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EVALUATION OF A DIVER COOLING SYSTEM FOR USE WITH PERSONAL PROTECTIVE EQUIPMENT IN CONTAMINATED WATER DIVING

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Current Navy recommendations for diving in contaminated water include wearing a vulcanized rubber dry suit mated to a MK 21 diving helmet to isolate the diver from the contaminated environment. However, even in situations (e.g., visible oil spills, noxious fumes, and sewer outflows) where the need for protective gear is unequivocal, thermal stress from working in a warm environment often precludes the use of such gear. The purpose of this study was to identify and evaluate a commercially available diver cooling system through field trials for overall effectiveness, comfort, durability, and ease of use in and of incorporation into Navy diving practices. Ten dives were completed over 2 days in November 2003 at Naval Base Guantanamo Bay, Cuba. No systematic testing was performed. During dives, divers were asked to report on their level of thermal stress, and after diving, each diver completed a feedback survey. Overall, the suit performed well in cooling the divers, despite temperatures greater than 100 °F by heat index. Divers found the suits comfortable and easy to use, with minimal change to normal diving procedures. Problems were found with overly buoyant cooling hoses and hose connectors that detached too easily. Despite these shortcomings, however, all divers recommended the system for diving in warm environments with maximal protective gear, and we recommend that the Navy consider further evaluation of the suit for inclusion on the ANU List.

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INTRODUCTION

Current Navy recommendations for diving in contaminated water include wearing a vulcanized rubber dry suit mated to a MK 21 diving helmet to isolate the diver from the contaminated environment.[1,2] However, even in situations (e.g., visible oil spills, noxious fumes, and sewer outflows) where the need for protective gear is unequivocal, thermal stress from working in a warm environment often precludes use of such gear. In the recent salvage operation of the USS COLE in Yemen, thermal stresses (water temperatures 90–93 °F) compelled divers to dress in wet suits and dive skins in lieu of dry suits.[3] The resulting lack of protection exposed divers to copious quantities of obvious contaminants including diesel fuel, hydraulic oil, biological hazards, and others. The only acute ill effect noted at that time was minor skin irritation; however, long-term effects of the exposures are unknown.[3] Additionally, the porous nature of the wet suits required significant decontamination efforts to attempt to clean them. Because of their continuous use in the contaminated water and the decontamination process they underwent, these suits were ultimately destroyed and discarded.

In 2002 the Navy Experimental Diving Unit (NEDU) was tasked with identifying and evaluating a commercially available personal diver cooling system for use with contaminated water diving gear in warm water operations.[4] Such a system had been briefly used at NEDU in 2000 as part of a warm water diving study with encouraging preliminary results.[5] In that study, fully dressed divers wearing the MK 21 mated to a dry suit and using this system in 96.5 °F (35.8 °C) water showed little, if any, thermal stress over a 1-hour period, although typically divers wearing dry suits with no cooling system experienced appreciable core temperature increases in water temperatures as low as 78 °F (25.6 °C).

Some commercial organizations report having used the cooling suit to complete dives several hours long in industrial cooling ponds with temperatures greater than 120 °F (48.9 °C).[6] Such examples merely illustrate the purported capabilities of this cooling system. For future U.S. Navy operations, the present evaluation is not intended to support using the suit in any similar situation where it can be construed as life support. Rather, if approved for Navy use, the cooling suit should be used to enhance diver comfort in thermally challenging situations by extending working times to facilitate use of a dry suit when use of such protective gear may not otherwise be considered a viable option.

The purpose of this study was to test the COOLTUBEsuit™ (Med-Eng Inc.; Pembroke, Ont., Canada) diver cooling system to determine its overall effectiveness and evaluate its potential for being integrated into Navy diving operations. Specifically, we intended to field-test the suit by having a Navy operational diving unit evaluate its comfort, dexterity, encumbrances, and ease of operation. We were also particularly interested in how the system's supply lines can be incorporated with Navy umbilical hoses, dressing procedures, and manning requirements.

METHODS

GENERAL

In November 2003, testing of the COOLTUBEsuit diver cooling system was conducted at Naval Base Guantanamo Bay, Cuba because of the warm water temperatures at that site. Originally, Underwater Construction Team 1 had taken the cooling equipment for possible use and evaluation in the Persian Gulf. However, the suits were not used and were returned to NEDU, which identified an alternate operational unit to participate in testing. Divers from the Guantanamo Bay dive locker provided equipment and assistance and served as test divers for the study. Three divers from NEDU went to Guantanamo Bay to train divers to use the cooling equipment, oversee dives, serve as test divers, and assist with manning the dive station.

