References

[1]Beckman, E. L., "Thermal Protection During Immersion in Cold Water," AD601044, March 1964, Naval Medical Research Inst., Bethesda, Md.

[2]Tauber, J. F. and Rawlins, J. S., "Theoretical Thermal Requirements for the Mark II Diving System," AD694013, 1964, Naval Medical Research Inst., Bethesda, Md.

[3]Beckman, E. L., "Thermal Protective Suits for Underwater Swimmers," Rep. 8, 1967, Naval Medical Research Inst., Bethesda, Md.

[4]Bowen, H. M. and Pepler, R. D., "Studies of the Performance Capabilities of Divers: The Effects of Cold," SSD 67-399, March 1967, Dunlap and Associates, Darien, Conn.

[5]McQueen, J. D., "Effects of Cold on the Nervous System," *The Physiology of Induced Hypothermia*, edited by R. D. Dripps, NAS-NRC Publ. 451, 1956, NASA.

[6]Martorano, J. J., "Evaluation of Diver's Dress Suits in Maintaining Body Temperature in Cold Water," AD-265907, Oct. 1961, U.S. Naval Medical Field Research Lab., Camp Lejeune, N.C.

[7]Stolwijk, J. A. J. and Hardy, J. D., "Temperature Regulation in Man—a Theoretical Study," *Pfluger Archiv. Ges. Physiologie*, Vol. 291, Pt. 2, 1966, pp. 129–162.

[8]Stolwijk, J. A. J. and Cunningham, D. J., "Expansion of a Mathematical Model of Thermoregulation to Include High Metabolic Rates," NASA CR-092443, 1968, John B. Pierce Foundation, New Haven, Conn.

[9]Stolwijk, J. A. J., "Expansion of a Mathematical Model of Thermoregulation to Include High Metabolic Rates," NASA CR-102191, 1969, John B. Pierce Foundation, New Haven, Conn.

[10]Stolwijk, J. A. J., "A Mathematical Model of Physiological Temperature Regulation in Man," NAS-9-9531, 1970, John B. Pierce Foundation, New Haven, Conn.

[11]Craig, A. B., Jr. and Dvorak, M., "Thermal Regulation During Water Immersion," *Journal of Applied Physiology*, Vol. 21, Pt. 5, 1966, pp. 1577–1585.

[12]Reeves, E., Stephens, M. P., and Beckman, E. L., "An Evaluation of the Foamed Neoprene "Diver's Wet Suit" as a Survival Garment for Helicopter Aircrews," Research Rept. 7, Project MF-011.99-1001, 1963, Naval Medical Research Institute.

[13]Barsell, A. W., Montgomery, L. D., and Arnold, J. E., "Thermal Behavior of SNAP Reactor Fuel Elements During Atmospheric Reentry," Atomics International, Div. of Rockwell International, NAA-SR-11502, 1966.

[14]Sherwood, T. K. and Reed, C. E., *Applied Mathematics in Chemical Engineering*, McGraw-Hill, New York, 1939.

JULY 1974 J. HYDRONAUTICS VOL. 8, NO. 3

Thermal Protection for Divers

W. W. McCrory*
Naval Coastal Systems Laboratory, Panama City, Fla.

Providing proper heat balance for divers in cold water requires adding distributed heat to an insulated garment. A garment consisting of a heat distribution network, a pump, and an outer dry suit with helmet was developed and evaluated. A modified Apollo cooling garment was used to distribute the heat. A problem area concerns the outer suits, which are dry in their original state but difficult to keep dry and to maintain a practical fit when required modifications are made. Pressure compensation techniques are not adequate in flexible expanded neoprene foam dry suits.

Introduction

CONDUCTIVE and conductive/convective heat exchange from the immersed diver are two processes that cause subnormal body temperatures. Direct conductive heat transfer from the diver's body to the water constitutes the bulk of the loss. However, under certain conditions, conductive/convective heat exchange within the diver's lungs can account for a significant part of the loss. Difference in body and water temperatures, body area exposed to the water, film coefficients, respiration rate, gas density, specific heats, and material conductance provide classic engineering parameters for solving these problems. One must understand what the term "thermal protection" is intended to mean. It should be clear that ideal thermal protection is an ideal thermal insulator; one that would allow an acceptable heat exchange between the diver's body and surrounding water. An acceptable heat exchange is one in which the diver's body temperatures, skin, and deep core, remain in a comfortable range under all conditions, with no subnormal or abnormal physiological readings.

