Cooling options for shipboard personnel operating in hot environments

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Abstract

DRDC Toronto was asked by the Director of Maritime Health Services to provide information and guidance about the use of cooling vests for shipboard personnel exposed to hot environments. A review of the literature suggested that three options might be available; liquid- or air-cooled systems; phase change material cooling vests; and, extremity cooling. The Steele Vest®, which uses water and corn starch as the phase change material, is currently in use by the US Navy. Laboratory studies have shown that the use of this vest will effectively double tolerance times during light exercise in hot environments (in excess of 40ºC). Extremity cooling through the immersion of the hands and forearm in cool buckets of 10ºC or 20ºC water is currently recommended for use by the UK Royal Navy. As long as 20-30 minute rest periods can be scheduled each hour this is as effective as the use of continuous cooling with the Steele Vest®. The use of a liquid-cooled suit with a battery-operated pump has been shown to reduce the heat strain of boiler room personnel.

The use of an ice vest or alternative phase change material cooling vest would be most effective for personnel performing light exercise such as cage operators involved in the movement of food and equipment, personnel manning the 50-calibre machine guns, brow staff, and firefighters standing in the hangar lobby. The use of forearm and hand immersion in buckets of cool water may provide a better alternative for boarding parties than the cooling vest. Rotation of personnel could be implemented to allow forearm and hand immersion to occur every 30 minutes for a 20-30 minute period. Liquid-cooled suits should be considered as an option for engine stokers.

Other factors such as maintaining proper hydration and a high level of cardiovascular fitness during long operations at sea are also critical for enhancing performance in the heat.

Résumé

Le directeur - Service de santé du personnel maritime a mandaté RDDC Toronto de fournir de l'information et des conseils sur l'utilité des vestes réfrigérantes pour le personnel de bord qui est exposé à des ambiances chaudes. Il ressort d'une étude de la documentation que trois options sont possibles : des vestes refroidies au liquide ou à l'air, des vestes de refroidissement en matériau à changement de phase et le refroidissement des extrémités. La Steele Vest©, dans laquelle l'eau et l'amidon de maïs servent de matériau à changement de phase, est actuellement utilisée par la marine américaine (US Navy). Des études en laboratoire ont démontré que le port de cette veste double effectivement la période de tolérance d'une personne faisant de l'exercice léger dans une ambiance chaude (température supérieure à 40 ºC). Par ailleurs, la marine britannique (UK Royal Navy) recommande plutôt le refroidissement des extrémités par l'immersion des mains et des avant-bras dans des seaux d'eau froide à 10 ºC ou 20 ºC. On peut prévoir des périodes de repos de 20 à 30 minutes par heure, ce qui est aussi efficace que le refroidissement continu à l'aide de la Steele Vest©. Il a été démontré qu'une veste refroidie au liquide à l'aide d'une pompe à piles est efficace pour réduire le stress thermique du personnel travaillant dans la salle des chaudières.

Le port d'une veste réfrigérante ou d'une veste de refroidissement en matériau à changement de phase conviendrait davantage au personnel qui n'a pas à fournir de gros efforts physiques comme les préposés à la cage chargés du transport de la nourriture ou de l'équipement, le personnel affecté aux mitrailleuses de calibre 50, le personnel d'embarquement et les pompiers en service qui attendent dans le hall d'un hangar. L'immersion des avant-bras et des mains dans l'eau froide pourrait constituer une meilleure solution pour les équipes d'abordage que la veste de refroidissement. Une rotation du personnel pourrait être planifiée de manière que l'immersion des avant-bras et des mains dans l'eau froide puisse s'effectuer à 30 minutes d'intervalle pendant 20 à 30 minutes. Le port de vestes refroidies au liquide devrait être considéré comme une option pour les matelots de salle des machines.

D'autres facteurs comme le maintien d'une bonne hydratation et d'un excellent état cardio-vasculaire pendant les longues opérations en mer sont également cruciaux pour améliorer le rendement dans une ambiance chaude.

