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DEPARTMENT OF DEFENCE

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION

AERONAUTICAL RESEARCH LABORATORIES

MELBOURNE, VICTORIA

Systems Technical Memorandum 87

A LABORATORY EVALUATION OF LIQUID COOLED VESTS FOR NON-COMBATANTS

by

Karen NAGLE and B.A.J. CLARK

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SUMMARY

A laboratory experiment was used to assess the value of two commercial liquid cooled vests in alleviating some of the physiological and psychological effects of heat stress on human performance. For conditions of 55°C (dry bulb) and 55% relative humidity, both vests reduced the rate of rise of body temperature, heat storage rate, and mass loss due to thermoregulatory sweating of three subjects. All subjects stated that the vests provided some relief from heat stress, but no effects of heat stress on performance were demonstrated. It is suggested that for non-combatant personnel, vests like those tested may provide a practical and economical way of alleviating some of the discomfort and adverse physiological effects of heat stress when environmental control is not practicable.

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CONTENTS

AUTHORSHIP NOTE

The task described in this report, viz the evaluation of particular liquid cooled vests, was assigned in 1980 to Ms Karen Nagle with assistance in psychological aspects to be given by Mrs Jocelynne Gordon. Ms Nagle carried out the literature survey and was responsible for all non-medical aspects of the practical evaluation of the vests in the environmental chamber at the RAAF Institute of Aviation Medicine, Point Cook.

A first draft of the literature survey and practical evaluation was written by Ms Nagle. Other members of Human Factors Group at the time, Mr K.C. Hendy and Dr K.W. Anderson, examined the draft and suggested improvements. Ms Nagle revised the draft before she transferred to another Department in mid-1983, but this second draft was still not of the standard required for publication in the ARL series. In the interests of providing a published record of work done, this account of the work was prepared in 1984 as a complete re-write of the second draft by the Group Leader, Dr B.A.J. Clark. Subsequent attempts to have further editing input by Ms Nagle have been unsuccessful and the text is now published with the caveat that Dr Clark has no specialist training in physiology and was not present at any of the experimental sessions. It is for this reason that the work is published as a Technical Memorandum rather than as a Report, reflecting the tentative, as opposed to authoritative, nature of its conclusions.

At the time the task was proposed, it was (and still is) closely related to the aviation heat stress work being done by Human Factors Group, and its acceptance then was favoured by the opportunity it provided for new staff to gain experience in the application of academic skills to practical problems. Although the experimental design and procedures described have some obvious shortcomings, this account of work done nevertheless serves to indicate some methods by which heat stress can be investigated. The problem of heat stress and its effects on performance in the military environment is a long-standing issue. Interest in it is increasing because of the increasing apparent need for clothing which will provide protection in the presence of toxic chemical and biological agents; in general, such clothing exacerbates environmental heat stress.

1. INTRODUCTION

It is a common problem in the Australian military environment for the ambient conditions to tend towards the uncomfortably hot. There has long been a suspicion, hard to prove or disprove by experiments, that heat-stressed personnel may not perform their allotted tasks well. In some cases air conditoning has been installed to moderate otherwise near intolerable conditions, but in most cases this is impracticable for reasons of expense or physical constraints. Typical heat-stress situations might arise in military vehicles, ships and aircraft, or in fixed installations. The personnel at risk of performance degradation may be doing physical or sedentary duties and may be either combatant (e.g. infantry) or non-combatant (e.g. firemen, fixed radar operators) although the distinction may not always be sharp.

ARL was tasked by a military agency to test two commercially supplied liquid cooled vests as a possible palliative for heat stress in a fixed installation where the duties were predominantly non-combatant and sedentary. Although this was an attempt at a 'quick-fix' solution to a specific problem, the work is reported in the context of wider applicability within the Defence system in that the equipment, methodology and findings may be considered in and for other tasks and situations, particularly of the non-combatant types.

In discussions with the tasking agency, it was agreed that experiments would be carried out with the actual operating staff, i.e. a user trial. Unfortunately, the agency workload was at that time so high that only three subjects could be spared, and then only for a few days at most. This unanticipated restriction was largely counter to the requirements of experimental design which is generally a precondition for sufficiently precise and statistically valid results to be expected. Nevertheless the evaluation was continued in the reasonable expectation that any practical benefits and disadvantages would at least become known. Furthermore, assessment of the experimental method devised (including the suitability of the human performance tests) and the original author's experience in running the trials were considered as further useful output which would be of value in planning experiments for related tasks in future. The task was thus conceived, progressively, as having two components:

(i) a literature survey restricted to the topics of possible heat stress effects on sedentary workers, and methods of alleviating heat stress such as the use of personal cooling garments; and

(ii) a user trial of specific equipment, with an externally imposed condition of fewer subjects and/or exposures than would normally be required for a scientific experiment.

