Evaluation of Three Cooling Systems Used in Conjunction With the USCG Chemical Response Suit

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In the early 1970s and 1980s, Congress enacted two very important pieces of environmental legislation. The first act was The Federal Water pollution Control Act, later amended to the Clean Water Act (Public Law 92-500). The second act, which proved to be even more encompassing than the Clean Water Act, was CERCLA (Public Law 96-510), which was recently amended and authorized (SARA).

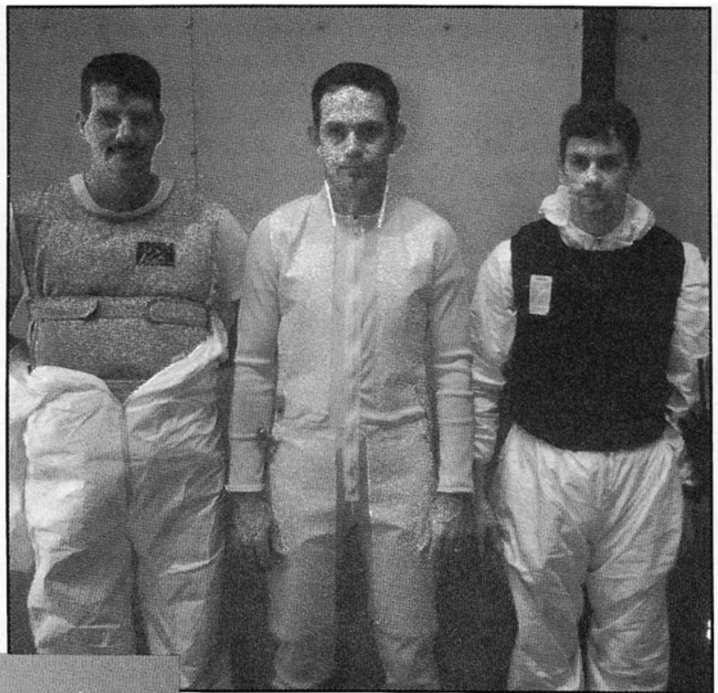
These laws include provisions for federal funds to initiate removal activities at hazardous waste sites. The US. Coast Guard and the US EPA provide the predesignated federal on-scene coordinators for these responses, mandated by law Due to the nature of the hazards at these Superfund cleanup sites, it is a legal requirement that personnel use personal protective clothing and respiratory protective equipment (required by OSHA) during operations on-site.

While inside these suits, the personnel are subjected to severe heat stress conditions as a result of the body's inability to manage the metabolic and environmental heat (NIOSH 1985) The qualities of these suit materials that prevent the toxic atmospheres from entering the workers' inner "microclimate," also prevent the homeostatic process of heat regulation.

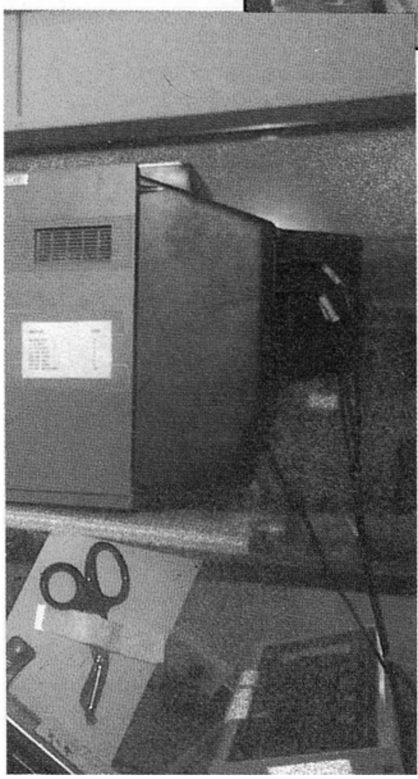
As a result of mutual responsibilities and interests in the field of protective clothing and chemical response, the US Coast Guard and NIOSH, Division of Safety Research, developed a Memorandum of Understanding to conduct a human subject laboratory study.