Executive summary

DRDC Toronto was asked by the Director of Maritime Health Services to provide information and guidance about the use of cooling vests for shipboard personnel exposed to hot environments. A review of the literature suggested that three options might be available; liquid- or air-cooled systems; phase change material cooling vests; and, extremity cooling. The Steele Vest®, which uses water and corn starch as the phase change material, is currently in use by the US Navy. Laboratory studies have shown that the use of this vest will effectively double tolerance times during light exercise in hot environments (in excess of 40ºC). Extremity cooling through the immersion of the hands and forearm in cool buckets of 10ºC or 20ºC water is currently recommended for use by the UK Royal Navy. As long as 20-30 minute rest periods can be scheduled each hour this is as effective as the use of continuous cooling with the Steele Vest®. The use of a liquid-cooled suit with a battery-operated pump has been shown to reduce the heat strain of boiler room personnel.

The use of an ice vest or alternative phase change material cooling vest would be most effective for personnel performing light exercise. For boarding parties that can last for many hours and for more rigorous activity the use of forearm and hand immersion should be considered. Liquid-cooled suits should also be considered as an option for engine stokers.

Other factors such as maintaining proper hydration and a high level of cardiovascular fitness during long operations at sea are also critical for enhancing performance in the heat.

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Sommaire

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Le port d'une veste réfrigérante ou d'une veste de refroidissement en matériau à changement de phase conviendrait davantage au personnel qui n'a pas à fournir de gros efforts physiques. Pour les équipes d'abordage, qui sont en service pendant des heures, et pour des activités plus exigeantes, le recours à l'immersion des avant-bras et des mains devrait être envisagé. Le port de vestes refroidies au liquide devrait aussi être considéré comme une option pour les matelots de salle des machines.

D'autres facteurs comme le maintien d'une bonne hydratation et d'un excellent état cardio-vasculaire pendant les longues opérations en mer sont également cruciaux pour améliorer le rendement dans une ambiance chaude.

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1. Introduction

In support of recent Allied operations shipboard personnel are being exposed to high ambient temperatures and vapour pressures with wet bulb globe temperatures in excess of 35ºC. Since dry bulb temperatures exceed skin temperatures, avenues for convective heat loss are not possible. In fact, radiative and convective heat transfer would be directed towards the body and would represent a source of heat gain. As a result, the only avenue for heat dissipation in these environments is through the evaporation of sweat at the skin surface and through respiration. Depending on the clothing that is worn and the rate of heat production that will vary with activity it is quite possible that the evaporative heat loss required to maintain a thermal steady-state can exceed the maximal evaporative capacity of the environment. In these uncompensable heat stress situations [1], the body constantly stores heat. This results in body temperature continuing to increase until exhaustion and collapse occurs, or else the severity of the set of environmental conditions decreases by seeking shade, removing clothing layers to promote greater evaporative heat loss, or being immersed in a cold water bath or provided with some other source of cooling.

Because of the severity of the heat-stress conditions on board our ships traversing the Persian Gulf and Arabian Sea, DRDC Toronto was contacted by the Director of Maritime Health Services to provide guidance on the potential use of cooling systems for shipboard personnel.

2. Background literature

In essence there are three options available to provide cooling to shipboard personnel. One would be the use of a tethered air- or liquid-cooled system that provides continuous cooling in a controlled workspace environment or a battery-powered liquid cooling suit that offers somewhat greater flexibility of movement but requires replacement of ice blocks every 30 minutes. The second option would be the use of commercially available phase change material (PCM) cooling vests that are worn over a T-shirt or the duty uniform. PCMs could be water or other material that freezes at higher temperatures and thus require less refrigeration power. These systems are less intrusive and provide for freedom of movement but require scheduled breaks every 90-120 minutes to allow for the replacement of frozen PCM. The third option involves the immersion of the hands and/or the feet in cool water during scheduled rest periods. This option requires that a 20-30 minute rest period can be scheduled each hour to allow for sufficient cooling before personnel return to their shipboard activity.

2.1 Air- and liquid-cooled systems

There are an abundance of government reports and open-literature publications that have examined the effects of both liquid- and air-cooled systems during exercise in hot environments while wearing protective clothing. In general, these studies have shown the efficacy of cooling systems compared with no cooling in an operational scenario [2, 3, 4, 5, 6], the effects of cooling provided only during rest periods to simulate operational capability [7, 8], or the combined effects of ambient and conditioned air-cooling provided during exercise and rest periods, respectively [9]. During light and moderate intermittent exercise no difference between liquid- and air-cooling has been reported [4, 5, 7, 10].