EQUIPMENT

The cooling equipment used was the COOLTUBEsuit diver cooling system, a lightweight knit garment laced with a network of multiple hollow tubes through which cool water flows in close proximity to the diver's skin.[6] A cooler and surface-based pump system (to which water, chilled with ice, is added) supplies chilled water to the suit through an umbilical via a sealed penetration in the dry suit. The chiller, filled with tap water and ice, is a commercially available 48-quart cooler with a pneumatic flow control valve retrofitted to circulate coolant via a standard air cylinder. The pneumatic pressure controller varies the water flow rate to enhance diver comfort, and the pressure level ranges from 1 to 30 pounds per square inch gauge (psig). As ice melts in the chiller, more is simply added to continue cooling. No electric chillers are employed. Since the system is a closed loop, the diver never directly contacts the chilled water. The suit is typically worn beneath an insulating garment (e.g., sweat suit) that is also worn under a standard dry suit fitted with a hose penetration. The simple design — with few moving parts and no electrical requirements — is lightweight and highly portable.

All dives were conducted with MK 21 helmets mated to AMRON AHD1600™ vulcanized rubber dry suits. Air was supplied via the U.S. Navy MK 3 surface-supplied diving system. Divers were also equipped with standard required diving equipment (e.g., weights, knives, harnesses) per Navy regulations, and all dives were conducted according to procedures in the *U.S. Navy Diving Manual*.[1] The full cooling system was used, with tape attaching cooling hoses to the divers' air umbilical lines. An in-water thermometer monitored ocean water temperatures.

PROCEDURES

No systematic testing was conducted with the cooling system. Divers were instructed to dress in the suit as part of their routine and then perform normal working dives in accordance with their standard operating procedures — with no further modification than that of wearing a MK 21 with dry suit and cooling suit. Weather, water, and bottom conditions were recorded each day. During diving, technical data such as the operating pump pressures, pump pressure adjustments, and air cylinder pressures were collected. Divers were asked to report their subjective comfort levels with a "thermal status scale" on which they rated their thermal status from 1 to 10, with 1 representing complete comfort and 10 representing overheating. Divers reported their thermal status before, at 10-minute intervals during, and at the end of dives. On day 1, they conducted a routine pier inspection that stretched the air umbilical to full length. On day 2, they inspected a buoy.

After dives ended, diver subjects completed a short survey to record qualitative information about their comfort and dexterity as well as the encumbrances and overall ease they experienced in using the cooling system. Surveys also asked the divers to offer any suggestions on how the system might be improved. At the conclusion of all diving, these surveys were reviewed and all remarks recorded.

RESULTS

Seven test divers using surface supplied air from a MK 3 surface-supplied diving system performed a total of 10 open water dives. During dive operations, air temperature was relatively constant at 89 °F, and water temperature was constant at 84 °F. Humidity ranged from 64 to 84%, with a calculated heat index range from 99 to 104 °F. Conditions and information for each dive are shown in Table 1, Appendix A.

The maximum depth for all dives was 50 feet; the minimum, 42 feet. Bottom times ranged from 25 to 30 minutes. The water surface on day 1 was calm, with 1-foot seas, and the bottom condition was deep mud and silt with 2–5 ft visibility. As a result, divers reported expending much energy walking through the silt to perform the pier inspection.

On day 2 the weather was windy and the water choppy, with 3–4 ft waves; the bottom was sand and coral, with visibility of 30 to 50 ft. These conditions made dressing a diver more difficult than conditions on the previous day had.

Diver thermal status for all dives ranged from 1 to 7 on the 10-point scale (see **PROCEDURES**). The average predive thermal status was reported to be 3.5; the average postdive thermal status, 3.1. On day 1, diver thermal status ranged from 1 to 7, with an average predive status of 3.3 and average postdive status of 2.8. Only two divers of eight on day 1 reported thermal state of 7. One of the divers reported having buoyancy problems on the bottom; problems that had increased his work rate and heat generation. The other diver's cooling suit had disconnected from the penetrator device when his weights and harness compressed the connector. Before that connection problem could be identified, that diver spent 10 minutes without cooling on the surface.

On day 2, diver thermal status ranged from 4 to 5, with an average pre- and postdive state of 4.5. Divers on day 2 reported feeling relatively comfortable; however, they also reported that cooling seemed less effective than on the day before.

Pneumatic pump pressures ranged from 15 to 30 psig. On day 1, pump pressure was adjusted frequently, according to diver thermal status. Pressure was increased as divers reported increasing thermal stress and was decreased when they reported feeling completely comfortable. On day 1, predive pump pressures ranged from 15 to 28 psig, with average predive pressure of 22 psig and average postdive pressure of 18.8 psig. Pump pressure for the last two divers of the day was 15 psig throughout their dives. Before these two dives the overall average pump pressure was 22.2 psig. On day 2 the pump pressure was set continuously at 30 psig (maximum), as divers reported minimal cooling.

