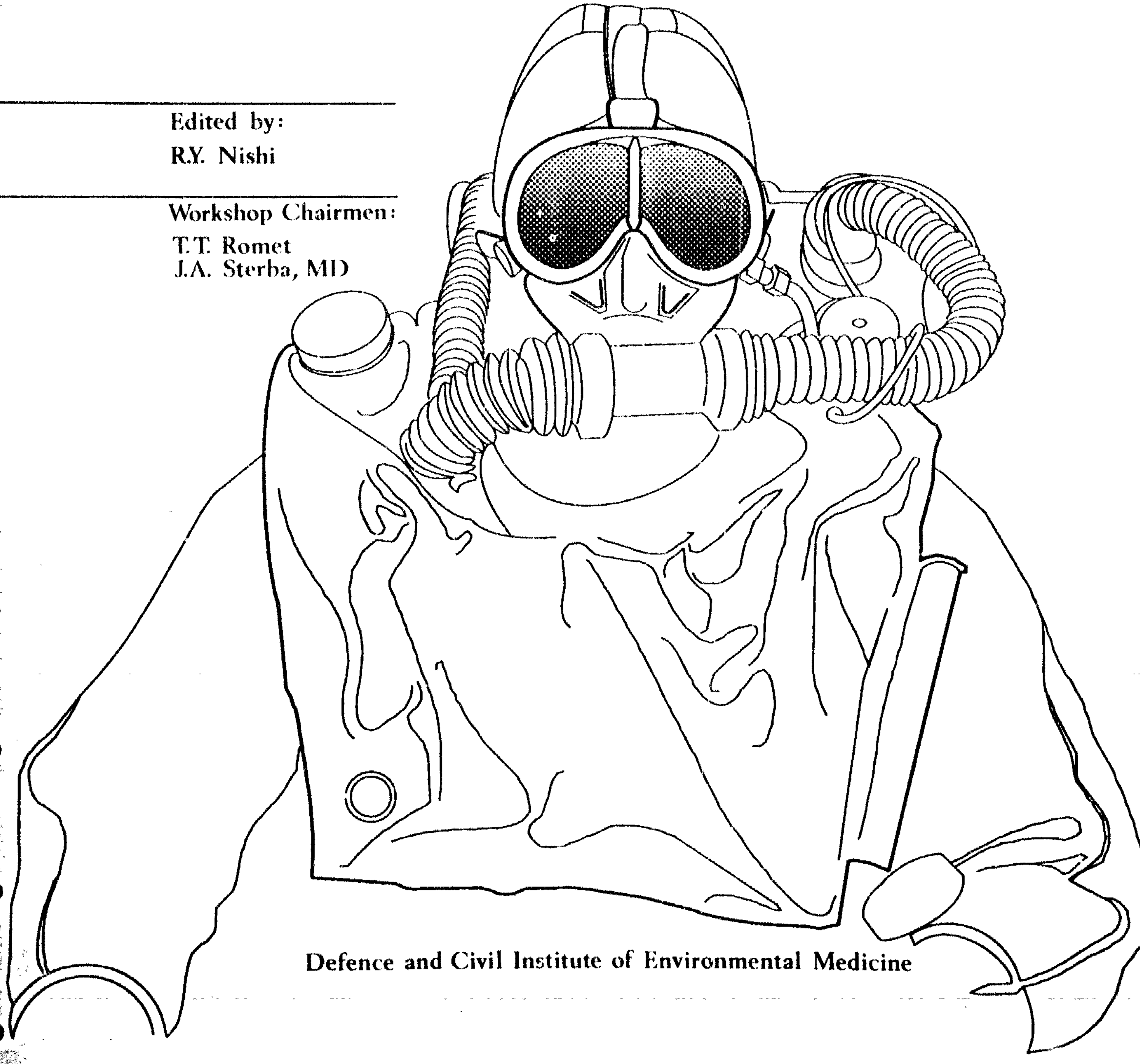
January 1992 DCIEM No. 92-10

Proceedings of the DCIEM Diver Thermal Protection Workshop

31 Jan – 2 Feb 1989



Edited by:
R.Y. Nishi

Workshop Chairmen:
T.T. Romet
J.A. Sterba, MD

Defence and Civil Institute of Environmental Medicine

January 1992 DCIEM No. 92-10

PROCEEDINGS OF THE DCIEM DIVER THERMAL PROTECTION WORKSHOP

31 Jan - 2 Feb 1989

Edited by:
R.Y. Nishi

Workshop Chairmen:
T.T. Romet
J.A. Sterba, MD

Defence and Civil Institute of Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ontario, Canada M3M 3B9

DEPARTMENT OF NATIONAL DEFENCE - CANADA

Table of Contents

PREFACE

The military diver performs a wide range of operational duties encompassing ship repair, search and salvage, mine countermeasures and other special operations. Since all the world's oceans can be the diver's operational domain, diving can take place in a diverse range of water temperatures, depths and durations.

Although research and development in thermal aspects of diving has never disappeared, until recently the R&D efforts have been primarily directed at other technological advances related to diving. With the successes obtained, the diver is now exposed to deeper and/or longer profiles under new scenarios, and thermal limits to performance have once again emerged as the prime limiting factor. Research is being carried out in all aspects of thermal protection. Passive thermal protection, whether wet or dry, is seeing the introduction of new materials and effective clothing ensembles. Active thermal protection was traditionally just the free flow of hot water into a diving suit but is now being approached by new and novel methodologies.

It is, therefore, as a result of the renewed interest in thermal issues that the concept of this workshop was developed. It was organized under the auspices of the ABCA-10 (America, Britain, Canada and Australia) Information Exchange Program on Naval Diving and its purpose was to bring together representatives from all the components concerned with military diving; the operators who must dive in the various conditions and who will know the shortcomings as well as the strengths of a protective ensemble; the manufacturers, who through their own research as well as feedback from the user must produce the protective ensembles; and the researchers, whether basic or applied who through their creativeness develop the concepts and physiological basis for thermal protection. It is hoped that under this format, each member of the community can contribute their own specific expertise and instill mutual interest and a co-operative spirit which will lead to safer and therfore more successful military diving.

Tiit T. Romet*
John Sterba, MD†
Workshop Co-Chairmen

Present Addresses

* National Defence Headquarters
c/o CIS/DSTI
Ottawa, Ont. K1A 0K2
Attn: DSTI 3-3

† J.A. Sterba, MD, PhD
Wright State University School of Medicine
Department of Emergency Medicine
Cox Heart Institute
3525 Southern Blvd.
Kettering, Ohio 45429

ACKNOWLEDGEMENTS

The organization and success of the workshop is dependent upon the help and support received from numerous sources, in particular, the Defence and Civil Institute of Environmental Medicine and the US Navy Experimental Diving Unit. We would like to thank Dr. M.W. Radomski, Chief, DCIEM for the use of the DCIEM facilites and for allowing the concept of the meeting to be fulfilled. Administrative support from the Biosciences Division, under the direction of Dr. K.N. Ackles, is gratefully acknowledged. Thanks go to the DCIEM School of Operational and Aerospace Medicine for providing the facilities and the audio-visual support. The assistance of the staff of the DCIEM Experimental Diving Unit under the command of LCDR Henry Mark was most welcome, especially in carrying out all the small chores which made the meeting run smoothly. Finally, we would like to thank the participants and attendees from all segments of the diving community who joined the meeting and provided the interaction required to make the meeting a success.

For the preparation of these Proceedings, the editors would like to acknowledge the assistance provided by Mr. R. MacLean in scanning most of the submitted manuscripts into a computer, Mrs. B. Zajakovski for retyping some manuscripts, WO M. Huard and Sgt. B. Laakso of the Diving R&D Group for the final assembly of the proceedings, and the US Navy Experimental Diving Unit for proof-reading the final text.

Tiit T. Romet
John Sterba, MD
Ron Nishi

LIST OF ATTENDEES

Dr. K.N. Ackles
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Mr. Gavin Anthony
Admiralty Research
Establishment (Alverstoke)
Alverstoke, Hants
England PO12 2AG

PO(D) Kevin Barratt, RN
SDV Group, c/o FOST
Portland Naval Base
Weymouth, Dorset
England DT5 2JS

Mr. Steven M. Barsky
Viking America, Inc.
30700 Solon Industrial Parkway
Solon, Ohio 44139

Dr. Rand Biggars
Naval Coastal Systems Center
Materials Science Branch, Code 2110
Panama City, FL 32407-5000

Mr. James Braun
Navy Experimental Diving Unit
Panama City, FL 32407-5001

Mr. Paul Browne
Exotemp Ltd.
320 Boundary Road, R.R. 4
Pembroke, Ont. K8A 6W5

Dr. Arthur Callahan
US Naval Submarine Medical
Research Laboratory
Box 900, Naval Submarine Base NLON
Groton, CT 06349-5900

Mr. Bob Chaplin
Viking America, Inc.
54 Boutelle St.
Leominister, MA 01453

Major Richard Clifford, Royal Marines
SDV Group, c/o FOST
Portland Naval Base
Weymouth, Dorset
England DT5 2JS

LCDR J.S. Coggins
HQ Fleet Diving Group
HMS Nelson (Gunwharf)
Portsmouth, Hants
England PO1 3HH

Mr. George Conway
S-Tron Corp.
101 Twin Dolphin Dr.
Redwood, CA 94065

Mr. Randy Cummings
Dept. of the Navy
Naval Sea Systems Command, Code 06Z
Washington, DC 20362-5101

Mr. M. Ducharme
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Mr. John Dudinsky
Naval Coastal Systems Center
Materials Science Branch, Code 2110
Panama City, FL 32407-5000

Ms. Gale Feline
c/o Pajesga
Box 601
Renfrew Ont. K7V 4A2

Dr. Philip Hayes
Director of Research
National Hyperbaric Centre
Aberdeen, Scotland AB2 SFA

Cmdr Peter Kent
Naval Medical Research and
Development Center
Code 401
Bethesda, MD 20814-5044

Dr. Gunnar Knudsen
Norwegian Underwater Technology Centre
Gravdalsveien 255-5034 Ytre Laksevag
Bergen, Norway

Sgt Ron Lien
1st Special Operations Command
USA JFKL SWCS
Fort Bragg, NC

Lt(N) Larry Linn
Navy Facilities Engineering Command
200 Stovall St.
Alexandria, VA 22332

Dr. Syd Livingstone
Defence Research Establishment Ottawa
Department of National Defence
Ottawa, Ont. K1A 0Z4

Mr. Dick Long
Diving Unlimited Int. Inc.
1148 Delevan Dr.
San Diego, CA 92102

Capt. M.J. McClurkan
Special Warfare Grp Command
San Diego, CA 92155

Lt(N) Scott McDougall, CF
HQ Fleet Diving Group
HMS Nelson (Gunwharf)
Portsmouth, Hants
England PO1 3HH

LCDR Henry Mark
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Lucie Martineau
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Karen Mittleman, PhD.
Naval Medical Research Institute
Mail Stop 38, DBTFA
National Naval Medical Center
Bethesda, MD 20889-5055

LCDR Dave Morrison
SDV Team 1
NAB Coronado
San Diego, CA 92155

LCDR Paul Morson
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Mr. R.Y. Nishi
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Mr. Rick Nolan
Defence Research Establishment Ottawa
Department of National Defence
Ottawa, Ont. K1A 0Z4

Prof M.L. Nuckols
Ocean Engineering Dept
US Naval Academy
Annapolis MD 21402

Surg Capt R. Pearson
Institute of Naval Medicine
Alverstoke, Hants
England PO12 2DL

Mr. Richard Porter
Director General Underwater
Weapons (Naval)
UW211E
Southwell
Portland, Dorset
DT5 2JS England

Mr. Paul Potter
CORD Group
Suite 215, 70 Neptune Cres.
Dartmouth, N.S. B5Y 4M9

Mr. Richard Roesch
Naval Coastal Systems Center
Materials Science Branch, Code 2110
Panama City, FL 32407-5000

Mr. T.T. Romet
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Mr. Peter Ruden, PMS-395 A16
Naval Sea Systems Command
Bldg. NC3, Rm 7S13
2531 Jefferson Davis Highway
Arlington, VA 22202

Maj. K.D. Sawatzky, MD
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Mr. Tom Schmidt
Lockheed Corp.
Advanced Marine Systems
San Diego, CA 92123

Mr. Ed Smallhorn
CORD Group
Suite 215, 70 Neptune Cres.
Dartmouth, N.S. B5Y 4M9

CDR John Smith, MD
Maritime Command Headquarters
FMO Halifax, N.S. B3K 2X0

Dr. John Sterba
Wright State University School of Medicine
Department of Emergency Medicine
Cox Heart Institute
3525 Southern Blvd.
Kettering, Ohio 45429

Mr. Bob Sutherland
Mustang Industries
440 Laurier Ave., Suite 200
Ottawa, Ont. K1R 5C4

Capt E. Thalmann, MD.
Naval Medical Research Institute
Mail Stop 38, DBTFA
National Naval Medical Center
Bethesda, MD 20889-5055

Mr. A.J. Thomas
Admiralty Research
Establishment (Alverstoke)
Alverstoke, Hants
England PO12 2AG

Mr. Julian Thomson
National Hyperbaric Centre
Aberdeen, Scotland AB2 5FA

Dr. Peter Tikuisis
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Dr. Andre Vallerand
Defence and Civil Institute of
Environmental Medicine
1133 Sheppard Ave. W., P.O. Box 2000
North York, Ont. M3M 3B9

Robert Weinberg, PhD.
Naval Medical Research Institute
Mail Stop 38, DBTFA
National Naval Medical Center
Bethesda, MD 20889-5055

CWO Larry Wilson
EOD Team, Attn:EODMU 6
Charleston, SC

Dr Eugene Wissler
Dept. Chemical Engineering
Univ. of Texas
4704 Ringe Oak Drive
Austin, TX 78731

Chief Chris Wynn
EODMU Three
Naval Amph. Base Coronado
San Diego, CA 92155

SESSION 1

DIVER PROTECTION TODAY

Session Chairman:
LCDR Henry Mark

PREFACE

In order to best meet the goals of our meeting, it is most appropriate to be first acquainted with the current status of thermal protections being used by our military divers and viewpoints of the manufacturing industry in terms of their interests.

The first paper was presented by PO DeJong of the host country, Canada, a description of the thermal protection ensembles used and the philosophy behind their selection. This was followed by the presentation by the Royal Marines, Mr. R. Porter and Maj. Clifford, who described their ensemble developed for long endurance dives. The presentation included a demonstration of the donning of the ensemble. Medical implications of such dives, arising from the long inactive time spent in the water was subsequently addressed by Surg. Capt. Pearson. The first half of the session ended with a description by CWO Wilson of the U.S. Navy, EOD program, and included the problems with the diving ensembles experienced by their divers.

The second half of the session began with a presentation by Lt(N) McDougall of the Royal Navy's 75 msw diving procedures and the thermal problems associated with such dives. Two presentations by industry representatives concluded the session. The first was by S. Barsky of Viking America who described a series of experiments on flooded dry suit buoyancy characteristics. The second and final presentation was by D. Long of DUI who provided a personal view based on his experiences, of the status of thermal protection for divers and the future for new developments.

Tiit Romet
Co-Chairman

CURRENT THERMAL PROTECTION FOR THE CANADIAN FORCES DIVER

J. DeJong and G. Cox
Experimental Diving Unit
Defence and Civil Institute of Environmental Medicine

INTRODUCTION

A diver in the Canadian Forces (CF) requires specialized protection to handle Canada's rugged environmental conditions. These conditions vary between the east and west coast. The east coast experiences colder water conditions throughout the year with only a slight warming trend in late summer and early fall. The coldest time on the west coast is in late December and January. The water and surface temperatures in the west seldom get as low as the east coast and so there are definite differences in the type of diving suit and thermal protection preferred. In the CF we rely on both passive and active suit heating. The wet and dry suits rely on the body to heat up the layer of water or air that is between the diver and the suit. In the hot water suits, hot water is pumped down to the divers to heat the area between the diver and the suit.

WET SUITS

The standard diving dress in the CF is the wet suit. It is made of 1/4 - inch (6.35 mm) neoprene rubber and is designed and custom fit to all CF divers that have successfully complete a qualifying course. The construction specifications for these and ready made wet suits are laid out in CFTO D-87-003-003/SF-001. The tailored suit consists of two main pieces, a "Farmer John" style pant and a jacket fitted with a diagonal zipper. The neoprene rubber has rubber one side and nylon on the other. The nylon is normally worn inside for ease of entry, although many Clearance Divers prefer nylon outside. The divers feel they get better thermal value with rubber against skin (less free-communication with water) and the nylon protects the suit from abrasions.

The suit is designed so that a 1/8 - inch (3.17mm) neoprene vest may be worn under the Farmer John. In some cases a hood is attached to provide greater protection around the neck. The hood is normally worn separately over the jacket and is long enough to form down over the shoulders, however the hood is sometimes attached to the jacket. The suit is also supplied with three finger gloves made with 1/4 - inch (6.35 mm) neoprene for colder water or five finger gloves made with 3/16 - inch (4.76 mm) neoprene for warmer conditions. Wet suit boots are made of 1/4 - inch (6.35 mm) neoprene and can have a hard or soft sole.

DRY SUITS

There are two basic dry suits in the CF, compressible and non-compressible. The non-compressible suit currently in use is the Viking Variable Volume Suit. This suit was brought into use when the military started diving in helium atmospheres and breathing helium gas mixtures. It was found that helium broke down the neoprene rubber in compressible suits.

PRECEDING PAGE BLANK

NON-COMPRESSIBLE DRY SUITS

The Viking suit is made of a rubber coated polyester tricot (plain knitted fabric) with sewn and vulcanized seams. There are three different fabric weights: Sport (800 g/m2), Standard (1000 g/m2), and Heavy Duty (HD) (1500 g/m2). The neck and wrist seals are made of latex rubber and are glued to the suit. The HD suit uses thicker latex rubber seals. The suit can be fitted with boots of different construction. They can be made of suit material or have a weighted boot bonded to the legs.

DIVING UNDERWEAR

The underwear first used with the Viking suit was an Open Cell type made by Viking. This underwear is made of double laminated, 10 mm polyester foam with open cells. The open cell structure conveys body moisture away from the body where it condenses against the colder suit surface. This type of underwear is still in use, however it is being replaced by a more durable poly-pile "Woolly Bear" underwear.

The polyester pile underwear because of it's durability provides more thermal protection even after numerous washing. This underwear is made with a polyester-pile fabric inner surface and a porous knit outer surface. Most divers use an 19 oz. under-garment, however heavier weights up to 36 oz. are available.

COMPRESSIBLE DRY SUITS

The compressible dry suit currently in use is the Poseidon Unisuit. The CFTO that covers the specifications for the General Purpose Dry Suit is D-87-260-000/SF-001. This CFTO is currently under review and other dry suits are being tested for use in the CF. The Unisuit is made of 5/16 - inch (7.93 mm) neoprene rubber with two-way stretch nylon fabric laminated on both sides. The neck and wrist seals are made from 3/16 - inch (4.76 mm) neoprene nylon fabric one-side. The smooth side of the neoprene is put outside so that the seals can be either rolled in or donut-sealed, as with the wrist. Gloves are fitted over the smooth surface forming a water tight fit. The hood is normally made out of the same material as the suit and uses a border of 1/8 - inch neoprene to seal around the face. The zipper that allows entry into the suit is fitted with a 3/16 - inch neoprene insulating flap to prevent heat transfer through the zipper.

The suit should be built or fit so that a diver wearing a pair of undershorts, T-shirt, wool socks, and heavy pile underwear (19 oz. or greater) can move comfortably with little restriction. Both compressible and non-compressible dry suits are fitted with both suit inflation and exhaust valves to control buoyancy and increase/decrease air space in suit when descending/ascending during diving.

SURFACE-SUPPLIED HOT-WATER SUITS

The surface-supplied hot water suit used in the CF is of an open-circuit design. Hot water is supplied from the surface via a hose connected at waist level to a valve and distribution block. The water channels throughout the suit and to the extremities through a network of tubes. The suit is made of 1/4 - inch neoprene with nylon fabric laminated on both sides. The gloves and boots used with this suit are 1/8 - inch neoprene. The neck of the suit is interfaced with the SL-17B Helmet using a cold water neck dam attached to a helmet retaining seat. This cold water neck dam is normally made with 3/16 - inch neoprene. The diver also wears a 1/8 - inch neoprene undergarment to protect him from extreme temperature fluctuations.

The diver is supplied approximately 2 to 2 1/2 gallons (9 to 12 litres) of water per minute at 38 °C. The temperature is controlled from the surface and is increased according to the length of supply hose and the temperature of the surrounding water. When the diver is breathing a Helium mixture a small hose tapped off the suit hose supplies hot water to a shroud fitted over the helmet second stage regulator.

All the steps that are taken to protect the diver from the cold environment lessen the divers chances of developing hypothermia; increase the divers productivity; and remove one of the main factors that cause decompression sickness, namely, cold.

One factor recently under consideration is contaminated water diving. With more of Canada's water becoming polluted the need for diver protection is essential. The CF is currently investigating the use of a Viking HD Dry Suit with water tight seals at the neck (to SL-17B helmet), and at the wrist (chemical gloves and heavy duty mitts) to keep the diver free of contaminants. Currently these suits are only used for low grade contaminants (i.e. raw sewage).

THERMAL PROBLEMS IN ROYAL NAVY 75 METRE OXYHELIUM DIVING

Lieutenant(N) Scott A McDougall, CF
OIC Fleet Diving Unit Three, Royal Navy

ABSTRACT

75 metre Oxyhelium Diving is carried out by Units of the Royal Navy Fleet Diving Group. The 75 m diving system is intended for maximum flexibility, including deployment from small craft down to rubber-boat size. Some of the tasks assigned to this system require moderately long bottom times, and thermal stress is imposed on divers in the cold waters surrounding the UK. Thermal protection is passive in nature only, due to the flexibility required of the system. A review of passive thermal protection equipment currently in use with the RN 75 m diving system is presented, along with a discussion of tasks, in-water exposure times and water/weather conditions normally encountered in UK waters. An illustration of space constraints is also presented, to show the limitations imposed. Some projections of future direction in this area are also discussed.

INTRODUCTION

It is the intention of this paper to describe some of the practical thermal problems encountered by the Royal Navy in carrying out Oxyhelium diving to 75 metres seawater (msw). The RN 75 msw system is intended for maximum flexibility and portability. The primary operating platform is a pair of rubber boats, so one can easily see that the options for thermal protection are limited in both mass and volume.

Furthermore, the water temperatures and topside climatic conditions are relatively severe in northern UK waters, so these are immediate concerns of the system users. Taskings for the system vary, but may involve substantial in-water exposure times. Procedures and equipment are documented in Chapter 8 of BR 2806 (Supp), which will be reviewed for the benefit of those who are unfamiliar with its contents.

BACKGROUND

The Royal Navy has carried out deep diving from open boats for over 20 years. In the beginning, compressed air was used as the breathing medium for ECD, Weapon recoveries and aircraft salvage to a depth of 75 msw. Breathing equipment was relatively basic compared to that in use today. Thermal protection consisted primarily of weeding out the "non-hackers" during their initial training. That useful work could be carried out at such depths with the equipment of the day is a tribute to the training and determination of the divers. Fortunately, there has been an ongoing effort to improve the divers equipment over the years, so the level of pain-tolerance required to qualify a professional diver is lower than ever before. There remain several areas where equipment could be improved, however, and thermal protection is one of those areas.

CURRENT SITUATION

In recent years, the RN has used 20/80 Oxyhelium for diving deeper than 54 msw due to the lowered work of breathing associated with the gas. The KMB 10 and HELIOX 18 have been brought into service, and new decompression tables developed with the assistance of the RN Institute of Naval Medicine.

Present policy on employment of the 75 msw diving system is unclear, as the entire RN Underwater Intervention Policy is under review. It can be said though, that the most likely employment of the 75 msw diving system is on light-work, rapid-deployment tasks. The option exists to carry out manned seabed EOD or limited MCM without having to place a large vessel at risk directly over the object. The ethics of placing several divers and attendants in a rubber boat at risk are questionable, but anyone with friends in the insurance underwriting business will see the relative advantage of a rubber boat vs. a Diving Support Vessel. The lowered numbers of human lives and reduced magnetic influence associated with the rubber boat approach are, of course, accompanied by severe restrictions on space. The bottom line for rubber-boat 75 msw diving is Passive Thermal Protection (PTP).

This diving system is also capable of being deployed aboard a vessel of opportunity, provided deck space is adequate. Some more complicated tasks could be undertaken and we might begin to look at Active Thermal Protection (ATP) in this scenario to allow for longer bottom times with their accompanying longer decompression times.

PROCEDURES

Procedures and equipment are defined in BR 2806 (Supp) and BR 2807 (1), respectively. Topside, there are a number of portable aluminium cylinders to store Oxyhelium and Oxygen. Gas Panels for the divers, Communications for the divers and, within 300 metres horizontal radius, an RCC, are required. Down the umbilical, we find the divers in "Wooly Bear" woolen underwear, Avon non-compressible dry-suits and KMB 10 or Heliox 18 masks. Suit inflation is a diver-carried flask of compressed air.

All decompression is carried out in accordance with BR 2806, with 20 minutes being the maximum normal exposure bottom time at 75 msw. Stops are carried out on a shot rope, in the water. Surface decompression is classified as an emergency procedure and hence cannot as yet be used to reduce in-water exposure as a matter of routine.

When operating from a larger vessel of opportunity, more gas can be carried topside. This would allow for longer bottom times considered in isolation, but thermal constraints usually preclude extending beyond the 20 minutes.

ENVIRONMENT

The most active area for RN diving is off the west coast of Scotland. Sheltered deep water is found here, as well as Navy exercise areas. Water temperature varies considerably in this part of the world, depending on proximity to the Gulf Stream. The Firth of Clyde, for example, is relatively warm throughout the year, while slightly further north, in the Loch Linnhe area, the water is more typical of the latitude.

Generally the sea off the west Coast of Scotland is warmer than one might except in latitudes 55 to 60 degrees North, because of the influence of the Gulf Stream. Mean surface temperatures range from approximately 7.5 °C in February to 13°C in August. Temperature at depth in winter is generally the same as at the surface; in summer it is up to 4° colder at depth. Close in shore and the Sea Lochs the temperatures may be considerably different for those in the open sea because of fresh water running off the land, which frequently causes cold water to form a layer near the surface in winter.

Air temperature is quite important as well. Divers spend several hours in a rubber boat (or open deck area) with no protection from the weather, tending or carrying out other topside duties. When their turn comes to dive, they may already be hypothermic. On completion of the dive, they are passed by the momentum of the operation back into a topside task and do not often have the luxury of a re-warm period.

DISCUSSION

The thermal difficulties encountered during 75 msw diving are not overly complicated, but require careful management. The operational effectiveness of the divers could be greatly enhanced by better thermal protection. The woolen underwear is not optimum for long dives and the Avon dry suit provides no inherent insulation. Divers' heads are wet, as a result of the KMB design, which is a significant area of heat loss. Hot-water suits are in use with the RN's Saturation Diving System, but not yet with the 75 msw diving system.

Topside, the supporting cast is not adequately protected from the elements. The practicalities of the situation preclude building weather barriers, and better clothing would help the situation considerably.

LINES OF ENQUIRY

Evaluation of new PTP drysuit underwear should be carried out. Work already done on behalf of the Royal Marines has improved their protection greatly by providing them with Thinsulate underwear. Thinsulate retains most of its insulating value even when wet. There is no need to assume that this is the acme of diving underwear, however, and evaluation of new materials should continue.

Neoprene drysuits are being evaluated for use in 75 m diving. Although it is acknowledged that there is little difference between neoprene and non-compressible material at depths greater than 30 msw, neoprene, based on trials to date, seems to be considerably warmer during the decompression stops, which are spent mainly at 9 and 6 msw. Why is this, given that the loft of neoprene can be duplicated by extra underwear beneath a non-compressible dry-suit (such as the Avon)?

For employment with vessels of opportunity, ATP systems require some evaluation. Several well-proven portable hot-water systems are available off-the-shelf. The question of correlation between ATP and higher DCS incidence needs to be resolved. Also, is diver-carried ATP necessarily out of the question?

Development and validation of a safe surface decompression techniques would allow longer bottom times and reduce in-water stresses on the diver. This should be pursued. Thermal protection for topside personnel needs to be addressed and it is suggested that the RN could take some practical advice from a "cold-weather" diving service such as the CF in this area.

SUMMATION

This has been a brief review of how the Royal Navy conducts 75 msw diving, some of the thermal problems associated with it and some suggested lines of enquiry. We hope we have provoked some questions on matters discussed above.

REFERENCES

Royal Navy. B.R. 2806 (Suppl.). Procedures for Deep and Saturation Diving. Ministry of Defence, Director of Naval Warfare. London. Dec. 1985, Chapter 8.

Royal Navy. B.R. 2807(1)(N). 75 Metre Diving Equipment. Ministry of Defence, Sea Systems Controllerate. London. March 1984.

OBSERVATIONS ON FLOODED DRY SUIT BUOYANCY CHARACTERISTICS

Steven M. Barsky
Viking America, Inc.
30700 Solon Industrial Parkway
Solon, Ohio 44139

John N. Heine
Moss Landing Marine Laboratories
7711 Sandholt Rd.
Moss Landing, CA 95039

ABSTRACT

Military and scientific divers have increasingly turned to dry suits for thermal protection in cold water and ice diving. Concurrent with this increase comes a concern for proper training procedures, underwear requirements, and safe configuration of the diving system. One area of common concern among all dry suit divers is the residual buoyancy available, or not available, in the event of a catastrophic dry suit failure. This issue must be considered due to the persistent use of dry suits as buoyancy compensators by many dry suit divers. This paper examines dry suit buoyancy under simulated failure conditions with a variety of suit/underwear combinations. Of the 13 combinations tested, after complete flooding and removal of the diver's lead weights, 2 systems remained positively buoyant while the other systems eventually all became negatively buoyant. Recommendations are given for equipment requirements, training, and emergency procedures for dry suit usage.

INTRODUCTION

Dry suits are the suit of choice for military and scientific divers who must operate under demanding diving conditions. When the water is cool and the job requires long bottom times, dry suits make diving pleasant and the observations more likely to be accurate, (Roverud, et al, 1987). For under ice diving, dry suits eliminate much of the risk, most obviously the dangers associated with hypothermia. Indeed, Egstrom and Bachrach (1987) and Bachrach (1985), have made the observation that one of the leading contributors to diving accidents is exposure to cold water.

Even in warm water environments, dry suits are used frequently for protection from contaminated water conditions. For example, Stanton (1987) reports on dry suit diving operations conducted in Palau in a micturitic lake.

This expanded use of dry suits has lead to a number of safety concerns on the part of divers, diving officers, academic institutions, and dry suit manufacturers. Many divers are using dry suits, or attempting to use dry suits, without the benefit of an organized training program. Without proper training, it is unreasonable to expect a diver to be able to take a dry suit and make it work under hostile operational conditions. Interestingly, only a minimum amount of training is required for most divers to reach a reasonable level of competence with a dry suit, (Barsky, 1987). A diver who has completed scuba training through a recognized diving program should be able to achieve confidence and control in a dry suit with a combination of classroom, pool, and open water training which does not exceed twelve hours. The minimum number of recommended open water dives is three.

Divers who have no dry suit experience and/or training typically are most concerned with procedures for coping with sudden shifts of buoyancy. Most diver's fears revolve around critical incidents of sudden, unexpected positive buoyancy leading to uncontrolled ascents or "blow-ups". Injury accidents precipitated by this type of event would include lung over-expansion injuries, decompression sickness due to rapid ascent, and possible damage due to collisions with surface objects such as vessels or piers. Proper training, however, reveals that even in situations where the diver's buoyancy change is radical, a trained diver will be able to regain control with a minimum change in position in the water column.

Dramatic changes in buoyancy, where the diver becomes negative and can not re-establish positive buoyancy, also represent a serious hazard, but are very infrequent. Sudden negative buoyancy was more common with early dry suit technology with inferior suit materials and the lack of power inflators. Today's dry suits offer very high reliability and such incidents are rarely reported. However, as late as 1987, a diving fatality involving a neck seal failure was reported (Linton, 1987). In this incident, and others like it, death occurs due to drowning.

Primary contributing factors to dry suit accidents include a number of erroneous beliefs and attitudes. Principle among these myths are:

1) *Myth: Dry suits require no special training.*
   Reality: Although many divers do not feel that dry suit training is necessary, most of the accidents investigated and reviewed by this author can be largely related to a lack of training. Conversely, there is probably an equal number of divers who believe that dry suits are inherently unreliable, dangerous, and that no amount of training will make them acceptable.

In the past three years, one of the authors has provided dry suit orientations and training to over four hundred divers. The majority of these divers were novices, while some were intermediate and others were highly trained. Virtually all of these individuals reported that the dry suit was much simpler to use than expected, was much easier to don than a wet suit, and was far more comfortable than imagined. Many of these individuals have gone on to be permanent dry suit users following a minimum amount of additional information and training.

2) *Myth: Dry suit use requires the diver to use large amounts of additional weight to dive and remain on the bottom.*
   Reality: Divers who use large amounts of weight with their dry suits must subsequently use large volumes of air in their suits to achieve neutral buoyancy. When this air shifts due to a change in swimming attitude, the diver with no training may find it difficult to control the buoyancy of the suit.

3) *Myth: By using a dry suit, the diver does not need to use a buoyancy compensator. The dry suit acts as a buoyancy compensator.*
   Reality: Buoyancy adjustment with a dry suit is achieved principally through the use of the suit itself. The diver adjusts for changes in his/her personal buoyancy through the addition or subtraction of small quantities of air in the suit.

Although the diver relies upon his/her dry suit for buoyancy adjustment, a buoyancy compensator should always be worn. The buoyancy compensator is used for three purposes:

1) To compensate for small additional amounts of weight (not to exceed 10 pounds) acquired during the course of the dive.
2) To provide positive buoyancy on the surface during long surface swims. Excess air in the dry suit at the surface creates undue pressure on the carotid artery.
3) To provide a back-up in the event of a catastrophic dry suit failure.

At the diving safety officer's meeting following the 1987 American Academy of Underwater Sciences (AAUS) conference, the subject of using dry suits as buoyancy compensators came under discussion. Despite the fact that no major manufacturer endorses this policy, some diving safety officers still felt it was a viable practice. A search of the literature provided no empirical data on any tests which could confirm the safety, or dangers, of this diving procedure.

There are a variety of dry suit designs, materials, and underwear available today. Although it might seem reasonable to predict the outcome of a catastrophic dry suit failure, only objective testing can give a definitive answer to the buoyancy characteristics of a dry suit system under these conditions. To this end, 13 different dry suit/underwear combinations were tested for their buoyancy characteristics in the catastrophic failure mode.

MATERIALS AND METHODS

DRY SUITS

Four different types of dry suits and four different types of dry suit underwear were obtained either from manufacturers or individuals for these tests. None of the suits were new and only one set of the underwear was new. All of the suits were equipped with waterproof zippers and air control valves.

The types of dry suits were as follows:

1) **Foam neoprene dry suit:** This suit was made of closed cell neoprene of the type used to fabricate wetsuits. The suit material thickness was 1/4", and this type of rubber is considered to have positive buoyancy. Entry to the suit was via a waterproof zipper across the shoulder. The suit was equipped with a combination inflator/exhaust airway.

   This type of suit design is generally considered old technology and is declining in popularity.

   Due to the form fitting design of this type of dry suit, no underwear is normally used in conjunction with it. Accordingly, this suit was tested by itself, with no underwear worn beneath it.

2) **Vulcanized rubber dry suit:** This suit was fabricated from a combination of natural and synthetic rubber with a lining of polyester tricot. This material has no inherent buoyancy. Suit entry is through a waterproof zipper across the shoulders. Separate inflator and exhaust valves are included on this suit.

Figure 1. Foam neoprene dry suit.

Figure 2. Vulcanized rubber dry suit.

Figure 3. Crushed neoprene dry suit.

Figure 4. Tri-butyl laminate dry suit.

3) **Crushed neoprene dry suit:** This suit was manufactured from foam neoprene material which has been compressed, collapsing the cells. By itself, the suit will not float. Suit entry was through the chest using a self-donning zipper. Both inflator and exhaust valves are used on this suit.

4) **Tri-butyl laminate dry suit:** This suit was manufactured from nylon or "pack-cloth" which had been coated with a butyl rubber to make it waterproof. Entry to the suit was through a chest mounted, self-donning zipper. An inflator valve is mounted on the chest while the exhaust valve is on the upper left arm.

DRY SUIT UNDERWEAR

The types of dry suit underwear used in this test were:

1) **"Wooly Bear":** Wooly bear is a generic term used to describe a variety of garments made from synthetic fleece. The "wooly bear" was a one piece jump suit constructed of nylon.

2) **Thinsulate ® B:** Thinsulate ® B is a trade name for a type of material designed and patented by the 3M Corporation. Thinsulate ® is used by a variety of dry suit manufacturers in the fabrication of dry suit undergarments. Thinsulate ability to maintain a high degree of insulation even when completely wet, hence its popularity as a dry suit undergarment material.

3) **Radiant Insulating Material:** Radiant insulating material is an exceptionally good combination of synthetics which maintains a very high degree of insulation even when thoroughly soaked. Radiant insulating garments consist of a layer of synthetic fleece, a layer of aluminized polyethylene, and a nylon outer shell. The garment used in this test did not have the polyethylene layer.

4) **Open Cell Foam:** Open cell foam rubber is coated with nylon on both sides when used as dry suit underwear. This material is highly resistant to compression and provides good insulation even when damp. However, it will not keep the diver warm once the material becomes saturated with water.

DIVING EQUIPMENT

The subject wore his personal diving equipment. The buoyancy compensator used also included an integral weight system with weight pockets. The weight pockets were used to carry the diver's weight and allowed the diver to ditch the weight instantly. The weights were all weighed on a laboratory scale prior to the tests and their weight was written on them with an indelible marker.

The subject wore a standard steel 75 cubic foot diving cylinder. The buoyancy of this cylinder when full is 5.5 pounds, negative buoyancy. When this type of cylinder is empty, it is still negative by .13 pounds. When the cylinder was half empty, a fresh cylinder was substituted. The maximum buoyancy change calculated for this cylinder was 2.6 pounds, which was felt to be negligible.

TEST LOCATION

The test location was a 14 foot deep fresh water swimming pool located in northern California. The pool temperature was 80 degrees Fahrenheit.

Figure 5. Wooly bear type undergarment.

Figure 6. Thinsulate undergarment.

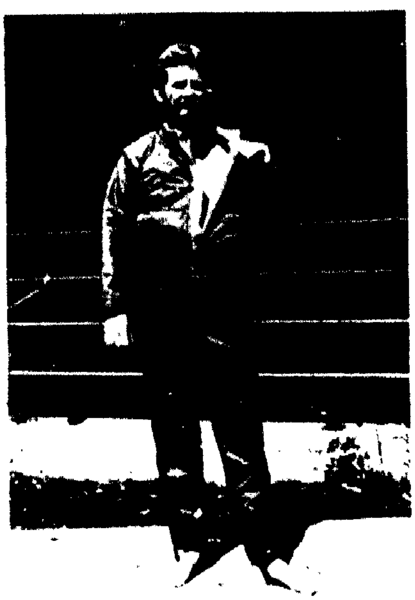


Figure 7. Radiant insulating undergarment.

Figure 8. Open cell foam undergarment.

SUBJECT

The subject was a 33 year old diving instructor with 10 years diving experience. The subject has used three different types of dry suits and has been diving in a variety of cold water locations.

The subject's height was 5' 11". His weight was 155 pounds, and his personal buoyancy is approximately 3 pounds negative in fresh water.

PROCEDURES

For each test run, the subject dressed into the diving gear with help from an assistant. Based upon past experience with several dry suits, the subject selected a combination of weights which he felt appropriate to the particular suit and underwear.

The subject entered the water and vented all the air from the suit and buoyancy compensator, using the pressure differential at the surface. The subject then adjusted the weight in his buoyancy compensator until he floated vertically at eye level with full lungs. Upon exhalation, the subject would slowly begin to sink.

Once the subject was on the bottom, he opened the zipper on the suit and flooded the suit completely. In most cases it was necessary for the subject to pull the suit away from his lower body and/or turn upside down to ensure the complete filling of the suit. In some cases, it took several minutes before the underwear was fully saturated.

With the suit completely flooded, the subject then ditched the weights from the weight pockets of the buoyancy compensator. At that time, he completely relaxed and allowed the buoyancy of the suit/underwear combination to either take him up to the surface or hold him on the bottom. In the trials where no residual buoyancy was evident and the subject remained on the bottom, the next step was to attempt to re-establish positive buoyancy by pushing the inflator button on the suit and trapping air in the upper part of the suit or the arms of the suit. Any air added to the suit at this time was vented before the next part of the test.

The next portion of the test called for the subject to establish positive buoyancy by adding air to the buoyancy compensator. Only enough air was added to the buoyancy compensator to lift the diver to the surface. Once positive buoyancy was established, the subject was instructed to remove his tank. The buoyancy compensator was then separated from the tank.

Individual weights were added to the weight pockets of the buoyancy compensator (BC) until the BC would just begin to sink . The weights were then removed from the BC and totaled. This measurement represented the amount of flotation (lift) required to make the diver positively buoyant. The same measurement also indicated the negative buoyancy of the diver under these conditions.

RESULTS

Due to a limited number of sets of dry suit underwear and suits, not all combinations could be tested starting in dry condition. For this reason, data for all suit/underwear weight requirements were not available. However, for the eight combinations for which the data exists, the system requiring the least amount of weight, 12.5 pounds, was the vulcanized rubber suit used with the radiant insulating garment. The most weight, 19.5 pounds, was needed with the crushed neoprene suit used with open cell foam (see Table 1).

After flooding the suit and ditching the weights, only two suit/underwear combinations remained positively buoyant; the foam neoprene dry suit and the crushed neoprene suit used with open cell foam. The other 11 combinations were all either negatively buoyant immediately, or were initially positive and became negative in 2 to 3 minutes. Under no circumstances was any of the combinations so negative that the subject could not swim to the surface under his own power, nor did he need to inflate the BC to surface.

The subject found that by pushing the inflator button on the suit and holding his arms overhead, it was possible to trap enough air in each of the suits to create a positively buoyant condition.

Aside from the two combinations which remained positively buoyant, the system with the least negative buoyancy, 2.3 pounds, was the crushed neoprene suit used with the Thinsulate ®. Under flooded conditions, the most negative system was the tri-butyl laminate suit used with the wooly bear, which required 13.8 pounds of lift to achieve positive buoyancy. Complete results are presented in Table 1.

DISCUSSION

Although the weighting requirements for the various suit/underwear combinations were not the primary focus of this study, they are of interest. The weight requirements are a function of the amount of air trapped in the underwear and the density of the underwear itself. Obviously, from both a logistical and personal comfort standpoint, it is desirable to dive with the least amount of weight possible. This should be an important consideration to dry suit manufacturers when selecting materials.

Although the foam neoprene dry suit remained buoyant when flooded, this should not be interpreted as a primary positive factor in selecting a dry suit for a military or scientific operation. These suits offer neither the warmth nor reliability of today's dry suits.

The only dry suit/underwear system which remained positively buoyant was crushed neoprene/open cell foam. However, even the buoyancy demonstrated here was minimal. If the subject had been wearing a different scuba cylinder, with greater negative buoyancy, this small amount of buoyancy would have been lost.

Based upon our observations made during this experiment, we would like to make the following recommendations to military and scientific divers:

> Dry suit training is essential to establish correct procedures and to ensure proper responses during emergency situations (Barsky, 1987). Divers must learn how to correctly configure their dry suit system and understand the consequences of improperly assembled gear. In addition, it is unreasonable to expect the appropriate behavior in an emergency unless the desired response is overlearned. Using a dry suit is like any other set of skills in diving. However, controlling buoyancy with a dry suit is different than controlling buoyancy with a buoyancy compensator, since the diver's entire body is encapsulated in the buoyancy envelope. Although it is extremely rare for a catastrophic dry suit failure to occur, military and/or scientific divers who use dry suits for their work should understand how to establish positive buoyancy using the suit even when the zipper or

neck seal has failed.

A buoyancy compensator should always be worn with a dry suit. In most cases, the shift to negative buoyancy in a catastrophic dry suit failure does not represent an excessive weight change. However, to ensure the diver's safety, a buoyancy compensator should always be worn. This is especially important for divers whose bodies are negative when nude, and for divers who may not be particularly strong or experienced.

The weight belt should be ditched in any situation where the dry suit does not hold air as it should. This is especially important when the diver can not immediately locate the source of failure. Should the suit suddenly lose all of its remaining air, the diver could find himself unexpectedly negative, particularly if he is carrying heavy combat or salvage equipment.

Divers should always adhere to the minimum weight/minimum dry suit volume concept. Any weight beyond what is required to achieve neutral buoyancy will extract a serious penalty in the event of a catastrophic dry suit failure. What might have been a minor emergency can quickly become life threatening for the diver who has overweighted and fails to take corrective action immediately.

Divers should exit the water immediately following any type of catastrophic dry suit failure. Although most people will not remain in cold water once a dry suit has flooded, far too often there is a tendency for military divers to stay to finish the work. We believe this is a dangerous practice. While several makes of the dry suit underwear tested are reputed to keep the diver warm even in the event of a flood, our tests indicate that in most cases, the diver's weights must be dropped, or a large volume of air must be introduced into the buoyancy compensator to achieve neutral buoyancy again. If the diver is burdened with heavy equipment and must add more air to the buoyancy compensator to return to the surface, the volume of air in the BC could lead to an ascent rate in excess of that allowable by the decompression tables or his dive computer. This is an unacceptable hazard.

Additional studies might examine the same combinations of suit and underwear in salt water, as well as other suit/underwear systems.

As a final note, it should be recognized that virtually all of the major dry suit manufacturers recommend the use of a buoyancy compensator with their dry suits.

ACKNOWLEDGEMENTS

The authors would like to thank the following people who helped make this study possible: Dick Long of Diving Unlimited in San Diego for providing suits and underwear, Richard Zahorniak of Hi Tech Diving in Florida for providing dry suit underwear, and Ron Russell of Zeagle Systems for providing assistance and technical support with buoyancy compensators.

REFERENCES

Bachrach, A.J. Cold Stress and the Scientific Diver. In C. Mitchell (Ed) Diving for Science: Proceedings of the Joint International Diving Symposium, 1985. La Jolla, CA: American Academy of Underwater Sciences, 1985, 31-37.

Bachrach, A.J., and Egstrom, G.H. Stress and Performance in Diving. Best Publishing, San Pedro, CA. 1987 Barsky, S. Dry Suit Diving Specialty Course. NAUI News. Montclair, CA: National Association of Underwater Instructors, 1987, 38-44.

Ronnestad, I., Roverud, H.P., Strand, I., Hope, A., Vaernes, R. Cold Stress In Scuba Diving, thermal and mental effects on wet and dry suit divers in 18 meters sea water. In M. Land (Ed) Cold Water Diving for Science: Proceedings of the American Academy of Underwater Sciences, 1987. Seattle, WA: American Academy of Underwater Sciences, 1987, 237-245.

Stanton, G. Florida State University. Personal communication. 1987.

Linton, S. Dive Rescue International. Personal communication. 1987.

TABLE 1: FLOODED DRY SUIT BUOYANCY CHARACTERISTICS

Suit/Underwear Combination	Initial Weight Req'd.(Pounds)	Results of Flood*	Flotation Req'd. to Achieve Positive Buoyancy (Pounds)
Foam Neoprene	17	Positive buoyancy	0
Vulcanized Rubber/ Open Cell Foam	17	Negativebuoyancy	7.15
Crushed Neoprene/ Thinsulate	19	Initially positive, became neutral after several minutes.	2.3
Tri-butyl laminate/ Radiant insulating matl.	16	Negative	6.6
Vulcanized Rubber/ Wooly Bear	14	Negative buoyancy	10.6
Crushed Neoprene/ Open Cell Foam	19.5	Positive buoyancy	0
Tri-butyl laminate Thinsulate	Unavailable**	Negative	6.5
Vulcanized Rubber/ Thinsulate	Unavailable**	Negative	8.5
Crushed Neoprene/ Radiant Insulating Matl.	16	Initially positive, became negative after 2 minutes.	8
Tri-butyllaminate/ Wooly Bear	Unavailable**	Negative	13.8
Vulcanized Rubber/ Radiant Insulating Matl.	12.5	Negative	10.85
Crushed Neoprene/ Wooly Bear	Unavailable**	Negative	8
Tri-butyl laminate/ Open Cell Foam	Unavailable**	Negative	5.6

* Buoyancy remaining after flood and ditching all lead weights.

** Weight requirements unavailable due to failure of underwear to dry between tests.

WHERE WE ARE TODAY, WHAT WE BELIEVE WORKS BEST, AND WHERE WE THINK WE SHOULD BE GOING AND WHY

Dick Long and Bob Stinton
Diving Unlimited International, Inc.

I'd like to start off this paper by clarifying some definitions and assumptions so that you know the position from which I offer you my thoughts.

1. When I first entered this business, I was befriended by the commanding officer of one of the underwater demolition teams. Not long after that he lost two divers during a night diving exercise. I visited him the next day, knowing he had to be more than a bit alone that morning. He shared with me a thought that has stayed with me to this day. He said "Dick, it is times like these that I understand that we are all in fact amateurs in this business, simply some of us have more experience than others. And further, any time we have a tendency to forget that, Mother Nature is more than prepared to slap us down and prove it again." So I come to you and say I am not an expert but merely I have some experiences which I wish to share with you.

2. In the process of searching for newer and better solutions, I have found that first we must establish communications between all of the people within our collective society. This includes everyone from the end users, their administrators, the government laboratories, supportive basic researchers, equipment designers and manufacturers. If we are effective in establishing communications, then we are apt to generate understanding. If we are successful in generating an understanding of the different points of view and the different discipline components that can potentially be used in formulating a solution, then we will attain cooperation. If we attain cooperation between the various different disciplines from the end users on the one end to the designers and manufacturers on the other end, then we have the opportunity to maximize our success. And only by maximizing communication and understanding can we in fact attain the goal for which we were sent here.

3. I would suggest to you that our society is made up of a large number of people and disciplines. First we have, and most important, the end users. These are the people who apply our art and our science to the ultimate task. They are mission- driven. Our ultimate and their ultimate goal has to be for them to accomplish their mission with the highest degree of reliability and repeatability possible. Nothing less is acceptable to the end users. They in turn are governed by a group of administrators, some of who were at one time end users and many of whom were not. As administrators they must adhere to the administrative and congressional mandates of our system.

These administrators in turn are supported by government laboratories who in turn are assigned the task of finding scientific and engineering solutions for their problems. Those government laboratories in turn are supported by basic researchers from a wide variety of disciplines to gather the basic raw information from which to put together various proposed solutions.

In the end, the proposed solutions must go to a manufacturer who must then take the information from the end users, the administrators, the government laboratories and basic researchers and manufacture a product that in turn the end user can use.

It is only when our collective society has completed the various steps outlined, i.e. communications, understanding and cooperation that we accomplish our goal and the end user accomplishes his mission. Our collective goal is for the end user to accomplish his mission and to do so with the least amount of encumbrance possible. Any encumbrance that our solution imposes upon the end user reduces his ability to accomplish his mission. At some point the encumbrance that we have placed upon him will compromise his capability to such an extent that he is incapable of going any further or accomplishing any more. Therefore in the process of designing our solution we must pay very close attention to the encumbrances we put upon him. (As of today, our encumbrances place limits on our end user.

Let me give you a bit of criteria DUI uses in judging what is an encumbrance. We would say that our end user must be capable of putting on all his equipment and then go to a football scrimmage practice. He must be able to go through several plays of knocking down and being knocked down, and rolling around in the dirt. He then must be able to get up, run at full speed across a field and shimmy up a tree into its branches. Once there, take out and operate a calculator with his fingers and properly operate a sophisticated weapon from the top of that tree. If he is not able to go through the rough and tumble of the football game without his equipment being destroyed, or have the agility and freedom to be able to run at full speed across the land, or to climb the tree without breaking something, or tearing something, and not have the freedom of movement to operate the calculator and the strength and endurance and dexterity to be able to operate a weapon accurately, then he is going to be something less than capable of accomplishing his mission when it comes time for him to do it. As of yet, I am sorry to say, we have not been able to accomplish, and cannot fully implement the above criteria.

Over the years DUI has had the opportunity to participate in a wide variety of underwater activities. We've been very successful in developing hot water suits, bell survival systems, bell heating systems and bell support systems. We have made thousands of wet suits, thousands of dry suits. We've made both active and passive systems. We have been successful in supporting numerous government laboratories in various projects in which they have allowed us to participate. From that collective experience, I offer you the following lessons that we have learned.

1. Wet suits are more affected adversely by water depth than they are by water temperature.

2. The amount of insulation required to be used in a dry suit will be more controlled by the exercise rate of the diver than it will be by the water temperature.

3. That any dry suit must be made of a thin, very tough membrane which in turn merely keeps the water out. The seals must allow free blood circulation to keep the body as close to the normal condition as possible.

4. That of all the insulations that we have tested to date, we have found nothing to compare with Thinsulate type B. We have seen a great confusion between the use of Thinsulate type B and Thinsulate type C. Thinsulate type B is a special compressed

form of insulation which does not compress with depth, nor does it take on water easily. Thinsulate type C has a polyester fiber in it to give it loft and is designed to be used above water in an air atmosphere. It will take on water when flooded. We have found that any of the springy insulations which includes any form of pile give greater buoyancy control problems when used in a zero G diving situation.

We found that any system we use we normally want to have a very low out-of-the-water weight so that should the diver be required to perform some function on land, he isn't carrying excess weight with him. We have developed various insulation strategies that maximizes amount of insulation around the body with the least amount of air. We have found that any suit and underwear combination must be tested in such a manner to insure the maximum freedom of movement of the body under the worst of operational conditions.

We have found that no single dry suit meets the needs of everyone. We make suits out of a wide variety of materials. We are fundamentally a custom house, we make suits both in custom design for a given operation; we also make them custom fitted to given individuals. We make suits out of Gortex that allow water vapor to transmit. We use Butyl rubber which has certain resistant to hostile chemicals. We make suits out of several different types of Neoprenes which are resistant to petro-chemicals and we use several different types of Urethanes for different types of operations or economic envelopes. We also work with vulcanized rubber suits for some specific applications.

Within that experience we have found that no one insulation system works for all divers in the same water temperature because each diver has a different mass-to-surface ratio and a different metabolic rate. Therefore their heat production and heat loss is different. We also know that different size of divers and different age of divers and different physical conditions will require different insulation for each individual diving under the exact same conditions. We have learned a lot about how to adjust for these differences through investigation and experience.

We have also learned that radiant barriers are really not a factor in the insulations of today. Most of the radiant barriers used are either a) they don't contain enough air in them to warrant their being an insulation outrigger, or b) are not effective at all in the diving application.

We've learned that foam Neoprene rubber is a very poor material to make a dry suit out of; that the material collapses with compression in a vertical water column; that over a period of time it starts to pin-hole and begins to leak. When one measures the amount of bulk required to achieve the given amount of insulation, it is a very poor tradeoff.

We know that the greatest wear and tear on the suit is achieved during the process of putting on and taking the suit off as opposed to the wearing of it. This fundamentally comes from the stretching of the seams, closures and seals.

We've learned that the insulation of the hands and feet are the most critical and most difficult at this time. When it comes to insulating the feet we find ourselves often at cross purposes. In diving, as on land, we normally wear a pair of boots with a thin amount of insulation between the foot and the boot. In order to supply more insulation we must supply more trapped air around the foot. This in turn requires a larger boot to be able to hold the insulation. Since the boots only come in a given set of sizes it means then that the insulation is crammed in the boot which in turn restricts blood circulation which in turn rather than making our feet warmer has a tendency to make them colder. Further, we usually need some kind of a reasonably tight fitting boot for giving support both for when we're walking or hiking and when we're climbing. This is at cross purposes to insulating the foot and keeping it from getting cold during the long transits under water.

Further, all of the fins that we use were not designed to be used with a large boot. We're stuck with the human foot as the driving force for the blade of a fin. The blade is the most efficient method we have found to date (all things considered), to propel the person through the water. However, the methods that we currently use to attach the blade to the foot are horribly archaic. We were to start with the purpose of designing to attach a blade to a foot, we would not choose a design we are currently utilizing. This method has grown up with us through a series of evolutions. This plus the and financial expediency in turn gives a very poor at best combination.

Currently we have a foot pocket with a fin rubber strap cramming the foot down into the foot pocket holding the foot under tension for the entire time that the fin is worn. There's no other piece of equipment that we attach to the body by the same manner under tension. We need a better engineering solution to this problem. However, unless some funds are allocated to that purpose, we do not see a solution for cold feet in the near future.

The weight systems we are currently using are totally inadequate and archaic. We take a body that has insulation and therefore buoyancy evenly distributed over it, we put lead weight right in the small of the back to compensate for that buoyancy. Even when we are capable of achieving neutral buoyancy we are rarely in neutral trim so far as an even attitude in the water. We have designed and experimented with different weight systems that bring this much closer into a meaningful balance but they require looking at the problem from a quite different perspective. It is our experience that most are not ready to do that quite yet.

In truth when it comes to divers performing work in the water, all they really need are hands. They do all the useful work. The best gloves we have tested are a modification of a design developed by Dr. Ted Delaca of the National Science Foundation which he called Polar Paws. This is a thin membrane mitt attached to the suit by virtue of a ring seal, in which we have a Thinsulate liner. We think anything beyond this is going to require artificial heat to augment because of the mass-to-surface ratio of the hands and the temperature differential across them.

We have learned that in the U.S. Military today, there are a lot of dry suits currently in existence. Most of them are not usable. By and large the field command staffs expect to have operational capability because they own the equipment. However, at this time this is not true. We find that the people who have the suits by and large are untrained in the proper use of the suit. In addition, they virtually have no maintenance program of any kind. The end users have little or no understanding or discipline in the use of the equipment. This means that for a commander under combat situation, who chooses to use his dry suits, is taking a very great risk of not accomplishing his mission and is placing his people at higher risk. I believe the answer is to use the dry suits on an every day basis. The only way you're going to do that is to take the wet suits away from them. They should use the dry suits in every day training which will develop dry suit awareness. They should learn how to determine how much insulation they need for the type of mission they're going on until it becomes totally second nature. Once that level is achieved then if the unit is called upon to make a diving mission in which a wet suit is acceptable then they can always down grade the people and put them into wet suits in which they will easily be able to use. But they cannot go in the other direction. If they use wet suits for normal training and then go to dry suits only when the mission becomes the most arduous and difficult, they are sure to fail most of the time. Under those conditions I think we are asking for a failure in advance. In some cases, under these conditions, we have seen people attempt to modify the dry suits so that they will be more reliable. In fact they're looking for an engineering solution to a training problem. (We think that it is very easy to do an adequate job of training the people by simply using the suits in the every day training and diving exercises and they will gain the skill and knowledge without any special or additional training.)

Let me move on to another issue. Most of us have grown up in our engineering world to believe that physics rules the world -- in fact it does not. Economics rules the world. Let me give you a good example. Currently we are prepared to pay as much as $1000 for a good dry suit but they only want to pay roughly $100 for a good pair of gloves. Yet if you examine the technical challenge of keeping the hands warm vs the rest of the body. If you look at the jobs which usually requires the use of the hands in the process of accomplishing the mission, I would suggest we have our economic priorities backward. We should be spending $1000 for the gloves and only $100 for the suit and we would have an overall better performing diver at the end of the day.

I'd like to point out another situation in the world of economics. Today we spend almost zero dollars in the development of any piece of equipment. We spend a very large number of dollars on the testing of equipment that was primarily designed for the use by sport and recreational divers, and then procurement is always let out to the lowest bidder. The acquisition of equipment usually comes out of very small budgets or OPTAR money. Let me share with you some simple numbers that you can take home with you. A diving equipment manufacturing company can afford to spend some where between 3 and 7% of their gross annual income on R & D and that depends on whether the company is in the proprietary product business where it will be to 7% or if they're in a very competitive area where price is a primary issue, then it may be even less than 3%. Take the number of divers that you have. Assume that you buy a new suit for each diver every five years. Take the 3 to 7% of that money and you figure that's what the entire industry has to spend on R & D in support of your divers. You can easily see that there's not going to be very much money there for finding a new solution to your old problems. If you added to that the total profit of the industry which should be running some place between 5 to 7% and most of us less than that, and you added that to the R & D budget, you still wouldn't have very much for manufacturers to invest.

DUI currently is the largest manufacturer of dry suits in the United States by far, and the second largest in the world. Last year we did a total of a little over $4 million worth of business, so you can see what our R&D budget is and what our profit picture is even if we plowed 100% of it back into R&D. I would suggest reprioritizing some of the funds from testing to development. It wouldn't take much to make a real difference in performance. However, before we go off on any great R&D projects, I would suggest to you that we have a lot of knowledge and information that could be applied to current operations. This information would greatly enhance your operational capability. We are simply not now using what we know to the fullest. In particular we are not taking the knowledge that we have already developed over the years and that supplying it in such a format that our field commanders are able to apply it to their every day diving operations. As a result, we have knowledge and information that might as well not exist. For instance, we have lots of knowledge on insulation strategies that is not being used at all and most of the equipment that's currently being issued as brand new equipment to the people, represent insulation strategies developed five to eight years ago. There is no method right now of informing people on what the latest information available is. The result is, our field commanders are constantly placed in a position of reinventing the wheel trying to find solutions that we already know. I would suggest that all of us who have this information are more than willing to share if we can simply find some way and some format to put it in to get it to the field commanders. Fundamentally, we still have these guys going to hacket school out there, grinning and gutsing it through. It is simply no longer necessary to do that.

As far as directions I think we should go in the future, I think we need to gather a lot of our baseline information, our knowledge and skill and begin to apply that in an every day manner. I believe that we can do a better job. For instance, we now have reasonably decent methods for urine elimination. We have various different methods of adjusting seals that we can share with people. Before we can go forward we must put this knowledge on the end user level. We must supply information until the base knowledge at the end user level comes up to today's knowledge. This must be done before we can expect to have any higher degree of technology integrated into the field.

Dry suit awareness must become routine and they must have dependable performance. We must have very predictable performance on an everyday basis before we can move on to the next level of increasing performance. We must get full use of what we now have before we can ever expect to go anywhere forward. Where is forward? Well, I think there's a lot to be said for developing variable insulation that can be changed during the actual course of a dive. I think there's a lot to be done insofar as supplying active energy to boost the current insulations that we now have. We need to create cooperation within our society which allows communications between the end users and the manufacturer so that in turn the end user gets what he wants. We need to create the shortest link possible of the communications through the administrators, the government laboratories, the basic researchers and the manufacturer so that we get the best piece of equipment to the end users that meets his need. We need to begin to remove some of the pre-existing restrictions, impeding information and knowledge flow so that in turn we end up with a diver in the water who gets the job done carrying our flag with the least amount of encumbrances as possible.

Another challenge we face is that of diver acceptance and/or rejection. Divers are a unique group of people with very strong beliefs in both themselves and in their mission in life. The reason they are very successful in getting their job done is because of their fierce tenacity and individualism both as a group and as individuals. These same characteristics are what make it very difficult for us to put any new concepts into play.

By and large, divers only want to accept something that came from divers and most of all something that came from themselves. (Because historically with new pieces of equipment someone has died in its perfection; they don't want to be that person. They have survived to this date because they have confidence in what they have used. They do not have confidence in a new piece of equipment so therefore until that new piece of equipment has proved itself they would prefer not to use it. The only way they're going to get confidence in it is by using it, therefore they're in a catch 22 situation. Our experience has been that if one wishes to introduce anything that is new and different, they must prepare themselves for a long and arduous journey. The only time that journey will be a short one is when the job absolutely cannot be done with the current equipment that they have available to them. Only then will the new piece of equipment be embraced and accepted, if it in fact does the job. Furthermore, any new piece of equipment must be interfaced to the entire system and normally very little attention is given to that prior to handing it over to the diver so the diver is left to his own resources by which to accomplish that interface. Military divers get a little more assistance in that end than do civilians, but usually the system does not lend itself well to that end. There is a great deal to be said for a field commander's decision to use something in a very stressful situation which the divers have confidence in, as opposed to using something that is probably a better piece of equipment, but that the divers do not have confidence in. For there is no question that once the diver leaves the surface, he is alone in most cases, and his capacity to deal with the situations at hand has more to do with his mental attitude, awareness and alertness than it does with any other single issue. For instance, if I were a field commander and in a a very marginal situation and I knew that the proper use of dry suits would ensure that I would accomplish the mission but the people had not been using them much and/or the equipment was in questionable repair, the accomplishment of my mission would be safer if I chose to use wet suits instead of dry suits. Sadly, this is currently the case in some of our military organizations.

In closing, the dry suit systems we have today will not take us everywhere we need to go. However, they will take us much farther than wet suits will or our dry suits of the past. If we do not master the dry suit we have today, we will not be able to take the step into the suit of the future. It is difficult for an individual to tell us what is needed in the future if the individual lives and works in the past.

ADDENDUM

Our society in total needs to be more responsive to the needs of the end users. From the time the end user identifies a particular mission requirement and need, we need to be able to come forth with solutions to him in a much shorter period of time. These solutions must reflect his need. There needs to be more direct coordination between those who are responsible for designing, developing, or producing those solutions with the end user. The current period of time can exceed 10 years. This is too long for us to collectively respond to his need. The end users could contribute measurably to the success of developing solutions by taking the time to learn as much as possible about the new technologies and how to apply them to the task; to making sure they become proficient in the new technologies before sitting in judgment on whether they will or will not solve the problem. It is rare that any solution that is originally dreamed up actually makes it to the field in the same form because the solution has to be debugged. End users need to exhibit the understanding of some of the aforementioned basic principles when participating in the final resolutions of the problems.

SESSION 2

PASSIVE THERMAL PROTECTION

Session Chairman:
LCDR John A. Sterba, MC, USNR

PREFACE

This session focussed on advances in passive thermal protection including: (1) varying insulation using thermotropic crystals, (2) increasing insulation by changing the dry suit gas, (3) influence of body composition and work level on insulation, (4) varying insulation using liquid filled suit/inner suit, (5) thermal conductivity (wet vs. dry), compressibility and absorbency of state-of-the-art undergarment materials, and (6) the thermal insulation of flooded dry suits.

Paper (1) discussed how thermotropic liquid crystal material could provide a variable clo material for future use in dry suit materials. By changing the applied electric field to the liquid crystals, an exercising diver could eliminate excess body heat due to the increased heat transfer through the material. Stopping exercise or remaining at rest, the liquid crystals could be realigned to provide increased insulation. Preliminary experimental data was reviewed.

Paper (2) reviewed how insulation with dry suits is due to trapped air within the fibers of the undergarment. Carbon dioxide gas has a relative insulation that is 65% greater than air. Substituting carbon dioxide for air increased insulation by 32% with dry suited divers in 3 °C water.

Paper (3) reviewed how the potential of passive thermal protection is dependant upon a number of variables including depth, gas mixture, water temperature, work rate, tissue insulation and clothing insulation. This paper reviewed data of thermal balance at rest and working, body cooling rates, and the contribution of body fat to insulation during diving in cold water.

Paper (4) discussed the concept of using a doubled walled dry suit with various fluids pumped into the inner space to increase passive insulation without affecting diver buoyancy. The fluid could be drained prior to swimming or underwater work to decrease insulation with higher heat production. Engineering data supporting the concept was reviewed.

The opinions or assertions contained in this article are the private views of the author and are not to be construed as reflecting the view of the United States Department of the Navy or the Department of Defense.

In paper (5), state-of-the-art undergarments were studied for degree of thermal conductivity, compressibility simulating dry suit squeeze, and the degree of absorbency simulating dry suit leaks. Controlled wetting of the undergarments simulating a dry suit leak decreased insulation by 80-90%. Compressibility demonstrated which undergarments lost most insulation with minimal dry suit squeeze. Absorbency testing demonstrated those undergarments with high capacity to continue absorbing water, decreasing dry suit insulation and buoyancy if there was a leak. Undergarments were ranked based on this data.

Paper (6) investigated the heat flux from divers wearing two different dry suits with various undergarments. Dry suit flooding decreased insulation by an average of 58%. Insulation values are reviewed for manned dives comparing different dry suits and undergarments.

J. Sterba
Co-Chairman

THERMOTROPIC LIQUID CRYSTALS: A VARIABLE CLO MATERIAL

Rand R. Biggers
Materials Science Branch
Naval Coastal Systems Center

ABSTRACT

Control of heat flow both to and from a diver continues to be one of the foremost problems facing the diving community. Thermotropic liquid crystals comprise a class of mesophase materials with variable heat-transfer characteristics. Utilization of their unique thermal transport properties in a diving garment would add an additional dimension of flexibility to diver thermal protection.

INTRODUCTION

Present inventory passive diving suits provide the diver with essentially a single value or a pressure-dependent value of CLO insulation regardless of the water temperature or the diver's activity level. Under many diving conditions, the diver's time in the water is limited by thermal constraints. Figure 1 depicts an approximate time in hours before a diver would be in danger of hypothermia (loss of 200 kcal of body heat) or hyperthermia (increase of body temperature by 1.5°C) as a function of water temperature, activity level, and CLO of insulation. A controllable-variable CLO material, depending on its minimum and maximum CLO values, could not only increase the time until hypo/hyperthermia is approached, but maintain the diver's skin temperature at much closer to normal as well.

Mesophase materials, such as those with characteristics intermediate between liquid and solid, show properties of significant promise in the development of advanced technological systems. Thermotropic liquid crystals comprise a class of mesophase materials with variable heat-transfer characteristics. These materials are composed of elongated molecules with a rigid core and flexible tails (see Figure 2). Anisotropic material properties (such as the thermal conductivity, electrical conductivity, magnetic susceptibility, dielectric constant, and index of refraction) are a direct result of the cylindrical symmetry of the molecules. This molecular structure permits the formation of differing ordered mesophases at different temperatures. Each mesophase exhibits a different internal ordering, and the level of ordering per mesophase increases with decreasing temperature. The orientations of the liquid-crystal molecules are also sensitive to applied electric fields, and it has been demonstrated (1,2) that this property has a significant influence on the transport of heat through the liquid crystal. The response of the effective thermal conductivity of the liquid crystal to applied fields is sufficiently strong that an excellent opportunity exists to exploit the heat-transfer characteristics of these materials to produce variable-CLO garments.