McLellan and Frim [10] showed that tolerance time could be extended three-fold from 50 to 150 minutes during heavy exercise at 40ºC and 30% relative humidity while wearing nuclear, biological and chemical protective clothing and an air- or liquid-cooled vest that continuously extracted about 150-200 W of heat from the body. The findings from this same study also revealed that air- or liquid-cooling applied during light exercise changed the conditions from uncompensable to compensable heat stress where core temperatures remained below 38ºC after three hours of treadmill walking.

For all of these studies it must be remembered that the efficiency of the cooling systems is at best 50% since a significant portion of their cooling power is directed towards the surrounding hot environment. In addition, clothing layers between the cooling vest and skin surface slow the transfer of heat from the body. Thus, for optimal efficiency the cooling vest should be worn as close to the skin surface as possible. However, to reduce the initial discomfort of cold air or water in contact with the skin surface it is desirable to wear the cooling vest over a T-shirt or long-sleeved shirt.

The liquid-cooling garment used by McLellan and Frim [10] is actually a component of a portable personal cooling system that uses a plastic bottle filled with ice as the heat sink. The ice bottle, water pump and battery are carried in an insulated nylon pouch that can be strapped to the body in a variety of positions. The volume of the heat sink pack is about 2 L, its weight is about 4 kg, and it provides useful cooling for a period of about 30–45 min under hot ambient conditions for engine room personnel [11] before the ice must be replenished. The heat of fusion for 2 kg of ice is 670 kJ; if released over the above periods of time one could obtain total maximum cooling levels of 372 and 280 W, respectively. With the loss of cooling to the environment, therefore, one might expect approximately 150-200 W of cooling for the body over this 30-45 minute period. This cooling system was used during the Gulf War for our CF Sea King helicopter pilots to extend sortie mission time approximately three-fold [12]. The limitations of this system involve the awkwardness of carrying the pouch to support the block of ice and battery-operated pump, and the need for refrigeration space to freeze the blocks of ice. For a six-hour watch 8-12 blocks of ice would be required to deliver continuous cooling. Short 5-minute breaks would also be necessary to change the blocks of ice.

2.2 Phase Change Material cooling vests

In situations where externally powered air- or liquid-cooled systems are not an option, the use of PCM cooling vests have been examined. The US Navy have provided a series of laboratory and field reports that have documented the efficacy of ice vests for shipboard personnel. Banta and Burr [13] reported on the efficacy of a 6-pack ice vest (Steele Vest®) on the reduction of the heat stress experienced by engine and fire room personnel onboard US ships stationed in the Persian Gulf during the summer of 1989. Over a four-hour watch involving light work not exceeding 250 watts mean heart rates decreased from 97 to 84 beats per minute while wearing the vest. However, core temperatures did not change significantly over the watch or as a result of the cooling vest indicating that these personnel actually were not experiencing much, if any, heat stress during the data collection periods. Subsequently Banta and Braun [14] reported on the use of the Steele Vest® for US Navy H-3 helicopter aircrew during two-hour flights in the Persian Gulf. In-flight and hover temperatures averaged 30.5ºC and 49ºC, respectively. Once again heart rates were reduced approximately 10 beats per minute but little, if any, reductions in core temperatures were observed. Thus these early field studies revealed little benefit for reducing the heat stress but some minor reductions in cardiovascular strain as indicated by the lower heart rates that were recorded.