2. EFFECTS OF HEAT STRESS

The literature about heat stress and its effects on human task performance covers the range of tasks from heavy physical work through fine manipulation to mental activities, and the range of stress variously imposed by temperature, humidity, radiant heating, air movement, clothing insulation and clothing permeability. There appears to be no simple way of using current knowledge to set boundary conditions of heat stress for a given amount of performance degradation on a specific task, although there have been numerous attempts to provide an empirical basis for broad classes of tasks and conditions, e.g. NIOSH (1972), Ramsay and Morrissey (1978).

2.1 Physiological Responses

Within the ambient 'prescriptive zone' (about 5°C to 31°C Effective Temperature (ET)), human body temperature is generally regulated within well defined limits (Slonim 1974, Ernsting 1978). Outside this zone, additional thermoregulatory responses are necessary to counter heat gain or loss. The initial effects of exposure to high temperature include lassitude, discomfort, irritability, difficulty in performing physical work and a predisposition to muscular cramps. The first and most readily observable physiological reactions to overheating during prolonged exposure to hot environments are the adjustments to cutaneous blood flow and the presence of sweat. It is the cardiovascular system which is the primary effector mechanism of these responses.

2.1.1 Cardiovascular Adjustments

Vasomotor adjustments occur particularly in the distal parts of the body (e.g. hands and feet) where surface-area: volume ratios for heat exchange are high. There are marked increases in blood flow to these regions under conditions of thermal stress, accomplished primarily through the graded release from vasoconstrictor tone and adjustments of heart rate rather than stroke volume. Associated with these adjustments of cardiac output are redistributions of blood flow away from the viscera and to the body periphery. Severe heat stress is generally manifested by heart rates greater than 140 beats/min, decreased systemic arterial pressure and often, syncope (heat collapse) (Slonim 1974, Leithead and Lind 1964).

2.1.2 Sweating

Sweating is a thermoregulatory process which is under both central nervous system (sympathetic) and peripheral control. Sweat glands secrete in response to a combination of raised core temperature (above 36.6°C or so) and skin temperatures greater than about 34°C. Cooling of the skin will inhibit sweating even if core temperatures remain elevated Skin temperature is linked to subjective comfort (Allnut and Allan 1973).

The rate of sweat evaporation from the skin and hence net cooling effect is dependent on three physical factors:

(i) the water vapour pressure difference between the skin surface and surrounding air;
(ii) air movement over the skin surface; and
(iii) the fraction of the skin surface that is wet with sweat.

Hidromeiosis (inhibition of sweating) may occur if the skin remains wet during prolonged exposure to high temperatures although such inhibition rapidly ceases if the skin is dried. If fatigue of the sweat glands ever occurs, it is a small factor compared with the effects of local skin temperature and hidromeiosis (Kerslake 1972).

Provided that hydration levels are maintained, extremely high rates of sweating (> 0.8 kg m^{-2} h^{-1}) can be sustained for extended periods. If subjects do not drink water while working in the heat there is a progressive reduction in sweat rate (Pearcey 1956). The effect of dehydration on circulatory adjustments to heat stress is mediated primarily through the effect of unreplaced water and secondarily through the effect of sodium chloride losses. Substantial mineral losses may occur as a result of prolonged sweating.

As early as 1928, Adolph (1928) showed that dehydration resulted in a reduction in circulating plasma volume much greater than if plasma volume loss were directly proportional to the total volume of fluid lost. Up to 50% of this lost fluid can however be replaced by shifting fluid from other body compartments (Myhre and Robinson 1971). Water deficits of as little as 1 to 2% of body mass may result in increases in circulatory strain, heart rate and rectal temperature (which is a good indicator of core temperature). The magnitude of these responses increases linearly as water deficit increases. During prolonged work in the heat, dehydration and loss of salt may be the most important limiting factors which eventually lead to heat exhaustion. One of the initial effects of sweating is to increase plasma tonicity, thereby stimulating the thirst mechanism, although only 1/2 to 2/3 of the net fluid loss is replaced by ad libitum drinking in the short term. Water replacement and even overhydration is therefore of considerable importance in coping with heat stress as it tends to lower core temperature and helps to maintain sweating at high rates.