Three possible modes of liquid crystal utilization have been identified:

(1) Reorientation of the molecules with small electric fields to vary the CLO value by about a factor of 2 (see Figure 3);

(2) inducement of convective motion with large electric fields (also shown in Figure 3) to decrease the CLO factor by up to a factor of a 100 or more; and

(3) phase transitions in which the lower-temperature phase has a larger CLO value (see Figure 4).

PRESENT RESULTS

Although very large increases in thermal transfer rates have been achieved, they require very large DC fields (36 kV/cm). These inordinately large DC fields are restricted to laboratory usage and generally cause rapid deterioration of the liquid crystal. Therefore, we have decided to evaluate AC field effects which are not nearly as detrimental to the liquid crystal.

Liquid-crystal thermal-transfer rate measurements for the induced convection mode, have been in progress for over a year utilizing a measurement system designed specifically for application of high-voltage AC fields to liquid samples. The experimental setup, along with the experimental associated software, has been modified several times to improve the precision and repeatability of the measurements. The measurements have been made on samples approximately 0.635 cm thick and 1 to 2 square cm in area to correlate better to the cell sizes envisioned for placement in actual undergarments.

The single-substance MBBA [N-(p-methoxybenzylidene)-p-butylaniline] continues to be evaluated due to the number of new discoveries being made (3), such as the thermal-transfer-rate dependence on frequency (see Figure 5). MBBA is also the only liquid crystal of more than 6000 (4) for which a large amount of information is available and for which the thermal conductivities (2.8×10^{-4} and 5.0×10^{-4} cal/cm–sec–degC) have been published.

The results of our thermal-transfer rate measurements suggest that the best utilization of liquid crystals would be in a cooling mode (compare Figure 1 and Figure 6). Inclusion of liquid crystals in a thermal undergarment significantly reduces the danger of hyperthermia in all but the warmest water conditions and with a minimum or small loss of insulating ability. Addition of a water retaining vest-like outer garment would also provide a useful amount of cooling ability in out-of-the-water situations. As long as the vest remained wet and surface conditions were conducive to evaporation, the diver would be cooled.

The minimum thermal conductivity of MBBA gives it a CLO value roughly one-half that of an equivalent thickness of neoprene. It is expected that when more liquid crystals are accurately measured, they might approach the CLO values of thinsulate. If a 2.5 CLO undergarment becomes practicable, then replacement of 5% of the surface area with MBBA would avert the 200 kcal body-heat loss or a 1.5°C body temperature rise for over 12 hours for all combinations of diver activity levels in water temperatures ranging from 29 to 85°F (see Figure 6). These time calculations are based on the minimum published thermal conductivity of MBBA and the maximum thermal-transfer rate achieved in our lab (90×10^{-4} cal/cm–sec–degC).

Recent experimental measurements have provided information which suggests that inclusion of liquid crystal cells in a thinsulate undergarment, as depicted in Figure 7, would provide a cooling ability while retaining about 95% or more of the garment insulating ability. The liquid crystal offers the capability to optimize the diver's skin temperature for many of the above situations. A synoptic comparison between conventional and composite undergarments has been made in Figure 8. The results presented in this figure indicate that for all depicted conditions, on the average the composite garment provides nine hours of protection while the conventional garment provides only three hours.

FUTURE PLANS

A detailed understanding of the liquid crystal's thermal transfer mechanism is necessary for the efficient use of liquid crystals in any of the indicated modes. We are experimentally evaluating the thermal behavior while also trying to develop a theoretical understanding of the behavior. A number of experimental parameters, such as the AC signal shape and the amount of ionic impurities in the sample, significantly influence the attainable thermal-transfer rates. The effect of these parameters on the thermal-transfer rate needs to be evaluated to enable optimum utilization of the unique thermal-transfer capabilities provided by thermotropic liquid crystals.

The formulation of an analytical model in which DC fields are applied has essentially been completed and agrees qualitatively with published data. This model is being extended to include the effects of AC fields on liquid crystals. The model emphasizes the importance of boundary conditions and indicates that a well-aligned sample may produce larger thermal-transfer rates than a nonaligned sample for the same applied voltage. The next sample to be measured will be aligned MBBA.

REFERENCES

1. CARR, E.F. (1984). "A Heat Switch Using Liquid Crystals in the Presence of Electric Fields," Mol. Cryst. and Liq. Cryst., Vol. III, pg.161-170.

2. IGNER, D., and J.H. FREED (1982). "Electrohydrodynamic Instabilities Observed in a Nematic Phase Under Oblique Boundary Conditions," J. Chem. Phys., Vol. 76, No. 12, pg.6095-6119.

3. BIGGERS, R., J. RISH III, and G. HENDERSON (1988). "Influence of Electric Fields on Heat Transfer through Thermotropic Liquid Crystals," Proceedings of Fourteenth Southeastern Conference on Theoretical and Applied Mechanics, pp.454-461.

4. KELKER, H., and R. HATZ (1980). "Handbook of Liquid Crystals," Verlag Chemie, Weinheim.

NCSC 1288-0878

ELAPSED TIME IN HOURS PRIOR TO DANGER OF HYPO / HYPERTHERMIA

Basic Undergarment Insulation in (CLO)	Body Thermal Output in (Watts)	WATER TEMPERATURE (°F)						
		29	32	35	40	60	80	85
1.2 CLO	150W	1.6	1.8	2.1	2.9	6.6	2.1	1.4
	325W	12+	12+	12+	12+	1.1	0.5	0.5
	500W	1.3	1.1	1.0	0.8	0.4	0.3	0.3
1.5 CLO	150W	2.6	3.1	3.8	6.3	12+	1.6	1.2
	325W	12+	9.4	4.6	2.4	0.8	0.5	0.4
	500W	0.7	0.7	0.6	0.6	0.4	0.3	0.3
2.0 CLO	150W	7.2	10.8	12+	12+	5.2	1.3	1.1
	325W	1.6	1.4	1.3	1.1	0.6	0.5	0.4
	500W	0.5	0.5	0.5	0.4	0.3	0.3	0.3
2.5 CLO	150W	12+	12+	12+	12+	2.6	1.2	1.0
	325W	1.0	0.9	0.9	0.8	0.6	0.4	0.4
	500W	0.4	0.4	0.4	0.4	0.3	0.3	0.3

6.3 Hypothermia

0.6 Hyperthermia

NAVAL COASTAL SYSTEMS CENTER—PANAMA CITY, FLORIDA

Figure 1. Estimated Diver Endurance Limits with a Conventional Thinsulate Undergarment

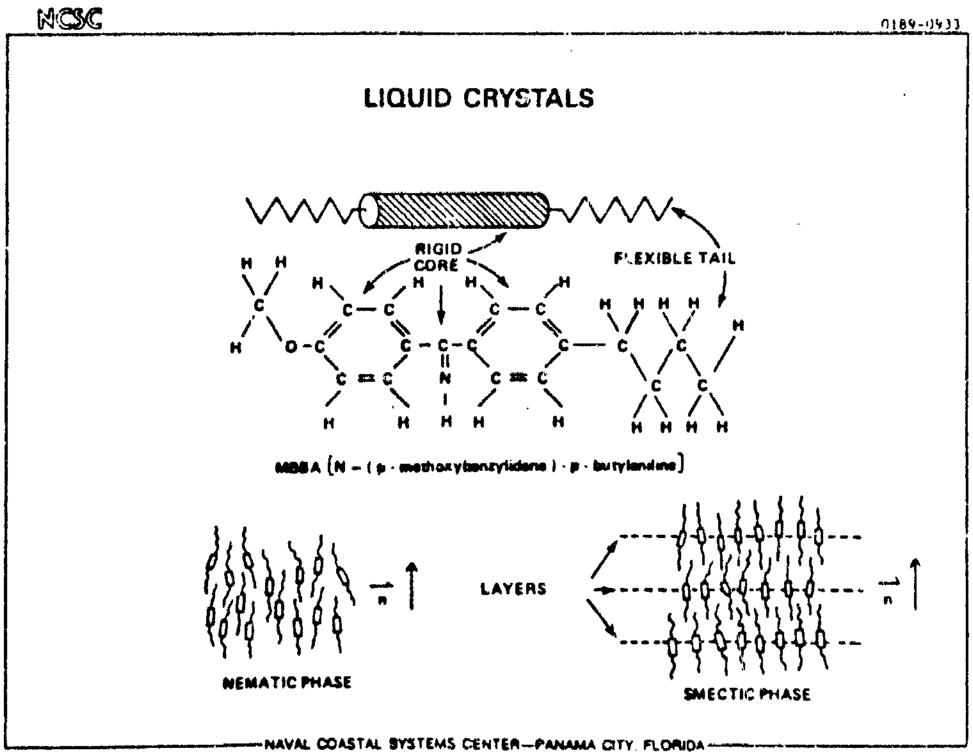
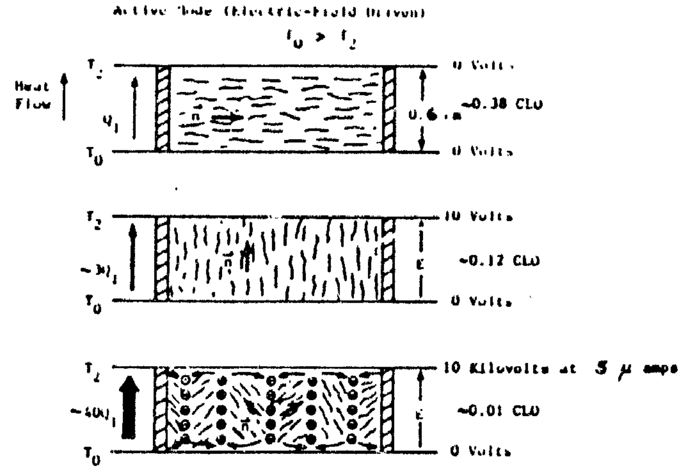


Figure 2. Liquid Crystal Depiction

NCSC

INCREASE IN THERMAL-ENERGY TRANSFER



COMPARISON OF HEAT - TRANSFER RATES
FOR EQUIVALENT THICKNESSES (0.4 cm)

LIQUID CRYSTAL (NEMATIC PHASE-NO FIELDS)	1.0 Q_1
NEOPRENE	0.5 Q_1
THINSULATE	0.3 Q_1

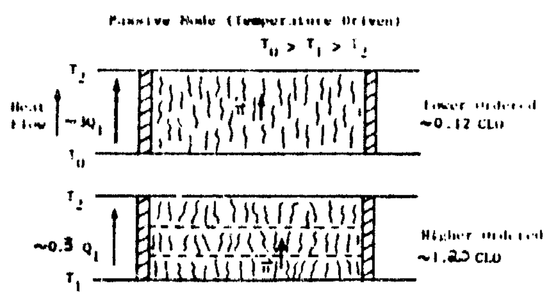
NAVAL COASTAL SYSTEMS CENTER—PANAMA CITY, FLORIDA

Figure 3. Liquid Crystal Modes for Increasing the Thermal-Transfer-Rate (Cooling)

NCSC

0186 40 1584

INCREASE IN INSULATING ABILITY



COMPARISON OF INSULATING ABILITIES
FOR EQUIVALENT THICKNESSES (0.4 cm)

LIQUID CRYSTAL (NEMATIC PHASE-NO FIELDS)	0.12 CLO
NEOPRENE	0.75 CLO
THINSULATE	1.20 CLO

NAVAL COASTAL SYSTEMS CENTER—PANAMA CITY, FLORIDA

Figure 4. Liquid Crystal Mode for Possible Passive Increase in Insulation

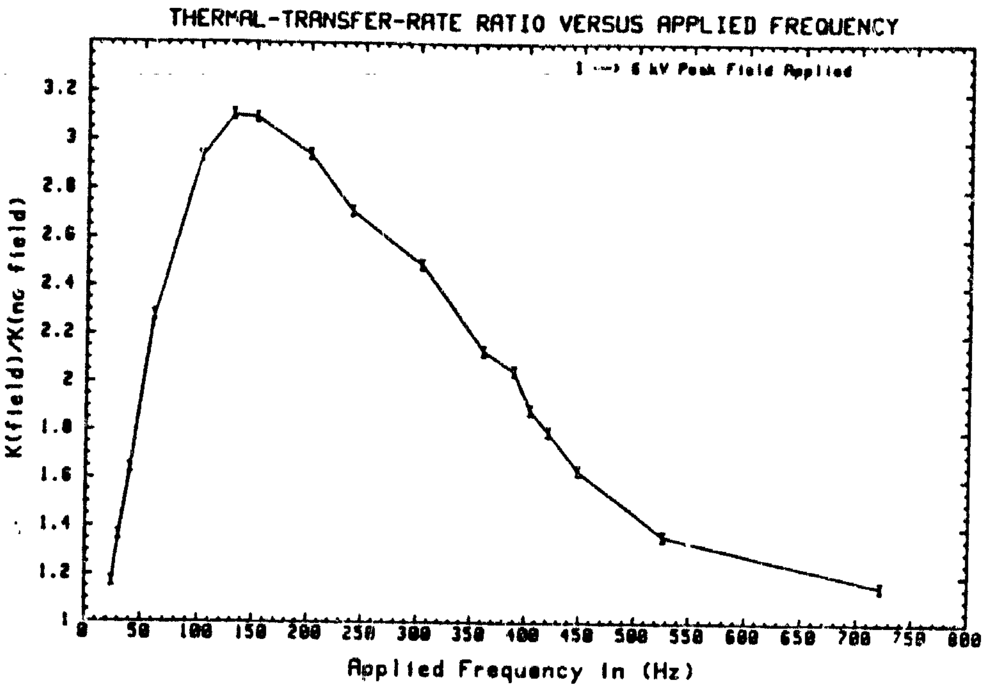


Figure 5. Variation of Thermal-Transfer-Rate with Frequency (6 kV peak applied field)

NCSC

1288-0877

ELAPSED TIME IN HOURS PRIOR TO DANGER OF HYPO / HYPERTHERMIA

Basic Undergarment Insulation in (CLO)	% Liquid-Crystal in Undergarment	Body Thermal Output in (Watts)	WATER TEMPERATURE (°F)						
			29	32	35	40	60	80	85
1.2 CLO	1%	150W	1.5	1.7	2.0	2.7	5.9	12+	5.1
	1%	325W	12+	12+	12+	12+	12+	0.6	0.6
	1%	500W	12+	12+	12+	12+	12+	0.6	0.3
	5%	150W	1.3	1.5	1.7	2.2	4.2	12+	12+
	5%	325W	12+	12+	12+	12+	12+	12+	12+
	5%	500W	12+	12+	12+	12+	12+	12+	1.1
	10%	150W	1.1	1.2	1.2	1.8	3.1	12+	12+
	10%	325W	6.7	12+	12+	12+	12+	12+	12+
	10%	500W	12+	12+	12+	12+	12+	12+	12+
1.5 CLO	1%	150W	2.4	2.8	3.3	5.5	12+	12+	3.5
	1%	325W	12+	12+	12+	12+	12+	0.8	0.6
	1%	500W	12+	12+	12+	12+	12+	0.4	0.3
	5%	150W	1.9	2.1	2.6	3.7	11.4	12+	12+
	5%	325W	12+	12+	12+	12+	12+	12+	12+
	5%	500W	12+	12+	12+	12+	12+	12+	1.0
	10%	150W	1.5	1.7	1.9	2.6	5.5	12+	12+
	10%	325W	12+	12+	12+	12+	12+	12+	12+
	10%	500W	12+	12+	12+	12+	12+	12+	12+
2.0 CLO	1%	150W	6.6	9.6	12+	12+	12+	12+	2.6
	1%	325W	12+	12+	12+	12+	12+	0.7	0.6
	1%	500W	12+	12+	12+	12+	0.9	0.4	0.3
	5%	150W	5.0	6.7	10.0	12+	12+	12+	12+
	5%	325W	12+	12+	12+	12+	12+	12+	12+
	5%	500W	12+	12+	12+	12+	12+	12+	0.9
	10%	150W	3.8	4.8	6.5	12+	12+	12+	12+
	10%	325W	12+	12+	12+	12+	12+	12+	12+
	10%	500W	12+	12+	12+	12+	12+	12+	12+
2.5 CLO	1%	150W	12+	12+	12+	12+	12+	12+	2.3
	1%	325W	12+	12+	12+	12+	12+	0.7	0.5
	1%	500W	12+	12+	12+	12+	0.7	0.3	0.3
	5%	150W	12+	12+	12+	12+	12+	12+	12+
	5%	325W	12+	12+	12+	12+	12+	12+	12+
	5%	500W	12+	12+	12+	12+	12+	12+	0.9
	10%	150W	7.8	12+	12+	12+	12+	12+	12+
	10%	325W	12+	12+	12+	12+	12+	12+	12+
	10%	500W	12+	12+	12+	12+	12+	12+	12+

[5.3] Hypothermia   [1.0 hatched] Hyperthermia

Figure 6. Estimated Diver Endurance Limits with Composite Liquid-Crystal Undergarment

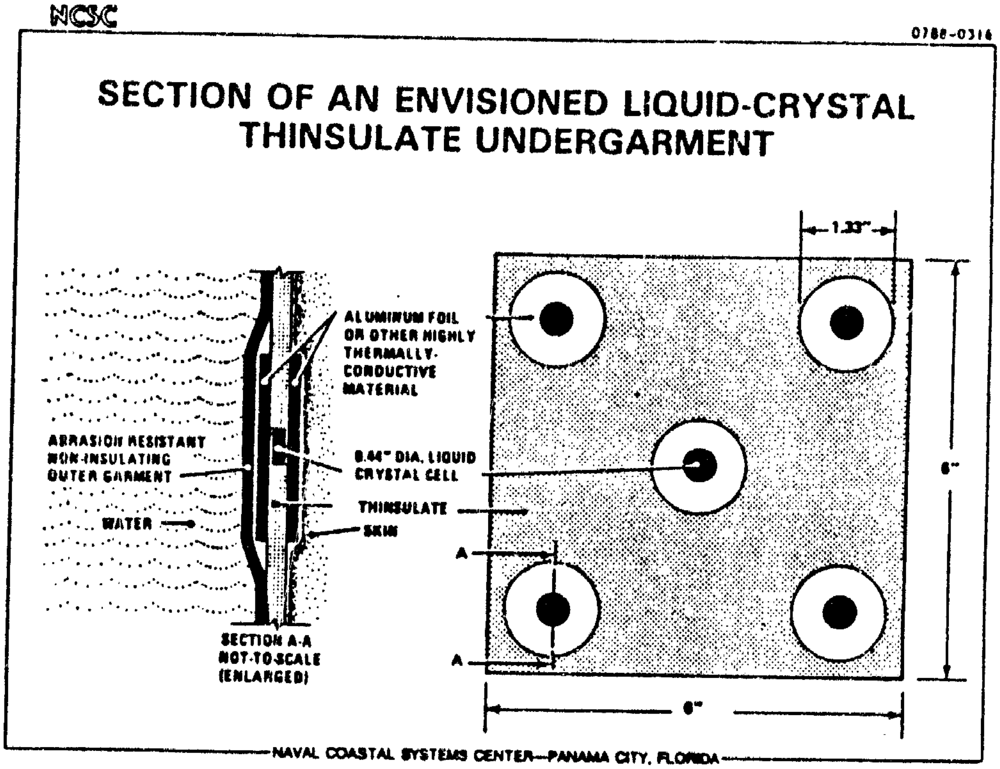


Figure 7. Envisioned Encapsulation of Liquid-Crystal in Diving Undergarment

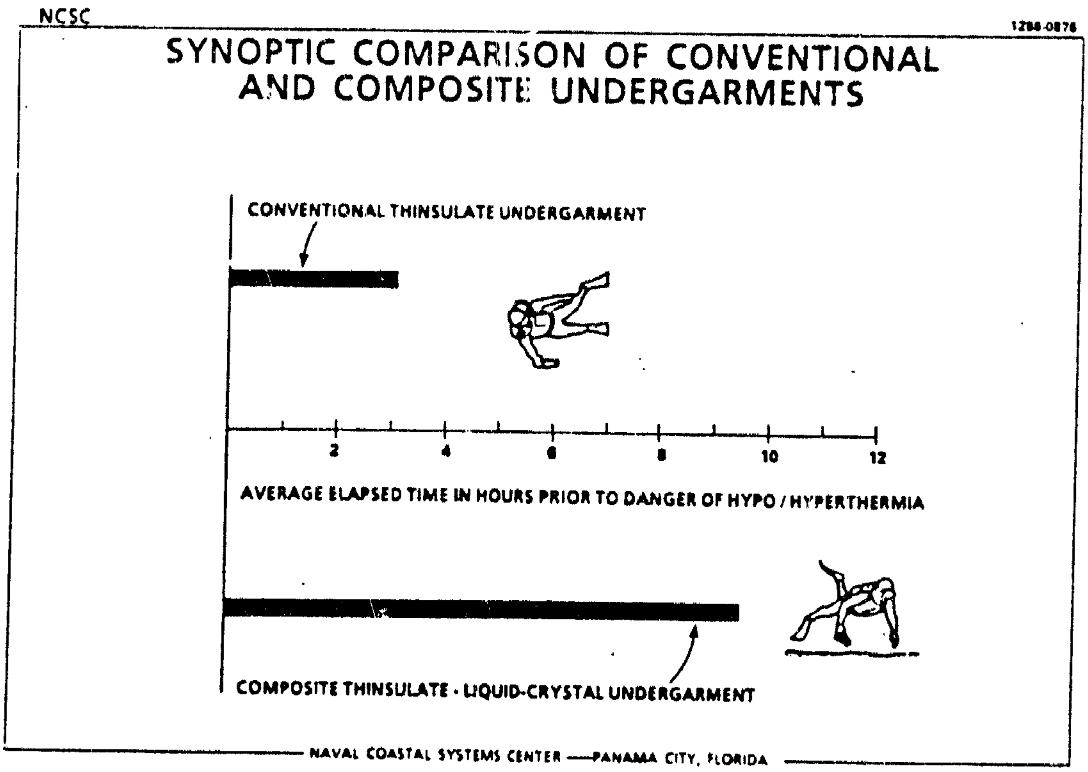


Figure 8. Synoptic Comparsison of Conventional and Composite Undergarments

ALTERNATE DRY SUIT INFLATION GAS FOR IMPROVED THERMAL INSULATION

Robert P. Weinberg
Diving Medicine Department
Naval Medical Research Institute, Bethesda, MD 20814-5055

ABSTRACT

Current insulation used in thermal protection garments derives its insulative property from trapped gas, with the garment fabric serving as a matrix to reduce gas convection and prevent compression. This trapped gas is air in the case of open weave garments worn under dry suits. The trade-off between increasing insulation garment thickness and decreasing range of motion is nearly maximized in current dry suits employing Thinsulate undergarments. Thinsulate insulative batting provides approximately 80% of the theoretical insulation of still air; the 20% loss due to the required supporting fiber matrix. Use of a gas such as carbon dioxide (CO_2), which has a relative insulation value 58% greater than air, could enhance the insulation of existing dry suits. To investigate this theory, a series of matched 4-hour shallow immersions in 3± 0.1 °C water were performed by eight U.S. Navy divers. Substituting CO_2 for air (AIR) as the dry suit inflation gas resulted in a significant ($p<0.05$) increase in overall suit insulation from 2.6 ± 0.3 CLO (AIR) to 3.1±0.3 CLO (CO_2). Suit CO_2 concentration averaged 86±8% in the CO_2 group and 4±0.8% in the AIR group. The respiratory quotient was not significantly different between the AIR group (0.87±0.02 and the CO_2 group (0.88±0.03). However, expired CO_2 (ml/min kg) was elevated in the CO_2 group (5.3±0.6) compared to the AIR group (4.7±1.0). Extension of this study to 150 FSW is planned to further investigate the characteristics of depth range for operational use of this alternate dry suit inflation gas.

Current insulation used in thermal protection garments derives its insulative property from trapped gas, with the garment fabric serving as a matrix to reduce gas convection and prevent compression, both of which act to decrease insulation. The trapped gas is air in the case of open weave garments worn under dry suits. The trade-off between increasing garment thickness to obtain greater insulation, and the resultant decreasing range of motion is less than optimal in current dry suits employing Thinsulate undergarments. Cold water immersions of several hour duration by a diver at rest require thermal protection garments of a thickness that greatly reduce range of motion and mobility. Using a thinner garment provides adequate mobility but reduces safe exposure time due to increased heat loss. Presently, Thinsulate insulative batting in use by several clothing manufacturers provides approximately 80% of the theoretical insulation of still air; the 20% loss is due to the required supporting plastic fiber matrix. Use of a gas such as carbon dioxide (CO_2), which has a relative thermal insulation value 58% greater than air could enhance the insulation of existing dry suits. The amount of this theoretical increase achieved is a function of the suit insulation garment and the concentration of carbon dioxide achieved.

Thermal garment insulation is a function of both the insulating gas and the supporting matrix. The heat flowing through the garment will be a function of the total

PRECEDING PAGE BLANK

garment conductivity (reciprocal of insulation) multiplied by garment thickness and the temperature gradient across the garment. Knowing the thermal conductivity of the inflation gas and the matrix, the conductivity of both components can be weighted to obtain the contribution of both components using a simple model.

The Thinsulate garment used in this study is comprised of a polypropylene microfiber batt and trapped gas. Using the relationship:

garment conductivity = [A • gas conductivity + (1-A) • matrix conductivity]

where A is the fraction of gas comprising the garment, one obtains a fraction of 95.5% using the known properties of air, polypropylene, and the measured conductivity of Thinsulate with air as the trapped gas. The calculated gas fraction can be checked by another method: Thinsulate has a reported density of 0.057 g/cm^3, and polypropylene has a specific gravity of 0.91, so the plastic must occupy 6.3% and air the remaining 93.7%. Substituting 100 % carbon dioxide for air, and using an average gas fraction of 95%, the garment insulation should be 3 CLO/cm. This is nearly a 41% insulation increase compared to Thinsulate filled with air.

To investigate the practicality of this theory, a series of matched four hour shallow immersions in 3 +/- 0.1 °C water were performed by eight U.S. Navy divers. The divers wore Thinsulate undergarments beneath a DUI TLS drysuit, five finger neoprene gloves under gauntlett mitts. The hands were held at chest level during each exposure. Expired gas was collected from a modified AGA mask for volume and composition analysis at five minute intervals. Surface and core temperatures, and regional heat flows were recorded every minute.

Bouyancy compensation weights were fixed at 25 kg for all divers. Neglecting the divers bouyancy and assuming an average diver body surface area of 2 square meters, this would permit an average gas layer thickness between the dry suit and the diver (undergarment) of 1.25 cm. Thinsulate is reported to compress by 60% under the 2 psi pressure expected due to the hydrostatic pressure differential experienced by an upright diver in the water. Assuming the Thinsulate had an initial thickness uncompressed of 1.8 cm and was compressed an average of 30%, the resulting thickness of approximately 1.26 cm agrees with the expected gas layer thickness. How well distributed this gas was is a function of suit fit for each diver. Several sizes of standard suits were purchased, each man wore the same suit in both the air and CO_2 exposures.

The divers were instrumented in the early morning and diving gear donned. The standard left thigh suit inflator was connected to either air or carbon dioxide and the diver inflated/deflated the suit suit gas sample was taken from a sample line located in the right leg and right arm and analyzed for CO_2 content. The diver was then immersed, and remained at rest for four hours. Suit inflation gas was adjusted early in the dive to provide slight negative bouyancy. After the exposure, divers were rewarmed by head-out immersion.

The measured garment insulation increase when using carbon dioxide was about 20%, less than the 41% predicted for Thinsulate filled with 100 % CO_2. However, the carbon dioxide concentration achieved in the suit gas was only 86%. Using the relationship between the conductivity of a gas mixture and the conductivity, molecular weight, viscosity, and concentration of each gas component; the thermal resistance of

Parameter	Air	CO_2	
CO_2 concentration (%)	4.0 ± 0.8	86.0 ± 8.0	$p<0.05$
Metabolic rate (W/m2)	82 ± 11	71 ± 11	$p<0.05$
Mean skin temp (°C)	22.6 ± 2.3	24.1 ± 2.3	$p<0.05$
Suit heat loss (w/m2)	64 ± 2	59 ± 4	$p<0.05$
Suit insulation (CLO)	2.6 ± 0.3	3.1 ± 0.3	$p<0.05$
RQ	0.87 ± 0.02	0.88 ± 0.03	NS
Expired CO_2 (ml/min*kg)	4.7 ± 1.0	5.3 ± 0.6	NS
Rectal temp (°C)	36.9 ± 0.2	36.8 ± 0.2	NS

the suit gas mixture (85% CO_2, 15% AIR) can be calculated to be 3.8 CLO/cm. Substituting into the above relationship between garment insulation, the estimated value is 2.9 CLO/cm. The estimated improvement is 32% when corrections relating to gas composition obtained is applied to the garment insulation equation.

The difference between theoretical and measured suit insulation improvement can be further reconciled by the fact that even when using air some CO_2 is found to accumulate in the suit. The actual gas composition in the garment is unknown, only the gas between the undergarment and the dry suit was sampled. This may have led to an overestimate of the CO_2 levels in the garment.

Extension of this study to 150 FSW is planned to further investigate the characteristics of transcutaneous CO_2 uptake under hyperbaric conditions, and to establish a safe depth range for operational use of this alternate suit inflation gas.

(Supported by NMRDC Task No. 63713N M0099.OIB-1004)

COMPARISON OF HELIOX AND AIR AS SUIT INFLATION GASES

T.T. Romet
Experimental Diving Unit
Defence and Civil Institute of Environmental Medicine

ABSTRACT

It is well accepted that the primary disadvantage of helium based breathing gas also acting as the suit inflation gas is its higher thermal conductivity. Although thermal conductivity of helium is six times that of nitrogen, a helium/oxygen mixture similar to air is only four times as great. It has been further suggested that for each °C that the ambient air is below mean skin temperature, the skin will be 0.1°C lower in a HeO_2 gas than air. Chamber studies have shown exposure to a helium environment results in a skin cooling, higher ambient temperatures to maintain comfort but no effect on core temperature. This study investigated the differences between HeO_2 and air as a suit inflation gas during in-water dives ranging in depth from 36 to 86 msw. In the double blind study neither the divers or investigators were told which gas was provided for suit inflation. Core temperature was determined by rectal thermistor and skin heat flow by heat flux transducers. Results showed resting heat flows were 31% higher with HeO_2 as the suit inflation gas (137 vs 102 W/m^2) while the peak difference was 61% (190 vs 118 W/m^2) at 10 min. The difference remained approximately 50% for the majority of the in-water time. There were no significant differences in core temperatures but skin temperatures were significantly lower ($p<0.05$) at all depths and time points. The greatest differences observed were 2.9°C with steady state differences near the end of immersions of 1.5°C. Absolute values however seldom dropped below 28.5°C except when some water leaked into the suit. Most divers perceived themselves as cool with the helium while rating themselves as comfortable or cool but comfortable with air. The results suggest that while thermal comfort would be improved substituting air for HeO_2 as the suit inflation gas, physiologically there were no significant advantages over the depth and time profiles investigated.

INTRODUCTION

With the requirement of achieving greater depths for the military diver, helium based breathing gas is required by the diver. Its lack of narcotic effects and lower density making breathing easier are the primary factors influencing its choice for dives of greater depths. Its one physical property, a higher thermal conductivity as compared to nitrogen has been suggested as its major disadvantage in the diving environment. In dry suit diving, since it is technically the simplest to use the breathing gas also as the suit inflation gas, the question arises whether the helium based gas will promote heat loss at a rate sufficiently greater than with air to produce a thermal problem for the diver.

Earlier studies have shown that for each degree Celsius the ambient gas temperature is below mean skin temperature in air, the skin temperature will be 0.1°C lower in an helium-oxygen mixture (Hiatt and Weiss, 1968). The temperature zone to maintain thermal comfort has also been shown to be 3 to 5°C higher in a helium-oxygen

PRECEDING PAGE BLANK

environment. Raymond et al. (1968) showed a linear increase in convective heat loss under hyperbaric conditions ranging between 33 msw and 136 msw., with the rate reaching three times that of air at maximum depth.

This study investigated the differences in heliox (84/16) and air as suit inflation gases during in-water dives ranging in depth from 36 to 86 msw.

METHODS

Fourteen young healthy males (ages 20 - 34) participated in a twelve dive series with depths varying between 45 and 69 msw. Due to the experimental protocol, two subjects were randomly assigned as the wet divers for each dive. This prevented a balanced experimental format in which each subject would have been exposed to the same dive profile twice, once with each suit inflation gas.

Each subject was fitted with four heat flow transducers, with an incorporated thermistor for skin surface temperature, (Thermonetics, Cal.) and placed on the chest, forearm, thigh and calf. Rectal temperature was recorded with a rectal thermistor (YSI series 400) placed 15 cm beyond the anal sphincter. Both mean skin temperature and body heat flow were calculated according to the weighting factors described by Ramanathan (1964). Suit insulation was calculated from the mean heat flow and skin-water temperature difference as described by Kuehn and Zumrick (1978).

Twelve dives were performed over a two week period. Subjects were divided into two groups, diving on alternate days. Each wet diver wore a non-compressible dry suit with a crushed neoprene undergarments. They were provided with a suit inflation but were not informed to which one they received. The monitoring personnel similarly were not told of the identity of the gas.

Upon entry into the water, the divers attached themselves to the bicycle ergometer and rested for five minutes. Following compression to depth, the subjects began cycling for 10 min, with the load adjusted from the surface to produce a heart rate approximately 150 bpm. The exercise period was followed by a 10 min rest period and the cycle repeated until the beginning of decompression. There was no physical activity during the decompression phases.

RESULTS

Resting, in-water heat flows were on average 31% higher with heliox as the suit inflation gas as compared to air (137 vs 102 W/sqm). This difference increased upon compression to depth and the commencement of exercise with a peak difference of 61% (190 vs 118 W/sqm) at 10 min of immersion; and maintained on average, a 50% difference for the duration (Figure 1). Suit insulations were significantly different averaging 1.3 clo with air, 0.75 clo with heliox, while tissue insulations remained essentially identical (Figure 2). Mean skin temperature was significantly different during the compression and decompression phases averaging 2.2°C (range 2.9 to 1.5°C). Rectal temperature between the two conditions however were not significantly different (Figure 3).

DISCUSSION

It has long been known that thermal conductivity of helium is greater than nitrogen. However, when it is combined with oxygen and considering other factors (viscosity, density and specific heat), it has been suggested heliox is only about twice as effective in promoting convective heat transfer. Raymond et al. (1968) indicated that by 14.6 ATA, convective heat loss in a helium environment was three times that of air

This present study has shown for depths between 45 and 69 msw, the convective heat loss from the skin, as measured by heat flow transducers was on average 50% higher. In-water resting values prior to compression were 31% higher, less than the 100 % value predicted by Hiatt and Weiss (1968). The results would indicate that effective heat loss from the skin is not as great as predicted. Skin temperatures were lower with the heliox suit inflation gas, but this did not have any effect on the core temperature. Although no metabolic rates were measured, it is speculated an increased metabolic rate resulting from the lower skin temperature provided sufficient heat production to maintain core temperature. Thermal comfort was perceived as cool but comfortable with heliox as the suit inflation gas. This compared to ratings perceived as comfortable with the air suit inflation.

Average suit insulations were calculated as 1.21 clo with air and 0.75 of using heliox. As each subject was permitted to voluntarily select the amount of gas they wanted to inflate the suit, this study is unable to provide an exact comparison suit insulation. whether in clo/cm or clo/unit volume. It is clear that while differences do exist, the increased heat flow is tolerable by the divers. It must be further noted that while the in-water durations of these dives were not long, a suit providing 0.75 clo insulation at depth, as observed with the heliox gas, does provide sufficient thermal protection without the need for a separate suit inflation gas supply. It still remains to be determined whether the differences in heat flow and resultant lower skin temperatures become a significant factor in dives of greater than 70 min duration carried out in the present study or in conditions where divers already have a negative thermal balance.

REFERENCES

Hiatt, E.P. and H.S. Weiss. 1968. Physiological effects and convective heat loss in helium-oxygen atmospheres: A review. from Physiological and Behavioural Temperature Regulation, ed.J.D. Hardy, A.P. Gagge and J.A.J. Stolwijk, Charles C. Thomas Pub., Springfield, IL

Kuehn, L.A. and J. Zumrick. 1978. Thermal measurements on divers in hyperbaric helium-oxygen environments. Undersea Biomed. Res. 5:213-231.

Ramanathan, N. 1964. A new weighting system for mean surface temperature of the human body. J. Appl. Physiol. 19:531-533.

Raymond, L.W., Bell, W.H., Bondi, K.R. and Lindberg, C.R. 1968. Body temperature and metabolism in hyperbaric helium atmospheres. J. Appl Physiol. 24:678-682.

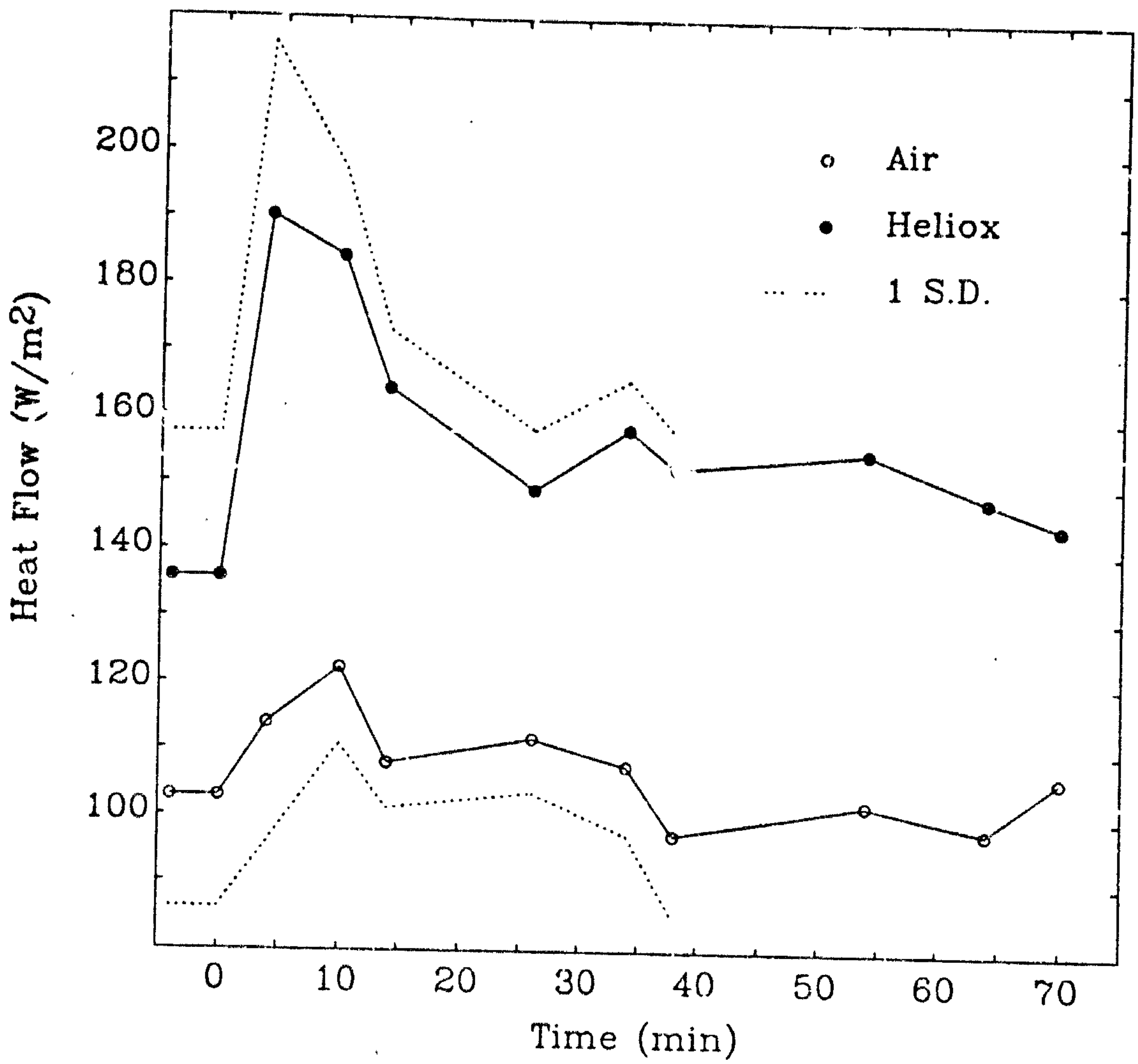


Fig. 1. Comparison of in-water heat flow with air and heliox as suit inflation gases.

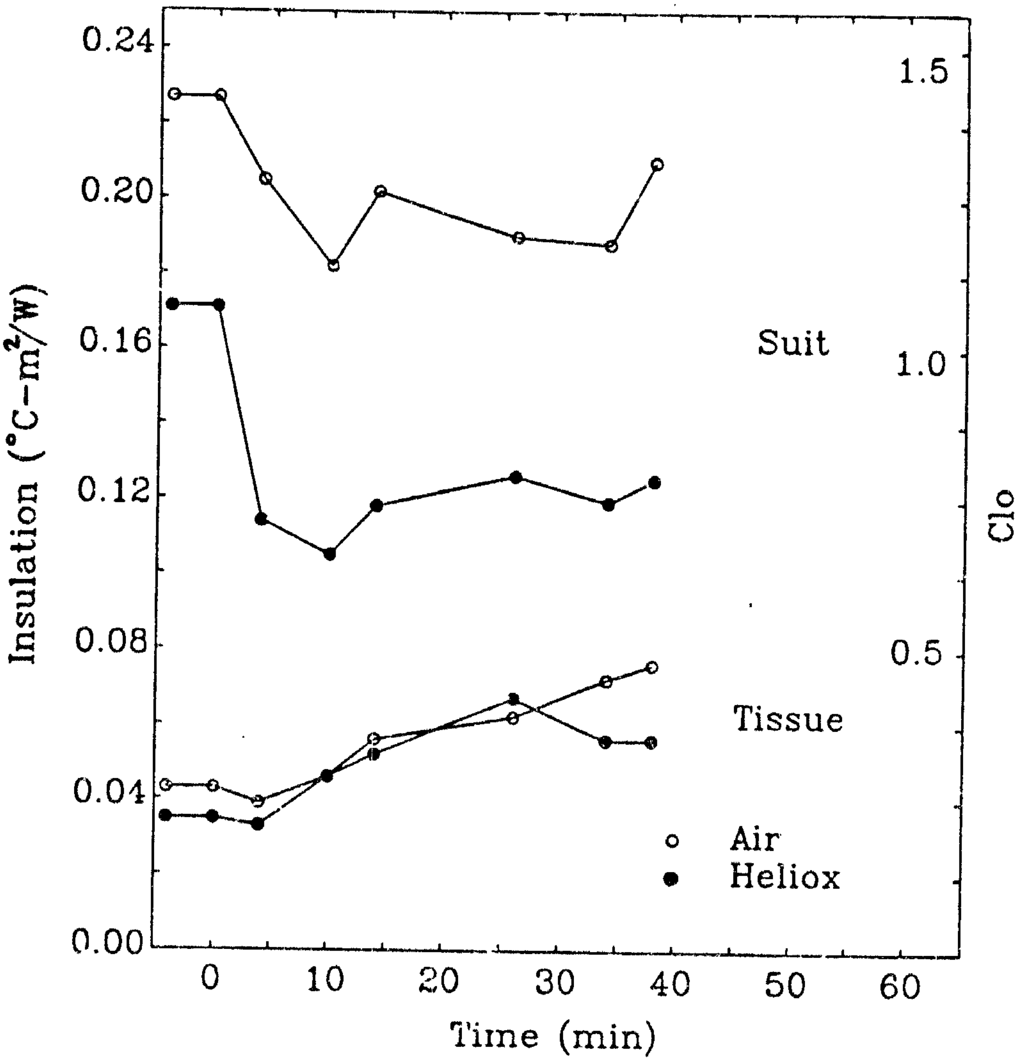


Fig. 2. Comparison of suit insulation with air and heliox as suit inflation gases.

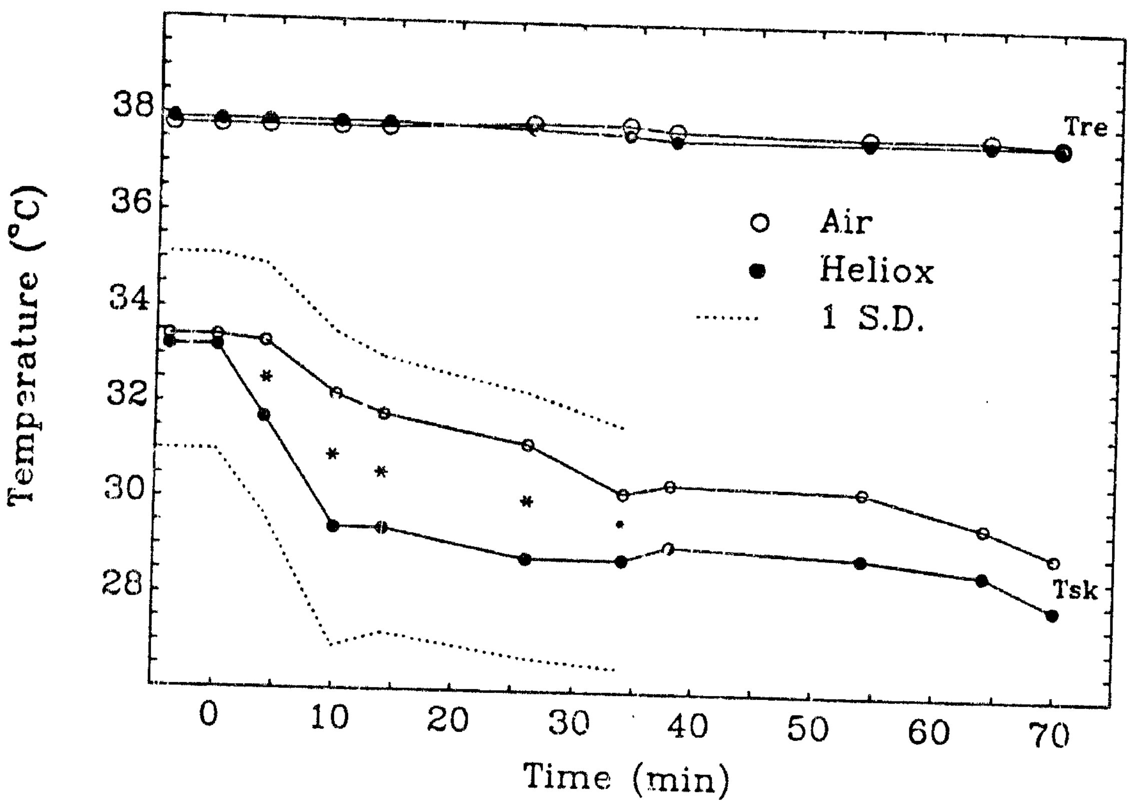


Fig. 3. Comparison of rectal and skin temperature with air and heliox as suit inflation gases.

THE POTENTIAL OF PASSIVE THERMAL PROTECTION IN COLD WATER DEPENDENT UPON BODY COMPOSITION AND WORK LEVEL

P. A. Hayes
National Hyperbaric Centre
Aberdeen, Scotland, AB2 SFA.

ABSTRACT

Suggestions abound as to the minimal and maximal levels of peripheral and core temperatures and acceptable rates of fall or heat transfer that can be tolerated by the diver in cold water. What is not so commonplace is an indication of whether the sometimes arbitrary limits are acceptable lower levels or the upper levels of a dangerous condition which one should rarely encounter. The influence of the level of work and the impact of differences in body composition are rarely considered in the application of these limits. This paper examines the potential of passive systems to provide the required flexibility of thermal protection over a range of activity in water below 5°C. The magnitude of respiratory and suit heat loss are estimated with respect to changing heat production, tissue conductance and net heat loss.

POTENTIAL OF PROTECTION

This paper is a semi-empirical analysis of the heat balance of a diver in shallow water. Although the precise values for the thermal limits and the values of heat transfer chosen may not receive universal agreement, it is the essential concept and method of manipulation that are of interest. This present approach owes much to the technical paper by Thornton (1981).

The thermal balance of a diver is a complex function of a number of variables including depth, gas mixture, water temperature, rate of work, inherent tissue insulation and clothing insulation. Additional factors include size of the man, level of habituation to cold and perhaps physical (endurance) fitness. The problem of protection can be reduced to two interrelated requirements:

1. Reduce the level of overall body heat loss, such that any fall in core temperature does not jeopardize cognitive performance or safety over a specified dive duration.
2. Reduce peripheral and extremity heat loss such that the body nervous tissue is maintained above a level where manual performance and sensation are badly affected or pain is felt.

It is generally taken that these requirements can be met by designing protection to meet the following criteria:

a) Deep body temperature should not fall below 36.0°C;
b) The maximum acceptable net heat loss from the diver should not exceed 840 kJ, equivalent to 0.23 kWhr;

c) Mean skin temperature should be maintained above 25°C; no individual site should be less than 20°C, save the hands and feet where the limit is 15°C;

d) Respiratory heat loss should not exceed 200 W, thereby providing a minimum inspired gas temperature limit dependent upon depth and average level of ventilation. Recent NPD/D of En. guidelines suggest respiratory heat loss should not exceed 15% of energy expenditure.

When diving at night it should be noted that no consideration has been given to the effect of a fall in deep body temperature of 1.0°C below the normal body temperature, at say 0400 hrs, when the natural circadian rhythm may result in an initial temperature as low as 35.5°C.

Note that the risk of non freezing cold injury may exist at 15°C for extensive (24-48 hrs) exposure, particularly in previously damaged or injured tissue, but could occur at temperatures below 8°C over much shorter times, perhaps 60 minutes. However, there are many incidents of hands and feet maintaining function and integrity of tissues at temperatures below 5°C for considerable time, particularly in habituated or "locally" acclimatised individuals. Incidents of sudden exposure to sea water below freezing, as in a sudden rip in a suit, can result in recoverable damage to the skin and vasculature resembling severe bruising.

THERMAL BALANCE

Respiratory heat losses, without exchanger or shroud, and typical body surface rates of heat transfer estimated for a diver carrying out work in 4°C are shown in the following Table I (values in Watts).

Depth m	Respiratory Loss 8 (0.3)	20 (1.1)	40 (2.2)	Clothing Togs	Dry Suit + insulation loss(W)	Heat Production (0.3)	(1.1)	(2.2)	Net Heat Loss (0.3)	(1.1)	(2.2)
1	6	11	22	1.5	170	100	290	575	76	-109	-383
10	9	17	34	1.5	170	100	290	575	79	-103	-331
30	18	34	69	1.0	400	100	290	575	318	144	-106

Table I: Table of respiratory heat losses, heat losses through dry suit and insulation (e.g. PTS), heat production at 25% efficient work and net heat loss from the body. The numbers 8, 20 and 40 are representative values of ventilation (L min^{-1}, BTPS) with the corresponding values of oxygen uptake (0.3, 1,1 and 2.2 L min^{-1} STPD) below.

It is noted from Table I that there is, a net heat loss at all depths if the diver is resting (typically $\dot{V}O_2$ = 0.3 L min^{-1}), but there is a net heat gain as a result of moderate activity (VO_2 typically 1.1, V/VO_2 approx.= 18), at depths of 1 and 10 m, but a loss at 30 m. At heavy work there is a net heat gain.

These estimates should be taken in the light of typical diving activities such as:

SCUBA/SDV	Depth 10m	Duration 6 hrs
Bandmask/Aga/CDBA	30m	Duration 1 hr

Rates of heat transfer can subsequently be turned into quantities by the product of time (see Table II below).

Depth	Time	Net Heat Loss Rest	Moderate	Heavy	Reduction in body heat content kJ (kWhr)		
1	6 hr (21600s)	76	-109	-383	1642(0.46)	-2354(0.65)	-8273(2.3)
10	6 hr (21600s)	79	-103	-371	1706(0.47)	-2225(0.62)	-8014(2.2)
30	1 hr (3600s)	318	144	-306	1145(0.32)	518(0.14)	-1102(0.31)

Table II. Quantities of heat lost from the body during representative dive durations in shallow water.

All resting dives result in a reduction in body heat content of more than the recommended level of 840 kJ (0.23 kWhr). Moderate exercise at 30 m results in a minor negative balance but would be acceptable for the 1 hr dive. Any active dive of approximately $\dot{V}O_2 = 1$ L. min^{-1} continually would result in a positive heat balance and the diver would need to lose heat, by some means, at a rate of about 100 Watts whilst in water of 10 m depth or less. Any sustained work would result in a diver becoming overheated. The tolerance time, according to the formula suggested by Blockley (1963) would be in the order of 1.5 hrs at 1 to 10 m performing moderate amounts of work.

If moderate or hard work is required at the end of a long period of minimum activity in cold water then a compromise may be necessary whereby suit insulation is reduced but work is artificially substituted for the resting state.

Work should be performed without subsequent overheating and/or degradation of the insulation as the result of sweating. Data from Hall and Polte (1956) suggest that 500 grams of sweat, not an unreasonable amount over a sustained period, would reduce insulation by about 15%. This reduction occurs irrespective of the choice of underwear, be it of polyolefin, acrylic or animal origin. A total of 1000 grams of sweat would reduce the 1.5 tog rated assembly to 0.6 togs and heat loss would be accelerated to 240 Watts.

In summary, for the diver to remain in balance it would be necessary to either recover 80 Watts of heat or promote an additional energy expenditure of approximately 110 Watts (total 210 W or $\dot{V}O_2 = 0.6$ L min^{-1} STPD).

BODY COOLING RATE

If one looks at the relationship between the fall in core temperature ΔTc) and the net quantity of heat removed from the body (kJ kg^{-1}) it is evident that the correlation is poor, particularly when using a large number of subjects of different build and various rates of cooling. Webb (1984) pointed out that a man of 70-75 kg cooled rapidly by the extraction of 840 kJ (200 kcals) over 30 minutes would probably be in poor state (Tc < 34.5°C), perhaps semi conscious), whereas the same quantity of heat extracted over 2 hours results in a core temperature of about 35.5°C. A 50% increase in the heat extracted but occurring over an 8 hour period results in a core temperature maintained about 36°C. Tissue thermal conductances the relative size of "core" and "shell" and the impact net heat loss can have on central function and the risk of hypothermia are clearly different between these three cases. So what is the relevance and significance of the limit of 840 kJ (about 11 kJ kg^{-1} for the 75 kg man) in each case? It is apparent that a fall of 1.5°C can be caused by anything between 18 and 45 kJ kg^{-1} (Hayes, 1988) depending upon the rate of cooling and the individual concerned. In effect, the simplified analysis presented in Tables I and II above may represent an inaccurate extrapolation of the measured data because the process of heat loss and temperature change is far from "linear" in its development. Despite this reservation the derived numbers appear to accord reasonably well with the findings of Piantadosi et al (1979). However, strict adherence to the principle of "... no more than 200 kcals..." highlights the question of whether we are offering acceptable limits (routinely encountered) or dangerous levels (always to be avoided); time will tell the difference! However, it is apparent that over 6 hours it is likely that the shallow water diver can tolerate the loss of more than the recommended level. Does a temperature drop of a certain amount represent the same risk however it occurs?

BODY FAT

The role of body fat in any study of heat balance is complex. Tissue thermal insulation will increase and the rate of heat loss will be reduced in fatter, persons. This in itself will alter the relationship between ΔTc and kJ kg^{-1} (net heat loss). Additional fatness often infers increased tissue mass and this too will modify our view of how much heat can be safely lost. If there is a reduced heat loss there is usually a reduced heat production and this may be borne out by the frequent observation that fat people shiver less for the same conditions of "core" and "skin" temperature.

Tissue thermal insulation depends not only on the amount of subcutaneous fat but also on the metabolic activity of the underlying muscles, i.e. how much shivering and perfusion is taking place?

Below a certain water (skin) temperature total tissue insulation will decrease as shivering (and consequently muscle perfusion) increase. Non shivering men demonstrate total tissue insulations of between 0.1 °C m^2W^{-1} (1 tog) and 0.22 °C m^2W^{-1} (2.2 togs) across the range from thin to obese, (Wade et al, 1979). The muscular component can vary from 0.8 to 1.5 togs, dependent upon the bulk of muscle, its blood flow and also the amount of overlying fat. However, working divers are likely to display much greater conductances and level of heat transfer through the muscles. Values of 0.6 togs (0.4 clo or 0.06 °C m^2W^{-1} or 16 W m^{-2} °C^{-1}) were reported by Kang et al (1983), and 0.35 togs by Pugh and Edholm (1955) for a thin man. The review by Rennie (1988) indicates that muscle insulation is negligible, irrespective of fat levels, at energy expenditures above 300 Watts and it seems likely that the origin, whether work or shivering, will make little difference. Padbury (1984) reports body tissue conductances of 17.3 ± sd 1.5 W m^{-2} $°C^{-1}$ with skin temperature between 28°C and 32°C, corresponding to a resistance of 0.6 togs. Values range from 0.4 (thin) to 1.2 togs (fat). Corresponding diver heat losses for the condition of core = 37°C and skin = 30°C would be 101 Watts for the fattest man but 316 Watts for the thin. If both men, fat and thin, wore a suit which maintained the mean skin temperature at 30°C, the latter would lose 3 times more heat than the former. The fat man could afford to rest virtually indefinitely whereas the thin man would expect to lose 840 kJ from body stores in 45 minutes. In reality the skin and core would both fall and tissue insulation may reduce still further due to high shivering levels. One may therefore expect a large variation in diver capability and cooling rate, with perhaps 3 times the duration spent in water before reaching a critical phase, dependent on a large subcutaneous fat thickness of the big man compared to the small and thin.

However, the same fat layer which provides a resistance to convection heat loss in the cold constitutes a risk during high levels of activity when the man would be overinsulated, not only as a result of the suit but also due to his own tissues.

REFERENCES

BLOCKLEY, W V: (1963) Heat storage rate as a determinant of tolerance time and duration of unimpaired performance above 150°F. Fed. Proc.22:887.

HALL, J F and POLTE, J W: (1956) Effect of water content and compression on clothing insulation. J.Appl.Physiol.,8:539-545.

HAYES, P A: (1988) The physiological basis for the development of immersion protective clothing. Chapter 12 of "Environmental Ergonomics", Ed. Mekjavic, I B, Banister, E W, Morrison, J B: 221-239.

KANG, D H, PARK, Y S, PARK, Y D, et al.: (1983) Energetics of wet-suit diving in Korean women breath-hold divers. J.Appl.Physiol.54:1702-1707.

NUCKOLS, M L: (1978) Thermal considerations in the design of divers' suits. Paper presented to Winter Annual Meeting, Am. Soc. of Mech. Eng. OED-Vol.6:83-99.

PADBURY, E H: (1984) Thesis entitled "A practical evaluation of the thermal problems of man in the diving environment". London University

PIANTADOSI, C A, BALL, D J, NUCKOLS, M L, THALMANN, E D: (1979) "Manned evaluation of the NCSC diver thermal protection (DTP) passive system prototype": US Navy Experimental Diving Unit Report No.13-79.

PUGH, L G C E, EDHOLM, 0 G: (1955) The physiology of channel swimmers. Lancet 2:761-768.

RENNIE, D W: (1988) Tissue heat transfer in water: lessons from the Korean divers. Med.Sci.Sports Exerc., Vol.20, No.S (Supplement): 177-184.

THORNTON, A G: (1981) The potential of passive methods for thermal protection of divers. AMTE(E) R80522. EDU, HMS Vernon, Hampshire.

WADE, C E, DECANAY, S, SMITH, R M: (1979) Regional heat loss in resting man during immersion in 25.2°C water. Aviat. Space Environ. Med.50:590-593.

WATTENBARGER, J F, BRECKENRIDGE, J R: (1978) Dry suit insulation characteristics under hyperbaric conditions. ASME OED-6:101-116.

WEBB, P: (1982) Thermal Limits. Outline of discussion at the Workshop for Evaluation of Thermal Models, University of Texas at Austin.

LIQUID-FILLED SUIT/INTERSUIT CONCEPT
PASSIVE THERMAL PROTECTION FOR DIVERS

M. L. Nuckols*, M. W. Lippitt+, John Dudinsky+

*US Naval Academy
Naval Systems Engineering
Annapolis, MD 21401

+Naval Coastal Systems Ctr
Code 5110
Panama City, FL 31407

ABSTRACT

Active thermal protection methods are being considered for Navy divers during prolonged missions in 29°F - 40°F water. Previous estimates for heating requirements during low activity dives range from 300 - 500 watts per diver. This power level will create a significant storage requirement on prolonged missions, where up to 24 Kw-hrs could be required for diver heating alone. One means of reducing or eliminating active heating requirements is investigated here. This concept, referred to as the Liquid-Filled Suit/Intersuit, consists of a double-walled drysuit with a good passive thermal undergarment. A low conducting fluid is pumped into the interspace between the drysuit layers to improve the insulating qualities of the garment during periods of low diver activity. Prior to high activity, where metabolic heat production is high and good mobility is required, the liquid is drained from the suit giving a garment comparable in insulation to the present Passive Diver Thermal Protection System (PDTPS). Applications for this concept could be found in the Navy Specwar community where minimal surface support is available, and EOD community where long, in-water decompressions might be required.

INTRODUCTION

The liquid-filled suit/intersuit concept, shown in Figure 1, is intended to give a passive means for providing thermal protection for long, cold underwater missions. Conventional passive approaches use micro-fibrous batts beneath lightweight drysuits to provide thermal protection during the entire mission. The required insulation thickness to maintain thermal comfort during long, cold missions at low metabolic levels (typical of SDV missions) would be excessively bulky, and overly buoyant, for subsequent swimming scenarios.

In a SDV mission, the liquid-filled suit/intersuit can provide the resting diver with a liquid layer having a density approximately that of water, and having a low thermal conductivity for protection. In so doing, the diver is provided with added insulation without the additional buoyancy and bubble migration in the shoulders and neck region found when inflating drysuits with a gas. When the diver is required to swim from the SDV, the liquid can be drained from the interlayer to give a low suit bulk with reduced insulation. With the liquid removed, the diver is essentially swimming in a conventional drysuit with a Thinsulate undergarment.

This concept can also be beneficial during extended in-water decompressions for deep salvage missions. As the diver rests on the decompression stage, he can inflate his suit/intersuit with insulating fluid to better endure the cold water.

The primary advantage of this concept, as listed in Table 1, is that the diver can be protected from the cold without an active heating source. A beneficial side effect is that the insulating liquid is unaffected by suit squeeze, giving the feet and legs further protection. By properly selecting the insulating liquid to have a specific weight approximately that of water, minimal buoyancy variations will occur as the fluid level in the suit is varied. Table 2 lists some potential fluids for this concept based on their low thermal conductivities. Although toxicological and suit material compatibility concerns are not addressed in this analysis, the importance of these issues is not intended to be overlooked.

THERMAL INSULATION POTENTIALS

The liquid-filled suit/intersuit consists of a Passive Diver Thermal Protection System (PDTPS), having a B400 Thinsulate undergarment and a tri-laminate drysuit, covered with an elastic outer drysuit, Figure 1. Previous testing has characterized the insulation value of the PDTPS as 1.2 CLO (0.95 BTU/ft^2-hr-°F). The outer drysuit is assumed to be a 0.030-inch thick reinforced elastomer (K = 0.12 BTU/ft-hr-°F).

The total thermal conductance of the liquid-filled suit/intersuit can be approximated as

$$\text{Total Suit Conductance, } H_{TOTAL} = \frac{1.0}{\dfrac{1}{H_{PDTPS}} + \dfrac{X_{OG}}{K_{OG}} + \dfrac{X_{LIQ}}{K_{LIQ}}}$$

where:

- X is the layer thickness, ft
- K is the thermal conductivity, BTU/ft-hr-°F
- H is the thermal conductance, BTU/ft^2-hr-°F
- subscripts OG outer garment drysuit; LIQ liquid layer

$$H_{TOTAL} = \frac{1}{\dfrac{1}{0.95} + \dfrac{0.03/12}{0.12} + \dfrac{X_{LIQ}}{K_{LIQ}}} = \frac{1}{1.073 + \dfrac{X_{LIQ}}{K_{LIQ}}}$$

The effective suit insulation, expressed in units of CLO can then be written

$$\text{Effective Suit CLO} = \frac{1.136}{H_{TOTAL}} = 1.22 + 1.136 - \frac{X_{LIQ}}{K_{LIQ}}$$

Figure 2 shows effective suit insulation values obtainable when using a light oil (K = 0.077 BTU/ft-hr-°F) in this suit configuration. These insulation values can possibly be improved as other suitable liquids are identified.

Estimates of the mission durations that would be permissible with the liquid-filled suit can be made by looking at an energy balance for a diver as follows:

$$\dot{Q} + \dot{M} - (\dot{Q}_{RESP} + \dot{C}_S + \dot{R} + \dot{W}) = \dot{S} \qquad \text{(EQU 1)}$$

where

$\dot{Q}$ = Supplemental heating (active)
$\dot{M}$ = Metabolic heat production
$\dot{Q}_{RESP}$ = Respiratory heat loss
$\dot{C}_S$ = Suit heat loss
$\dot{R}$ = Radiation heat loss
$\dot{W}$ = Diver work rate
$\dot{S}$ = Rate of energy storage/loss from diver

Assumptions:

$\dot{Q}$ = 0 since concept depends on passive insulation only
$\dot{W}$ = 0 since the diver is resting
$\dot{R}$ = 0 since radiation heat loss is negligible under water

Based on the BUMED thermal criteria for cold water diving, the dive should be terminated when

$$S/m = -5.4 BTU/lb$$

where

m is the mass of the diver's body
s is the lost body heat.

Since $\dot{S} = S/t$ where t is the mission time, then

$$\dot{S} = -5.4\ m/t$$

By substituting the above assumptions and equalities into Equation 1, we obtain

$$(\dot{M} - \dot{Q}_{RESP}) - \dot{C}_S = -5.4\ m/t$$

But

$$\dot{C}_S = H\ A(\bar{T}_{MS} - T_\infty) = (1.136/CLO)\ A\ (\bar{T}_{MS} - T_\infty)$$

where

H is the overall convective heat transfer coefficient between the diver and the water
A is the body surface area
$\bar{T}_{MS}$ is the mean skin temperature of the diver
T_∞ is the surrounding water temperature

If we assume the "average diver" is 178 lbs (1) and has a surface area of 19.4 ft^2, with a minimum mean skin temperature given by BUMED (2) as 77°F (this assumption will give conservatively high estimates of suit heat loss as the diver becomes chilled), then we can solve Equation 1 for the permissible mission duration as

$$t,\ hrs = \frac{-961}{(\dot{M} - \dot{Q}_{RESP}) - 22.04(77 - T_\infty)/CLO} \qquad \text{(EQU 2)}$$

For shallow depths, as in most Specwar missions, $\dot{Q}_{RESP}$ is small compared to $\dot{M}$ (approximately 5% at the surface). Therefore, estimates for $\dot{M} - \dot{Q}_{RESP}$ will be assumed for this analysis to be the metabolic level for a resting diver in cold water; 450 BTU/hr.

Figures 3 through 5 show the estimated mission durations from Equation 2 (tabulated in Appendix A) that would be permissible when using the liquid-filled suit concept. Acceptable mission durations in excess of 6 hours are indicated with this passive protection method with only a 0.5-inch liquid layer thickness in 28°F water; this compares with approximately 2 hours when using the PDTPS. This improvement is further magnified in 35°F water; 17 hour durations are indicated with a 0.5-inch liquid layer, whereas, only 3 hours are allowable with the PDTPS.

Perhaps even more significant is the absence of suit squeeze in the legs and feet with this concept, providing added thermal comfort in difficult regions noted with conventional drysuits. It is possible that localized active heating would still be necessary when using this concept in long, cold missions, however, the power storage requirements would be only a fraction of that needed with current active heating of the whole diver.

REFERENCES

1. Beatty, H. T., Berghage, T. E., "Diver Anthropometrics", NEDU Report 10-72, Naval Experimental Diving Unit, Panama City, FL 32407.

2. Webb, P., Beckman, E. L., Sexton, P. G., Vaughan, W. S., "Proposed Thermal Limits For Divers: A Guide For Designers of Thermally Protective Equipment", ONR Contract N00014-72-C-0057, July 1976.

ACKNOWLEDGMENT

The authors wish to express their sincere appreciation to Mr. Martin Harrell, Eastport International, Inc for the initial proposal and encouragement in pursuing this concept.

