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Summary

Problem.

Identification of anti-exposure suits (AESs) for use during cold-water flooding repair operations is of interest to shipboard damage control personnel. The findings from laboratory studies indicate that water-impermeable, whole-body AESs attenuate decreases in body temperature in personnel performing arm exercise and experiencing prolonged cold-water exposure. However, before a specific AES design can be accepted by the fleet, it is necessary to evaluate the effectiveness of appropriately designed AESs during simulated flooding repair operations in a shipboard environment.

Objective.

The purpose of the present investigation was to evaluate the effectiveness of the whole-body Naval Clothing and Textile Research Facility experimental-immersion suit (NAVCLO) in maintaining normal body temperatures in naval personnel performing simulated flooding repair activities in cold water. Preliminary evaluations were also conducted on subjects wearing the Marine Corps (MARCOR) experimental-immersion suit, and MultiFabs Survival™ (MULFAB) suit. These were compared with subjects wearing NAVCLO and those wearing coveralls, cotton T-shirt, shorts, and socks which represented the control (CON) condition.

Approach.

Eight males trained in damage control flooding operations served as volunteers. The average age, height, and weight of the subjects were 22.0 ± 2.1 years, 178.8 ± 10.7 cm, and 82.2 ± 8.4 kg, respectively. Data collection occurred during 15 tests conducted over 4 days aboard the Ex-USS SHADWELL (LSD-15), a damage control research ship located in Mobile, AL. In all tests, naval personnel attempted to rapidly complete hull-patching ($n = 4$) and pipe-patching ($n = 4$) assignments in a single-compartment flood simulator located in the port wing wall. During each test, water was released into the compartment through ruptures in the hull and two pipes, and allowed to rise to about midchest level.

During the tests, subjects were dressed in either CON or in NAVCLO AES. In a limited number of tests, subjects wore MARCOR and MULFAB. In these tests, NAVCLO, MARCOR and MULFAB were worn over CON. Subjects also wore a firefighter helmet, gloves (Kevlar™ or rubber), and firefighter boots in association with CON and the AES.

During each test, portable data logger recordings were made of heart rate (HR), rectal (T_{re}), chest (T_{ch}), arm (T_{ar}), finger (T_{fi}), right thigh (T_{rth}), left thigh (T_{lth}), right calf (T_{rca}), left calf (T_{lca}), right big toe (T_{rto}), and left big toe (T_{lto}) temperatures. The two thigh, two calf, and two big toe temperature values were averaged to yield a mean thigh (T_{th}), calf (T_{ca}), and big toe (T_{to}) temperature. HR was recorded using a Polar^{TM} heart rate telemetry system.

Statistical analysis included analysis of covariance to compare CON with NAVCLO and MARCOR end-of-exposure body temperature responses after adjustment for pre-water-entry value and minutes of water exposure. Mean ($\bar{X} \pm SD$) preentry and end-of-exposure responses for subjects wearing MULFAB were calculated, but no comparative statistical analysis was conducted because of an unequal number of subjects and tests.

Results.

During all tests, water temperature averaged ($\bar{X} \pm SD$) 9.6 ± 1.1 °C (50 ± 6 °F). Differences in exposure time for subjects involved in the CON and NAVCLO tests were nonsignificant and averaged 12:12 ± 3:18 min:s. T_{re} increased slightly during and after each test, but differences in T_{re} between subjects wearing CON and NAVCLO were nonsignificant. However, cold-water exposure was associated with decreases in T_{ar}, T_{fi}, T_{th}, T_{ca}, and T_{to} for subjects wearing both CON and NAVCLO. Comparison of end-of-exposure responses revealed significantly higher average T_{ar}, T_{th}, T_{ca}, and T_{to} for subjects wearing NAVCLO compared with those wearing CON. Differences in T_{fi} at the end of exposure for subjects wearing CON and NAVCLO were nonsignificant.

Wearing MARCOR and MULFAB also attenuated decreases in T_{ar}, T_{th}, T_{ca}, and T_{to} during cold-water exposure. For subjects wearing MARCOR and MULFAB, skin temperatures at the end of exposure were similar to those of subjects wearing NAVCLO. T_{fi} for subjects wearing MULFAB were similar to those of subjects wearing CON and NAVCLO but higher for subjects wearing MARCOR. HR increased during the initial minutes of the repair tasks and then declined throughout the remainder of the work period. Differences in HR for subjects dressed in CON and NAVCLO were nonsignificant. HR was similar between the hull- and pipe-patching tasks.

Conclusion.

In conclusion, the whole-body NAVCLO AES attenuated decreases in skin temperatures during short-term hull- and pipe-patching activities conducted in progressively rising cold water. MARCOR and MULFAB showed comparable effectiveness in maintaining skin temperatures, however, further shipboard studies of these AESs are required. These findings will aid in the development of an effective AES for use in shipboard flooding repair operations.

Introduction

Damage control activities conducted in cold water pose a serious threat to the health and safety of naval personnel. Acute exposure to cold water leads to rapid decreases in skin temperatures. Accompanying this response is cutaneous and skeletal muscle vasoconstriction which redistributes blood into the thoracic cavity maintaining core temperature (Horvath, 1982). With prolonged exposure, large thermal gradients between the body core and skin surface extract heat from the core. When rectal temperature (T_{re}), a representative measure of core temperature, declines to 35.0°C, the individual has reached the point of clinical hypothermia. At this temperature, the coordinated systems responsible for body heat regulation begin to fail, and compensatory mechanisms designed to elevate metabolic heat production (e.g., shivering and voluntary exercise) are unable to readily reestablish a normal body heat content (Keatinge, 1969). However, excessive decreases in body temperature and loss of body heat can be minimized through the use of insulated whole-body anti-exposure suits (AESs) (Hayward, 1984; Hagan et al., 1996). The use of AESs by damage control personnel involved in flooding repair operations in cold water appears to be a viable approach to maintaining body temperatures, reducing the risk of hypothermia, and increasing operational effectiveness.