The study was designed to investigate the benefits of using cooling garments with the US Coast Guard Chemical Response Suit (CRS), a fully-encapsulated Teflon-coated Nomex suit. This CRS was designed to provide the maximum protection to Coast Guard response personnel at hazardous chemical releases. Cooling garments have been used in industry and in space exploration to reduce the effects of thermal stress, and have been applied in the new field of chemical response (1).

The primary research objective of this study was to evaluate the effectiveness of cooling garments in reducing heat strain in three volunteer subjects performing work tests in a controlled



Cooling system test ensembles (left to right): Steele vest, Us. Coast Guard cooling garment, Thermacore system.



Treadmill performance by test subject in fully encapsulated Coast Guard chemical response suit

temperature environment, while wearing the Coast Guard CRS. The physiological changes that were monitored included heart rate, skin temperature, rectal temperature, axillary temperature, and weight loss. Additional goals included an evaluation of the protective equipment used during this study, focusing on the CRS and cooling garments.

Methods

Subjects. The three healthy male volunteers used as the subjects for this study were active duty Coast Guard personnel. All volunteers were non-smokers and had prior experience using self-contained breathing apparatus (SCBA) and protective clothing.

The ages of the participants ranged from 29 to 35 years, with a mean of 32 (+ or – 2.5) Prior to inclusion in the study, all participants signed a NIOSH informed consent statement, completed a detailed medical questionnaire developed for this study through a cooperative effort between the University of Cincinnati College of Nursing and College of Medicine, were given a medical examination by a NIOSH staff physician (which included a 12 lead electrocardiogram and pulmonary function test), and completed a maximal exercise tolerance test. This prescreening was conducted to evaluate each subject's state of health and suitability for the study and to determine each subject's maximal aerobic capacity.

The exercise tolerance tests were conducted by a doctor who is certified by the American College of Sports Medicine, using a modified Balke protocol (2). Treadmill tests began at 5.6 km/hr and 2.5% grade and increased 2.5% in elevation every 2 minutes until the subject reached his maximal exertion level. The maximal aerobic capacity was determined by recording the peak oxygen consumption (V02 max) measured by a Beckman Horizon Metabolic Measurement System. The maximum heart rate recorded was the highest value observed during the treadmill test. A physician was present during these exercise tolerance tests. Percent body fat was calculated from the sum of four skinfold measurements (3). After each subject completed this preliminary testing, he was given training with the protective clothing and equipment to be used in the study, with an emphasis on the fully-encapsulating suit, cooling garments and SCBA. All subjects were thoroughly briefed on the details of the five tests and were given time to practice the subjective scales to be used during the tests. All subjects were randomly assigned their test orders for the first four tests, to minimize any training effects. The fifth test, utilizing the Steelevest, was added after completion of the other four tests due to late delivery of the equipment. The subjects were not provided any heat training prior to their tests.

Procedures. Each of the three subjects participated in all five of the conditions, with a minimum of 24 hours rest between each condition. All subjects were instructed not to eat or ingest caffeine for at least 2 hours prior to each trial, and to only drink water before the test condition. The five conditions (or trials) selected for investigation in this study were:

• the control test, with the subjects wearing shorts, tee shirts, SCBA, helmets and running shoes (weight of the ensemble: 17.84 kg);

• shorts, tee shirts, SCBA, helmets and the Coast Guard Chemical Response Suit (CRS) (weight of the ensemble: 24.48 kg);

• shorts, tee shirts, SCBA, helmets, CRS and cooling garment-the Coast Guard system (an ice and water system) (weight of the ensemble: 31.62 kg);

• shorts, tee shirts, SCBA, helmets, CRS and cooling garment-the Thermacor system (a freon coolant system) (weight of the ensemble: 29.69 kg); and

• shorts, tee shirts, SCBA, helmet, CRS and cooling garment-the Steelevest system (a frozen ice pack unit) (weight of the ensemble: 30.13 kg).