At approximately the same time collaborative laboratory studies were being conducted by the US Navy Health and Research Center in San Diego and the US Navy Clothing and Textile Research Facility in Natick, Massachusetts. Initial studies by Pimental et al. [15] and Heaney et al. [16] clearly revealed the benefit of the Steele Vest® to reduce thermal strain and extend tolerance time during controlled laboratory conditions. Pimental et al. [15] exposed 14 subjects to 3 environmental conditions of 44ºC and 49% relative humidity, 51ºC and 33% relative humidity and 57ºC and 25% relative humidity for up to 6 hours of alternating 20 minutes of treadmill walking at 4 km per hour with a 3% grade and 40 minutes of seated rest. Subjects completed the trials once without and once with the cooling vest worn over a T-shirt and work shirt. At 44ºC all subjects completed the six-hour trial while wearing the cooling vest whereas only 5 subjects could complete the trial without cooling. Core temperatures were reduced by 0.4ºC after 200 minutes of exposure. In the hotter environments the use of the vest more than doubled tolerance times by extending exposure more than 3 hours at 51ºC and 1.5 hours at 57ºC. Core temperature was reduced 0.7ºC after 80 minutes of exposure to 51ºC and 0.8ºC after 60 minutes of exposure to 57ºC. Whole body sweating was also reduced by 40-50% in the three conditions indicating less dehydration and subsequent requirement for fluid replacement. The cardiovascular strain was also lowered substantially as indicated by the smaller upward drift in heart rate over the course of the exposure [16]. Heaney et al. [17] also reported similar benefits of the Steele Vest® for both men and women although absolute tolerance times were greater for the men because of higher fitness levels. Tolerance times increased from 139 to 340 minutes for the males and from 93 to 240 minutes for the females with the cooling vest during the 20 minutes of treadmill walking and 40 minutes of seated rest at 51ºC and from 88 to 242 minutes for the males and from 71 to 168 minutes for the females with the vest during exposure to 57ºC.

The Steele Vest® used in the above studies consisted of an insulated, fire-retardant cotton canvas vest with six pockets (three vertically positioned on the front and three horizontally positioned on the back) that each contained a frozen 765-g gel strip. The total weight of the vest was 5.1 kg. In an attempt to reduce the total carried weight of the cooling system and to reduce the encumbrance of this original Steele Vest® which involved coverage of the groin and buttocks regions, the Naval Health Research Centre completed laboratory-based studies that compared the efficacy of a smaller four-pack version of the Steele Vest® for Navy firefighting personnel [18, 19]. The fitting of a subject with this 4-pack cooling vest is shown below in Figure 1.

Bennett et al. [18] compared the efficiency of a smaller cooling vest that had four 425-g gel packs with the larger six-pack Steele Vest® during two hours of alternating 30 minutes of rest and treadmill walking at 34.5ºC and 65% relative humidity while wearing firefighting protective clothing. All 12 subjects completed the two-hour protocol with the cooling vests whereas only three subjects completed the trial without cooling. Both cooling vests led to significant reductions in heart rate and core temperatures but these reductions were greatest with the larger cooling vest that became most evident during the latter stages of the exposure. These findings would suggest that the gel packs would require more frequent changing with the use of the smaller vest or that larger gel packs would be required to provide greater cooling with the four-pack vest.

Subsequently, Hagan et al. [19] compared the effects of two four-pack cooling vests using the same protocol described by Bennett et al. [18] except that ambient conditions were more severe at 48ºC and 50% relative humidity. The frozen gel packs were either 425 or 765 g. Tolerance times were increased 20% with the use of either cooling vest but the high ambient temperature and vapour pressure limited exposures to 60 minutes with either vest. Thus the protocol was not long enough to test differences in the cooling power of the two vests. This is consistent with our own findings that have shown little influence of hydration status [20], heat acclimation [21] and endurance training [21])]on tolerance to uncompensable heat stress when exposures are less than one hour. Further, Bain [22] reported that the 6-pack Steele Vest® did not extend tolerance time or reduce core temperature during very heavy exercise (approximately 700 W) that subjects could tolerate for only 40 minutes without cooling while encapsulated in protective clothing. The small 10% increase in tolerance time while wearing the cooling vest was not significant for the six subjects that were tested.

Ramirez et al. [23] studied the effects of the larger four-pack Steele Vest® during a rest and exercise protocol that simulated firefighting exposures of 20 minutes (for one bottle of air) to 48ºC and 50% relative humidity followed by 20 minutes of rest in a cooler environment of 29ºC and 65% relative humidity. After 42 minutes of exposure, core temperatures were significantly lower with the cooling vest and these differences increased to 0.5ºC after 80 minutes of heat stress. Subjects also had lower ratings of thermal stress and consumed less fluid during the cooling vest trial.