Presented as Paper 73-1350 at the AIAA Crew Equipment Systems Conference, Las Vegas, Nev., November 7–9, 1973; submitted December 20, 1973; revision received March 15, 1974.

The thermal protection garment development described in this paper was sponsored by Naval Ship Systems Command, Office of Ocean Engineering, Supervisor of Diving and Salvage.

Index categories: Undersea Extra-Vehicular Activity; Heat Conduction.

*Senior Project Engineer, Diving and Salvage Department.

Providing adequate thermal insulation to the diver's body is a difficult task because of the operating environment. Insulation of clothing worn by man in a gaseous atmosphere is provided, to a large extent, by trapped gas. Once in the water, the trapped gas is lost from clothing or the stagnant layer of gas is lost from the unclothed diver's bare skin. Since 32°F water has a thermal conductivity 24.5 times more than air at the same temperature, the immersed diver will lose body heat 24.5 times faster in 32°F water than in 32°F air. Thus, if he is in water, the diver's garments must provide him with thermal insulation that is much more effective than the best available for use in his normal gaseous environment, i.e., in air. A material that can be practically fashioned into a diver's garment and provide adequate thermal insulation is not available. With this stumbling block in the way of providing adequate thermal protection, techniques other than insulation must be employed.

A satisfactory alternate solution is to provide a dry atmosphere with a uniform insulative gas layer and supplemental heat between the diver's body and the surrounding water. The supplemental heat should be sufficient to offset the heat the diver would lose if he had no protection. No attempt should be made to force extra heat into him because his physiological processes will maintain proper body temperature if the supplemental heat balances what he would lose to the water.

Turning to body heat loss from the lungs, the problem is not so severe from an engineering standpoint. The breathing gas must be warmed to slow the conductive/

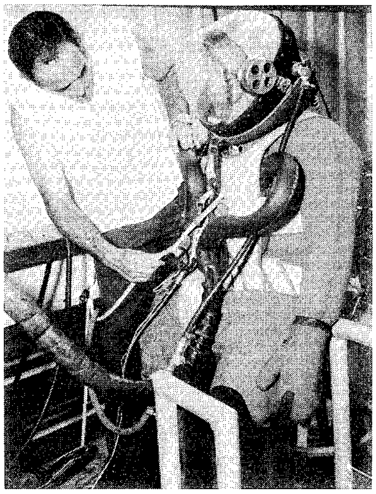

Fig. 1 Diver suited in garment system.

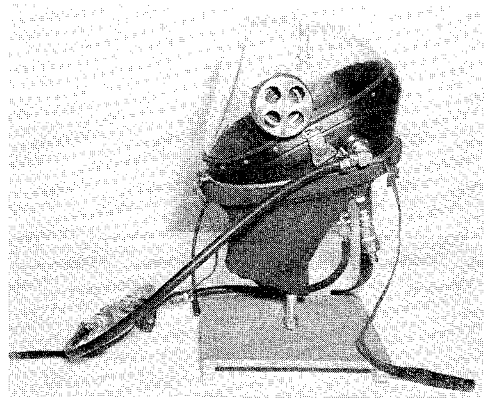

Fig. 3 Thermal helmet, Mod 1.

convective respiration heat loss. Since respiratory heat loss is significant under some diving conditions, this part of thermal protection is as necessary as that for the remainder of the body.

Improved methods of keeping the diver dry have been provided in the new constant gas volume dry suits. These suits offer a layer of insulative gas to this dry atmosphere. One of the better methods of heat distribution is a network of plastic tubes located about the body in patterns designed for optimal heat exchange. Proper interfacing and refinement of these techniques can provide the diver with adequate thermal protection.

The thermal protection garment (Fig. 1) discussed here is an attempt to provide a completely dry atmosphere with provisions for distributing heat and a layer of insulating gas for the diver. Heat distribution is provided by a tubing system similar to the liquid cooling garment used in the Apollo space program. The tubing system has the same pattern as the Apollo garment and is held together by the same type spandex fabric. The major difference is that it is sewn on the outside of a soft, comfortable nylon pile fabric and uses larger diameter tubing. Commercially available dry suits are modified for use as the outer garment. A thermal head protector was designed and built to keep the diver's head warm and dry. The head protector consists of a light-weight helmet built in two parts; a lower neck shroud and seal, and an upper dome. Supplemental heat is distributed about the head by a tubing network similar to the garment, and breathing gas is warmed by a water-to-gas heat exchanger built into the neck shroud.