Identification of whole-body AESs that maintain body temperatures during cold-water flooding repair operations is of interest to naval personnel. Findings from laboratory studies (Hayward et al., 1978; Shannon et al., 1995; Hagan et al., 1996) indicate that personnel receive the most protection against decreases in body temperature during cold-water exposure from wearing whole-body AESs. However, before an appropriately designed AES can be selected by the fleet, it is necessary to evaluate the whole-body concept design during simulated flooding scenarios in a shipboard environment.

In a study comparing three whole-body AESs, Hagan et al. (1996) reported that decreases in body temperatures were least in personnel wearing the MultiFabs Survival^{TM} (MULFAB) suit followed by those in experimental-immersion suits developed by the Naval Clothing and Textile Research Facility for shipboard flooding activities (NAVCLO) and amphibious landings by those wearing the Marine Corps (MARCOR). However, despite the ability of these AESs to retain body heat, they showed remarkable differences in durability. For example, MULFAB and MARCOR were prone to punctures and tears as a result of normal handling and use, while NAVCLO resisted this type of damage, making it the most durable of the AESs. Therefore, the purpose of the present investigation was to evaluate the effectiveness of the NAVCLO AES in maintaining normal body temperatures in naval personnel performing flooding repair activities in cold water. Pilot evaluations were also conducted on subjects wearing the MULFAB and MARCOR AESs for comparison with subjects wearing coveralls, cotton T-shirt, shorts, and socks (CON), which served as the control condition, and with those wearing NAVCLO.

Methods

The protocol and procedures used in this study were approved by the Naval Health Research Center Committee for the Protection of Human Subjects. Testing occurred aboard the Ex-USS SHADWELL (LSD-15), a damage control research ship, located at Little Island, Mobile, AL (Carhart & Williams, 1988) from 12 Feb to 15 Feb 96.

Subjects.

Eight males served as volunteers. All subjects were active-duty naval personnel trained in damage control operations. The average ($\bar{X} \pm SD$) age, height, and weight of the subjects were 22.0 ± 2.1 years, 178.8 ± 10.7 cm, and 82.2 ± 8.4 kg, respectively.

Medical Screening.

All subjects were screened for medical contraindications to damage control flooding activities by a naval medical officer. Each subject completed a medical history questionnaire, reviewed a Privacy Act statement, and signed an Informed Consent prior to participation in the study.

Test Schedule.

Data collection occurred over 4 days. During this time, 15 tests were conducted to evaluate the various AESs. The testing schedule included two tests in the morning from about 0900 to 1100, and two tests in the afternoon from about 1300 to 1500, except for the first day which included one test in the morning and two tests in the afternoon. The second tests commenced approximately 45 min after the completion of the first. During this interim period, subjects recovered from the first test, and the flooded compartment was drained of water.

The average water temperature during the tests was 9.6 ± 1.1°C, while the average upper compartment air temperature and relative humidity were 13.9 ± 3.9°C and 81.0 ± 12.4%, respectively. The weather deck ambient temperature, relative humidity, and wind speed averaged 14.9 ± 3.8°C, 79.5 ± 16.6%, and 4.0 ± 1.3 $m \cdot s^{-1}$, respectively.

During five tests, 8 subjects dressed in CON, while during nine tests, 7 subjects wore NAVCLO. During eight tests, 1 subject wore MULFAB, while 7 subjects wore MARCOR during one test. The test schedule and clothing ensembles are listed in Table 1.

Table 1. Test schedule and clothing ensembles.

Test No.	Test Date	Test Designation	Clothing Ensemble & Subjects
1	12 Feb	CW-1	CON $(n = 8)$
2	12 Feb	CW-2	CON $(n = 8)$
3	12 Feb	CW-3	CON $(n = 8)$
4	13 Feb	CW-4	NAVCLO $(n = 7)$ MULFAB $(n = 1)$
5	13 Feb	CW-5	NAVCLO $(n = 7)$ MULFAB $(n = 1)$
6	13 Feb	CW-6	NAVCLO $(n = 7)$ MULFAB $(n = 1)$
7	13 Feb	CW-13	NAVCLO $(n = 7)$ MULFAB $(n = 1)$
8	14 Feb	CW-14	NAVCLO $(n = 6)$ MULFAB $(n = 1)$
9	14 Feb	CW-15	NAVCLO $(n = 6)$ MULFAB $(n = 1)$
10	14 Feb	CW-7	NAVCLO $(n = 6)$ MULFAB $(n = 1)$
11	14 Feb	CW-8	NAVCLO $(n = 6)$ MULFAB $(n = 1)$
12	15 Feb	CW-11	CON $(n = 7)$
13	15 Feb	CW-10	CON $(n = 7)$
14	15 Feb	CW-12	MARCOR $(n = 7)$
15	15 Feb	CW-9	NAVCLO $(n = 6)$ MARCOR $(n = 1)$

CW = cold water designation

Repair Teams.

During each test, subjects attempted to minimize compartment flooding that resulted from ruptures to water pipes and the hull. The subjects comprised three teams and were designated as A, B1, and B2. Team A (*n* = 4) performed shoring and hull-patching, while teams B1 (*n* = 2) and B2 (*n* = 2) performed pipe-patching. The teams were composed of the same subjects throughout the entire test series.

Test Protocol.

Upon the sounding of a general alarm, teams A, B1, and B2 moved from the #4 Repair Locker staging area to a ladder and descended into a single-compartment flood simulator. During each test, water was released into the compartment through holes in the starboard hull and two water pipes. The objective was to patch the ruptures and keep water out of the compartment. Personnel were monitored by naval safety personnel and video cameras inside the compartment.

Water flow into the compartment was terminated either by an effective hull- and/or pipe-patch repair or when the water line reached about midchest level of the subjects. The average water height attained for the 15 tests was 1.23 ± 0.21 m. Upon completion of the patching tasks or upon command from a safety officer, subjects left the compartment by way of the same ladder used for entrance into the compartment. The compartment was then drained of water. After leaving the compartment, all subjects returned to sick bay where they removed their wet clothing. Heaters placed in the room helped subjects to rewarm. At the end of each day of testing, subjects attended a postbrief to discuss the effectiveness of the hull- and pipe-patching methods.