Work/rest regimen. Each test consisted of alternating work and rest periods performed in the heat for a total of 45 minutes (5 minutes of rest followed by 10 minutes of walking, repeated for 45 minutes), and was followed by a 10 minute recovery period (2 minutes of slow walking followed by 8 minutes of doffing procedures). All tests were conducted at a workload equivalent to 30% of each subject's maximum aerobic capacity.

The pretest results, primarily V02 max, were used to establish an individualized work rate. The treadmill speed was kept constant at 4 km/hr (2.5 mi/hr) with the elevation adjusted to correspond to each subject's pretest. This speed was selected based on the investigators' belief that this speed could be maintained comfortably by the subjects wearing the fully-encapsulating suit without markedly altering their stride or biomechanics.

The work regimen and time length of the tests were also based on operational field experiences and seemed to parallel the work levels chosen in other studies (4). All of the tests were performed on a Quinton motor-driven treadmill, Model Q55.

The average forcing function was 3.6% grade, 4.1 Mets, 5.2 kcal/min and the distance walked was approximately 1.2 miles. All 15 tests were conducted inside an Environmental Growth Chamber walk-in room under controlled conditions of 33.9 °C and 82% RH.

Measurements. The laboratory was equipped with a Hewlett-Packard (H-P) Series 200 Technical computer, a 3497 A Data Acquisition System (709), a 3456A digital voltmeter, plotter, printer, and disk drives. The instrumentation used during this study was interfaced with the H-P system, providing direct measurement of heart rate, skin temperature, rectal temperature, axillary temperature, and chamber conditions. The measurements were recorded at 1-minute intervals, plotted real-time graphically and printed out on data sheets.

The heart rate was monitored continuously on a Physiocontrol Life-Pak 6, which was also interfaced to the H-P system through the use of a CWE R-Wave Detector. Two ECG reference electrodes were placed on the subject, mid-sternum and V5 position, and the information transferred utilizing a Physiocontrol Corporation Telemetry System. ECG tracings were run and recorded approximately every 3 minutes during testing.

The temperature measurements were obtained utilizing the thermocouple compensation features of the H-P system. The skin temperatures were measured at six sites using copper-constant thermocouples, calibrated in distilled water ice baths to 0.02 °C (The thermocouples were uncovered.) The mean weighted skin temperatures for the subjects were calculated in the following manner:

$T_{skin} = (0.125\,T1 + 0.125\,T2 + 0.125\,T3 + 0.125\,T4 + 0.07\,T5 + 0.1\,T6/0.67$

where T1 = lateral thigh, T2 = medial thigh, T3 = back, T4 = chest, T5 = arm and T6 = cheek (5).

The rectal temperatures were measured using a flexible vinyl-covered probe (Yellow Springs Instrument Type 401) inserted 10 cm into the rectum. The nude body weight was determined within 5 g, using a platform scale GSE Inc. Model 630, before and after each test condition. Clothed or ensemble weights were obtained prior to entering the chamber.

All of the tests progressed at the prescribed workloads for 45 minutes followed by the 1 O-minute recovery or until one of the following criteria was met:

.90% of the individual's maximum heart rate, obtained during the pretest,

• rectal temperature of 39.0 °C or greater,

•cross-over between rectal and mean skin temperature (provided that rectal-temperature was above 38.0 °C, or

• any objective or subjective signs of the subject's inability to continue with the testing.

The recovery period began at termination and included 2 minutes of slow walking (1.2 mi/hr at 0% grade) followed by 8 minutes of doffing procedures. The subject remained seated during most of the doffing, physiological data continued to be collected and subjective scales were presented twice. The subjects left the chamber after this recovery period and completed the post-test routine prior to leaving the laboratory.

Pre- and post-test data were collected to ensure the safety and health of the subjects. Blood pressure, pulse, temperatures, nude weight, and attitude were monitored before the testing.

Once the testing was completed, blood pressure, pulse, and temperatures were taken again. The time it took for each subject to return to a core temperature of 38°C was recorded.

Sweat loss was calculated from the change in nude weight. Subjective scales and questionnaires were completed after each test. The subjects completed exit interviews following their final test session with summary subjective ratings of the tests, which will be considered below.

