Dry suit	**Mean**	**54.0**	**1.9**	**23.1**	**38.4**
	No. of dives	12	8	12	12
	Std. Dev	26.9	0.2	22.2	0.8
94 °F					
Dry suit	**Mean**	**45.5**	**1.8**	**24.6**	**38.5**
	No. of dives	19	17	19	19
	Std. Dev	22.6	0.3	25.6	1.0
Validation (Swimsuited)	**Mean**	**171.8**	**1.6**	**14.6**	**38.6**
	No. of dives	21	17	21	21
	Std. Dev	82.6	0.2	9.9	0.6
96.5 °F					
Dry + cooling suit	**Mean**	**49.8**	**1.9**	**20.3**	**38.2**
	No. of dives	12	12	12	12
	Std. Dev	18.5	0.2	8.2	0.5
Dry suit	**Mean**	**31.7**	**1.8**	**35.0**	**38.8**
	No. of dives	9	8	9	9
	Std. Dev	10.2	0.1	9.5	0.5
Skin	**Mean**	**96.0**	**1.6**	**21.5**	**39.1**
	No. of dives	20	20	20	20
	Std. Dev	38.9	0.1	9.3	0.6
MK 21 with dry suit	**Mean**	**40.3**	**-**	**20.7**	**37.2**
	No. of dives	17	-	16	16
	Std. Dev	16.8	-	15.2	0.3
99 °F					
Skin + cooling suit	**Mean**	**53.1**	**1.6**	**24.4**	**38.7**
	No. of dives	7	7	7	7
	Std. Dev	14.0	0.2	9.4	0.4
Skin	**Mean**	**48.2**	**1.6**	**35.5**	**39.0**
	No. of dives	19	19	19	19
	Std. Dev	23.0	0.1	15.1	0.9

Two aspects of the data were statistically analyzed: what the effects of the acclimation techniques on the physiological measures are, and whether the cooling suit proves to be beneficial to divers.

Acclimation

To statistically compare dry and wet acclimation strategies, it was necessary to collapse many conditions: the dry suit dives at 90 and 94 °F (32.2 and 34.4 °C) were merged, all the dive skin dives were combined (including those in which a cooling suit was worn), and the 96.5 °F (35.8 °C) dry suit and MK 21 (with dry suit) dives were grouped (see Table 5). The swimsuited dives were also included in the analysis.

Table 5.
Collapsed Data from Phase 2

Wet acclimation					
Water temp (°F)		Length of dive (min)	Mean $\dot{V}\,O_2$ of dive (L/min)	Temp rate increase in first 30 min (.001 °C/min)	Max core temp in water (°C)
94 °F: Swimsuited	**Mean**	**212.1**	**1.54**	**18.03**	**38.8**
	No. of dives	11	11	11	11
	Std. Dev	45.5	0.2	9.2	0.7
96.5, 99 °F: Skin	**Mean**	**72.2**	**1.6**	**28.6**	**39.0**
	No. of dives	25	25	25	25
	Std. Dev	38.8	0.1	14.7	0.8
90, 94 °F: Dry suit	**Mean**	**57.8**	**1.9**	**32.5**	**38.8**
	No. of dives	18	16	18	18
	Std. Dev	23.5	0.2	26.6	0.9
96.5 °F: Dry suit	**Mean**	**41.4**	**1.9**	**27.6**	**38.0**
	No. of dives	19	10	19	19
	Std. Dev	17.8	0.2	12.3	0.8
Dry acclimation					
Water temp (°F)		Length of dive (min)	Mean $\dot{V}\,O_2$ of dive (L/min)	Temp rate increase in first 30 min (.001 °C/min)	Max core temp in water (°C)
94 °F: Swimsuited	**Mean**	**127.5**	**1.6**	**10.8**	**38.4**
	No. of dives	10	6	10	10
	Std. Dev	93.3	0.2	9.6	0.4
96.5, 99 °F: Skin	**Mean**	**61.2**	**1.6**	**28.1**	**39.0**
	No. of dives	21	21	21	21
	Std. Dev	30.9	0.2	13.2	0.6
90, 94 °F: Dry suit	**Mean**	**36.2**	**1.8**	**12.2**	**38.0**
	No. of dives	13	9	13	13
	Std. Dev	20.0	0.4	13.4	0.7
96.5 °F: Dry suit	**Mean**	**41.0**	**1.9**	**20.3**	**37.9**
	No. of dives	19	10	18	18
	Std. Dev	16.8	0.2	13.6	0.8

Test 2.1. A two-way between-subjects analysis was carried out with the acclimation strategy among the four groups of dives shown. This analysis was made for each of the four dependent variables.

Results 2.1. For the length of dive, acclimation showed a significant main effect ($F[1,127] = 6.0$, $p < 0.05$). The wet acclimation strategy dives were significantly longer than the dry acclimation dives: a mean of 64.8 minutes, compared with a mean of 52.3

minutes across all four groups. The main effect of dress was also significant ($F[1,127] = 3.6$, $p < 0.05$). The swimsuited dives were significantly longer than the dry suit dives at 96.5 °F (35.8 °C) [see Table 5].

For the mean $\dot{V}O_2$ of the dive, the only significant main effect was for dress ($F[3,99] = 16.0$, $p < 0.05$). The mean $\dot{V}O_2$ of the swimsuited dives was significantly lower than that for the dry suit dives at 90, 94, or 96.5 °F (32.2, 34.4, or 35.8 °C). Also, the mean $\dot{V}O_2$ for the skin dive combination (1.57 L/min) was significantly lower than it was for the 90 and 94 °F (32.2 and 34.4 °C) dry suit dives.

The temperature rate increase in the first 30 minutes was significantly higher for the wet acclimation strategy dives (0.0277 °C/min) than for the dry acclimation dives (0.0192 °C/min; $F[1,126] = 10.7$, $p < 0.05$). Dress also demonstrated a significant effect ($F[3,126] = 3.6$, $p < 0.05$). The temperature rate increase in the first 30 minutes for the swimsuited dives was significantly lower than for the skin dives and the 96.5 °F (35.8 °C) dry suit dives (see Table 5).

The maximum core temperature in the water was significantly higher in the wet acclimation 101.5 °F (38.6°C) than in the dry acclimation dives (38.4 °C; $F[1,126] = 5.0$, $p < 0.05$). Dress also displayed a main effect ($F[3,126] = 13.8$, $p < 0.05$). The maximum core temperature in the 96.5 °F (35.8 °C) dry suit dives was significantly lower than in the dives with a different type of dress (see Table 5).