Figure 1. *The use of the Steele Vest® with four gel packs positioned two vertically on the front and two horizontally across the back. Reprinted with permission from J.H. Heaney and the Naval Health Research Center, San Diego.*

Other PCM technologies besides ice can be used to provide cooling in the vests. McLellan and Frim [24] evaluated a PCM developed by MicroClimate Systems

Incorporated that changed from solid to liquid at 18.3ºC. Because of its higher phase-change temperature compared with water (i.e., 18.3ºC vs 0ºC) less refrigeration power is required to solidify the PCM and there is less subject discomfort due to contact with a cold surface close to the skin. Although this PCM was less efficient than a tethered air- or liquid-cooled vest for reducing the heat strain of light exercise at 40ºC while wearing protective clothing, the cooling vest did extend tolerance times 30% from 100 to 130 minutes and slowed the rate of heat storage and rise in core temperature.

Presently, the US Navy uses the Steele Vest® with four 765-g gel packs for shipboard personnel in the Persian Gulf (JH Heaney, Naval Health Research Centre, personal communication). Personnel are required to follow existing exposure limits that were developed for different metabolic rates and environmental conditions without the provision of cooling. There are sufficient gel packs (usually a 2:1 or 3:1 ratio) available to allow enough time for packs to be refrozen after two hours of use. An example of the use of the Steele Vest® is shown below in Figure 2 on board one of the US Navy ships.

Figure 2. *An example of the use of the Steele Vest® on board a US Navy ship. Reprinted with permission from J.H. Heaney and the Naval Health Research Center, San Diego.*

2.3 Extremity cooling

In contrast to the US Navy, the UK Navy has performed a series of studies that have examined the efficacy of hand and/or feet immersion in cool water as a means to cool their shipboard personnel. Clearly this method of cooling must occur during scheduled rest periods although the development of liquid-cooled gloves or socks may follow in the future. Cooling through hand or foot immersion occurs through heat exchange in the small arteriovenous anastamoses that remain open and dilated when core temperature is elevated. House [25] reported on a series of studies that were conducted at the Institute of Naval Medicine in the UK. In the first study the effects of hand and forearm immersion in 10ºC, 20ºC and 30ºC was compared following light exercise at 40ºC and 50% relative humidity while wearing firefighting clothing until core temperature reached 38.5ºC. Hand immersion then followed for 30 minutes. Ear canal temperature (as a measure of core temperature) returned to pre-exercise values around 37.0ºC after the 30 minutes of cooling at either 10ºC or 20ºC whereas the cooling provided with the warmer water temperature of 30ºC was less efficient.

The second study reported by House [25] compared three different commercial cooling vests worn continuously with hand immersion in 20ºC water provided only during rest in a two-hour protocol that alternated 30-minute rest and exercise periods. Subjects were again dressed in firefighting clothing and exposed to 40ºC temperatures. After the first 30 minutes of exercise there were no differences among any of the trials. However, after the first rest period ear canal temperature had returned to pre-exercise values around 37.0ºC with the cooling vests and the hand immersion whereas core temperature remained elevated at 37.3ºC with no cooling. After the next 30-minute exercise period core temperatures had increased to 38.1ºC with no cooling and 37.9ºC following the period of hand immersion. Core temperature was lower with two of the commercial cooling vests at 37.6ºC during this second exercise period. However, following the second rest period core temperatures had again returned to around 37.0ºC for the cooling vest and hand immersion trials but remained elevated at 37.8ºC with no cooling. Thus hand immersion in 20ºC water during rest breaks would be as effective as a cooling vest worn continuously during an alternating work and rest schedule. However, if rest breaks could not be scheduled within a two-hour shift then hand immersion may not be a practical alternative. Hand immersion does have the advantage of being low-cost and does not require large areas of refrigeration space to freeze the gel packs.

The final study discussed by House [25] compared hands, feet and hands plus feet immersion in 10ºC water. Following the same protocol review in study 1 above, the data revealed similar cooling with the immersion of either the hands or the feet. The immersion of both the hands and feet was slightly improved over the first 10 minutes of immersion but the time required to undo and then lace the boot after cooling may negate this advantage in the operational setting.