Equipment. The fully-encapsulating suit examined in this study was developed by the US Coast Guard in order to safely respond to hazardous chemical releases. This suit is intended to provide the response personnel with the highest level of protection (level A) against toxic atmospheres (6). The CRS is constructed of a Teflon/Nomex/Teflon laminate. The layers of Teflon provide protection from chemicals; the Nomex core provides the structural integrity of the suit. The suit is closed by a non-chemically resistant airtight zipper and a chemically resistant Teflon cofferdam that is heat sealed at the time of use (the suits were not heat sealed in this study). A variety of gloves may be used with the suit; butyl rubber gloves were selected for this study. The Teflon suit has a soft bootee, and over boots are worn to prevent damage to the suit. Neoprene over boots were selected for use in this study.

The cooling system developed for the CRS was designed based on a closed-loop water-recirculated cooling system. The system consisted of three major parts: a full body garment; a heat exchanger and ice-water slurry reservoir; and a centrifugal pump with battery pack. The full-body garment was developed by ILC Dover and consisted of cooling panels located at the neck, front and back torso, and front and back of the upper legs.

The cooling garment was interfaced with a heat exchanger installed in the outer front of the CRS, which is packed with ice to remove the heat from the circulating water.

For this study, 2.27 kg of ice were added to the outer pouch and approximately 1.5 liters of water were used to charge the inner circulating system.

The Thermacor cooling garment provides cooling by evaporating refrigerant inside a flat, thin membrane capsule. The vest utilized in this study contained 16 capsules inside a black nylon upper body, sleeveless vest. Freon R-114 is used as the refrigerant in the vest, due to its properties of non-flammability, low toxicity and boiling point. The flow-rate of the Freon was controlled by small solenoid valves operated by a small, micro-chip control device, battery operated, worn on the outside of the vest. The Freon 114 is stored in small cylinders; for this study, we used a dual cylinder configuration strapped to the back of the SCBA.

The Thermacor unit utilizedin this study was an open circuit device, allowing Freon to be vented out of the suit. During this study, a special venting procedure (developed by Thermacor) was utilized to draw the Freon from the vest and chamber to an exhaust hood in an adjacent laboratory.

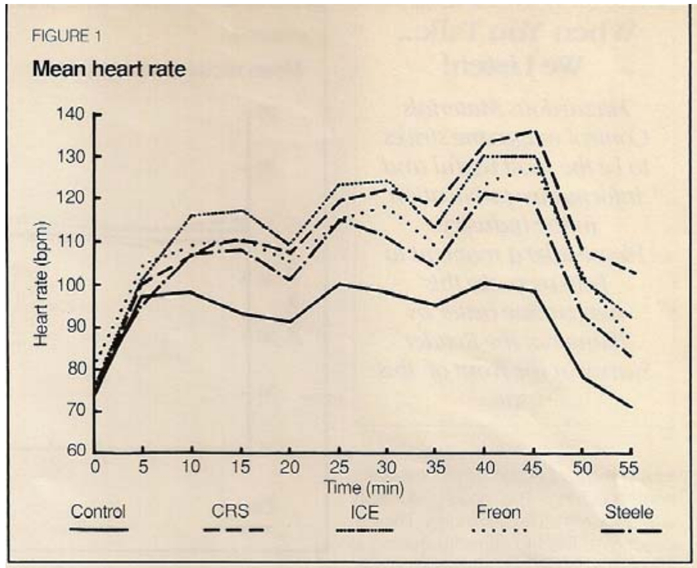
The Steelevest consists of a cotton shell fabric with six externally-insulated pouches, three in the front and the same number in the back. Each pouch is designed to hold either a 5-ounce or 9-ounce cold pack. These packs are mixtures of water and cornstarch that, when frozen, provide an area for heat exchange. The vest is sleeveless and is donned through a hole between the front and back pouches. Once donned, it can be secured to the body with four velcro straps. The vest weighs approximately 5.4 kg when equipped with the six 9-ounce packs used for this study.