Test 2.2. A comparison was made of the differences in the dependent variables for the dives carried out at 96.5 °F (35.8 °C). To increase the range of dress, the 96.5 °F (35.8 °C) swimsuited exercise dive from Phase 1 was included. The POC dives were not included in the analysis of the length of the dive, since investigators ended all these dives at one hour.

Results 2.2. All four dependent variables showed significant differences (Mann-Whitney U was used instead of the ANOVA where there was no homogeneity of variance). Table 6 shows a summary of the results.

Table 6.
Summary of Analysis

Dependent variable	F and χ^2 values	Significant differences
Length of dive	$\chi^2(4) = 33.6, p < .05$	• Swimsuited longer than all other dress • Skin longer than dry suit and MK 21 dives
Mean $\dot{V}O_2$	$F(3,46) = 15.1, p < 0.05$	• Swimsuited lower than all other dress • Skin lower than POC and dry suit
Temp rate increase in first 30 min	$\chi^2(4) = 17.3, p < 0.05$	• Dry suit higher than all other dress
Max core temp in water	$F(4,67) = 36.5, p < 0.05$	• MK 21 lower than all other dress except skin • POC higher than swimsuited and skin

Effects of the cooling suit

Test 2.3. A between-subjects t-test was carried out on the skin and POC dives (cooling suit under dive skin) at 99 °F (37.2 °C) for each of the four dependent variables.

Results 2.3. No significant differences between the skin-suit dives and the skin and cooling-suit dives were found for any of the four dependent variables.

PHASE 3

The physiological data from Phase 3 are summarized in Table 7. As in Phase 2, many different types of dress were used. In Phase 3, finning was also included as a form of exercise, and the work required on the cycle was reduced from 50 W to 30 W in all but the swimsuited conditions.

Table 7.
Phase 3 Physiological Data Summary

Water temp (°F)		Length of dive (min)	Mean $\dot{V}O_2$ of dive (L/min)	Temp rate increase in first 30 min (.001 °C/min)	Max core temp in water (°C)
90 °F					
Dry suit, Fin	**Mean**	63.4	2.0	17.1	38.2
	No. of dives	11	9	11	11
	Std. Dev	38.8	0.4	10.9	0.6
94 °F					
Swimsuited, Cycle, 50 W	**Mean**	165.9	1.5	17.3	42.9
	No. of dives	23	23	23	23
	Std. Dev	56.8	0.3	23.1	22.2
96.5 °F					
Skin, Cycle, 30 W	**Mean**	165.0	1.4	17.7	38.8
	No. of dives	20	19	20	20
	Std. Dev	61.1	0.4	7.2	0.5
Dry suit, Fin	**Mean**	42.1	2.0	35.0	38.6
	No. of dives	8	5	8	8
	Std. Dev	14.3	0.6	8.2	0.8
Dry suit + cooling, Fin	**Mean**	43.4	1.6	22.9	38.6
	No. of dives	11	10	11	11
	Std. Dev	10.9	0.2	13.8	0.6
98 °F					
Swimsuited, Resting	**Mean**	63.2	1.0	14.3	38.0
	No. of dives	12	12	12	12
	Std. Dev	8.1	0.3	5.4	0.5
Skin, Fin	**Mean**	67.0	1.7	26.0	38.7
	No. of dives	19	18	19	19
	Std. Dev	27.1	0.3	11.5	0.8
99 °F					
Skin, Cycle, 30 W	**Mean**	64.3	1.5	31.9	39.2
	No. of dives	19	18	19	19
	Std. Dev	22.1	0.2	16.0	0.7
Skin, Fin	**Mean**	53.7	1.6	30.9	39.0
	No. of dives	18	16	18	18
	Std. Dev	23.6	0.4	13.2	0.8
101.5 °F					
Skin, Cycle, 30 W	**Mean**	34.7	1.5	30.2	38.9
	No. of dives	18	18	18	18
	Std. Dev	11.1	0.4	28.9	0.9

Three aspects of the data were statistically analyzed: the type of exercise, the garment worn, and the water temperature.

Effects of type of exercise

Test 3.1. The dives at 99 °F (37.2 °C) in dive skins with participants either finning or cycling at 30 W were compared to assess if the types of exercise caused any differences in the four dependent variables. From Phase 2, the 50 W cycling dives at 99 °F (37.2°C) in dive skins were also included in the comparison. Each of the four variables was examined separately with a one-way independent subject ANOVA.

Results 3.1. No significant differences were found for any of the four dependent variables.

Test 3.2. Dry suit dives (both cycling at 50 W) in Phase 2 at 90 and 96.5 °F (32.2 and 35.8 °C) were compared with dry suit dives in Phase 3 at the same temperatures, with finning as the exercise. This comparison was made with a two-way between-subjects ANOVA.

Results 3.2. For the length of the dive and temperature increase in the first 30 minutes, the effect of temperature was significant ($F[1,35] = 5.5$, $p < 0.05$; and $F[1,35] = 9.3$, $p < 0.05$, respectively). No other differences were significant. Therefore, finning and cycling appear to be equivalent exercises.

Test 3.3. A comparison was made between Phase 2 cycling at 50 W and 30 W with dive skins in 96.5 and 99 °F (35.8 and 37.2 °C) water. This comparison was made with a two-way ANOVA for each of the four dependent variables.

Results 3.3. The 30 W cycling dives were significantly longer than the 50 W ones ($F[1,73] = 20.1$, $p < 0.05$), and the 96.5 °F (35.8 °C) dives were significantly longer than the 99 °F (37.2. °C) dives ($F[1,73] = 60.1$, $p < 0.05$). The temperature rate increase in the first 30 minutes was also higher at 99 °F (37.2 °C) than it was at 96.5 °F (35.8 °C), ($F[1,73] = 351.6$, $p < 0.05$). No other main effects or interactions were significant for these dependent variables — or for the mean $\dot{V}O_2$ of the dives, or for maximum temperature in the water.

Effects of the Cooling Suit

Test 3.4. To assess the effects of the cooling suit, an independent sample t-test was used to compare the performance of the dry suit and the combination of the dry and cooling suits in the 96.5 °F (35.8 °C) dives.

Results 3.4. The only significant difference was that the temperature increase during the first 30 minutes was lower in the dry suit dives in which a cooling suit was worn ($t[17] = 2.2$, $p < 0.05$).

Effects of T_w

Test 3.5. An independent sample t-test was used to compare dry suit dives at 90 and 96.5 °F (32.2 and 35.8 °C).

Results 3.5. The only significant difference was that the temperature rate increase in the first 30 minutes was greater in the 96.5 (35.8 °C) than in the 90 °F (32.2 °C) dives ($t[16] = 3.6$, $p < 0.05$).