Hull- and Pipe-Patching Methods and Procedure.

Large storage tanks situated behind the hull supplied water for the hull-patching tasks. Two types of hull ruptures were presented for repairs. The first rupture was intended to simulate an explosion rupture. This rupture consisted of a single circular hole with a diameter of approximately 178 mm. Initially, the water flow rate was 13,497 $L \cdot min.^{-1}$ After 3 min of unobstructed flow (i.e., no repair in progress) the rupture flow rate was 6,233 $L \cdot min.^{-1}$ The second rupture simulated a rip or gash in the hull. This rupture had a hole area of approximately 161 $cm.^2$ Initially, the water flowed at a rate of 10,064 $L \cdot min.^{-1}$ After 3 min of unobstructed flow, the rupture flow rate was 8,709 $L \cdot min.^{-1}$ The effectiveness criteria for patching of both hull ruptures was a reduction in flow rate to less than 945 $L \cdot min^{-1}$ (which was less than the assumed compartment water drainage rate).

Patches employed during hull repairs included bucket and box patches with and without metal shoring, and use of plugs and wedges. The procedures for each of these repairs were similar.

Both the bucket and the box had predrilled holes in them. Depending on the type of hull rupture, either "J" or "T" bolts were inserted through the holes in the bucket or box with the "J" or "T" outside of the concave side of the patch. The bolts were secured with nuts and washers on the convex side. Gasket material available from the repair locker was positioned between the bucket or box and the hull, while the "J" or "T" bolts were positioned over the solid plating. The patches were then drawn tight to the hull/gasket with the nuts on the inner end until the leakage was stopped or terminated. In cases where metal shoring was used in conjunction with the bucket or box patch, the patch was held in place over the shore by two or three of the team members. The remaining team members positioned the shoring to hold the patch in place over the rupture.

The hull ruptures were also repaired using plugs, wedges, and a gasket material. The largest plug or wedge that could be wedged in the hole was inserted first. This was followed with progressively smaller plugs and wedges, wrapped with a sealant material such as gaskets, canvas, and oakum, that were inserted into the remaining parts of the hole until water flow was reduced or stopped.

Water flow during pipe-patching came from a storage tank behind the hull. Water flow through the pipes was controlled by a computer program. Pipe-patching was performed on a 6.0 cm (2.375 inches) fresh water line, a 8.9 cm (3.5 inches) fire main, and a 11.4 cm (4.5 inches) fire main. The residual pressure in the water line, when the leak was initiated, and the average flow rate are shown in Table 2. The effectiveness criterion for pipe-patching was a 90% to 100% reduction in water flow.

Table 2. Pipe size and type, residual pressure, and water flow rate.

Pipe Size & Type	Residual Pressure (bar)	Flow Rate ($L \cdot min^{-1}$)
6.0 cm fresh water	0.28 ± 0.04	108 ± 11
8.9 cm fire main	3.7 ± 0.7	602 ± 66
11.4 cm fire main	2.3 ± 0.3	968 ± 110

Pipe-patching occurred using a pipe wrench with a Banding kit(s) or Jubilee patch. The Banding kits consisted of a gasket material, screen wire, prefabricated metal plates, a chain wrench, metal bands, and a banding tool. The Banding kits were applied as follows. First, the pipe hole was covered with the gasket material, screen mesh, and metal plates. Then, the chain wrench was clamped in the center of the patch to hold it in place while the banding tool was used to secure bands on each end. Once the ends were banded, the chain wrench was removed and the patch was banded in the center. Additional bands were placed on the pipe, as needed, to reduce water flow.

The Jubilee patch consisted of a gasket material and a light, flexible cylinder split on one side. The split incorporated flanges and bolt holes that allowed the cylinder to be closed. The patching procedure included wrapping the gasket material around the pipe, placing the cylinder around the gasket material with the bolt holes approximately 180 degrees from the rupture, and inserting bolts through the flanges and tightening them until the leak was stopped or significantly reduced.

Clothing Ensembles.

During the tests, subjects dressed in CON or the NAVCLO experimental AES. In other tests, subjects dressed in the MARCOR experimental-immersion suit or MULFAB suit. During all AES tests, personnel wore the NAVCLO, MARCOR, and MULFAB suits over the CON clothing items. Firefighter helmet with visor, firefighter flash hood, cut-resistant Kevlar^{TM} gloves or rubber gloves, and firefighter boots completed the CON and AES ensembles. The clothing ensemble assignments and number of subjects wearing CON and AESs are presented in Table 1.

All AESs evaluated were "dry suits" and consisted of water-impermeable "booties" or foot coverings, and tight-fitting sleeves and neck collar. NAVCLO consists of a whole-body, single-piece suit composed of polyvinyl chloride-coated cotton with closed-cell neoprene booties, wrist seals, and neck collar. The suit is constructed as "one size fits all" and fits loosely on most subjects. Entrance to the suit occurs through a shielded zipper that extends across the back and shoulders and down the back of the upper arms. The NAVCLO booties were placed inside the firefighter boots.

MARCOR consists of a whole-body, single-piece suit composed of clear urethane and vinyl foot coverings. The suit is also constructed as "one size fits all" and fits loosely on the subjects. Entrance to the suit is gained through an opening at the top of the shoulders. Two elastic drawstrings are used to close a hood around the face and neck and to close the shoulders around the neck. Around the wrists, waist, and ankles are straps and spans to pull the suit tight to the body. In a previous laboratory study (Hagan et al., 1996) the booties were worn over safety boots. However, in this shipboard study, the MARCOR booties were placed inside the firefighter boots.