Livingstone et al. [26] have also shown the benefits of hand immersion for subjects wearing chemical protective clothing in cool environments. Subjects immersed their gloved hands for 20 minutes in different temperatures of water between 10ºC and 30ºC while continuing to exercise on the treadmill. Heat lost through hand immersion was significant enough to decrease skin temperature and produce small decreases in core temperature.

Presently, advice given to the Royal Navy is that simple and safe heat-strain management can be achieved by using hand immersion in cool water during regular rest periods rather than by using ice-vests [25].

3. Practical considerations

3.1 Cooling power

The heat of fusion for 1 kg of ice is 335 kJ. Thus, the larger 6-pack Steele Vest®, which contains six 765-g ice packs, would have a total of approximately 4.6 kg of ice available to provide cooling. The heat of fusion for this amount of ice would be 1,340 kJ. In addition, the heat capacity of ice is 2.1 kJ/kg/ºC and for water is 4.2 kJ/kg/ºC. Although the gel packs are frozen at around –20ºC the temperatures of the packs are closer to –5ºC at the beginning of their use and continue to increase in temperature to around +10ºC by the end of 90-120 minutes of use in a hot environment [23]. Thus there would be an additional 48 kJ of heat absorbed as the ice warms to 0ºC and an additional 193 kJ of heat absorbed as the melted ice warms to +10ºC. Thus, in theory the Steele Vest® could absorb 1580 kJ of heat for an average cooling power over 2 hours of approximately 220 W. If we assume 50% efficiency since a significant amount of the cooling power will be directed to the environment, then a reasonable estimate might be 100 W of cooling available for the body for 2 hours. For light exercise, that could be continued for 2 hours, the additional 5 kg mass of the vest would elevate heat production approximately 10 W thereby creating a net cooling advantage of 90 W for the individual. Because of the curvilinear relationship that exists between tolerance time and metabolic rate during uncompensable heat stress [27], 90 W of cooling could double tolerance times during light intermittent work equivalent to a metabolic rate of approximately 210 W from 150 to 300 minutes as shown by Pimenthal et al. [15] and Heaney et al. [17]. However, as the rate of heat production increases with heavier exercise 90 W of cooling would provide less of an improvement in tolerance times. Thus although improvements of 20-30% might still be evident at metabolic rates close to 500 W, the absolute increase in tolerance time might only be 10-15 minutes. At very heavy metabolic rates, in excess of 750 W, the cooling vest would not provide sufficient cooling to noticeably affect tolerance times [22].

Other smaller-sized vests would of course provide less cooling. In theory, the 4-pack Steele Vest® that contains four 765-g gel packs would provide two-thirds of the cooling power of the larger six-pack configuration. One would expect, therefore, that the improvements in tolerance time and reductions to core temperature would be less with the four- versus the six-pack vest. However, direct comparisons between these vest configurations have not been made. Instead, Bennett et al. [18] showed the advantage of the larger six-pack configuration versus a smaller vest that contained only four 425-g packs and Hagan et al. [19] reported no difference between four-pack designs that contained either 425-g or 765-g gel packs. Presently, the US Navy uses the four-pack Steele Vest® that contains the larger 765-g gel packs.

In theory, 10 litres of 20ºC could absorb 42 kJ of heat for every 1ºC increase in water temperature. Thus, if water temperature increased 5ºC over a 10-minute period this would indicate the absorption of 210 kJ of heat or a cooling power of 350 W. These numbers are in agreement with the values calculated from the changes in body temperature by House [25].

3.2 Comparison to other physiological manipulations

We, and others, have examined extensively the separate and combined effects of heat acclimation, aerobic training and hydration status on tolerance during uncompensable heat stress. During heavy exercise where tolerance times are less than 60 minutes, little, if any, benefit has been observed following an aerobic training program and/or 6 days of heat acclimation [21], glycerol hyperhydration prior to [28] or rehydration during the heat exposure [20]. Thus, the use of a cooling vest may provide a small advantage during heavy exercise compared with these other physiological manipulations. Increases in heat tolerance of 20-30 minutes during light exercise at 40°C and 30% relative humidity while wearing protective clothing are common following heat acclimation [29], short-term aerobic training [30] or rehydration during the heat exposure [20]. These improvements are only slightly less than the 40-minute increase in tolerance time noted with the use of phase change material cooling vest under similar environmental conditions, exercise intensity and clothing configuration [24]. Thus a cooling vest could offset the impairment associated with fluid restriction [20] or enhance the tolerance for those unaccustomed to exposure to hot environments [29].