2.1.3 Respiratory adjustments

An elevation of body temperature to above 39°C may produce accelerated breathing (hyperpnoea) in some susceptible individuals. This hyperpnoea and the resulting CO_2 'washout' (hypocapnia) has serious consequences and may impair both physical and mental workload capacity and could, ultimately, result in the cessation of breathing. Particularly in an aviation environment, hyperpnoea is of importance for it increases the susceptibility of aircrew to other stressors such as hypoxia and acceleration. Moreover, voluntary control of hyperpnoea is extremely difficult.

2.1.4 Metabolic responses

An increase in body temperature is generally associated with an increased metabolic rate (Q_{10} effect). Adaptation to prolonged exposure to high temperatures generally involves a lowering of basal metabolic rate associated with a reduction in thyroid activity (Ernsting 1978).

2.2 <u>Mental and Psychomotor Responses</u>

2.2.1 Mental performance

Wing (1965) and Wing and Touchstone (1965) suggested that the time-temperature curve for unimpaired mental performance lies below the comparable thermo-physiological tolerance curve at every point in time. Wing's work formed the basis for a proposed standard (NIOSH 1972) for exposure times for human performance in hot environments. The NIOSH proposal represented a general limit for all stages of task practice, all degrees of temperature acclimatisation, all types of mental performance tasks and all types of working conditions. However, it is unrealistic to expect a single curve to represent this spectrum of data, and furthermore, there is a paucity of empirical support for Wing's findings. One current view is that for simple tasks, there may be only a marginal decrement in mental performance before imminent thermo-physiological collapse (Hancock 1981, 1982). Experiments with mental tasks and reaction time tasks indicate that increases of exposure time and/or temperature will increase the likelihood of performance impairment (Ramsey and Morrisey 1977). Mental performance impairment during heat exposure may be reduced by practice, motivation and repeated exposure (Hancock 1982).

2.2.2 Tracking performance

The tracking response is one of the most widely studied measures of human performance under heat stress. Three factors are involved in tracking performance:

(i) fine control sensitivity;
(ii) arm-hand steadiness; and
(iii) analysis of movement.

Viteles and Smith (1946) suggested that tracking performance deteriorated under conditions of combined noise and heat stress. In a comprehensive study of tracking performance in the heat, Blockley and Lyman (1951) suggested that the onset of heat-related performance decrements was a function of individual tolerance time. Furthermore, heat-stress induced deterioration was reduced by superior operator skill. Generally, performance deterioration coincided with a 0.9°C rise in body temperature. In contrast, Russell (1957) could establish no systematic effect of repeated exposure to heat stress on either movement or pressure tracking. He concluded that performance impairment was highly dependent on individual task characteristics and appeared only when ambient temperature varied outside rather narrow limits.

Mackworth (1961) found a decrement in tracking performance during heat exposure. Mackworth's experiment was on the effects of heat stress on wireless operator performance and involved intermittent heavy physical effort in combination with precise muscular control. It is possible that his results may have been confounded by effects of muscular work: this work presumably added to the environmental effect of increased body temperature.

Nunneley, Dowd, Myhre, Stribley and McNee (1979) examined the effects of two heat stress levels on a compensatory tracking task with three configurations of task difficulty. Compared with task performance in a thermally comfortable environment, there was no effect of heat on the two most difficult tasks but there was a significant small improvement on the simplest task at elevated temperatures. Epstein, Keren, Moisseiv, Gasko and Yachin (1980) used a tracking and vigilance task, with competition between subjects to provide motivation. At ambient temperatures above 50°C, rectal temperature and heart rate rose to mean values as high as 38.5°C and 130 min^{-1} respectively. Despite a 15 times increase in drinking rate there was a 1.4% dehydration response. The performance parameters of speed, accuracy, coordination and vigilance all changed significantly in the hot environment. Epstein et al. suggested a trade-off between speed and accuracy as an explanation of some of the observed changes with the greatest performance decrement occurring at the highest exposure temperature (35°C ET) and when core temperature was also elevated by about 0.9°C. The increase in speed of performance could be not be explained as an improvement in vigilance alone as it was also accompanied by an elevation in percentage error rate.

2.2.3 Dual task performance

Bursill (1958) reported performance decrements due to attentional narrowing on a concurrent visual reaction time task during exposure to heat stress (35°C ET). In contrast, Iampietro, Melton, Higgins, Vaughan et al. (1972) found no performance decrements after 30 minute exposure to 35°C ET on a test of paired combinations of arithmetic tasks, and on monitoring and tracking tasks. At 43.3°C ET however, performance decrements were manifest after 5 minutes. Iampietro et al. explained this as an inability of their subjects to attend adequately to the dual task and suggested that this mechanism may be instrumental in accounting for earlier time-related decrements in dual task paradigms. Azer, McNall and Leung (1972) found a significant deterioration in both a central tracking task and peripheral reaction time during a 125 minute exposure to 32.2°C ET. In apparent contrast, Bell and Provins (1962) reported an initial beneficial effect of heat on performance and no decrement in long-term performance.