MULFAB consists of a whole-body, single-piece suit made of 100% vinyl and coated with polyurethane. The suit also incorporates a tight-fitting hood for the head, wrist seals, and foot coverings made of the same material. Personnel enter the suit through a waterproof zipper placed vertically over the chest and abdomen. This suit is available in small, medium, and large sizes. The one suit at our disposal was a size "medium." The MULFAB booties were placed inside the firefighter boots.

Procedures and Physiological Measurements.

Body height and weight were measured using a standard medical scale. During each test, heart rate (HR) and body temperatures were recorded continuously for each subject by a Squirrel data logger (Science/Electronics; Miamisburg, OH). The data logger was enclosed in a waterproof bag and sealed with waterproof tape. The bag was then placed in a small backpack strapped over the shoulders. When dressed in an AES, the backpack was worn under the AES.

Prior to each test, subjects inserted a rectal thermistor to a depth of 20 cm into the rectum for measurement of T_{re}. Skin thermistors were placed on the right upper chest (T_{ch}), right upper arm on the medium deltoid muscle (T_{ar}), right lateral index finger (T_{fi}), right lateral thigh (T_{rth}), left lateral thigh (T_{lth}), right lateral calf (T_{rca}), left lateral calf (T_{lca}), right inside lateral big toe (T_{rto}), and left inside lateral big toe (T_{lto}) for determination of skin temperatures. The values for right and left thighs, calves, and big toes were averaged to provide a mean thigh (T_{th}), calf (T_{ca}), and big toe (T_{to}) temperature. HR was recorded using a telemetry system (Polar USA; Stamford, CT) based on a bipolar chest electrode configuration.

Statistical Analysis.

Statistical analyses were conducted using SAS® System software (SAS Institute Inc.; Cary, NC). Comparison of CON and NAVCLO end-of-exposure body temperatures were performed by analysis of covariance (ANCOVA). Since the test order sequence was established prior to the start of the test series (Table 1), ANCOVA included evaluation of the effects of repeating subjects and tests. In this analysis, the end-of-exposure dependent variables were adjusted for differences in preentry values and duration of water exposure. ANCOVA based on adjustment for preentry values and duration of water exposure was necessary because multiple tests were conducted in the morning and afternoon hours of each day, and cold-water exposure duration varied from test to test. An alpha level of .05 was accepted as significant.

ANCOVA was also conducted to compare end-of-exposure body temperature for subjects wearing CON, NAVCLO, and MARCOR. Values for the single MARCOR test were compared with dependent variable averages from five tests for subjects wearing CON and NAVCLO. Mean (X ± SD) preentry and end-of-exposure body temperatures for subjects wearing MULFAB were calculated, but no comparative statistical analysis was conducted because of the unequal number of subjects and tests among all AES.

Results

Water temperature during the tests averaged (X ± SD) 9.6 ± 1.1°C (50 ± 6°F). Differences in hull- and pipe-patching repair times for subjects wearing CON and NAVCLO were nonsignificant and averaged 10:27 ± 5:18 min:s. Average cold-water exposure time for subjects wearing MARCOR (*n* = 7, test = 1) and MULFAB (*n* = 1, tests = 7) were 14:17 ± 0:57 min:s and 12:53 ± 3:26 min:s, respectively. Comparison of body temperatures prior to and at the end of water exposure for subjects wearing CON and AES are shown in Tables 3 and 4.

T_{re} of subjects wearing CON and NAVCLO, and other AESs, increased slightly during and after each cold-water exposure test (Figure 1). However, the gradual increase in T_{re} during the short period of cold-water exposure and differences in T_{re} between subjects wearing CON and NAVCLO were nonsignificant. Conversely, cold-water exposure was associated with decreases in T_{ch}, T_{ar}, T_{fi}, T_{th}, T_{ca}, and T_{to} for subjects wearing CON and NAVCLO. Comparison of end-of-exposure responses revealed significantly higher mean T_{ch}, T_{ar}, T_{th}, T_{ca}, and T_{to} for subjects dressed in NAVCLO compared with CON (Table 3).

Wearing MARCOR also attenuated decreases in T_{ar}, T_{th}, T_{ca}, and T_{to} during cold-water exposure. End of exposure T_{ch}, T_{ar}, T_{th}, T_{ca}, and T_{to} for MARCOR were similar to NAVCLO and significantly higher than CON (Table 4). T_{fi} at the end of exposure was equivalent for CON and NAVCLO, but it was significantly higher for MARCOR (15.0 ± 0.8°C). While no statistical comparison was conducted, skin temperatures at the end of exposure for subjects wearing MULFAB were similar to those of subjects wearing NAVCLO and MARCOR (Table 4).

HR increased during the initial minutes of each repair task and then declined throughout the remainder of the work period (Figure 2). Differences in HR during each test for subjects dressed in CON and NAVCLO were nonsignificant. HR was similar among the various repair tasks and between MARCOR and MULFAB.

Table 3. Means (X ± SD) of preentry (Pre) and end-of-exposure (EOP) body temperatures (°C) for subjects wearing CON and NAVCLO. ANCOVA of CON and NAVCLO body temperatures (with repeated subjects and tests) represents EOP least square means (EOPLSM ± SE) after adjustment for differences in preentry value and duration of water exposure.