TABLE 1

LIQUID-FILLED SUIT/INTERSUIT ADVANTAGES

-NO ACTIVE HEATING REQUIRED

-LIQUID UNAFFECTED BY SUIT SQUEEZE IN LEGS OR FEET

-MINIMAL BUOYANCY VARIATIONS

-NO SUIT BALLOONING IN NECK OR SHOULDERS

-SUIT INSULATION EASILY VARIED

TABLE 2

POTENTIAL INSULATING LIQUIDS LIQUID-FILLED SUIT/INTERSUIT CONCEPT

LIQUID	THERMAL CONDUCTIVITY BTU/FT-HR-F	DENSITY LB/CUFT
FLUORINERT FC-77**	0.037	110.0
LIGHT OIL	0.077	57.0
ANILINE	0.100	63.8
n-BUTYL ALCOHOL	0.089	50.6
ETHYLENE GLYCOL	0.100	69.2
GLYCERINE	0.113	78.7
ISOBUTYL ALCOHOL	0.082	50.0
KEROSENE	0.086	51.2
TURPENTINE	0.073	53.9
PROPYLENE GLYCOL	0.116	65.5
ETHYL ALCOHOL	0.097	49.2
HEPTYL ALCOHOL	0.094	51.2
PENTANE	0.078	39.1
*WATER	0.348	62.3

**FLUORINERT IS AN ELECTRONIC LIQUID TRADENAME
* WATER IS SHOWN FOR COMPARISON

APPENDIX A

ESTIMATED MISSION DURATIONS

$$t, \text{hrs} = \frac{961}{(M - Q_{resp}) - 22.04(77 - T)/CLO}$$

LIQUID THICKNESS, in		T °F	t, hrs	
			$M - Q_{resp} = 350$	$M - Q_{resp} = 450$
0.0	(1.22 CLO)	28	1.8	2.2
		35	2.4	3.1
		45	4.2	7.5
		55	20.3	24+
0.25	(1.53 CLO)	28	2.7	3.8
		35	3.8	6.2
		45	8.7	24+
		55	24+	24+
0.50	(1.83 CLO)	28	4.0	6.9
		35	6.2	17.2
		45	24+	24+
		55	24+	24+
0.75	(2.14 CLO)	28	6.2	17.6
		35	11.6	24+
		40	24+	24+
1.0	(2.45 CLO)	28	10.6	24+
		35	24+	24+

FIGURE 1: LIQUID-FILLED SUIT/INTERSUIT CONCEPT

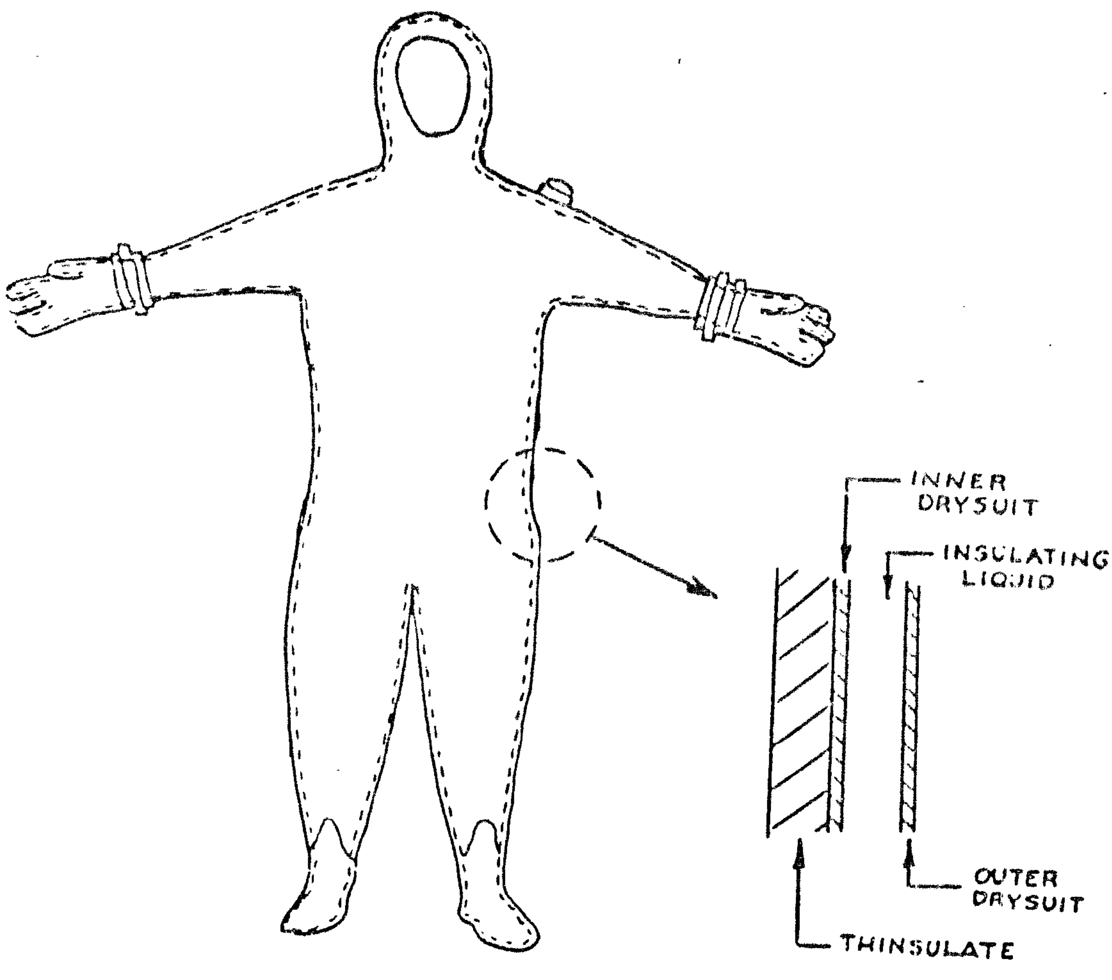
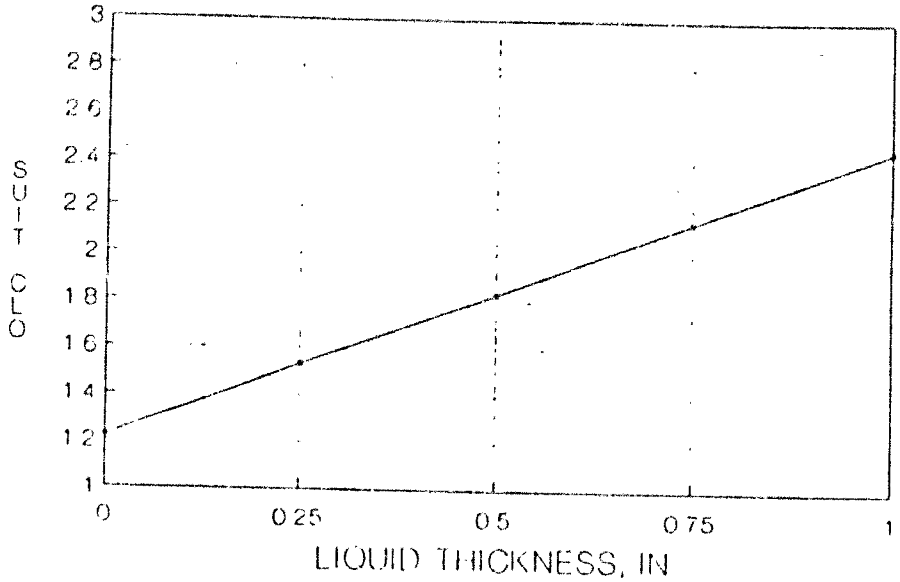
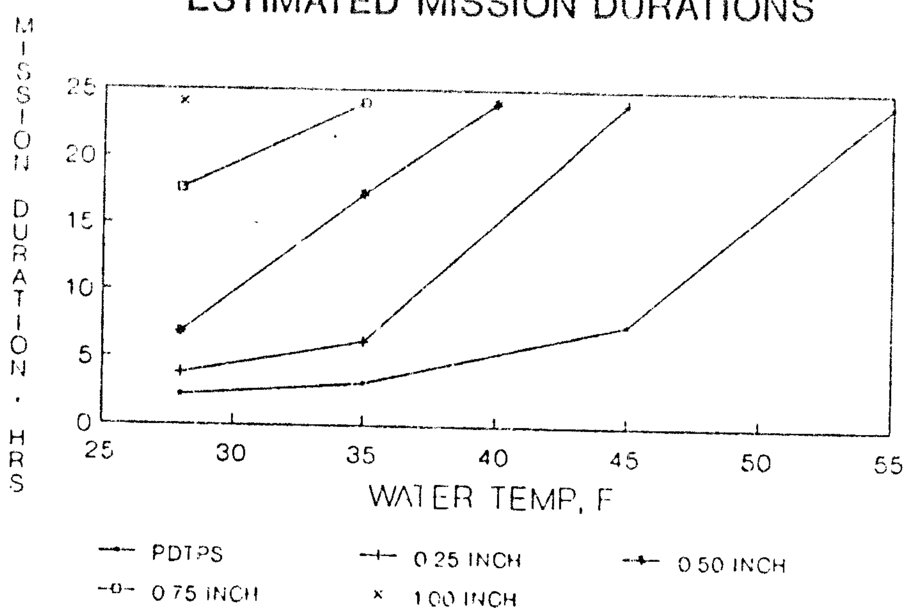


FIGURE 2: LIQUID-FILLED SUIT/INTERSUIT INSULATION POTENTIALS



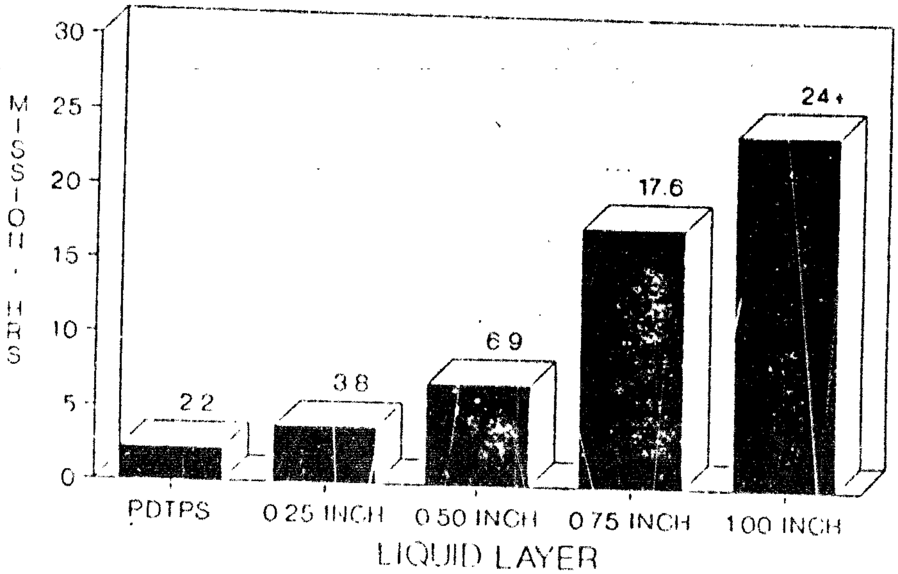
LIGHT OIL K = 0.077 BTU/FT HR F

FIGURE 3: LIQUID-FILLED SUIT/INTERSUIT ESTIMATED MISSION DURATIONS



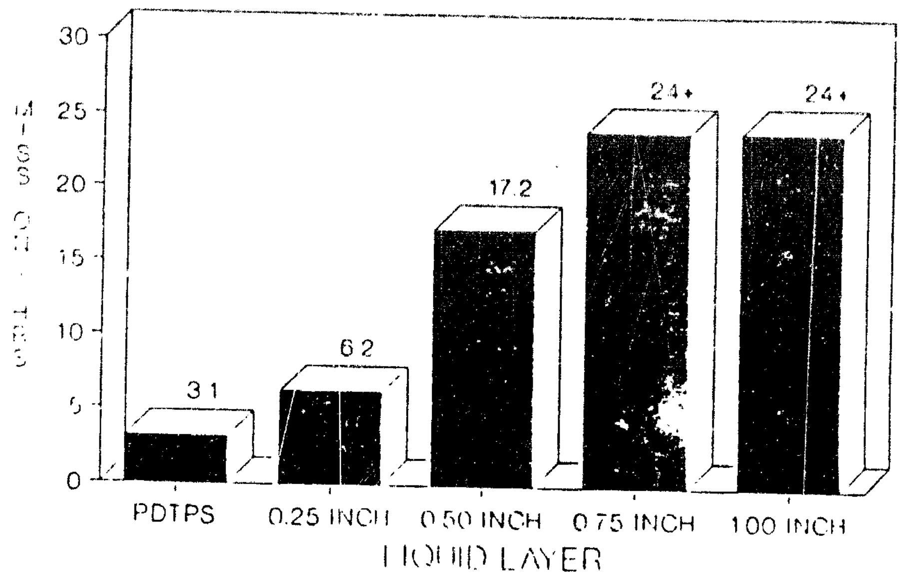
[illegible] 450 BTU/HR, LIQUID K = 0.077

FIGURE 4: LIQUID-FILLED SUIT/INTERSUIT ESTIMATED MISSIONS IN 28 F WATER



[illegible]-M-450 BTU/HR, LIQUID [illegible] 0.077

FIGURE 5: LIQUID-FILLED SUIT/INTERSUIT ESTIMATED MISSIONS IN 35 F WATER



[illegible]-M-450 BTU/HR, LIQUID [illegible]

UNDERGARMENTS: THERMAL CONDUCTIVITY (WET VS. DRY), COMPRESSIBILITY AND ABSORBENCY

LCdr John A. Sterba, MC, USNR
Navy Experimental Diving Unit
Panama City, FL 32407-5001

ABSTRACT

Selection of undergarments (U/G) for cold water diving has recently been based on anecdotal reports rather than scientific evidence. Previous studies in the late 70's revealed hydrophobic microfibrous material (Thinsulate) to be superior in both insulation when wet and compressibility compared to open-cell foam. The objectives of this study included comparing Thinsulate against the new U/G materials in a controlled, unmanned laboratory. Following a market survey and preliminary testing of 32 U/G composites, nine U/G were chosen: four using arctic fleece, radiant barrier and non-Thinsulate battin from Defense Marketing Consultants (DMC), four using Thinsulate M-400 and M-600 from Diving Unlimited International (DUI) and the Flectalon U/G composite from Arktis Outdoor Products. All U/G samples were 12" X 12" (30.5 cm X 30.5 cm). Thermal conductivity was measured in a calibrated, Rapid "K" machine (Holometrics, Cambridge, MA). Multiple trials verified accuracy and reproducibility for all U/G tested. Significant difference between U/G samples was achieved by ANOVA and Turkey HSD tests with $p < 0.05$ accepted as significant. Compressibility data at 1.1 psi (2.5 fsw equivalent suit squeeze) demonstrated Flectalon most compressible (-60.7%), DMC moderately compressible (-48.6%) and DUI least compressible (-34.5%). Further compression to 2.2 psi (5.0 fsw) was minimal. Absorbency testing was analyzed for the water weight gain for the U/G, per se, and U/G per unit thickness. Overall, DMC U/G were very absorbent compared to DUI and Flectalon U/G. Insulation values were analyzed dry and wet (saturated), at 1.1 psi for both the U/G, per se, and U/G per unit thickness. In summary, dry U/G per unit thickness showed few differences, range 1.55 ± 0.02 to 1.78 ± 0.11 Clo/cm, mean ± SD, n=5. Saturated with water, the superior U/G, per se, were Flectalon, DUI M-600 and one DMG U/G using Dupont Dacron-II batting. The range was 0.14 ± 0.01 to 0.19 ± 0.07 Clo. The superior wet U/G, per unit thickness, included the above and M-400 DUI U/G, the range being 0.21 ± 0.03 to 0.32 ± 0.08 Clo/cm. In conclusion, rating compressibility, absorbency and insulation (wet), the superior U/G included Flectalon and DUI U/G, M-400 and M-600 weights. Other DMC U/G were ranked next, primarily due to high absorbency. The DMC radiant barrier, though not studied, would not significantly contribute to reflected radiant energy based upon the small gradient between skin and water temperature according to work done by Stefan and Boltzmann.

The opinions or assertions contained in this article are the private views of the author and are not to be construed as reflecting the view of the United States Department of the Navy or the Department of Defense.

PRECEDING PAGE BLANK

INTRODUCTION

Selection of undergarments for cold water diving has recently been based upon anecdotal reports of subjective comfort. The presently perferred undergarments are of single-piece construction and are thicker than the two-piece, fleet issued undergarment known to allow cold air to baffle next to the diver's skin with underwater movement. To assist Special Warfare (SPECWAR), Explosive Ordnance Disposal (EOD) and Underwater Construction Team (UCT) divers in the U.S. Navy, a controlled study was undertaken at NEDU to determine the optimal undergarment for cold water diving. This study was part of our task from NAVSEA to evaluate diver Passive Thermal Systems (PTS), i.e., dry suits with thick undergarment insulation.

A preliminary study of 39 different undergarment samples determined that the nine chosen for this study were the most promising for use in extreme cold water. These nine samples were evaluated for the degree of thermal insulation, both dry and wet, by measuring thermal conductivity. With suit squeeze limiting the trapped dead air space which is the insulation, compressibility testing was done at various equivalent suit squeeze depths. Being that all dry suits develop leaks due to improper use, defects in materials or lack of attention to maintenance, the degree of water absorbency was also determined. A flooded dry suit can not only decrease thermal insulation, trapped water within the undergarment material can create a dangerous negative buoyancy problem. In addition, the weight of the absorbed water within the undergarment may make it impossible for the diver to exit the water without topside assistance.

Since undergarments vary in thickness, the result of these tests were expressed in unit thickness as well, to comment on the material, per se. All undergarment samples were new, 12" X 12" (30.5 cm X 30.5 cm) swatches received from the companies. The manufacture key and composition key are listed below. In Table #1, the sample number of the nine samples, along with the sample name, manufacturer and composition are listed. The DMC,B sample is known as either Underwave or DMC, 27 F, which is the currently perferred undergarment by SPECWAR SDV Team One. Flectalon is also a production composite undergarment perferred by the Special Boat Squadron, U.K. Special Forces, Royal Navy. The flannel covering on the Thinsulate is a permeable covering, opposed to the vapor barrier. The M-400 weight Thinsulate is the undergarment currently issued to U.S. Navy divers using Passive Thermal Systems (PTS), M-600 Thinsulate is composed of two layers of Thinsulate, M-400 plus M-200.

COMPRESSIBILITY

The thickness of each sample in the uncompressed and compressed state were measured repeatibly with a caliber. The degree of suit squeeze for an equivalent depth of 2.5 feet of sea water (fsw) is 1.1 pounds per square inch (psi), and for 5.0 fsw, it is 2.2 psi. Using lead weights equally distributing weight over a known surface area of the dry undergarment material, caliper measurements were made to determine the degree of compressibility.

Compressibility to 2.5 fsw (1.1 psi) ranged in percent change from -30.4% for M-400, flannel Thinsulate to as high as -62.5% for DMC, version C. Further compression to 5.0 fsw (2.2 psi) only compressed the garments an additional -3.2 to -13.1%. Figure 1 illustrates the changes in compressibility for the garment samples.

ABSORBENCY

The dry garment samples were weighed on an electronic scale. Samples were then completely saturated in water, and allowed to drip such that only a small amount of excess water could be expressed when the wet sample was placed in the thermal conductivity machine. Repeated measurements were made of the dry weight, wet weight, water weight increase and water weight increase per unit thickness. The multiple trials allowed statistical tests (ANOVA and Turkey HSD) to be run on these results. In summary, the DMC and Arctic Fleece undergarments were significantly shown to be much more absorbent over the four Thinsulate undergarments and Flectalon. This was true not only for the undergarment but for the undergarment per unit thickness. In other words, the materials used by DMC are inherently more absorbent to water than the hydrophobic microfibrous batting of Thinsulate and for some unknown reason, the relatively less absorbent polyester batting and filaments found in Flectalon. These results are illustrated in Figure 2.

THERMAL CONDUCTIVITY

The effectiveness of these undergarments to insulate the diver was actually determined by measuring their capacity to conduct heat, known as thermal conductivity. This was repeatedly measured in all undergarments using a calibrated thermal conductivity instrument, (Rapid-k, Holometrics, Inc., Cambridge, MA). The unit of thermal insulation, the Clo, was then calculated from the thermal conductivity measurements. All thermal conductivity measurements were made with a simulated 2.5 fsw suit squeeze. Being that these values were very accurate and reproducible plus they may benefit others concerned with predictive modeling for PTS performance, Table 2 lists the insulation Clo values for the undergarment and undergarment per unit thickness, dry and wet. In summary, the degree of insulation for the dry undergarments was of course related to the thickness of the undergarment and ranged from 0.67 to 1.07 Clo. As expected, the differences between dry undergarments per unit thickness, was very small ranging from 1.56 to 1.78 Clo/cm. The important comparisons were the degree of insulation if the undergarments were wet, which is also listed on Table 2. Both of the M-600 Thinsulate undergarments were not significantly different in insulation from Flectalon, however, DMC,B which is perferred by SPECWAR had less insulation than Flectalon. DMC,B was not significantly different from the two M-600 Thinsulate undergarments. The undergarment per unit thickness is a measure of the insulation of the material, per se. In summary, the two M-600 Thinsulate undergarments, Flectalon and DMC,B were not significantly different when comparing the undergarments per unit thickness. The results of insulation, wet vs. dry for each undergarment are shown in Figure 3 and per unit thickness in Figure 4.

CONCLUSIONS

The best undergarments for insulation dry and most importantly wet were the M-600 Thinsulate undergarments and Flectalon. Next, due to less thickness but excellent insulating capacity when wet would be the M-400 weight Thinsulate undergarments. What detracts from DMC,B being a superior undergarment is the extremely high absorbency to water and the subsequent loss of insulation compared to Thinsulate or Flectalon. One can speculate that the Flectalon undergarment could improve its insulation value when wet if its polyester batting was replaced with the hydrophobic batting, Thinsulate.

The other DMC undergarments and Arctic Fleece were found to be very substandard for reasons of relatively high compressibility and absorbency giving overall poor insulation values when wet. This method of measuring thermal conductivity cannot determine if a vapor barrier is important to help prevent evaporative heat loss at the diver's skin. Also, this method does not measure the effect of the Mylar barrier to reflect back the diver's radiant heat. However, with the temperature difference between the diver's average skin temperature and coldest water only being about 40°F, and Stefan's Law requiring the temperature difference to be raised to the fourth power to calculate the amount of radiant energy, the effect of Mylar radiant barrier to reflect any heat back to the diver is insignificant underwater.

NEDU report Number 10-89, entitled "Diver thermal protection: insulation, compressibility and absorbency", includes all data with statistics plus the ranking used to compare undergarments based upon the results of these tests.

TABLE 1
UNDERGARMENT SAMPLES

SAMPLE #	SAMPLE NAME	MANUFACTURER	COMPOSITION (OUTSIDE TO SKIN SIDE)
1	Arctic Fleece	DMC	E, E*
2	DMC,B	DMC	A, D, F, D, E
3	DMC,C	DMC	A, D, D, I, D, E
4	DMC,W	DMC	E, D, H, D, E
5	Flectalon	AOP	J, K, L, M**
6	M-400 Flannel Backing	DUI	B, G, N
7	M-400 with Neoprene Vapor Backing	DUI	B, G, C
8	M-600 Flannel Backing	DUI	B, G, H, N
9	M-600 with Neoprene Vapor Backing	DUI	B, H, G, C

* Sample 1 is two sheets of Arctic Fleece
** Sample 5 is a production composite.

MANUFACTURER KEY

AOP = Arktis Outdoor Products (Exeter, England)

DMC = Defense Marketing Consultants (Seattle, Washington)

DUI = Diving Unlimited International (San Diego, California)

COMPOSITION KEY

A = Nylon (Taslin), one layer

B = Nylon (Taffeta), one layer

C = Nylon (Taffeta), coated with neoprene (vapor barrier)

D = Mylar radiant film, two layers with three alternating layers of fine nylon setting

E = Arctic fleece, 16 oz polyester

F = Dacron II (DuPont), 4 oz batting covered on both sides with one layer each of mylar and fine nylon netting

G = Thinsulate (3-M), M-400 batting

H = Thinsulate (3-M), M-200 batting

I = Thermolite (DuPont), 8 oz batting

J = Pertex, lightweight nylon, one layer (4 oz)

K = Flectalon filaments, polymer or PVC small filaments, coated with aluminum (150 gms) covered by a scrim

L = Slimtex polyester batting (3.3 to 18.0 d'tex fiber size) covered on both sides by a thin bonded layer and one one side by 2 oz nylon

M = Bodypelt, 100% nylon pile, 3mm

N = Flannel, thin, bonded layer

TABLE #2 INSULATION GARMENT AND GARMENT/CM

	SAMPLE # AND NAME	CLO DRY* MEAN ± SD	CLO/CM DRY MEAN ± ISD	CLO WET* MEAN ± ISD	CLO/CM WET MEAN ± ISD
1	Artic Fleece	.749 ± .014	1.559 ± .029	.051 ± .024	.103 ± .044
2	DMC, B	.735 ± .007	1.657 ± .017	.119 ± .021	.276 ± .049
3	DMC, C	1.096 ± .070	1.780 ± .113	.094 ± .043	.155 ± .070
4	DMC, W	1.019 ± .011	1.550 ± .013	.071 ± .016	.109 ± .025
5	Flectalon	1.086 ± .101	1.765 ± .008	.192 ± .073	.315 ± .082
6	M-400 Flannel	.680 ± .010	1.696 ± .031	.081 ± .011	.212 ± .029
7	M-400 VB	.668 ± .004	1.632 ± .011	.099 ± .010	.248 ± .024
8	M-600 Flannel	1.022 ± .005	1.657 ± .009	.140 ± .015	.231 ± .028
9	M-600 VB	1.065 ± .100	1.710 ± .031	.182 ± .017	.308 ± .030

* Mean and standard deviation of five tests.

FIGURE # 1 COMPRESSIBILITY

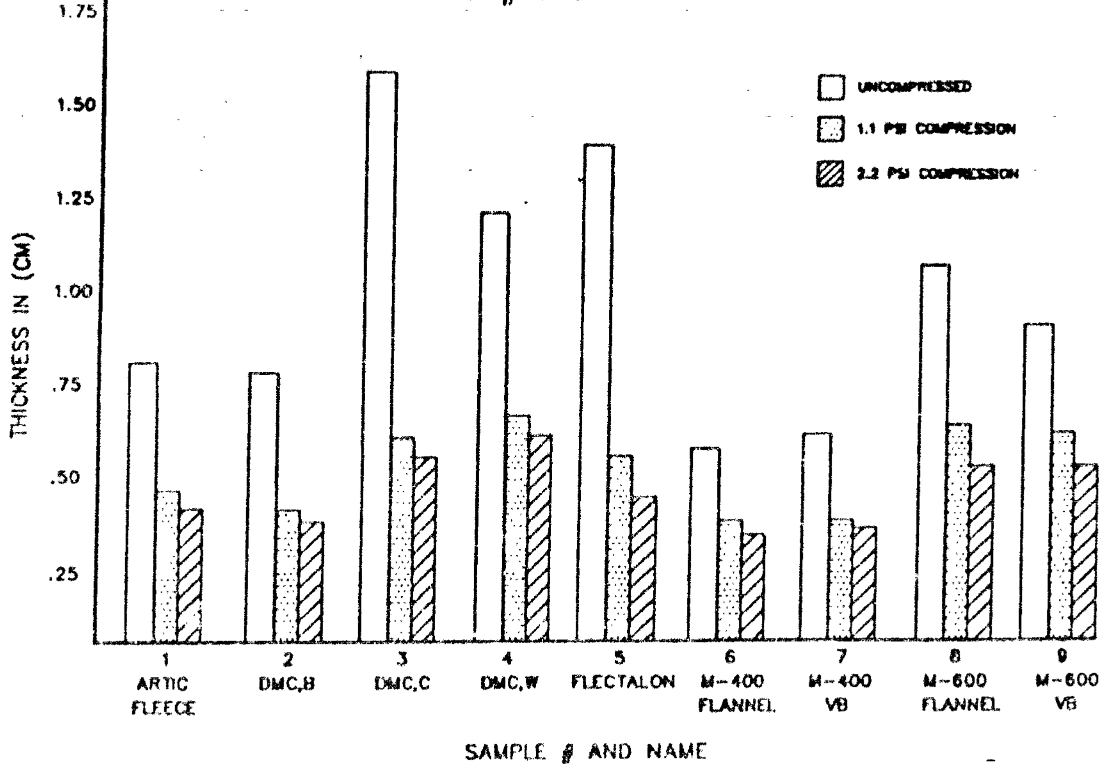


FIGURE # 2 DEGREE OF ABSORBENCY: GARMENT AND GARMENT PER UNIT THICKNESS

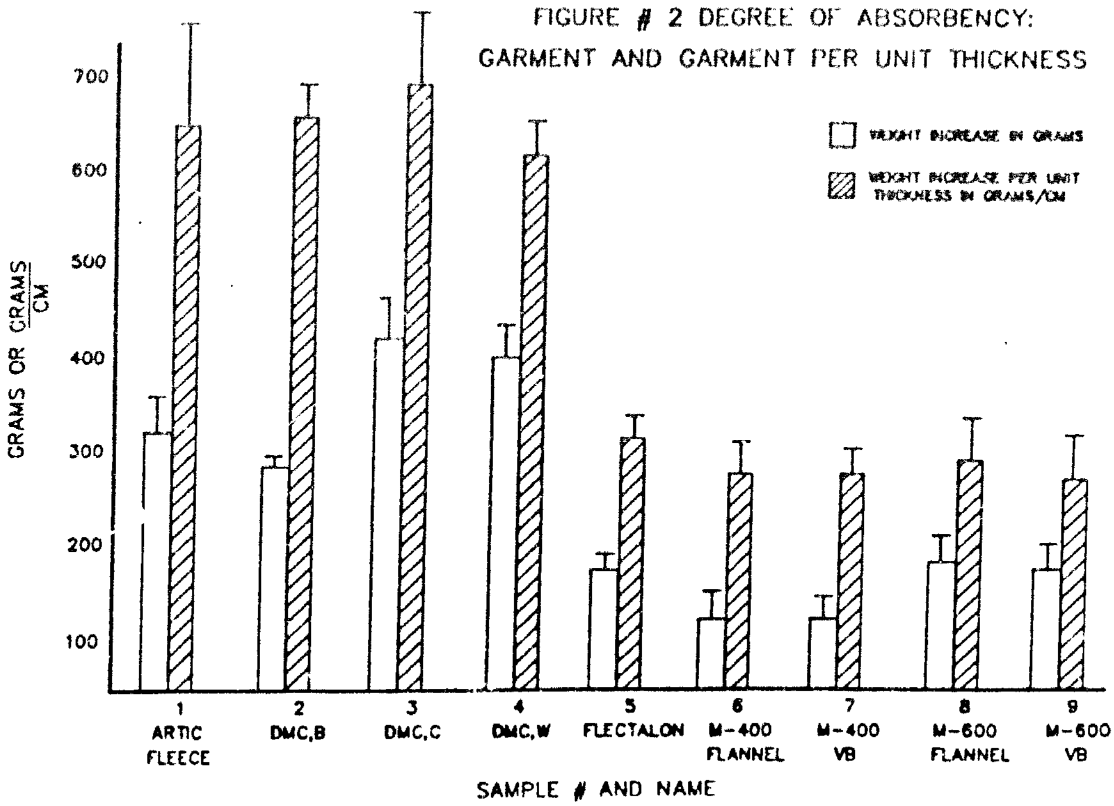


FIGURE # 3 INSULATION WET VS DRY

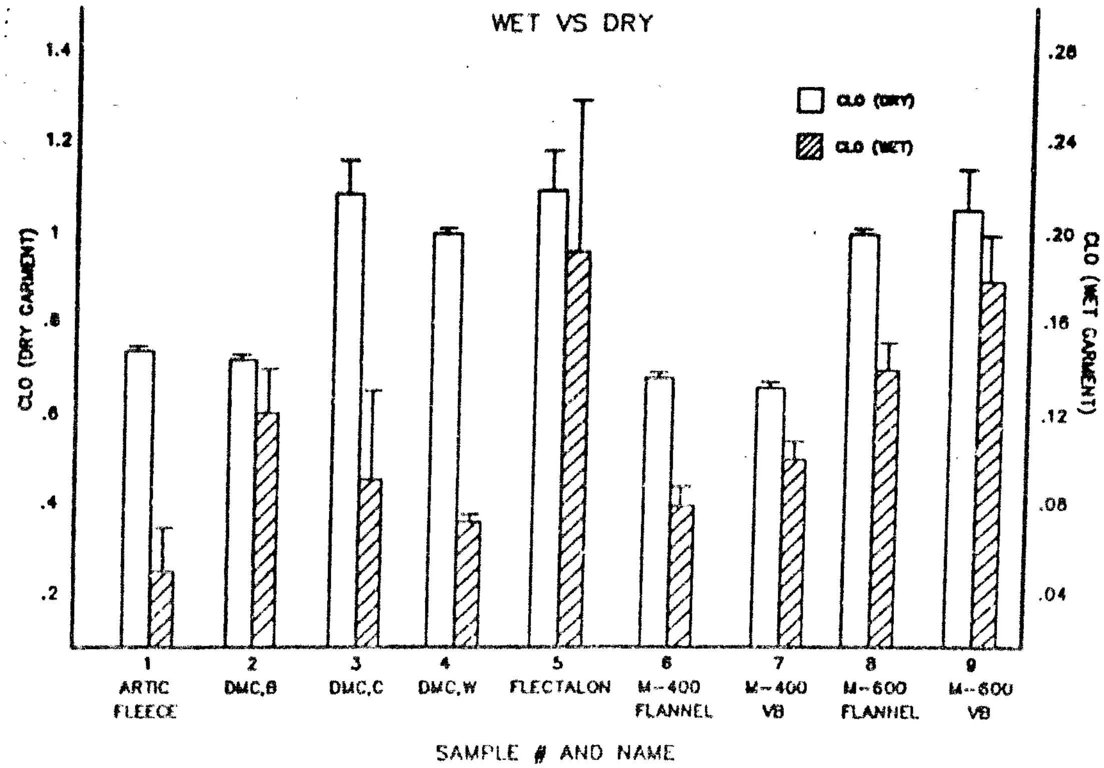
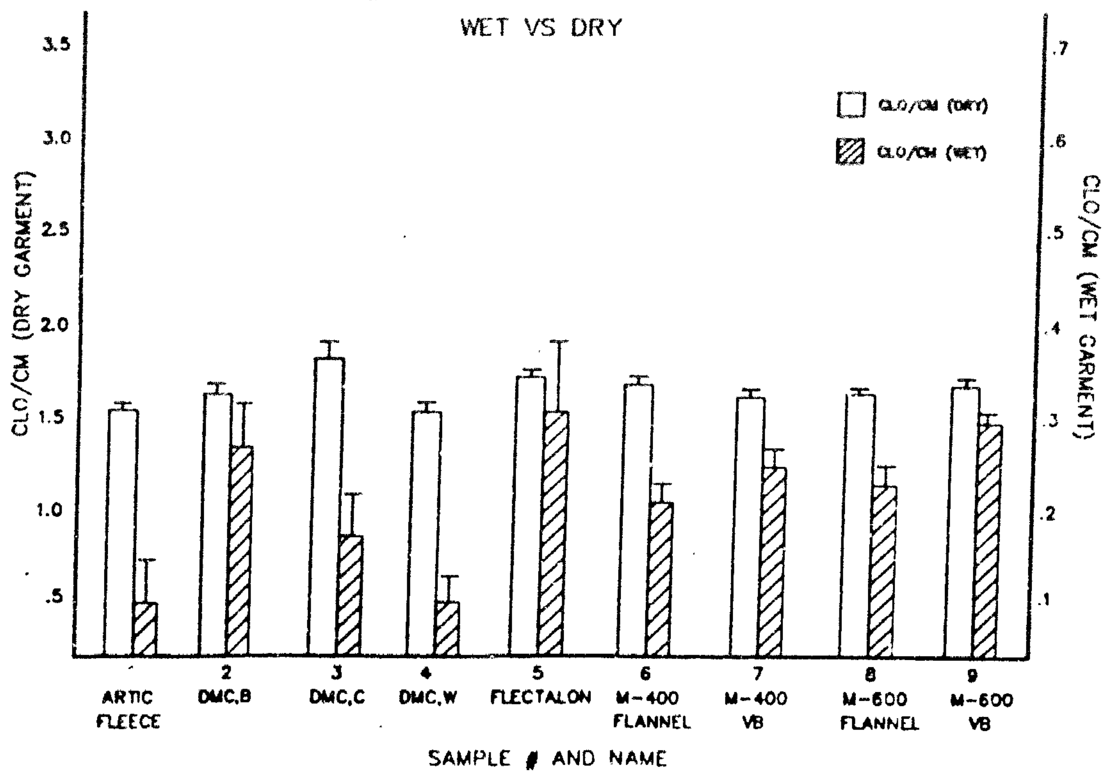


FIGURE # 4 INSULATION PER UNIT THICKNESS WET VS DRY



THERMAL INSULATION IN VARIOUS DRY AND FLOODED DRYSUIT/PILE UNDERGARMENT COMBINATIONS

T.T. Romet
Experimental Diving Unit
Defence and Civil Institute of Environmental Medicine

ABSTRACT

Passive thermal protection in the form of drysuit and undergarment is often the choice during diving operations in the Canadian Forces. Recently, a program has been undertaken to evaluate various suits and undergarments. While manikin or other laboratory techniques may give accurately defined insulative characteristics of the materials or garments, it was also felt that human trials would provide a better understanding of the inter-relationship between the clothing characteristics and the diver. Seven various dry suits (5 neoprene and 2 non-compressible) and three different synthetic pile undergarments were evaluated. Seven heat flux transducers, placed according to the 7-point scale of Burton were used to measure heat flux from the body from which suit insulations were calculated. Results showed that 7 mm St. Albins neoprene compared to Rubatex based neoprene drysuits provided approximately 15-18% more insulation during immersion at the surface, but with the effects of compression, the differences disappeared with the Rubatex neoprene providing better insulation during all the decompression phases. Insulation of the suits following complete flooding showed a small but significant relationship where suits with a lower initial insulation, generally because of tighter fits, showing the least decrement. The decrease averaged 58% from the unflooded condition. Prolonged immersion at depth, under resting conditions with the various drysuit/undergarment combinations provided between 1.1 and 1.5 Clo of protection. However, for the inactive diver, thermal comfort could not be maintained at a comfortable or cool but comfortable level for periods exceeding 90 min.

INTRODUCTION

As operational requirements for the military diver involve greater depths, longer durations and in colder waters, the need for improved thermal protection is again a major concern. Passive thermal protection is most often sought as this permits maximum mobility by the diver and eliminates the need for the technical support required for active heating systems. Dry suits, which can be worn with various undergarment combinations, are the usual choice. The outer layer of the dry suit was originally a non-compressible rubber canvas material but in recent years, the closed cell neoprene dry suit has become the more popular. In theory, the neoprene suit has the advantage that although it compresses at depth, it regains its thermal insulation as the depth decreases. This is especially valuable since it is at the longer decompression stops in shallower depths that maintaining thermal comfort becomes the greatest problem.

Thermal insulation of a suit material can be theoretically determined by a thermal conductivity measuring apparatus, such as the Rapid-K. Further, whole suits can be evaluated by means of thermal manikins. While both of these techniques produce accurate and reproducible results, they do not necessarily provide information on how the suit will behave when worn by a diver and factors such as suit fit and activity become important considerations. With the introduction of heat flow transducer technology, it was the intent of this study to determine suit insulations directly from measurements taken with the drysuits being worn by divers, both during immersion at surface and at depth.

METHODS

Seven various drysuits (5 neoprene and 2 non-compressible) together with three synthetic pile undergarments were evaluated. Seven heat flow transducers (Concept Engineering, Conn.) were placed on seven body sites as described by Hardy and Dubois (1938). Both skin temperature and heat flow were continually monitored and minute averages recorded.

First series of immersions took place in a static tank (2m x 2m x 3.2m) with water controlled at 18°C. Each combination, drysuit alone, drysuit with undergarment and drysuit with undergarment but flooded were evaluated. Immersion for each condition was continued until mean heat flow had stabilized (average time 35 min). Insulation (clo) was calculated from mean values obtained over the last five min of immersion, according to the following formula:

Insulation = (Mean skin temp - water temperature / mean heat flow) / 0.155

A second series of immersions were then carried out at various depths and decompression profiles. Maximum depths achieved were 75 msw, with the longest duration of 110 min. Suit insulations were calculated continually using the above mentioned formula.

RESULTS

A - Dry Suits - The dry suits tested were manufactured with one of two types of closed cell neoprene, Rubatex or St. Albins. As can be noted in Table 1, St. Albins neoprene suits provided greater insulation during surface immersions as compared to the Rubatex. This difference, however, disappeared at depth and was often reversed (see Figure 1). The reversal in insulation was noted both during the compression and decompression phases. Non-compressible suits provided on average 0.166 clo, and as expected did not change at depth.

B - Undergarments - The insulative value of the synthetic pile undergarments varied between 0.464 and 1.20 clo (see Table 2). The differences were directly related to the thickness (or weight) of the material. Figure 2 shows the total insulation provided divers with the various weight undergarments and a Rubatex neoprene drysuit measured during identical dive profiles.

C - Flooded Suits - The percentage decrement in overall insulation ranged from 43 to 67 percent after total flooding of the drysuit/ undergarment ensemble. The smallest decreases were observed from ensembles which were the tightest fitting but also with the lowest initial insulation. Final flooded clo values ranged from 0.50 to 0.71 clo (average 0.56 clo ± 0.08).

DISCUSSION

Despite the identical thickness of neoprene, the St. Albins showed a higher insulation capacity than the Rubatex. Examination of the two materials showed that the St. Albins was a larger celled, softer neoprene which would have allowed for greater trapping of air. This proved to be a disadvantage at depth a the St. Albins material was subject to greater compression leading to less insulative value. The material also did not return to its initial insulation as readily.

Unpublished work from DCIEM has shown that all three synthetic pile undergarments have the same thermal conductivity. This is not surprising since essentially the same polyester fibre (kirklon) is the primary material in the undergarments. It was therefore not unexpected to note that thicker the material more effective the insulation. The drysuit/undergarment (19 oz) ensembles will provide minimally 1.2 to 1.6 clo of protection at the surface. Since this study used only minimal suit inflation, it could be expected that some additional insulation could be obtained. Increasing the undergarment thickness will also further increase insulation, but at the expense of increased bulk and reduced mobility.

Completely flooding the suits reduced the insulation on average by 58%. The average insulation of 0.56 clo is somewhat greater than the dry pile undergarment on its own, but less than the drysuit itself. Since no flushing or flow through of water occurred, it can be expected that the body would slowly raise the internal temperature of the trapped water and the final flooded suit insulation would approach that of the neoprene.

The values of insulation determined from these evaluations compare well with measures obtained from thermal manikin studies (Nuckols, 1978). Studies on humans however also provide additional information on diver thermal comfort, specific regional insulation and mobility. In conclusion, it has been shown that heat flow transducer technology provides good comparative information on the effectiveness of suit insulations while allowing the opportunity to obtain specific information on comfort, fit and mobility. The results also confirm the concept that suits must be evaluated both at surface and at depth to obtain a complete understanding of its insulative characteristics.

REFERENCES

Hardy, J. and E. Dubois. 1938. J. Nutr. 15:421.

Nuckols, M.L. 1978. Thermal considerations in the design of diver's suits. from Hyperbaric Diving Systems and Thermal Protection, ed. C.E. Johnson and M.L. Nuckols, Amer. Society of Mech. Engineer., New York.

TABLE 1

COMPARISON OF NEOPRENE INSULATIONS (CLO)

	mean±SD
Rubatex 7.1mm (Rapid-K)	0.856
Rubatex 6.5mm (Human)	0.826±0.14
St. Albins 6.5mm (Human)	1.129±0.06
Non-Compressible	0.166±0.01

TABLE 2

RELATIONSHIP BETWEEN UNDERGARMENT WEIGHT AND INSULATION

19 oz kirklon (polyester pile)	0.464 Clo
28 oz kirklon (polyester pile)	0.901 Clo
36 oz kirklon (polyester pile)	1.200 Clo

Fig. 1 Comparison of Rubatex and St. Albins Neoprene

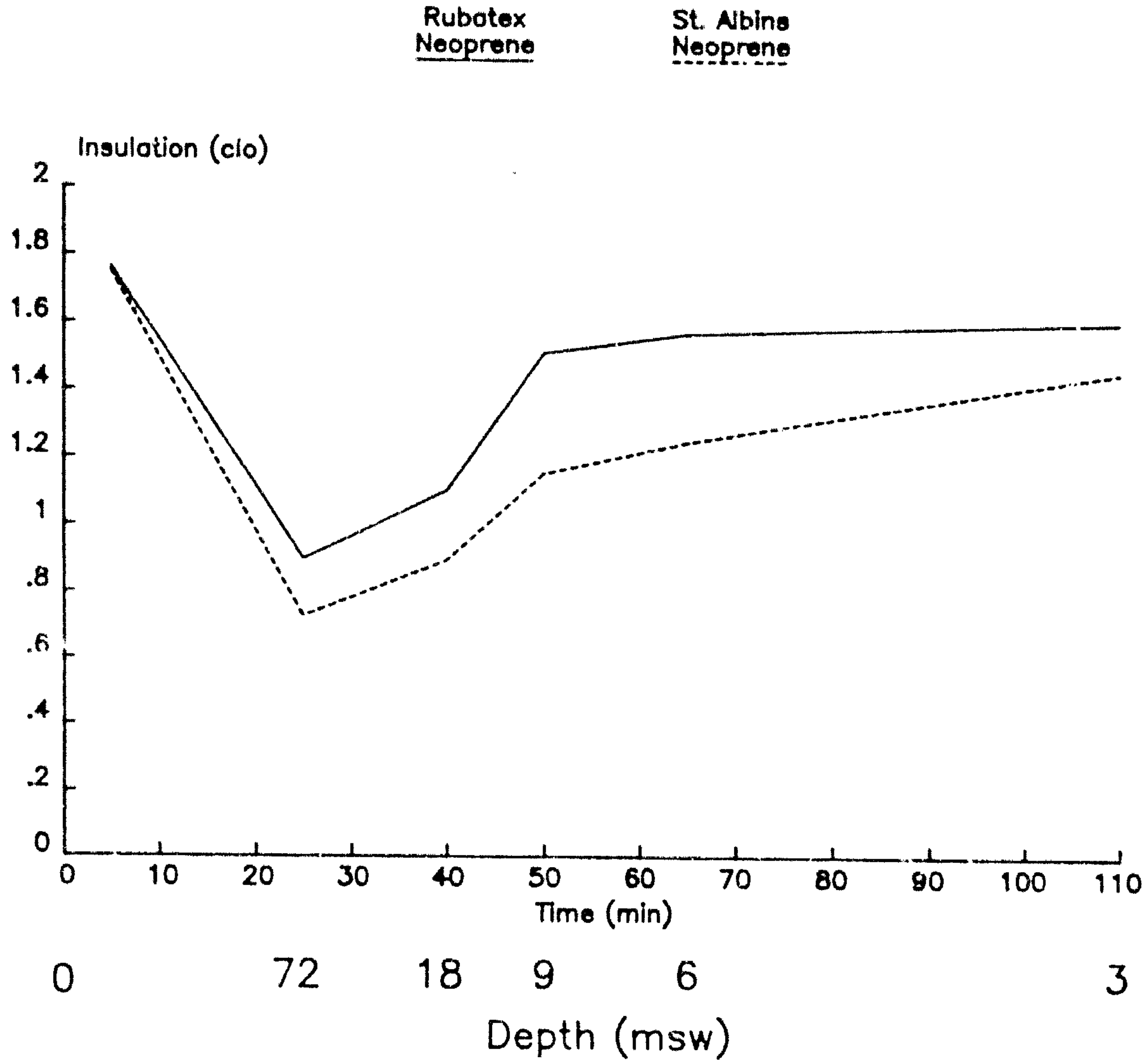
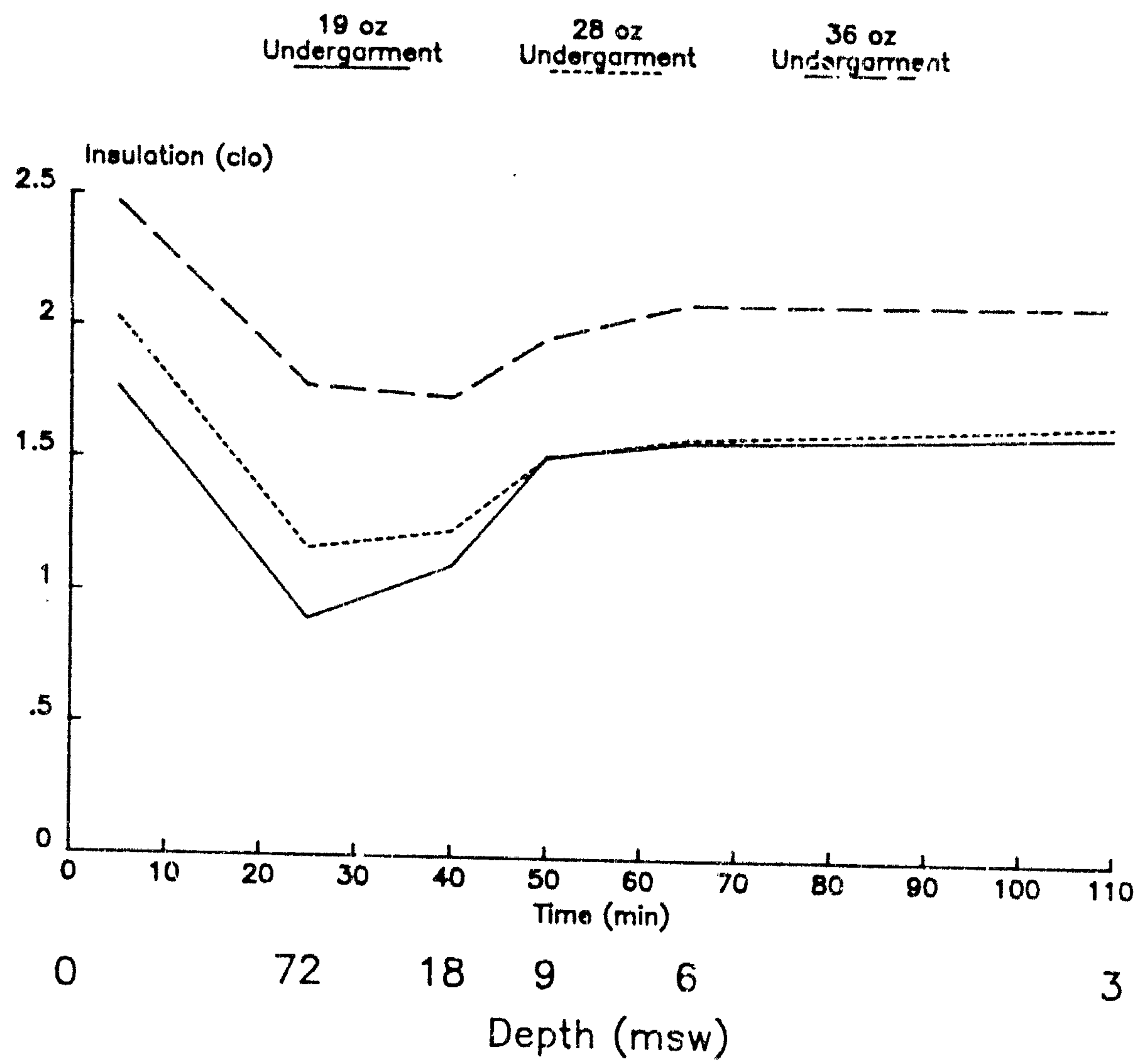


Fig. 2 Comparison of Different Weight Undergarments



SESSION 3

ACTIVE THERMAL PROTECTION

Session Chairmen:
LCDR J.A. Sterba, MC, USNR
Thomas C. Schmidt

PREFACE

Prolonged diving in near-freezing water requires active thermal protection of the diver. This session included papers discussing: (1) actively heating divers using a tube suit, (2) planned dives for active thermal protection of divers at rest and free-swimming, (3) actively heating closed- circuit underwater breathing apparatuses (UBA) to improve carbon dioxide absorption, and (4) using the catalytic combustion of alcohol for diver active thermal protection.

In paper (1), the thermoelectric heat pump was used to provide warm water to a diver wearing a closed circuit tube suit. Power consumption was measured to be 300 watts for a dive in 2 °C water using a dry suit and light weight undergarment. Temperature measurements revealed body rectal core temperature to be 36.75 °C at the completion of a six hour dive.

Paper (2) reviewed the long range planning of dives at the Navy Experimental Diving Unit using eight U.S. Navy divers for prolonged dives in 2 °C water. The protocol to test two, tube suit active thermal systems (ATS) included a physiological and human factors evaluation during eight hour dives with divers at rest in a submersible and free-swimming in the NEDU cold water flume. Termination criteria, diving equipment, and diving procedures were reviewed, and collaboration with other U.S. Navy and civilian laboratories were discussed.

Paper (3) discussed the beneficial effects of carbon dioxide scrubber heating in a UBA including an increase in scrubber efficiency and decrease in condensation in the UBA and the diver's mask. Data were presented and reviewed.

The opinions or assertions contained in this article are the private views of the authors and are not to be construed as reflecting the view of the United States Department of the Navy or the Department of Defense.

Paper (4), abstract only, discussed the controlled, flameless combustion of alcohol as a new method to provide supplemental heat to the diver. By heating circulating fluid using a tube suit concept, this chemical reaction of the catalytic combustion of alcohol using a small portable burner could provide active thermal protection during diving.

J. Sterba
Co-Chairman

THE PHYSIOLOGICAL EFFICACY AND ENERGY EFFICIENCY OF HOT-WATER SUIT HEATING USING THERMOELECTRIC HEAT PUMPING

T.C. Schmidt
Lockheed Advanced Marine Systems
3929 Calle Fortunada, San Diego, CA 92123

ABSTRACT

Part A: THERMOELECTRICS. Cold water operations are frequently constrained by a lack of adequate diver heating. For autonomous systems and vehicles this is typically due to the limitations of on-board power. For tethered systems, it is typically due to hot water umbilical heat loss. Heat pumps are very energy efficient in the heating mode as the heat produced is equal to the heat pumped plus the heat equivalent of the power consumed. As thermoelectric (TE) heat pumps are solid state they eliminate the refrigerant, compressor, condenser and evaporator common to conventional type (i.e., vapor compression) heat pumps. Manned dives have been performed using a prototype TE heat pump which pumps heat from the ambient water to a closed circuit hot-water loop circulated through a tube-suit worn under Thinsulate and dry suit. Using M200 Thinsulate and 36-39°F (2-4°C) water as the heat source, the power required to supply 102-104°F (39-40°C) water to the diver's suit was less than 300 watts. Use of M400 Thinsulate (vs M200) reduces the power consumption by about 1/3, and use of warmer water as the heat source provides further reductions in the power required. For surface supplied hot-water operations, a similar approach may be used to boost the water temperature and/or serve as an energy efficient emergency backup. Also, by reversing the current a heater becomes a cooler for use in hot woter diving applications.

Part B: PHYSIOLOGICAL. The direct effects of cold are hypothermia and performance degradation, including reduction of grip strength and loss of manual dexterity. In the case where free flooding submersibles are used, during transit the divers may be inactive for long durations and the physical resistance of the amount of insulation that is required further contributes to reduced work capability. Use of active heating (particularly during transit) would reduce the effects of cold and the amount of insulation required. Manned dives have been performed using a prototype thermoelectric heat pump. They have been of up to 6 hours duration in 35-40°F (1.7-4.4°C) water, with little or no activity, using a Dover ILC hot-water tube suit worn over a thin polypro liner and under Thinsulate insulation and TLS dry suit, with AGA mask, hood and dry gloves. The tube suit covers the tops of the feet but terminates at the wrists. The 6-hr dive used the lightest Thinsulate available (M200), with 103°F (39.5°C) supply to the tube suit. After 6-hr, T_{rectal} was 36.75°C, and the temperatures of the forearm, back of hand, ring finger and big toe were 35, 23 18.3 and 17.2°C, respectively.

PART A: THERMOELECTRICS

The primary advantage of heat pumping is that the heat produced is equal to the heat pumped plus the heat equivalent of the power consumed. That is, watts of heat produced is always greater than the watts of power consumed. Compared to other alternative heating approaches (e.g. exothermic reaction and sensible/latent heat storage) the other potential advantage is that the heat available will also increase in direct proportion to any future breakthroughs in battery power storage.

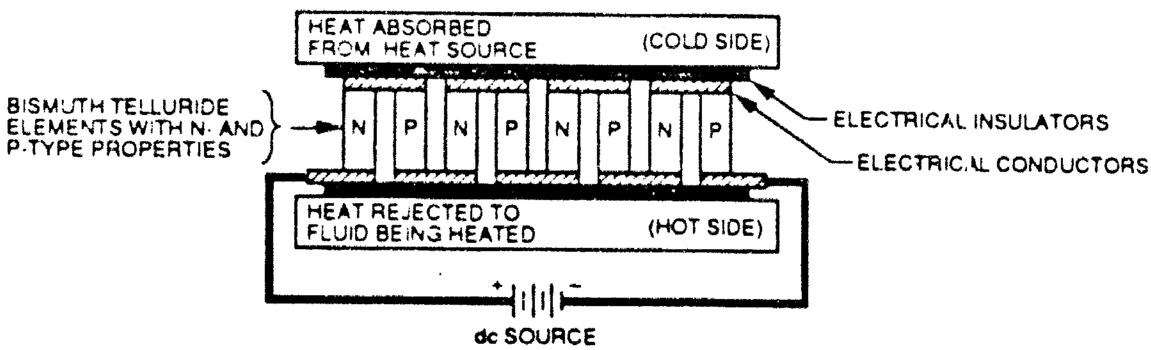
Figure/Slide 1

HEAT PUMPING
ADVANTAGE = ENERGY EFFICIENCY
Provides more heat than the heat equivalent of power consumed
THERMOELECTRICS
ADVANTAGE = SIZE, WEIGHT, AND SIMPLICITY
Eliminates refrigerant, compressor, condenser, and evaporator

The advantages of thermoelectrics is size, weight and simplicity – being solid state it eliminates the refrigerant, compressor, condenser and evaporator associated with the vapor compression cycle approach. Also, whereas a vapor compression heat pump typically has one particular load capacity regardless of load required, by simply varying the applied voltage a TE heat pump operating capacity may very easily be matched to the particular load required.

Figure/Slide 2

A thermoelectric (TE) module consists of semi-conductor (p-n) junctions connected in series. When low voltage DC power is applied, one side gets hot, the other side gets cold, and heat is pumped from the cold side to the hot side. The heat rejected from the hot side is equal to the heat pumped, plus the heat equivalent of the power consumed.



Figure/Slide 3

This shows the particular modules used, being mounted onto one of the heat exchangers. Each module measured 1.2 inches square, with (p-n) elements of a quaternary alloy of bismuth, tellurium, selenium and antimony with small amounts of suitable dopants.

All variations on the basic concept, consist essentially of passing the fluid to be heated through a heat exchanger that is in intimate contact with the hot side of the modules, while passing the fluid serving as the heat source through a heat exchanger that is in intimate contact with the cold side of the modules.

The fluid to be heated may be water for suit and/or secondary gas heating, or the gas may be heated directly. While the ambient seawater is obviously the most copious

FIGURE/SLIDE # 3

source of heat, for open circuit SCUBA heat may be pumped from the warm expired gas directly to the (otherwise cold) inspired gas.

Figure/Slide 4

The theoretical coefficient of performance (watts heat per watts of power) depends primarily on the temperature differential across the module, and to a lesser extent the module hot side temperature. The figure shows a performance envelope somewhat representative of that applicable to manned subsea applications. The solid curve to the left is based on a hot side temperature of 68°F (20°C) and the curve on the right a hot side temperature of 104°F (40°C). They are intersected on the right by a vertical dotted line arbitrarily chosen as a minimum useful differential of about 10°F (5°C), and on the bottom by a dashed curve for a cold side temperature at the freezing point of seawater.

Figure/Slide 5

s = Seebeck coeff (volt/deg K) = $s_0 + s_1T + s_2T^2$
r = elec resistivity (ohm-cm) = $r_0 + r_1T + r_2T^2$
k = thermal cond (watt/cm deg K) = $k_0 + k_1T + k_2T^2$

where $s_0, S_1, s_2, r_0, r_1, r_2, k_0, k_1, k_2$ are specific to the semi-conductor material used, and T = avg temperature between the hot and cold sides

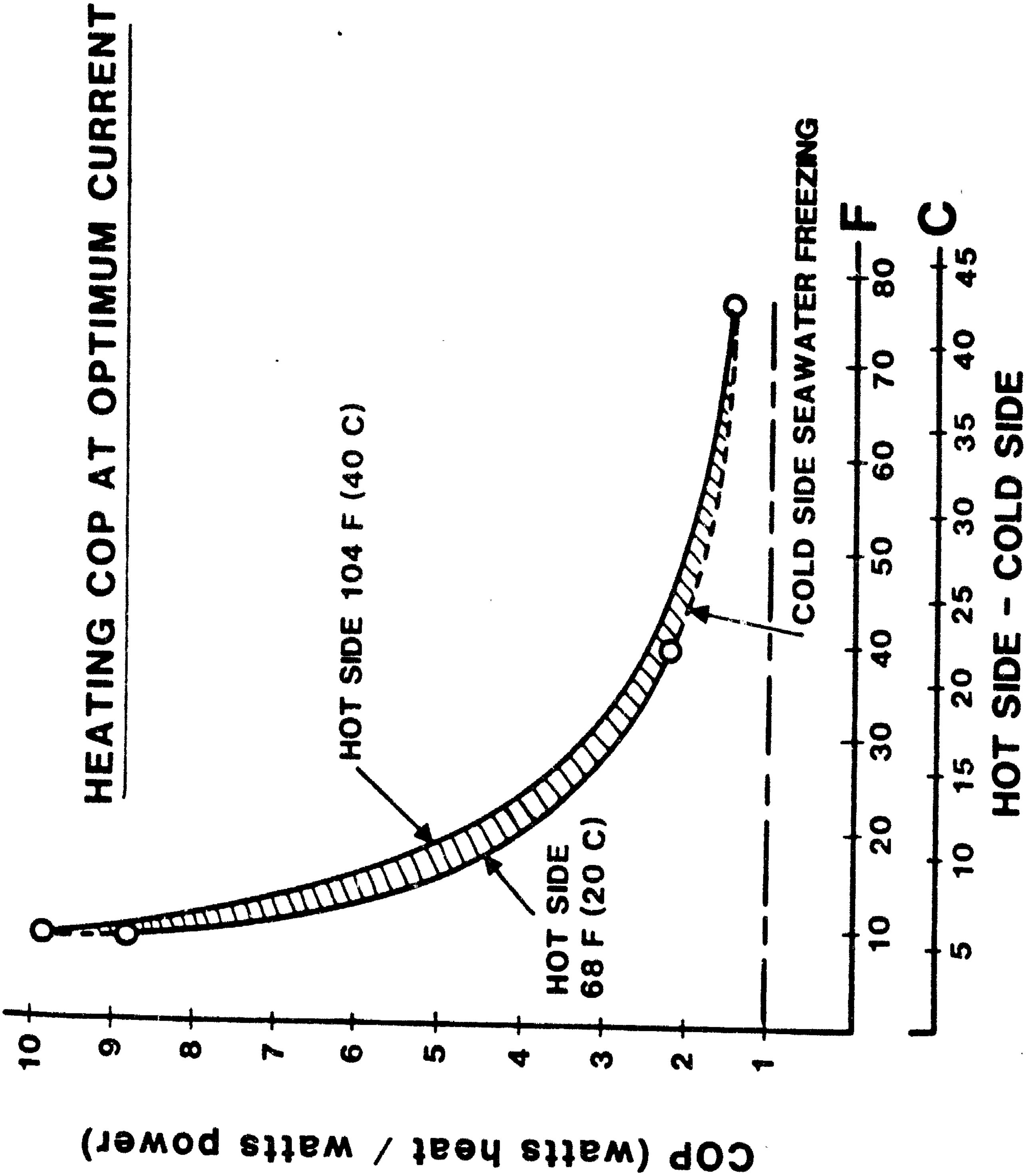
N = # p-n elements
L = length/area ratio of the elements
Tc = cold side temperature
dT = temperature difference between the hot and cold sides
N and L are specific to the particular module construction

optimum current in amps = $k\ dT(1 + (1 + s^2T/rk)^{0.5}/s\ T\ L)$
voltage to obtain Iopt for the particular dT = $N(I\ r\ L + s\ dT)$
heat pumped in watts (Q) = $N(s\ I\ Tc - I^2r\ L/2 - k\ dT/L)$
module power consumption = (volt)(amp)

It should be noted that the performance shown in the preceding figure assumes that the heat pump design is such that the current draw resulting from the applied voltage is the most optimum one for the amount of heat being pumped, and the particular hot and cold side temperatures. This is also specific to the number of p-n elements (N) and the length/area ratio of each element (L). For the modules available commercially, N (per module) may range from less than 10 more than 250, and L may range from less than 1 to more than 50. For a given set of boundary conditions an optimized design is relatively straight forward (albeit time consuming), while for operation over a wide range of variables a much more involved design effort is required.

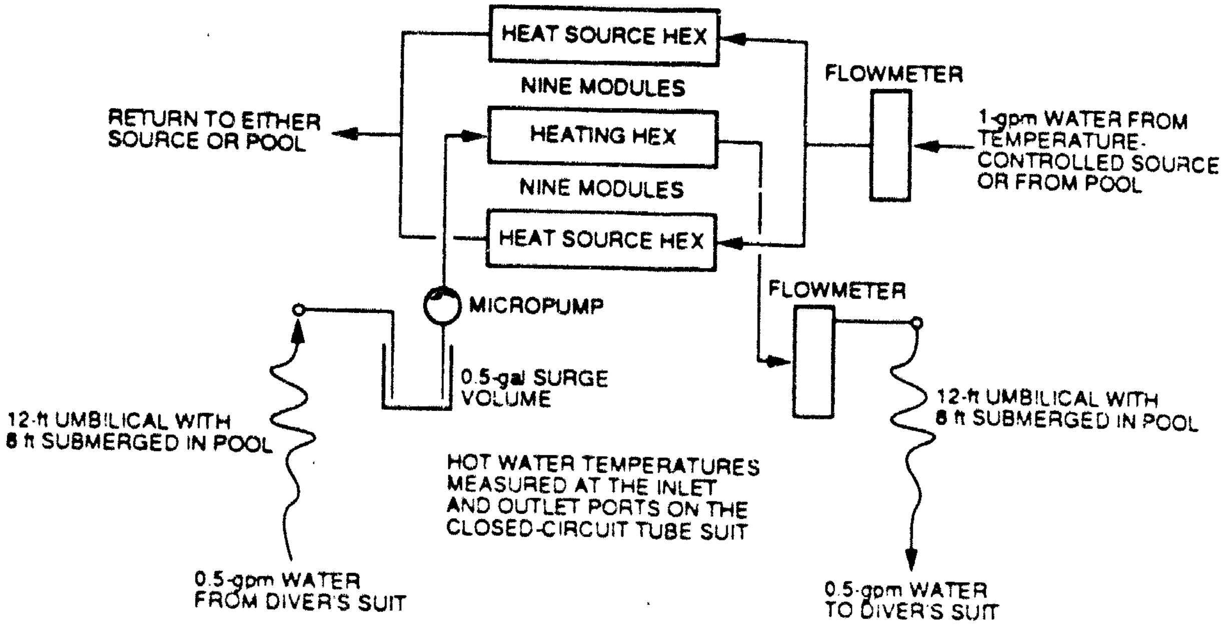
The theoretical performance does not include system heat losses which for the heat pump *per se* consist of losses from the hot side heat exchanger. These can be minimized by keeping unused heat exchanger surface areas to a minimum, and may be precluded by operating in a vacuum.

Initially, a year of unmanned simulation testing was performed to obtain empirical performance data for the various heat pumping modes (water-to-water, water-to-gas


HEATING COP AT OPTIMUM CURRENT
HOT SIDE 104 F (40 C)
HOT SIDE
68 F (20 C)
COLD SIDE SEAWATER FREEZING
COP (watts heat / watts power)
1 2 3 4 5 6 7 8 9 10
10 20 30 40 50 60 70 80 F
5 10 15 20 25 30 35 40 45 C
HOT SIDE - COLD SIDE

and gas-to-gas), over the anticipated range of dependent variables. The intent was to validate the efficacy of the approach, and to obtain empirical performance baseline data for follow on designs.

Figure/Slide 6



Following this a prototype heat pump was constructed as shown, and used to provide hot water suit heating during a series of manned dives in 35-55°F (1.5-12.5 °C) water -- i.e., providing hot water heating to an ILC Dover closed circuit tube suit worn over a thin polypro liner and under Thinsulate and drysuit. For a majority of the dives, the cold tank water was used as the heat source, and drysuit inflation was limited to only that necessary to prevent suit squeeze.

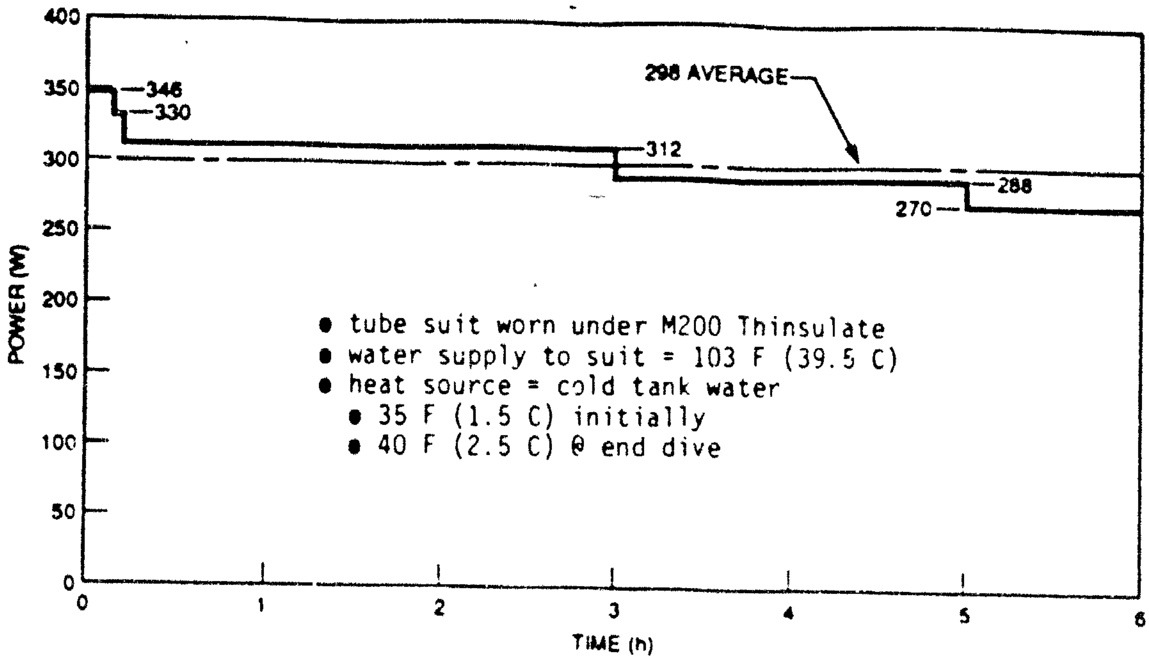
Figure/Slide 7

Test Condition	Heat Source	Appar Htg (W)	Pwr Pwr (W)	COP		Theo Min Pwr (W)
				Act	Theo	
40°F Pool, M200	65°F	400	225	1.75	2.1	190
40°F Pool, M200	Pool	425	320	1.25	1.55	275
40°F Pool, M400	65°F	275	140	2.0	2.2	125
40°F Pool, M400	Pool	285	200	1.4	1.7	170

The heat pump performance during some early demonstration dives performed in the NEDU cold tank in 40°F (4.5 °C) water is shown in the table. It is based on the provision of 100°F (37.75°C) water at the suit inlet, using both M200 and M400 Thinsulate, with a heat source consisting of the 40°F pool water, and also using a water source of 65°F (18°C).