Recently we have shown that endurance-trained subjects can tolerate higher increases in core temperature than their unfit counterpart [31]. The difference of almost 1ºC translated into an increase in tolerance time from 70 minutes for the untrained to approximately 115 minutes for the endurance-trained subjects while performing light exercise in a hot environment and wearing protective clothing. Thus ensuring personnel maintain a high level of aerobic fitness and do not carry an excess amount of body fat will optimise their tolerance during work in hot environments. Cooling vests would, of course, be beneficial for all personnel performing light exercise but the vests may be especially beneficial for personnel that have allowed their fitness level to deteriorate while aboard the ship.

3.3 Storage and recharging

The use of a cooling vest necessitates a large refrigeration space to freeze and recharge gel packs. The US Navy presently employs a minimum 2:1 ratio of unused frozen packs to packs used in the vests. Thus if each ship had 100 four-pack vests maintaining this 2:1 ratio would involve refrigeration space for a total of 1200 gel packs. If the gel packs are replaced every two hours this 2:1 ratio would allow a minimum four-hour period for the refreezing of the packs. Replacement of gel packs every two hours implies the availability of personnel to assist with the transfer of gel packs or the availability of additional vests that could be equipped with frozen packs and exchanged for the used vests after two hours.

If extremity cooling is to be used, enough space and buckets are required for personnel to immerse their hands and forearms for 30 minutes in cool water every 30-60 minutes. Thus more defined work and rest schedules are necessary to ensure the effectiveness of this method of cooling.

3.4 Mobility

Although the cooling vests are relatively light at around 5 kg they do impose a penalty by increasing heat production and restricting movement. The increase in heat production will be most noticed during weight-bearing activities such as walking or climbing and could vary anywhere from 5 to 40 W depending on the intensity of work.

3.5 Integration with other clothing

The use of the cooling vests will effectively increase the size requirements of any other protective clothing layers that are to be worn over the duty uniform. Specifically, the use of frag vests or body armour may prevent the fitting of the cooling vest under these protective layers.

3.6 Laundering

The vests need to be washed and laundered on a regular basis to prevent the build-up of sweat odours that would accumulate with continued use.

4. Recommendations

1. The Steele Vest® or some comparable commercially-available vest would provide the greatest benefit to personnel performing light to very light work. Thus cage operators involved in the movement of food and equipment, personnel manning the 50-calibre machine guns, brow staff, and firefighters standing in the hangar lobby would notice the greatest benefit with the cooling vests.

2. Unless refrigeration space is available for boarding parties, the use of the cooling vests would not seem practical since these boarding activities can last up to 12 hours. The use of forearm and hand immersion in buckets of cool water may provide a better alternative than the cooling vest as long as rotation of personnel could be implemented to allow forearm and hand immersion to occur every 30 minutes for a 20-30 minute period. If rotation of personnel is not possible then the use of ice vests would provide some initial relief for up to 2 hours but the added weight of the vest would eventually represent a metabolic disadvantage. Ultimately the decision to use a cooling vest should depend on the expected duration of the boarding party. Ensuring proper hydration schedules (see below) becomes even more critical if no cooling can be provided because of the length of the operation on board another ship.

3. Either cooling vests or hand and forearm immersion in cool water may provide some alleviation of the heat strain experienced by stokers in the engine room. Because of the higher temperatures and heavier work rates the vests may have to be changed more frequently to continue to provide benefit. Alternatively, a portable battery-powered liquid-cooling suit has been shown to provide effective relieve from the heat stress experienced by these personnel [11].

4. Maintaining proper hydration is critical to optimise performance in the heat. The use of the camel-back® water supply system has been shown to be an effective means of encouraging proper rehydration for US Navy personnel.

5. A high level of aerobic fitness is the most important factor determining tolerance to heat stress. Personnel should be given ample opportunity to maintain or even improve their current fitness level throughout the duration of the shipboard operation.