Variable	Phase	CON *n* = 7 tests = 5	NAVCLO *n* = 7 tests = 5
T_{re}	Pre	37.3 ± 0.7	37.1 ± 0.3
	EOP	37.6 ± 0.8	37.3 ± 0.4
	EOPLSM	37.4 ± 0.1	37.4 ± 0.1
T_{ch}	Pre	34.1 ± 1.0	34.8 ± 1.0
	EOP	32.6 ± 1.5	34.3 ± 1.8
	EOPLSM	30.6 ± 0.5	33.7 ± 0.4*
T_{ar}	Pre	31.6 ± 1.7	32.5 ± 1.7
	EOP	22.9 ± 4.0	31.3 ± 2.3
	EOPLSM	23.2 ± 0.7	30.8 ± 0.7*
T_{fi}	Pre	19.6 ± 3.4	16.7 ± 3.7
	EOP	11.6 ± 2.4	10.2 ± 1.6
	EOPLSM	11.1 ± 0.7	10.7 ± 0.7
T_{th}	Pre	28.3 ± 3.3	31.1 ± 1.3
	EOP	14.4 ± 2.4	20.7 ± 2.6
	EOPLSM	14.5 ± 0.8	20.9 ± 0.8*
T_{ca}	Pre	28.3 ± 3.3	30.3 ± 1.7
	EOP	14.4 ± 2.4	20.2± 2.5
	EOPLSM	14.5 ± 0.8	20.2 ± 0.7*
T_{to}	Pre	21.4 ± 3.9	21.1 ± 4.3
	EOP	14.8 ± 1.8	17.3 ± 2.8
	EOPLSM	14.7 ± 0.4	17.3 ± 0.3*

* $p < 0.05$ between CON and NAVCLO EOP least square means.

Table 4. Means (X ± SD) of preentry (Pre) and end-of-exposure (EOP) body temperatures (°C) for subjects wearing CON (average of 5 tests), NAVCLO (average of 5 tests), and MARCOR (average of 1 test). ANCOVA of CON, NAVCLO, and MARCOR body temperatures (with repeating subjects) represents EOP least square means (EOPLSM ± SE) after adjustment for differences in preentry value and duration of water exposure. No statistical significance testing was conducted among CON, NAVCLO, MARCOR, and MULFAB because of unequal sample sizes and tests.

Variable	Phase	CON $n = 6$	NAVCLO $n = 6$	MARCOR $n = 6$	MULFAB $n = 1$ tests = 8
T_{re}	Pre	37.4 ± 0.2	37.2 ± 0.2	37.4 ± 0.3	37.7 ± 0.1
	EOP	37.7 ± 0.6	37.5 ± 0.1	37.7 ± 0.6	37.9 ± 0.6
	EOPLSM	37.7 ± 0.2	37.3 ± 0.2	37.7 ± 0.2	----
T_{ch}	Pre	33.9 ± 1.1	35.0 ± 0.9	37.4 ± 0.3	35.6 ± 0.5
	EOP	30.2 ± 0.6	34.5 ± 1.4	34.6 ± 1.6	35.4 ± 0.6
	EOPLSM	30.0 ± 1.2	34.5 ± 0.7*	34.7 ± 1.1*	----
T_{ar}	Pre	31.8 ± 1.0	32.8 ± 1.0	35.9 ± 0.9	32.9 ± 1.0
	EOP	23.3 ± 2.3	31.6 ± 1.4	32.3 ± 1.5	30.7 ± 1.4
	EOPLSM	23.9 ± 0.9	31.6 ± 0.6*	31.5 ± 0.9*	----
T_{fi}	Pre	19.9 ± 1.2	18.4 ± 3.1	24.1 ± 3.6	19.2 ± 3.7
	EOP	10.8 ± 0.7	10.5 ± 1.0	15.4 ± 1.2	11.6 ± 1.4
	EOPLSM	10.9 ± 0.6	10.8 ± 0.7	15.0 ± 0.8*	----
T_{th}	Pre	29.8 ± 2.4	31.6 ± 1.0	32.6 ± 1.3	32.5 ± 1.7
	EOP	14.8 ± 1.8	21.3 ± 0.8	23.0 ± 2.4	24.8 ± 3.3
	EOPLSM	15.0 ± 1.6	21.3 ± 1.1*	22.8 ± 1.4*	----
T_{ca}	Pre	28.0 ± 2.2	31.0 ± 1.1	32.3 ± 1.3	32.1 ± 1.3
	EOP	14.4 ± 1.3	20.2 ± 2.0	21.9 ± 2.3	23.7 ± 1.7
	EOPLSM	16.2 ± 2.0	19.8 ± 1.1*	20.6 ± 1.7*	----
T_{to}	Pre	21.8 ± 1.5	22.9 ± 4.0	24.8 ± 2.9	21.1 ± 4.0
	EOP	14.2 ± 0.5	18.4 ± 2.2	18.7 ± 1.6	16.0 ± 3.0
	EOPLSM	15.2 ± 0.6	18.6 ± 0.5*	17.5 ± 0.6*	----

* $p < 0.05$ between NAVCLO/MARCOR and CON EOP least square means.

Discussion

The primary objective of the present study was to evaluate the effectiveness of the NAVCLO AES to maintain normal body temperatures during cold-water exposure, and hull- and pipe-patching activities. A limited number of tests were conducted with subjects dressed in MULFAB and MARCOR. However, an unequal number of subjects and tests precluded significance testing among all clothing ensembles. While body temperature responses for subjects wearing MARCOR and MULFAB appear to be similar to subjects wearing NAVCLO, further testing is required before definitive statements can be made concerning the efficacy of MARCOR and MULFAB for cold-water shipboard flooding operations.

Cold-Water Exposure Time.

Subjects wearing CON and NAVCLO experienced an average water-exposure time of 12:12 ± 3:18 min:s (*n* = 7, tests = 5). Average water-exposure time for subjects wearing MARCOR (*n* = 7, test = 1) was 14:17 ± 0:57 and 12:53 ± 3:26 min:s for the subject wearing MULFAB (*n* = 1, tests = 8). Cold-water exposure times were related to the effectiveness of the hull- or pipe-patching activities to terminate water flow into the compartment, and they were unaffected by test order sequence.

Rectal Temperature Responses.

In the present study, T_{re} increased gradually during and after cold-water exposure, and it was unrelated to test order sequence. The response was similar among subjects wearing CON, NAVCLO, MARCOR, and MULFAB. Differences in T_{re} for subjects wearing CON and NAVCLO prior to entry, during cold-water exposure, and at the end of exposure were nonsignificant.