Subsequent to this, unmanned testing was performed to determine the best means of most evenly distributing the water flow path through the finned portion of the heat exchangers. The result was a discernable increase in performance efficiency.

Figure/Slide 8



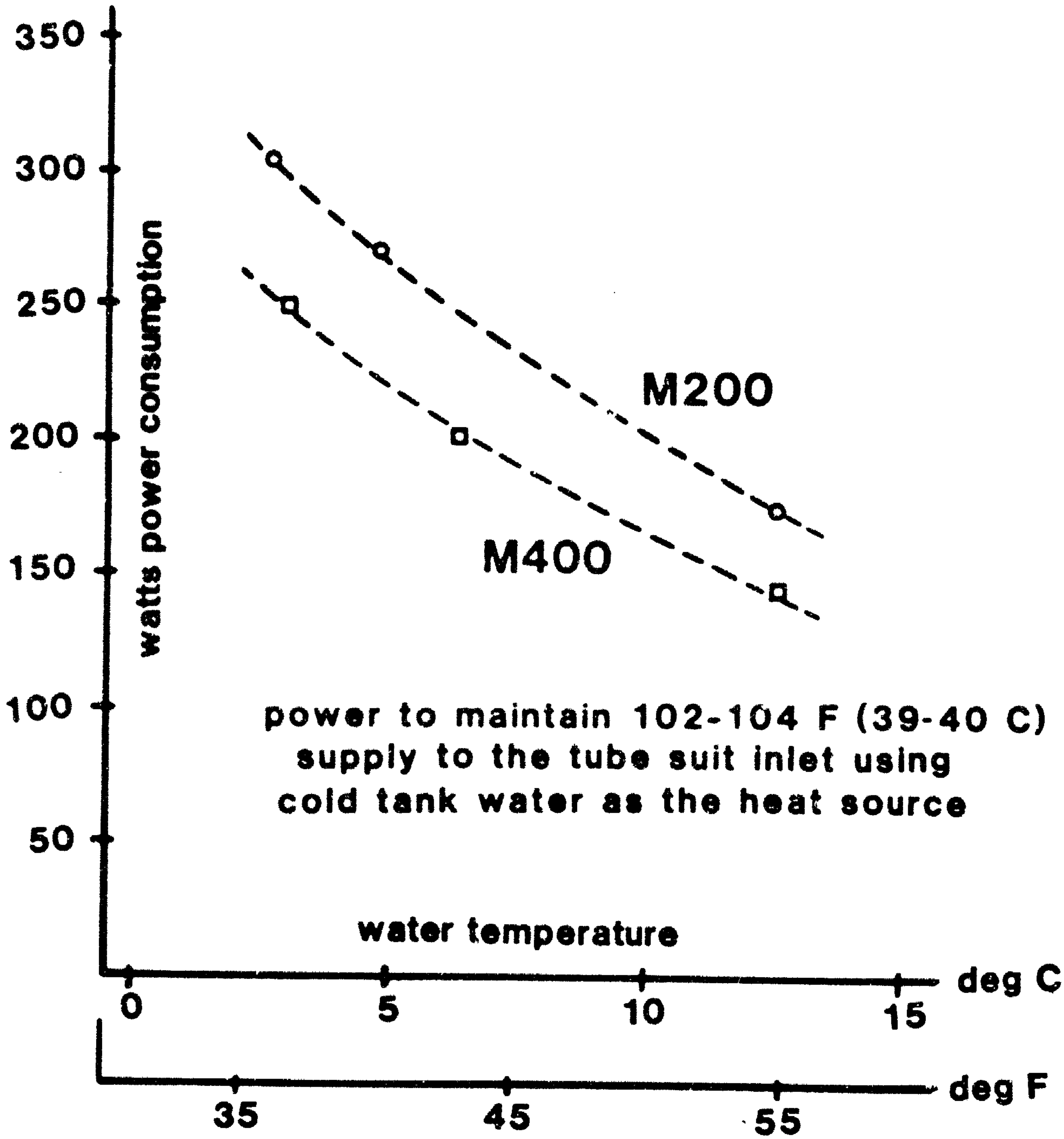
As shown here, the average power required to maintain a 103°F (39.5°C) supply to the suit throughout a 6-hr dive performed at our cold tank in 35-40°F (1.5-4.5°C) water, using M200 Thinsulate (the lightest weight available) using the cold tank water as the heat source, was less than 300 W. That is, after initial warmup, 312 W were required at 35°F, which decreased to 270 W as the cold tank water warmed to 40°F during the course of the 6-hours.

Figure/Slide 9

Increasing water temperature and/or use of heavier Thinsulate appreciably reduces the power required. During dives in 36-38°F (2-3°C) water using M400 and the cold tank water as the heat source, the power required to maintain 103°F (39.5°C) suit supply was 250 W. Similarly, with M200 in 55°F (12.75°C) water it was 175 W, and with M400 in 55°F water it was less than 150 W.

Efforts are presently underway on a more optimally designed suit heating system which will be about one-half the size of the previous prototype, will be fully submersible, and which will be enclosed inside an evacuated housing. Based on a suit supply temperature of 104°F (40°C) and using cold ambient seawater as the heat source, over a range of 29-60°F (-1.5 to 15°C) ambient, the heating COPs (watts heat/watts power consumed) should range from slightly less than 1.4 to somewhat greater than 2.0.

FIGURE/SLIDE #9



PART B: PHYSIOLOGICAL

Figure/Slide 10

16 dives, 1 to 6 hours duration
water temperature 1.5°C to 1 2.5°C (35°F to 55°F)
6 different diver/subjects
M200 and M400 Thinsulate under TLS drysuit
hot water tube suit - no active heating of hands
drygloves / wetgloves / wetgloves w/gauntlets

The previously described prototype heat pump was used to provide hot water heating during a series of 16 manned dives. They were of about 1 to 6 hours in duration, in water temperatures of 35-55°F (1.5-12.5°C), with little or no diver activity (i.e., resting quietly).

Figure/Slide 11 - 15

Hot water at a flow rate of 1/2 gpm was supplied to a closed circuit ILC Dover tube suit worn over a thin polypro liner and wool socks. The tubes cover most of the body including the tops of the feet, but terminate at the wrists. Thus, the hands are unheated. Worn over this were M200 or M400 Thinsulate undergarments, with M200 booties, and a TLS Rev. D drysuit with an inner dry hood, plus a Thinsulate skull cap and outer neoprene hood. Insulated four-finger dry gloves were used predominantly, but some dives used five-finger wet gloves, both with and without three-finger neoprene gauntlets. A full-face AGA mask was used exclusively, with air supplied from SCUBA bottles submerged in the cold tank.

Figure/Slide 16

The water in 1,000 gal cold tank did warm during the course of each dive, however at a rate of less than 1°F to 0.5°C) per hour. Drysuit inflation was only that sufficient to prevent suit squeeze. Some dives also included drysuit flooding ranging from minor to extensive, both intentionally and unintentionally. rectal temperature (T_{re}) was monitored during all dives, and most dives also provided skin temperatures -- measured at the thigh, forearm, back of the hand, big toe, and ring finger. Some measurements of grip strength were also obtained.

With only two exceptions, for all of the exposures, rectal temperature (T_{re}) consistently remained above 36.5°C. One of the two exceptions was during the earlier stage in which we thought that an average suit water temperature about that of normal mean skin temperature might possibly suffice -- when used with the M200 Thinsulate in 37.5°F (3°C) water, T_{re} decreased to 36.25°C after 4.5 hours.

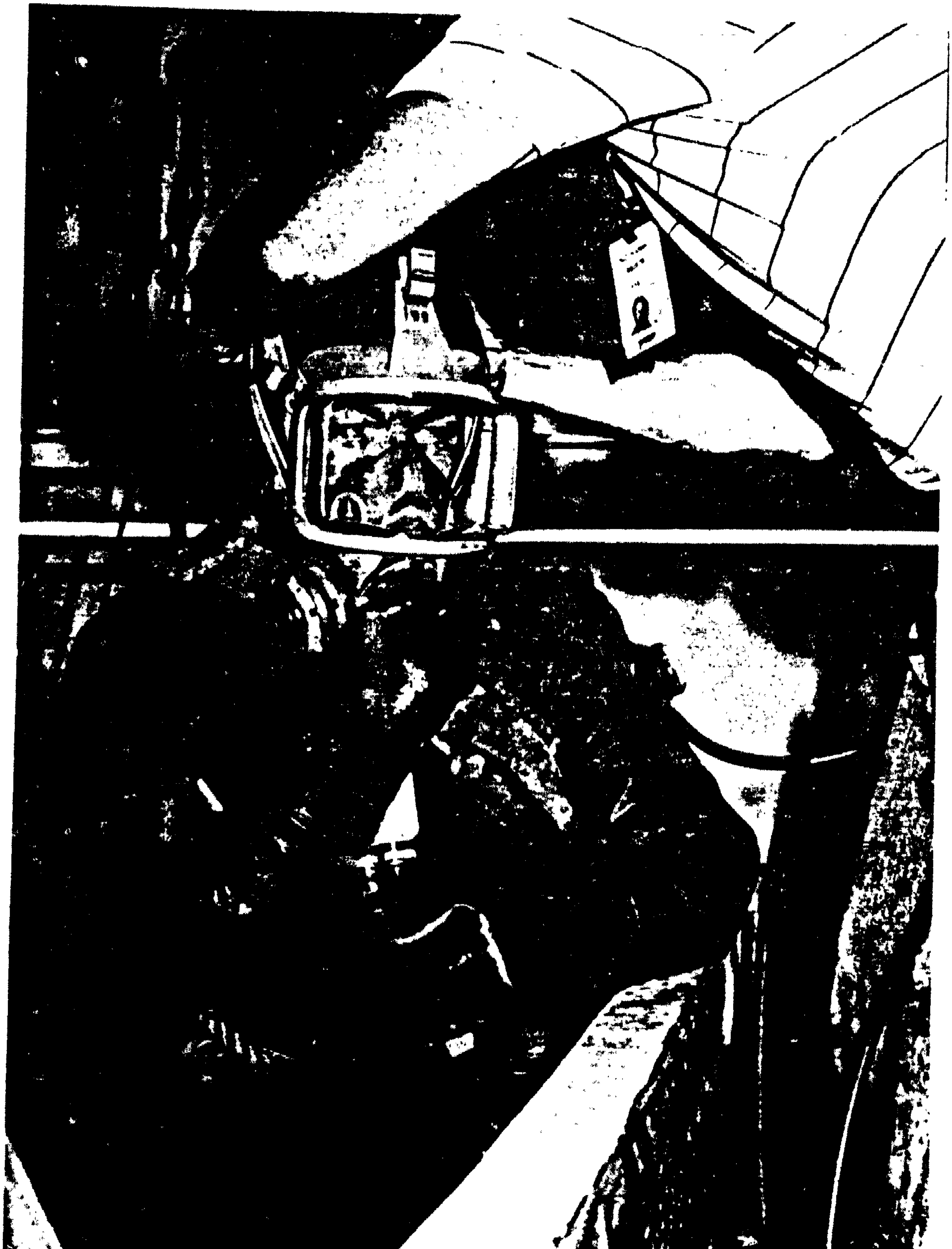
FIGURE/SLIDE # 11

FIGURE/SLIDE # 12

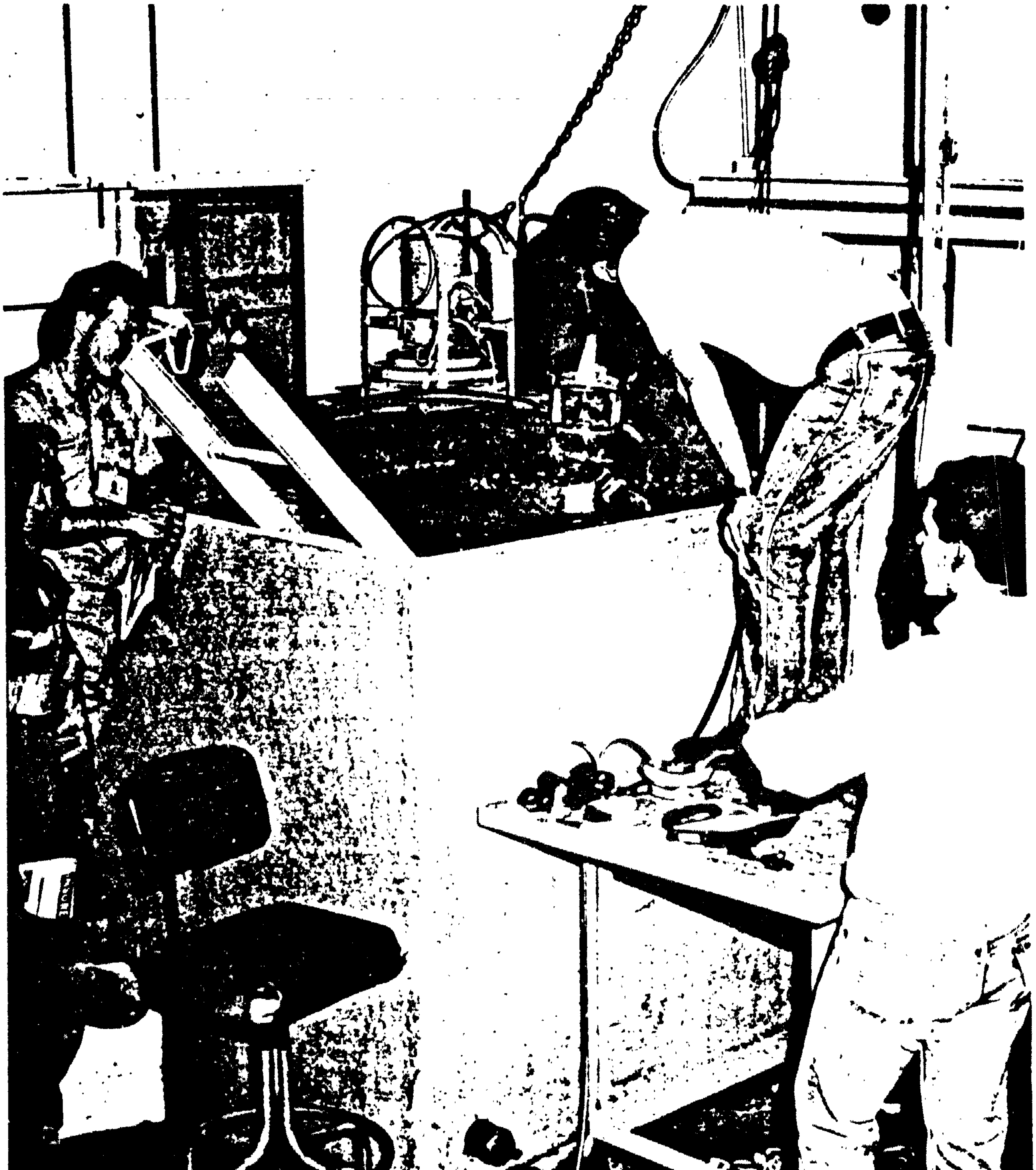
FIGURE/SLIDE # 13

FIGURE/SLIDE # 14

FIGURE/SLIDE # 15



FIGURE/SLIDE #16



Figure/Slide 17

With two exceptions, for all 16 dives T_{re} remained above 36.5°C
(1) Inadequate suit supply temperature
- M200 Thinsulate in 37.5°F (3°C) water
- Suit inlet approx 95-98°F (35-37°C) latter half of dive
- T_{re} decreased to 36.25°C after 4.5 hours
- Same diver, same dress, same cold tank temperature
- Suit inlet temperature 103°F (39.5°C) throughout dive
- T_{re} decreased to only 36.75°C after 6-hours

(2) Diver/subject had 36.5°C T_{re} normal baseline to start with

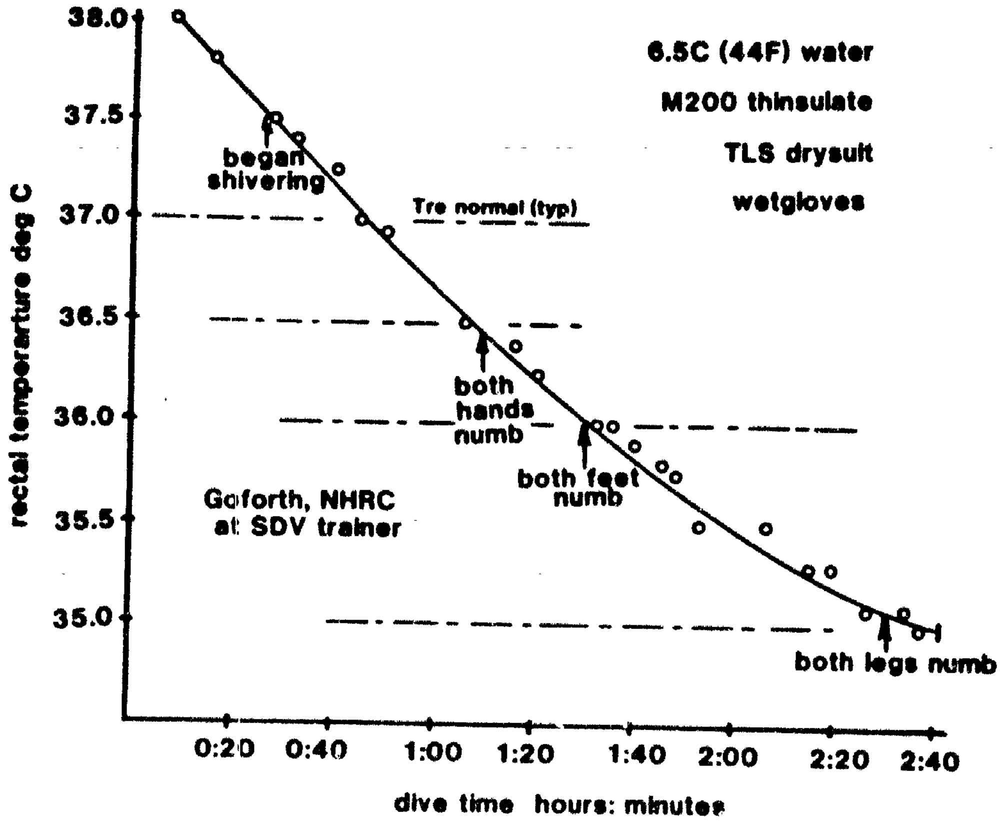
By subsequently increasing the supply temperature such that the average suit water temperature was slightly greater than normal core temperature (i.e., 39-40°C inlet), for the same diver again wearing M200 in the same temperature water (3°C ± 1.5), near thermal neutrality was maintained throughout an entire 6-hour exposure, i.e., T_{re} was 36.75°C at the end of the 6-hours. The other exception was a subject whose normal predive baseline T_{re} (as measured on three separate occasions) was only 36.5°C to begin with.

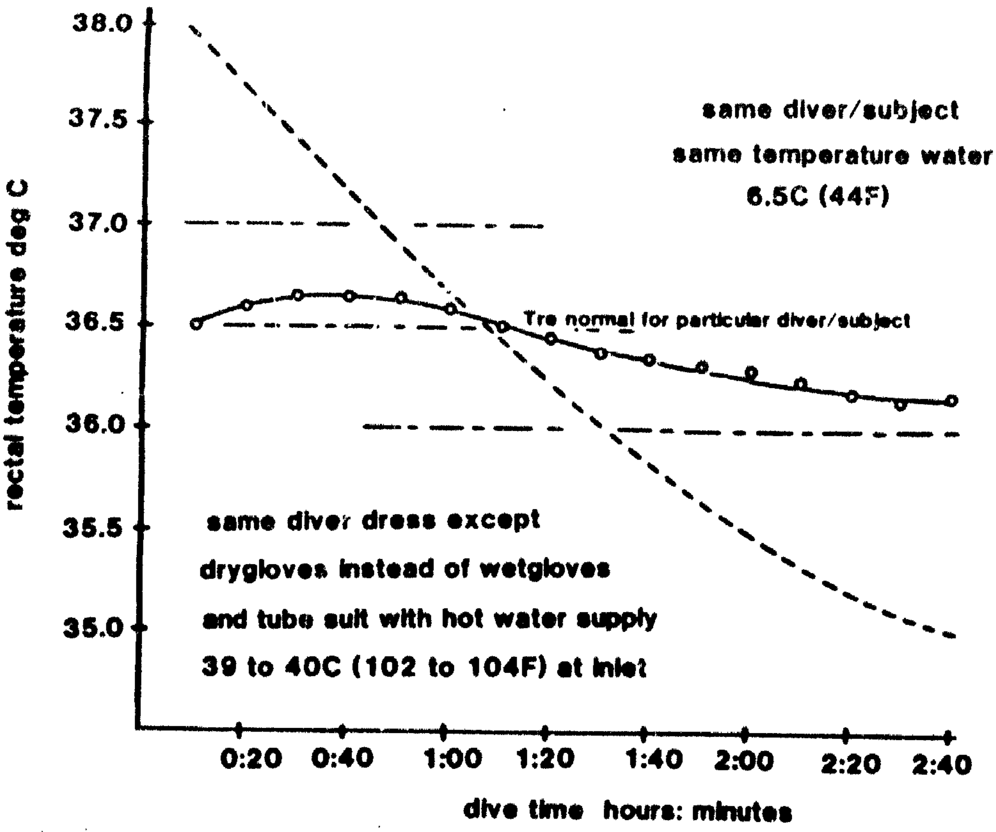
Figure/Slides 18 (a) and (b)

18 (a): This shows data obtained independently by another investigator -- Dr. H. Goforth of NHRC. It was performed in 44°F (12.5 °C) water, using M200, a TLS drysuit, wetgloves and an AGA mask with hood. From an initially elevated temperature of 38°C, T_{re} fell to 35°C in the subsequent 2 hrs and 40 minutes, at which time the dive was terminated. Note that shivering began at about 37.5°C, after about 1 hour both hands became numb, both feet became numb within the next 30 minutes, with both legs becoming numb just prior to termination.

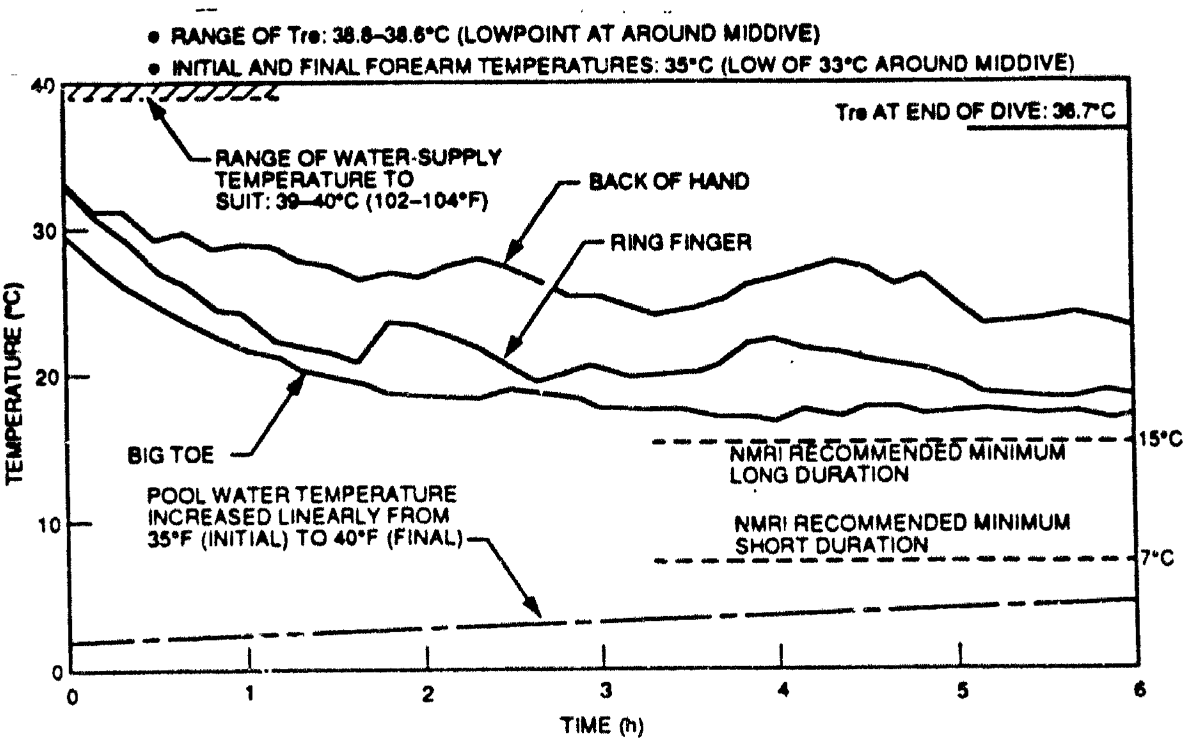
18 (b): This shows comparative data on a dive we performed in the same temperature water with the same diver wearing the same dress, except that it was supplemented with the hot water tube suit, and drygloves instead of wet gloves. From an initial T_{re} of 36.5, there was a slight initial rise followed by a thermal stability occurring at slightly less than his particular pre-dive baseline of 35.5°C -- i.e., the diver/subject mentioned previously.

FIGURE/SLIDE # 18 (a)&(b)





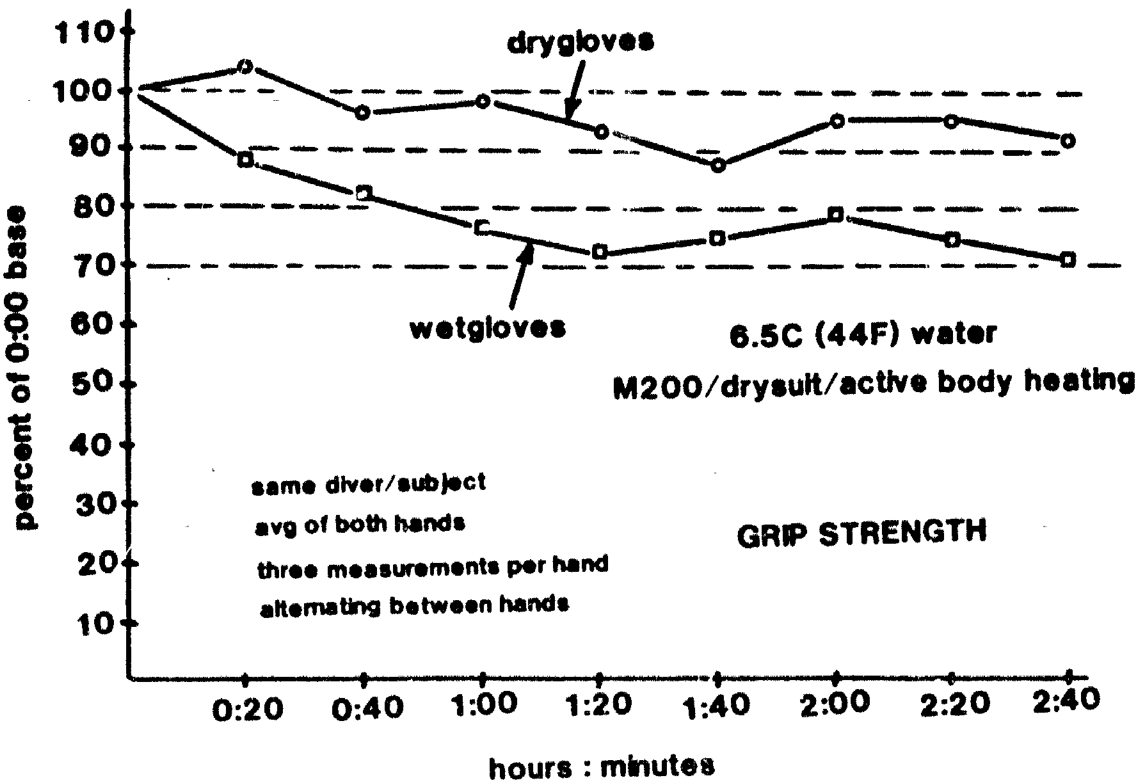
Figure/Slide 19



This shows skin temperatures for the 6-hour dive in 3°C water, using M200 Thinsulate with active body heating and unheated drygloves. As shown for the big toe, ring finger and back of the hand, extremity temperatures remained above recommended minimum values for long duration exposures. T_{re} (not plotted) remained fairly constant throughout, ranging from an initial value of 36.8°C to 36.75°C after 6-hours, with a minimum of 36.65°C occurring about mid-dive. Similarly, initial and final forearm temperatures were 35°C, with a low of 33°C occurring about mid-dive.

Although hand and finger temperatures with the five-finger wetgloves were not measured, after 2-hours and 40 minutes in 44°F (6.5°C) water the hands and fingers were still tactile, and had good color immediately post-dive. Subjectively, the thermal protection afforded by the insulated drygloves was far superior to that of the wetgloves.

Figure/Slide 20



This shows grip strength as a percent of initial baseline (i.e., wearing gloves). The data is for the same diver/subject on two different dives in the same temperature water -- 44°F (6.5°C). Both were performed with suit heating and M200 Thinsulate. The upper curve is for unheated drygloves and remained within 90% of initial baseline. The lower curve is for unheated wetgloves, and fell to 70% of baseline after 2 hours and 40 minutes.

It should also be noted that throughout all the exposures for which they were used, both the insulated four-finger drygloves (6-hrs) and the five-finger wetgloves (2hrs, 40 min.), permitted the diver to write legibly underwater with an ordinary pencil. In terms of diver comfort, the use of three-finger gauntlets in conjunction with the wet gloves were of no additional benefit.

PASSIVE AND ACTIVE THERMAL PROTECTION: EVALUATION AT REST AND FREE-SWIMMING

LCdr John A. Sterba, MC, USNR
Navy Experimental Diving Unit
Panama City, FL 32407-5001

ABSTRACT

Passive Thermal Systems (PTS) are dry suit outergarments worn over insulating undergarments. Active Thermal Systems (ATS) include supplying heat to the divers using, for example, a tubulated undergarment. Naval Sea Systems Command (NAVSEA) has tasked the Navy Experimental Diving Unit (NEDU) to test and evaluate PTS and ATS in divers at rest and free-swimming in water as cold as 29°F. Also, NEDU is tasked to evaluate rewarming strategies to treat hypothermia in the field. The questions being asked include: (a) how long can a diver stay warm in a PTS at rest and can underwater swimming rewarm both the core and extremities, and (b) following prolonged cold water exposure using the ATS at rest, can free-swimming with PTS or ATS maintain adequate core and extremity temperatures and what are the energy expenditures? For the field treatment of hypothermia, in a cold air environment, a passive, insulated bag called a Thermal Recovery Capsule with and without portable airway rewarming will be evaluated. Nutritional and body fluid requirements and hand dexterity testing during long-term submersion using PTS and ATS in cold water will be a collaborative effort with Naval Coastal Systems Center (NCSC), Naval Health Research Center (NHRC), and Naval Medical Research Institute (NMRI). Physiological criteria terminating exposure will be finger/toe temperature to 8°C for 30 mins, or anytime to 6°C, and 35°C core temperature, measured at either esophageal or rectal sites. In addition to extremity and core temperatures being monitored, skin temperature and heat flux (12 skin sites), tube-suit calorimetry data, and oxygen consumption by monitoring oxygen bottle pressure on a closed circuit underwater breathing apparatus (MK-15) will be simultaneously monitored in two USN diver-subjects. Eight diver-subjects are presently trained for these PTS and ATS dives. Open discussion will be encouraged for revision and criticism of the proposed three experimental protocols investigating PTS and ATS, at rest and free-swimming.

Presently, cold water training missions in excess of four hours for Special Warfare (SPECWAR) are being hampered primarily by extremity hypothermia, such as pain and loss of sensation in the hands. The currently used diver Passive Thermal Systems (PTS) are dry suits with thick undergarment insulation. Loss of hand dexterity and inadequate thermal protection while at rest are the principal limiting factors which have prompted research in diver Active Thermal Systems (ATS). Diver ATS are dry suits utilizing tubulated undergarments or panels circulating warm fluids near the diver's skin. By actively heating the diver, less insulation improves hand dexterity, decreases the required passive insulation and allows regulation of the required heat for

The opinions or assertions contained in this article are the private views of the author and are not to be construed as reflecting the view of the United States Department of the Navy or the Department of Defense.

a diver at rest or free-swimming. The design goal is to thermally protect a diver for up to eight hours using a heat source. Present research on the ATS Conox heater is being done by S-Tron, Redwood, CA Preliminary results of the efficacy and efficiency of a whole body tube-suit using a second type of heater, a thermo-electric heat pump, will be presented at this workshop by Mr. T. Schmidt of Lockheed. Current research on selective hand warming with the ATS tube-suit glove is being done by Dr. R. Weinberg, Naval Medical Research Institute (NMRI).

Naval Sea Systems Command (NAVSEA) is directing the research and development on the ATS, coordinated by Mr. R. Cummings of SPECWAR (SEA, Code 06Z) and Mr. J. Dudinsky of Naval Coastal Systems Center (NCSC, Code 5110). NAVSEA has also tasked the Navy Experimental Diving Unit (NEDU) to conduct the test and evaluation of both diver PTS and ATS in sea water to 29°F (-2°C) or fresh water to 33°F (0.6°C). NAVSEA has granted the authority for interface between NCSC and NEDU for the research and development and test and evaluation, respectively. The Project Manager of these cold water studies at NEDU is LCdr J. Sterba. The SPECWAR human factors engineer assigned to this project is Mr. R. Roesch, NCSC, Code 5410.

The questions being asked by NEDU, NCSC and NAVSEA with input from NMRI and S-Tron include the following: (a) how long can a diver in the trimmed or swimming configurations stay adequately warm in a PTS, avoiding extremity and core hypothermia, with the diver wearing currently used PTS and an underwater breathing apparatus (UBA) such as the MK-15?; (b) can underwater swimming rewarm the hands and feet of diver that is already very cold?; (c) following prolonged exposure at rest wearing the ATS, can a free-swimming diver stay adequately warm if the active heating is disconnected, or is ATS required for thermal protection?; (d) what are the ATS energy requirements and the metabolic energy expenditures for adequate ATS protection in rest/swim/rest testing protocols lasting up to eight hours?.

NAVSEA has also tasked NEDU to test current field rewarming devices which can be conveniently evaluated following these prolonged cold water dives. The devices being physiologically evaluated for their efficacy to retard body core temperature after-drop and accelerate rewarming include the Thermal Recovery Capsule (Lifeguard Systems, Inc., Hurley, NY), Heat-Treat airway rewarming (Thermo-Genesis International, Inc., Victoria, B.C., Canada). Heatpac Rescue Bag (A.B. Russell Co., Waitsfield, VT). These devices will be evaluated in 0°F (-18°C) air temperature. For accelerated active rewarming, one-man immersion tanks capable of changing the water temperature from 85 to 108°F (29 to 42°C) in 15 mins will be used. By starting the immersion rewarming at 85°F and rapidly increasing the temperature to the recommended 104 to 108°F range, the initial scalding sensation can be avoided.

Criteria for termination of a cold water exposure will include core temperature of 95.0°F (35.0°C) measured by rectal or esophageal core thermister or extremity hypothermia of any monitored finger or toe temperature to 46.4°F (8°C) for 30 mins or at anytime to 42.8°F (6°C). These criteria have been proposed to avoid non-freezing cold injury to the hands and feet and will be physiologically evaluated in these trials.

Physiological monitoring will include: 12-site skin temperature and heat flux measurements; three finger and two toe temperatures, bilaterally; esophageal (42 cm from the nose) and rectal (15 cm insertion) core temperatures. Tympanic membrane or external auditory temperature will not be measured due to the influence of scalp temperature making interpretation of this temperature difficult. ATS tube suit water inlet and outlet temperatures will allow a determination power delivered. Oxygen consumption will be determined by measuring the change in oxygen bottle pressure in the MK-15 UBA, insuring no loss of gas occurs and diluent gas consumption is controlled.

The underwater performance evaluation includes measurements of grip strength, manual dexterity and the effects of cold water distraction on completing complex underwater tasks involving the hand-glove-tool interface. Human factors questionnaires have been developed to assess performance of two dry suits, the Viking, Pro model and Diving Unlimited International (D.U.I.) Tri-Laminate System (T.L.S.) model. Both Viking and D.U.I. dry suits were custom measured over custom M-400 weight Thinsulate undergarments, purchased from D.U.I. (San Diego, CA). Human Factors evaluation of various PTS and ATS accessories will include: buoyancy compensators with integrated weight systems, automatic dry suit inflator systems, urinary overboard dump systems (UODS), cold water fins for attachment and swimming efficiency, dry glove attachment systems plus wrist and neck seal performance.

In a separate study, presented at this workshop, we evaluated nine commonly used undergarments for thermal conductivity (wet vs. dry), compressibility simulating suit squeeze and degree of absorbency simulating suit leaks. The Thinsulate material was superior for these characteristics

Regarding the many dry suits in use today by military divers, a NEDU report was recently published entitled Market Survey of Commercially Available Dry Suits (Brewster and Sterba NEDU Report 3-88). This report describes the following information from ten dry suit companies: company address and telephone number, company information, users of the dry suit, dry suit material, sizes, nonmagnetic capability, zipper configuration, valve placement, wrist seal and glove connection, hood and boot configuration, manufacturing lead time, cost and additional information for the military diver. For U.S. Navy divers, the selection of a dry suit, like a wet suit, is by personal preference (NAVSEAINST 10560.2).

It has been strongly recommended by authorities in dry suit diving (Viking-Stavanger and D.U.I.) that a diver needs a minimum of ten supervised dry suit orientation dives in cold water before becoming competent in dry suit diving. Thereafter, the diver can reliably evaluate the performance of a dry suit on a demonstration dive. At NEDU, the eight U.S. Navy divers selected for the Cold Water Dive Team had a range of dry suit experience from no dives to over 100. To help standardize the degree of dry suit experience, a formal one week course was conducted to train these divers in dry suit design, construction, repair plus dry suit diving. The first dry suit divers were done in warm water with minimal insulation. This allowed easy adaptation to the buoyancy changes when too much weight was carried as well as easy identification of potential leak points with improper use of the seals, undergarments, valves and the zipper. By adding more undergarment insulation and diving in colder water to 40°F (4.4°C), proper weight selection and distribution along with buoyancy control was easily learned. A minimum of ten cold water dives were then conducted before any work-up dives began in preparation for the evaluation of both PTS and much later, ATS.

In order to physically condition the Cold Water Dive Team for prolonged underwater swimming, a 6 week, 5 days per week, program of fin swimming, calisthenics, weight training and running was undertaken. The emphasis was on both surface and underwater fin swimming to condition the legs for these dives. It is very doubtful that the fleet military divers using the PTS or ATS would be cold acclimatized. At NEDU, the water temperature for the physical conditioning program was 85°F (29.4°C) preventing any cold acclimatization. With work-up dives in the 33°F (0.6°C) water kept to a minimum and of short duration, no cold acclimatization in the diver-subjects would also have been expected.

At the time of this workshop, work-up dives are underway for the first data collecting dives evaluating PTS at rest and with underwater swimming. The total evaluation of both PTS and ATS plus the field rewarming procedures is scheduled through September of 1989. NEDU reports on each protocol evaluating these systems will be published thereafter.

SOME RESULTS OF CLOSED-CIRCUIT UBA HEATING ON CO_2 ABSORPTION

T.C. Schmidt
Lockheed Advanced Marine Systems
3929 Calle Fortunada, San Diego, CA 92123

ABSTRACT

Manned dives were performed in 36-39°F (2-3°C) water using a MK15 Closed Circuit UBA filled with Sodasorb, both heated and unheated. Although a relatively limited number of dives were performed, the following are consistent with the data obtained.

(1) When setting operational time limits, the point in the dive profile where exercise is performed is just as important as total cumulative activity during the dive.

(2) Inspired CO_2 levels are quite sensitive to the temperature of the gas entering the CO_2 absorbent canister, with this effect increasing in direct proportion to dive duration.

(3) UBA heating has a significantly beneficial effect on CO_2 absorption capacity and alleviates problems associated with condensation within both the mask and UBA.

(4) The duration of this beneficial effect following cessation of heating concurrent with exercise is useful but time limited.

(5) The effect of initial starting temperature is surprisingly long-lived and becomes the controlling factor within about 30 minutes after cessation of active heating concurrent with exercise.

Figure/Slide 1

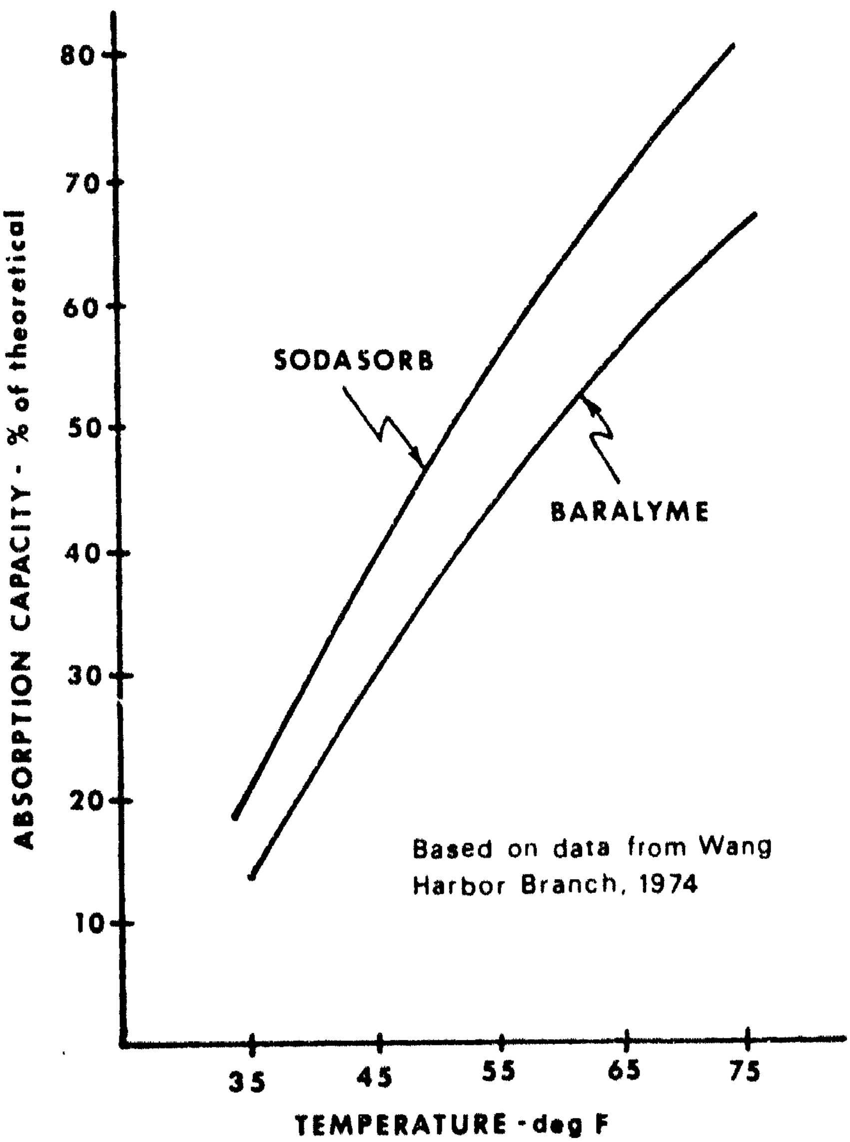
Cold temperatures typically have a deleterious effect on the CO_2 absorption capacity of certain hydroxide absorbents. As shown, this is quite marked for Baralyme and Sodasorb -- e.g., for the latter the absorption capacity as a percent of theoretical decreases from 80% at 75°F(24°C) to only 20% at 35°F(1.5° C). It should be noted however, that this reflects the temperature of the absorbent chemical per se., and the data shown is specific to 1% CO_2 in 1 ATA nitrogen at 90% relative humidity.

In an attempt to establish the potential merit of underwater breathing apparatus (UBA) heating on performance in cold water, manned dives were performed in 34-38 F (1-3°C) water, using a MK15 Closed Circuit UBA filled with Sodasorb, with the UBA in both the unheated and heated conditions.

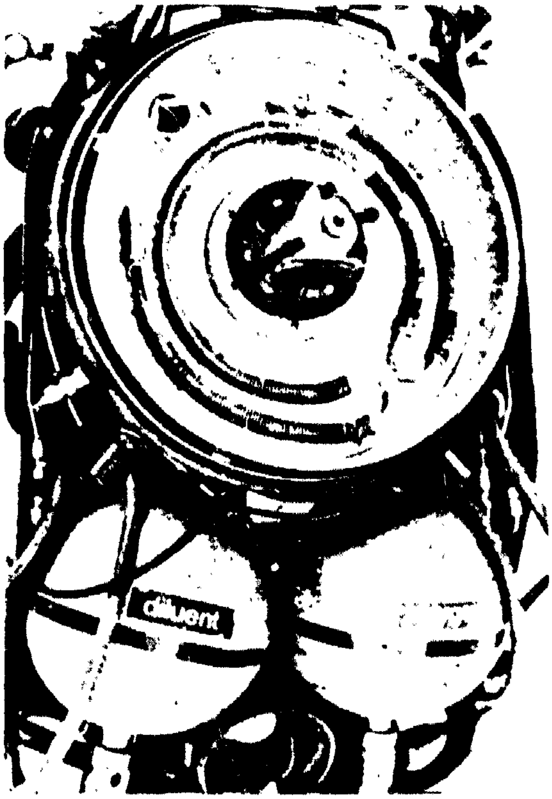
Figure/Slide 2

This shows the method of UBA heating used. It consisted of a tube/fin type heat exchanger (HEX) located in the space which normally exists beneath the CO_2 absorbent canister. In this manner, the recirculated gas is heated immediately prior to its entrance into the CO_2 absorbent canister. The prototype heat pump (described elsewhere) was used by simply supplying an additional 1/4 gpm to the UBA HEX (at the same temperature as the suit supply) -- approximately 104°F(40°C). Although the temperature within the canister was not readily attainable, the temperature within the volume below the canister (i.e., the canister inlet area) was measured and recorded.

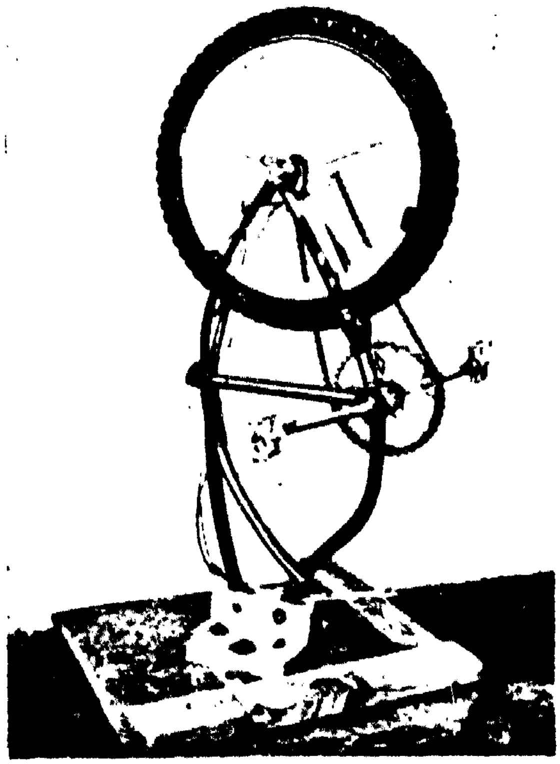
Figure/Slide #1



Figure/Slide #2



Figure/Slide #3



The exercise performed in the first two dives to be discussed consisted simply of weighted arm exercises and simulated swimming against the wall of the tank at a work rate that was subjectively moderate.

Figure/Slide 3

The exercise performed in all the others was performed using a bicycle type ergometer. While this was not calibrated in terms of work load per se., it did have an RPM readout such that the work loads used (i.e., approximately 35 RPM which was deemed subjectively to be equivalent to a non-stressful average swim) were consistently reproducible. By comparison, maximum work capacity was 46-48 rpm -- sustainable for 5-minutes duration.

All three subjects were experienced/active divers -- one was a former SEAL and another was an active EOD reservist.

Figure/Slide 4 (a)&(b)

As shown for the cases with the UBA unheated throughout the dive profile, moderate exercise performed after 3-hours produced a CO_2 level of 0.2%, which was also the resting value after a total exposure of 6-hours. By comparison, moderate exercise performed after 6-hours, beginning at a resting CO_2 level of 0.2%, resulted in a CO_2 level which is considered as "breakthrough" (0.5%). More significant however, is the fact that the measured canister inlet gas temperatures and inspired CO_2 levels are almost mirror images of each other.

Figure/Slide 5

When the data points of inspired CO_2 vs canister inlet gas temperature for both dives are plotted (irrespective of time), there is not a good correlation between the two.

Figure/Slide 6

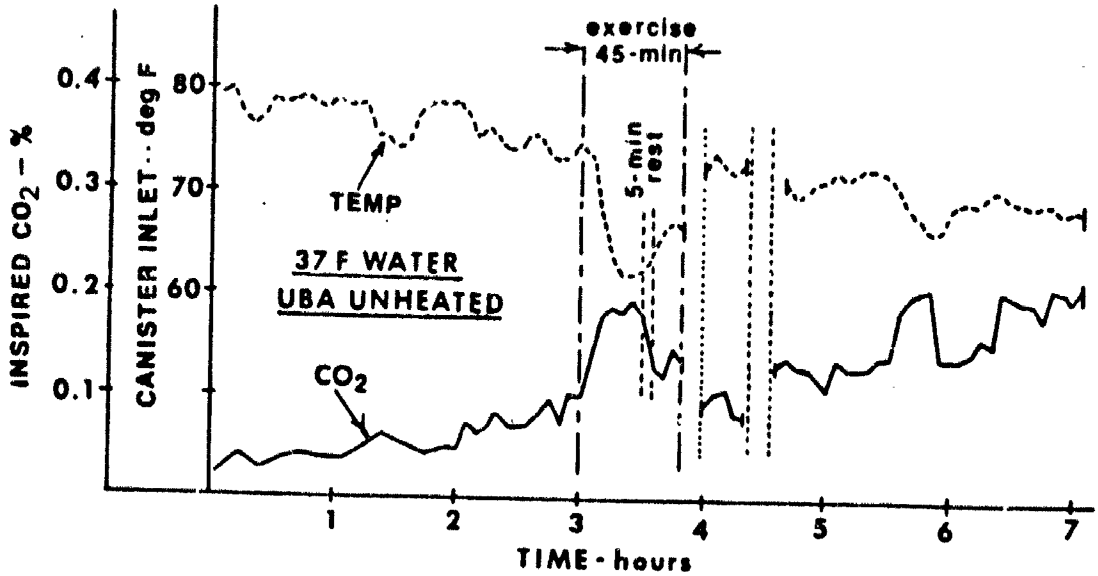
	slope - percent CO_2 per deg F (based on canister inlet temp)	std error (of slope)
First 2-hours, n = 21	0.0042 percent/deg F	0.0017
2-hrs to 4-hrs, n = 31	0.0081 percent/deg F	0.0007
4-hrs to end, n = 46	0.0201 percent/deg F	0.0017

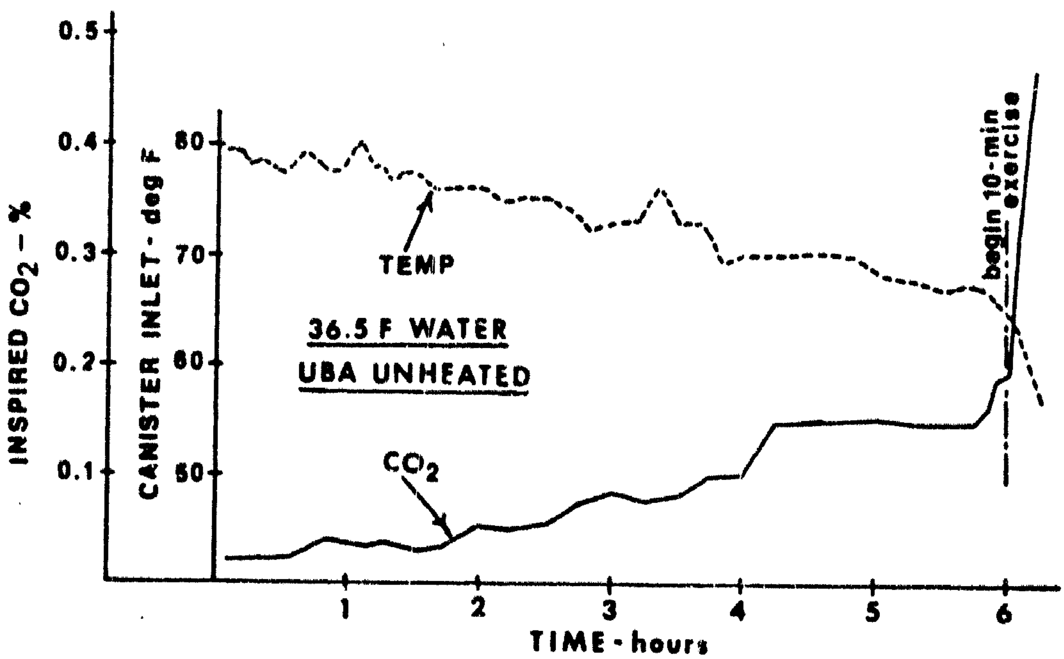
However, when the combined data was divided into three groups (i.e., the first 2-hrs; 2-hrs to 4-hrs; and 4-hrs to end dive), a linear regression analysis showed a significant correlation between both dives, and a significant difference between each group in sensitivity to inlet temperature -- the inspired CO_2 as a function of canister gas inlet temperature during the middle 1/3 of the dive was about twice that of the first 1/3, and the last 1/3 was again about 2.5 times that of the middle 1/3.

Figure/Slide 7

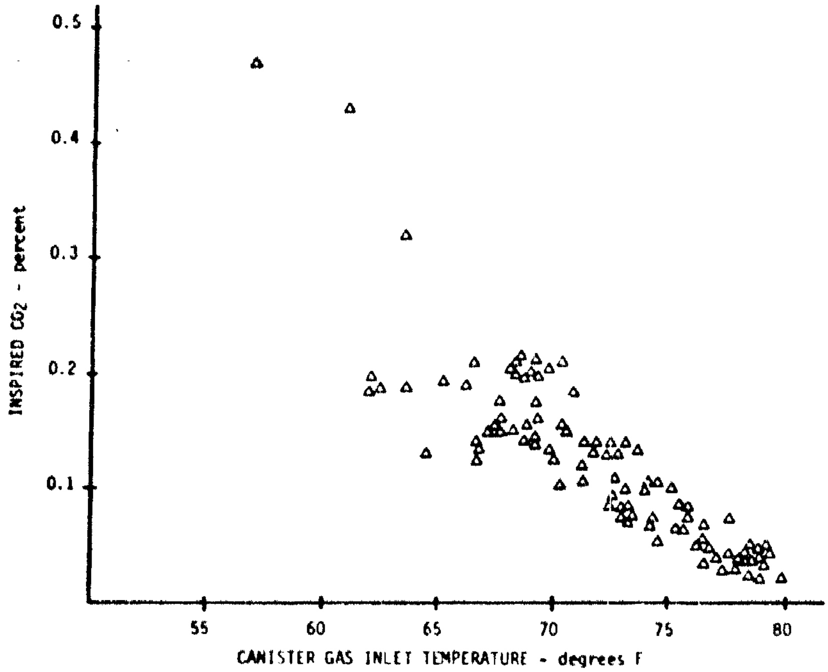
This shows the results of alternating 5-minutes work/10-minutes rest, with both unheated and heated UBA. The data shown here (and in all subsequent data) are based on the same reproducible work rate (35 rpm on the bicycle ergometer). The data points are immediately pre- and post-work, and halfway through the rest period.

Figure/Slide #4

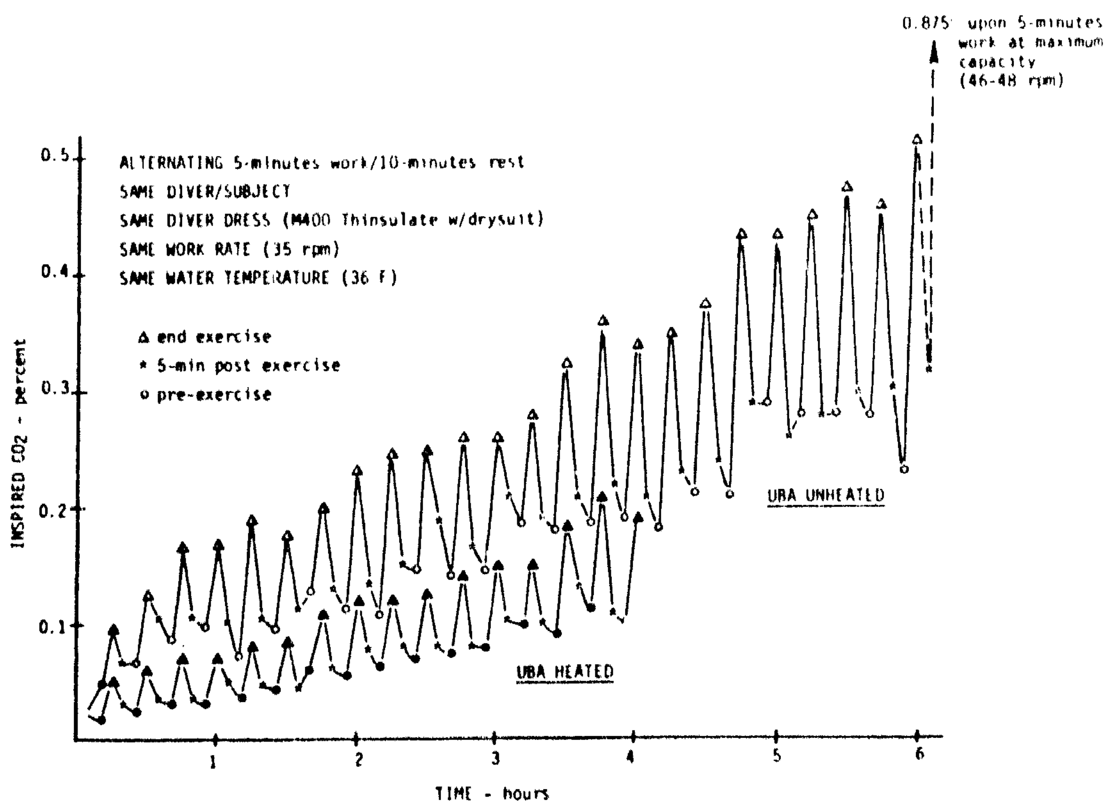




Figure/Slide #5



Figure/Slide #7



(1) In the unheated case, exercise at 6-hours resulted in an increase in CO_2 about the same as that shown previously (i.e., 0.3% increase from 0.2% pre-exercise) at the same point in time.

(2) The magnitude of increase in CO_2 upon exercise increases as dive time increases

(3) Both dives (heated vs unheated) involved the same diver, in the same temperature water, with the same reproducible level of exercise. With UBA heating, the CO_2 levels (both peak and pre-exercise) and the magnitude of increase during exercise, were approximately one-half the unheated values.

(4) Compared to all the unheated dives where mask microphone flooding became a significant problem due to condensation, this did not occur during the heated dive, and post-dive inspection of the UBA interior showed the surfaces to be significantly dryer.

Figure/Slide 8

As shown, the unheated UBA attained a steady state canister gas inlet temperature of about 60°F(15.5°C), while for the heated condition it was about 20°F(11°C) warmer, and still increasing at a rate of about 1.8°F(1°C) per hour.

Figure/Slide 9

Several dives were then performed in 35.5°F(1.5°C) water, with UBA heating during the resting (non-exercise) portion only, i.e.,

- 30-minutes of exercise (UBA unheated), followed by
- 2-hours resting (UBA heated), followed by
- 1-hour of exercise (UBA unheated), followed by
- 10-15 minutes resting (UBA heated).

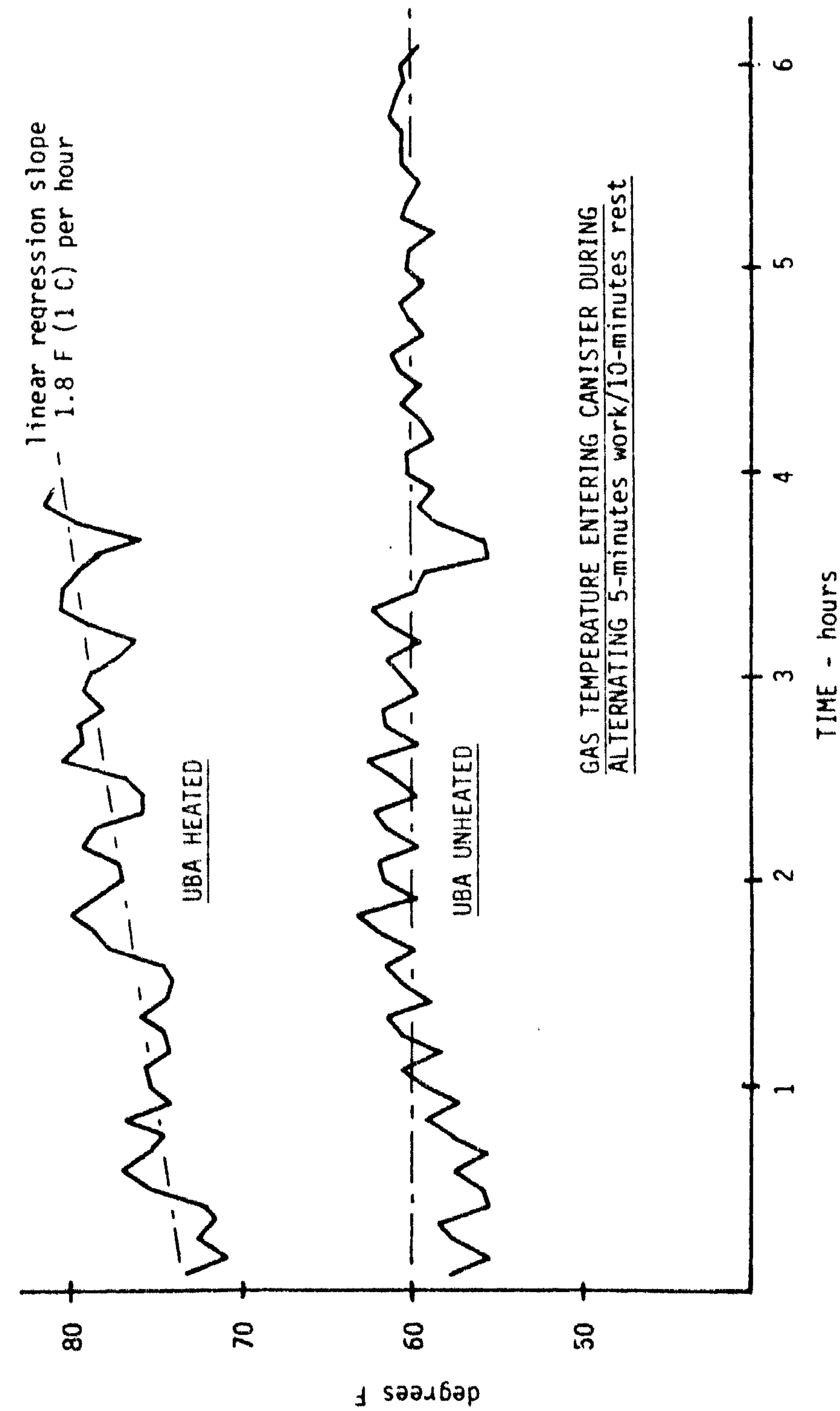
Although inspired CO_2 and canister inlet temperatures were inversely related during the course of the 1-hr of unheated exercise, all three dives showed different inspired CO_2 levels, which did not correlate with the gas inlet temperatures per se. During unheated exercise, the canister inlet temperature sought the 60°F(15.5°C) equilibrium point seen previously -- i.e., in all cases it was 60°F ± 5 (15.5°C ± 2.75) after about 30-minutes of unheated exercise. This included both the initial exercise periods, and also 30-minutes into the 1-hour ones which started from pre-exercise inlet temperatures of 84°F ± 3 (29°C ± 2) and decreased exponentially with a half-time of about 10-minutes.

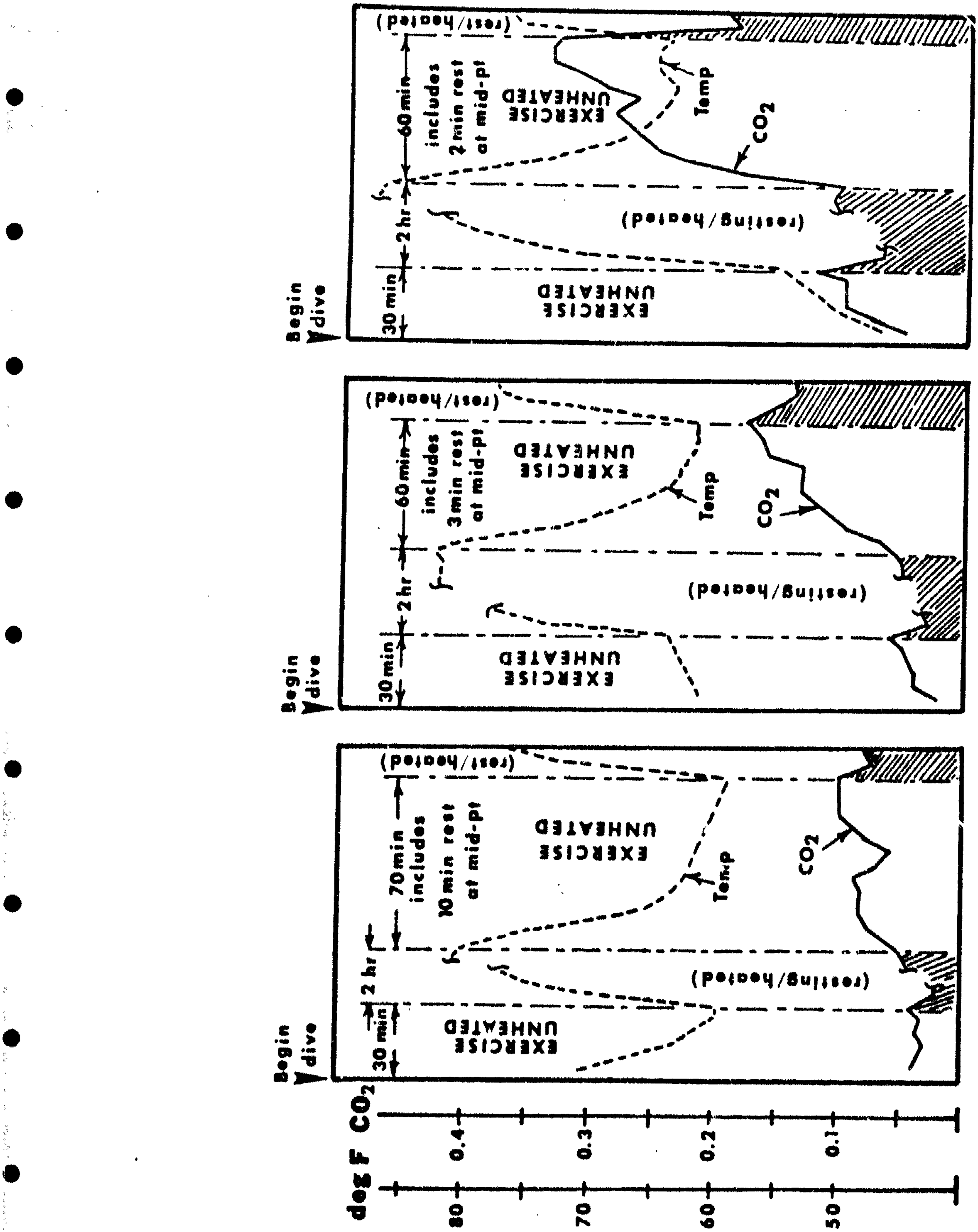
Figure/Slide 10

This data appeared to correlate however, with the initial UBA temperatures at the start of each dive (as measured by the canister inlet gas), which were about 70°F, 60°F and 45°F (21, 15.5 and 7.25°C) respectively -- due to different pre-dive ambient temperatures (in the unheated lab June through December).

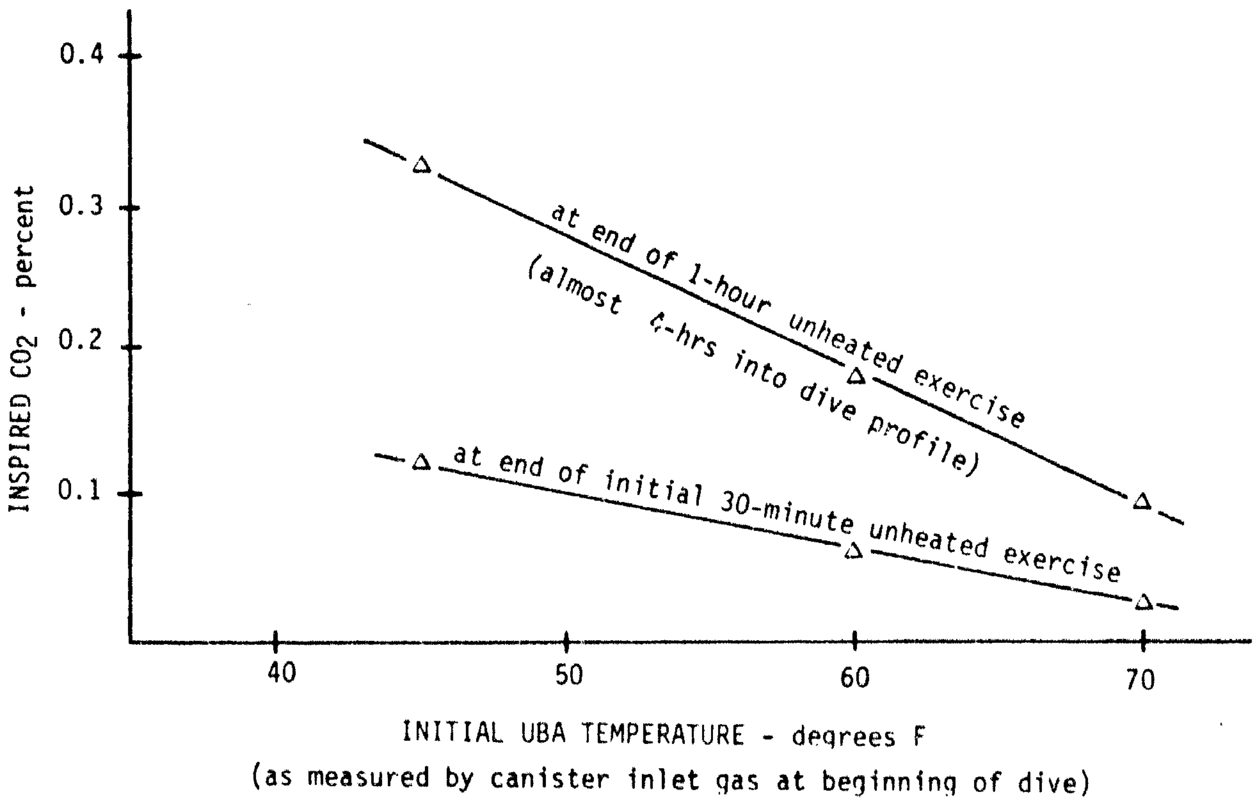
Although possibly coincidental, these results appear to indicate that the efficiency of the CO_2 absorption is dependent on both the temperature of the canister inlet gas, and the initial starting temperature, that is, that there is a residual mass specific heat effect which is surprisingly long-lived -- e.g., possibly manifesting itself throughout the entire usable dive profile.