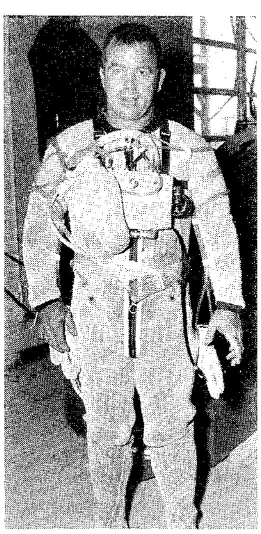

Fig. 2 Tube heat distribution garment with pump and distribution manifold.

Developmental History

The test model garment was designed and fabricated in the following order: First, commercially available, constant volume dry suits, with neck and wrist seals and volume compensation devices, were modified to form-fit the test divers. A pouch for carrying a pump and manifold was fashioned into the suits. Waterproof penetrations were provided in this pouch for water circulation, temperature sensing, and pump power.

Second, a commercially available pump capable of delivering up to 2 gallons of water per minute against static pressure of up to 17 psig was modified to interface with the tube suit and to be submersible.

Third, since it was known that the pressure drop through the ⅛-in.-diam tubes of the standard Apollo cooling garment was excessive, two suits having larger diameter tubes, 5/32-in. and 3/16-in., were fabricated. Larger tube sizes in the suit would reduce the pressure drop, thereby reducing the size and weight of the pump/battery pack. The tube pattern in each suit is like that of the standard Apollo cooling garment. Gloves and hood are separate from the suit to avoid interference with the dry suit wrist and neck seals (Fig. 2). A spandex material is used on the outer side of the tubing and a soft, comfortable nylon pile material is sewn on the inside. Nylon pile underwear offers an excellent method of reducing the tube suit hot spots and squeeze problems. The soft, comfortable pile between the diver's body and the tube network also offers trapped gas space for added insulation.

Fourth, a thermal head protector was designed and fabricated. Two models of this helmet have been developed. Mod 1 (Fig. 3) and Mod 2 (Fig. 4) are basically the same with Mod 2 incorporating design improvements suggested from tests on Mod 1. It became evident during initial testing that the tube hood unnecessarily complicated the system, thus, the heat exchanger in Mod 2. It was also evident that the Mod 1 helmet was excessively buoyant; thus, a change from aluminum to CRES for all metallic parts. The basic design idea is to provide universal fit, thermal protection of the head, heated breathing gas, communication, and a means of quick donning and doffing. Three components, a harness, a neck shroud, and the helmet, make up the system. The harness is an arrangement which fits the diver like a vest with shoulder, chest, waist, and crotch straps. It contains hip pockets for weights and three D-ring buckles for cinching the neck shroud down. The neck shroud houses the neck seal, communication components, hot water and breathing gas penetrations, gas dispenser, straps for attachment to the harness D-rings, catches for connection to the helmet, and for the Mod 2 system, the breathing gas heat exchanger, and exhaust valve. The Mod 1 helmet, which is thermoformed Lexan, contained the exhaust valve, but this was moved to the neck shroud in the Mod 2.

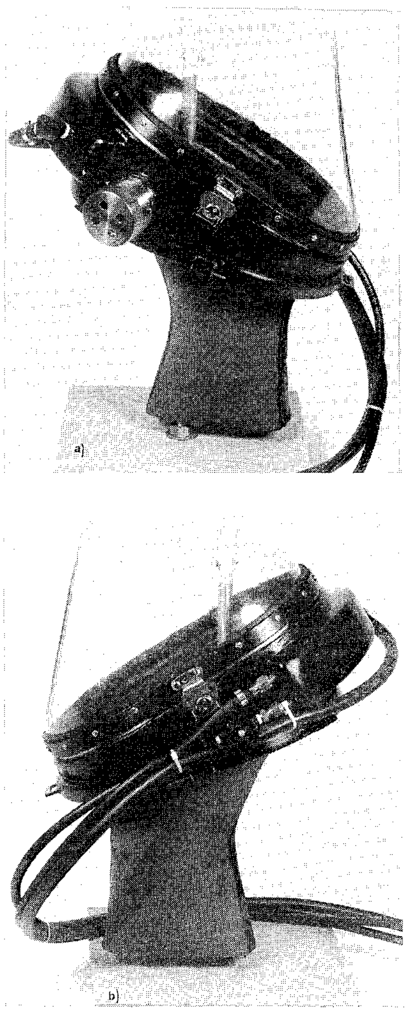

Fig. 4 Thermal helmet, Mod 2: a) right-side view; b) left side view.