Immersion in cold water normally promotes a decline in core temperature (Keatinge, 1969). However, the absence of a decrease in T_{re} in subjects wearing CON and NAVCLO is likely due in part to the short duration of cold-water immersion that precluded serious convective heat loss. The small increase in T_{re} (~0.21 °C) during cold-water exposure may reflect the shunting of warm blood into the thoracic cavity due to peripheral vasoconstriction (Hayward & Eckerson, 1984), and/or increases in energy expenditure due to shivering and muscular work (Nadel, 1984). In a previous study, Hagan et al. (1996) reported an energy expenditure of 237 W for simulated pipe-patching and shoring activities. However, exercise HR averaged 90 bpm suggesting that the two simulated hull-pipe-patching protocols may not have been similar.

The rate of decline in T_{re} during cold-water exposure is either attenuated or eliminated when subjects wear a whole-body AES. Hayward (1984) reported a rate of decline in T_{re} of $0.13\,^{\circ}C \cdot hr^{-1}$ for subjects immersed to the neck and wearing a whole-body AES, while Shannon et al. (1995) and Hagan et al. (1996) reported that T_{re} remained constant for up to 80 min during immersion in 7.5°C water to the waist and midchest, respectively.

Heart Rate Responses.

HR throughout cold-water exposure was similar for subjects wearing CON and NAVCLO, and was unrelated to the test order sequence. The average HR response patterns (Figure 2) suggest that water immersion and repair tasks were the primary factors affecting HR. The rapid increase in HR during the initial stages of water exposure is likely the result of an increase in sympathetic drive associated with patching activities. However, the gradual decline in HR during the latter stages of repairs may be due to a decrease in exertion as patching became effective or ineffective, or to an increase in stroke volume as a result of shunting of blood from the periphery into the central circulation (McArdle et al., 1984; Haffor et al., 1991).

Skin Temperature Responses.

In the present study, cold-water exposure was associated with decreases in T_{ar}, T_{fi}, T_{th}, T_{ca}, and T_{to} for both CON and NAVCLO, and was unrelated to the test order sequence. However, in subjects wearing NAVCLO, the decreases in T_{ar}, T_{th}, T_{ca}, and T_{to} were significantly less compared with wearing CON. Skin temperatures in subjects wearing MARCOR and MULFAB decreased to levels similar to those recorded for subjects wearing NAVCLO (Tables 3 and 4). These findings support those from previous studies (Hayward, 1984; Toner et al., 1989; Shannon et al., 1995; Hagan et al., 1996) and show that wearing a whole-body AES during cold-water exposure substantially reduces the magnitude of decline in skin temperatures.

T_{fi} dropped rapidly and remained low during cold-water exposure. T_{fi} was equivalent for CON and NAVCLO and averaged $11.0 \pm 0.5\,^{\circ}C$. Slightly lower T_{fi} ($10.7 \pm 1.8\,^{\circ}C$) was recorded for the one subject wearing MULFAB. During the one test in which subjects wore MARCOR, adjusted T_{fi} averaged $15.0 \pm 0.8\,^{\circ}C$ at the end of the cold-water exposure. This response is likely due to the rubber gloves worn by the subjects. The similarity in T_{fi} response for subjects wearing CON, NAVCLO, and MULFAB likely occurred because all subjects wore the water-permeable Kevlar™ gloves during these tests. T_{fi} recorded during the shipboard flood simulator tests was lower than similar temperatures recorded during a laboratory study by Hagan et al. (1996) when subjects were gradually immersed to midchest and showered with 7.5°C water. The lower T_{fi} observed in the present study may be related to the combined effects of the low water temperature (9.6°C) and high water flow rates. The high flow rates could have increased conductive and convective heat loss in the hands and fingers when they were in the water flow around the patch.

Finger Temperature and Patching Effectiveness.

The effectiveness of the various hull- and pipe-patching methods to reduce water flow was 53% and 17%, respectively (Hill & Williams, 1996). The effectiveness of the patching tasks may be the result of low T_{fi} values. It has been shown that hand skin temperatures below 13°C significantly impair manual performance (Clark & Cohen, 1960). Repair work gloves designed to keep the hands and fingers dry and warm may increase the effectiveness of patching activities.

Implication for the Design of Future Damage Control AES.

In a previous study, Hagan et al. (1996) evaluated the effectiveness of NAVCLO, MARCOR, and MULFAB to maintain body temperature during progressive immersion in cold water to midchest level. The findings from that study showed that MULFAB and NAVCLO provided the best protection against decreases in body temperatures during prolonged (up to 80 min) exposure. In the present study, NAVCLO again was shown to provide protection against cold-water exposure, as evident by the higher skin temperatures. Thus, the higher skin temperatures associated with NAVCLO and the other whole-body AESs demonstrate that preventing cold water contact with the skin decreases convective heat loss and maintains a higher body heat content. Wearing the AES over the CON clothing items increased the level of insulation and helped to retain body heat.

An important factor in reducing convective heat loss is the insulation capacity of the AES (Hagan et al., 1996). Hayward et al. (1978) reported that AESs constructed of insulative foam or air-trapping materials are effective in reducing convective heat loss. Shender et al. (1996) reported that the body segments most to least sensitive to changes in insulation level are the chest and abdomen followed by the legs, head, and arms, while Steinman et al. (1987) suggested that AESs should provide thermal protection over the head, arms, torso, legs, and feet using a whole-body design. However, the level of insulation of the AES should not be so large that it promotes heat strain and an increase in heat storage during physical activity. Maintenance of hand and finger temperature is also critical if fine motor skills are to be retained (Clark & Cohen, 1960).

During the present study, the resistance of NAVCLO to rips, tears, and puncture in the presence of rough handling and use was remarkable. However, while leaks through the material of the suit were nonexistent, leakage of water into the suit did occur at the juncture of the skin and wrist seals. This occurred during hull repairs when the hands and arms were placed in line with the high water flow, and during pipe-patching when the hands were held above the head and in line with water flowing from the ruptured pipes. The consequences of these leaks were cold fingers, hands, arms, and greater personal discomfort. In some cases, water soaked the coveralls, wetting portions of the arms and torso; however, skin temperatures from the chest and upper arm recording sites were unaffected.