Test 3.6. A comparison was made among the "skin," 30-W cycling dives at 96.5, 99, and 101.5 °F (35.8, 37.2, and 38.6 °C). This comparison was made with the Kruskal-Wallis test because the data lacked a homogeneity of variance.

Results 3.6. Differences for lengths of total dive time were significant at all three temperatures ($chi^2[2] = 40.3$, $p < 0.05$). Temperature rate increases in the first 30 minutes also significantly differed ($chi^2[2] = 6.8$, $p < 0.05$). The 99 °F (37.2 °C) values were significantly higher than the 96.5 °F (35.8 °C) values (see Table 7).

GENERAL RESULTS

The decreasing endurance with increasing T_w appears to be significant whether the diver is exercising or at rest. Once the T_w is greater than normal body temperature, diver tolerance to warm water diving decreases markedly, as Figures 1 and 2 graphically display for resting and exercising swimsuited dives, respectively. In both resting and exercise dives, the rate of increase in T_{rec} during the first 30 minutes rises rapidly, and endurance decreases as T_w approaches and then exceeds body temperature. The first 30 minutes was chosen for analysis, because it appeared that this was where the "cooler" dive T_{rec} change curves started to flatten out — i.e., where divers reached steady state during the nonthermally stressful dives.

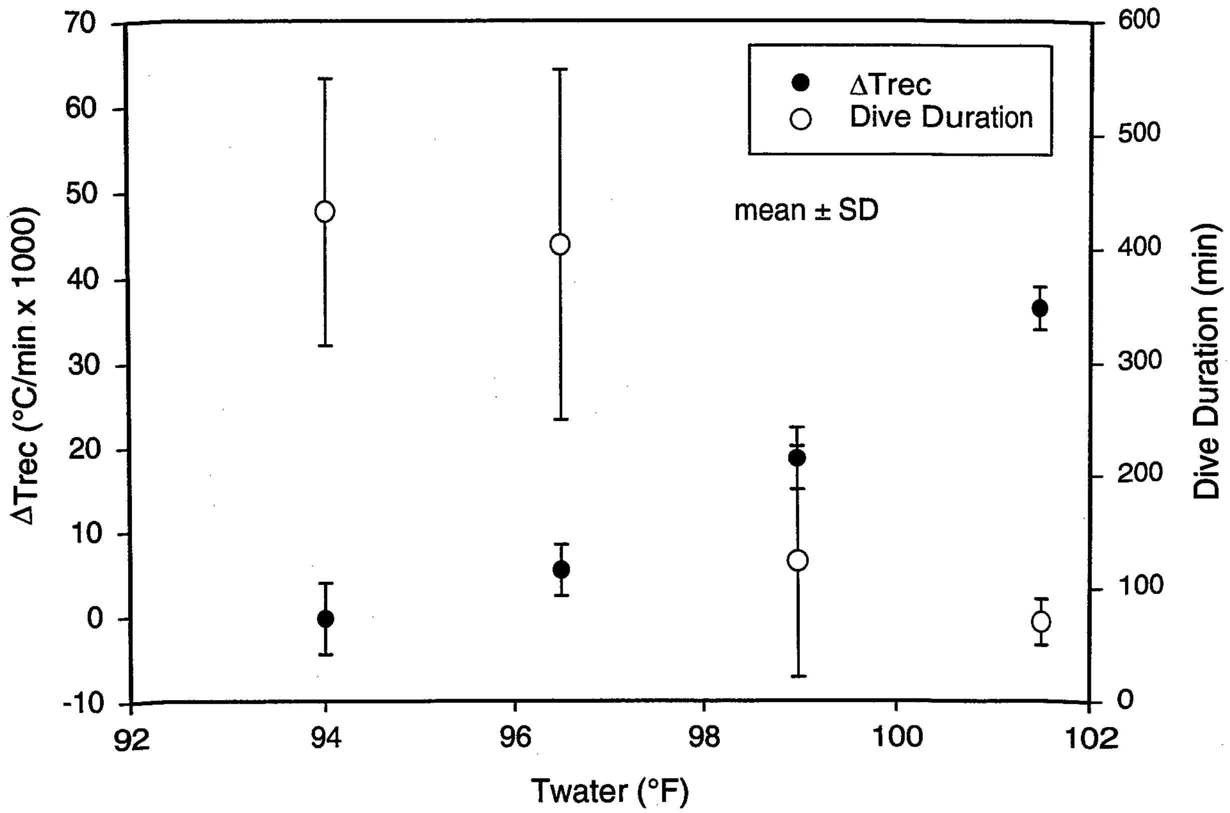

Figure 1. Swimsuited Resting Dive, Phase 1: Comparison of average rectal temperature (T_{rec}) increase during first 30 minutes of dive (black-shaded region) and average dive duration (gray-shaded region).