Figure/Slide #8




deg F
CO2
80
70
60
50
0.4
0.3
0.2
0.1
Begin dive
30 min
2 hr
70 min includes 10 min rest at mid-pt
60 min includes 3 min rest at mid-pt
60 min includes 2 min rest at mid-pt
EXERCISE UNHEATED
(resting/heated)
(rest/heated)
Temp
CO2

Figure/Slide #10



POTENTIAL OF DIVER HEATING THROUGH CATALYTIC COMBUSTION OF ALCOHOL

P.A. Browne
Atomic Energy of Canada, Ltd.

ABSTRACT

Research at AECL's Chalk River Nuclear Laboratories has resulted in the development of a number of advanced catalytic alcohol burners. These new devices do not employ radioactive materials, but rather rely on a chemical reaction to generate heat. The new designs, while particularly simple in concept, offer the advantages of alcohol as a fuel, operation without an ignition device, and a controllable, enclosed, flameless combustion. Two classes of heaters have been developed, forced and natural circulation. Investigations are presently underway to determine its potential in providing supplemental heat to the diver by various means such as flooding parts of the body with a heated liquid, circulating a heat exchange fluid through tubing and placing heaters with heat conductive pads in contact with the body surface.

SESSION 4

PHYSIOLOGICAL CONSIDERATIONS

Session Chairman:
R. Weinberg

PREFACE

While physical protection for the diver can provide the majority of thermal insulation, an understanding of the physiological responses, and their contribution to the overall thermal protection, is necessary to provide a complete picture. Moreover, a physiological understanding should assist in clothing development as well by better integrating the effects of physiological responses and the diving ensemble itself.

The first presentation covered specific biochemical and fluid responses to cold exposure. The session was opened by Dr. A. Vallerand of DCIEM who gave an overview of various pharmacological approaches to enhancing cold response. This was followed by L. Martineau of DCIEM who described her findings relating substrate availability and the body's thermoregulatory responses. Dr. K. Mittelman from NMRI presented two papers on behalf of T. Doubt. The first described results relating carbohydrates and caffeine effects on promoting performance in cold water. The second described the physiological changes in fluid and electrolyte balances during cold water exposure. The two presentations were separated by a talk on lipid metabolism in cold exposed humans presented by Dr. Vallerand.

The last half of the session addressed more general or practical physiological concerns of thermoregulation. The first pages presented by Dr. E. Wissler of the UMV of Texas/Austin described the physiological responses to passive and electrically heated survival suits in a "lost bell" scenario at a depth of 450 msw. Dr. P. Tikuisis of DCIEM followed by describing his modelling work in attempting to predict thermoregulatory responses in clothed individuals immersed in cold water. The session concluded with G. Knudsen's presentation, for NUTEC, of the contribution of respiratory heat loss in maintaining thermal balance during deep diving.

Tiit Romet
Co-Chairman

REVIEW OF PHARMACOLOGICAL APPROACH TO IMPROVE COLD TOLERANCE

A.L. Vallerand and I. Jacobs
Environmental Physiology Section
Defence and Civil Institute of Environmental Medicine
Toronto Ont. M3M 3B9 Canada

ABSTRACT

A pharmacological approach to the problem of enhancing cold tolerance in humans is currently the subject of greater attention. Two approaches are possible. First, drugs that minimize heat loss could delay hypothermia but would also be associated with lower mean skin temperature, the loss of manual dexterity and a greater danger of frostbite. Secondly, agents that increase heat production could increase resistance to cold by producing warmer body temperatures. By using hormones, theophylline, caffeine, amphetamines etc for various periods of time, heat production and cold tolerance have been improved in animal studies. However, a generalization to humans should be made with caution particularly in view of the small animal's capacity for brown fat nonshivering thermogenesis. In humans exposed to comfortable ambient temperatures, recent studies have firmly established that β-adrenergic drugs such as ephedrine, and methylxanthines such as caffeine increase heat production. Similarly, a mixture of ephedrine/caffeine is presently considered a very promising thermogenic drug in man because it has shown safe thermogenic properties in both short- and long-term studies. Since its thermal benefit to cold-exposed humans is unknown, the influence of ephedrine (1mg/kg)/caffeine (2.5mg/kg) on cold tolerance was investigated in 9 healthy young male subjects during two semi-nude exposures to cold air (3 h at 10°C). The drug ingestion reduced the total drop in core, mean skin and mean body temperatures ($p<0.01$), thus producing significantly warmer final core, mean skin and mean body temperatures in comparison to the placebo ingestion. The drug ingestion increased the total 3 h energy expenditure by 18.6% in comparison to that of the placebo ingestion in the cold ($p<0.01$). Using the non-protein respiratory exchange ratio to calculate the rates of substrate oxidation, it was found that the drug ingestion increased carbohydrate oxidation by 41.7% above that of the placebo ($p<0.05$), but did not alter lipid or protein metabolism. The results demonstrate that the ingestion of an ephedrine/caffeine mixture improves cold tolerance in man by significantly increasing body temperatures in the cold. These improvements were caused by a greater energy expenditure, which appears to be dependent on an enhanced carbohydrate utilization.

Pharmacological agents that impair the ability to regulate body temperatures in the cold or that decrease resistance to cold, have been well described in numerous studies. The opposite, enhancing cold tolerance with pharmacological agents, has been shown to be more difficult to achieve. Considering the greater number of animal studies related to the influence of drugs on cold tolerance, it appears important to review this part of the literature before examining the relevant human studies.

ANIMAL STUDIES

During the investigation of endocrine responses to the cold, several hormones that were administered for various periods of time were found to markedly improve cold tolerance. They include: (1) catecholamines, which mimick the cold adaptation induced enhancement of nonshivering thermogenesis; (2) thyroxine, which greatly affects basal metabolic rate and act as a permissive hormone in the thermogenic effect of catecholamines; (3) thyroxine with cortisol and (4) growth hormone (for a review see LeBlanc, 1975; Sellers, 1972). Although useful in the understanding of cold thermogenesis, it is apparent that these studies have little direct application to human work since: (1) the catecholamines-induced improvements are directly related to brown adipose tissue thermogenesis; (2) long-term use of high doses of thyroxine is not recommended in euthyroid subjects; (3) long-term use of high doses of cortisol increase protein breakdown and is associated with Cushing's syndrome; (4) long-term use of high doses of growth hormone leads to insulin resistance and is associated with acromegaly. In contrast, a wide variety of potentially useful drugs have been shown to successfully improve cold tolerance in animals. Dinitrophenol has been shown extremely potent in enhancing cold resistance since it uncouples oxidative phosphorylation, where a large amount of heat and little ATP are produced whenever substrates are oxidized (Hall, 1948). However, this uncoupling effect is generalized to virtually all tissues. Combined with thyroxine, the thermogenic effect of dinitrophenol is even greater (Frommel, 1950), but again it is difficult to see an application to man at least in the presence of a generalized effect. Other compounds have also been shown to be effective in the improvement of cold tolerance. They include vitamin C, alpha amino acids, strophantin, chlorpromazine, coramine, cardiozol (Gilman et al, 1970; Grab, 1956; Gunther 1946; Hahn, 1942; Scheurer, 1942; Vacirca, 1946). Of greater interest today, is the methylxanthine caffeine. Caffeine is an established thermogenic agent at comfortable ambient temperatures (Acheson, 1980) that has been shown to significantly improve cold tolerance in animals (Gennari 1940; Estler 1978). Another effective methylxanthine is theophylline. During the last decade Dr Wang has decisively shown the significantly warmer body temperatures associated with the thermogenic effect of theophylline in rats (Wang, 1982, 1985). Other successful drugs in the cold include amphetamines (Gilman et al 1970) with or without epinephrine (Pick, 1948) which markedly increased oxygen consumption and produced significantly warmer core temperature in the cold.

Whether these endocrinological pharmacological studies are applicable to humans is not clear. Some of the above studies used agents on a long-term basis which would be contraindicated in humans. Other studies improved resistance to cold by enhancing brown adipose tissue oxidative capacity, a poorly-developed mechanism in humans, or by uncoupling mitochondrial oxidative phosphorylation. Therefore, sympathomimetics and methylxanthines appear to be two classes of drugs that stand out from the rest of the other drugs used in the cold, and they would likely be useful in human studies.

HUMAN STUDIES

As early as 1942, Scheurer had reported in man that caffeine ingestion increased mean skin temperature at an undisclosed cool ambient temperature (Scheurer, 1942). During cold air exposure, Macnaughton & Graham (1988) have reported a small thermogenic effect of caffeine in the cold with no changes in body temperatures. Similarly, LeBlanc et al (unpublished manuscript) has reported that the ingestion of caffeine before bedtime increased heat production and mean skin temperature in cold-exposed subjects, but also produced a large fall in core temperature, suggesting little or no change in mean body temperature, due to increased heat loss. It is interesting to note the magnitude of changes in metabolic rate and body temperatures reported in a few successful human studies. As an example, heat production in the cold was enhanced 10% by glycine (Beavers 1959), 4% by theophylline with exercise (Wang 1987) and remained unchanged by theophylline at rest (Wang 1986). The overall fall in T_{re} and $\bar{T}_b$ were reduced by 33% and 10.5% respectively by theophylline with exercise, whereas theophylline at rest reduced the fall in T_{re} by 50% but increased the fall in $\bar{T}_b$ by 5% (Wang 1986, 1987). Finally the administration of a diet supplement reduced by 25% the fall in T_{re} (Kreider, 1957). Although only a limited number of human studies are available, it is clear that small improvements in maximal cold thermogenesis and small changes in body temperatures are to be expected in humans acutely exposed to the cold. This would be similar to the relatively small changes in maximal aerobic capacity brought about by normal exercise training.

THERMOGENIC DRUGS IN OBESITY RESEARCH

We have noted that several thermogenic drugs presently used in obesity research, could be useful in the cold. Of the various classes of drugs available today, sympathomimetics, mainly B-adrenergic agonists such as ephedrine (Astrup, 1985), and methylxanthines such as caffeine (Acheson, 1980), were effective in increasing heat production at comfortable ambient temperatures. Interestingly, the combination of ephedrine/caffeine was also found highly thermogenic with little side effects in both short- and long-term human studies (Dulloo, 1986). Whether this increase in heat production would enhance resistance to cold in humans is not known.

EPHEDRINE/CAFFEINE AND COLD TOLERANCE

The goal of the present study was therefore to determine the influence of an ephedrine (1mg/kg)/caffeine (2.5mg/kg) mixture on cold tolerance was investigated. Nine healthy young male subjects during two semi-nude exposures to cold air (3 h at 10°C; 1 m/s wind). The drug ingestion (at time 0) significantly reduced the total drop in core, mean skin and mean body temperatures ($p<0.01$), thus producing significantly warmer final core, mean skin and mean body temperatures in comparison to the placebo ingestion in the cold. The drug ingestion increased the total 3 h energy expenditure by 18.6% in comparison to that of the placebo ingestion in the cold ($p<0.01$). Using the non-protein respiratory exchange ratio to calculate the rates of substrate oxidation, it was found that the drug ingestion increased carbohydrate oxidation by 41.7% above that of the placebo ($p<0.05$), but did not alter lipid or protein metabolism. The results demonstrate that the ingestion of an ephedrine/caffeine mixture improves cold tolerance in man by significantly increasing body temperatures in the cold. These improvements were caused by a greater energy expenditure, which appears to be dependent on an enhanced carbohydrate utilization. In conclusion, the substrate mobilization and/or utilization effect of the B-adrenergic agonist and the methylxanthine appear to be an important factor in the improvement of human resistance to cold. Based on the present review of the pharmacological approach to improve cold tolerance in animals and humans, it is suggested that sympathomimetics and methylxanthines are two classes of drugs likely to benefit regulation of body temperatures in cold-exposed humans, and that future studies should continue in this direction.

ACKNOWLEDGEMENTS

The expert technical assistance of Ingrid Schmegner is highly appreciated.

REFERENCES

Acheson K.J. et al., Am. J. Clin. Nutr. 33: 989-997, 1980.

Astrup A. et al. Am. J. Physiol. 248(Endo. Metab. 11): E507-E515, 1985.

Beavers W.R., J. Appl. Physiol. 14(3):390-392, 1959.

Dulloo, A.G. et al., Int. J. Obesity 10: 467-481, 1986.

Estler, C.J. et al., Psychopharmacol. 58: 161-166, 1978.

Frommel, E., Arch Sc. Geneve 3(1): 54-56, 1950.

Grab, W., Klin Wochenschr 24-25: 40-41, 1946.

Gennari, G., Rendic Ist San Pubb Roma 2(3): 515-522, 1940.

Gilman, A.G., L.S. Goodman et al., The pharmacological basis of therapeutics. Macmillan, New York, 1970.

Gunther, B et al., Rev. Soc Argent Biol 22:35-43, 1946.

Hahn, F., Klin Wochensch 21: 460-461, 1942.

Hall, V.E. et al., Proc Soc Exp Biol. N.Y. 69: 413-415, 1948.

Kreider, M.B. et al., J. Appl. Physiol. 11(3): 339-343, 1957.

LeBlanc, J., Man in the cold. Charles C. Thomas Publisher Springfield IL 1975.

Macnaughton, K. & T.E. Graham. The Physiologist 31(4): A43, 1988.

Pick, E.F. et al., Arch Int. Pharm Dyn Paris 77(2): 219-225, 1948.

Scheurer, O. et al., Munchen Med Wochensch 89: 907-911, 1942.

Sellers, E.A. In: The pharmacology of thermoregulation. Eds.: E. Schonbaum & P. Lomax. S. Karger, Basel, pp.57-71, 1972.

Vacirca F., Boll. Soc. Ital. Biol. Sper. 21: 114-116, 1946.

Wang, L.C.H. et al., J. Appl. Physiol. 53: 16-20, 1982.

Wang, L.C.H. et al., Life Sci. 36: 2539-2546, 1985.

Wang, L.C.H. et al., In: Homeostasis and thermal stress. Ed. K. Cooper et al, S. Karger Basel p. 22-26, 1986.

Wang, L.C.H. et al., J. Appl. Physiol. 63(2): 589-596, 1987.

SUBSTRATE AVAILABILITY AND TEMPERATURE REGULATION DURING COLD WATER IMMERSION IN HUMANS

Lucie Martineau and Ira Jacobs.
Defence and Civil Institute of Environmental Medicine
Department of Community Health, Exercise Sciences Program
University of Toronto, Toronto,

ABSTRACT

Increased thermogenesis in humans during cold exposure is caused by shivering. Although there is much evidence that both circulating and intramuscular substrates are used to fuel this enhanced skeletal muscle activity, there are no studies describing the effects of altering substrate availability on human temperature regulation. This abstract reports the results from two studies. The importance of skeletal muscle glycogen as a fuel for shivering thermogenesis in humans during cold water immersion was first clarified. It was then investigated whether a reduced availability of plasma free fatty acids (FFA) would impair cold tolerance.

Study I. Eight lean male subjects, wearing only bathing suits, were immersed to the chest in 18°C water three times over a three-week period. Each immersion continued until 90 min had elapsed or rectal temperature (T_{re}) *decreased to 35.5°C. Each immersion followed 2.5 days of a specific dietary and/or exercise regimen designed to elicit low (L), normal (N), or high (H) glycogen concentration in large muscle groups. Biopsies from the vastus lateralis muscle showed that glycogen concentration before the immersion was significantly* ($p<0.01$) *lower for L than for N or H. The calculated metabolic heat production during the first 30 min of immersion was significantly lower* ($p<0.05$) *during L as compared to N or H. The rate at which* T_{re} *decreased was more rapid* ($p<0.05$) *during L than either N or H, and the time during the immersion at which* T_{re} *first began to decrease also appeared sooner* ($p=0.08$) *during L than N or H. The immersion time was significantly shorter* ($p<0.05$) *during L than either N or H. There were no differences between the thermoregulatory responses of N and H.*

Study II. Seven seminude male subjects were immersed in 18°C water after 2 hours of intermittent oral ingestion of either a placebo (PLAC) or nicotinic acid (NIC), a potent antilipolytic agent. Plasma FFA levels immediately before the immersion were eight times lower ($p<0.05$) *in NIC than in PLAC. Although FFA levels increased* ($p<0.05$) *in NIC after the immersion, they remained five times lower* ($p<0.05$) *than in PLAC throughout the immersion. Muscle glycogen concentrations in the vastus lateralis decreased* ($p<0.05$) *following cold water immersion in both trials, but the rate of glycogen utilization was similar. The decrease in plasma glucose levels following immersion was greater* ($p<0.05$) *in NIC than in PLAC. Mean RER immediately before the immersion was greater* ($p<0.05$) *in NIC than in PLAC. There were no intertrial differences either in the calculated metabolic heat production during immersion or between the thermoregulatory responses of PLAC or NIC.*

The results demonstrate clearly that low skeletal muscle glycogen levels may be associated with more rapid body cooling in humans. Higher than normal glycogen levels, however, do not increase cold tolerance. Furthermore, the data indicate that a reduced availability of FFA does not alter human temperature regulation during cold water immersion. Apparently, any reduced heat production transduced from plasma FFA may be replaced by energy from other substrates.

PRECEDING PAGE BLANK

BACKGROUND

Acute exposure to a cold environment rapidly stimulates the metabolic rate through shivering to increase heat production and, thus, prevent central hypothermia. In both humans and animals, this skeletal muscle activity requires an increased mobilization of both circulating (for a review see 7) and intramuscular (4) substrates to fuel the increased energy expenditure. Some laboratories have investigated whether alterations in either the carbohydrate (3) or lipid (1) metabolism during cold exposure would affect cold tolerance in animals. In humans, the only data available have demonstrated that hypoglycemia produced severe disturbances of temperature regulation by inhibiting shivering activity (2). So far, no study has compared the effects of varying carbohydrate and fat substrate availability on thermogenesis during shivering in humans. In a first study, we therefore attempted to clarify whether muscle glycogen availability would alter temperature regulation during cold water immersion in men. We then investigated whether a marked reduction in the concentration of plasma free fatty acids (FFA) would alter cold tolerance in cold-exposed men.

STUDY I

Eight lean males (9 ± 1% body fat content; mean±SE) were immersed up to the shoulders in 18°C water, on three different occasions. The first immersion (control) followed three days of a normal mixed diet. The two experimental immersions followed 2.5 days of specific dietary and exercise regimen designed to elicit low or high glycogen levels in large skeletal muscle groups. On the day of the immersion, subjects were instrumented and resting metabolic rate was measured for 20 min. Subjects were then immersed until their rectal temperature (T_{re}) decreased to 35.5°C or 90 min elapsed, whichever came first. During the immersion, oxygen consumption ($\dot{V}O_2$), respiratory exchange ratio (RER), and T_{re} were recorded continuously. Pre- and post-immersion venous blood samples were obtained and assayed for various metabolites. Muscle tissue samples were taken from the *vastus lateralis* before and immediately after the immersion, and assayed for total glycogen concentration.

As we expected, the combination of exercise and dietary manipulations induced significant changes in glycogen levels of the *vastus lateralis* muscle in the low glycogen condition (L) (247 ± 15 mmol glucose units·kg dry muscle^{-1}), normal glycogen condition (N) (406 ± 23 mmol glucose units·kg dry muscle^{-1}), and high glycogen condition (H) (548 ± 42 mmol glucose units·kg dry muscle^{-1}). Overall body cooling rate during the immersions was significantly greater in L (1.5 ± 0.1°C·h^{-1}) than either N (1.3 ± 0.1°C·h^{-1}) or H (1.1 ± 0.1°C ·h^{-1}). There were no significant differences between the thermoregulatory responses of N and H. These results suggest that ingestion of a CHO-poor or fat and protein-rich diet for a short period of time deteriorates cold tolerance in man. There are a few potential mechanisms that might explain the observed alterations in temperature regulation during cold water immersion in L.

Cold exposure increased the $\dot{V}O_2$ similarly in all conditions (from 252 ± 14 to 918 ± 81 ml·min^{-1}). However, the dietary manipulations preceding the low glycogen trial induced marked shifts in metabolism towards lipolysis, as suggested not only by the lower RER during the first 30 min of immersion in L, but also by the higher FFA, glycerol, and β-hydroxybutyrate concentrations observed either at rest or during immersion in L. Such a shift of metabolism towards lipolysis has profound consequences not only on the usual metabolic responses to cold, but also on the maintenance of heat balance. The energy yield per L O_2 combusted during fat oxidation is lower than that for CHO oxidation. Therefore, in spite of similar increases in $\dot{V}O_2$ during the different cold water immersions, this resulted in a significantly ($p<0.05$) reduced heat production during the first 30 min of immersion in L (15.1 ± 1.5 kJ $\cdot min^{-1}$) as compared to N or H (17.4 ± 0.4 $kJ \cdot min^{-1}$). This finding is consistent with the reduced heat production reported by Wang et al. (9) for cold-exposed rats fed a fat emulsion as compared with carbohydrate feeding, and may be partly responsible for the failure to maintain T_{re} in the low glycogen condition.

Another possible mechanism for the decreased cold tolerance observed in L may be related to the low levels of glycogen prior to the immersion. However, there was still a considerable amount of glycogen remaining in the muscle tissue at the end of the immersion (218 ± 15 mmol glucose units$\cdot$kg dry muscle^{-1}). Furthermore, the net glycogen breakdown in L was minimal, as reported in exercise studies following ingestion of a fat-rich diet. Taken together, this would argue against the hypothesis that intramuscular glycogen per se would be responsible for the decreased cold tolerance observed in L. However, it is possible that the lack of glycogen in individual muscle fibres preferentially recruited during shivering thermogenesis impaired muscle's capacity to produce heat. Indeed, it has been reported that during exercise requiring an energy expenditure similar to that observed during cold water immersion, glycogen depletion occurs selectively in ST fibres (8). If the same ST fibres are recruited during shivering thermogenesis in man, this may be a complicating factor.

Our finding of a decreased cold tolerance in L contrasts sharply with results from earlier studies, which have suggested that consumption of fat-rich diets for a few weeks could exert a favorable effect on cold tolerance in man (5). One possible reason might be related to the duration of the fat-rich diet ingestion period. Indeed, some studies have found that prolonged ingestion of fat-rich diets may induce metabolic and hormonal adaptations that counteract at least some of the detrimental effects on exercise performance observed after shorter dietary period (6). It is reasonable to speculate that more prolonged ingestion of fat-rich diets would induce adaptations to avoid impairments of cold tolerance.

STUDY II

In this study, we examined how reducing the delivery of FFA to the shivering musculature, by oral administration of nicotinic acid, would alter temperature regulation. Nicotinic acid effectively prevents the breakdown of white adipose tissue triglycerides to FFA and glycerol by decreasing cyclic-AMP production in that tissue. Given the strong transient vasodilating effects of nicotinic acid, we waited 2h after ingestion of the first dose (3.2 $mg \cdot kg^{-1}$) before immersing our subjects in cold water. A dose of 1.6 $mg \cdot kg^{-1}$ nicotinic acid was given every 30 min until the subject's withdrawal from the water. Seven lean subjects (11 ± 1% body fat content) were immersed on two occasions, a week apart. The order of the drug (NIC) or placebo (PLAC) administration was counterbalanced among the subjects. We performed the same measurements during the cold water immersions as described for the previous study, with the exception that blood samples were taken every 30 min until the subject's withdrawal.

Fig. 1 shows the changes of plasma FFA levels before and during the immersions. Plasma FFA levels were markedly depressed by nicotinic acid, averaging 87 $\mu mol \cdot L^{-1}$ at the end of the 2h-rest period. Although cold water immersion increased FFA levels by 73% in NIC, these concentrations were only 20% of those measured in PLAC. Considering that FFA fuel approximately 40% of oxidative metabolism in men exercising at an intensity requiring an energy expenditure similar to that observed in this study (approx 27% $\dot{V}O_{2max}$), thus a quantitatively important energy source was withdrawn. Nevertheless, we did not observe any significant intertrial differences in either the initial T_{re} before the immersions (37.0 ± 0.1°C), the total change of T_{re} (1.3 ± 0.2°C), the mean rate of decrease of T_{re} (1.3 ± 0.4°C·h^{-1}) or the immersion times (71 ± 10 min). $\dot{V}O_2$ also increased similarly in the two conditions, to 3.8 ± 0.2 times resting values. Furthermore, the total metabolic heat production, as calculated from $\dot{V}O_2$ and RER values, remained unchanged in our nicotinic acid-treated subjects, presumably because metabolism shifted towards a greater utilization of carbohydrate substrate to meet the energy requirements (Fig. 2).

Apparently, any reduction of heat production transduced from plasma FFA was compensated by increased oxidation of circulating carbohydrates in NIC compared to PLAC, as suggested by the lower plasma glucose levels in the former condition (Fig. 1, B). Indeed, since both cold exposure and nicotinic acid enhance hepatic glycogenolysis and gluconeogenesis, our results would suggest an insufficient hepatic glucose release to fully match the increased peripheral glucose utilization. Although muscle glycogen was utilized to fuel the increased energy expenditure, it was clearly not an alternate fuel when FFA availability was reduced, as suggested by similar rates of glycogen utilization (1.00 ± 0.27 mmol glucose units·kg dry $muscle^{-1} \cdot min^{-1}$) during the immersions. This finding would be consistent with the observation that muscle glycogenolysis was not greater in cold-exposed mice in which a 50% reduction in plasma FFA levels was induced, when compared to a control group (1).

Although plasma FFA concentration following nicotinic acid administration was reduced to only 20% of the control values during the immersion (Fig. 1, A), the calculated total fat oxidation was decreased by less than 40% (11.0 ± 1.7 g vs. 17.5 ± 3.4 g). Plasma FFA may have partly contributed to this lipid oxidation, as suggested by the significant increase in FFA levels observed during cold water immersion in NIC (Fig. 1, A). But it is unlikely that these very low plasma levels could have provided all the substrate for the lipid oxidation. Plasma and liver triglycerides could also have provided an alternate lipid substrate under such conditions, as has been reported for nicotinic acid-treated rats. The possibility also remains that FFA may be furnished to the shivering muscles from intramuscular stores.

CONCLUSIONS

The present results demonstrate that low muscle glycogen stores are associated with a reduced cold tolerance in man. An alternative mechanism proposed to explain this finding is through a reduction in the rate of body heat production related to dietary-induced shifts in metabolism. Higher than normal muscle glycogen levels, however, do not have any prophylactic effect regarding cold tolerance in man. The results also suggest that plasma FFA are not critical substrates for the fueling of thermogenesis in the shivering musculature in man. The energy derived from plasma FFA may be replaced by energy from other substrates, so that the thermogenic response is maintained, and cold tolerance is not impaired.

REFERENCES

1. Estler, C.-J., H.P.T. Hammon, and B. Lang. Eur. J. Pharm. 9: 257-260. 1970.

2. Haight, J.S., and W.R. Keatinge. J. Physiol. 229:87-97. 1973.

3. LeBlanc, J. and A. LaBrie. J. Appl. Physiol. 51:1428-1432. 1981.

4. Martineau, L., and I. Jacobs. J. Appl. Physiol. 65:2046-2050. 1988.

5. Mitchell, H. H., Glickman, N., E.H. Lambert, R.W. Keeton, and M.K. Fahnstock. Am. J. Physiol. 146: 285-291. 1946.

6. Phinney, S.D., B.R. Bistrian, W.J. Evans, E. Gervino, and G.L. Blackburn. Metabolism 32: 769-776. 1983.

7. Thompson, G.E. In: Robertshaw D (ed.) International Review of Physiology II. vol 15 Univ. Press Baltimore, p. 29-69, 1977.

8. Vollestad, N.K., and P.C.S. Blom. Acta Physiol. Scand. 125: 395-405. 1985.

9. Wang, L.C.H., and T.F. Lee. Life Sciences 36: 2539-2546. 1985.

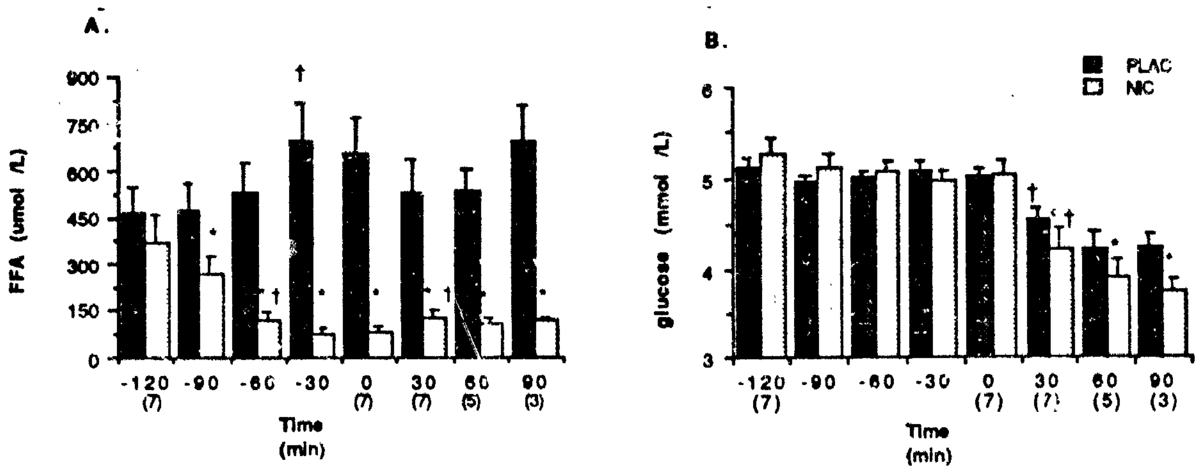


Fig. 1. Changes in metabolite levels following ingestion of either placebo (PLAC) or nicotinic acid (NIC) in seven seminude subjects, before and during cold water immersion at 18°C. Number of subjects who have completed a given 30-min period for both conditions is shown in parentheses. Data are expressed as means ± SE.

* significant intertrial difference ($p<0.05$)

† significantly different from previous 30-min mean value ($p<0.05$).

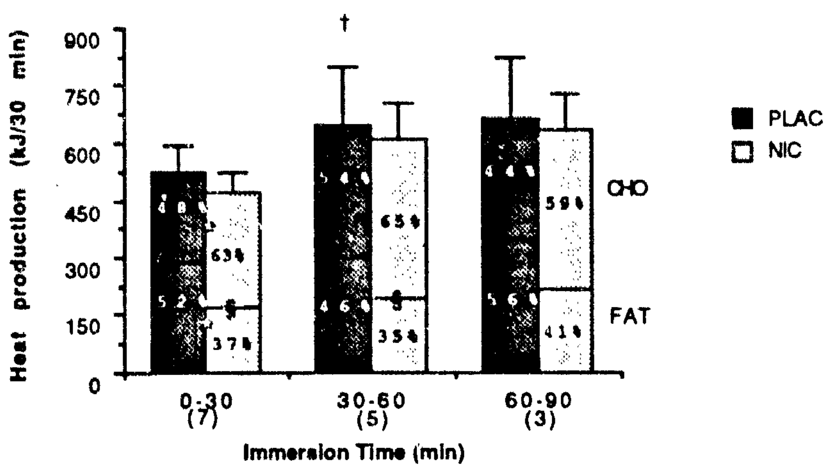


Fig. 2. Total heat production (mean±SE) during immersion for the placebo (PLAC) and nicotinic acid (NIC) conditions, as calculated from the RER and VO_2. The calculated percentage contribution of fat (lower part of the bar) and carbohydrate (upper part of the bar) to the total heat production is also shown. Number of subjects who have completed a given 30-min period for both conditions is indicated in parentheses.

* significant intertrial difference

§ significant within trial difference

† significantly different from previous 30-min period.

USE OF CARBOHYDRATE OR CAFFEINE TO PROMOTE PERFORMANCE DURING COLD WATER EXPOSURES

T.J. Doubt, J.W. Thorp, P.A. Deuster, and S. Hsieh
Diving Medicine Department
Naval Medical Research Institute, Bethesda, MD 20814 USA

ABSTRACT

Ingestion of either carbohydrate or caffeine is purported to be an ergogenic intervention that improves work capacity. Studies at NMRI have examined the potential of carbohydrate or caffeine to increase endurance or to provide a thermogenic benefit.
Glucose polymer ingestion during cold water immersion: Ten divers were immersed in 25 or 35°C water for 3 hr while at rest. serum glucose levels remained stable throughout the 3-hr period when no fluid was consumed. Ingestion of 250 ml of a glucose polymer solution each hour transiently raised blood glucose levels and suppressed the usual rise in free fatty acids at both 25 and 35°C. Blood lactate levels rose in 25°C water and were not affected by glucose ingestion.
Carbohydrate loading prior to cold water exercise: Ten divers attempted to perform 8 bouts of 10-min rest/20-min exercise at 80% maximum capacity while immersed in 25°C water. One test was done after a 3-day normal diet, and one test after 3 days of a high carbohydrate diet. Carbohydrate loading resulted in a small but significant increase (5%) in the amount of total work done during the 4-hour immersion. Exercise oxygen consumption was the same with both diets. Core temperature was slightly higher at the end of immersion with the carbohydrate diet, but there were no differences in peripheral heat flux.
Caffeine ingestion and cold water exercise: Ten divers performed 60 min of leg exercise at 65% maximum capacity in 18 and 28°C water. One test at each temperature was done 90 min after ingesting caffeine (5 mg/kg) and once after ingesting a placebo. Caffeine significantly raised the exercise oxygen consumption, thereby resulting in a slight decrease in exercise efficiency. Greater decreases in efficiency occurred in the colder water. Caffeine raised blood levels of both free fatty acids and lactate in a non-temperature dependent manner, and did not alter the decline in blood glucose levels. Skin and rectal temperatures were higher with caffeine at both water temperatures.
Discussion: These studies indicate that glucose ingestion during resting immersions will elevate blood glucose and suppress free fatty acid release. Future studies will be needed to determine if this effect persists during exercise. Carbohydrate loading will increase the amount of hard work that can be done during immersion. Caffeine appears to enhance thermal status during cold water exercise, but does not provide a significant ergogenic benefit.

INTRODUCTION

There are a variety of dietary or pharmacological manipulations that are used to enhance performance during athletic events. Two of the more common manipulations for endurance type events involve either use of carbohydrate or caffeine. Neither intervention increases muscle strength per se, but both increase endurance through actions on metabolic energy pathways.

Several lines of evidence suggest that supplemental carbohydrate ingestion is an important determinant of endurance time. Muscle glycogen depletion correlates directly with the onset of fatigue (1, 2). Paradigms to increase the absolute amount of muscle glycogen, termed "carbohydrate loading", have been shown to lessen the extent of muscle glycogen depletion and thereby increase endurance time (1, 2). It is also recognized that development of hypoglycemia (low blood glucose levels) hastens the onset of exhaustion, irrespective of muscle glycogen or blood free fatty acid concentrations. This recognition has led to the separate practice of ingesting glucose solutions during prolonged exercise, with subsequent delays in the onset of fatigue (3, 4).

Caffeine ingestion is also considered to be an ergogenic aid that promotes endurance through actions that lessen muscle glycogen use, increase mobilization of free fatty acids, and increase the oxygen pulse (5, 6). It is also widely known that caffeine increases the basal metabolic rate and the rate of urine production. These latter effects may have positive and negative effects, respectively, during cold water immersion.

This paper will discuss two studies involving carbohydrate ingestion (7, 8) and one study involving caffeine ingestion (9). The intent of the studies was to determine if such dietary/pharmacological manipulations would benefit performance during cold water immersion.

CARBOHYDRATE LOADING STUDY:

To test whether carbohydrate loading could increase the capacity to do strenuous intermittent work in 25°C water, 8 males attempted to complete 8 bouts of 10 min rest and 20 min of exercise at 80% of their maximum aerobic capacity during a 4 hour immersion. One test was conducted after the subjects had been on a 3 day CONTROL diet (≅300 gm carbohydrate/day), and one test was conducted after a 3 day carbohydrate loading diet (CHO, ≅600 gm carbohydrate/day). If a subject could not complete a full 20 min exercise bout, the pattern was reduced to 5 min rest/10 min work for the remainder of the immersion. Total work (watt-min) was measured for the full 4 hour immersion period.

There was a small, but significant, increase of 5 % in total work performed when the CHO diet was consumed as compared to the CONTROL diet. Four of 8 divers completed all 8 exercise bouts with both diets, while the other 4 subjects completed more full 20 min exercise periods with the CHO diet. Since the study was not designed to measure endurance per se, the difference in total work achieved between diets likely underestimated the true extent to which CHO would increase total work.

There were no differences in oxygen consumption between the diets. However, there was a noticeably higher respiratory exchange ratio (RER) with the CHO; indicating a greater fractional aerobic utilization of carbohydrate substrate. Since carbohydrate has a higher energy yield per liter of oxygen consumed, this may account for the slightly higher rectal temperature noted with the CHO diet during the course of the immersed exercise, as shown in Figure 1.

In summary, this study demonstrated that carbohydrate loading can increase the amount of strenuous work accomplished during immersion; possibly through the same mechanisms noted with dry land exercise. Furthermore, carbohydrate loading may result in greater heat production during exercise that could be a potential thermal benefit during cold water immersion.

GLUCOSE POLYMER INGESTION DURING IMMERSION:

As part of a study designed to examine the efficacy of fluid replacement during immersion, 10 divers were at rest for 3 hrs while immersed in 25 or 35°C. During one immersion at each water temperature the subjects did not drink any fluid, while during a second immersion they consumed 250 ml of a glucose polymer solution each hour. Venous blood samples were obtained every 30 min during each immersion.

Stable blood glucose values were measured during immersions at 25 and 35°C when no fluid was ingested. In contrast, there was about a 40% increase in blood glucose measured 30 min after glucose polymer ingestion in 35°C water, and about a 50% increase noted in 25°C water. These transient rises in blood glucose after glucose polymer ingestion resulted in small but significant increases in RER at both water temperatures.

When no fluid was consumed there was a small temporal rise in plasma free fatty acids (FFA) in 35°C water, and a much greater FFA rise in 25°C water due to the thermal stress (average heat flux ≅105 W/sq m). In contrast, glucose polymer ingestion suppressed the rise in FFA at both water temperatures. Blood lactate levels increased only in the 25°C water, and to a similar extent with either no fluid or glucose polymer ingestion.

In summary, this study demonstrated that blood glucose levels will be transiently increased at rest with hourly glucose polymer ingestion. The rise in blood glucose will suppress the usual rise in FFA noted with cold exposure. The additional glucose will not, however, affect the cold-induced increases in blood lactate. Furthermore, although there were wide differences in total substrate availability between the no-fluid and glucose polymer conditions there was evidence of greater metabolic heat production per liter oxygen with the glucose polymer.

CAFFEINE INGESTION BEFORE COLD WATER EXERCISE:

To examine the possible ergogenic effects of caffeine during cold water exercise, 10 subjects performed 60 min of leg exercise at 1.5 W/kg during head-out immersion in 28 and 18°C water. One test at each water temperature was conducted 90 min after ingestion of caffeine (5 mg/kg), and once after ingestion of a placebo capsule. All subjects completed the exercise protocol under all conditions.

Steady-state oxygen consumption (VO2) was higher in 18°C water than at 28°C with the placebo conditions. At each water temperature caffeine raised VO2 by an average of 0.2 L/min. Thus, aerobic work efficiency (ratio of work energy to total energy expenditure) was slightly lower with caffeine use.

Blood glucose levels declined steadily under all conditions, with greater rates of decline noted with caffeine ingestion. Plasma FFA rose steadily during exercise under all conditions, with larger increases noted for the caffeine conditions. Lactate values peaked at 20-30 min after the onset of exercise, with significantly higher peaks observed after caffeine ingestion.

The fractional utilizations of glucose and FFA, derived from the RER, are shown in Figure 2. Note that FFA utilization was depressed at 20 min, coincident with the peak of glucose use. FFA use was slightly higher after caffeine ingestion.

As shown in Figure 3, net thermal balance was little affected by caffeine during immersion in 18°C water. Since caffeine raised oxygen consumption, and therefore metabolic heat production, this finding suggests that a greater rate of heat loss occurred that balanced the increased heat production. In 28°C water the use of caffeine significantly raised net thermal balance when compared to the placebo condition, indicating that heat production exceeded than heat loss.

In summary, this study demonstrated that caffeine will increase exercise oxygen consumption during head-out immersion. Since external work did not change, efficiency was slightly reduced thereby ruling out caffeine as a beneficial ergogenic aid. In cold water there appeared to be no thermal benefit of caffeine ingestion, whereas in slightly warmer water caffeine produced a larger net gain in body heat.

GENERAL DISCUSSION:

Carbohydrate loading appears to be a useful intervention to increase work capacity during immersion. The manner in which it improves work performance may be the same as noted for dry land studies, e.g. increasing muscle glycogen levels. Additional studies, using different water temperatures and work patterns, will be required before carbohydrate loading can be recommended unequivocally to working divers. In the interim, available evidence supports its use for long duration work efforts, especially since carbohydrate use may have some thermal benefits apart from muscular work. Glucose polymer ingestion during immersion will raise blood glucose concentration in a resting diver. A study is planned to determine if this effect persists in the working diver, and if it will prolong endurance. Whether at rest or working, glucose ingestion will likely lessen the rate of decline in plasma glucose (as noted in the caffeine study). From a practical standpoint, it may be more convenient to provide a working diver with a glucose polymer solution to drink periodically during a dive, than to attempt 3 days of carbohydrate loading. However, if sufficient time is available before a particularly long and arduous dive, both carbohydrate loading and glucose polymer ingestion may provide an important advantage to accomplish a mission.

The use of caffeine as an ergogenic aid during diving does not appear to be justified by the present data. Although endurance per se was not studied, the higher exercise oxygen consumption after caffeine ingestion resulted in a lower aerobic work efficiency. The data further suggest that under nearly thermoneutral immersed conditions (28°C, no thermal protection) the combination of hard exercise and caffeine use may cause an unfavorable accumulation of metabolic heat. On the other hand, caffeine has no apparent thermal benefit during exercise in colder water (18°C). Additional studies will be needed to further refine these conclusions and balance them against the diuretic effects of caffeine.

REFERENCES

1. Forgac, M.T. Carbohydrate loading: a review. J. Am. Dietetic Assoc. 75: 42-45, 1979.

2. Blom-Per, C.S., D.L. Costill, and N.K. Vollestad. Exhaustive running: inappropriate as a stimulus of muscle glycogen supercompensation. Med. Sci. Sports Exer. 19: 398-403, 1987.

3. Hargreaves, M., D.L. Costill, A.R. Coggan, W.J. Fink, and I. Nishibata. Effect of carbohydrate feeding on muscle glycogen utilization and exercise performance. Med. Sci. Sports Exer. 16: 219-222, 1984.

4. Noakes, T.D., E.V. Lambert, M.I. Lambert, P.S. McArthur, K.H. Myburgh, and A.J. Benade. Carbohydrate ingestion and muscle glycogen depletion during marathon and ultramarathon racing. Eur. J. Appl. Physio. 57: 482-489, 1988.

5. Costill, D.L., G.P. Dalsky, and W.J. Fink. Effect of caffeine ingestion on metabolism and exercise performance. Med. Sci. Sports Exer. 10: 155-158, 1978.

6. Gaesser, G.A., and R.G. Rich. Influence of caffeine on blood lactate response during incremental exercise. Int. J. Sports Med. 6:207-211, 1985.

7. Thorp, J.W., K.D. Mittleman, J. Bilanin, K.J. Haberman, and T.J. Doubt. Carbohydrate loading increases capacity to work intermittently in cool water. F.A.S.E.B. 1989 (in press).

8. Doubt, T.J., P.A. Deuster, K. Haberman, C. Ryan, J. Bilanin, and L. Montgomery. Fluid replacement during cold water immersion: hydration and thermal status. Proc. 3rd Int. Conf. Environ. Ergonomics, eds. R. Ilmarinen and A. Pasche, p. 58, 1988.

9. Hsieh, S., J. Bilanin, K. Haberman, and T. Doubt. Effects of caffeine and cold on exercise metabolism. Med. Sci. Sports Exerc. 20: S85, 1988.

This work was supported by Naval Medical Research and Develpment Command Work Unit M0099.OlA.1003

Figure 1: Average rectal temperature during the first 6 bouts of rest/exercise in 25 °C water. Time at 0 min was the start of the first 10 min rest period, followed sequentially by 20 min exercise. TEST diet was the carbohydrate loading diet.

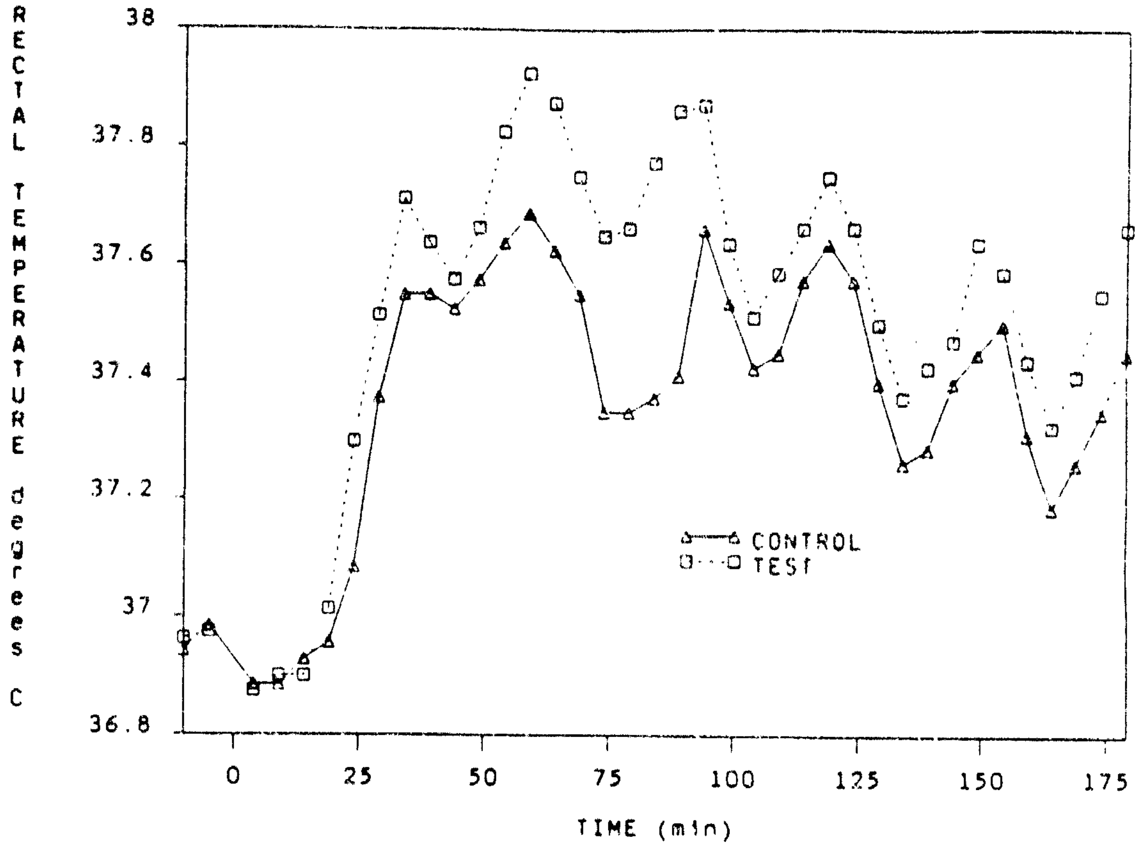
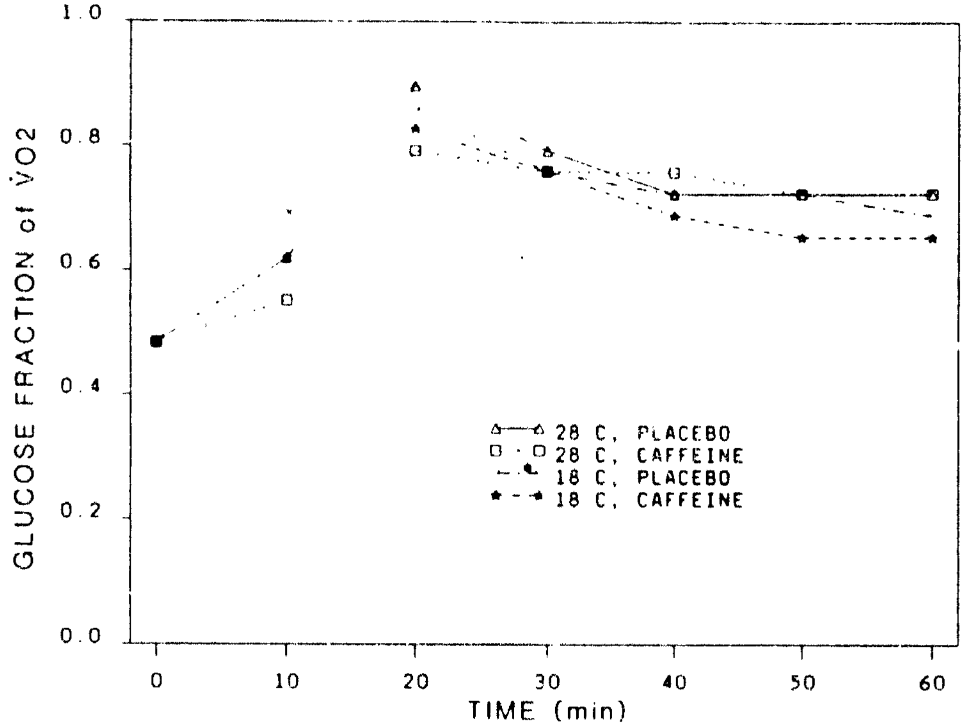


FIGURE 2: TOP PANEL: Fraction of oxygen consumption used for carbohydrate oxidation, where F_{cho} = (RER - 0.71)/0.29 for the 10 min averages of oxygen consumption and RER.
LOWER PANEL: Fraction of oxygen consumption for FFA oxidation, based on $F_{ffa} = 1 - F_{cho}$.



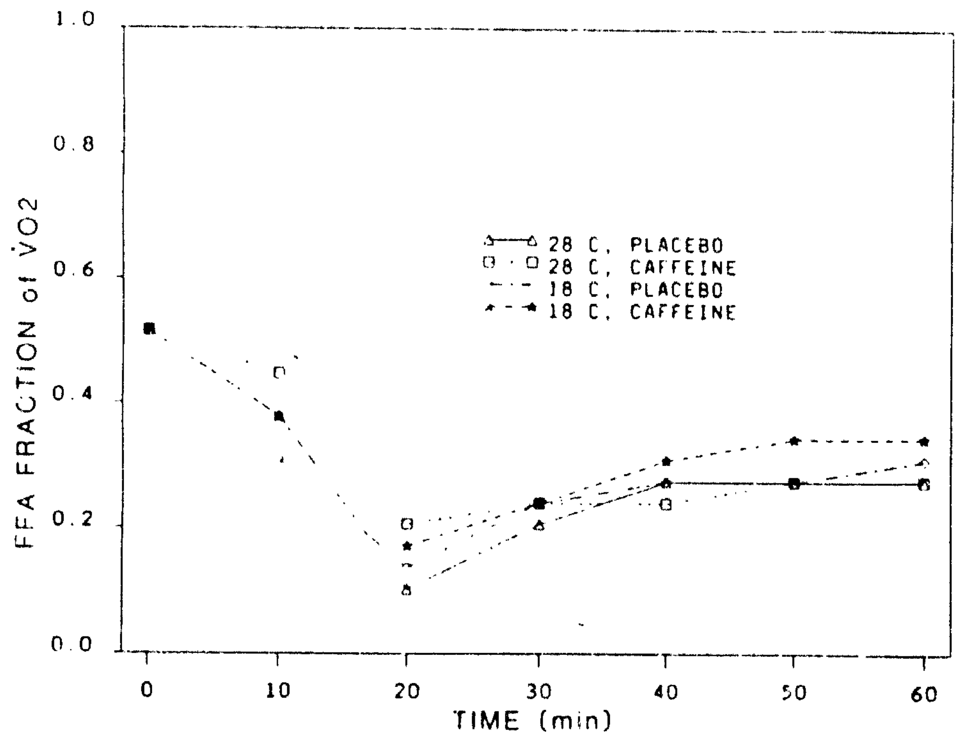
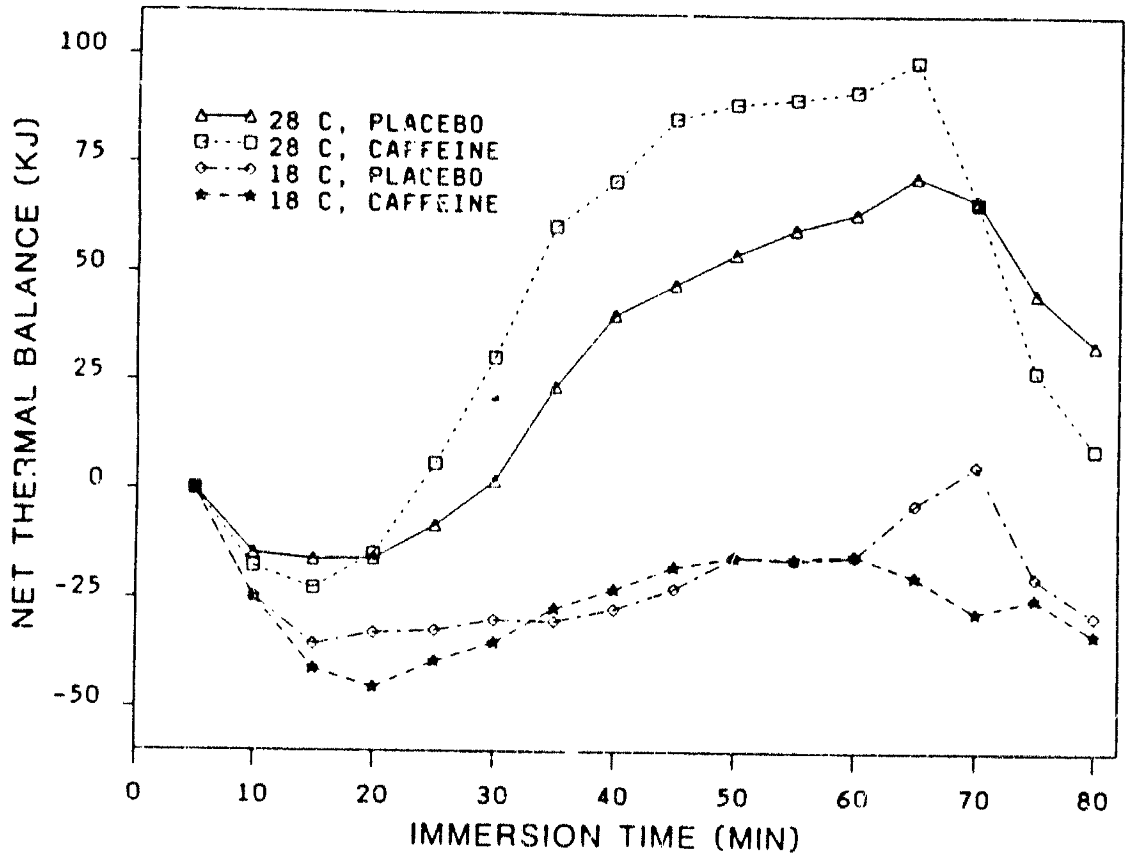


FIGURE 3: Net thermal balance derived from mean skin temperatures at 4 sites and rectal temperature, according to:

Body temp = $0.87T_{rectal} + 0.13T_{mean\ skin}$, and
Body heat = body temp x WT x surface area x 3.48



LIPID METABOLISM IN COLD-EXPOSED HUMANS.

A.L. Vallerand and I. Jacobs
Environmental Physiology Section
Defence and Civil Institute of Environmental Medicine
Toronto Ont. M3M 3B9 Canada

ABSTRACT

The goal of this study was to determine the changes in lipid utilization associated with cold exposure in humans, and whether plasma triglyceride (TG) and lipolysis play an important role in lipid metabolism during cold exposure. This was achieved by: calculating the rates of substrate oxidation from indirect calorimetry, by performing an intravenous fat tolerance test (IVFTT; an index of plasma TG utilization) and by measuring changes in plasma glycerol levels (an index of lipolysis). Since fat clearance is increased 24 h after exercise, a second cold exposure combined with an IVFTT were also performed 24 h after the first cold exposure, to evaluate the possibility of a delayed increase in fat tolerance. Six healthy males were therefore subjected to an IVFTT (1 ml/kg 10% Intralipid) on 3 occasions (fasting semi-nude) while resting for 160 min: 1) at thermal neutrality (29°C), 2) in the cold (10°C, 1 m/s wind) and 3) in the cold 24 h after the first cold test. One week separated the warm test from the two cold tests. Cold exposure reduced mean body temperature by 3.2 ± 0.1°C and increased energy expenditure 2.6 times in comparison to warm values ($p<0.01$). It also increased fat oxidation by 71% ($p<0.01$) and plasma glycerol levels ($p<0.05$), but did not alter the removal rate of the infused plasma TG. Although the second cold test entailed essentially the same changes in body temperatures and heat production as the first one, the second cold test was accompanied by a further increase in fat utilization (142% above warm values, $p<0.01$; or 56% of the energy expenditure), a further increase in plasma glycerol levels ($p<0.05$) and an unchanged fat tolerance. The results of the present study demonstrate that cold exposure in humans significantly increases the oxidation of lipid, and that plasma TG do not appear to be an important energy substrate in the cold, even when lipid metabolism is further increased by the second cold test. It is suggested that white adipose tissue and possibly intramuscular TG, not plasma TG, are the preferred sources of fatty acids for oxidation in cold-exposed humans.

INTRODUCTION

The level of heat production that mammals can achieve and maintain is of vital importance for survival during severe cold weather. When body heat loss is greatly increased by cold exposure, additional substrates must be oxidized to provide energy for a sustained high metabolic rate. Numerous animal studies have shown that both carbohydrate and lipid play an essential role in fuel metabolism during cold exposure (for a review see Vallerand et al, 1983, 1987; Thompson 1977). In contrast to these animal studies, little is known about fuel metabolism in cold-exposed humans. Although it has been reported in man that cold alters basal levels of plasma metabolites and hormones, these data do not reveal whether such changes are the results of alterations in the rate of appearance or disappearance. The goal of this study was to determine the changes in lipid utilization associated with cold exposure in humans, and whether plasma triglyceride (TG) plays an important role in lipid metabolism during cold exposure. This was achieved by calculating the rates of substrate oxidation from indirect calorimetry and the nonprotein respiratory exchange ratio measurements, and by performing an intravenous fat tolerance test (IVFTT; an index of plasma TG utilization; Rossner 1974). Since fat clearance is increased 24 h after exercise (Annuzi et al 1987), a second cold test with an IVFTT was also performed 24 h after the first cold test, to evaluate the possibility of a delayed increase in fat tolerance.

METHODS

Six healthy young male volunteers participated in the present study. Subjects were given the opportunity to familiarize themselves with the protocol and the cold air test for 1 h on a familiarization visit. Their standard physical characteristics were (mean ± SEM): 31.5 ± 1.3 yr old, 1.81 ± 0.02 m in height, 75.5 ± 2.2 kg body mass, 52.9 ± 3.1 ml•kg^{-1}•min^{-1} maximal aerobic power (VO_{2max}; Bruce protocol), and 14.8 ± 1.4 % body fat (underwater weighing technique). Subjects were exposed to both the warm (29°C) and the cold (10°C, 1 m/s wind) for 160 min while wearing a bathing suit and resting on a reclining lawn chair. The second cold test occurred 24 h after the first cold test. One week separated the warm test from the two cold tests. All subjects were instrumented early in the morning with a rectal probe, 7 heat flux transducers (to measure mean skin temperature and mean body temperature, $\overline{T}_b$) and an antecubital i.v. catheter to infuse Intralipid and to collect blood samples. Indirect calorimetry and the nonprotein respiratory exchange ratio were used to estimate heat production and the rates of substrate utilization (Lusk, 1928; Vallerand et al, in press). The IVFTT was administered after a 2 h period in the climatic chamber, to ensure a high level of shivering activity before the infusion (in the cold). It consisted of the rapid infusion of 1 ml/kg 10% Intralipid (Travenol Can.). Plasma samples were collected before and after the infusion at min -15, 0, 5, 10, 20, 30 and 40 for the determination of the elimination rate of the infused TG by nephelometry (Rossner, 1974). Results were analyzed by one-way anova for repeated measures.

RESULTS

Cold exposure reduced $\overline{T}_b$ by 3.2 ± 0.1°C and increased total metabolic rate 2.6 times in comparison to warm values ($p<0.01$). The increase in thermogenesis was accompanied by a marked increase in carbohydrate oxidation ($p<0.01$) which accounted for 51% of the total energy expenditure. Cold exposure also increased fat oxidation by 71% ($p<0.01$), but did not alter the removal rate of the infused plasma TG. Although the second cold test entailed essentially the same changes in body temperatures and heat production as the first one, the second cold test was accompanied by a further increase in fat utilization (142% above warm values, $p<0.01$; or 56% of the total energy expenditure), which again was not dependent on the breakdown of plasma TG since the fat tolerance remained unchanged.

DISCUSSION

The present results confirm numerous previous studies that have shown that acute cold exposure in man markedly decreases body temperatures in spite of a greatly increased heat production. The results also show cold exposure increased carbohydrate utilization to such an extent that it represented the major portion of the total energy expenditure. Such data would be in line with the recent demonstration that acute cold exposure in humans greatly improves glucose tolerance, in spite of a reduced insulin response (Vallerand et al 1988). The results of the present study also demonstrate that cold exposure in humans significantly increases the oxidation of lipid, confirming the cold-induced enhancement in FFA turnover previously described in rats (Paul et al 1973). However, cold did not alter the fractional rate of removal of exogenous TG, suggesting an unchanged rate of removal of endogenous TG. Since fat clearance is increased 24 h after exercise (Annuzi et al, 1987), a second cold test combined with an IVFTT was administered to the same subjects to evaluate the possibility of a delayed increase. Although a delayed increase in plasma TG removal was not observed, a further enhancement of lipid oxidation was found during the second cold test (representing 56% of the total energy expenditure). In general, exercise studies have shown that with increased work duration (or increased cold exposure from 3 to 6 h), the utilization of lipid increases compared to that of carbohydrate, and the utilization of blood-borne substrate increases relative to that of intramuscular substrates. Thus it is possible that the present cold-induced increase in energy expenditure was not high enough to increase the TG removal capacity and it may be related to a relatively small utilization or absence of depletion of intramuscular glycogen (Martineau and Jacobs, 1988) and possibly intramuscular TG stores. In conclusion, the results demonstrate that cold exposure in humans increases the oxidation of lipids and that plasma TG do not appear to be an important energy substrate in the cold. It is suggested that adipose tissue and intramuscular TG, not plasma TG, are the preferred sources of FFA in cold-exposed humans.

ACKNOWLEDGEMENTS

It is a pleasure to acknowledge the expert technical assistance of Ingrid Schmegner.

REFERENCES

Annuzi, G. et al. Metabolism 36(5): 438-443, 1987.

Lusk, G. The elements of the science of nutrition. Saunders, Philadelphia PA, p. 64-67, 1928.

Martineau, L. & I. Jacobs. J. Appl. Physiol. 56(5): 2046-2050, 1988.

Paul P. & W.L. Holmes. Lipids 8: 142-150, 1973.

Rossner, S. Act. Med Scand. Suppl. 564, 1974.

Thompson, G.E. In: Robertshaw D (Ed) International Review of Physiology II. vol 15 University Press Baltimore MD, p. 29-69, 1977.

Vallerand A.L. et al. Am J Physiol 245(Endocrinol Metab 8): E575-E581, 1983.

Vallerand A.L. et al. Am J Physiol 253(Endocrinol Metab 16) E179-E186, 1987.

Vallerand, A.L. et al. J Appl Physiol 65(8): 2395-2399, 1988.

Vallerand, A.L. & I. Jacobs. Eur. J. Appl. Physiol., 58:873-878, 1989.

EFFECTS OF CHANGES IN FLUID AND ELECTROLYTE ON PERFORMANCE DURING COLD WATER EXPOSURES

T.J. Doubt, P.A. Deuster, and D.J. Smith
Diving Medicine Department
Naval Medical Research Institute, Bethesda, MD 20814 USA

ABSTRACT

Loss of body fluid and electrolytes during cold water immersion can limit a diver's performance and contribute to decrements in thermal balance. This presentation will discuss three NMRI studies designed to assess hydration status during cold water immersion.

Study I: Sixteen U.S. Navy divers were submerged in 5°C water at a depth of 6.1 msw for periods of up to 6 hr while wearing passive thermal protection (M600 Thinsulate beneath a dry suit). Urine production was greater during AM immersions 1000-1600 hr) than PM immersions (2200-0400 hr) due to circadian changes in pre-immersion baseline values. However, urinary losses of Na, K, Ca, Mg, and Zn were the same for AM and PM dives. Significant decreases in blood concentrations of Na and Zn occurred post dive. Overall, there was 17% decrease in plasma volume, reflecting a marked dehydration that correlated with declines in exercise performance.

Study II: Eight U.S. Navy divers underwent a 7-hour sequential wet-dry-wet cold exposure (2.5 hr in 5°C water, 2 hr in 5°C air, 2.5 hr in 5°C water) while wearing a dry suit with M-400 Thinsulate passive insulation. Although divers drank 500 ml of water during the dry phase , net loss of body water averaged 960 ml and was associated with a reduction in body weight averaging 2.1 kg. Plasma volume declined by 13%. Sitting at rest during the dry cold phase resulted in continued loss of body heat, and was associated with decreases in cognitive performance tests associated with vigilance and reaction time. In contrast, walking at a speed of 3 km/hr during the dry phase enabled the divers to maintain a relatively normal thermal balance; but they had a decrement in the cognitive ability to learn new information.

Study III: Ten U.S. Navy divers were immersed for 3 hr in 25°C water wearing only bathing trunks (average heat flux similar to wearing a dry suit in 5°C water). Each hour the subjects drank 250 ml of water to determine if fluid ingestion would offset immersion diuresis effects. Compared to the same immersion profile without water ingestion, subjects had a significant increase in urine production, but no change in their hydration status. Reductions in plasma volume averaged 6-11%. In contrast to water ingestion during 35°C immersion, drinking fluid in the cool water transiently raised metabolic heat production indicating a thermal benefit of fluid replacement.

Discussion: These studies demonstrate that significant loss of body fluid and electrolytes will occur with long duration cold exposures. Drinking fluid during immersion will not reverse this effect, but may provide a transient thermal benefit. Decrements in mental function appear to be more dependent on thermal balance than hydration status.

INTRODUCTION

Immersion will induce diuresis (increased urine production) that peaks 1-2 hours after the onset of immersion (1, 2). The nature of the diuresis results in both loss of free water and electrolytes (3, 4). In the absence of fluid or electrolyte replacement, the diuresis will result in dehydration (net loss of body fluid).

It is well documented in the exercise literature that dehydration will impair physical performance (5, 6). No doubt the dehydration will decrease exercise capacity and impair thermoregulation. While such impairments are recognized risks for dry land endeavors such as marathon running, similar problems might be encountered in a cold working dive (although through somewhat different physiological mechanisms).

This paper presents the results of 3 NMRI studies (7-9) that examined hydration status during cold water exposures. The purposes were, in part, to quantify the extent of fluid loss, changes in performance, and in one study to determine if fluid replacement during immersion would offset the effects of diuresis.

STUDY I: 6 HOUR DIVES IN 5°C WATER

In support of extended operations, 16 Navy divers were submerged in 5°C water at a depth of 6.1 msw for periods up to 6 hours. Divers wore M-600 Thinsulate passive thermal protection beneath a tri-laminated dry suit. Each diver performed 2 whole body immersions during the course of 5 day air saturation dives, one beginning at 1000 (AM) and one beginning at 2200 (PM) to determine circadian effects on fluid balance. A period of 54 hours elapsed between immersions. After a one week interval the immersions were repeated with the times of onset reversed. Venous blood samples were obtained about 15 min before and 15 min after each immersion. A urine collection device was worn to collect all urine voided during immersions.

When compared to similar time periods on a non-immersion control day, immersion resulted in 240-290% increases in urine flow for AM and PM. The actual volume of urine voided during PM immersions (0.82 ± 0.07 L) was significantly less than for AM immersions (1.63 ± 0.20 L) because of normal circadian differences in urine flow. Plasma volume was reduced by an average of 17% following AM and PM immersions, reflecting a marked dehydration.

There was also a significant loss of electrolytes during the immersions. Compared to normal excretion values, there was approximately a 200% increase in excretions of sodium, calcium, and magnesium for AM and PM immersions referenced to their respective time of day normal values. Zinc losses were 400 and 300% greater than normal for AM and PM, respectively. There was a significant circadian variation in potassium loss, with larger amounts excreted during AM immersions. Significant reductions in plasma concentrations of potassium and zinc occurred post-immersion for AM and PM exposures.

In summary, this study demonstrated that prolonged submersion in very cold water results in a significant dehydration. The associated loss of electrolytes was in excess of that occurring normally with water loss. Although excess electrolytes were excreted, only plasma values of potassium and zinc were significantly reduced; but not to the point of being abnormal. Loss of body fluid could account for the higher exercise heart rates encountered in this study.

STUDY II: 7 HOUR WET-DRY-WET COLD EXPOSURE

Eight divers, dressed in a dry suit with M-400 Thinsulate passive thermal protection, underwent a sequential exposure to 2.5 hr in 5°gC water, 2 hr in 5°C air, and 2.5

hr in 5°C water. During one exposure the divers walked on a treadmill (3.2 km/hr, 0% grade), while on a second exposure they remained at rest during the dry phase.