The respirator used during this study was the Mine Safety Appliances (MSA Custom 4500) unit, a 50-minute positive pressure, open circuit, SCBA. The helmet used was a Bell bicycle helmet. Each subject was issued underwear (Hanes), shorts, socks and tee shirts from the laboratory stock.

All of the medical and electronic equipment was calibrated in accordance with the manufacturers recommendations prior to use in this study.

FIGURE 1

Mean heart rate



Results

The physiological parameters selected for study included heart rate, rectal temperature, mean weighted skin temperature, and axillary temperature. The general trends will be discussed below. The cooling duration for each cooling garment, obtained by subject notification and then confirmation by the investigator (going inside the CRS and touching the cooling system), was recorded with the mean cooling time for the Coast Guard system (ice) of 37.5 minutes (± 2.7 S.D.), the mean cooling time for the Thermacor (Freon) system of 33-4 (±8.3 S.D.), and the Steelevest over 55 minutes (the actual times were not recorded since it outlasted the testing period).

Mean heart rates increased during all treadmill exercise work periods under all five experimental conditions and decreased during the rest periods (Figure 1). The drops in heart rate during the 5-minute rest periods resulted in only partial recovery, never returning to the original levels. The peak heart rates occurred in all cases during the end of the last work period. The mean rectal temperatures in all experimental conditions showed gradual increases over time (Figure 2) The maximum rectal temperatures occurred during the recovery periods. Over the duration of the tests, mean skin temperature rose under all experimental conditions. The rate of increase was greatest in conditions 1 and 2, the conditions without the cooling garments (Figure 3). The maximum skin temperatures were reached at the end of the last work period.

The average body weight loss was greatest in condition 2, and least under the control condition 4 (Figure 4). The results from the exit interviews, recorded by the subjects after all five experimental conditions were completed, indicated subjective preferences for the ensembles as follows: 2 of 3 subjects rated the Steelevest as their most favorable experimental condition, all of the subjects considered the exercise without any cooling garment as the least favorable (Figure 5).

Discussion

Review and analysis of the data generated from this investigation suggested that the physiological strain induced by exercising with the Coast Guard's Chemical Response Suit (CRS), in a hot environment was reduced when using cooling garments. Differences in skin temperature, heart rate, weight loss, gradient for heat exchange and rectal temperature recovery time were improved when subjects used a cooling garment. Subjective preferences of the users favored the use of cooling garments when performing work with the fully-encapsulating suit.

Personnel must utilize protective equipment when their job responsibilities involve known or suspected atmospheric contaminates, when gases or particles can be generated, and when direct skin contact of materials is a possibility. Respirators can be used to protect the lungs and other organ systems from potential inhalation hazards, while chemical resistant clothing (suits, gloves, boots) can provide protection against direct contacts (29 CFR Parts 1900-1910, NIOSH 1985).

Observations made by investigators during this study indicate that many ergonomic considerations have been overlooked in the design and production of fully-encapsulating suits. Most of the problems identified related to the size (fit) of the clothing.

The awkwardness of wearing the CRS increases the metabolic cost of any activity or exercise performed in these suits (7).

Visibility was also a noticeable problem to the users. This problem resulted from the poor fit and viewing through both the SCBA facepiece and the suit facepiece. All subjects had noticeable problems with fogging inside the suits. The problem was reduced by utilizing defogging agents and training the subjects to clear the facepiece while exercising. This problem can also be reduced by using a nose cup with the SCBA facepiece.