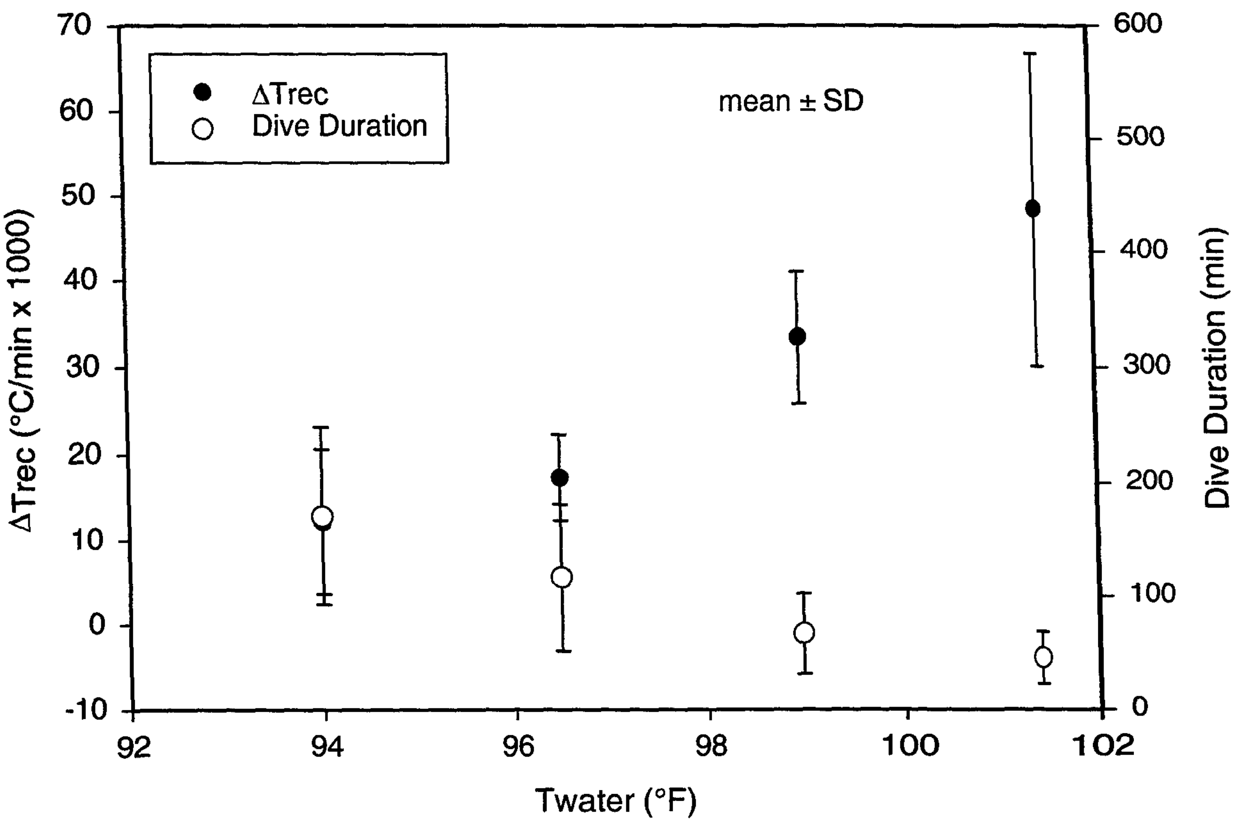

Figure 2. Swimsuited 50 W Exercise Dives, Phase 1: Comparison of average T_{rec} increase during first 30 minutes of dive and average dive duration.

No thermal aborts (T_{rec} limits reached) were made at T_w less than 99 °F (37.2 °C) for the swimsuited exercise dives, and none below 101.5 °F (38.6 °C) for the resting swimsuited dives (see Table 8). When the dive skin was added as dress, the temperature at which divers reached thermal abort criteria decreased, as shown in Table 9. Few thermal aborts occurred with the dry suit, and these were at less than the maximum T_w in which the dry suit was dove, as Table 10 indicates. The area that puts divers at significant risk is that in which they continue to exercise even as their core temperature is rising to 104 °F (40 °C) or higher. Dives with thermal aborts occurred -here the increase in T_{rec} during the first 30 minutes was greater than 0.0300 °C/min.

Table 8.
SWIMSUITED DIVE SUMMARY

Water Temp °F	Exercise* Type (watts)	Phase	Diver Dress	# Dives	# Completing scheduled dive	Maximum Dive Time, if < scheduled dive time	# Diver T_{rec} Aborts	% T_{rec} Aborts
78	EXER (50)	I	Swimsuited	18	11	---	0	0%
94	EXER (50)	I	Swimsuited	19	9	---	0	0%
94	EXER (50)	II	Swimsuited	21	18	---	0	0%
94	EXER (50)	III	Swimsuited	23	21	---	0	0%
96.5	EXER (50)	I	Swimsuited	16	7	---	0	0%
99	EXER (50)	I	Swimsuited	15	0	2:19	2	13%
101.5	EXER (50)	I	Swimsuited	14	0	0:55	2	14%
94	Rest	I	Swimsuited	19	16	---	0	0%
96.5	Rest	I	Swimsuited	8	7	---	0	0%
99	Rest	I	Swimsuited	7	6	5:35	0	0%
101.5	Rest	I	Swimsuited	5	0	1:35	1	20%

* EXER (30) and (50) represent cycle ergometry as forms of exercise at either 30 or 50 watts, respectively.

Table 9.
DIVE SKIN DIVE SUMMARY

Water Temp °F	Exercise* Type (watts)	Phase	Diver Dress	# Dives	# Completing scheduled dive	Maximum Dive Time, if < scheduled dive time	# Diver T_{rec} Aborts	% T_{rec} Aborts
96.5	EXER (30)	III	Skin	20	6	---	0	0%
96.5	EXER (50)	II	Skin	20	0	3:54	1	5%
98	FIN	III	SkinFin	19	0	1:54	2	11%
99	EXER (30)	III	Skin	19	0	1:42	4	21%
99	EXER (50)	II	Skin	19	0	2:02	3	16%
99	FIN	III	SkinFin	18	0	1:44	2	11%
101.5	EXER (30)	III	Skin	18	0	0:52	2	11%
[T] **99**	EXER (50)	II	Skin POC	7	6	---	0	0%
94	EXER (50)	II	Swimsuited	20	18	---	0	0%

* EXER (30) and (50) represent cycle ergometry as forms of exercise at either 30 or 50 watts, respectively.
FIN represents finning as a form of exercise.
[T] These dives were designed to be no longer than 60 minutes.

Table 10.
DRY SUIT DIVE SUMMARY

Water Temp °F	Exercise* Type (watts)	Phase	Diver Dress	# Dives	# Completing scheduled dive	Maximum Dive Time, if < scheduled dive time	# Diver T_{rec} Aborts	% T_{rec} Aborts
90	EXER (50)	II	Dry Suit	12	0	3:32	0	0%
90	FIN	III	DrySuitFin	10	0	2:34	0	0%
94	EXER (50)	II	Dry Suit	19	0	1:26	3	16%
96.5	EXER (50)	II	Dry Suit	9	0	0:52	0	0%
96.5	FIN	III	DrySuitFin	9	0	1:15	0	0%
T **96.5**	EXER (50)	II	Dry Suit POC	12	11	---	0	0%
T **96.5**	EXER (50)	II	MK 21	17	2	---	0	0%
T **96.5**	FIN	III	Dry Suit PCM	11	2	---	0	0%
94	EXER (50)	II	Swimsuited	21	18	---	0	0%

* EXER represents cycle ergometry as the form of exercise.
FIN represents finning as the form of exercise.
T These dives were designed to be no longer than 60 minutes in duration.

DISCUSSION

Selection of Study Water Temperatures. The first exercise dives were completed at 78 °F (25.6 °C), a temperature 1 °F lower than that which the National Collegiate Athletic Association (NCAA) uses for competitive swimming because that temperature does not create heat stress.[19] This temperature allowed verification dives to be performed independent of thermal effects. Selecting a thermal stress starting T_w was based primarily on expected operational environments, study temperatures were also chosen with consideration for diver safety. Previous research had been safely completed with long-duration oxygen dives at 94 °F (34.4 °C).[16] This study differed in that divers were breathing gas at least as warm as the water (vice surface-supplied gas at ambient air temperature) and were exercising continuously (vice working/resting in intermittent cycles). Therefore, following recommendations from the CPHS, we added 2.5 °F increments from the 94 °F (34.4 °C) to reach our warmest T_w of 101.5 °F (38.6 °C).