Initial Testing

There have been two series of tests. The first series provided pump performance, and flow and pressure drop for the two new tube suits (5/32-in. and 3/16-in.-diam tube). The second series was man testing.

Series 1: Flow and Pressure Characteristics

These tests consisted of flowing tap water through a calibrated flow meter and the suits while measuring pressures with a calibrated pressure gage. Pump voltage from 10–16 v was recorded with corresponding amperage, flow, and pressure.

Series 2: Man Testing

Man testing of the system was performed solely to gain engineering data. There have been no physiological tests yet, but a core temperature record was kept for the test diver's protection. Temperature distribution about the diver's body and throughout the system was of interest.

Temperature sensors at the head, midchest, midback, left hand, left thigh, left foot, and a core probe were fixed on the test divers to show temperature distribution about his body. After the diver put on the tube suit, and the pump and distribution manifold were connected, the outer suit was then partially donned and all undersuit connections made. Finally, the garment system was completely donned along with a heat exchanger which simulates a self-contained heat system. At this point, the closed-loop system was thoroughly purged. Thorough

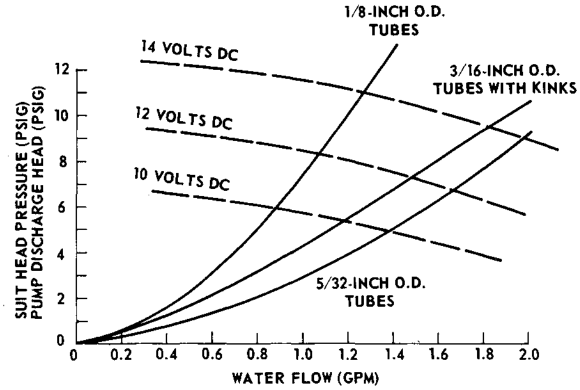

Fig. 5 Pump/suit flow and pressure characteristics.

purging of the entire system is of major importance because an air bubble in the tubing or heat exchanger will cause the pump to lose its prime. However, once proper purging is accomplished, no pump prime problems will appear. Once the garment system is properly donned and primed, the test is started. The bath is a 6-ft-diam by 8-ft-deep tank filled with fresh water and chilled to from 32°F to 34°F by a conventional chill unit and filtration system. Warm water to the heat distribution garment and suit pump is provided via the heat exchanger. Heated water into the heating side of the heat exchanger is provided by a conventional domestic hot water heater. Both water loops (suit and hot water heater) are plumbed through flow meters and their inlet and outlet temperatures are monitored by thermocouples.

All seven temperature sensors mounted on the diver, the four thermocouples mounted in the water circuits, and the suit flow rate are processed continuously by a digital acquisition system. Medical personnel monitor the diver's core temperature and all testing is terminated if this temperature drops 0.1°F below normal.

Results of Initial Testing

Testing was performed to establish a pressure drop vs flow characteristic pattern for the pump and the tube suits. Figure 5 is a plot of these pressure and flow characteristics showing various pump capacities (voltages) in relation to the tube suits.

Human tests were performed to establish heat distribution characteristics of the tube suits. Figure 6 is a plot of

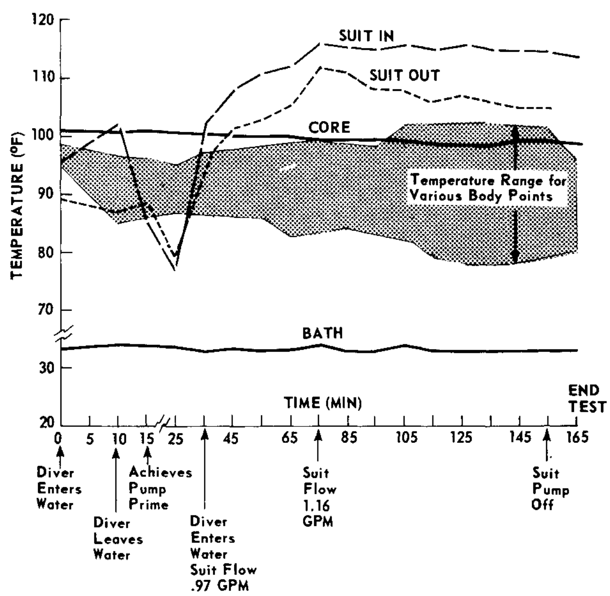

Fig. 6 Man testing.