Without being refilled, a single 80 ft^3 air cylinder was used for both diving days. The starting pressure for the cylinder was 3000 psig. At the end of the first day's diving (after approximately 5 hours of continuous use), the pressure was 2000 psig. At the end of the second day of dives (2 hours of continuous use), the cylinder pressure was 1800 psig.

After 3.75 hours on day 1, ice in the cooler melted and was replaced. Divers in the water when the ice was found to be melted reported that they still experienced cooling, however, and water in the cooler was cold.

On day 2 of diving, the length of cooling hose was increased to 150 feet. Both divers on this day reported little to no cooling coming into the cooling suit.

Nine diver questionnaires were completed by the seven test divers (one questionnaire for each dive). All surveyed divers recommended the suit as part of warm water diving equipment, and all said that they would prefer to use the suit for warm water operations, if it were available. Seven divers reported that the suit was "good" or "very good" at keeping them cool, and two divers reported that it was "poor" at cooling. Eight divers reported that the suit was "reliable" and "durable"; two divers considered the suit to be "unreliable" and not "durable." Two divers reported experiencing difficulties with the cooling system. One had suffered buoyancy problems from the extra positive buoyancy of the cooling system connector hoses attached to the air umbilical lines. The other diver reported problems with the connector devices: pressure from his weights or harness caused the cooling suit to disconnect from the dry suit penetrator. Divers also recommended several improvements they felt could be made to the system:

- better, more durable connectors (5 diver comments);
- less buoyant connector hoses (5 diver comments);
- less compressible tubing throughout the suit, to enable it to withstand pressure from a dry suit squeeze (2 diver comments); and
- hose/tubing with increased diameter for greater circulation (4 diver comments).

DISCUSSION

Results suggest that the COOLTUBEsuit™ diver cooling system performs well in reducing thermal stress from diving in a warm environment with full protective diving gear. Although the water temperature was lower than that on dives during the USS COLE salvage operation, the heat index made the air temperatures feel greater than 100 °F for most of the diving. Also of note was that the dry suits are black and thus absorb heat very quickly from the tropical sun.

Despite using heat-absorbing dry suits, most divers reported little to no thermal stress while dressing out, and they appeared to sweat much less than the tenders and other dive station support personnel. Furthermore, averages from diver thermal status reports showed a decrease from predive to postdive results, indicating that the suits cooled the divers despite their exertions in the water. Only two divers reported thermal status greater than 5, and both of these divers experienced equipment problems. One reported that he had been very hot before dressing out and then had a poorly fitting (too large) suit; the other diver's cooling hose had disconnected but was subsequently reconnected. Both of these divers reported improved cooling once their dives commenced, however, and by the time they had surfaced, the heating level of their thermal status had decreased.

The equipment was easy to use and to incorporate into Navy diving practices. The air cylinder that provided pneumatic pressure was used both days without having to be refilled or replaced. The pump pressure was easily changed with a simple dial, and the cooling effect increased or decreased quickly (usually within about 10 minutes), depending on how the pressure had been altered. This rapid response to pump pressure manipulation was noted only when the 100 ft cooling hose was used. Furthermore, the quietness of the pneumatically driven pump indicated that it would not interfere with normal diving communications.

The cooler seemed adequate in maintaining ice: it had to be refilled with ice only once during the first day's diving; however, this was necessary after less than four hours of use. Despite running out of ice in the middle of a dive, divers still reported receiving adequate cooling in the suits. No diver indicated that this consumption of ice in less than four hours would be an operational problem, but several divers pointed out that increasingly effective coolers may be commercially available.

The major problems with the system involved the suit and cooling hose connectors. Two types of connectors are on the suit: one connects the pants to the shirt and the shirt to a hood; the other connects the cooling suit to the dry suit penetrator. Although most divers felt that the shirt/pants/hood connectors seemed "flimsy," none of the divers experienced any problems with these. However, the other connectors to the penetrator came loose under the pressure of a diver's weights or harness. The same type of connector was also used to connect segments (each segment was 50 feet long) of cooling hose, and on one occasion a segment of cooling hose became disconnected when a dive tender accidentally stepped on it. Most divers agreed that a more durable connector is preferable to the ones currently included with the system.

Another major problem was that the cooling hoses were too buoyant. This caused some difficulties on the first day of diving, as some divers lacked adequate weight and were in danger of becoming positively buoyant. The cooling hose was equally troublesome: even if the diver had adequate weight, this hose caused the air umbilical to float and thus made it increasingly difficult for dive tenders to accurately track the diver's location. In situations when it may be necessary for tenders to keep close track with divers, it might be necessary to somehow weigh down the umbilical-cooling hose assembly.