As expected, for at least two reasons the length of the dives was shorter in the exercise than in the rest conditions. First, the study was designed with the duration for resting dives longer than that for exercise: an 8-hour resting period was chosen to simulate an SDV scenario in which divers are at rest for most of such a mission. The 4-hour exercise scenario was based on Naval Special Warfare and Very Shallow Water Mine Countermeasures mission profiles for combat swimmers.

A second explanation is intuitive: endurance tends to increase at reduced levels of activity. This study took that reduction in activity to the extreme of total inactivity or rest. Within each exercise grouping (rest versus cycling), endurance was reduced at the higher temperatures. The mean $\dot{V}O_2$, the temperature rate increase in the first 30 minutes, and the maximum core temperature in the water were greater in the exercise dives than in the resting dives. Furthermore, within each exercise group the mean $\dot{V}O_2$ was greater at the higher temperatures than it was at the other temperatures in that same group.

These results demonstrate that durations of dives decrease significantly as T_w increases, even when divers are at complete rest. Most notable is a sharp decrease in dive times as T_w approaches or exceeds normal body temperature. This decrease can be explained by considering whether the diver's body is able to shed heat to the water — i.e., whether $T_w < T_{rec}$ — or whether the diver acts as a heat sink — i.e., whether $T_w > T_{rec}$. Under the latter condition, the body starts to absorb heat from the water column.

It is not surprising that some divers terminated before they reached the T_{rec} study termination criteria due to headache, nausea, dizziness, and cramping, all normal symptoms of heat stress. The remaining divers showed little or no symptoms and had to have their swims aborted for exceeding T_{rec} of 104 °F (40 °C). Therefore, free-swimming, unmonitored divers may exceed their physiological limits and continue to work to the point of becoming hyperthermic and incapacitated.

During the three years of this study, the investigator halted 28 dives because they met the T_{rec} termination criteria (see Table 1). These instances always occurred in dives involving great thermal stress, from either T_w or diver dress, and 71.4% (20 of 28) involved the same 5 divers. One diver alone accounted for 25% (7 of 28) of these T_{rec} terminated dives. Although no particular characteristic of these divers stood out to explain that 71.4% result, these divers tended to have thinner body habitus and to be well-conditioned endurance athletes. An alternative explanation may be simply that some individuals tolerate a higher heat strain better than others do, for unknown reasons.

The three phases in this report show that wearing any type of dress that restricts transfer of heat from the body generally reduces dive duration. In addition, temperature rate increases in the first 30 minutes, and increases in the maximum T_{rec} in the water are greater than those occurring when divers do not wear such dress. However, T_{rec} for divers immediately out of the water and undressed quickly returns to the baseline predive body temperature regardless of dive duration, T_w, or type of dress.

Rebreather gas no doubt adds to the thermal load of the diver, as measured inhalation gas temperatures were consistently 6+ °F higher than those of ambient T_w. Of note, the MK 21 dives were surface supplied, with the divers breathing gas that was at ambient air temperature. During the longer duration dives, the OxyLUNG gas cylinders did not last the entire length of the dive, and a bottle change-out was necessary. All divers noted the remarkable difference in inhalation gas temperatures when their new bottles were in place. They also noted that the "cool" gas effect lasted less than 5 minutes.

Acclimation strategy. Results from Phase 1 indicated that 96.5 and 99 °F (35.8 and 37.2 °C) appear to be in the temperature range where diver endurance and other features of performance begin to decline precipitously. Some evidence indicates that acclimation strategy affects some of the four physiological measures examined. Those dives using a wet acclimation strategy resulted in significantly longer durations than those using a dry acclimation strategy. The temperature rate increase in the first 30 minutes and the maximum temperature in the water for the wet acclimation dives were also significantly higher in dives with a wet than with a dry acclimation strategy.

These two acclimation strategies were parts of a cooperative research effort between this NEDU study funded by NAVSEA and a project funded by Special Operations Command (SOCOM) and Naval Special Warfare (NSW).[20] Preliminary results indicate that successive days of warm water exposure allow divers ultimately to complete 4-hour dives in T_w of 98 ± 0.5 °F (36.7 ± 0.28 °C), at the exercise intensity used in this study. However, although divers were heat acclimated in the water, during the testing phase they typically made one dive per week, and the most they ever made were two dives in a week's time. Divers were required to a have a minimum of 48 hours between warm water dive exposures. Therefore, rather than maintaining warm water acclimation, we may have been keeping the divers in a state of only partial acclimation or deacclimation.

Some evidence indicates that the wet acclimation strategy affords a dive duration superior to that with the dry acclimation strategy. However, the temperature rate increase in the first 30 minutes and the maximum T_{rec} was higher in the wet than in the dry strategy dives. Therefore, body temperatures of the wet acclimation divers tended to increase more quickly than those of other divers. A proper repeated-measures experiment that compares wet, dry, and no-acclimation strategies needs to be designed to investigate the effect of wet or dry acclimation in more detail.

Dry Suits. Although dry suits are not normally associated with warm water diving, U.S. Navy divers require them for protection in contaminated waters.[6,11] Therefore, four different combinations of dry suit ensembles were tested: the rebreather UBA and a dry suit, the dry suit with a cooling suit, the dry suit finning with a PCM vest, as well as the dry suit with the MK 21 Deep Sea Diving System (DSDS).

Among the dive combinations at 96.5 °F (35.8 °C) [Phase 2 dives carried out in skin, dry suit, dry suit and cooling suit, and dry suit with the MK 21 (Table 4)], the temperature rate increases during the first 30 minutes in the water were higher in the dry suit than in the other suit combinations. The MK 21 dives also showed a significantly lower maximum T_{rec} in the water than did the dives in the other types of dress. Although the MK 21 dives were shorter than those in which a cooling suit was worn, the difference was not significant. Most likely, these differences are in some part attributable to evaporative cooling of the head and neck in the air space provided by the MK 21 helmet. Another influence that may have been significant was the temperature of the breathing gas: during MK 21 dives, gas was supplied via an umbilical and the temperature was ambient air, which would have registered around 75–80 °F (23.9–26.7 °C).

Combining the cooling suit and the dry suit resulted in a lower temperature rate increase in the first 30 minutes than diving the dry suit alone (Table 4). However, the cooling suit dives were limited by design to a maximum of 60 minutes, because they were conducted as POC dives to determine whether a benefit could be derived from wearing a cooling suit under the dry suit and whether this benefit warranted additional study. Therefore, if these cooling suit/dry suit dives had been allowed to continue until the divers self-terminated them or met dive termination criteria, this difference in temperature rate increases may have been quite significant: 11 of 12 divers (92%) completed the researcher-imposed 60-minute dive. The only diver who failed to complete it lost cooling flow to his suit approximately 30 minutes into the dive and did not report this problem to topside until the dive had ended.