The Coast Guard cooling garment required significant modifications to the

FIGURE 2

Mean rectal temperature

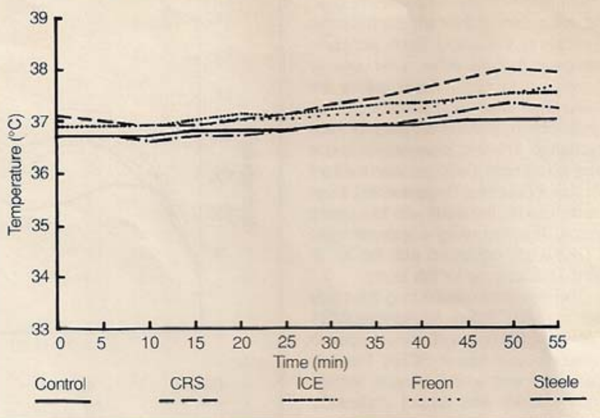
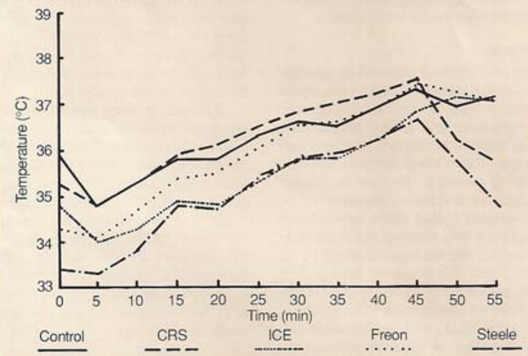


FIGURE 3

Mean skin temperature



tubing and connections to prevent leaks from occurring. The cooling duration was approximately 37 minutes. The ice pouch was filled to capacity, making it impossible to increase the cooling time. This short cooling duration is a severe limitation for this system. The surface area cooled by this unit includes the torso and upper thighs, providing cooling to a greater area than the Thermacor garment. When the CRS was used with the water-ice cooling system, additional weight was placed on the chest and neck, creating stability problems.

The cooling duration for the Thermacor garment was approximately 33 minutes. This system had the potential to cool for an estimated 55 minutes; the lower cooling performance of this unit was traced to an engineering design flaw in a valve and to problems with the Freon cylinders. These problems were resolved by the manufacturer, who has reported improved cooling durations with these corrections.

Researchers testing this Freon cooling garment have also reported improved working times for personnel in fully-encapsulating suits (8) and greater cooling durations,

The Steelevest provided cooling for the entire test period, This system was easy to operate, as it had no mechanical components, It was also the least expensive of the cooling s,y;stems tested, The respiratory protective equipment used in this study (MSA) proved to be extremely reliable throughout the 35 tests,

Conclusion

This study indicates several benefits of wearing cooling garments in conjunction with fully-encapsulating suits under the experimental conditions and environmental factors selected during this investigation, These benefits, comparing the cooled and un-cooled experimental conditions, are manifested in reductions in physiological indicators of heat strain (skin temperature, heart rate, weight loss, gradient for heat exchange and rectal temperature recovery time) and also in the subjective preferences of the users,

Two of the cooling garments tested in this study provided insufficient cooling duration for the subjects; cooling for an average of 35 minutes out of the 45 minutes in the exercise period The third system cooled for the entire test. Further testing of other commercially available products is necessary

Acknowledgement

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Any mention of products or manufacturers is not intended as an official endorsement by either the US Coast Guard or NIOSH,

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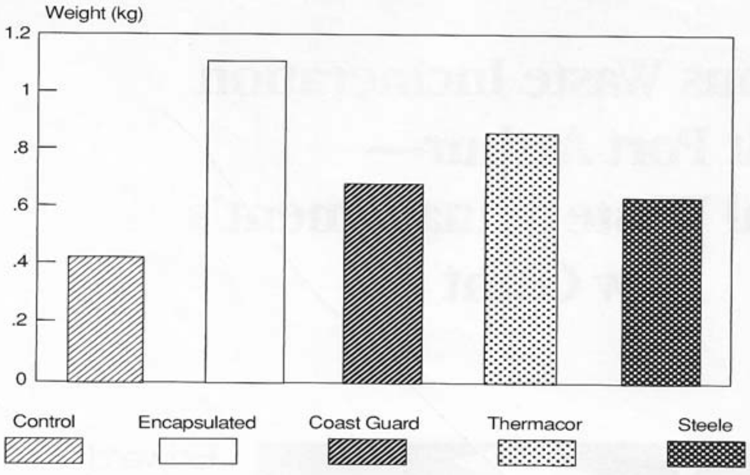
FIGURE 4

Weight loss



Subjective preference of ensembles