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List of symbols/abbreviations/acronyms/initialisms

DRDC	Defence R&D Canada
PCM	phase change material
kJ	kilojoule
W	watt

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14. ABSTRACT

(U) DRDC Toronto was asked by the Director of Maritime Health Services to provide information and guidance about the use of cooling vests for shipboard personnel exposed to hot environments. A review of the literature suggested that three options might be available; liquid- or air-cooled systems; phase change material cooling vests; and, extremity cooling. The Steele VestÒ, which uses water and corn starch as the phase change material, is currently in use by the US Navy. Laboratory studies have shown that the use of this vest will effectively double tolerance times during light exercise in hot environments (in excess of 40ºC). Extremity cooling through the immersion of the hands and forearm in cool buckets of 10ºC or 20ºC water is currently recommended for use by the UK Royal Navy. As long as 20-30 minute rest periods can be scheduled each hour this is as effective as the use of continuous cooling with the Steele VestÒ. The use of a liquid-cooled suit with a battery-operated pump has been shown to reduce the heat strain of boiler room personnel.
The use of an ice vest or alternative phase change material cooling vest would be most effective for personnel performing light exercise such as cage operators involved in the movement of food and equipment, personnel manning the 50-calibre machine guns, brow staff, and firefighters standing in the hanger lobby. The use of forearm and hand immersion in buckets of cool water may provide a better alternative for boarding parties than the cooling vest. Rotation of personnel could be implemented to allow forearm and hand immersion to occur every 30 minutes for a 20-30 minute period. Liquid-cooled suits should be considered as an option for engine stokers.
Other factors such as maintaining proper hydration and a high level of cardiovascular fitness during long operations at sea are also critical for enhancing performance in the heat.

(U) Le directeur - Service de santé du personnel maritime a mandaté RDDC Toronto de fournir de l'information et des conseils sur l'utilité des vestes réfrigérantes pour le personnel de bord qui est exposé à des ambiances chaudes. Il ressort d'une étude de la documentation que trois options sont possibles : des vestes refroidies au liquide ou à l'air, des vestes de refroidissement en matériau à changement de phase et le refroidissement des extrémités. La Steele Vest©, dans laquelle l'eau et l'amidon de maïs servent de matériau à changement de phase, est actuellement utilisée par la marine américaine (US Navy). Des études en laboratoire ont démontré que le port de cette veste double effectivement la période de tolérance d'une personne faisant de l'exercice léger dans une ambiance chaude (température supérieure à 40 ºC). Par ailleurs, la marine britannique (UK Royal Navy) recommande plutôt le refroidissement des extrémités par l'immersion des mains et des avant-bras dans des seaux d'eau froide à 10 ºC ou 20 ºC. On peut prévoir des périodes de repos de 20 à 30 minutes par heure, ce qui est aussi efficace que le refroidissement continu à l'aide de la Steele Vest©. Il a été démontré qu'une veste refroidie au liquide à l'aide d'une pompe à piles est efficace pour réduire le stress thermique du personnel travaillant dans la salle des chaudières.
Le port d'une veste réfrigérante ou d'une veste de refroidissement en matériau à changement de phase conviendrait davantage au personnel qui n'a pas à fournir de gros efforts physiques comme les préposés à la cage chargés du transport de la nourriture ou de l'équipement, le personnel affecté aux mitrailleuses de calibre 50, le personnel d'embarquement et les pompiers en service qui attendent dans le hall d'un hangar. L'immersion des avant-bras et des mains dans l'eau froide pourrait constituer une meilleure solution pour les équipes d'abordage que la veste de refroidissement. Une rotation du personnel pourrait être planifiée de manière que l'immersion des avant-bras et des mains dans l'eau froide puisse s'effectuer à 30 minutes d'intervalle pendant 20 à 30 minutes. Le port de vestes refroidies au liquide devrait être considéré comme une option pour les matelots de salle des machines.
D'autres facteurs comme le maintien d'une bonne hydratation et d'un excellent état cardio?vasculaire pendant les longues opérations en mer sont également cruciaux pour améliorer le rendement dans une ambiance chaude.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) heat stress; cooling vests; hand immersion; liquid-cooled suits