Fig. 7 Gas distribution about body, side view.

data collected on one of these tests. The gray area of Fig. 6 represents temperature range of the diver-mounted sensors. All these readings fall within a range of from about 80°F to 100°F. Readings diverting farthest away from the 100°F were those at the hands and feet.

Conclusions

1) The $5/32$-in.-diam tube suit is the most practical to use. First, the pressure drop through this tube size is significantly less (especially at high flow rates) than the standard $1/8$-in.-diam size (Fig. 5). The pressure drop is even less than that through the $3/16$-in.-diam tube suit because of kinks in the larger diameter tube. The tubing was kinked during manufacturing. Second, manufacturing processes are established for the standard $1/8$-in.-diam tube size. The capability and limitations of equipment used for the $1/8$-in. tube suits can be easily extended to include the $5/32$-in. suit. Modifications to the manufacturing equipment are required for proper use of the $3/16$-in.-diam tube.

2) The tubing network provides adequate heat distribution about the body and hot spots from tube contact with the body have been eliminated. Body squeeze caused by the tubes is still present but not to a degree that is uncomfortable. In fact, it is not noticeable until the suit is removed and the tube marks on the diver's body can be seen. The suit tubing becomes soft and flexible when the warm water (110°F ± 5°F) is pumped through it. Pump suction tends to collapse the tubing and kinking becomes easier under these conditions.

3) The pump system has a wide range of flow capacities making it well-suited for many applications in addition to this program.

4) The mechanisms in the constant volume dry suit for adding the insulative gas layer perform satisfactorily. However, there are some inherent difficulties with the suits. The insulative gas layer inside the suit is not uniform about the diver's body because the suit material is flexible and, while achieving an internal suit over-pressure, the suit expands with all the gas seeking the uppermost point (Fig. 7).

5) The Mod 1 helmet exhaust valve is not satisfactory because of its physical size and location. An additional distributed weight must be added to reduce some of its positive buoyancy.

6) From the diver-user standpoint, the over-all garment system that was tested is not practical primarily because of the complexity in donning the garment. Other reasons include outer suit leakage, lack of a uniform insulative gas layer, and the discomfort of the garment. However, dives of up to 4 hr in 32°F to 34°F water have been made with the system providing uniform heat distribution with no abnormal physiological temperature readings. In all cases, the dives were terminated because the test diver became unbearably uncomfortable because of garment fit. The distribution of supplemental heat was always satisfactory. However, because of leakage, heat input to the garment was excessive in most cases.

Discussion

The program is being continued in an effort to alleviate problems encountered in the development and evaluation of the test garment. As mentioned earlier, a Mod 2 thermal head protector has been fabricated and a new outer suit is in the fabrication stage. The following discussion describes these components.

Head Protector

The Mod 2 thermal head protector has the same basic design as the Mod 1. However, improvements suggested from evaluations on the Mod 1 are incorporated into the second version. The exhaust valve has been moved to the neck shroud and redesigned to reduce its size. A water-to-gas heat exchanger has been fashioned into the neck shroud for warming the breathing gas. The neck shroud is insulated to reduce heat loss and an oral-nasal breathing circuit has been incorporated to prevent breathing carbon dioxide dead space within the suit. The neck shroud is flanged to interface with the suit which eliminates the need for a neck seal.

Outer Suit

The new outer suit is designed to facilitate donning the system. Technology on materials, penetrations, sealing, and fabrication from the space industry is being incorporated into the suit. Beginning at the neck, the new suit will have a matching flange to interface with the helmet neck shroud. Next, a transition piece will hold the helmet neck shroud in position and provide a uniform contour between the neck and shoulders. The suit will be tailor-made to fit the test diver with a $1/16$-in. thick layer of neoprene bonded onto a nylon-reinforced, neoprene, non-stretch fabric making up the outer material of the suit. A spacer material for providing a positive gas layer and to minimize contact with the outer wall is fixed on the inside of the outer material. Mechanical penetrations for hot water circulation, physiological monitoring, and suit pressurization and exhaust are provided through the suit front.

Upon completion of the Mod 2 thermal head protector and the new outer garment, the tube suit will be integrated into the system. Another engineering evaluation will be performed on the system to ensure that it is performing satisfactorily and providing the desired results. Once all the required engineering parameters are satisfied, the system will be handed over to physiologists for their evaluations. Upon satisfactory completion of these evaluations, field evaluations will be performed. After these evaluations are complete and all modifications are incorporated into the system, design drawings will be updated and military specifications compiled. The system at this point will be ready for procurement and issue to the Fleet diver.