Although the subjects drank 500 ml of water during each dry phase, net loss of body weight after 7 hrs averaged 2.1 ± 0.4 kg irrespective of whether they were resting or walking during the dry phase. Net fluid loss (urine volume - water intake) was 950 ± 186 ml. Plasma volume decreased 12-13% over 7 hrs.

Leg exercise at 50 W for 30 min at the end of the first wet phase and at the beginning of the second wet phase resulted in peak exercise heart rates that were 17 ± 4 bpm higher during the second immersed exercise. This finding could be explained by the reductions in plasma volume noted above.

At the mid-point of each dry phase the subjects were given a cognitive Performance Assessment Battery (NMRI-PAB). Overall, there were decreases in reaction time and accuracy of response. Of note, when the divers were at rest in the dry phase they exhibited slight, but significant, reductions in the ability to match visual patterns and in the reaction time to sustained attention. Furthermore, after the subjects had been walking on the treadmill they exhibited a significant impairment in the ability to learn new information.

In summary, this study revealed that significant dehydration will occur in the course of a sequential wet-dry-wet exposure. Consuming 500 ml of fluid during the dry phase only partially offset the loss of body fluid (13% reduction in plasma volume vs 17% noted in study I). While the net reduction in rectal temperature averaged 1.1°C over 7 hrs, greater amounts of body heat were lost in the dry phase while resting compared to walking on the treadmill. This greater loss of heat may have contributed to the decrements in mental performance noted with dry rest. However, the declines in ability to learn new information were apparently not related directly to loss of body heat since the divers were walking prior to the cognitive testing.

STUDY III: FLUID REPLACEMENT DURING 3 HOURS RESTING IMMERSION

Ten males performed 3 hour resting head-out immersions in 25 and 35°C water to determine if fluid replacement during immersion would offset the effects of immersion diuresis. During one immersion at each water temperature the subjects drank 250 ml of either water or glucose polymer solution each hour beginning at the start of immersion. Five of the subjects also completed 3 hr immersions at each temperature where no fluid was given.

In terms of fluid balance, there were no differences between drinking water or glucose polymer solution. Averaged over 3 hours the magnitude of the immersion diuresis was the same at 35°C and 25 C for the matched fluid conditions, indicating that immersion per se rather than thermal stress was the major factor in the diuresis. When no fluid was consumed, urine flow averaged 5.0 ± 0.8 and 5.8 ± 0.3 ml/min at 35 and 25°C respectively, compared to a pre-immersion value of 1.6 ± 0.1 ml/min.

When fluid was ingested during immersion urine flow significantly increased over the corresponding no fluid conditions. urine flow averaged for all fluid and temperature conditions was 8.9 ± 0.4 ml/min. The increase in urine flow paralleled the increased fluid intake. Consequently, overall fluid balance (intake - output) was the same regardless of whether the subjects did or did not drink fluid.

Changes in plasma volume, reflecting hydration status, were independent of fluid ingestion. However, changes in plasma volume were dependent on water temperature. In 35°C water plasma volume initially increased during the first 30-60 min, and then declined such that at the end of 3 hrs it was not significantly different from pre-immersion values. In contrast, plasma volume declined steadily over 3 hrs in 25°C water; becoming 6-12% lower than pre-immersion values by the 3rd hour.

When subjects consumed fluid (temperature = 10°C) there was a transient rise in resting oxygen consumption of about 2 ml/min/kg during 25°C immersions, but not during 35°C immersions. This transient rise in oxygen consumption lasted 30-40 min, consequently raising metabolic heat production. However, since the increase was transient there were no notable differences in net thermal balance between no fluid and fluid conditions.

In summary, this study indicated that ingesting fluid during immersion will not offset the loss of body fluid due to immersion per se. Consuming fluids merely increased the rate of loss, with no net difference on hydration status. Drinking cool fluid while immersed in cool water will, however, transiently raise metabolic heat production.

GENERAL DISCUSSION:

Immersion results in an increase in the central blood volume due to hydrostatic forces of water moving blood into the thoracic region. As a consequence, normal physiological responses attempt to reduce the perceived volume overload by increasing the rate of urine flow. When no fluids are ingested the diuresis will continue until homeostatic mechanisms have lowered the central volume. It is evident that over 6-7 hrs this diuresis can result in a net reduction of body fluid on the order of 17%, evidence of a marked dehydration. Such a reduction would be expected to markedly reduced a diver's physical performance in water, with the effect being more pronounced if he were to attempt to work upon exiting the water. Ingesting fluid during immersion will not offset the effects of diuresis, but may lessen the extent of dehydration during long sustained operations.

REFERENCES

1. Epstein, M. Effects of head-out water immersion in man: Implications for understanding volume homeostasis. Physiol. Rev. 58: 529-581, 1978.

2. Graveline, D.E., and M.M. Jackson. Diuresis associated with prolonged water immersion. J. Appl. Physio. 17: 519-524, 1962.

3. Pendergast, D.R., A.J. DeBold, M. Pazik, and S.K. Hong. Effect of head-out immersion on plasma atrial natriuretic factor in man. Proc. Soc. Exp. Biol. Med. 184: 429-435, 1987.

4. Shiraki, K., N. Konda, S. Sagawa, J.R. Claybaugh, and S.K. Hong. Cardiorenal-endocrine responses to head-out immersion at night. J. Appl. Physio. 60: 176-183,

1986.

5. Costill, D.L., R. Cote, and W. Fink. Fluid ingestion during distance running. Arch. Environ. Health 21: 520-525, 1970.

6. Owen, M.D., K.C. Kregel, P.T. Wall, and C.V. Gisolfi. Effects of ingesting carbohydrate beverages during exercise in the heat. Med. Sci. Sports Exerc. 18: 568-575, 1986.

7. Deuster, P.A., D.J. Smith, B.L. Smoak, L.C. Montgomery, A. Singh, and T.J. Doubt. Prolonged whole body immersion: fluid and ion shifts. J. Appl. Physio. Jan, 1989 (in press).

8. Doubt, T.J., R.P. Weinberg, R.L. Hesslink, and S.T. Ahlers. Effects of serial wet-dry-wet cold exposure: Thermal balance, physical activity, and cognitive performance. NMRI Technical Report 1989 (in press).

9. Doubt, T.J., P.A. Deuster, K. Haberman, C. Ryan, J. Bilanin, and L. Montgomery. Fluid replacement during cold water immersion: hydration and thermal status. Proceedings 3rd Int. Conf. Environ. Ergonomics, eds. R. Ilmarinen and A. Pasche, p. 58, 1988.

Supported by Naval Medical Research and Development Command Work Unit M0099.01A.1003

EVALUATION OF PASSIVE AND ELECTRICALLY HEATED SURVIVAL SUITS FOR USE IN A "LOST BELL" AT 450 METERS

E.H. Wissler, Univ. of Texas, Austin
A. Pasche and B. Holand, SINTEF, Trondheim
G. Knudsen, NUTEC, Bergen
P.A. Hayes, National Hyperbaric Centre, Aberdeen.

ABSTRACT

Providing an emergency life-support system that allows saturation divers to survive for 24 hours while trapped on the bottom in an isolated bell is required of diving contractors who work in British or Norwegian waters. An important aspect of that requirement is preventing the divers from becoming excessively hypothermic as the bell cools toward the temperature of the ocean. It has been established that several passive systems with breathing gas heating based on CO_2 absorption provide adequate protection at 150 meters, but it is questionable whether they offer sufficient protection at 300 and 450 meters. Therefore, two different passive suits were modified by incorporating 115 and 160 watts of electrical heating just below the inner surface of the suit. This paper describes an evaluation of one of those suits using a rudimentary heated manikin in 31 bar heliox, and a manned trial involving two divers at 46 bar. These results are compared using a newly developed, two-dimensional, computer model to simulate human thermal response to hyperbaric cold stress. Although the three sets of experimental data are not totally sef-consistent, a plausible explanation for the differences can be constructed, and reasonable conclusions can be drawn from the results.

The probability of surviving a "lost bell" accident is determined largely by four factors: (l) cooling profile, (2) ocean depth, (3) thermal resistance of the survival bag, and (4) breathing gas temperature. The cooling profile is determined primarily by the location of the diver at the time of the accident. Divers trapped in a well- insulated bell should experience a cooling profile similar to those shown in Figs. 1 and 2, which were observed for bells immersed in cold water during the British Clansman and Swedish HMS Belos trials. On the other hand, divers trapped in a welding habitat, which generally has a much larger uninsulated surface than a bell, will experience more rapid cooling to a temperature close to the ocean temperature. The worst case scenario is probably represented by a diver who is in the water at the time the umbilical is cut, and has to swim back to a welding habitat.

The effect of changing the cooling profile is qualitatively well understood -- increasing the cooling rate decreases the probability of survival. However, currently available data do not answer the question, "How much is the probability of survival reduced by being trapped in a habitat instead of in an insulated bell?"

The effect of pressure is not as well understood. Although there are reasons for expecting divers to lose heat more rapidly as depth increases, most previous trials have taken place at relatively shallow depths (by today's standards), and it has not been possible to establish a quantitative relationship between depth and rate of diver heat loss. Therefore, results from the Igloo 88 trial are particularly significant because they

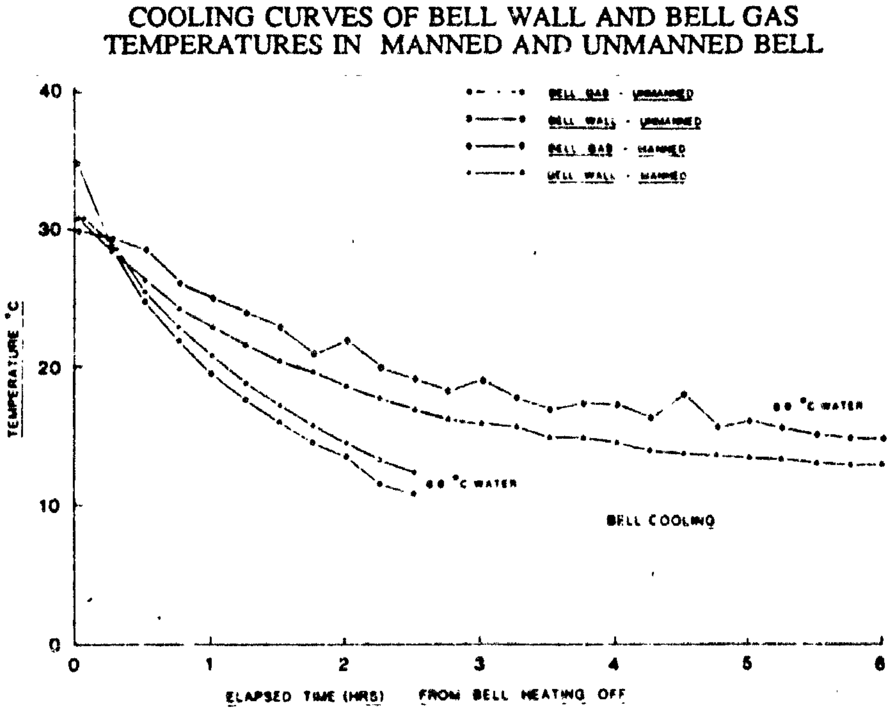


Fig. 1. Cooling Profile measured in the Clansman Trial. Copied from Ref. 2.

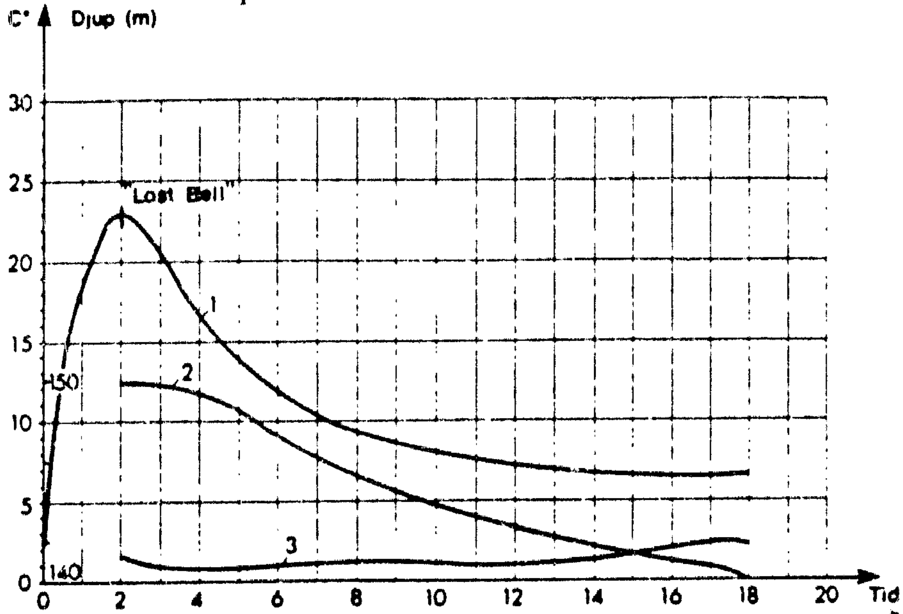


Fig. 2. Cooling Profile Measured in the HMS Belos Trial.
Curve 1 is the gas temperature;
Curve 2 is the pressure drop in the bell; and
Curve 3 is the water temperature. Copied from Ref. 3.

provide valuable new data at 460 meters which help to establish that relationship. Previous "Lost Bell" trials are summarised in Table 1.

Table 1. Summary of "Lost Bell" Trials

Trial	Location	Date	Depth	Result
Polar Bear II	NUI	1980	300 msw	Two divers tolerated 6°C for 10 hours
Clansman	RN Offshore	1981	250 msw	Three divers aborted after 6 hours
Polar Bear III	NUTEC	1982	150 msw	Two divers tolerated Clansmans cooling profile for 24 hours
HMS Belos	MDC	1982	150 msw	Two divers tolerated Clansmans cooling profile for 16 hours
Igloo 88	NHC	1988	460 msw	Divers were exposed to the Clansman cooling profile. Unheated diver: 6 hrs Heated diver : 12 hrs

Note: All divers were protected by a Kinergetics or similar survival kit.

The principal, pressure-dependent factor in diver cooling is sensible heat loss through the respiratory tract, which can be estimate for a given metabolic rate by making two assumptions. The first assumption is that expired gas temperature is linearly related to inspired temperature according to either the Webb (7) or Piantadosi (4) relationships; as a practical matter, these two relationships are equivalent. The second assumption is that the ventilatory minute volume is twenty times the oxygen consumption rate. Given those two assumptions the rate of respiratory heat loss depends on inspired temperature and depth as shown in Fig. 3.

Heat loss from a diver owing to conduction through the survival bag and conductive/convective transfer through the chamber gas to the cold wall may also be pressure dependent. Since the thermal conductivity of helium is not strongly pressure dependent, the rate of conduction through a stagnant gas layer does not vary greatly with pressure. However, stationary gas exists only when there is no blower in operation and the temperature decreases uniformly in the vertical direction. Forced convection caused by blowers may be a factor in a chamber trial, but not in an actual survival situation. On the other hand, natural convection is easily established by vertical temperature gradients, and will be a factor in every survival situation. If it were not for natural convection, the thick gas layer between the divers and the cold inner wall of the bell would provide excellent insulation. The rate of heat transfer between a surface and a fluid in which flow is driven by natural convection is proportional to the square root of density, and, therefore, depends on pressure.

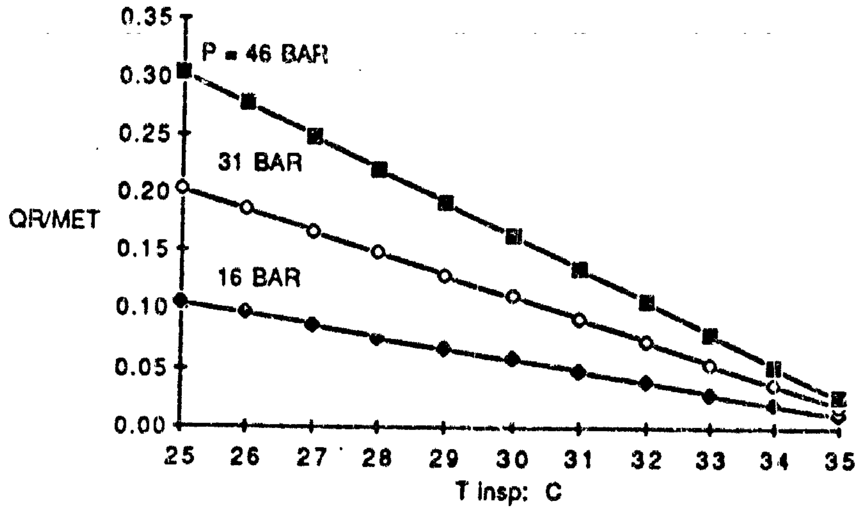


Fig. 3. Ratio of Rate of Respiratory Heat Loss to Metabolic Rate at Various Inspired Gas Temperatures and Pressures.

It is also possible that natural convection may exist within the survival bag itself, and, if that is an important factor, its thermal resistance could decrease with increasing pressure. The first manikin trial conducted by Kinergetics (l) indicated that the thermal resistance of their survival bag decreased nearly 50 percent as the depth increase from 150 to 300 msw, which, if true, would have very serious consequences. Data from the Igloo 88 trial provide an independent evaluation of that relationship. Survival data for the unheated and heated Kinergetics divers in the Igloo 88 trial were related to data from the earlier trials listed in Table 1 by attempting to formulate a model that describes reasonably well results from the Polar Bear II and III trials, as well as those from the 460 msw trial. Measured chamber temperatures were used in all of the simulations, and measured inspired gas temperature was used in all except the Polar Bear III trial, for which it was not available. Respiratory heat loss was simulated using the relationship represented in Fig. 1. The thermal resistance of the survival system was assumed to decrease slightly with increasing pressure, but not nearly as severely as suggested by the Kinergetics manikin results. For reference, regional thermal resistances of the Kinergetics survival system measured at 300 msw in the Kinergetics chamber are summarised in Table 2.

Thermal resistances used in the simulations were significantly larger than those deduced from the Kinergetics data. Values actually used for the upper and lower trunk at the three depths are presented in Table 3.

Measured data for the 150 msw Polar Bear III and HMS Belos trials are shown in Figs. 5 through 7, and the corresponding computed results are shown in Fig. 8. Although only the first 14 hours are shown in Fig. 8, the simulation agreed well with the observed results over the entire 24-hour period of the trial. These trials clearly establish that a properly employed, passive Kinergetics survival system provides

Table 2. Thermal Resistances of the Survival Suit

Region	Test	q_s w/(sq m)	T_s °C	R °C.sq m/w	Clo
Head:	1	77	21	0.246	1.59
	2	157	38	0.229	1.98
	4	80	31	0.362	4.68
Chest:	1	80	21	0.237	1.53
	2	80	25	0.288	1.86
	4	0	16	Indef.	Indef.
Back:	1	80	14.5	0.156	1.01
	2	252	29	0.107	1.04
	4	172	25.5	0.137	1.76
Groin:	1	80	21	0.237	1.53
	2	80	27	0.313	2.02
	4	0	14	Indef.	Indef.
Thighs (top):	1	80	11	0.112	0.73
	2	80	17	0.213	1.37
	4	0	11	Indef.	Indef.

Note: The three tests were conducted as follows:
Test 1. Only the manikin was heated.
Test 2. The manikin and survival bag were both heated.
Test 3. Only the survival system heater was turned on.

sufficient protection for 24-hour survival in a well-insulated PTC at a depth of 150 msw. Furthermore, good agreement between computed results and corresponding observed values suggests that our understanding of the basic phenomena involved in survival are understood.

The computed rectal temperature and metabolic rate for the 300 msw Polar Bear II trial are shown in Fig. 9. Unfortunately, measurements for this early trial are incomplete, and one must rely heavily on qualitative comments to assess the condition of the diver. For example, the rectal probe did not function properly during the trial, and the only measurement of central temperature was made after the trial. Even though a rectal temperature of 37 °C was measured then, the diver's comments indicate that he was very cold and had shivered vigorously during the last seven hours of the exposure, which is consistent with the simulation results shown in Fig. 9. This trial, unlike the others shown in Table 1, employed a steady cold chamber temperature of 7 °C, which is probably more representative of a welding habitat than a bell.

The principal, pressure-dependent factor in diver cooling is sensible heat loss through the respiratory tract, which can be estimated for a given metabolic rate by making two assumptions. The first assumption is that expired gas temperature is linearly related to inspired temperature according to either the Webb (7) or Piantadosi

Table 3. Regional Thermal Resistances (in Clo) Used to Compute Diver Heat Loss in the Kinergetics Bag at Three Depths

Region	A1	A2	A3	A4	A5	A6
		P = 16 Bar				
Upper Trunk	2.87	2.70	2.87	2.39	2.26	2.39
Lower Trunk	2.70	2.70	2.70	2.39	2.26	2.39
Head	2.99	2.99	2.99	2.58	2.45	2.58
Thigh	2.34	2.34	2.86	2.34	2.01	2.17
		P = 31 Bar				
Upper Trunk	2.74	2.57	2.74	2.26	2.13	2.26
Lower Trunk	2.57	2.57	2.57	2.26	2.13	2.26
Head	2.86	2.86	2.86	2.45	2.32	2.45
Thigh	2.21	2.21	2.73	2.21	1.88	2.04
		p = 47 Bar				
Upper Trunk	2.62	2.45	2.62	2.14	2.01	2.14
Lower Trunk	2.45	2.45	2.45	2.14	2.01	2.14
Head	2.74	2.74	2.74	2.33	2.20	2.33
Thigh	2.09	2.09	2.61	2.09	1.76	1.92

Note: Circumferential locations, A1 through A6, are shown in Fig. 4.

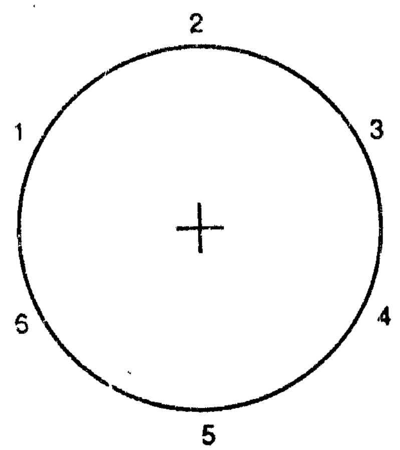


Fig. 4. Angular Positions Referred to in Table 3.

(4) relationships; as a practical matter, these two relationships are equivalent. The second assumption is that the ventilatory minute volume is twenty times the oxygen consumption rate. Given those two assumptions the rate of respiratory heat loss depends on inspired temperature and depth as shown in Fig. 3.

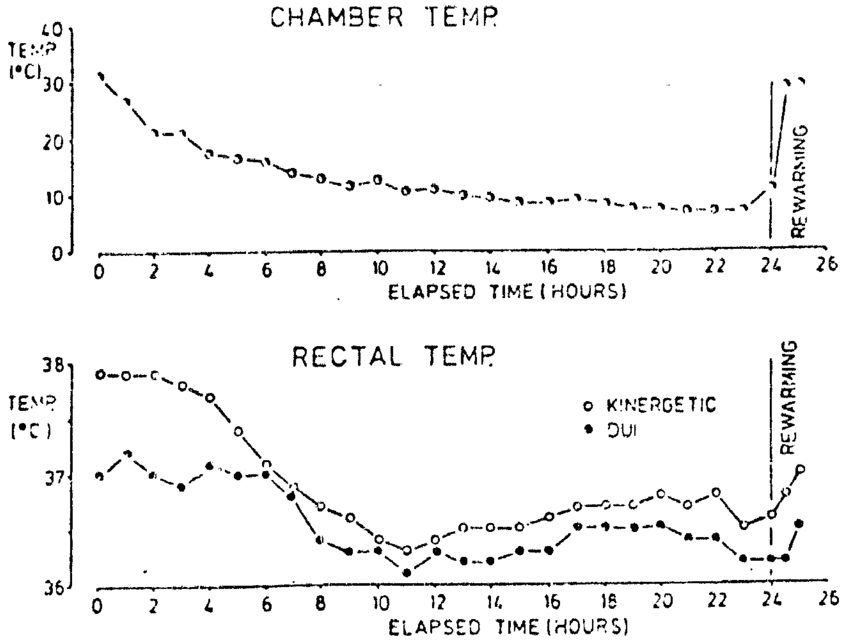


Fig. 5. Measured Cooling Curves from the 150 msw Polar Bear III Trial. Copied from Ref. 6.

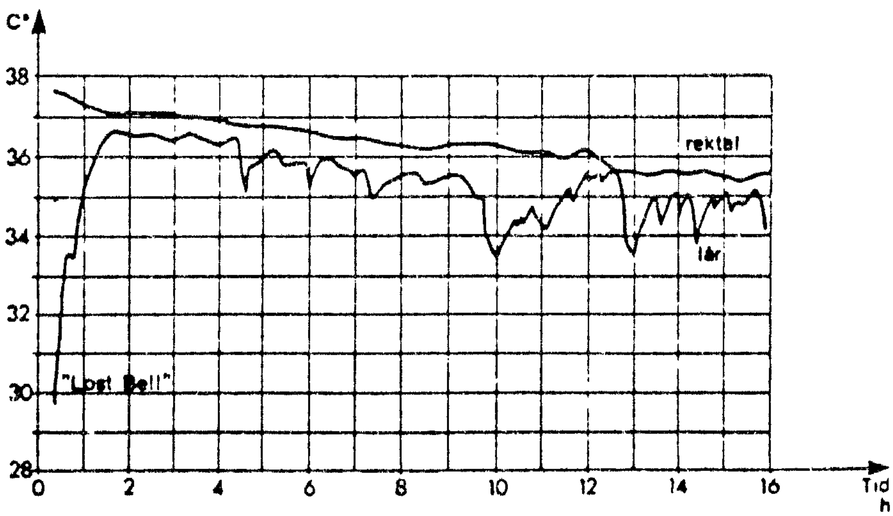


Fig. 6. Measured Rectal and Thigh Temperatures for One Diver in the 150 msw HMS Belos Trial. Copied from Ref. 3.

Heat loss from a diver owing to conduction through the survival bag and conductive/convective transfer through the chamber gas to the cold wall may also be pressure dependent. Since the thermal conductivity of helium is not strongly pressure dependent, the rate of conduction through a stagnant gas layer does not vary greatly with pressure. However, stationary gas exists only when there is no blower in

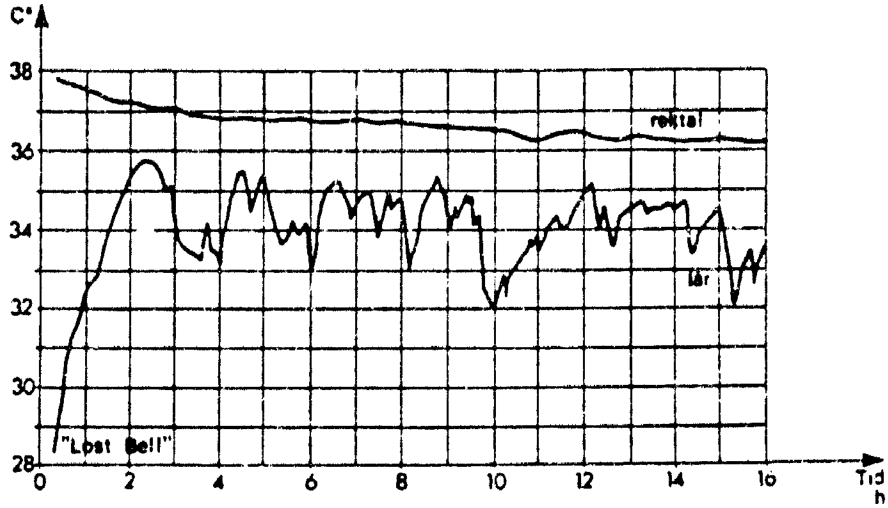


Fig. 7. Measured Rectal and Thigh Temperatures for One Diver in the 150 msw HMS Belos Trial. Copied from Ref. 3.

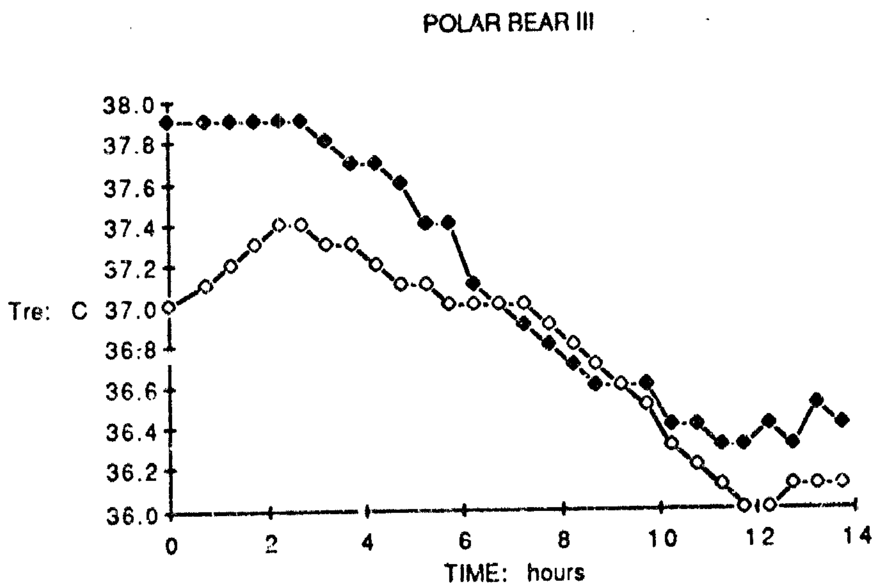


Fig. 8. Comparison of Measured (filled) and Computed (open) Rectal Temperatures for the first 14 hours of the 150 msw Polar Bear III Trial

operation and the temperature decreases uniformly in the vertical direction. Forced convection caused by blowers may be a factor in a chamber trial, but not in an actual survival situation. On the other hand, natural convection is easily established by vertical temperature gradients, and will be a factor in every survival situation. If it were not for natural convection, the thick gas layer between the divers and the cold inner wall of the bell would provide excellent insulation. The rate of heat transfer between a surface and a fluid in which flow is driven by natural convection is proportional to the square root of density, and, therefore, depends on pressure.

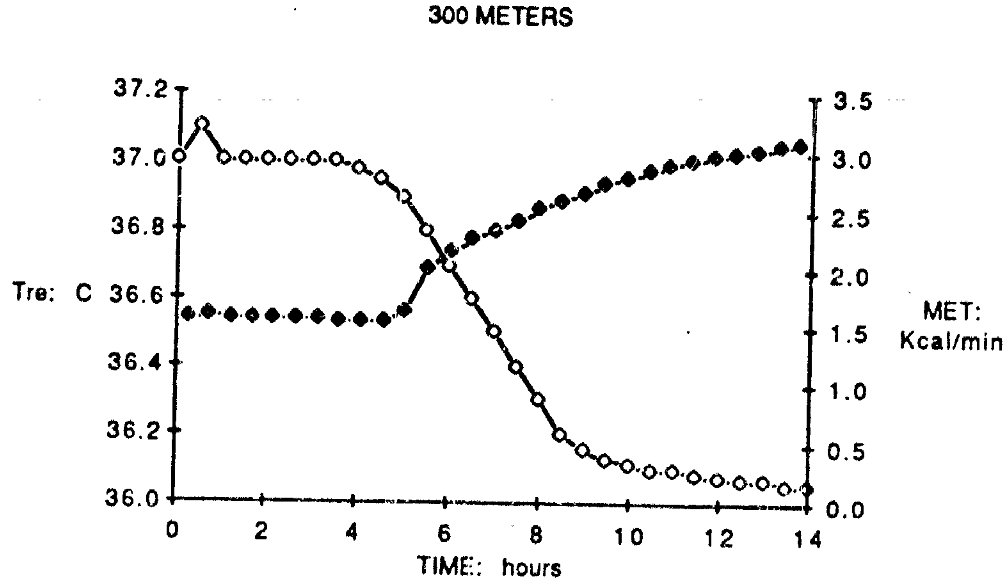


Fig. 9. Computed Rectal Temperature and Metabolic Rate for the 300 msw Polar Bear II Trial.

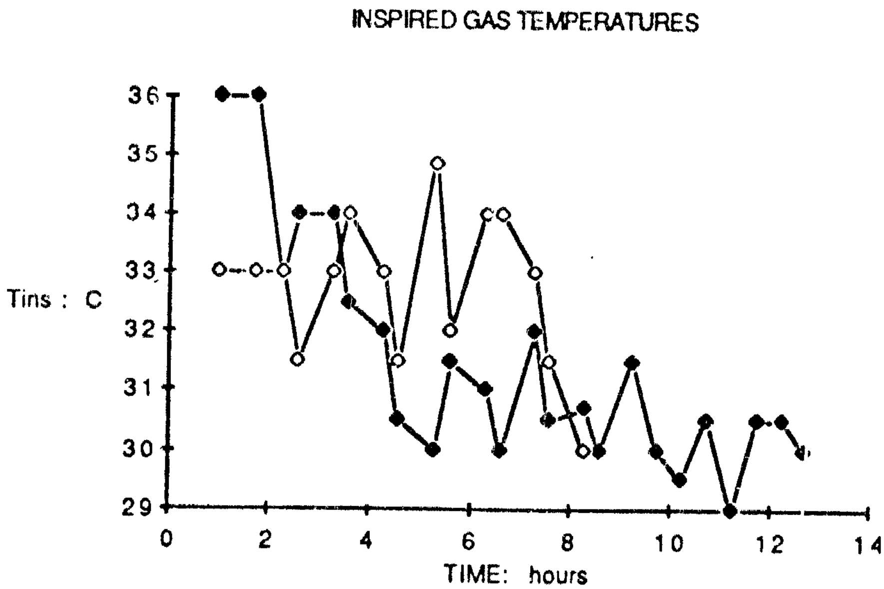


Fig. 10. Measured Inspired Gas Temperatures for Divers 1 and 2 in the Igloo 88 Survival Trial.

It is also possible that natural convection may exist within the survival bag itself, and, if that is an important factor, its thermal resistance could decrease with increasing pressure. The first manikin trial conducted by Kinergetics (1) indicated that the thermal resistance of their survival bag decreased nearly 50 percent as the depth increased from 150 to 300 msw, which, if true, would have very serious consequences. Data from the Igloo 88 trial provide an independent evaluation of that relationship. Measured inspired gas temperatures for Divers 1 and 2, who tested the Kinergetics survival systems in the NHC 460 msw dive, are shown in Fig. 10. These values and the measured local chamber temperatures shown in Tables 3 and 4 were used in the simulations. Computed and measured rectal, chest, and back temperatures are also compared in Tables 4 and 5, and computed and measured rectal temperatures for the two divers are shown in Figs.11 and 12.

Table 4. Measured and Computed Temperatures for Diver 2 in the Unheated Kinergetics Survival System.

Time	T_{chamb}	T_{re}	$T_{re(c)}$	T_{chest}	$T_{ch(c)}$	T_{back}	$T_{back(c)}$
1.00	28.1	37.5	37.0	35.1	33.83	35.0	34.72
1.50	25.6	37.6	37.1	34.6	35.11	34.7	34.49
2.00	20.9	37.5	37.0	34.6	35.35	34.5	34.50
2.50	16.7	37.4	37.0	36.5	35.11	34.8	34.06
3.00	18.7	37.2	37.0	36.6	34.82	34.7	33.51
3.33	17.5	37.1	37.0	35.7	34.7	34.1	33.3
4.06	14.3	37.0	37.0	36.4	34.17	34.1	32.59
4.54	13.2	36.7	37.0	36.3	33.46	34.0	31.28
5.04	12.6	36.6	36.9	36.0	32.89	33.7	30.05
5.60	11.7	36.6	36.8	36.1	32.48	33.9	29.26
6.10	10.7	36.5	36.7	36.2	32.06	33.7	27.66
6.60	9.9	36.6	36.6	36.2	32.25	33.2	26.68
7.10	9.2	36.6	36.5	35.9	32.48	33.0	25.99
7.61	8.1	36.5	36.4	35.8	32.61	32.5	25.46
8.11	7.6	36.6	36.2	35.9	32.66	32.	25.01
8.29	7.9	36.6	36.1	35.8	32.69	32.1	24.72

Results presented in this report indicate that the avenues by which a diver isolated on the bottom loses heat to his surroundings are reasonably well understood. That respiratory heat loss increases with increasing depth is indisputable, although the exact magnitude of the loss is still somewhat uncertain. The greatest uncertaintity involves the effect of increasing pressure on the rate of conductive/convective heat loss from the skin. Simulations at depths of 150, 300, and 460 msw assuming only a very moderate decrease in the thermal resistance of the survival bag with increasing depth provide reasonable predictions of changing rectal temperature for exposures as long as 24 hours. Since the thermal conductivity of helium is not a strong function of pressure, one would not expect the thermal resistance of the survival bag to decrease. The large difference between resistances measured at 150 and 350 msw in the Kinergetics chamber might have been caused by the rather powerful blower used to circulate gas in the chamber during that test. A separate measurement of the thermal resistance of a small segment of a bag, which will presumably be completed soon at the National Hyperbaric Centre, should help to resolve this issue.

Table 5. Measured and Computed Temperatures for Diver 1 in the Heated Kinergetics Survival System.

Time	T_{chamb}	T_{re}	$T_{re(c)}$	T_{chest}	$T_{ch(c)}$	T_{back}	$T_{back(c)}$
1.00	28.1	37.4	37.0	33.1	33.83	34.4	34.71
1.50	25.6	37.5	37.06	34.7	36.52	36.0	36.33
2.00	20.9	37.3	37.21	35.9	36.75	36.1	36.55
2.50	16.7	37.2	37.34	35.8	36.71	36.0	36.48
3.00	18.7	37.1	37.34	35.8	36.44	37.5	36.01
3.33	17.5	37.1	37.37	35.7	36.9	37.7	37.2
4.06	14.3	37.1	37.45	35.9	36.99	37.6	37.30
4.54	13.2	37.1	37.48	35.9	36.93	37.5	37.29
5.04	12.6	37.0	37.44	35.8	36.84	37.3	37.27
5.60	11.7	36.9	37.39	35.5	36.70	37.2	37.25
6.10	10.7	36.8	37.32	34.5	36.49	37.7	37.18
6.60	9.9	36.8	37.35	35.0	36.22	36.3	37.13
7.10	9.2	36.8	37.19	35.5	36.10	36.1	37.04
7.61	8.1	36.8	37.15	35.5	35.76	35.9	36.97
8.11	7.6	36.7	37.13	35.4	35.50	35.8	36.87
8.61	7.0	36.7	37.12	35.6	35.34	35.7	36.81
9.12	7.2	36.7	37.11	35.8	34.99	35.7	36.72
9.62	6.2	36.6	37.08	35.7	34.68	35.6	36.60
10.12	6.0	36.5	37.03	35.9	34.33	35.3	36.40
10.62	5.5	36.5	36.98	35.0	34.08	35.2	36.22
11.12	5.4	36.4	36.89	34.9	33.80	35.2	36.02
11.62	4.9	36.5	36.74	34.0	33.71	36.1	35.85
11.99	4.6	36.5	36.56	34.3	33.98	36.2	35.72

The greatest difficulty encountered in simulating the recent 460 msw trial was obtaining good agreement between computed and measured back temperatures. As the values in Tables 4 and 5 indicate, excellent agreement was obtained for the heated diver, but there is a large discrepancy for the unheated diver; at the end of the trial, the computed value is only 24.7 °C, while the measured value is 32.1 °C. Agreement between computed and measured back temperatures is quite good during the first half of the exposure, and becomes poor only during the last half of the trial when the model predicts that strong vaso-constriction will occur. Since Diver 2 has a fairly thick subcutaneous fat layer for which allowance was made in the simulation, cutaneous vasoconstriction caused a sharp decrease in computed skin temperature on the lower back. Another factor contributing to the discrepancy could have been that in the simulation the diver was assumed to remain on his back throughout the trial, but he reported after the trial that he actually spent about half the time on his side.

The model predicts that 150 Watts of electrical heating should be more beneficial than it seems to have been. One reason for assigning a low thermal resistance to the back of the survival bag was to dissipate a significant fraction of the electrically generated heat to the environment instead of using it to heat the diver. The discrepancy

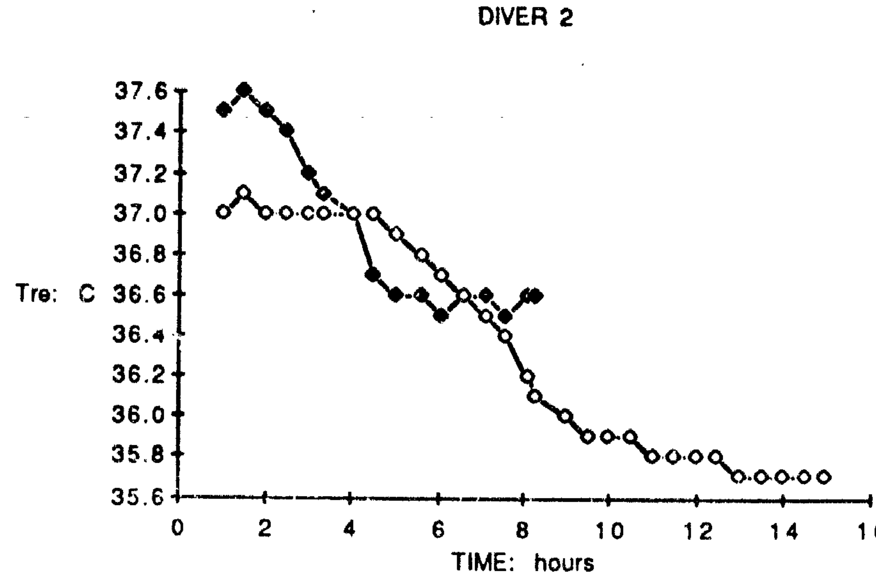


Fig. 11. Measured (filled) and Computed (open) Rectal Temperatures for Diver 2 in the Unheated Kinergetics Survival Bag.

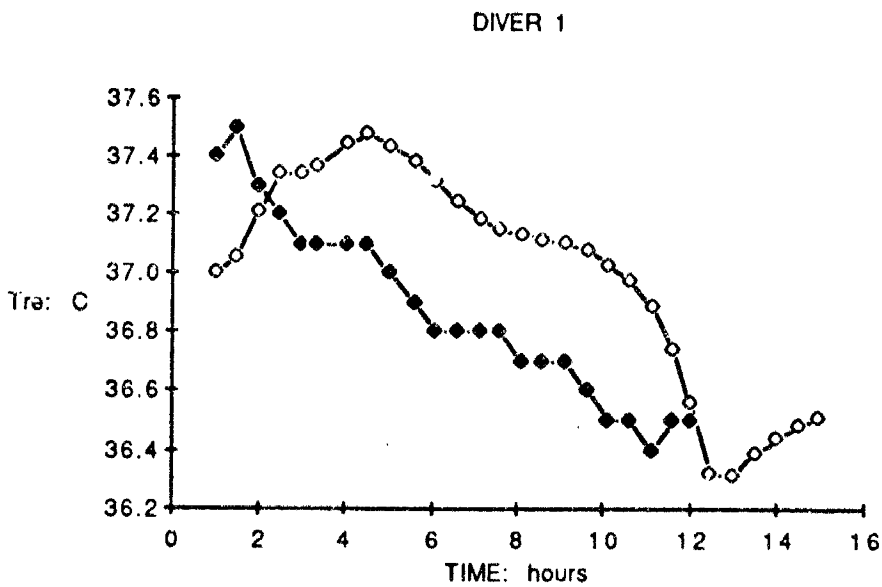


Fig. 12. Measured (filled) and Computed (open) Rectal Temperatures for Diver 1 in the Heated Kinergetics Survival Bag.

between measured and computed back temperatures for the unheated diver could have been reduced by increasing the thermal resistance of the survival bag on the back, but that would also have reduced the rate of conduction of electrically generated heat directly to the environment and increased the computed rectal temperature of the heated diver, which was already higher than the measure value. This is a matter that needs further study.

While these are interesting questions for an analyst, they are probably not of great interest to a diving supervisor, who needs to know whether a given survival system meets the mandated requirement for providing 24 hour protection. The Kinergetics and Diving Unlimited systems have been experimentally validated for use in a bell at 150 msw, which is completely consistent with the simulation shown in Fig. 8. Another system of considerable interest is a welding habitat in 200 msw. A 14-hour simulation for that case using the breathing gas temperature measured for the Kinergetics diver in the Polar Bear III trial and a chamber temperature that decreases to 5.4 °C in roughly 3 hours yields the cooling curve shown in Fig. 13. At the end of 14 hours, the diver is mildly hypothermic and shivering, but he is in no danger and should be able to survive easily for another 10 hours.

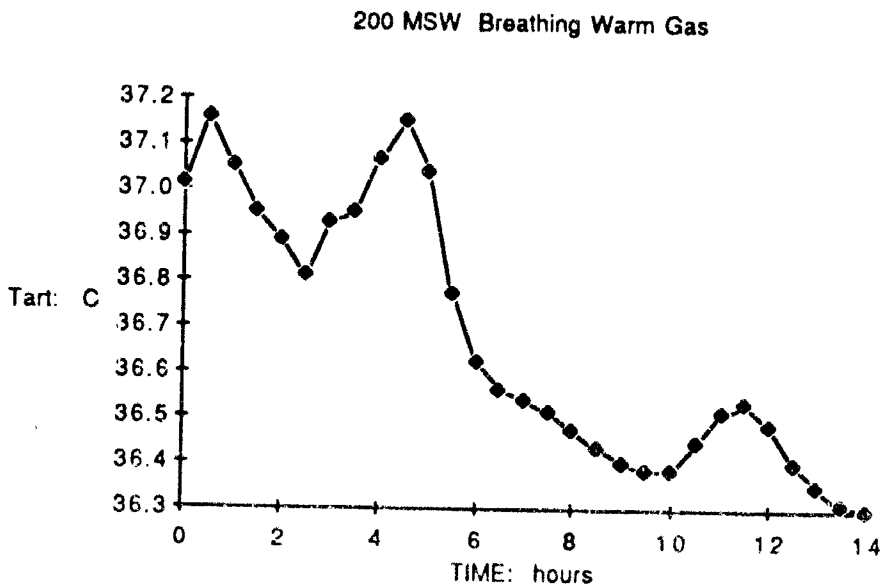


Fig. 13. Computed Arterial Temperature for a Well-protected Diver at 200 msw.

It cannot be emphasised too strongly that long-term survival is only possible when the survival system is in good condition and is properly used. For example, if the diver's breathing gas scrubber/heater does work properly, which was the case in the Inocean accident a year ago, the situation changes markedly. Neither diver's scrubber/heater was functional in that case, and they had to breathe cold gas. It is not clear from the brief report whether they breathed slightly warmed gas from within the bag, or whether they breathed cold gas and exhaled into the bag. A simulation carried out for this case assuming that they breathed cold chamber gas produced the results shown in Fig. 14. It is clear that the diver is in serious difficulty after only 7 hours, which was the time required for rescue in that accident. Their comments recorded several months post-dive indicated that the first two or three hours were not too bad, but then they began to suffer, which is consistent with the results of the simulation. It is doubtful whether they could have survived another 17 hours.

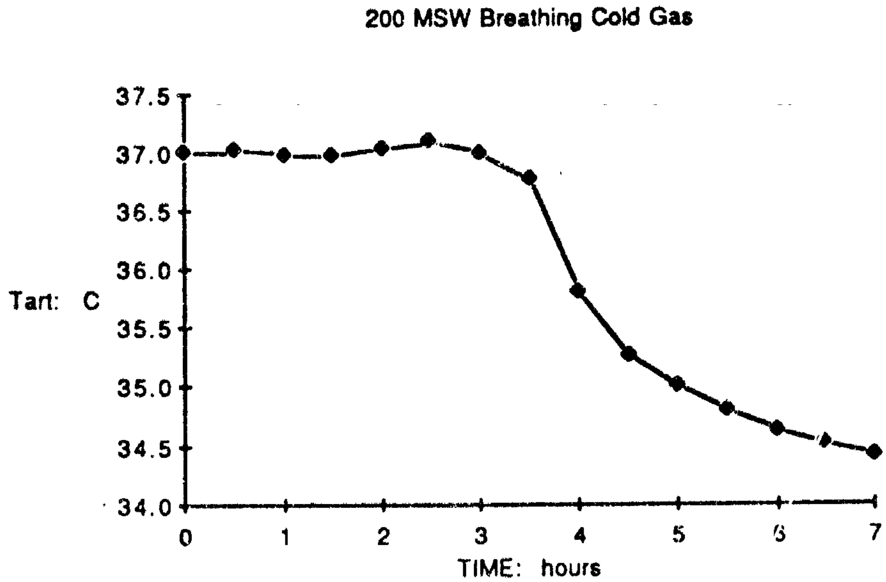


Fig. 14. Computed Arterial Temperature for a Diver in a Survival Bag Breathing Cold Gas at 200 msw.

Although no trial has lasted longer than 12 hours at a depth greater than 150 msw, one should not conclude that the survival systems are inadequate at deeper depths. Unfortunately, it is probably not possible to establish that a marginal system is adequate, because institutional review committees will not permit, and diver/subjects will not tolerate such exposures. One solution to that problem is to require that acceptable systems provide 24 hour survival in relative comfort, as is true of the Kinergetics and Diving Unlimited systems at a depth of 150 msw. While that has the advantage of providing a reasonable margin of safety, it is unlikely that any currently available system provides that kind of protection at depths greater than 300 meters. An alternative, less stringent procedure is to measure the properties of a candidate survival system at shallower depths, and then mathematically simulate a deeper exposure. If the simulation indicates that 24 hour survival is possible without exposing the diver to unreasonable stress, the system could be accepted. Unreasonable stress might be defined (somewhat arbitrarily) as a central temperature below 35 °C, or shivering of sufficient intensity to double the total metabolic rate.

When these criteria are applied to the Kinergetics system, it becomes marginally acceptable at 300 msw. The computed results shown in Fig. 9 indicate that, although the central temperature is still above 36 °C, it is maintained at that level by a shivering rate sufficient to double the metabolic rate. Such intense shivering could possibly be maintained for another 10 hours, but affecting a successful through-the-water rescue could be very difficult after such an exposure. It should be noted that the results shown in Fig. 9 were computed using a rather low inspired gas temperature and a uniform habitat temperature of 7 °C. The diver would certainly fare better if a higher inspired temperature and a bell cooling profile were used.

When these same criteria are applied to the Igloo 88 trial, it is clear that the unheated Kinergetics system fails. Therefore, the system will have to be perfected, or some form of electrical heating will be required.

The final point that needs to be stressed is the crucial importance of adequately heating the breathing gas at great depths. Systems currently in used can certainly be improved. For example, it may not be necessary to supply the system with gas from outside of the bag, which would permit one to design a much simpler system without a regenerative heat exchanger to recover sensible heat from expired gas. It is not necessary in this report to suggest a final design for a new scrubber/heater; suffice it to say that that endeavour should be given immediate attention.

REFERENCES

1. DiChiro, Anthony, Final Report: Electrical Survival Suit, p. 29, Kinergetics, Inc., Tarzana, CA, (23 January, 1987).

2. Hayes, P. A., E. H. Padbury, and P. J. Atherton, "Validation of Emergency Procedures - The Lost Bell Situation," in Proceedings of the International Conference DIVETECH '81, Society for Underwater Technology, London (1981).

3. Magnusson, J., I. Holmer, S. Elnas, and R. W. Hamilton, "Metabolic Rate of Divers in a Simulated 'Lost Bell' Survival Test," in Underwater Physiolog VIII, A. J. Bachrach and M. M. Matzen, eds., Undersea Medical Society, Bethesda, MD (1984).

4. Piantadosi, C., "Respiratory Heat Loss Limits in Helium Oxygen Saturation Diving," in Thermal Constraints in Diving, L. A. Kuehn, ed., p 49, Undersea Medical Society, Bethesda, MD, (1981) .

5. Tonjum, S., A. Pasche, D. Furevik, B. Holand, A. Brubakk, and C. Olsen, POLAR BEAR II: Test of survival systems for stranded bell divers at 31 bars, NUI Report No. 40-80 (1980).

6. Tonjum, S., A. Pasche, J. Onarheim, D. Furevik, P. Hayes, H. Padbury, and K. Segadal, POLAR BEAR III: Test of passive survival systems for 24 hours at 16 bars, NUTEC Report No. 21-82 (1982).

7. Webb, P. A., "Cold Exposure, " in The Physiology and Medicine of Diving, P. B. Bennett and D. H. Elliott, eds., p. 297, Williams and Wilkins Co., Baltimore, MD, (1975).

PREDICTION OF THERMOREGULATORY RESPONSE FOR CLOTHED IMMERSION IN COLD WATER

Peter Tikuisis, Ph.D.
Environmental Physiology Section
Defence and Civil Institute of Environmental Medicine

ABSTRACT

A multi-compartmental thermoregulatory model was applied to data of ten resting clothed males immersed for 3 h in water at 10 and 15°C. Clothing consisted of a dry suit and either a light or heavy undergarment, representing a total insulation of 0.15 (0.95) or 0.20 m^2°C/W (1.28 clo), respectively. Data were grouped according to low (<14%) and high (14 to 24%) body fat individuals. Mean decreases in rectal temperature ranged from 0.79 to 1.38°C, mean decreases in the mean weighted skin temperature ranged from 6.3 to 10.2°C, and mean increases in the metabolic rate ranged from 33.9 to 80.8 W. The model consists of eight segments, each representing a specific region of the body. Each segment is comprised of compartments representing the core, muscle, fat, skin, and clothing. Each compartment is assigned thermophysical values of heat conduction and heat capacitance, and with the exception of clothing, physiological values of blood flow and metabolic heat production. During cold exposure, responses are directed towards increased heat production in the form of shivering and heat conservation in the form of vasoconstriction and counter-current heat exchange. Agreement between the model predictions and the experimental observations was obtained by adjusting the parameters governing these responses. These adjusted parameters were 1) the delayed onset of limb shivering with an exponential half-time of 30 min, 2) the fractional value of 0.5 for the heat exchange between the core compartments of the limbs and the blood flowing through these compartments, 3) the fractional contribution of trunk shivering to overall shivering, which ranged from 0.77 to 0.95, and 4) the delayed onset of vasoconstriction with half-times, which ranged from 3 to 25 min. Steady state was predicted to occur within 4 h and an analysis of heat balance indicated that the limbs were responsible for most of the body's heat loss while acquiring most of their own heat from the trunk through conduction with the central blood.

INTRODUCTION

Mathematical models of human thermoregulation are being used increasingly for prediction beyond permissible cold exposure limits. Acceptance of such models is predicated on their predictive performance when compared to the limited data available. Previous models that we have used (Tikuisis et al., (1988a, 1988b)) evolved from the original concepts of Stolwijk and Hardy (1966, 1970, 1977). Essentially, the human body is divided into six distinct segments (see Fig. 1), the head modelled as a sphere and the trunk, arms, hands, legs, and feet modelled as cylinders. Each segment contains concentric annular compartments representing the core, muscle, fat, and skin. Each compartment is assigned thermophysical values of heat conduction and heat capacity, and except for the clothing layers, physiological values of metabolic heat production and blood flow. Model parameters are adjusted to obtain reasonable agreement with data of cold water immersion, and predictions can be extrapolated to obtain

PRECEDING PAGE BLANK

estimates of endurance (for example, based on glycogen depletion as proposed by Wissler (1985)).

In the present study, modifications to this model for the inclusion of clothing will be outlined. In addition to the potential for evaluating clothing protection effectiveness, more complete information on a person's thermoregulation, such as metabolic heat production, tissue-blood convective heat exchange, and both transient and steady-state temperature distributions, can be provided. The present model contains two major modifications (see Fig. 2).

METHOD

First, the arms and legs have been divided into two segments each representing upper and lower sections, and all segments contain clothing which are treated as separate compartments having fixed values of thickness, thermal conduction, and heat capacity. Second, the arterial (shown as the heavy dashed line) and venous (heavy solid line) blood flows have been more realistically represented. Blood flow originates from the central pool located in the trunk core and provides the only means by which heat is transferred among the various segments (tangential heat conduction between adjacent segments is not considered here). This mode of heat exchange is especially important for the extremities (hands and feet) during cold exposure since these segments generate little heat of their own. Arterial blood entering the upper segment of the limbs is separated into two channels, one that provides blood to the muscle, fat, and skin compartments of that segment and the other that flows through the core of the segment to provide blood for the core and a path for blood continuing downstream into the next segment. This pattern is repeated until the extremity is reached. Venous blood returns to the central pool through the reverse path except for the skin blood which flows via superficial channels of the head and limb segments.

The mechanism of tissue-blood (convective) heat exchange used here is similar to that of Miller and Seagrave (1974). For all compartments except the core of the limbs, complete thermal equilibrium with the blood is assumed. Through the core of the limbs, a partial convective heat exchange is assumed.

RESULTS

Data for the present model were obtained from 3 h immersions to the neck level in 10 and 15°C water. Clothing consisted of a polypropolene undergarment and a neoprene dry suit. Two thicknesses of the undergarment, designated LIGHT and HEAVY, were used and the total insulative values including the dry suit were 0.95 and 1.28 clo, respectively (Toner et al.(1989)). Ten young healthy males were separately immersed in the cold water during four different test conditions (2 clothing ensembles × 2 water temperatures). Data were collected on the subject's rectal temperature (Tre), mean weighted skin temperature (Tsk) and metabolic rate (MR). These data were grouped according to low (<14%) and high body fat (designated LBF and HBF, respectively).

Figure 3 shows the measured (±SE) and model-generated values (solid line) of Tre plotted against time for all four experimental test conditions for the LBF group. Results for the HBF group are shown in Fig. 4. The decrease in Tre was generally smaller in the HBF group compared to the LBF group. Figure 5 shows the measured

(±SE) and model-generated values (solid lines) of MR and Tsk for the 10°C water LIGHT clothing condition (which represents the most extreme test condition) for both groups.

DISCUSSION

To obtain the agreement between the measured and model-generated values shown in these figures, four model parameters were adjusted. Two of these were fixed under all test conditions: 1) 30 min half-time for the onset of limb shivering and 2) 0.5 for the fraction of heat exchange between the limb core compartments and the blood flowing through these compartments. The other two parameters were adjusted for each test condition: 1) the fractional contribution of trunk shivering to overall shivering was adjusted with values in the range from 0.77 to 0.86 and from 0.91 to 0.95 for the LBF and HBF groups, respectively, and 2) the half-time for the onset of vasoconstriction was adjusted with values in the range from 3 to 20 min and from 15 to 25 min for the respective groups.

A potentially useful prediction of the thermoregulatory model are the temperatures of the compartments and their arterial blood as shown in Fig. 6 for the LBF group in the 10°C water LIGHT clothing condition. There is a general tendency to lower temperatures in the limbs towards the extremities. This tendency is also repeated, but to a lesser extent, by the predicted arterial blood temperatures as a consequence of convective heat exchange. For example, at 180 min the predicted temperatures of the core compartments and the arterial blood of the hands and feet are 16.0 and 30.7°C, and 16.4 and 32.6°C, respectively. No direct data are available to test these predictions. Bazett et al. (1948) suggested that the temperature of arterial blood entering the hands may be as low as 20°C. The values predicted in the present study were based on the assumption that blood flowing through the core compartments of the upper and lower segments of the limbs exchanged one-half of the potential convective heat available with these compartments. Increasing this fraction would further lower the temperature of arterial blood entering the hands and feet.

The predicted temperatures of the hands and feet discussed here are considerably lower than their corresponding upstream segments . Since very little metabolic heat is produced in the extremities, they rely almost entirely on arterial blood for their source of heat. Convective heat available to the extremities is dependent on both the temperature and flow rate of the arterial blood. While the predicted arterial blood temperatures are relatively high compared to that of the compartments, blood flow is very low. According to the model prediction, blood flow to the hands and feet at steady state during the cold exposure is reduced to about 1/10 of their pre-immersion values due to vasoconstriction. Therefore, the hands and feet have little source of heat and cool considerably more than their corresponding upstream segments.

Figure 7 shows the various components of heat exchange predicted for the LBF group in the 10°C water LIGHT clothing condition at various times. These values are shown for the head and trunk segments, and for the sum of the upper limb segments (upper and lower arms plus hands), indicated by Arms, and for the sum of the lower limb segments, indicated by Legs. Mr is the metabolic heat production. Hc + Er is the sum of the convective and respiratory heat losses to the environment. BC is the convective heat exchange with the blood; positive values indicate that heat is given to the blood and negative values indicate that heat is removed from the blood. S is the rate of heat storage defined as MR minus (Hc + Er) minus BC. Negative values of S as shown indicate a net loss of heat and zero values indicate thermal steady state.

Accordingly, thermal steady state is predicted to occur by 240 min. Although specific values vary with each experimental test condition, this figure is qualitatively representative of both body fat groups and all test conditions. The trunk generates most of the body's heat while the limbs (Arms and Legs) are responsible for most of the body's heat loss. The heat loss by the limbs is largely supplied by the blood (-ve BC values) via the trunk (+ve BC values). The results shown here are consistent with other observations that the limbs may lose more heat than the trunk during cold water immersion.

REFERENCES

Bazett HC, Love L, Newton M, Eisenberg L, Day R, Forster R (1948). Temperature changes in blood flowing in arteries and veins in man. J Appl Physiol 1: 3 - 19.

Miller NC, Seagrave RC (1974). A model of human thermoregulation during water immersion. Comput Biol Med 4: 165 - 182.

Stolwijk JAJ, Hardy JD (1966). Temperature regulation in man - a theoretical study. Pflugers Archiv 291: 129 - 162.

Stolwijk JAJ (1970). Mathematical model of thermoregulation. In: Hardy JD, Gagge AP, Stolwijk JAJ (eds). Physiological and behavioral temperature regulation. Charles C Thomas, Springfield IL, pp 703 - 721.

Stolwijk JAJ, Hardy JD (1977). Control of body temperature. In: Lee DHK (ed) Handbook of physiology. Am Physiol Soc, Bethesda MD, pp 45 - 68.

Tikuisis P, Gonzalez RR, Pandolf KB (1988a). Thermoregulatory model for immersion of humans in cold water. J Appl Physiol 64: 719 - 727.

Tikuisis P, Gonzalez RR, Pandolf KB (1988b). Prediction of human thermoregulatory responses and endurance time in water at 20 and 24°C. Aviat Space Environ Med 59: 742 - 748.

Toner MM, Holden WL, Foley ME, Bogart JE, Pandolf KB (1989). Influence of clothing and body-fat insulations on thermal adjustments to cold-water stress. Aviat Space Environ Med (in press).

Wissler EH (1985). Mathematical simulation of human thermal behavior using whole-body models. In: Heat Transfer in Medicine and Biology, Plenum Press: New York.

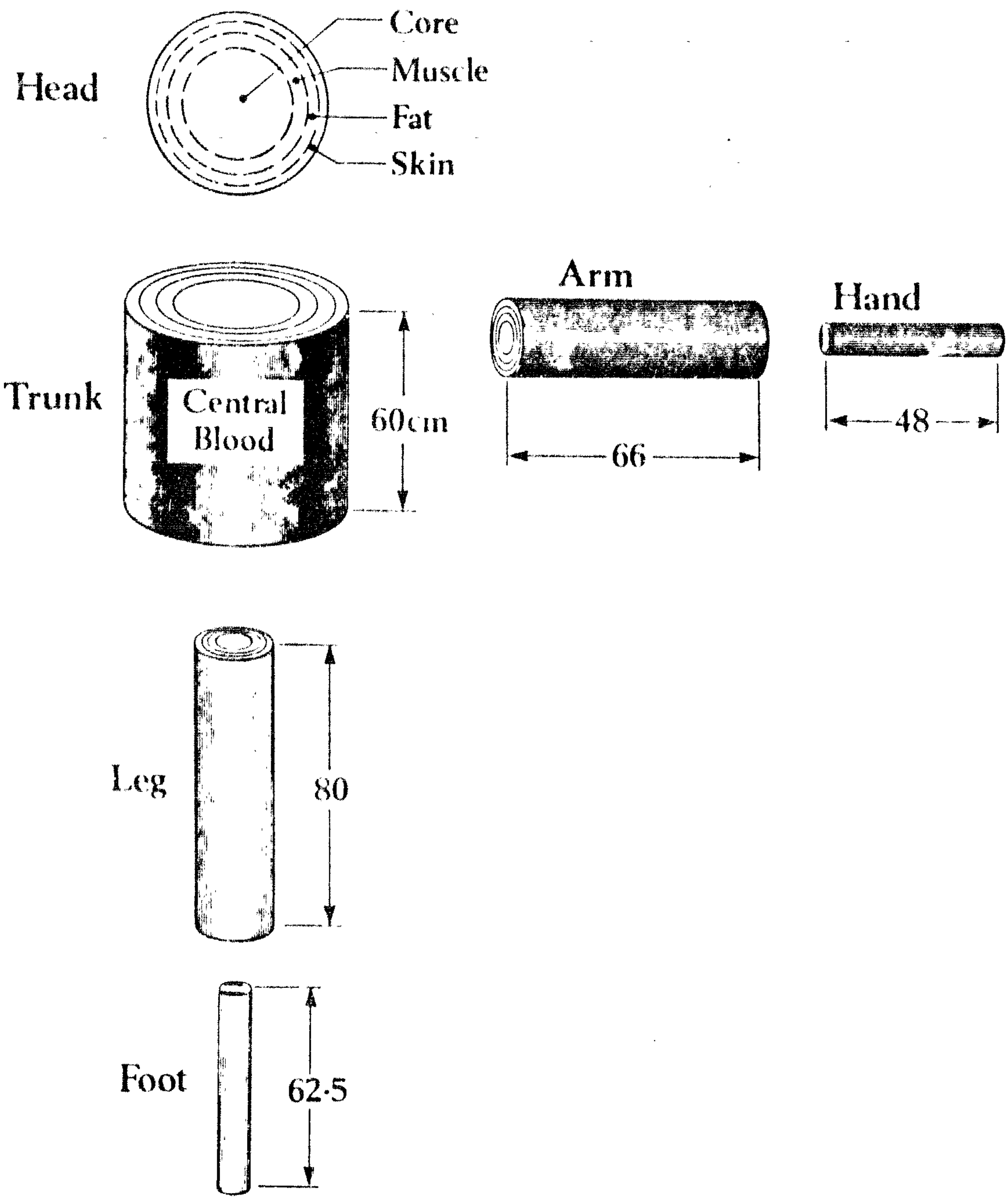


Fig. 1. Schematic of the human body (not drawn to scale) used in the previous thermoregulatory model. Each body segment is composed of four concentric annular compartments, the head modelled as a sphere and the others as cylinders. Length of the cylinders is given in centimeters. The central blood compartment is located within the trunk segment.

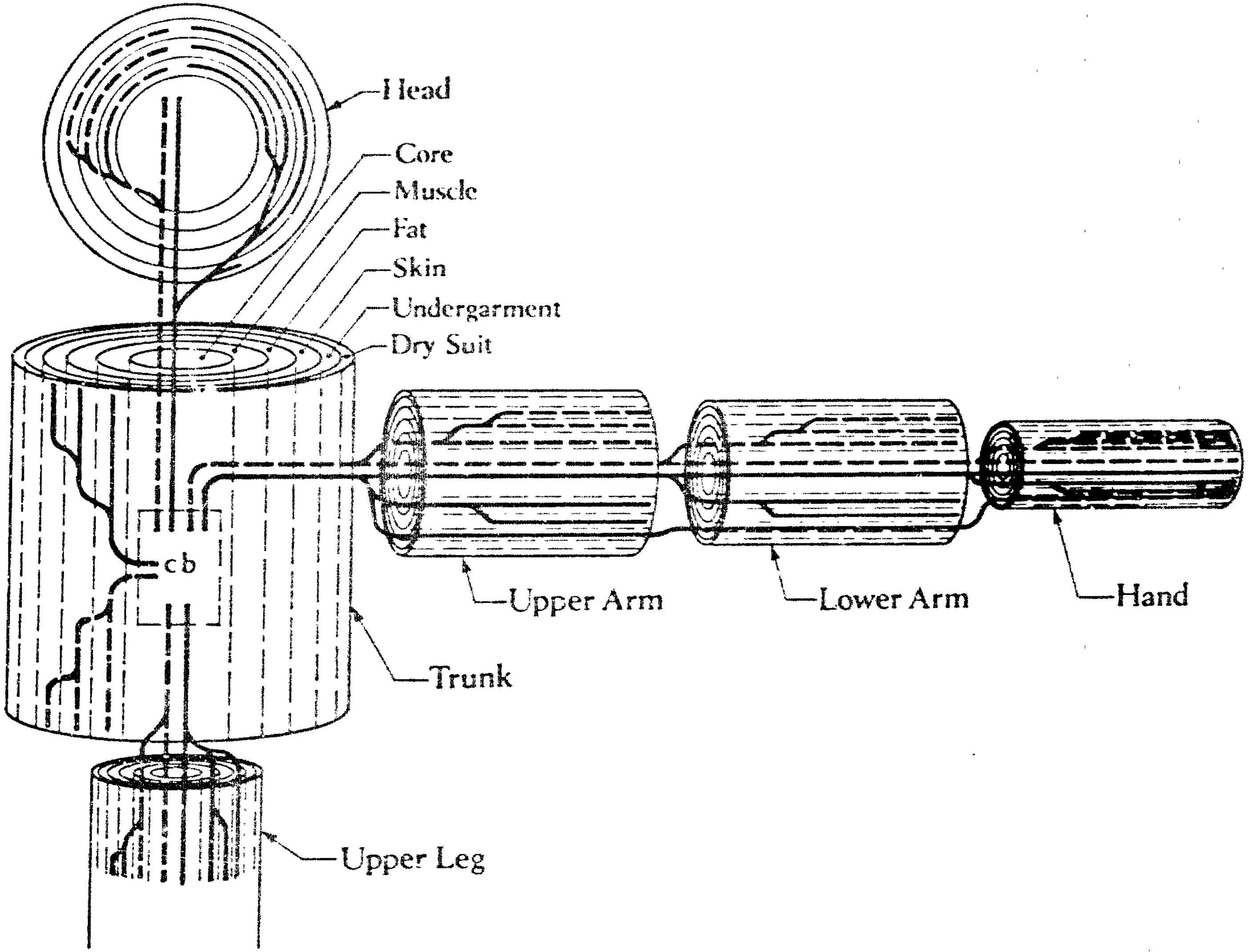


Fig. 2. Schematic of body segments (not drawn to scale) and arterial (heavy dashed line) and venous (heavy solid line) blood flow distribution. The head segment does not have an undergarment compartment and cb denotes the central blood. Characteristics of the lower limbs are similar to the upper limbs except for dimensions.