Perhaps most significantly, the system did not seem to cool effectively when the cooling suit hose was extended to 150 feet. Despite maximum pump pressure, divers reported receiving little cooling from the suit at this length of cooling hose. Whether this change in performance is due to operational depth or hose length is unclear. Cooling appeared adequate with 100-foot hoses, however.

Despite these concerns about some of the cooling system components, all the divers who tried the cooling suit seemed to agree that if one had to dive in a dry suit in a warm environment, they would choose and/or recommend that this cooling system be employed.

Five commercial diving firms who use the same cooling suit were contacted to check whether our test results were consistent with their experience. We found that these firms tended to be pleased with its performance while they were working inside nuclear reactor cooling pools, power plant outfalls, and sewage outfalls. They agreed that hose connections are problems and that longer hose lengths tended to need additional insulation.

CONCLUSIONS

Although limited numbers of dives and divers used and provided feedback about the COOLTUBEsuit™ diver cooling system for this study, results were promising. With some limitations, the system overall appeared to be effective at cooling divers, easy to use, and readily incorporated into Navy diving practices. The system also affords desirable benefits, since its use of plastic tubing to carry water may also enhance other operations by providing a heating system. This possibility is feasible and has been discussed with the manufacturer in a personal communication (2003).

The major limitations of the system — the weak connectors and the buoyant cooling hoses — are problems that can be easily remedied by asking the manufacturer to replace them more durable connectors and less buoyant material.

Because of its good performance and positive diver feedback, we recommend that the cooling system be tested further after the manufacturer makes changes to the gear based on the issues identified in this study. Ideally, future testing of the improved cooling system would be of a larger scale than this study including controls (i.e., diving in the suit with and without cooling) for comparison. If the improved suit and supporting equipment perform well in future tests, it may be considered for inclusion on the Authorized for Navy Use List (ANU). Since the Navy currently has no device for protecting divers from heat stress while they are in dry suits, incorporating this cooling system could maximize the effectiveness and comfort of divers who must remain in protective gear in warm water.

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APPENDIX A

Table 1. Results of trials using the COOLTUBEsuit™ diver cooling system.

Diver Number	Depth (fsw)	BT (min)	Air Temp (°F)	Water Temp (°F)	Hose Length (ft)	Starting Pump Pressure (psig)	End Pump Pressure (psig)	Connector Problems? Yes or No (Y or N)	Diver Thermal Status Start (1–10)	Diver Thermal Status End (1–10)	Comments
1	45	30	89	84	100	28	15	N	1	3	
2	45	30	89	84	100	28	15	N	1	3	
3	42	30	89	84	100	20	25	N	7	4	Poor suit fit, diver hot pre-dive
4	42	30	89	84	100	20	25	N	3	4	Buoyancy difficulties
5	42	30	89	84	100	25	20	N	4	1	Ice melts and is refilled
6	42	30	89	84	100	25	20	N	2	1	
7	46	25	89	84	100	15	15	Y	7	5	Hose disconnects prior to dive
8	42	25	89	84	100	15	15	N	1	1	Poor suit fit (too large)
9	45	30	88	84	150	15	30	Y	4	4	No cooling on surface or at depth
10	50	30	88	84	150	30	30	Y	5	5	

Table 2. Diver responses to post-dive questionnaires.

Survey Number	No. years experience using dry suits.	Difficulties using system?	Problems with other aspects of dive?	Suggested improvements	Suit recommended? (Y/N)	Additional comments
1	3	None	None	"stiffer hoses"	Y*	None
2	0 (first use)	"hose married to the umbilical was way too buoyant"	Dry suit too large, buoyancy problems	"stronger connectors"	Y	"hose tubes would be more effective if the diameter was slightly larger to produce more flow"
3	5	None	None	"more circulation", hoses "easily disconnected"	Y	"more flow in the suit would be better and more durable hose connectors"
4	1	"connectors seem flimsy, easy to detach"	None	"more durable hose connectors"	Y	
5	1	"suit did not fit properly"	None	"more durable hose connectors; make sure of proper fit of liner"	Y	"the cooling hose covers were too buoyant and definitely need to be more durable"
6	8	None	None	"the umbilical was too buoyant"	Y	"possibly go to different brand suit"
7	6	None	None	"different chilled water hoses, connector clips, sized to fit better"	Y*	Hose connector clips could be "more durable"
8	3	Cooling cut off		"stiffer hoses not prone to collapse"	Y	Suggests evaluating long term durability of suit (washing, etc.)

9**	6	None	None	“different chilled water hoses, connector clips, sized to fit better”	Y*	Hose connector clips could be “more durable”

* Diver recommends the suit only for shallow (“less than 30” fsw) work.
** Survey numbers 7 and 9 were completed by the same diver who dove twice for the study.