During some tests, water entered NAVCLO through the rear entry zipper. This occurred most frequently in subjects of short stature when the water level ascended above the base of the zipper. Although water entered the AES and soaked the coveralls over the upper back, skin temperatures at the chest and upper arm measuring sites were unaffected. The leakage problem associated with the rear entry zipper can be solved through the use of a waterproof zipper similar to that employed in the MULFAB suit. In addition, use of a vertical zipper extending over the chest and abdomen would allow for easier entry and exit from the NAVCLO suit.

Conclusions.

The major findings from this study show that while subjects conducting simulated hull- and pipe-patching repair activities in a shipboard environment experienced decreases in skin temperatures, subjects wearing NAVCLO maintained significantly higher skin temperatures compared with subjects wearing CON. Skin temperatures of subjects wearing MARCOR and MULFAB appeared to be maintained at a level comparable with subjects wearing NAVCLO. However, since MARCOR is designed as a "one-time-only" suit, and MULFAB is susceptible to tears to its outer surface, future shipboard evaluations of the durability of MARCOR and MULFAB are required to determine the efficacy of these AESs for use during flooding repair operations. The ability of NAVCLO to maintain higher skin temperatures might be enhanced through improvements in the wrist seals and the use of a waterproof zipper. The addition of a tight-fitting hood to NAVCLO might also reduce heat loss from the head and secure the neck from leakage. In addition, the pliable waterproof work gloves to keep the fingers and hands dry and warm are needed. Waterproof gloves attachable to the sleeves above the wrists of NAVCLO might prove helpful. Perhaps, a gauntlet with a neoprene or latex wrist seal would be effective. This would be especially true when working in a water flow or with hands over the head. If such a glove were to maintain hand and finger temperatures at higher levels, this would improve manual dexterity and patching effectiveness. Further studies of whole-body AES designs are required to identify an AES that meets all fleet damage control flooding repair requirements.

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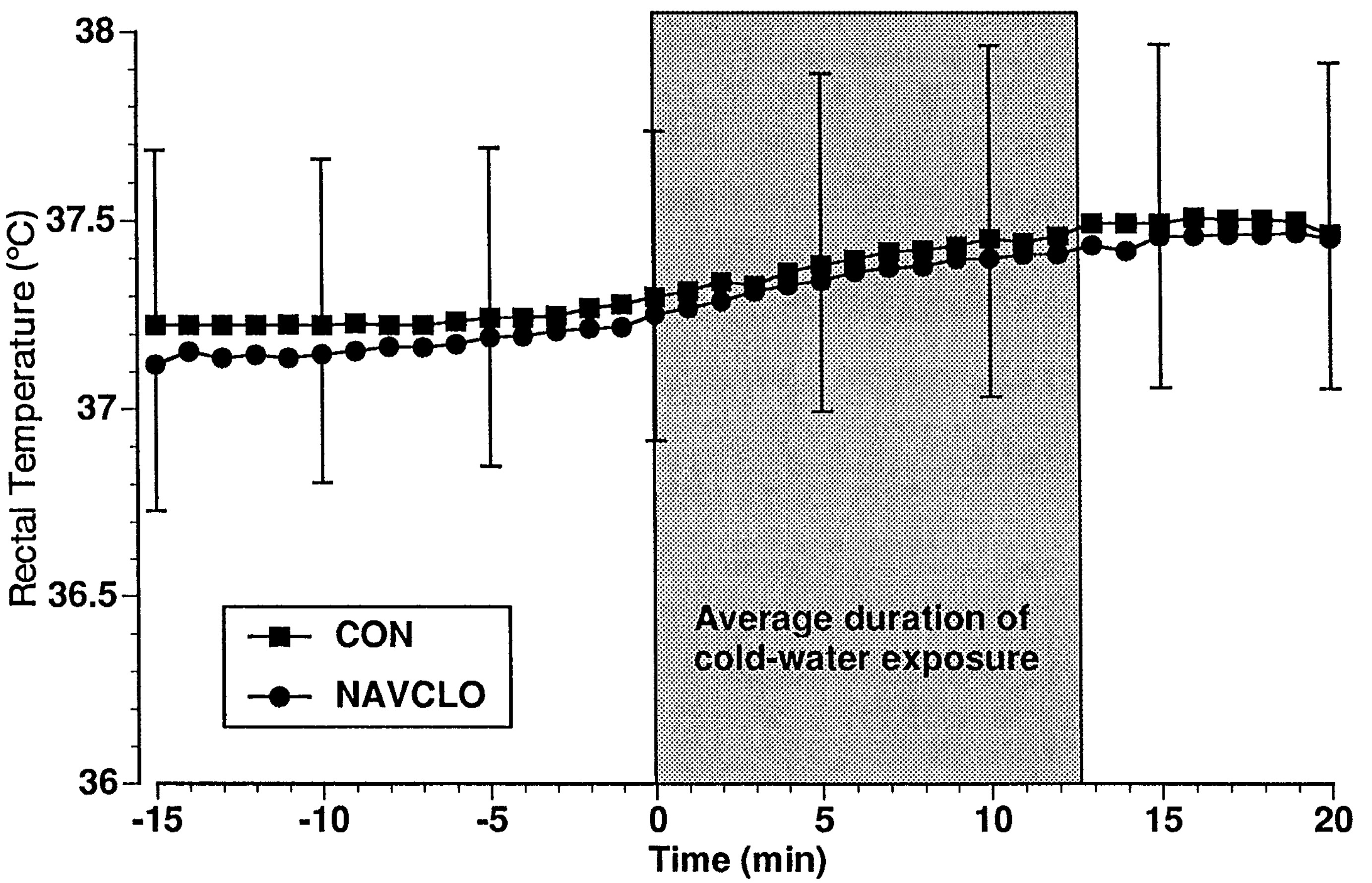

<u>Figure 1</u>. Mean (±SD) rectal temperatures prior to, during, and after cold-water exposure and flooding repair activities for subjects wearing CON and NAVCLO.