Of note were the results from wearing the cooling suit under a dive skin. Wearing this configuration at 99 °F (37.2 °C) does not appear to provide any significant benefits over wearing only a dive skin at this temperature.

Two different cooling suits were examined. In Phase 2 the cooling suit was worn under a dry suit at 96.5 °F (35.8 °C) and under a dive skin at 99 °F (37.2 °C). From comparing dry suit dive results with and without the cooling suit, we found the only significant difference to be that the temperature rate increase in the first 30 minutes was lower with the cooling suit than without it. However, when these values are contrasted with results from the dives using the MK 21, the results from the cooling suit dives were superior to those with the dry suit in all the measures examined except dive duration. This result suggests that combining the cooling suit with the MK 21 offers divers the best protection against warm water in conditions when a dry suit must be worn. Wearing the cooling suit under a dive skin at 99 °F (37.2 °C) did not result in any significant differences from wearing the dive skin at 99 °F (37.2 °C). However, this lack of difference may result from the fact that these dives had an investigator-imposed limit of 60 minutes: if these dives had been allowed to continue, all but one diver stated that he could easily have continued for a much longer period. The one exception was the diver whose cooling suit had lost its cooling flow.

In Phase 3 a PCM cooling vest was worn under the dry suit. As found in Phase 2, the main advantage of this vest appears to be that it reduces the temperature rate increase in the first 30 minutes. Therefore, the cooling vest appeared to be of some benefit to divers, at least for the first 30 minutes.

Exercise type. Finning and cycling at either 30 W or 50 W in a dive skin appear to afford similar levels of exercise intensity at 99 °F (37.2 °C). Comparing results of performances at 90 and 96.5 °F (32.2 and 35.8 °C) between divers finning and cycling at 50 W while wearing dry suits revealed no significant differences between the exercises. However, a comparison of the length of the 30 W and 50 W cycling dives showed that the lower intensity cycling dives were of longer duration than the 50 W ones.

It is interesting that no significant difference in the mean $\dot{V}O_2$ was found across all test conditions and temperatures. Why no such difference appeared — when it should have — cannot be easily explained. Perhaps the difference in effort is not great enough to appreciably affect $\dot{V}O_2$. Another possibility is that warm water temperature was contributing an increase in $\dot{V}O_2$ that was larger in proportion than whatever increase exercise was contributing. However, a physiological explanation for the latter possibility is difficult to surmise.

Comparing the dry suit dives with and without the PCM vest at 96.5 °F (35.8 °C) showed only one significant difference: the temperature rate increases in the first 30 minutes were lower for the PCM dives.

CONCLUSIONS

A total of 1,764 dives were completed over the three years of this study. The data collected from these dives allows guidance for diver endurance in various T_w and diver dress to be established. Following Phase 1 of the study, interim guidelines for warm water diving were written (see the interim guidelines column in Table 11). However, since the three phases of the study have been completed, a more detailed column of revised warm water diving guidelines is included in Table 11.

These guidelines should be used to direct dive planning, and not be regarded as absolute safe limits. Exceeding or even closely approaching the upper time limits in thermally stressful environments may result in significant diver injury, and even death. Therefore, the extremes of these limits should be approached cautiously.

The overall conclusion from this study may be intuitively obvious: a time duration or "stay time" can be used. Increasing T_w and/or wearing added thermally stressful diver dress under those conditions significantly reduces diver endurance and stay time.

Repeating warm water dives once or twice a week is probably not sufficient warm water exposure to develop and maintain warm water tolerance. Additional warm water studies at NEDU have shown daily warm water exposures of increasing intensity are required to develop significant tolerance or acclimation to T_w approaching and even exceeding normal body temperature.

Table 11.
A comparison of the revised warm water diving guidelines and interim guidelines provided after Phase 1 of the study.

Resting (swimsuited)		
Water Temp °F	**Revised Guidelines**	**Interim Guidelines**
< 94 °F	diver limited	unlimited
94 – 97 °F	6½ hrs	8 hrs
97 – 99 °F	2 hrs	2 hrs
99 – 101.5 °F	< 1 hr	should not attempt
> 101.5 °F	should not attempt	should not attempt

Exercise (swimsuited)		
Water Temp °F	**Revised Guidelines**	**Interim Guidelines**
< 94 °F	diver limited	diver limited
94 – 97 °F	2 hrs	3 hrs
97 – 99 °F	1 hr	< 1 hr
> 99 °F	should not attempt	should not attempt

#Resting (dive skin)		
Water Temp °F	**Revised Guidelines**	**Interim Guidelines**
< 94 °F	diver limited	no guidance provided
94 – 97 °F	4 hrs	no guidance provided
97 – 99 °F	2 hr	no guidance provided
> 99 °F	not advisable	no guidance provided

Exercise (dive skin)		
Water Temp °F	**Revised Guidelines**	**Interim Guidelines**
< 94 °F	diver limited	no guidance provided
94 – 97 °F	2 hrs	no guidance provided
97 – 99 °F	1 hr	no guidance provided
> 99 °F	should not attempt	no guidance provided

#Resting (dry suit)		
Water Temp °F	**Revised Guidelines**	**Interim Guidelines**
90 °F	2 hrs	no guidance provided
90 - 94 °F	1.5 hrs	no guidance provided
> 94 °F	not advisable	no guidance provided

Exercise (dry suit)		
Water Temp °F	**Revised Guidelines**	**Interim Guidelines**
90 °F	1 hour	no guidance provided
90 - 94 °F	45 minutes	no guidance provided
> 94 °F	should not attempt	no guidance provided

# Denotes that no controlled dives were conducted at these temperatures and under these conditions. These times show simply approximate exposure durations based on these

temperatures; conditions included resting and working-level dives performed in swimsuits and T-shirts.

RECOMMENDATIONS

1. Table 11 presents warm water diving temperature and duration guidelines based on results from this study. Additional guidelines are presented following this table and will assist planners in developing appropriate diving mission profiles. Implementing many of these recommendations should be standard practice for all diver operations. These recommendations become increasingly critical when elevated T_w diminishes the margin of safety.

2. The requirement to adequately hydrate both before and after warm water diving cannot be overemphasized. The need to both eat and drink before and after these dives is paramount to ensure that divers are able to continue to work without suffering heat casualties under these environmental conditions.