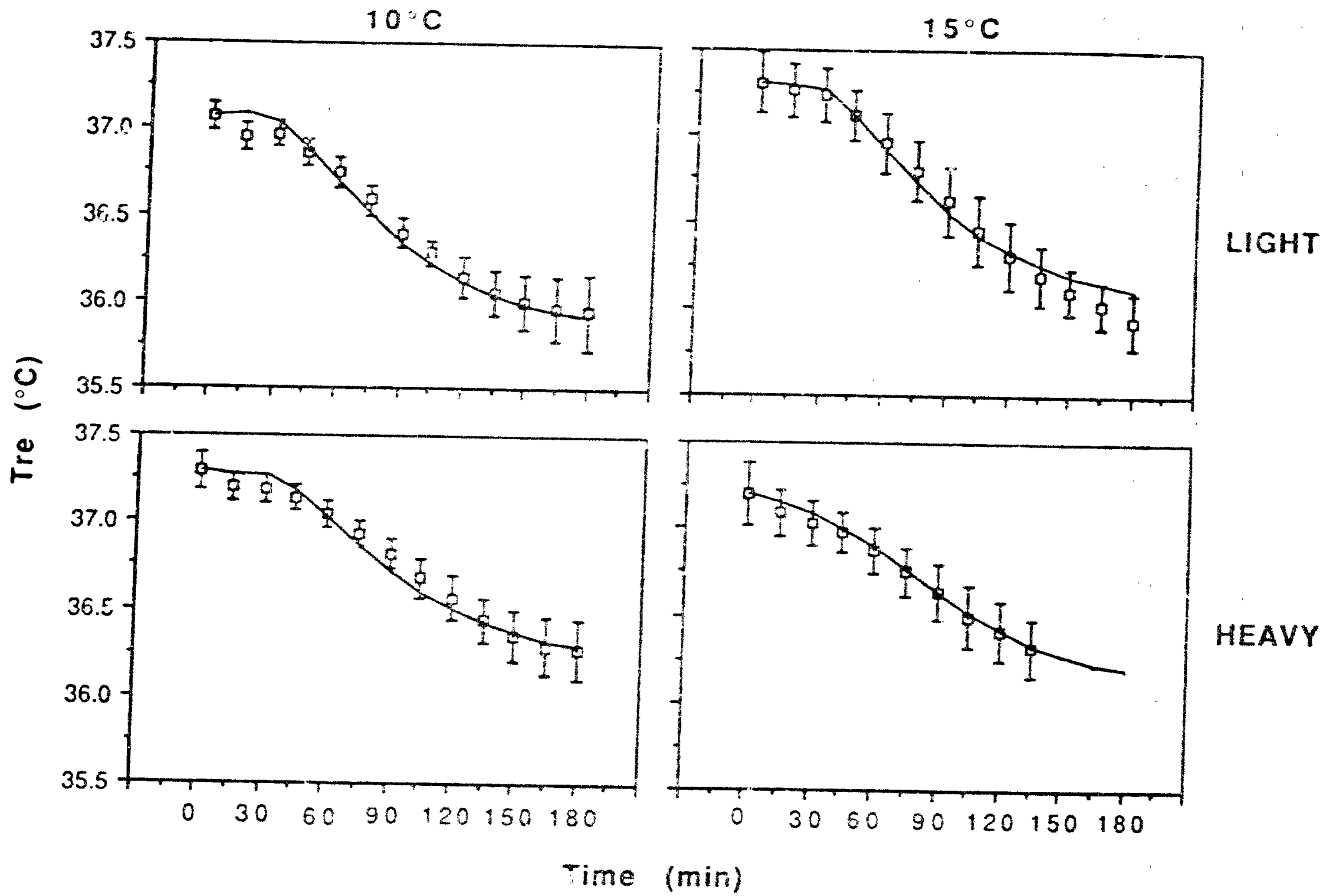


Fig. 3. Measured (±SE) and model (solid line) values of Tre plotted against time for the LBF group under the four experimental test conditions.

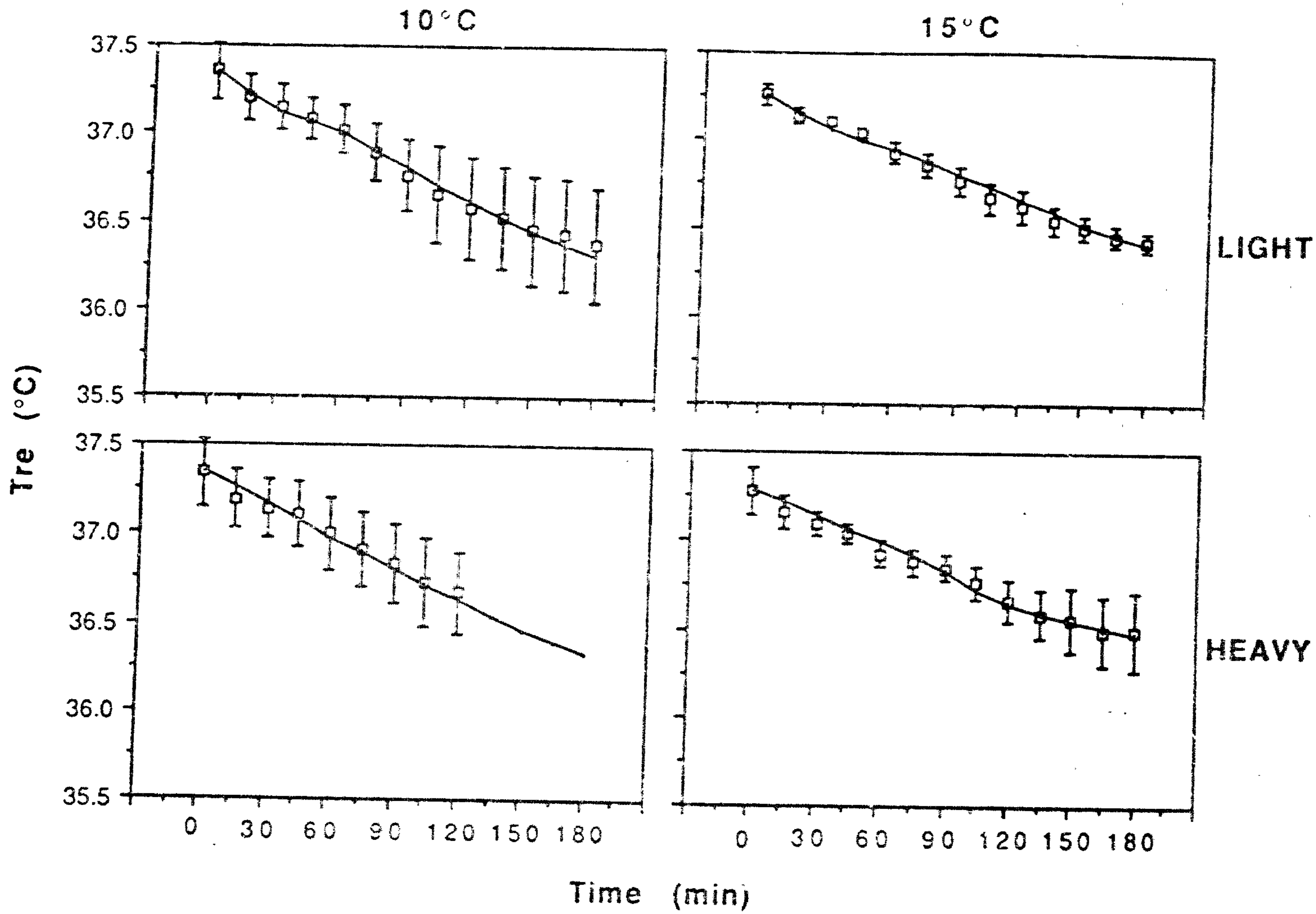


Fig. 4. Measured (±SE) and model (solid line) values of Tre plotted against time for the HBF group under the four experimental test conditions.

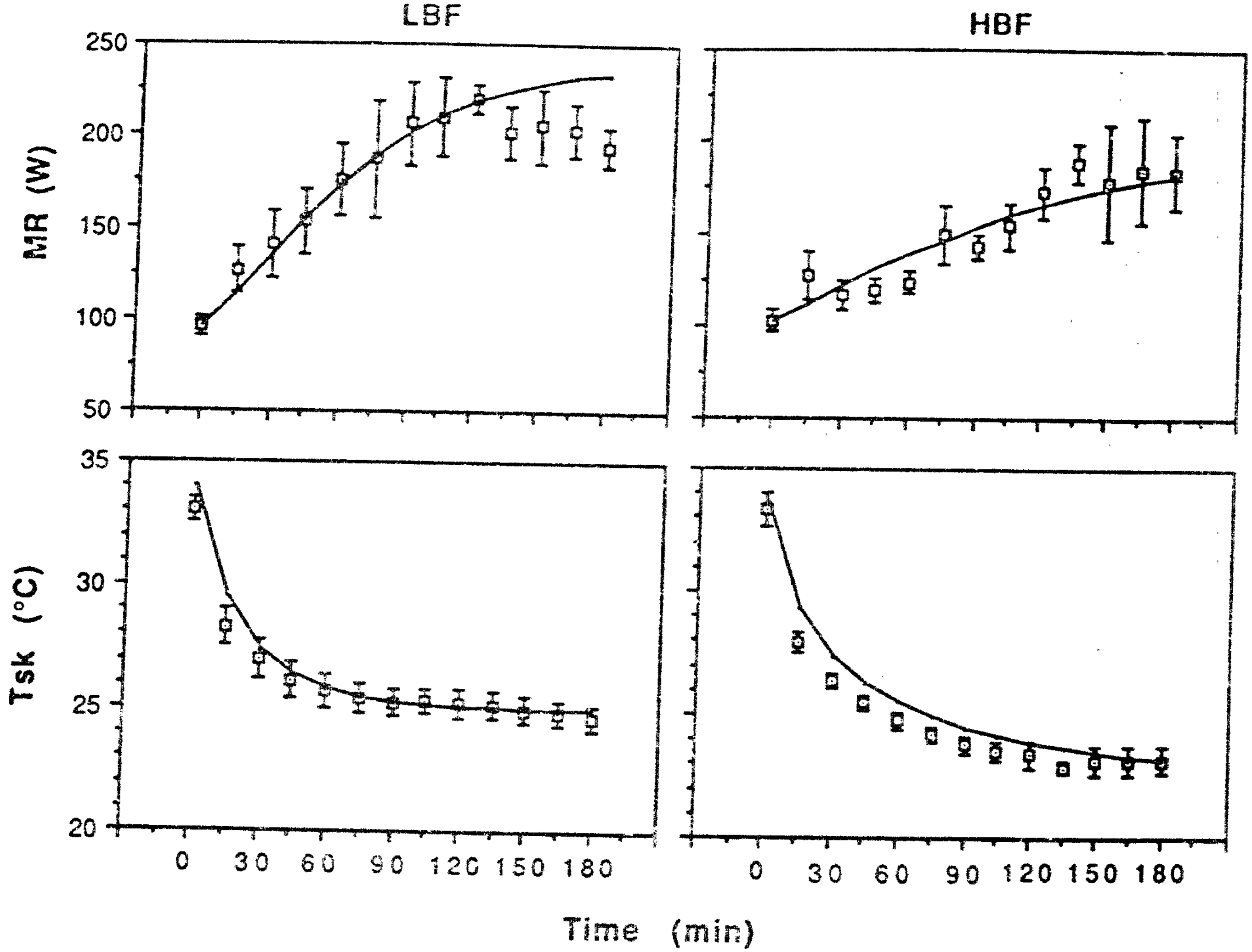


Fig. 5. Measured (±SE) and model (solid line) values of MR and Tsk plotted against time for the LBF and HBF groups under the 10°C water LIGHT clothing condition.

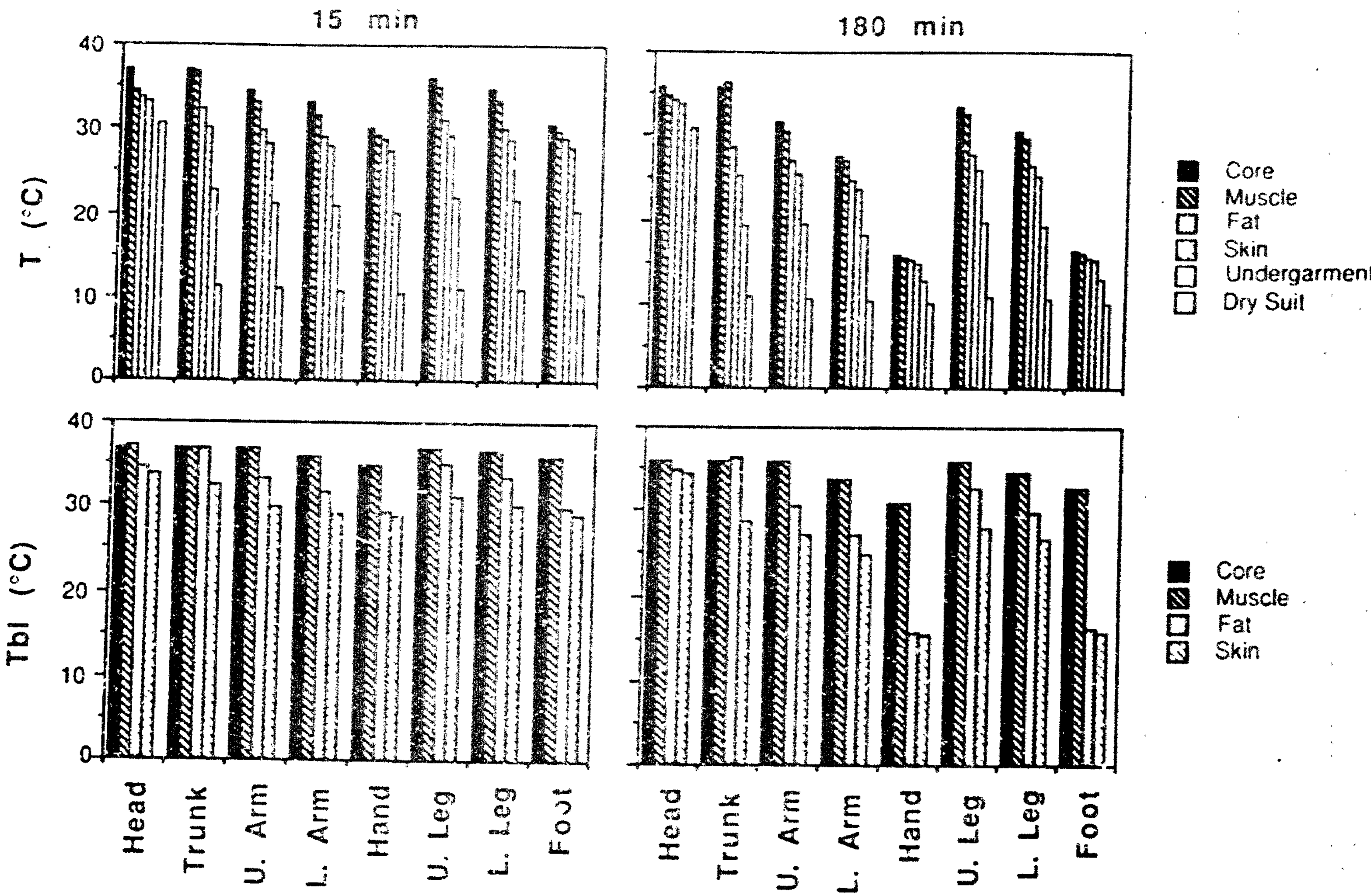


Fig. 6. Predicted temperatures of the compartments (T) and arterial blood (Tbl) at 15 and 180 min for the LBF group under the 10°C water LIGHT clothing condition. U and L designate upper and lower, respectively.

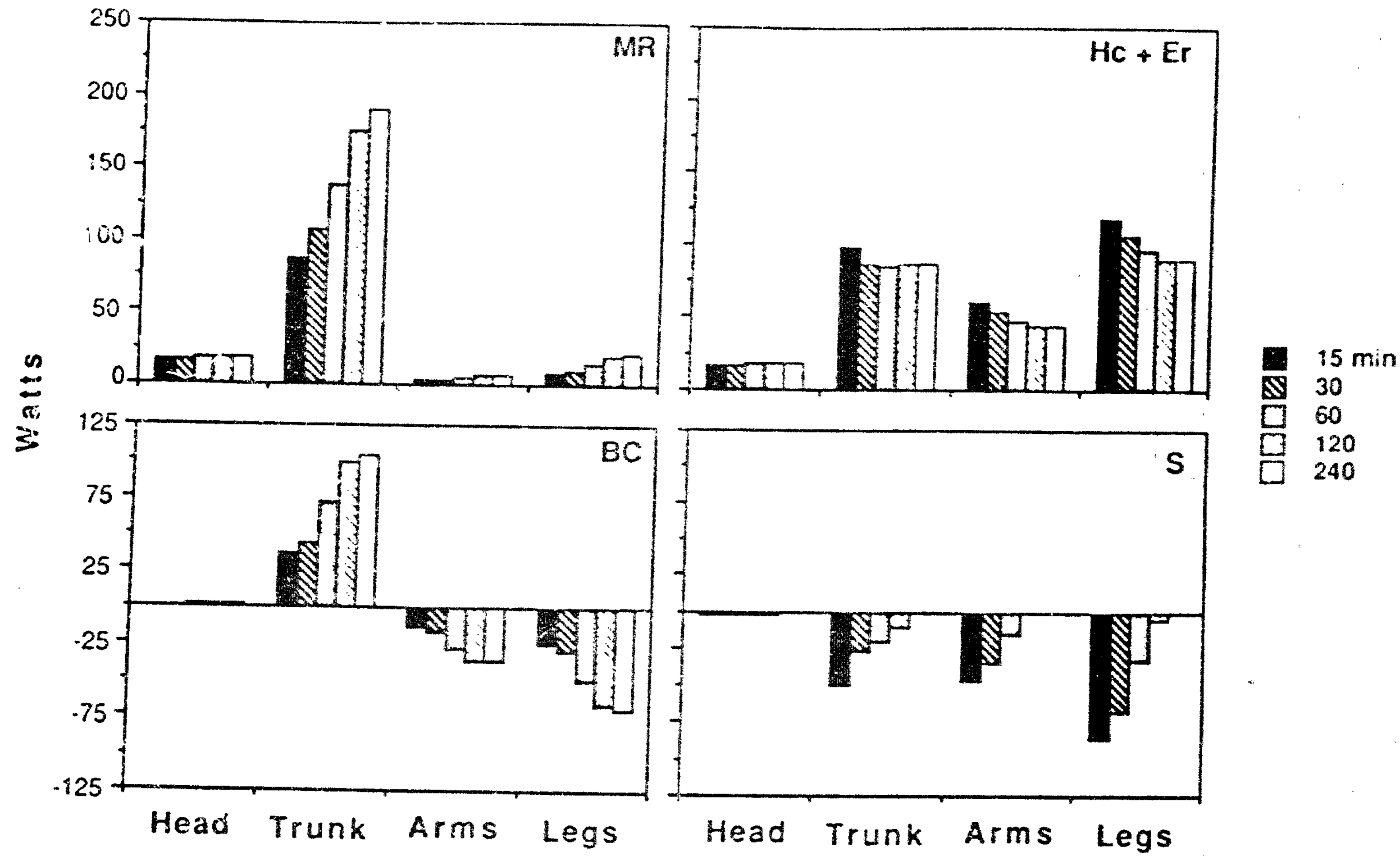


Fig. 7. Predicted values of metabolic rate (MR), convective plus respiratory heat losses (Hc + Er), convective heat exchange with the blood (BC), and the rate of heat storage (S) for various regions of the body at various times. Arms and Legs include the upper and lower limb segments and the extremities.

CONTROL OF DIVERS' THERMAL BALANCE IN DEEP OPERATIONAL DIVING

G. Knudsen, A. Hope, A. Pasche and E.H. Padbury
NUTEC, Norway.

ABSTRACT

The use of hot water suits in deeper diving may result in an abnormal situation for the divers temperature regulatory system, where the skin surface is within comfortable temperature limits, while the core temperature may slowly be reduced by breathing a cool and dense gas mixture (increased respiratory heat loss). This situation may not give symptoms of cooling (undetective hypothermia or symptom free cooling) and may be dangerous to the divers since even mild degrees of deep body cooling can produce impairments of cognitive functions. In experiments performed during onshore chamber dives (simulated depths 360 and 450 msw) we have shown that it is possible to induce a slow and symptom free body cooling (fall in Tre; 0 6-1.5°C) when the subjects breathe a cooled gas (16-19°C). The skin surface temperature was maintained at comfortable limits. However, during a chamber dive to 500 msw at NUTEC, a sudden loss of the preheating of the breathing gas occurred during a lock out dive in cold water. This fast cold stimulation of the respiratory system induced a strong and immediate metabolic response. These observations indicate that the cooling rate of the breathing gas is of importance for whether the cooling through the respiratory system might be symptom free or not. Monobaric experiments were designed in order to investigate if it was possible to stimulate central and peripheral thermal receptors independently at one atmosphere. A main objective was to establish if stimuli from the peripheral warm receptors would override stimuli from the cold receptors in the core (as postulate as an explanation to the symptom free cooling phenomenon). The experiments showed that it was possible to separate stimulation of the centrally and peripherally located receptors and to override cold stimuli of the body core by running warm water at about 35°C over the skin. The studies indicate that symptom free cooling might be a potential problem in operational diving. The characteristics of the thermal receptors and the centrally located integrating unit may explain the phenomenon, since stimuli from the peripheral warm receptors can dominate stimuli from the central core receptors.

PRECEDING PAGE BLANK

SESSION 5

MEASUREMENT TECHNIQUES

Session Chairman:
P. Hayes

PREFACE

The meeting concluded with a session on measurement techniques. Whether we are determining the effectiveness of a suit ensemble or the physiological response, the measurement of response, its accuracy and timeliness becomes important. This session addressed various aspects of these questions.

The first paper was presented by Dr. Sterba of NEDU on the development of an on-line, portable diver monitoring system. The following paper by T. Anthony of ARE (Alverstoke) described a microcomputer-based monitoring system. The importance of on-line, real-time monitoring was reinforced again by the third paper presented by Dr. K. Mittelman of NMRI, who described thermal balance measurements as a measure of thermal status. This paper was suitably followed by M. Ducharme of DCIEM who described the errors that can be associated with using heat flow transducers when measuring heat balance.

The session ended with a look to the future by Dr. Sterba who described the development of a cold water swimming flume that has been designed and is being put into operation at NEDU.

Tiit Romet
Co-Chairman

DIVER MONITORING SYSTEMS, ON-LINE AND PORTABLE FOR THERMAL AND METABOLIC MEASUREMENTS

James R. Braun and LCdr John A. Sterba
Navy Experimental Diving Unit
Panama City, FL, 32407-5001

ABSTRACT

The Portable Diver Monitoring System (Portable DMS) allows physiological monitoring of a free-swimming diver with data stored in a waterproofed, solid-state data logger (Science/Electronics, Model 1299, Dayton, Ohio). Special design characteristics include reduction in thickness from 60 mm to 40 mm, circuit boards providing 10 channels for skin and core temperature, ECG channel and a pressure channel for either depth or oxygen bottle pressure, used to measure oxygen consumption ($\dot{V}O_2$) with a closed circuit underwater breathing apparatus (UBA). Data can be stored, on multiple runs, up to 12 hours. A lap-top computer allows easy data retrieval and display in the field, and data storage for future statistical analysis. Using thermistors, accuracy of body core temperature is ±0.06 °C and skin temperatures ±0.30 °C. Portable DMS, with thermistors and waterproofing, cost $6,000 without the lap-top computer.

The On-line DMS provides real-time monitoring of two divers for the following temperatures: 12 fingers and toes, 1 rectal and 1 esophageal body core sites, 12 body skin temperatures, plus 12 heat flux measurements. Oxygen bottle pressure for $\dot{V}O_2$ using a UBA, tube-suit temperatures and water flow for calorimetry and ECG are also monitored and recorded. Desktop computer using Lab Tech Notebook and Lotus programs allows real-time display of temperatures in table and graph format. Data analysis of oxygen consumption, heat flux and insulation, plus data storage for later statistical analysis is provided. Sample data recordings and engineering wiring diagrams will be provided and discussed. A complete review of both Portable and On-line DMS will follow in an NEDU report.

1. INTRODUCTION

A need existed for the physiological monitoring of a free-swimming diver and the real-time monitoring of two divers in a cold water swimming flume. This provided the opportunity to investigate the state-of-the-art in portable recording devices and off-the-shelf computer based data acquisition, test and measurement systems. Although two different problems, the measurement requirements were similar, i.e., temperature for toes, hands and core, along with ECG for pulse and pressure for metabolic determinations.

The opinions or assertions contained in this article are the private views of the authors and are not to be construed as reflecting the view of the United States Department of the Navy or the Department of Defense.

2. PORTABLE DIVER MONITORING SYSTEM (DMS)

A survey of the market provided very little in the way of off-the-shelf monitoring systems that satisfied the requirements for a compact, user-friendly data logger that featured good accuracy, low cost, menu driven, data acquisition. Two systems were used or under development by various laboratories of the Navy and Air Force. The systems that came to light were the Solid State Physiological In-Flight Data Recorder (SSPIDR) under development for the Naval Air Test Center by Systems Research Laboratories, whose headquarters are located in Dayton, Ohio and the Squirrel Meter/Logger manufactured by Grant Instruments of Cambridge, England and supported in the United States by Science/Electronics, also located in Dayton, Ohio. Further investigation eliminated the SSPIDR because it was still under development and we were unable to purchase one. This caused us to settle on the Squirrel.

The Squirrel Meter/Logger has been specially configured for us by the manufacturer to be as compact as possible while still maintaining data collection and storage capability and without sacrificing reliability. The overall measurement is 180 X 124 X 40 mm. The weight of the unit is 2.2 lbs. Ten channels of temperature, one channel for heart rate (ECG derived) and one channel for pressure complete the data inputted into the Squirrel. Two of the channels are designed specifically for core temperature measurements and cover the range of 30 to 45°C. The other eight temperature inputs are for fingers and toes and cover the range from 0 to 75°C. The pressure gauge input, channel 11, is a 0 to 20 milliampere channel that can be used to measure water pressure as a depth gauge or oxygen bottle pressure on a closed circuit underwater breathing apparatus to measure oxygen consumption. Channel 12, heart rate, has a range of 0 to 250 beats/minute.

Thermistor inputs, for the Squirrel Meter/Loggers purchased by NEDU are required to be YSI Model 401 for rectal measurements and we have selected the YSI 44033 for finger and toe measurements with extra electrical insulation. The esophageal core temperature is measured by a thermistor manufactured by Mallinckrodt Critical Care, Glen Falls, NY (model 90050, size 9 Fr.). YSI 400 series thermistors are required to satisfy the logic design of the Squirrel which requires a thermistor that measures 2250 ohms at 25°C and has the same mathematical curve for the temperature to be measured as the YSI 401 and the 44033. We have not investigated other possible sources of compatible thermistors, and there may be some. Lockheed plugs are supplied to interface the thermistors with the Squirrel as is a special ECG cable for heart rate measurement.

A Grant Instruments Analysis Program was purchased from Science/Electronics for IBM P.C. Compatible Computers. The Zenith Z184 with a 3.5" floppy and a 20 MB Hard Drive was purchased for interface with the Squirrel. It was ordered with a 2.5 hour rechargeable battery and a Brother Model M-1109 small portable printer completed the data acquisition and analysis system.

The Analysis Program is menu driven which, makes it very easy to use. The physiological data, which has been recorded, is easily transferred into the computer with the aid of a Science/Electronics supplied interface cable. In addition to the physiological data, time and the day and month will also be transferred to the computer and will appear on printouts of data when it is recovered at a later time. The unit has a capacity of 12 hours of recording with a start/stop for multiple dives. Multiple dives can later be averaged and the data treated statistically.

Waterproofing is currently under investigation, but it is anticipated that it will not become an overwhelming task. At the present time, NEDU plans to modify a Water Safe waterproof bag marketed under the trade name "EWA" by Pioneer & Co., Westmont, NJ. Several schemes are being considered but none have been attempted at this date.

3. ON-LINE DIVER MONITORING SYSTEM (DMS)

To support the cold water studies being conducted in the NEDU Swimming Flume it was requested that a system be developed to measure and record critical temperature information from two swimming divers simultaneously. The following data are being recorded for each diver:

- 12 Heat Flux Sites
- 12 Skin Temperatures
- 1 ECG
- 3 Finger temperatures from left hand
- 3 Finger temperatures from right hand
- 2 Toe temperatures from left foot
- 2 Toe temperatures from right foot
- 1 Esophogeal core temperature
- 1 Rectal core temperature
- 1 Hot Water temperature into suit
- 1 Hot Water temperature out of suit

We decided to record the data in a fashion whereby the analysis could be done automatically, thereby reducing the many hours of manual measurement and data reduction. A computer based system was selected because of the tremendous amount of data to be recorded and the availability of proven programs to collect, store, display and present data in whatever format the investigator wishes to present.

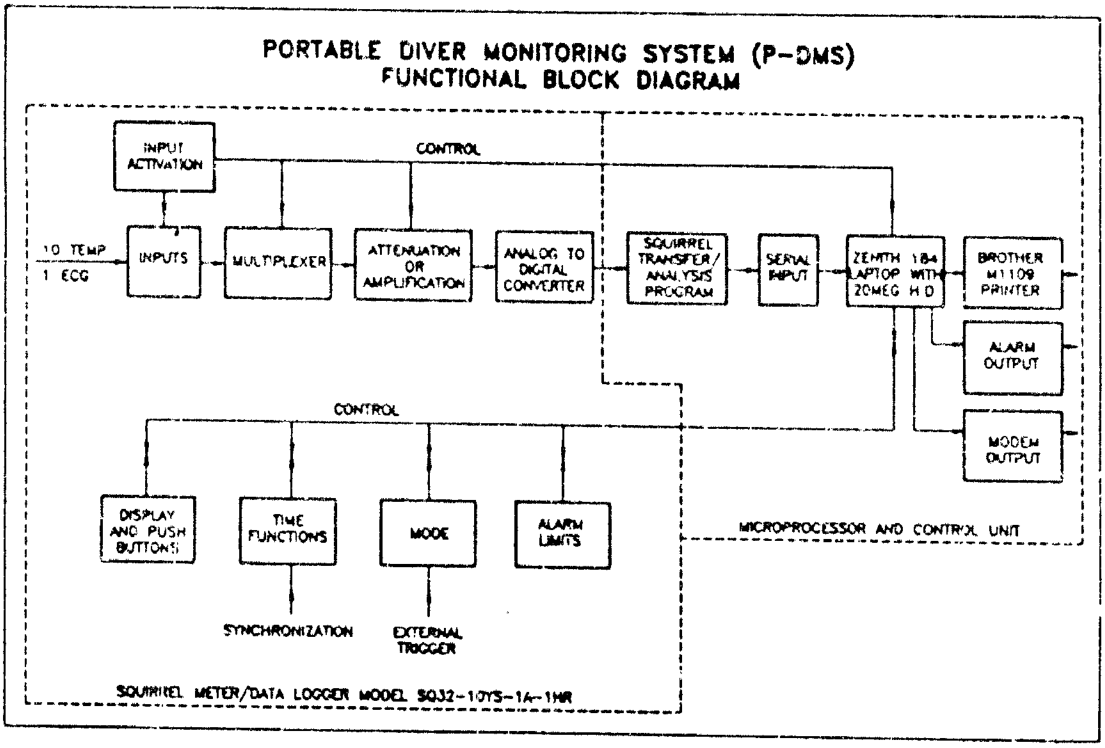
The system is built around a Zenith Z248 computer that is IBM compatible and has a 40 MB Hard Disc Drive. Off-the-shelf Labtech Notebook DAS Software was selected (MetraByte Corporation, Tauton, MA, telephone (508)880-0179) because it provides an easy to use menu driven system for production data acquisition. It can monitor up to 1000 channels with real-time display of up to 50 signals in up to 15 separate windows on the screen. Input signals can be plotted against time, against each other and displayed as line graphs, bar graphs or digital "meters".

Inputting the temperature to the computer is accomplished by using a DAS 16 Analog to Digital Converter (MetraByte Corp). The DAS 16 board is a full length board installed in the expansion slot inside the computer and turns the computer into a high speed, high precision data acquisition and signal analysis system.

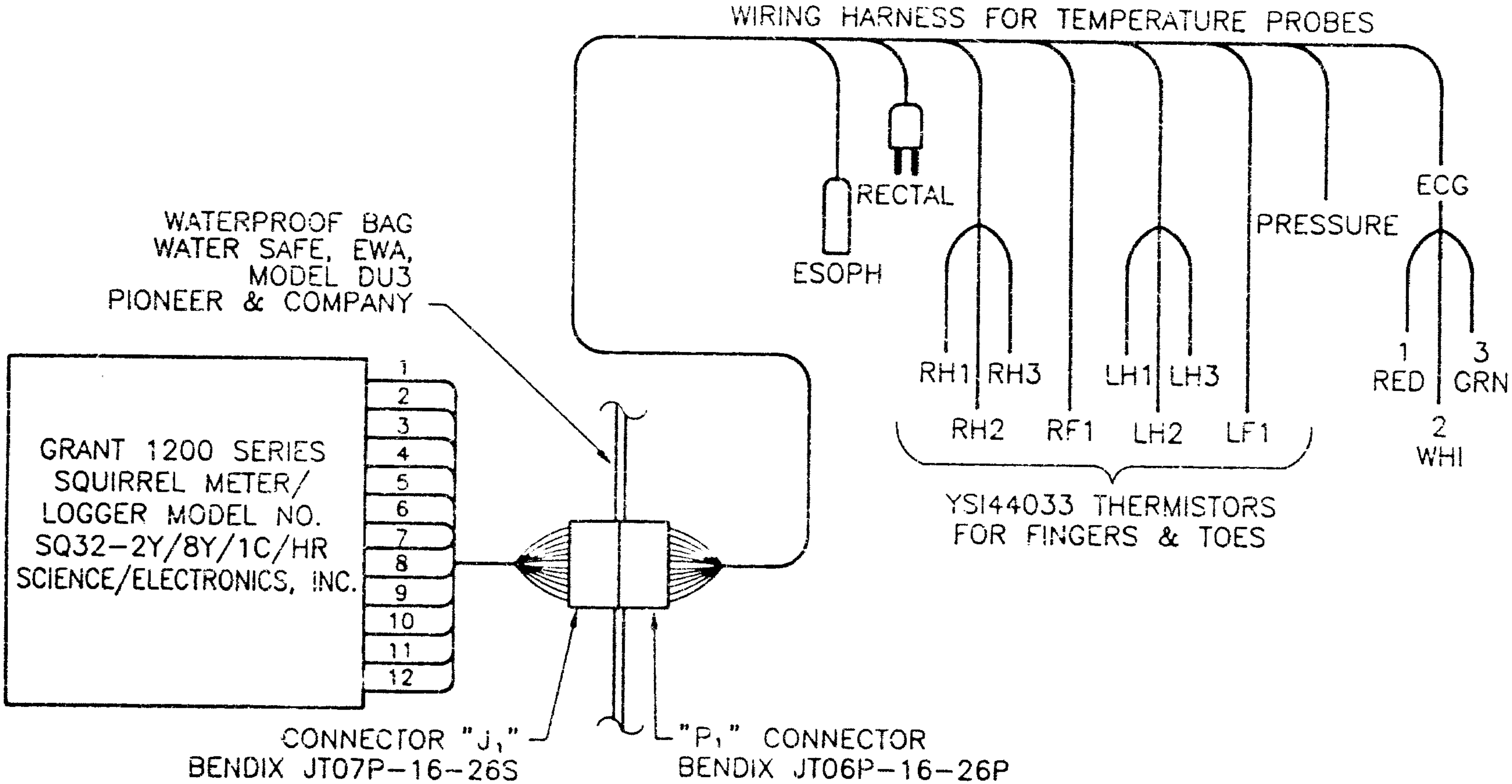
Thermistor outputs for the toes, fingers, water and core temperatures are inputted to the A/D Converter by way of EXP-RES Resistance Measurement Accessory Boards (MetraByte Corp.) cascaded to provide sufficient channels for two divers. Heat flux measurements are inputted to the A/D Converter by way of EXP-16 Expansion Sub-Multiplexers (MetraByte Corp.). These were cascaded to provide the necessary number of channels.

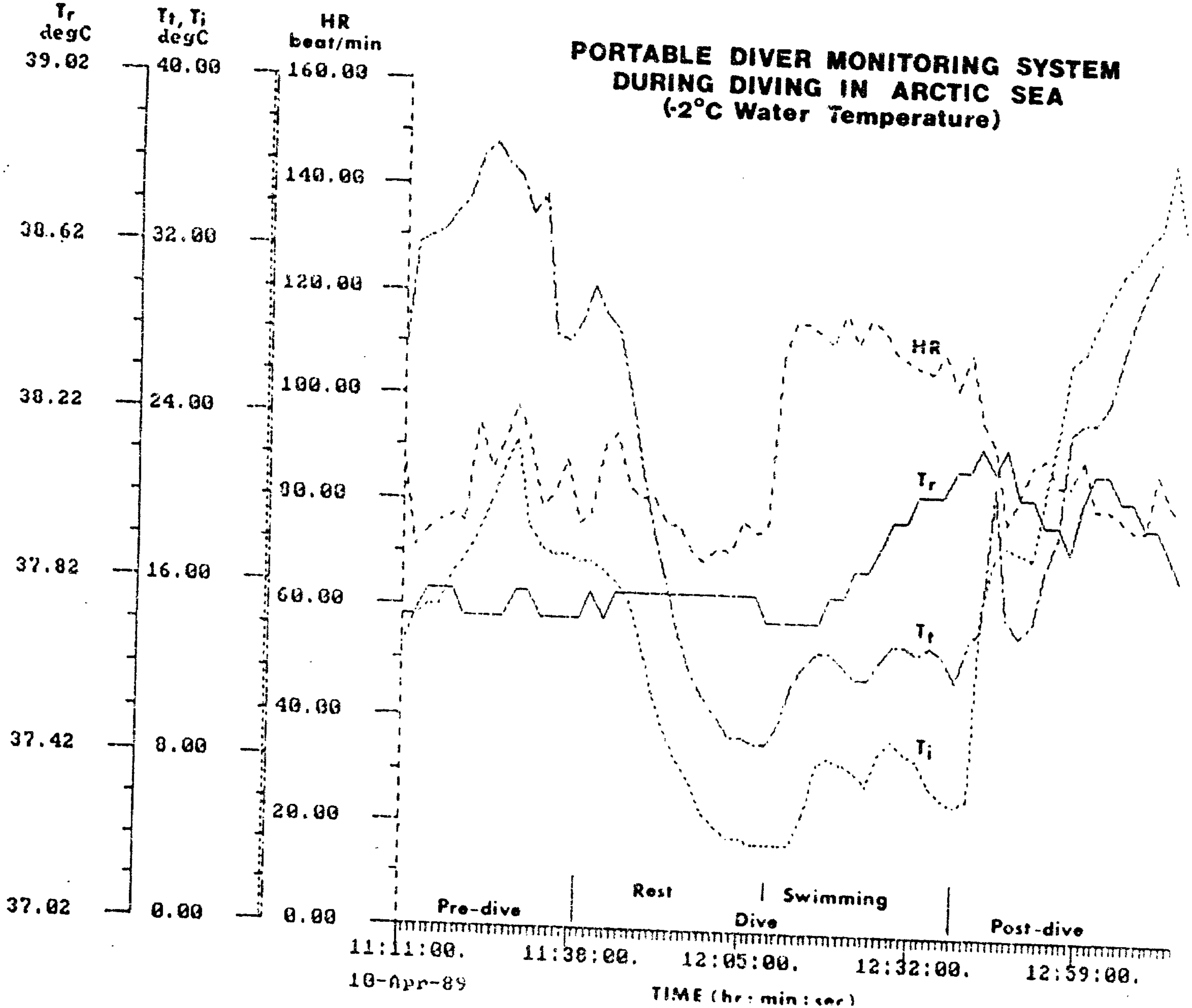
Suit penetraters, umbilical cables, heat flux discs are being provided by Hamburg Associates, Inc. (Jupiter, FL). The heat flux discs are a product of Concept Engineering, Old Saybrook, CT, part no. FR-050-TH44018.

At the present time the system has been assembled as a laboratory prototype and is being installed into the Medical Control Room above the Swimming Flume. It is expected that the entire system will be on-line for diver monitoring by mid-February. A NEDU report will follow on both the portable and on-line diver monitoring systems.

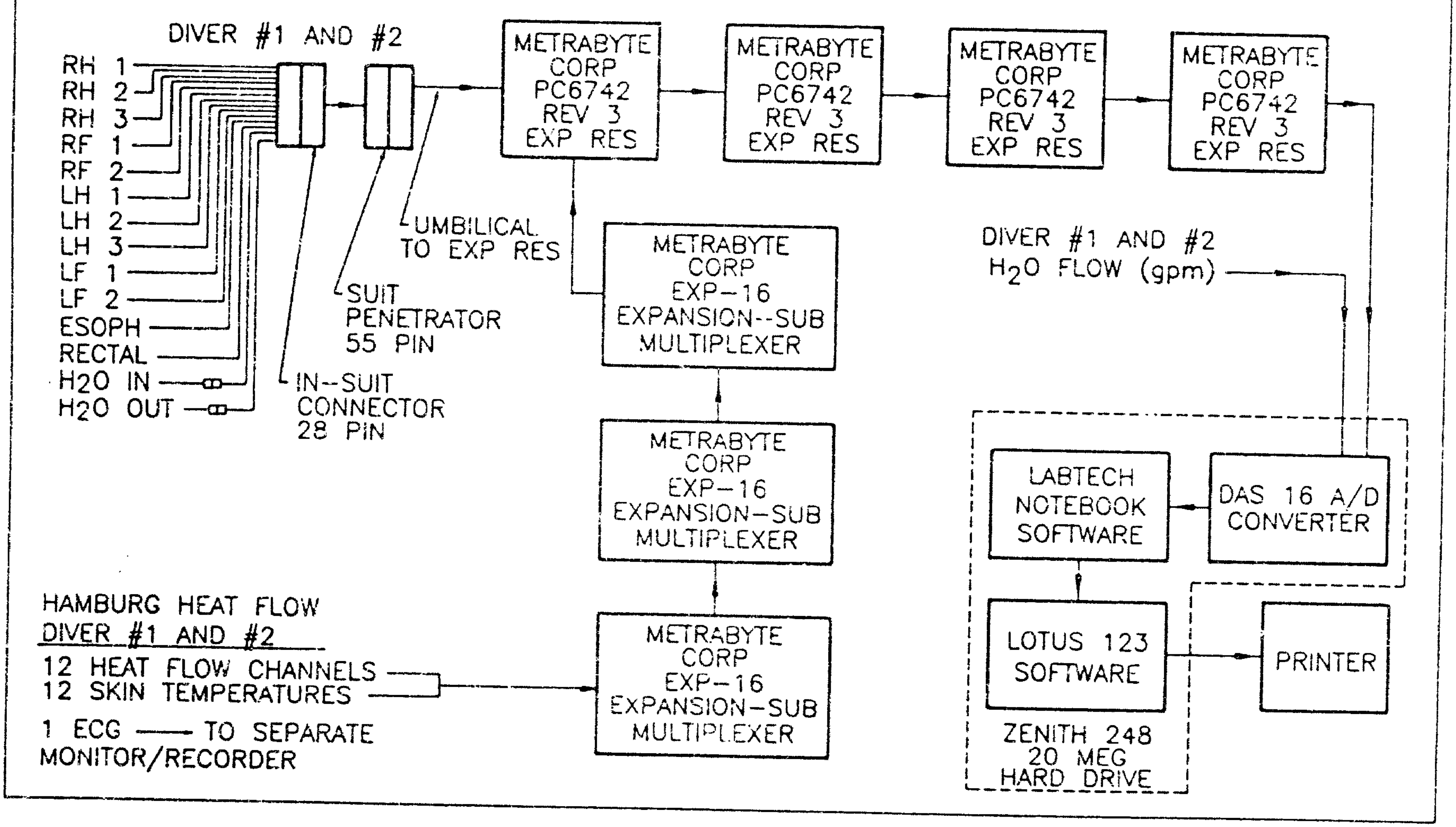


PORTABLE DIVER MONITORING SYSTEM (P-DMS)




PORTABLE DIVER MONITORING SYSTEM
DURING DIVING IN ARCTIC SEA
(-2°C Water Temperature)
Tr degC
39.02
38.62
38.22
37.82
37.42
37.02
Tt, Ti degC
40.00
32.00
24.00
16.00
8.00
0.00
HR beat/min
160.00
140.06
120.00
100.00
80.00
60.00
40.00
20.00
0.00
HR
Tr
Tt
Ti
Pre-dive
Rest
Dive
Swimming
Post-dive
11:11:00.
11:38:00.
12:05:00.
12:32:00.
12:59:00.
10-Apr-89
TIME (hr:min:sec)

ON-LINE DIVER MONITORING SYSTEM (O-DMS)



HF Temp 12	HeatFlow 12	Trend graphs						HeatFlow 12	HF Temp 12
HF Temp 11	HeatFlow 11	green-avg foot temp						HeatFlow 11	HF Temp 11
HF Temp 10	HeatFlow 10	white-avg hand temp						HeatFlow 10	HF Temp 10
HF Temp 09	HeatFlow 09	magenta-avg core temp						HeatFlow 09	HF Temp 09
HF Temp 08	HeatFlow 08							HeatFlow 08	HF Temp 08
HF Temp 07	HeatFlow 07							HeatFlow 07	HF Temp 07
		Diver 1			Diver 2				
			H20 Inlet			H20 Inlet			
		LFing 3	H20 Flow	RFing 3	LFing 3	H20 Flow	RFing 3	HeatFlow 06	HF Temp 06
		LFing 2	H20 Out	RFing 2	LFing 2	H20 Out	RFing 2	HeatFlow 05	HF Temp 05
HF Temp 06	HeatFlow 06	LFing 1		RFing 1	LFing 1		RFing 1	HeatFlow 04	HF Temp 04
HF Temp 05	HeatFlow 05		Esoph			Esoph		HeatFlow 03	HF Temp 03
HF Temp 04	HeatFlow 04		Rectal			Rectal		HeatFlow 02	HF Temp 02
HF Temp 03	HeatFlow 03	LToe 2		RToe 2	LToe 2		RToe 2	HeatFlow 01	HF Temp 01
HF Temp 02	HeatFlow 02	LToe 1		RToe 1	LToe 1		RToe 1		
HF Temp 01	HeatFlow 01		02 Press			02 Press			

Diver 1 Data

Diver 2 Data

All temperatures are in degrees Celsius
All heat flows are in watts/square meter
Oxygen bottle pressures are in PSI
Hot water flow is in GPM

DEVELOPMENT OF A MICROCOMPUTER-BASED DIVER THERMAL MONITORING SYSTEM

T. G. Anthony
Environmental Science Division, ARE Alverstoke
Fort Road Alverstoke, Gosport Hampshire P012 2DU

ABSTRACT

Thermal monitoring of divers has traditionally been undertaken using thermistors coupled to Wheatstone bridge monitoring circuits. This can result in some significant errors. The use of a microcomputer system instead of a Wheatstone bridge circuit to exploit the relationship between the temperature and the resistance of a thermistor was investigated. Several techniques were considered and a microcomputer-based system developed. The system simplified the process and allowed the relationship between temperature and resistance for YSI 400 thermistors to be expressed to an accuracy of 0.01 °K. The system can be applied to any thermistor, and may enable lower cost non-interchangeable thermistors to be used without long, involved calibrations procedures or a reduction in accuracy.

INTRODUCTION

1. There is a need to monitor the thermal status of divers in both an operational role and during diving research. Thermistors are readily available in a wide range of physical configurations and performance characteristics. The ease of use of thermistors in an underwater and high ambient pressure environment has made them ideal for diver thermal monitoring and they are probably the most commonly used temperature sensors for this purpose.

2. Thermistors are semiconductors where the resistance of the semiconductor decreases with increasing temperature; this is the converse of metallic conductors where the resistance increases with increasing temperature. The relationship between the temperature and resistance of the thermistor varies between thermistor types and within the same type of thermistor. However, thermistors are available commercially with matching temperature-to-resistance characteristics and a specified tolerance for interchangeability. Often the smaller the interchangeability tolerance the more expensive the thermistors.

3. The relationship between the temperature of a thermistor and its resistance is alinear; this is shown in the stated resistance/temperature data for the YSI 400 (Yellow Springs Instrument) series thermistors (Reference 1), Table 1, Graph 1. YSI 400 series thermistors are commonly used for thermal monitoring of divers and they will be used for examples throughout this text.

4. For practical thermal monitoring the resistance of the thermistor has to be measured by such means that the temperature can be determined. Many methods have been devised for this although traditionally Wheatstone bridge and amplifier circuits have been used. These are relatively easy to construct and they give a voltage output which

is approximately proportional to the temperature.

5. The bridge Circuit shown in Figure 1, designed for YSI 400 thermistors, was used in some early thermal monitoring studies at ARE. The output from the circuit over the temperature range of 0 to 50 °C was unsuitable for accurate monitoring with a deviation from the stated temperature as shown in Graph 2. It was considered that the temperature range of 0 to 50 °C was the most suited to diver monitoring. Alternative bridge and amplifier circuits may be produced which increase the linearity of the output.

6. With the increasing use of microcomputers for data acquisition and processing it was considered that a more versatile and accurate technique could be developed using these systems.

RESISTANCE/TEMPERATURE RELATIONSHIP

7. A microcomputer system would allow the relationship between the resistance and temperature of a thermistor to be incorporated in software as opposed to the conventional electronic circuits mentioned above. A general algorithm for the resistance/temperature relationship of thermistors had to be produced.

8. The resistance/temperature relationship for thermistors approximates to:

$$\text{Ln } R \ \alpha \ T$$

R = resistance (ohms)
T = temperature (Kelvin)

This relationship can be exploited in several ways, as shown below.

Linear regression

9. The relationship can be expressed in the form:

$$\text{Ln } R = \frac{\beta}{T} + C \qquad (1)$$

β and C = constants

10. A least-squares linear regression analysis of the resistance and temperature values for the YSI 400 thermistors was undertaken (Graph 3). The slope (Graph 3) is considered to be the 'material constant' for the thermistors which defines the sensitivity of the resistance with temperature. This equation was applied to the YSI 400 data, resulting in a deviation from the stated temperature as shown in Graph 4.

11. It can be seen from Graph 4 that the linear regression is able to derive the temperature from the resistance to an accuracy of 0.2 °C at the limits of the range, and with greater accuracy at other points. This may not be sufficiently accurate for some applications such as monitoring of core temperature.

12. The technique requires also many data points to undertake the regression analysis. A large number of resistance/temperature points are not always readily available for all thermistors, and having to employ a large number of data points does not

simplify the analysis technique.

Beta theory

13. A more practical method of employing equation (1) was to combine it with a second identical equation at a defined reference temperature and resistance:

$$\text{Ln } R_{ref} = \frac{\beta}{T_{ref}} + C \qquad (2)$$

T_{ref} = reference temperature (typically 25 °C)
R_{ref} = resistance at T_{ref}

14. Subtracting equation (2) from equation (1) eliminated the constant C and, after rearrangement, gave:

$$R = R_{ref} \bullet e^{\left[\frac{\beta}{T} - \frac{\beta}{T_{ref}}\right]} \qquad (3)$$

15. This is known as the Beta formula which is commonly presented by thermistor manufacturers and distributors as the equation for the thermistor material and its associated resistance to temperature relationship. The equation can be rearranged to express β (material constant) in terms of the temperature and resistance values:

$$\beta = \frac{T \bullet T_{ref}}{(T_{ref} - T)} \bullet \text{Ln} \left[\frac{R}{R_{ref}}\right] \qquad (4)$$

16. This enables β (material constant) to be determined from any 2 known temperature and resistance values. The Beta formula can also be rearranged to resolve the temperature, T:

$$T = \left[\left[\frac{1}{\beta}\right] \bullet \text{Ln} \left[\frac{R}{R_{ref}}\right] + \frac{1}{T_{ref}}\right]^{-1} \qquad (5)$$

17. Applying the material constant β, together with the known reference temperature and resistance to equation (5), the temperature at any other thermistor resistance can be interpolated. With a reference temperature of 25 °C and a second known temperature of 20 °C the material constant for the YSI 400 thermistors was found to have a value of 3893. This was then applied to the YSI 400 resistance data and the full range of temperatures calculated. These calculated temperatures deviated from the stated temperature shown in Graph 5.

18. The shape of the Beta formula deviation curve (Graph 5) is similar to the curve obtained by linear regression (Graph 4). The practical advantage of using the Beta formula is that the algorithm may be determined from only 2 known temperature and resistance values. Unfortunately, as shown in Graph 5, the algorithm is only accurate for small temperature ranges of the order of 15 °C. The range at which the algorithm

is accurate can be determined by the reference temperatures used. Several algorithms could cover the full range of temperatures required but would be awkward in use and may not give a satisfactory accuracy over the full range.

Steinhart-Hart equation

19. Many algorithms are derived empirically from polynomial regression of a data curve. Considering the fundamental relationship between the resistance and temperature of a thermistor, a polynomial of the following form could provide an empirical solution:

$$\frac{1}{T} = AO + A1(Ln\ R) + A2(Ln\ R)^2 + A3(Ln\ R)^3 + \ldots\ldots\ldots\ldots AN(Ln\ R)^N$$

20. A literature review showed that in 1968 Steinhart and Hart (Reference 2) investigated thermistor calibrations for the oceanographic temperature range -2 to +30 °C and suggested the use of the following equation:

$$\frac{1}{T} = A + B(Ln\ R) + C(Ln\ R)^3 \qquad (6)$$

T = temperature (Kelvin)
R = resistance (ohms)
A, B and C are constants

21. This equation is of the form outlined above. They reported that the equation would represent the relationship between temperature and resistance to an accuracy of 0.01 °C. If the $(Ln\ R)^2$ term is included then greater accuracy may be obtained.

22. In order to use the equation the constants A, B and C need to be determined. This requires 3 known values of temperature and resistance, and the solution of the resulting 3 simultaneous equations. A computer program using the equation in the form:

$$T = \frac{1}{A+B(Ln\ R)+C(Ln\ R)^3} - 273.15 \qquad (7)$$

T = temperature (Celsius)

was developed to calculate the constants from the solved equations (Annex). The constants determined for the YSI 400 thermistors were:

A = 1.46964928 E-3
B = 2.37894083 E-4
C = 1.03871858 E-7

23. The Steinhart-Hart equation was applied to the YSI 400 thermistor data using the constants shown above. All the interpolated temperatures were within 0.01 °C of the stated temperature. The deviation of the interpolated temperatures from the stated temperature is shown in Graph 6.

24. The Steinhart-Hart equation is a comparatively simple algorithm which can be

determined from only 3 resistance and temperature values; these values may be supplied by the manufacturer or determined experimentally. Although the algorithm has only been demonstrated using the YSI 400 thermistor, Steinhart and Hart (Reference 2) showed that it can be applied to any thermistor.

25. A comparison of the performance of the techniques described for representing the relationship between the resistance and temperature of a YSI 400 thermistor is shown in Table 2. The Steinhart-Hart equation was the only method to accurately describe the relationship over the range of the temperature 0-50 °C. This algorithm was incorporated in the software for the development of the microcomputer thermal monitoring system.

THE HARDWARE SYSTEM

26. Having identified a suitable algorithm for expressing the relationship between the temperature and resistance, it had to be incorporated into hardware to produce a practical thermal monitoring system. Most microcomputer systems are able to acquire and record data using analogue to digital (A/D) converters; these accept a voltage from a sensor system and convert it into a digital code for use by the computer.

27. Thermistors respond to temperature changes with a change in resistance; in order to determine the temperature the resistance needs to be monitored. Considering ohms law (represented as equation (8)):

$$V = I \bullet R \tag{8}$$

Y = voltage (volts)
I = current (amps)
R = resistance (ohms)

if a known constant current (I) is supplied to a thermistor then the voltage across the thermistor will be directly proportional to its resistance. The voltage across the thermistor can then be monitored by a microcomputer with an associated A/D converter; this is equivalent to directly monitoring the resistance.

28. Unfortunately, when a current is applied to a thermistor it may heat up. Each type of thermistor has a power limit before it will undergo self-heating. When the self-heat power limit is exceeded the thermal dissipation constant indicates the amount of self-heating that will occur. For a thermistor to be used at its most accurate the current supplied must be less than the limit for self-heating.

29. For the YSI 400 thermistors the power before self-heat is 0.1 mW with a dissipation constant (in still air of 6 mW/°C, i.e., for each 6 mW supplied the thermistor will self-heat by 1 °C. Using the Power Law (represented as equation (9)) the maximum current before self-heat can be determined:

$$P = I^2 \bullet R \tag{9}$$

P = power (watts)

30. At a resistance of 7356 ohms, equivalent to 0 °C with the YSI 400 thermistor (worst case for self-heating in the range 0-50 °C), the maximum current before self-

heat was calculated to be 0-12 mA. Constant current sources of 0.1 mA were constructed; the current was within the self-heat limit and from ohms law gave a voltage of 1.0 mV for each 10 ohms resistance. In a diving situation the thermistor is likely to be immersed either in water or in gas with a density greater than air at 1 bar; these conditions would reduce the dissipation constant, i.e., increase the heat transfer away from the thermistor, decreasing any potential error from this effect.

31. The constant current supplies were connected to the thermistors and to a BBC microcomputer via a 0-1 V 16 bit A/D converter; the 16 bit A/D converter gave a resolution equivalent to 0.3 ohm. The software used on the BBC microcomputer was programmed with the Steinhart-Hart algorithm to convert the acquired voltage (equivalent to resistance) to temperature. The complete monitoring system is shown diagrammatically in Figure 2.

32. The main Sources of error with the system are the interchangeability of the YSI 400 thermistors and the line resistances. YSI 400 thermistors are only interchangeable to within 0.1 °C (Reference 1). Accordingly, although the system as described has the potential for accuracies in the order of 0.01 °C, it is only as accurate as the accuracy with which the resistance-to-temperature relationship is known: this is known as the interchangeability tolerance of the thermistors. Additional line resistances also have to be considered; at 53 a line resistance of 3 ohms equates to a temperature error of 0.1 °C. Line resistances are a source of error for all thermistor monitoring systems.

33. The system has been demonstrated here using YSI 400 thermistors; with different constant current supplies and the correct constants for the Steinhart-Hart equation it has been shown to work with a range of thermistors.

FURTHER DEVELOPMENTS

Increasing accuracy and versatility

34. The major source of error in the system described is the interchangeability of the thermistors. Thermistors with small interchangeability tolerances can be extremely expensive; the system could be configured to use non-interchangeable thermistors.

35. The Steinhart-Hart equation will accurately represent the relationship between resistance and temperature for any thermistor. If the constants for the given thermistor are known then the thermistor could be used to the accuracy of the Steinhart-Hart equation (0.01 °C or greater). With the computer programme at the Annex, then providing 3 values of resistance and temperature are accurately known, the constants can readily be determined. The values could be either provided by the manufacturer or determined by the monitoring system using conventional calibration procedures. If the microcomputer monitoring system is used it would be able to generate the constants and feed them directly into the monitoring software. In addition, all line resistance errors would be overruled by being included as part of the individual thermistor's response.

36. Using the monitoring system in this way would allow low-cost thermistors to be used to an accuracy of 0.01 °C or better.

Dedicated microprocessor

37. A further development being considered is to replace the microcomputer with a dedicated microprocessor and preprogrammed ROM (read only memory). The ROM would be programmed with the algorithm and Steinhart-Hart constants. The computed temperature could then be output through a digital to analogue (D/A) converter for display or recording. This would allow the system to be physically reduced in size and used with conventional data recording and presentation equipment.

SUMMARY

38. The Steinhart-Hart equation has been shown to be the most suitable algorithm to represent the relationship between the resistance and temperature of a thermistor. From 3 known resistance and temperature values the constants for the equation can be determined and the temperatures interpolated to an accuracy of 0.01 °C.

39. Using a constant current supply, with the power less than the self-heat limit of the thermistor, the voltage across the thermistor, and hence its resistance, may be monitored by a microcomputer data acquisition system. The temperature may then be computed using the Steinhart-Hart equation, the accuracy of the temperature being dependent only on the accuracy to which the resistance-to-temperature characteristics of the thermistor are known.

40. A method by which the monitoring system could be used to identify the resistance-to-temperature relationship of a given thermistor and associated leads has been presented. This would allow line errors to be eliminated and the use of low-cost non-interchangeable thermistors to an accuracy of 0.01 °C.

REFERENCES

1. Instructions for YSI Series 400 temperature probes. Scientific Division, Yellow Springs Instrument Co Inc, Yellow Springs, Ohio 45387.