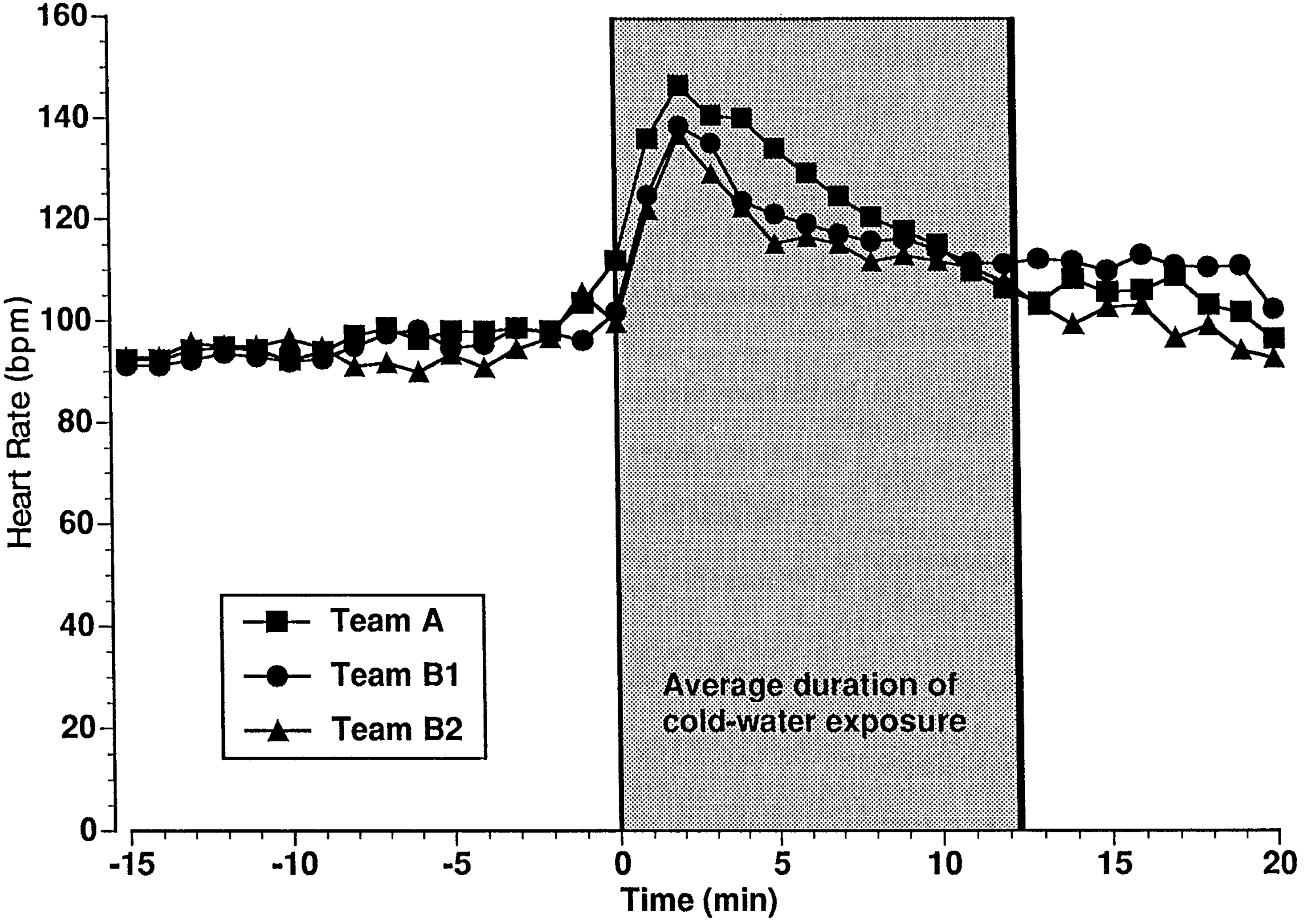

Figure 2. Mean heart rates prior to, during, and after cold-water exposure and flooding repair activities for repair teams A ($n = 4$, 13 tests), B1 ($n = 2$, 13 tests), and B2 ($n = 2$, 10 tests) wearing CON and NAVCLO.

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13. ABSTRACT *(Maximum 200 words)*

This study evaluated the effectiveness of a whole-body anti-exposure suit (AES) to maintain normal body temperatures during shipboard flooding repairs in cold water (9.6°C). Recordings of rectal (T_{re}), chest (T_{ch}), arm (T_{ar}), thigh (T_{th}), calf (T_{ca}), finger (T_{fi}), and big toe (T_{to}) temperatures were made in 8 males performing hull- and pipe-patching activities in a flooding simulator aboard the Ex-USS SHADWELL (LSD-15). A total of 15 tests were conducted over 4 days with subjects wearing coveralls, which represented the control (CON) condition or the Naval Clothing and Textile (NAVCLO) AES. CON clothing was the undergarment for NAVCLO. Average cold-water exposure time was 12:12 ± 3:18 min:s. T_{re} remained constant at 37.3°C during water exposure in subjects wearing CON and NAVCLO. However, cold-water exposure was associated with decreases in T_{ch}, T_{ar}, T_{fi}, T_{th}, T_{ca}, and T_{to} for both CON and NAVCLO. Comparison of end-of-exposure responses revealed significantly higher T_{ch} (33.7 vs. 30.6°C), T_{ar} (30.8 vs. 23.2°C), T_{th} (20.9 vs. 14.5°C), T_{ca} (20.2 vs. 14.5°C), and T_{to} (17.3 vs. 14.7°C) for NAVCLO compared with CON. T_{fi} were similar between CON and NAVCLO and averaged 10.9°C. In conclusion, NAVCLO provided protection against decreases in body temperatures during short-term immersion in cold water during pipe- and hull-patching activities. These findings will aid in the development of AESs for use in shipboard flooding repair operations.

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