3. **Careful operations planning** should consider a **diver's level of activity and heat exposure before diving** in warm waters, **and** the level of activity a diver will be required to perform **after exiting the water.** Manning the side or conducting land warfare operations may jeopardize diver safety if diving operations are planned with no adequate consideration for these activities.

4. Do not attempt to fluid load before diving to compensate for anticipated fluid loss: such an attempt may result in life-threatening pulmonary edema. However, it is important that all divers start their dives fully hydrated, regardless of T_w. Current recommendations for endurance athletes suggest that 500 mL (approximately 17 ounces) of fluid be consumed 2 hours before exercise.[21]

5. Consider conducting dive operations at night, dusk, or dawn to reduce heat stress imposed by sun exposure and high air temperatures. Since the dive skin currently worn by SEAL combat divers uses a hood, avoid wearing the hood during surface swims.

6. Ships husbandry divers should wear the minimum antichafing dress required. Diver dress and its effect on heat retention should be acknowledged during operations planning.

7. Conduct a week or so of reduced intensity diving as an acclimation period when first diving in warm water. This week will allow topside and support personnel, as well as divers, to acclimate to elevated air temperatures.

8. If heavy exercise rates be required by operational exigencies, the resulting increased risk of oxygen toxicity can be reduced by swimming at a shallow depth

(10 feet of seawater, if feasible) until a normal swim pace can be resumed. This technique for reducing risk is effective at any T_w.

9. Recognition and management of heat injuries should be added to dive planning and briefing.

10. Divers should maintain physical conditioning during periods of warm water diving, because maintaining such conditioning protects against heat injuries.

11. Some divers may tolerate high water temperatures better than other divers can because of individual variability. Dive supervisors should consider this variability in selecting divers and planning dives.

FUTURE RESEARCH NEEDS

1. Develop a battery of tests that simulates both the cognitive and physical skills as well as the abilities required by divers in real operations. It also must be possible for divers to complete the testing when fully submerged, and test responses must not be affected by wearing dive equipment that may hinder vision, movement, or manual dexterity. Such testing would constitute the next generation of SINDBAD.

2. Repeat exactly (as described in NEDU Protocol 00-07) the 99 °F (37.2 °C) dive skin dives (cycle exercise only) and simulate actual field conditions (i.e., high air temperatures, hydration with warm water, and no active cooling). Allow diver-subjects to self-determine when they start the SOF MRPM test battery, but document this time to learn how long it takes for the diver-subject to recover sufficiently to start the battery.

3. Confirm Table 11's untested durations recommended for resting conditions in dry skin and dry suits, if operationally relevant.

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APPENDIX A

DEVELOPMENT OF EXPOSURE GUIDANCE FOR WARM WATER DIVING

Principal Investigator: CDR E. T. LONG, MC, USN

NEDU Protocol
DIVER-SUBJECT DIRECTION SHEET

NAME ______________________ DATE______________

PREDIVE

Evening before scheduled dive.

1. No alcohol 48 hours before scheduled dive.
2. No caffeine 24 hours before scheduled dive.
3. Before leaving the day before scheduled dive, get 1 Meals Ready to Eat (MRE) and 1 urine collection bottle.
4. Eat 1 MRE for the evening meal the night before scheduled dive. (Diver may eat more than this, but at a minimum eat 1 MRE.)
5. Drink at least 1 liter of fluid (caffeine free) between 1800 and 2200 the evening before scheduled dive. (Fluid is diver's choice, but Gatorade will be made available to take home to drink.)

Morning of scheduled dive.

1. Measure resting heart rate upon initial wake-up.
2. Collect first void of morning.
3. **DO NOT** eat or drink until after blood draw at NEDU Blood Lab.
4. Arrive at Physiology Lab at ________.
5. Bring dry T-shirt; wear running shoes or equivalent. (No sandals, flip-flops, etc.)

POSTDIVE

1. Follow directions after exiting the water. Measurements will be made similar to those accomplished during predive in Physiology Lab.
2. Diver will be observed until heart rate and core temperature return to baseline (<99 °F) and fluids are drunk, and until they have urinated at least once since exiting the water and have been cleared by the DMO.
3. Diver will retain this sheet until the following morning.
4. In an emergency, call:
   CDO at 230-3100, or
   Duty DMO, Dr. ______________, at pager ___________________

APPENDIX B

DEVELOPMENT OF EXPOSURE GUIDANCE FOR WARM WATER DIVING

Principal Investigator: CDR E. T. LONG, MC, USN

NEDU Protocol

NEUROPSYCHOLOGICAL AND PHYSICAL PERFORMANCE ASSESSMENT

1. INTRODUCTION AND OBJECTIVES

The goals are to:

a. Assess the safety, from a neuropsychological and physical standpoint, of exposure to a warm water environment.

b. Ensure proper documentation of the saturation diver's neuropsychological state and physical level before and after warm water exposure.

c. Identify any residual effects of exposure to warm water.

d. Use the results of these tests to provide for timely medical intervention, where indicated.

Operational performance and safety are issues in any challenging environment. Working in extremely warm water is an unexplored subject that this study will address. The data gathered during this series of dives will assist in identifying potential changes in diver well-being and in investigating diver reports of subtle changes in cognitive functioning, if such reports arise.

2. MATERIALS

The following will make up the evaluation battery for Phase 1 dives in this study:

PHYSICAL PERFORMANCE

a. Grip Strength test

b. Pull-ups

c. Step-up task

COGNITIVE

a. Trail Making A and B

b. Symbol Digit Modalities Test (SDMT)

c. Wechsler's Memory Scale-R (Logical Memory I and II)

d. Tester's Workbench/Automated Neuropsychological Assessment Metrics (TWB/ANAM)

3. PROCEDURE

Each of the following will be given before and after the dives:

Grip Strength Test is a measure of motor strength of the upper extremities. It is administered individually and takes 3–5 minutes per subject.

Pull-ups are a stable measure of upper body strength. The measurement is the total frequency of pull-ups in one trial. It is administered individually and takes about 3–5 minutes per subject.

The Step-up task is a measure of coordination and lower body strength. It constitutes the frequency of ascensions on two steps in 60 seconds. It is administered individually.