2. Steinhart J S and Hart S R. Calibration curves for thermistors. Deep Sea Research, 1968, 15, 497-503.

ANNEX

COMPUTER PROGRAM TO DERIVE CONSTANTS FOR STEINHART-HART EQUATION.

```
10 REM Calculates Constants A, B, & C for a given thermistor.
20 REM Program written by Gavin Anthony - April 1988
30 REM
40 INPUT' "THERMISTOR TYPES" T$
50 INPUT' " TEMPERATURE 1, RESISTANCE 1 - " T1,R1
60 INPUT' " TEMPERATURE 2, RESISTANCE 2 - " T2,R2
70 INPUT' " TEMPERATURE 3, RESISTANCE 3 - " T3,R3
80 REM
90 R1=LN(R1)
100 R2=LN(R2)
110 R3=LN(R3)
120 REM
130 T1=T1+273.15
140 T2=T2+273.15
150 T3=T3+273.15
160 REM
170 F1=1/(T1*(R1-R3))
180 F2=1/(T3*(R1-R3))
190 F3=1/(T1*(R1-R2))
200 F4=1/(T2*(R1-R2))
210 F5=(R1^3-R3^3)/(R1-R3)
220 F6=(R1^3-R2^3)/(R1-R2)
230 REM
240 C=(F1-F2-F3+F4)*(1/(F5-F6))
250 REM
260 F11=1/(T1*(R1^3-R3^3))
270 F12=1/(T3*(R1^3-R3^3))
280 F13=1/(T1*(R1^3-R2^3))
290 F14=1/(T2*(R1^3-R2^3))
300 F15=(R1-R3)/(R1^3-R3^3)
310 F16=(R1-R2)/(R1^3-R2^3)
320 REM
330 B=(F11-F12-F13^F14)*1/(F15-F16)
340 REM
350 A1=1/T1-B*R1-C*R1^3
360 A2=1/T2-B*R2-C*R2^3
370 A3=1/T3-B*R3-C*R3^3
380 REM
390 A=(A1+A2+A3)/3
400 REM
410 PRINT' "THERMISTOR - "; T$
420 PRINT' "A = "; A
430 PRINT' "B = "; B
440 PRINT' "C = "; C
450 END
```

Table 1

Resistance-to-temperature characteristics for YSI 400 thermistors

Resistance (ohms)	YSI stated temperature (Celsius)
7356.0	0.0
6991.0	1.0
6646.0	2.0
6320.0	3.0
6012.0	4.0
5721.0	5.0
5446.0	6.0
5185.0	7.0
4939.0	8.0
4705.0	9.0
4484.0	10.0
4275.0	11.0
4076.0	12.0
3888.0	13.0
3710.0	14.0
3540.0	15.0
3380.0	16.0
3227.0	17.0
3083.0	18.0
2945.0	19.0
2815.0	20.0
2691.0	21.0
2573.0	22.0
2461.0	23.0
2354.0	24.0
2253.0	25.0
2157.0	26.0
2065.0	27.0
1978.0	28.0
1894.0	29.0
1815.0	30.0

Resistance (ohms)	YSI stated temperature (Celsius)
1740.0	31.0
1668.0	32.0
1599.0	33.0
1534.0	34.0
1472.0	35.0
1412.0	36.0
1355.0	37.0
1301.o	38.0
1249.0	39.0
1200.0	40.0
1153.0	41.0
1108.0	42.0
1065.0	43.0
1023.0	44.0
984.1	45.0
946.5	46.0
910.4	47.0
876.0	48.0
843.0	49.0
811.5	50.0

Table 2
Comparison of techniques for representing the resistance/temperature of YSI 400 thermistors

YSI 400 stated Temperature (Celsius)	Wheatstone Bridge		Linear regression		Beta formula		Steinhart-Hart equation	
	T	D	T	D	T	D	T	D
0.00	0.61	0.61	0.15	0.15	0.23	0.23	0.00	0.00
1.00	1.44	0.44	1.13	0.13	1.21	0.21	1.00	0.00
2.00	2.30	0.30	2.12	0.12	2.19	0.19	2.00	0.00
3.00	3.16	0.16	3.10	0.10	3.17	0.17	3.00	0.00
4.00	4.05	0.05	4.08	0.08	4.16	0.16	4.00	0.00
5.00	4.95	-0.05	5.06	0.06	5.14	0.14	5.00	0.00
6.00	5.87	-0.13	6.05	0.05	6.12	0.12	6.00	0.00
7.00	6.80	-0.20	7.03	0.03	7.11	0.11	7.00	0.00
8.00	7.73	-0.27	8.02	0.02	8.09	0.09	8.00	0.00
9.00	8.70	-0.30	9.01	0.01	9.08	0.08	9.00	0.00
10.00	9.66	-0.34	9.99	-0.01	10.07	0.07	10.00	0.00
11.00	10.64	-0.36	10.98	-0.02	11.06	0.06	11.00	0.00
12.00	11.64	-0.36	11.97	-0.03	12.05	0.05	12.00	0.00
13.00	12.63	-0.37	12.96	-0.04	13.04	0.04	13.00	0 00
14.00	13.63	-0.37	13.95	-0.05	14.03	0.03	14.00	0 00
15.00	14.66	-0.34	14.95	-0.05	15.03	0.03	15.00	0.00
16.00	15.68	-0.32	15.94	0.06	16.02	0.02	16.00	0.00
17.00	16.70	-0.30	16.93	-0.07	17.02	0.02	17.00	0.00
18.00	17.73	-0.27	17.92	-0.08	18.01	0.01	18.00	0.00
19.00	18.77	-0.23	18.92	-0.08	19.01	0.01	19.00	0.00
20.00	19.80	-0.20	19.92	-0.08	20.00	0.00	20.00	0.00
21.00	20.83	-0.17	20.91	-0.09	21.00	0.00	21.00	0.00
22.00	21.87	-0.13	21.91	-0.09	22.00	0.00	22.00	0.00
23.00	22.91	-0.09	22.91	-0.09	23.00	0.00	23.00	0.00
24.00	23.95	-0.05	23.92	-0.08	24.00	0.00	24.01	0.01
25.00	24.97	-0.03	24.91	-0.09	25.00	0.00	25.00	0.00
26.00	25.99	-0.01	25.91	-0.09	26.00	0.00	26.00	0.00
27.00	27.01	0.01	26.91	-0.09	27.00	0.00	27.00	0.00
28.00	28.01	0.01	27.91	-0.09	28.00	0.00	28.00	0.00
29.00	29.02	0.02	28.93	-0.07	29.02	0.02	29.01	0.01
30.00	30.02	0.02	29.93	-0.07	30.02	0.02	30.00	0.00
31.00	31.00	0.00	30.93	-0.07	31.02	0.02	31.00	0.00
32.00	31.98	-0.02	31.93	-0.07	32.03	0.03	32.00	0.00
33.00	32.95	-0.05	32.95	-0.05	33.04	0.04	33.00	0.00
34.00	33.91	-0.09	33.95	-0.05	34.04	0.04	34.00	0.00

T = monitored temperature (Celsius)

D = deviation from stated temperature (Celsius)

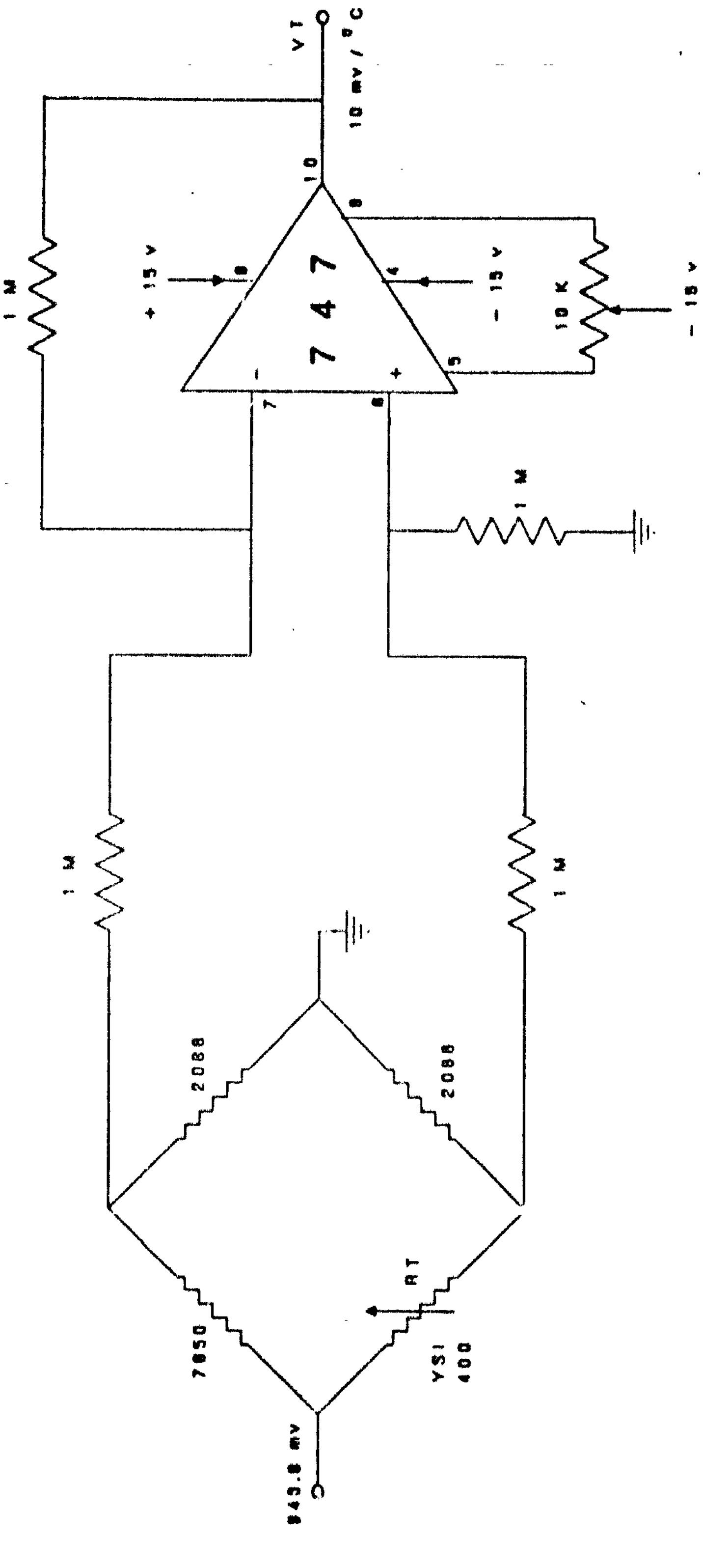
Table 2 (cont'd)

YSI 400 stated Temperature (Celsius)	Wheatstone Bridge		Linear regression		Beta formula		Steinhart-Hart equation	
	T	D	T	D	T	D	T	D
35.00	34.85	-0.15	34.95	-0.05	35.05	0.05	34.99	-0.01
36.00	35.79	-0.21	35.97	-0.03	36.07	0.07	36.00	0.00
37.00	36.71	-0.29	36.99	-0.01	37.08	0.08	37.01	0.01
38.00	37.62	-0.38	37.99	-0.01	38.09	0.09	38.00	0.00
39.00	38.52	-0.48	39.01	0.01	39.11	0.11	39.01	0.01
40.00	39.39	-0.61	40.02	0.02	40.11	0.11	40.00	0.00
41.00	40.26	-0.74	41.03	0.03	41.12	0.12	41.00	0.00
42.00	41.11	-0.89	42.04	0.04	42.14	0.14	41.99	-0.01
43.00	41.94	-1.06	43.05	0.05	43.15	0.15	42.99	-0.01
44.00	42.78	-1.22	44.09	0.09	44.19	0.19	44.01	0.01
45.00	43.56	-1.44	45.09	0.09	45.19	0.19	45.00	0.00
46.00	44.35	-1.65	46.11	0.11	46.21	0.21	46.00	0.00
47.00	45.12	-1.88	47.13	0.13	47.23	0.23	47.00	0.00
48.00	45.88	-2.12	48.15	0.15	48.25	0.25	48.00	0.00
49.00	46.62	-2.38	49.17	0.17	49.27	0.27	49.01	0.01
50.00	47.35	-2.65	50.19	0.19	50.29	0.29	50.00	0.00

T = monitored temperature (Celsius)

D = deviation from stated temperature (Celsius)

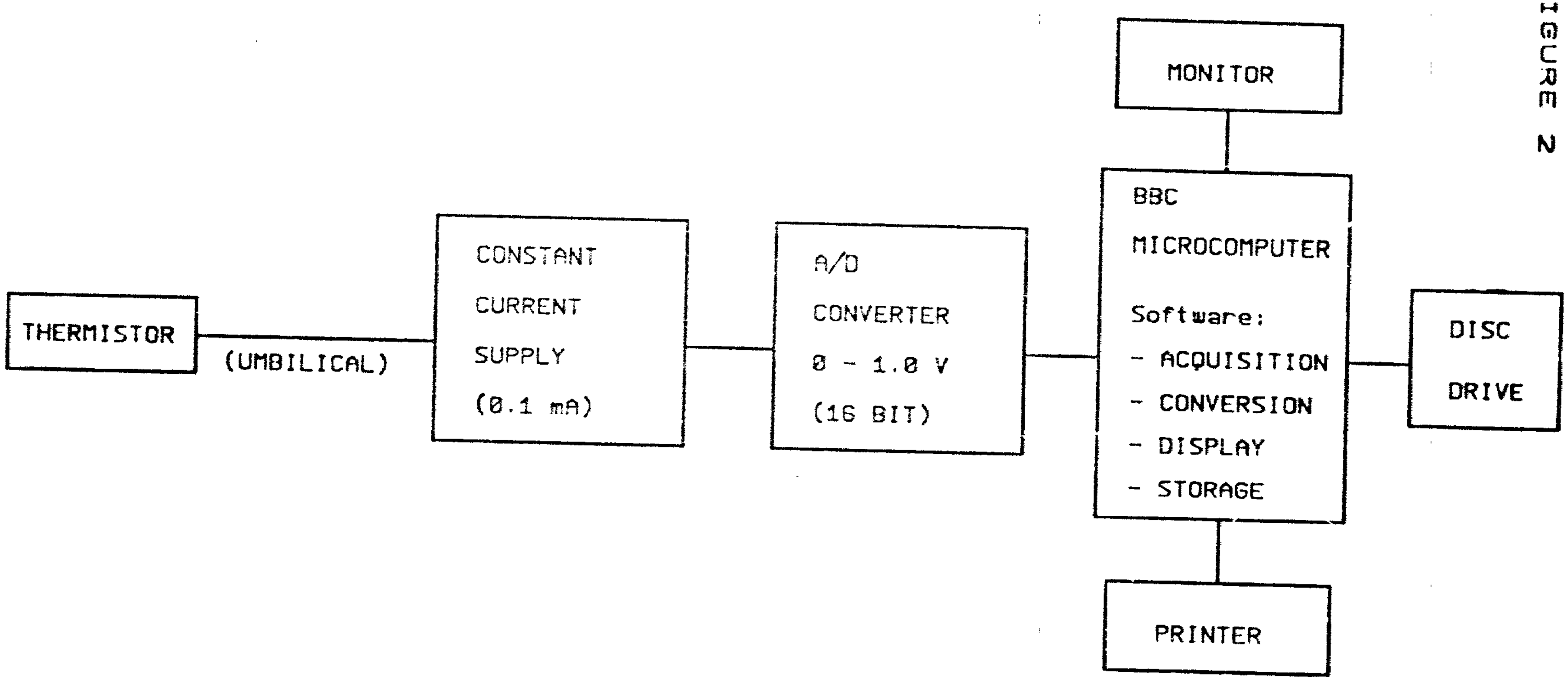
FIGURE 1

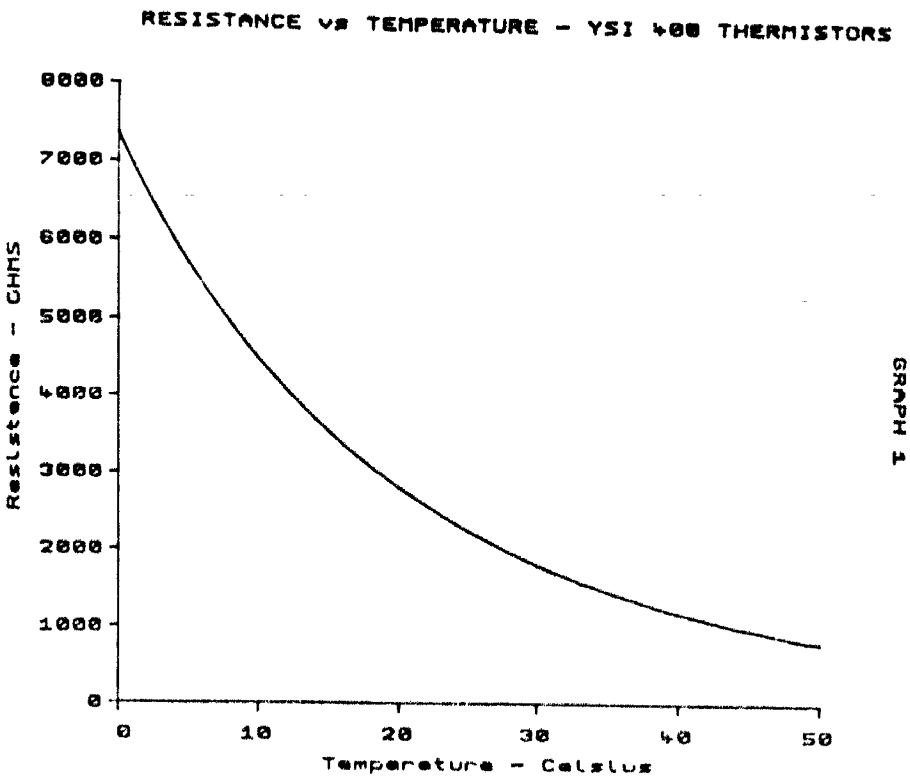


YSI 400 THERMISTOR - BRIDGE CIRCUIT - LINEAR AMPLIFIER

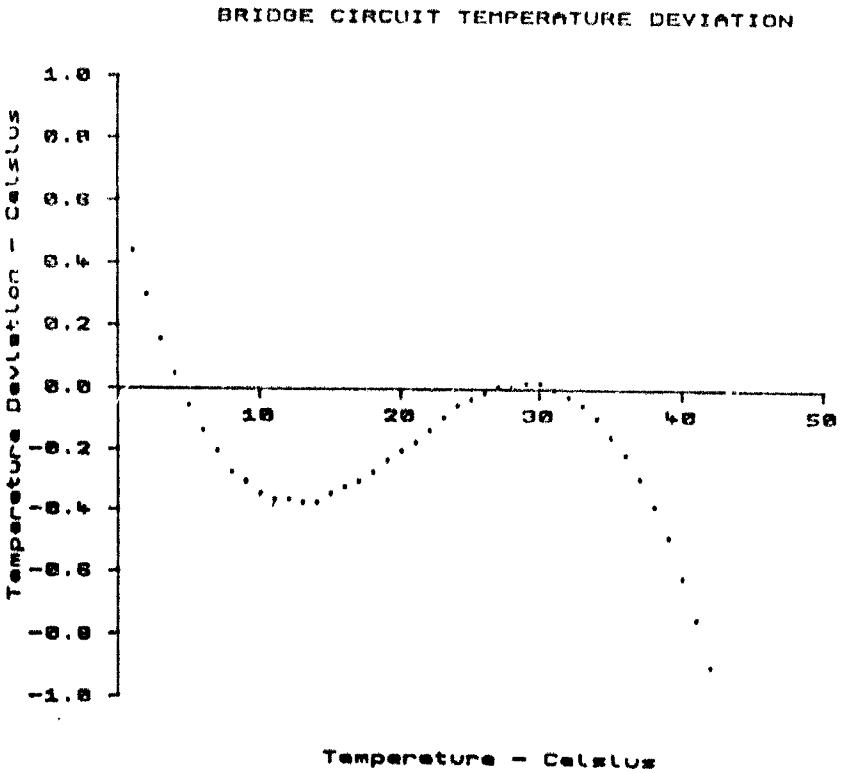
FIGURE 2

DIAGRAMMATIC REPRESENTATION OF MONITORING SYSTEM



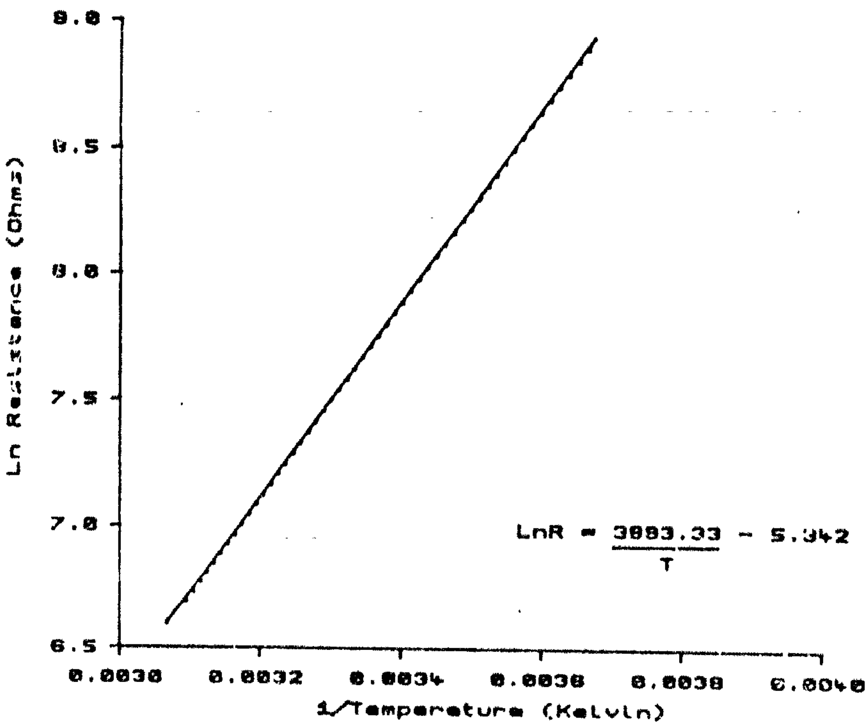


GRAPH 1



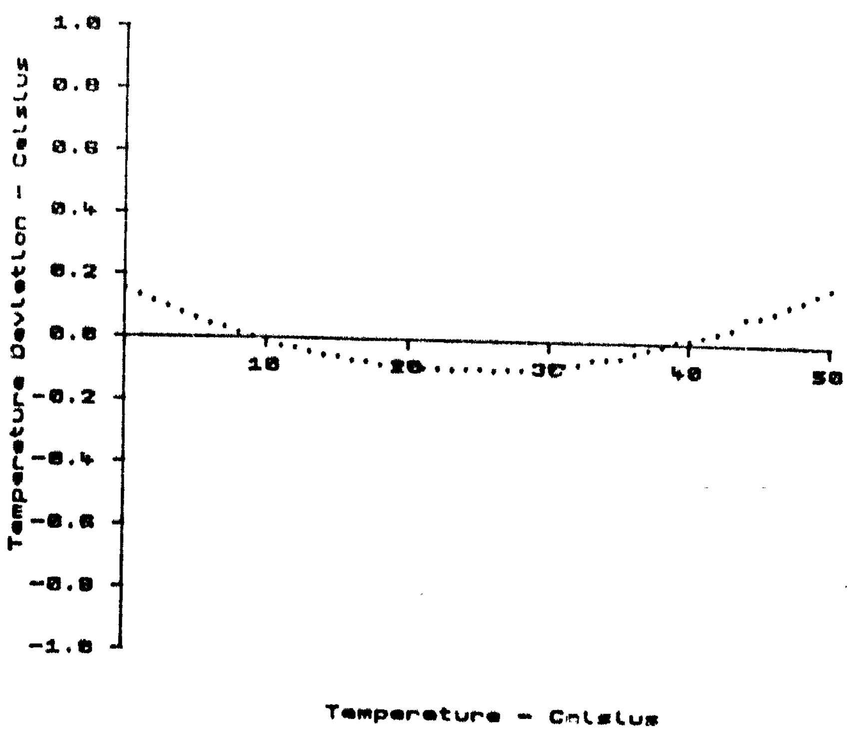
GRAPH 2

Ln RESISTANCE vs 1/TEMPERATURE - YSI 400



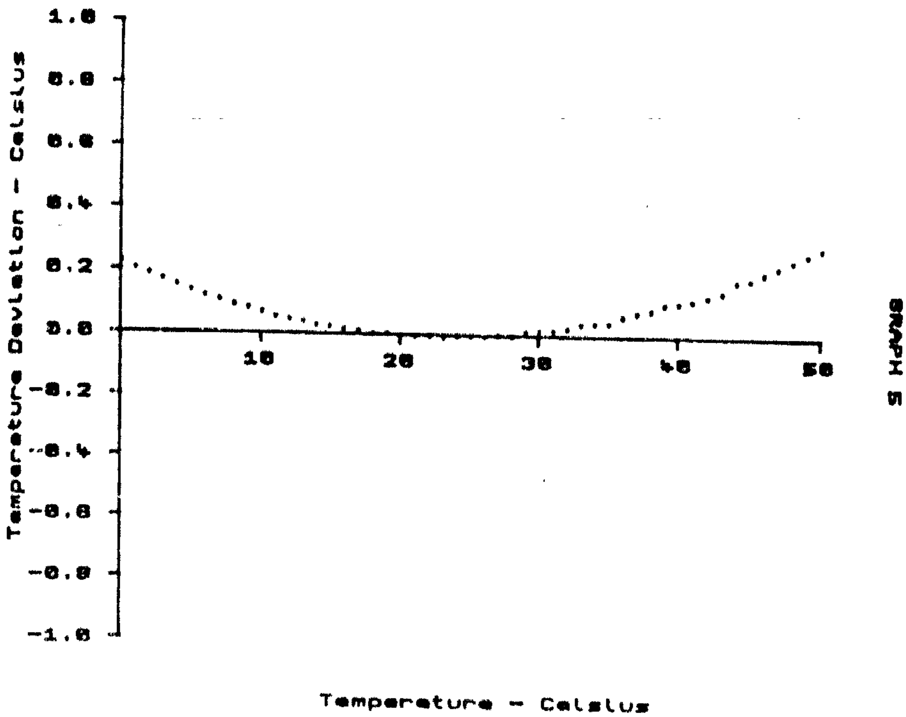
GRAPH 3

REGRESSION ANALYSIS TEMPERATURE DEVIATION

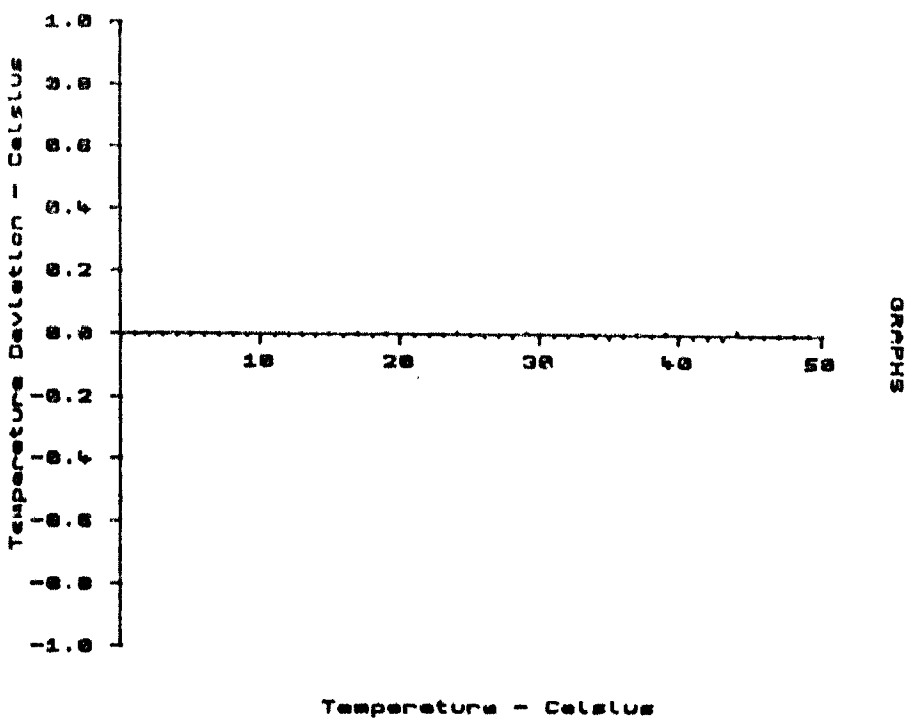


GRAPH 4

BETA FORMULA TEMPERATURE DEVIATION



STEINHART-HART TEMPERATURE DEVIATION



ON-LINE THERMAL BALANCE MEASUREMENTS TO DOCUMENT THERMAL STATUS DURING COLD WATER EXPOSURES

Karen D. Mittleman and Thomas J. Doubt
Diving Medicine Department
Naval Medical Research Institute, Bethesda, MD 20814-5055

ABSTRACT

A common method to document thermal stress is to expose subjects to a cold environment until their core temperature has dropped by a fixed amount. Heat flux measurements are often processed off-line and reveal variable amounts of heat lost by each subject for the same drop in core temperature or for the same time of exposure. This presentation discusses a method for on-line measurements of heat production and heat loss that provides near real-time assessment of thermal balance. Seven calibrated heat flux sensors are placed on the subject's body to obtain weighted regional measures of heat flux and skin temperature. The regional heat flux voltages are suitably amplified, input to a computer, and converted to heat fluxes. Total body heat loss is estimated from the sum of the regional fluxes. Oxygen consumption is measured using an automated metabolic measurement cart, with values entered manually into the computer to calculate metabolic heat production. Net thermal balance is the difference between heat production and heat loss. Heat fluxes, heat production, and thermal balance are stored in a data file and displayed on the computer monitor. The system initially used a multiplexer to sequentially sample the 7 heat flux sites for 5 sec each in order to compute a mean value for each site. Thermal balance was thus assessed in near real-time, with values computed every 2 min.

A study was conducted using this system to measure the thermal balance in 17 subjects during immersion in 25°C water. Subjects remained initially at rest until they had lost a net of 200 KJ of heat (thermal balance ≅ 200KJ), which required 19.9 ±2.1min. They then performed 15.2 ±0.9 min of leg exercise at 50 W (average oxygen consumption of 1.4 - 1.5 l/min) until net thermal balance returned to zero. The subsequent rest period lasted 24.9 ±3.2 min until net balance declined to ≅ 100 KJ, with 7.8±0.5 min of exercise at 50 W required to restore this loss. Overall, there were no significant changes in rectal temperature in spite of the large changes in thermal balance. The results of this study using an on-line system to compute thermal balance indicate that large amounts of heat can be lost, mainly from the periphery, without altering core temperature. The use of near real-time measurements of thermal balance offers a research tool that permits net heat loss or gain to be the independent variable.

INTRODUCTION

Cold water immersion imposes a challenge to the body's homeostatic mechanisms. In an attempt to maintain thermal balance, vasoconstriction and metabolic heat production (shivering thermogenesis) will be enhanced. If heat loss exceeds heat production, ultimately core temperature will be reduced to hypothermic levels.

Based on the physiological and performance effects of cold exposure, thermal limits for protective equipment have been recommended for the diving community (Webb et al., 1976). These include a maximum net body heat loss of 837 kJ (200 kcal) and a minimum core temperature of 36 °C, occurring concurrently. A common method to document thermal stress is to expose subjects to a cold environment until their core temperature has dropped by a fixed amount then relate this decrease to heat loss and heat production measurements during post-experiment analysis. However, studies have shown that there is a poor correlation between the fall in core temperature and the net heat lost from the body (Hayes, 1985).

In the present study a method for on-line measurements of heat production and heat loss, to provide near real-time assessment of thermal balance, was used in conjunction with the measurement of rectal temperature to study thermal stress of divers during head-out immersion in 25 °C water.

METHODS

Subjects: Seventeen males (age = 31.3 ± 4.8 yrs., A_D = 1.96 ± 0.11 m_2, %body fat = 17.7 ± 4.2) volunteered to participate having given their informed consent.

Measurements: Seven calibrated heat flux transducers (Thermonetics Corp.) were placed on the subject to obtain weighted regional values of heat flux. Placement of sensors and weighting factors were those described by Hardy and Dubois (1938). The 7 sites included forehead, abdomen, thigh, calf, foot, forearm and hand. A multiplexer was used to sequentially sample heat flux, with the average voltage recorded over 5 sec at each site providing a single input to an amplifier, with a corresponding output to the computer. A marker voltage was applied to the 8th channel of the multiplexer in order to delimit the 7 heat flux voltages in the computer buffer. This method of multiplexing required about 80 sec of real time. Therefore, the onset of heat flux sampling was begun every 2 min to coincide with onset of oxygen consumption measurements. Oxygen consumption and respiratory exchange ratio were measured each minute using an automated metabolic measurement cart. The minute value which corresponded to the period of sampling of heat flux voltages (i.e., every other minute) was entered manually into the computer for conversion to heat production. Total body heat loss was calculated from the sum of the 7 weighted heat flux measurements. Net thermal balance was calculated from the difference between heat production and heat loss. Regional and total heat flux, heat production, net thermal balance and cumulative thermal balance were stored in a data file and displayed on the computer monitor. Rectal temperature (T_{re}) was measured with a YSI 400 thermistor inserted 15 cm beyond the anal sphincter, and recorded manually every 5 minutes throughout the immersion.

Protocol: Subjects refrained from alcohol and caffeine consumption for 24 hours prior to their trial and consumed a light breakfast about 3 hours before immersion. Approximately 60-90 min prior to the immersion subjects consumed a volume of deionized water equal to 0.5% of body weight to ensure adequate hydration. After instrumentation was completed, subjects donned a lightweight running suit (80% nylon, 20% lycra) used to ensure the transducers remained attached to the subject during the immersion. The insulative value of the garment was minimal as determined from calibration of transducers with and without the material (average difference = 2.5%) using a Rapid-K thermal conductivity instrument (Dynatech). Following 10 min of resting data collection in room air (23.3 ± 2.5°C), subjects were assisted into the immersion tank and sat in a semi-recumbent position on an electrically-braked cycle ergometer (W.E. Collins, Inc.) modified for underwater exercise. The subject was immersed to the neck and water was continuously stirred and maintained at 25.1 ± 0.1 °C.

Immersion data collection was initiated one minute after the subject entered the water to allow time for stable positioning as well as to minimize the transient effects associated with onset of immersion into cold water. Subjects remained at rest until their cumulative net heat loss reached ≅ 200 kJ. Leg exercise at 50 W was then performed until net thermal balance returned to zero (gained ≅ 200 kJ). The subjects rested a second period until net thermal balance declined ≅ 100 kJ, followed by a second 50 W exercise period until this cumulative heat loss was replaced.

RESULTS

Resting Phase I -- During the initial resting phase cumulative net thermal balance reached -206.12 ± 2.17 kJ (Mean ± S.E.) in 19.9 ± 2.1 minutes. The average rate of heat production (8.02 ± 0.55 kJ min^{-1}) was less than the average rate of heat loss (16.71 ± 0.84 kJ min^{-1}). The change in T_{re} averaged -0.1 ± 0.0 °C, with 7 subjects exhibiting no decrease.

Exercise Phase I -- Exercise at 50 W increased heat production to 30.77 ± 1.01 kJ min^{-1} while heat loss was minimally altered (15.29 ± 0.78 kJ min^{-1}). Thus a net gain in thermal balance of 214.29 ± 3.27 kJ occurred in 15.2 ± 0.9 min. T_{re} was reduced 0.1 ± 0.1 °C with 6 subjects showing no change or a slight increase.

Resting Phase II -- The second rest period required 27.4 ± 3.8 min to reach a cumulative net thermal balance of -96.07 ± 8.11 kJ. The rate of heat loss (13.51 ± 2.73 kJ min^{-1}) was somewhat lower than in previous phases, but still exceeded metabolic heat production (9.13 ± 0.86 kJ min^{-1}). Three subjects did not reach the requirement of 100 ± 10 kJ net body heat loss after 45 min of rest as they were able maintain a balance between their heat loss and heat production. A net decrease in T_{re} of 0.2 ± 0.1 °C was observed during this phase, although 8 subjects did not show a decline in core temperature.

Exercise Phase II -- In the final phase, 50 W exercise resulted in the replacement of 117.84 ± 4.06 kJ of net heat in 7.8 ± 0.5 minutes. The rate of heat production (31.18 ± 0.57 kJ min^{-1}) was similar to that observed during the first exercise phase, while the rate of heat loss (13.48 ± 0.83 kJ min^{-1}) was slightly reduced. The change in T_{re} averaged -0.1 ± 0.0 °C, with 7 subjects showing no change or a slight increase.

Comparison of Responses -- Variability in the responses can be seen in three subjects. Subject 2 (wt = 74.7 kg, body surface area =1.88 m^2, %body fat = 11.6%) and subject 12 (wt = 85.0 kg, body surface area = 1.99 m^2, %body fat = 15 .0%), with similar percentages of body fat, showed similar responses in cumulative net thermal balance (Fig. 1). T_{re} declined throughout the immersion by 0.7 °C in subject 2 (lower body surface area), while subject 12 showed no overall change in core temperature (Fig. 2). In contrast, subject 3 (wt = 82.5 kg, body surface area =1.94 m^2, %body fat = 22.5%), with a higher percent body fat but similar body surface area to subject 12, had a similar net reduction in T_{re} to that seen in subject 12 (Fig. 2). However subject 3 needed a 33% greater time period to reach the cumulative net heat loss goal during both resting phases (Fig. 1). These results demonstrate variability in the correlation between thermal balance and changes in T_{re}. Furthermore, the data indicate that percent body fat and body surface area may not be simple predictors of a reduction in core temperature.

DISCUSSION

An on-line system was used to assess thermal balance during rest and exercise in 25 °C water, thus enabling both core temperature and net body heat loss to be measured concurrently. Whereas the desired results were achieved, this system may be improved by replacing the multiplexer with parallel heat flux inputs, thus removing the time interval between samples to enable data to be recorded continuously. We also observed minimal heat flows from the hand and foot regions in a number of subjects which may be indicative of an enhanced peripheral vasoconstrictor response. The present weighting formula assigned 12% of the total heat flux to the hand and foot. In subjects with enhanced peripheral vasoconstriction this may bias estimates of total body heat loss. The use of different measurement sites or weighting coefficients may alter the thermal balance results and needs further investigation.

Although cumulative net heat loss and heat gain reached ≅ 200 kJ, changes in rectal temperature were minimal, which agrees with the earlier findings of Hayes (1985). This indicates a relatively large amount of heat may be lost mainly from the periphery, without altering rectal temperature, during the first 20 minutes of immersion in 25 °C water. The initially large contribution of peripheral heat loss was reduced as the immersion continued which is evidenced by both the decreased rate of heat loss and the increased time required for the second rest phase, although the cumulative net heat loss was one-half of that required for the first rest phase. It is of interest to note that the gain of net body heat was not altered as the initial exercise phase (to replace ≅ 200 kJ) was approximately twice as long as the final exercise phase in which ≅ 100 kJ were replaced.

Comparison of the correlation between net body heat loss and change in T_{re} shown in subjects 2, 3, and 12, suggests that monitoring both core temperature and thermal balance would provide a more definitive picture of the thermal stress divers are exposed to when immersed in cold water. The T_{re} responses of subjects 2 and 12, who are similar in percentages of body fat, indicates the problems with assuming a simplified relationship between rectal temperature decrease and body fat. The lag time observed for rectal temperature changes associated with environmental perturbations (Cranston et al., 1954; Cooper and Kenyon, 1957; Mittleman and Mekjavic, 1988) may limit its usefulness as a real-time measure of thermal stress, especially when transient conditions (e.g. rest and exercise) are present.

The use of on-line measurements of thermal balance also offers a research tool that permits net heat loss or gain to be the independent variable studied, which may be beneficial in assessing protective quality of clothing materials.

REFERENCES

Cranston, W. I., J. Gerbrandy, and E. S. Snell. Oral, rectal and oesophageal temperatures and some factors affecting them in man. J. Physiol. Lond. 126: 347-358, 1954.

Cooper, K. E., and J. R. Kenyon. A comparison of temperatures measured in the rectum, oesophagus, and on the surface of the aorta during hypothermia in man. Br. J. Surg. 44: 616-619,1957.

Hardy, J.D., and E.F. Dubois. The technique of measuring radiation and convection. J. Nutr. 15: 461-475, 1938.

Hayes, P. Slow body cooling in water--summary of findings from experimental and modelling work. In: Proceedings of the 32nd Undersea Medical Society Workshop (No. 68(WS-SC)), edited by P. Webb. Bethesda, MD: Undersea Medical Society, 1985, p. 59-64.

Mittleman, K. D., and I. B. Mekjavic. Effect of occluded venous return on core temperature during cold water immersion. J. Appl. Physiol. 65: 2709-2713, 1988.

Webb, P., E. L. Beckman, P. Sexton, and W. S. Vaughan. Proposed thermal limits for divers: a guide for designers of thermal protective equipment. Office of Naval Research Report (N00014- 72-C-0057), July, 1956.

Supported by NMRDC Work Unit MO099.01A. 1003

Figure 1: Profile of cumulative thermal balance during the time course of immersion in three subjects. Subjects 2 and 12 had similar thermal balance profiles and percentages of body fat. Subject 3, who had a higher percent body fat, required a longer time interval to reach the required net body heat loss during the two rest phases.

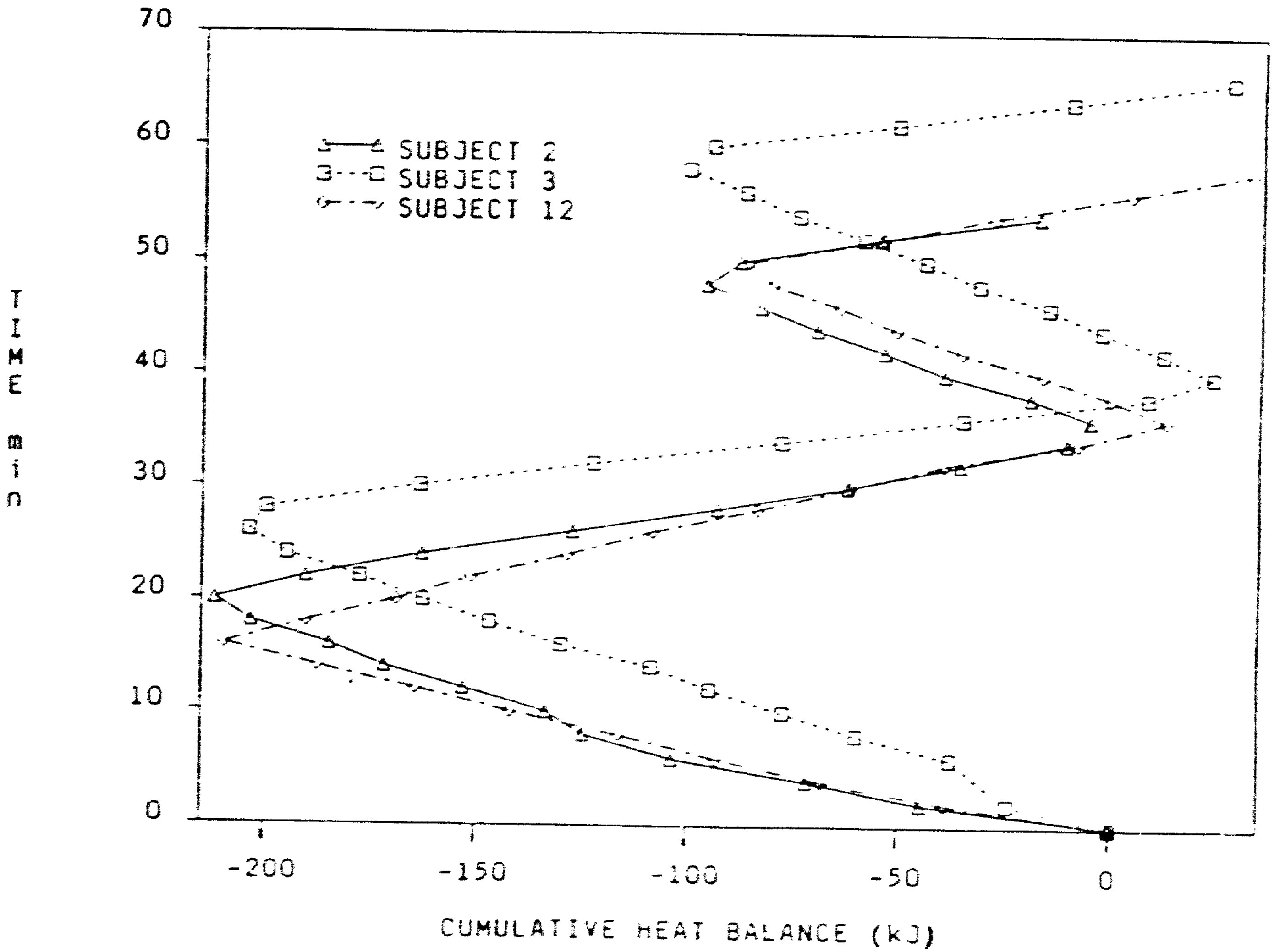
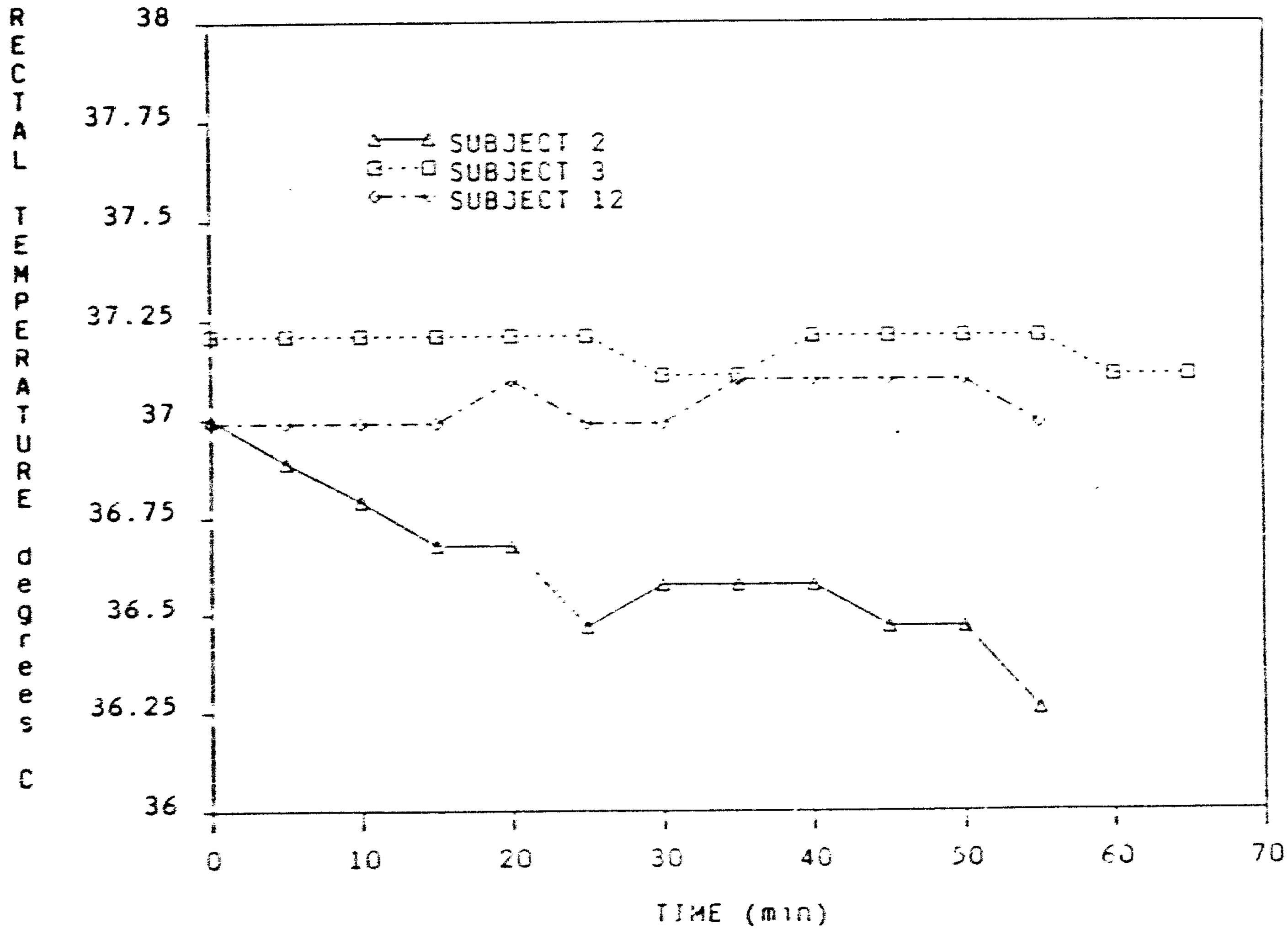


Figure 2: Rectal temperature responses for subjects 2, 3, and 12 are shown. Although subject 2 had a similar percent body fat and a reduced surface area when compared with subject 12, his T_{re} decreased by 0.7 °C whereas subject 12 showed no change in T_{re}. The T_{re} response was similar in subjects 12 and 3, who had similar surface areas even though subject 3 had 7.5% greater body fat.



ERRORS ASSOCIATED WITH THE USE OF HEAT FLOW TRANSDUCERS

M.B. Ducharme and J. Frim.
Department of Physiology, University of Toronto, Toronto, Canada, and
Defence and Civil Institute of Environmental Medicine, Downsview, Canada.

ABSTRACT

The direct assessment of heat flux from the body is a basic measurement in thermal physiology. Heat flux transducers (HFTs) are being used increasingly for that purpose under different environmental conditions. However, questions have been raised regarding the accuracy of the manufacturer's constant of calibration, and also about the effect of the thermal resistance of the device on the true thermal flux from the skin. Two different types of waterproofed HFTs were checked for their calibration using the Rapid-K heat flow meter conductivity instrument. The mean difference between the recalibration's and the manufacturer's constants is +20.2±7.1% (n=15) for Thermonetics Corporation's HFTs (San Diego, CA), and -0.7±4.8% (n=12) for Concept Engineering's HFTs (Old Saybrook, CT). The significant difference in the error of calibration between the two manufacturers (p<0.001) becomes an important criterion for the selection of HFTs. A model capable of simulating a large range of insulation values (variable-R model) was used in order to study the effect of the underlying tissue insulation on the relative error in thermal flux due to the thermal resistance of the HFTs. The data show that the deviation from the true value of thermal flux increases with the reciprocal of the underlying tissue insulation (r=0.99, p<0.001). The underestimation of the heat flux through the skin measured by a HFT is minimum when the device is used on vasoconstricted skin in cool subjects (3 to 13% error), but becomes important when used on warm vasodilated subjects (28 to 42% error), and even more important on metallic skin mannequins (>60% error). In order to optimize the accuracy of the heat flow measurements by heat flux transducers, it is important to recalibrate the HFTs from Thermonetics Corporation and to correct the heat flux values for the thermal resistance of the HFT when used on vasodilated tissue.

INTRODUCTION

The direct assessment of heat flux from the body is a basic measurement in thermal physiology. Heat flux transducers (HFTs) are being used increasingly for that purpose under different environmental conditions. However, questions have been raised regarding the accuracy of factory calibration, and also about the effect of the thermal resistance of the device on the true thermal flux from the skin. When HFTs are used on the skin, a significant local increase in resistance may occur and consequently a change in the skin temperature and heat flux. Therefore, the voltage obtained from the HFT is only representative of the heat flow from the tissue immediately below the disc, not that of the adjacent areas of exposed skin. Despite the suggestion by some authors that the error might be related to the vascular status of the underlying tissue, no further information is available in the literature. This study presents the recalibration of waterproofed HFTs from two companies and examines the importance of correcting the thermal flux values for the thermal resistance of HFT when used under certain conditions.

MATERIAL AND METHODS

Calibration of HFTs.

The HFTs from two manufacturers (model #HA 13-18-10-P(3) from Thermonetics Corporation, San Diego, CA, and model #FR-040-TH 44018 from Concept Engineering, Old Saybrook, CT) were checked for their calibration by using a calibrated Rapid-k instrument (Dynatech Corp., Cambridge, MA).

During the calibration, the transducers were exposed to heat flow ranging from 0 to $500 W \cdot m^{-2}$. Only values obtained during thermal equilibrium were used to calculate the calibration constant. The calculation of the calibration constant (in $W \cdot m^{-2} \cdot mV^{-1}$) was made by transforming the voltage output of the Rapid-k flow meter into a heat flow value H ($W \cdot m^{-2}$), using the calibration curve of the Rapid-k, and by using the voltage output of the HFT (V in mV) under investigation as follows:

$$\text{calibration constant} = \frac{\dot{H}_{rapid-k}}{V}$$

Effect of thermal resistance of HFTs: variable-R model.

A model capable of simulating a large range of insulation values was used to determine the relationship between the underlying tissue insulation and the relative error in thermal flux due to the thermal resistance of HFTs. The variable-R model consisted of an insulated water filled copper box (maintained at 37°C) immersed in a water bath maintained at 30°C. The thermal insulation of the model was varied by changing the material type and thickness on one wall to give insulation values ranging from $2.7 \cdot 10^{-4}$ to $4.4 \cdot 10^{-1}$ $°C \cdot m^2 \cdot W^{-1}$. For each setting, the thermal flux through the system was measured with 3 calibrated HFTs (either from Thermonetics or Concept Engineering) fixed on the external surface of the insulation with a thin surgical tape. The different surface temperatures were measured with calibrated fine gauge thermocouples. The thermal insulation of the model (R_m in $°C \cdot m^2 \cdot W^{-1}$) was calculated at thermal stability as follows:

$$R_m = \frac{T_c - T_s}{\dot{H}_{corr}}$$

where $\dot{H}_{corr}$ is the thermal flux ($W \cdot m_{-2}$) through the wall of the model, corrected for the insulating effect of HFT, T_c is the "core" temperature of the model (37°C) and T_s is the "skin" temperature of the model. $\dot{H}_{corr}$ was calculated by using Wissler and Ketch equation of correction (4) described as follows:

$$\dot{H}_{corr} = \frac{\dot{H}_{meas}}{1 - \dot{H}_{meas} \cdot R_T / (T_c - T_a)}$$

where $\dot{H}_{meas}$ is the measured heat flow value ($W \cdot m^{-2}$), R_T is the thermal insulation of the HFT ($°C \cdot m^2 \cdot W^{-1}$), and T_a is the ambient temperature surrounding the model (30°C).

Effect of thermal resistance of HFTs: immersion of human forearm in water.

The objective was to validate the data from the variable-R model with experimental data from immersions of human forearms at different water temperatures.

The experiments involved ten healthy males subjects between 18 and 30 years of age. Each experiment consisted of immersing the forearm in a water bath for 3 hours at a constant temperature ranging between 15 and 36°C. The water temperature were chosen to create a large range of tissue insulation. Each subject experienced two different temperatures chosen randomly and separated over a two week period. During the experiments, the subjects were in a sitting position and the ambient temperature of the room was 25±1°C. A total of 20 experiments were performed.

The muscle temperature at the axis of the first proximal third of the forearm (T_c) was continuously monitored during the immersion by using a fine calibrated multicouple probe implanted under local anaesthesia (2). The heat flux through the skin of the forearm was recorded with a recalibrated HFT from Thermonetics Corp., and the skin temperature was recorded with a fine calibrated 40 gauge thermocouple probe. Both the HFT and the thermocouple were fixed beside the site of the muscle temperature measurements with a thin surgical tape.

The $\dot{H}_{corr}$ values were calculated by using Wissler and Ketch's equation of correction previously described. All thermal flux and temperature values used were recorded during the last 15 minutes of each experiment, when thermal stability was achieved.

RESULTS

Calibration of HFTs.

The mean difference between our calibration constants and the manufacturer's constants was 20.2±7.1% (mean±S.D.; 8.3 to 32.2%) for 15 HFTs from Thermonetics Corp., and -0.7±4.8% (-8.6 to 8.8%) for 12 HFTs from Concept Engineering (4.0±2.5% in absolute value).

Effect of thermal resistance of HFT: variable-R model.

Eight experiments using 3 HFTs from Thermonetics Corp. and 7 experiments using 3 HFTs from Concept Eng. were performed using the variable-R model. Figure 1A presents the semi-log plot between the ratio $\dot{H}_{corr}/\dot{H}_{meas}$, which represents the relative error, and the ratio R_T/R_m for all the range of R_m studied (r^2=0.998; $p<0.001$). No significant difference ($p>0.05$) exists between the relationship determined for each type of HFTs. When only the physiological range for the ratio R_T/R_m is presented ($R_T/R_m<0.6$) the relationship between the ratio $\dot{H}_{corr}/\dot{H}_{meas}$ and the ratio R_T/R_m becomes linear (r^2=0.999; $p<0.001$; see Fig. 1B).

Effect of thermal resistance of HFTs: immersion of human forearm in water.

The values of $\dot{H}_{corr}$ were calculated by using the temperature and heat flux data for the last 15 minutes of a 3 hours immersion of the forearm in water at temperatures ranging between 15 and 36°C (n=20). The mean values of thermal flux corrected for the thermal resistance of the HFT ($\dot{H}_{corr}$) are 9.8±1.6% higher than $\dot{H}_{meas}$ for $T_w \leq 30$°C, and 25.3±7.0% higher than $\dot{H}_{meas}$ for T_w>30°C.

DISCUSSION

Calibration of HFTs.

The results indicate that the difference between the experimental calibration constants and the factory constants is 28 times larger for Thermonetics's HFTs (20.2%) than for Concept's HFTs (-0.7%). For each Thermonetics's HFT calibrated, the factory constant was overestimated, in contrast to the Concept's HFTs for which the factory constants were about equally over and underestimated.

It is recommended that in the case of the HFTs from Concept Engineering, the devices can be used without recalibration, since the difference between the manufacturer and the experimental calibration data is small (≈5%). However, potentially large errors in calculated heat flow may be present when HFTs from Thermonetics are not recalibrated.

Effect of thermal resistance of HFTs.

The study involving the variable-R model indicates clearly that a strong relationship exists between the underlying "tissue" insulation and the relative error in thermal flux due to the thermal resistance of HFT. The impact of that finding becomes particularly important when HFTs are used on high conductive materials such as on metallic skin mannequins (copper or aluminum). In that case, because the underlying material insulation value is low (R_T/R_m>1.5), the values of heat flux read by the HFTs may underestimate the true value of heat flux by more than 100% depending on the insulation of the mannequin skin.

From a physiological standpoint, the underestimation of heat flux through the skin measured by an HFT can be important when the device is used during vasodilation in warm subjects, as suggested by Gin et al. (3). In this case, the underestimation of the measured heat flux can range between 29 and 35% from the true value of heat flux (ratio R_T/T_m ranging between 0.45 and 0.6; ref 1), depending on the type of HFT used and the vasodilation status of the tissue. However, when HFTs are used on a vasoconstricted skin (ratio R_T/R_m ranging between 0.025 and 0.15; ref 1), the underestimation of the measured heat flux is much less serious, ranging between 3 and 13%. It is therefore less important to correct the heat flux values for the thermal resistance of the HFT when the device is used on vasoconstricted skin. In general, it is important to use Wissler and Ketch's equation (4) to correct the measured heat flux for the thermal resistance of the HFT when the device is used on vasodilated skin.

When the correction equation is used, the parameter R_T in the equation has the value of 0.0104°C·m^{-2}·W^{-1} for the Thermonetics's HFTs, and 0.0064°C·m^{-2}·W^{-1} for the Concept Engineering's HFTs. From those values, it becomes evident that the correction for the thermal resistance of the HFT is more important in the case of the Thermonetics's HFTs, since the thermal resistance of the device is 63% higher than the value for Concept's HFTs.

The data from the forearm immersions gave a practical example of the magnitude of error due to the thermal resistance of HFT that is involved when a recalibrated HFT is used to measure the thermal flux in water at different water temperature. The error due to the thermal resistance of HFT is only 9.8% when the tissues are in a vasoconstriction status ($T_w < 30°C$), but increases to 25.3% at water temperature of 36°C when the tissues are partially vasodilated. These data are in agreement with the results found with the variable-R model.

REFERENCES

1. Cannon, P., and W.R. Keatinge. J. Physiol. London 154: 329-344, 1980.
2. Ducharme, M.B., and J. Frim. J. Appl. Physiol. 65(5): 2337-2342, 1988.
3. Gin, A.R., M.G. Hayward and W.R. Keatinge. J. Appl. Physiol. 49(3): 533-535, 1980.
4. Wissler, E.H. and R.B. Ketch. Undersea Biomed. Res. 9(3): 213-231, 1982.

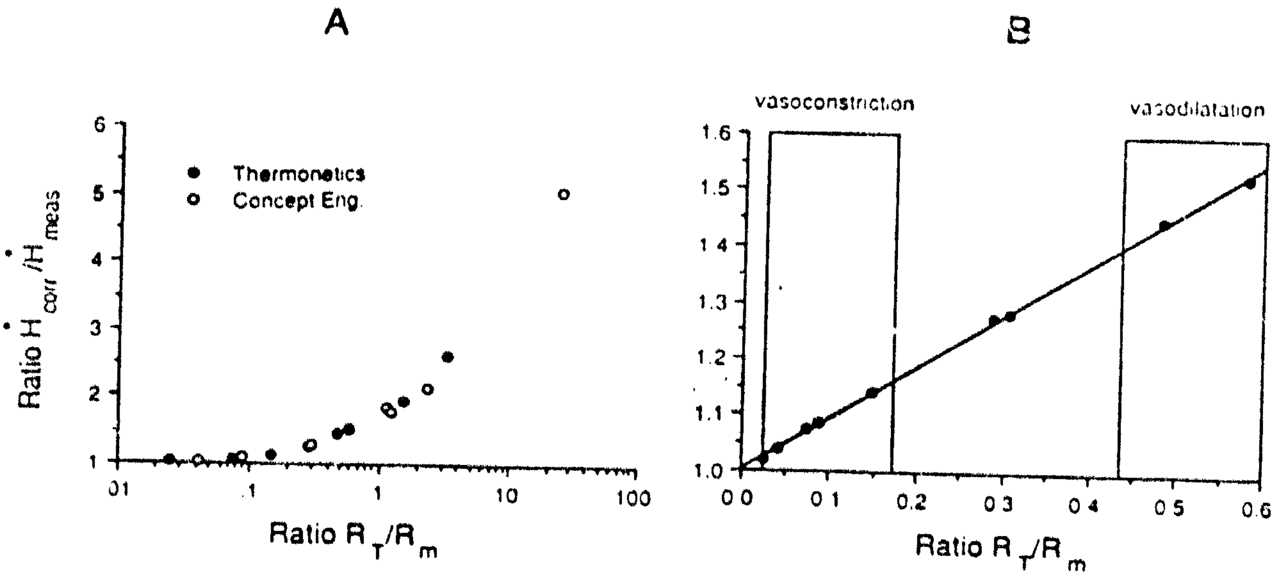


Figure 1: Relationship between the ratio $\dot{H}_{corr}/\dot{H}_{meas}$, which represents the relative error in the measured thermal flux due to the thermal resistance of HFTs, and the ratio R_T/R_m, for A) all the range of R_m studied, and B) the physiological range of R_T/R_m studied. The same relationship is valid for both types of HFTs.

Partially supported by the Department of National Defence of Canada. M.B. Ducharme is recipient of an Ontario Graduate Scholarship.

COLD WATER SWIMMING FLUME DESIGN AND OPERATION

James R. Braun and LCdr John A. Sterba
Navy Experimental Diving Unit
Panama City, Florida, 32407-5001

ABSTRACT

The Navy Experimental Diving Unit has designed, fabricated, and installed a Cold Water Swimming Flume which will provide increased cold water testing capabilities for existing and new diving systems in support of NAVSEA tasks. In order to meet existing requirements and to hold down development and construction costs, the Cold Swimming Flume was designed to use the existing NEDU Test Pool for its water source and cooling capabilities.

1. INTRODUCTION

The Navy Experimental Diving Unit was asked to determine if it was feasible to build a cold water swimming flume at the NEDU to provide increased cold water swimming capabilities. We surveyed the current technology and determined that an additional facility would be too costly and could not be designed and constructed soon enough to satisfy our needs. It was decided to modify the existing test pool and convert it into a cold water swimming flume.

2. DESIGN AND CONSTRUCTION

The flume was constructed to be modular so it could be installed into the test pool and be easily removed in the event it required modification or maintenance. The test pool measures 15' wide by 30' long and is 15' deep throughout. This allowed us to design the Flume in three sections, two for turning the water and one for supplying the system to move the water. The swimming area was designed to be 15' long by 7.5' wide with a depth of 15'.

The water is moved by two 6' diameter, three bladed propellers that are driven by two 15 HP Hydraulic Power Units. They are standard off-the-shelf Hydra-Mixers used in the waste treatment industry (Air-O-Lator Corporation, Kansas City, Missouri 64131) mounted one above the other and rotating approximately 60 RPM, a wall of water moves through the swimming area.

Flow measurements have been made at several hydraulic pressure settings (speeds) and the analysis of the data gathered indicates that there are limitations on the speed that the water can obtain. The upper propellers must be limited to a speed of 60 RPM or less to prevent excessive cavitation and "beating". Most of the flow is generated by the lower propeller, with the upper propeller used to fine tune the flow

The opinions or assertions contained in this article are the private views of the authors and are not to be construed as reflecting the view of the United States Department of the Navy or the Department of Defense.

pattern. With the propeller speed adjusted to the optimum setting, the flow pattern is constantly 1' away from the walls, bottom and surface. Flow is controlled within an accuracy of 0.1 Knots up to 1.5 Knots maximum flow for a large swimming area accommodating a small submersible and two free-swimming divers.

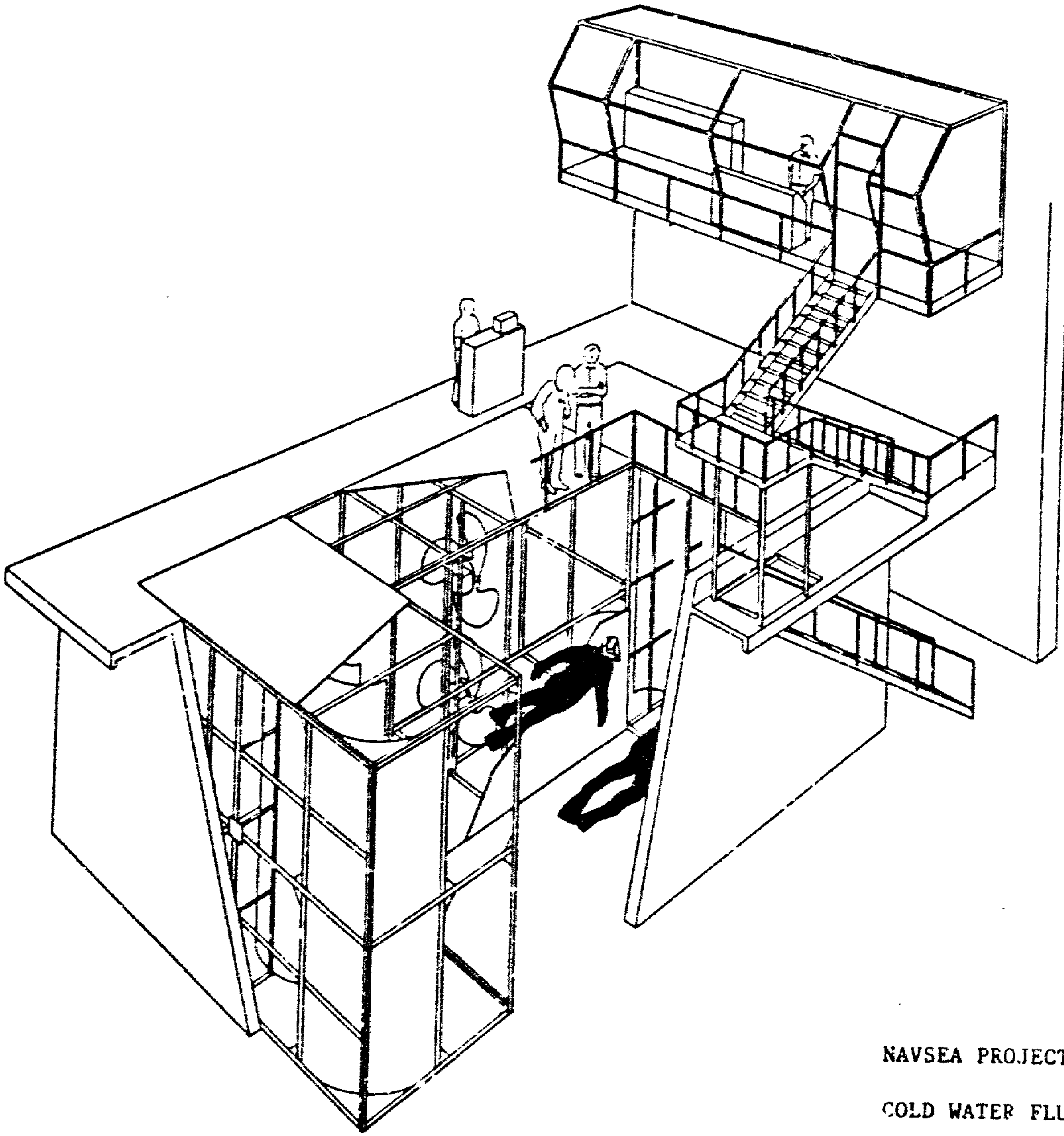
3. COLD WATER SYSTEM

Facilities for cooling the test pool existed prior to the decision to turn the test pool into a cold water swimming flume. However, to provide for water down to 28°F, an additional salt water compatible heat exchanger was added. A brine maker was installed and steel pipe was replaced with CPVC pipe because of he corrosive effects of salt water. In addition, the test pool was sandblasted and a special thick coating of polyurethane protection was applied to protect the test pool from the corrosive water.

Currently, it is planned to maintain a temperature of 33°F fresh water in the test pool. In the event that it becomes a requirement to lower the water temperature to below freezing, NEDU has the ability to do so without further modifications to the test pool.

4. SUMMARY

The utilization of a current NEDU asset (Test Pool) provided a cost effective approach to providing a swimming flume for cold water studies. The flume, which is removable, allows NEDU to test and evaluate diving equipment, in the free swimming configuration, with complete physiological monitoring near two diver-subjects.



NAVSEA PROJECT 88-18A

COLD WATER FLUME

APPENDIX

DIVER THERMAL PROTECTION WORKSHOP

January 31 - February 2, 1989.
Defence and Civil Institute of Environmental Medicine

PROGRAM

Tuesday, January 31, 1989

0900-0930 Registration and Coffee, DRF Facility

0930-1000 Welcome and Introduction to DCIEM, Dr. K.N.Ackles, Director, Biosciences Div.

Session 1: Diver Protection Today -- Chairman: LCdr Henry Mark, CF

1000-1020 *Current thermal protection for the Canadian Forces diver.* CPO J. DeJong, DCIEM, CAN.

1020-1100 *Equipment development for long endurance dives in cold water.* R. Porter, DGUW(N), UK and Maj. R. Clifford, RM, UK.

1100-1120 *Medical implications arising from long endurance dives in cold water.* Surg.Capt. R. Pearson, INM, UK.

1120-1130 *Demonstration* CWO Larry Wilson, USN EOD, USA.

1130-1230 LUNCH

1240-1300 *Thermal problems encountered with 75 msw diving.* Lt(N) S. McDougall, CF and LCdr J.S. Coggins, RN, UK

1300-1320 *Observations on flooded dry suit buoyancy characteristics.* S.M. Barsky and J.N. Heine, Viking America Inc., USA

1320-1400 *Where we are today, what we believe works best, and where we think we should be going and why.* R. Long, DUI, USA.

1400-1430 Summary Discussion

1430-1500 COFFEE

Session 2: Passive Thermal Protection -- Chairman: LCdr John Sterba, USN

1500-1520 *Thermotropic liquid crystals: A variable Clo material.* R.R. Biggers, NCSC, USA.

1520-1540 *Alternate dry suit inflation gas for improved thermal insulation.* R. Weinberg, NMRI, USA.

1540-1600 *Comparison of heliox and air as suit inflation gases.* T.T. Romet, DCIEM, CAN.

1630-1830 Meet and Greet (cash bar)

PRECEDING PAGE BLANK

Wednesday, February 1, 1989

Session 2 (continued): Passive Thermal Protection

0900-0920 *The potential of passive thermal protection in cold water dependent upon body composition and work level.* P.A. Hayes, National Hyperbaric Centre, UK.

0920-0940 *Liquid filled suit-inner suit concept: Passive thermal protection for the diver.* M.L. Nuckols, US Naval Academy, USA

0940-1000 *Undergarments: thermal conductivity (wet vs dry), compressibility and absorbancy.* J.A. Sterba, NEDU, USA.

1000-1020 *Thermal insulation in various dry and flooded drysuit/pile undergarment combinations.* T.T. Romet, DCIEM, CAN.

1020-1040 COFFEE

Session 3: Active Thermal Protection -- Chairman: T.C. Schmidt, Lockheed Corp. and LCdr J.A. Sterba, USN

1040-1100 *The physiological efficacy and energy efficiency of hot- water suit heating using thermoelectric heat pumping. Part A: Thermoelectrics.* T.C. Schmidt, Lockheed Advanced Marine Sys., USA.

1100-1120 *The physiological efficacy and energy efficiency of hot-water suit heating using thermoelectric heat pumping. Part B: Physiological.* T.C. Schmidt, Lockheed Advanced Marine Sys., USA.

1120-1140 *Current work on electrical heating for the diver.* A.J. Thomas, ARE(Alverstoke), UK.

1140-1240 LUNCH

1240-1300 *Passive and active thermal protection evaluation, at rest and free-swimming.* J.A.Sterba, NEDU, USA.

1300-1320 *Some results of closed-circuit UBA heating on CO_2 absorption.* T.C. Schmidt, Lockheed Advanced Marine Sys., USA.

1320-1340 *Potential of diver heating through catalytic combustion of alcohol.* P.A. Browne, AECL, CAN.

Session 4: Physiological Considerations -- Chairman: Dr. Robert Weinberg, NMRI.

1350-1410 *Review of pharmacological approaches to improved cold tolerance.* A.L. Vallerand, DCIEM, CAN.

1410-1430 *Substrate availability and temperature regulation during cold water immersion in humans.* L. Martineau and I. Jacobs, DCIEM, CAN.

1430-1500 COFFEE

1500-1520 *Use of carbohydrate or caffeine to promote performance during cold water exposures.* T.J. Doubt, J.W. Thorp, P.A. Deuster and S. Hsieh, NMRI, USA.

1520-1540 *Lipid metabolism in cold exposed humans.* A.L. Vallerand, DCIEM, CAN.

1540-1600 *Effects of changes in fluid and electrolyte on performance during cold water exposures.* T.J. Doubt, P.A. Deuster and D.J. Smith, NMRI, USA.

Thursday, February 2, 1989

0900-1000
Tour Experimental Diving Unit/DCIEM

1000-1030
COFFEE

Session 4 (continued): Physiological Considerations

1030-1050 *Evaluation of passive and electrically heated survival suits for use in "Lost Bell" at 450 meters.* E.H. Wissler, UofTexas/Austin, A. Pasche, B. Holand, SINTIF, G. Knudsen, NUTEC and P.A.Hayes, NHC.

1050-1110 *Prediction of thermoregulatory response for clothed immersion in cold water.* P. Tikuisis, DCIEM, CAN.

1110-1130 *Control of divers' thermal balance in deep operational diving.* G. Knudsen, A. Hope, NUTEC, A. Pasche, SINTIF, and E.H. Padbury, NUTEC, NOR.

1130-1230 LUNCH

Session 5: Measurement Techniques -- Chairman: Dr. Philip Hayes, National Hyperbaric Centre

1230-1250 *Diver monitoring systems, on-line and portable: thermal and metabolic measurements.* J.R. Braun and J.A. Sterba, NEDU, USA.

1250-1310 *Development of a microcomputer-based thermal monitoring system.* T.G. Anthony, ARE(Alverstoke), UK.

1310-1330 *On-line thermal balance measurements to document thermal status in near real-time during cold water exposures.* K. Mittleman and T.J. Doubt, NMRI, USA.

1330-1350 *Errors associated with the use of heat flow transducers.* M.B. Ducharme and J. Frim, DCIEM. CAN.

1350-1410 *Cold water swimming flume: Design and operation.* J.R. Braun and J.A. Sterba, NEDU, USA.

1415-1445 COFFEE

Session 6: Meeting Summary

1445-1615 *E.D. Thalmann, NMRI, USA.*

Discussion

DOCUMENT CONTROL DATA

(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)

1. ORIGINATOR (the name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Establishment sponsoring a contractor's report, or tasking agency, are entered in section 12)

DCIEM

2 DOCUMENT SECURITY CLASSIFICATION (overall security classification of the document including special warning terms if applicable)

Unclassified

3. DOCUMENT TITLE (the complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S,C,R or U) in parentheses after the title.)

Proceedings of the DCIEM Diver Thermal Protection Workshop, 31 Jan - 2 Feb 1989

4. DESCRIPTIVE NOTES (the category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)

Proceedings of Workshop

5. AUTHOR(S) (Last name, first name, middle initial. If military, show rank, e.g. Doe, Maj. John E.)

Editors:

Romet, Tiit T.
Sterba, John A.
Nishi, Ronald Y.

6. DOCUMENT DATE (month and year of publication of document)

7a. NO. OF PAGES (total containing information. Include Annexes, Appendices, etc.)

x+ 225

7b. NO. OF REFS (total cited in document)

8a. PROJECT OR GRANT NO. (if appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant)

8b. CONTRACT NO. (if appropriate, the applicable number under which the document was written)

9a. ORIGINATOR'S DOCUMENT NUMBER (the official document number by which the document is identified by the originating activity. This number must be unique to this document.)

DCIEM No. 92-10

9b. OTHER DOCUMENT NO.(S) (Any other numbers which may be assigned this document either by the originator or by the sponsor)

10. DOCUMENT AVAILABILITY (any limitations on further dissemination of the document, other than those imposed by security classification)

(X) Unlimited distribution
( ) Distribution limited to defence departments and defence contractors; further distribution only as approved
( ) Distribution limited to defence departments and Canadian defence contractors; further distribution only as approved
( ) Distribution limited to government departments and agencies; further distribution only as approved
( ) Distribution limited to defence departments; further distribution only as approved
( ) Other

11. ANNOUNCEMENT AVAILABILITY (any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (10). However, where further distribution (beyond the audience specified in 10) is possible, a wider announcement audience may be selected.)

12. SPONSORING ACTIVITY (the name of the department project office or laboratory sponsoring the research and development. Include the address.)

13. ABSTRACT (a brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both offical languages unless the text is bilingual).

The military diver performs a wide range of operational duties encompassing ship repair, search and salvage, mine countermeasures and other special operations. Diving can take place in diverse range of water temperatures, depths and durations. The diver is now exposed to deeper, and/or longer profiles under new scenarios and, as a result, thermal limits to performance have once again emerged as the prime limiting factor. Research is being carried out in all aspects of thermal protection. Passive thermal protection, whether wet or dry, is seeing the introduction of new materials and effective clothing ensembles. Active thermal protection is traditionally just the free flow of hot water into a diving suit but is now being approached by new and novel methodologies. It was, therefore, as a result of the renewed interest in diver thermal protection that the concept of this workshop was developed. It was organized under the auspices of the ABCA-10 (America, Britain, Canada and Australia) Information Exchange Program on Naval Diving and its purpose was to bring together representatives from all the components concerned with military diving; the operators who must dive in the various conditions and will know the shortcomings as well as the strengths of a protective ensemble; the manufacturers, who through their own research as well as feedback from the user must produce the protective ensembles; and the researchers, whether basic or applied who through their creativeness develop the concepts and physiological basis for thermal protection.

14. KEYWORDS, DESCRIPTORS or IDENTIFIERS (technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible, keywords should be selected from a published thesaurus. e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Diver

Thermal Protection

Diving Suits