Trail Making is a measure of the subject's executive mental functioning. Specifically, this test measures attention, mental shifting, working memory, and — to a point — tremors. It has been found to be highly reliant on frontal lobe functioning. This test requires about 5 minutes to administer and is also given individually. Scores are obtained from the time required to complete the forms and the number of errors that are made. These two results are factored together to yield a standard score on a 10-point scale.[1]

Symbol Digit Modalities Test (SDMT) is a pencil-and-paper test on which the subject has to match numbers randomly assigned to geometrical symbols. This test assesses sustained attention, visual-spatial motor coordination, and response speed; it requires about 3 minutes to administer. The SDMT gives a raw score.[2]

The Logical Memory subscale of Wechsler Memory Scale is a memory examination and is given individually. It specifically measures immediate and delayed recall as well as verbal memory. It takes about 5 minutes to administer and yields a raw score and percentage scores.[3]

The TWB/ANAM[4, 5] is a computer-based standard clinical subset of the Office of Military Performance Assessment Technology (OMPAT) Tester's Workbench (TWB). The ANAM is a set of TWB tests that have been reconfigured for use in clinical neuropsychological evaluations. Many components of the ANAM were derived from the UTCPAB/STRES Battery[6] and the Walter Reed Performance Assessment Battery.[7] The ANAM 2000, the latest version, is purported to precisely measure mental efficiency as well as accuracy.[5]

Tests in the ANAM 2000 battery were selected for assessing sustained concentration and attention, mental flexibility, spatial processing, cognitive processing efficiency, mood, arousal/fatigue level, and short-term, long-term, and working memory. Specifically, the ANAM 2000 battery for this dive series is composed of the following subtests:

- Demographics form.
- Stanford Sleepiness Scale — Measures alertness level.
- Mood Scale 2-R — Measures current mood level (state).
- Simple Reaction Time — Measures basic psychomotor speed.
- Code Substitution (Letter/Symbol Comparison) — Measures visual scanning and learning.
- Code Substitution — Measures immediate and delayed recall.
- Running Memory Continuous Performance Task (CPT) — Measures working memory and executive functions.
- Mathematical Processing Task — Measures computational speed and working memory.
- Matching to Sample — Measures delayed recall/longer-term memory.

Note: These subtests are purported measures and are discussed in more detail in Reeves et al.[5]

The following will occur during the conditioning phase of the study:

1. During the first week, each assessment instrument will be performed to reach a stabilized peak performance. This level is defined as:

- ±5% baseline stability for ANAM 2000,
- Physical performance of ±5% baseline stability for the Grip Strength component and the Stair Climb component, and
- Pull-up frequency of ±2 of stable baseline.

1. During the second week, the peak performance level of ±5% of baseline stability will be determined for the SINDBAD in the wet environment.

3. Each week except the first, a maintenance session with each task will be performed to ensure that baseline levels remain at peak performance.

4. During the conditioning phase, additional sessions will be conducted, as necessary, to maintain baseline measures.

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APPENDIX C

DEVELOPMENT OF EXPOSURE GUIDANCE FOR WARM WATER DIVING

Principal Investigator: CDR E. T. LONG, MC, USN

NEDU Protocol

DIVER-SUBJECT SYMPTOM QUESTIONNAIRE

		1	2	3	4	5
1.	Signs/Symptoms Oxygen Toxicity					
	a. Vision changes	[ ]	[ ]	[ ]	[ ]	[ ]
	b. Ringing in ears	[ ]	[ ]	[ ]	[ ]	[ ]
	c. Nausea	[ ]	[ ]	[ ]	[ ]	[ ]
	d. Tingling	[ ]	[ ]	[ ]	[ ]	[ ]
	e. Twitching	[ ]	[ ]	[ ]	[ ]	[ ]
	f. Irritability	[ ]	[ ]	[ ]	[ ]	[ ]
	g. Dizziness	[ ]	[ ]	[ ]	[ ]	[ ]
2.	Lightheadedness?	[ ]	[ ]	[ ]	[ ]	[ ]
3.	Weakness?	[ ]	[ ]	[ ]	[ ]	[ ]
4.	Muscle cramps?	[ ]	[ ]	[ ]	[ ]	[ ]
5.	Confusion?	[ ]	[ ]	[ ]	[ ]	[ ]
6.	Coordination: Decreased?	[ ]	[ ]	[ ]	[ ]	[ ]
7.	Thirsty?	[ ]	[ ]	[ ]	[ ]	[ ]
8.	Headache?	[ ]	[ ]	[ ]	[ ]	[ ]
9.	Rapid breathing?	[ ]	[ ]	[ ]	[ ]	[ ]
10.	Unsteady on feet?	[ ]	[ ]	[ ]	[ ]	[ ]
11.	Urge to have a bowel movement?	[ ]	[ ]	[ ]	[ ]	[ ]
12.	Do you wish to abort/terminate?	YES ____		NO ____		

APPENDIX D

CYCLE CONDITIONING

DEVELOPMENT OF EXPOSURE GUIDANCE FOR WARM WATER DIVING

Principal Investigator: CDR E. T. LONG, MC, USN

INTRODUCTION

GENERAL

The following program of cycle conditioning is designed so that all subjects should be able to meet the desired level of cycling fitness. This conditioning program should provide sufficient training to enable all subjects to perform a four-hour cycle ride on the underwater cycle ergometers by the end of the training period. During this conditioning, a percentage of maximum heart rate (max HR) is used to ensure sufficient training resistance. To calculate max HR for the aerobic condition phase of this study, use the following equations:

(220 – age) X 0.6 = 60% max HR

(220 – age) X 0.75 = 75% max HR

After warming up, all subjects should adjust cycle resistance to maintain their heart rates between 60% and 75% of their calculated maximum. Cycle pedal rates should be between 75 and 90 revolutions per minute (rpm) during conditioning.

METHODS

The following plan is provided as a general guideline. Actual sessions and time schedules may vary because of the subject's level of cycling conditioning and response to training.

<u>1st week</u>:

4–5 sessions for a minimum of 30 minutes at 60–75% $\dot{V}O_2$ max heart rate

2nd week:

4–5 sessions for a minimum of 45 minutes at 60–75% $\dot{V}O_2$ max heart rate

3rd week:

2 sessions at 60–75% $\dot{V}O_2$ max heart rate for one hour
90-min rides Friday or Saturday

4th week:

2 sessions at 60% $\dot{V}O_2$ max heart rate for two hours
2.5-hour bike rides Friday or Saturday

5th week:

1 session for 75 min at 75% $\dot{V}O_2$ max heart rate
1 session for 2.25 hr at 65% $\dot{V}O_2$ max heart rate
1 session for 3 hr at 50% $\dot{V}O_2$ max heart rate
1 4-hour bike ride at 60% $\dot{V}O_2$ max heart rate

APPENDIX E

FIN-SWIMMING APPARATUS AND SETUP

DEVELOPMENT OF EXPOSURE GUIDANCE FOR WARM WATER DIVING PHASE 3

Principal Investigator: CDR E. T. LONG, MC, USN
NEDU Protocol Number 01-06