2.3 Performance and Physiological State

The studies reviewed above have used environmental parameters such as ambient temperature as the experimental variables. Other studies have been done where body temperature(s) was manipulated, and examples are reviewed below.

Wilkinson, Fox, Goldsmith, Hampton and Lewis (1964) manipulated deep body temperature from a resting level of 36.5°C to values of 37.3°C, 37.9°C, and 38.5°C. Only at the highest of these levels was there an impairment in speed and accuracy on an arithmetic task. A rise of 2.0°C in body temperature was considered the minimum for a marginal impairment of mental performance.

Allan and Gibson (Allnut and Allan 1973, Allan, Gibson and Green 1979, Allan and Gibson 1979, Gibson and Allan 1979, Gibson, Redman and Allan 1980, and Allan, Belyavin, Flick and Higenbottam 1981) in particular have contributed greatly to knowledge of the relationship between body temperatures and task performance. Briefly, they found that performance correlated better with comfort than with any other single parameter, and is undoubtedly affected by the complex relationship between skin and deep body temperatures and their respective rates and direction of change. Comfort (or more correctly, 'discomfort') is strongly influenced by skin temperature, but even high levels of skin temperature are without adverse effect on performance until body temperature rises above 37.6°C. Even highly motivated subjects were strongly affected by heat and their performance was especially impaired when they were assigned complex missions that required a high state of vigilance, cooperation and coordination.

Nunneley, Reader and Maldonado (1982) provided further support for the hypothesis that the perceived level of discomfort strongly affects task performance under heat stress. Head cooling under conditions of heat stress not only reduced discomfort and increased accuracy, but also slowed reaction time. This is in accord with the result of Allan et al. (1981) that reducing skin temperatures (liquid conditioned garment inlet temperatures) reduces the reaction-time shortening characteristic of hyperthermia. (This characteristic is not usually considered advantageous as it is gained at the expense of an increase in errors.)

2.4 Discussion of Literature

The diversity of findings on the extent and even direction of performance changes as a consequence of heat stress indicates the complexity of the topic. Many factors appear to influence the results of experiments. For example, operator skill affects the limits of performance decrement in the heat, and extreme heat may differentially affect skilled and unskilled workers (Mackworth 1961). Nunneley et al. (1979) found that if subjects are trained to a plateau level before the commencement of an experiment then the temperature-induced performance decrement is smaller than for less trained subjects. Furthermore, the more complex the task, the earlier the heat stress-related decrement. These findings may be of special significance in new or emergency situations, outside the laboratory, for which previous operator practice might be limited. Concomitant exercise, high motivation and skill, sleep deprivation and fatigue may also interact and alter the effects of heat stress on performance (Hancock 1982).

Some of the papers reviewed above describe performance improvements under heat stress conditions. This is explicable in terms of the inverted-U hypothesis of arousal. Briefly, task performance is supposed to peak at some optimum level of 'arousal'. Arousal is difficult to define because of its multi-dimensional nature; e.g. motivation, fear, discomfort and the task itself affect an individual's state of arousal. If circumstances are such that increased arousal is required to improve task performance, mild heat stress may raise arousal by a suitable amount. Poulton (1976) drew this to attention and extended it by categorising the arousal into two components, one which acted prior to the experiment (a novel situation for subjects), and another of enhanced activity related to a desire to escape from the adverse situation during the experiment. Of course, some aspects of performance may improve with this enhanced activity (e.g. speed) at the cost of decreases in other aspects (e.g. accuracy).

Other apparent anomalies in experimental findings may appear when more than one stressor is present. Interaction between stressors (such as heat and sleep loss, Poulton et al. (1972)) does not necessarily result in the additive combination of effects from the stressors acting singly, again because of the complex nature of arousal and its effect on performance.

From the foregoing, it appears that careful experimental design and choice of experimental conditions should produce findings consistent with the state of physiological parameters such as skin and body temperature values and rates and directions of change of these temperatures. However, in many experiments, it is the environmental parameters such as ambient temperature and humidity which have been the experimental variables, and little or even no monitoring of physiological parameters has been done. This is presumably because the task of the experimenters has been to find a relationship between the factors of direct practical interest, viz environmental conditions and task performance. Ramsay and Morrissey (1977) collated accounts of this sort of work, i.e. laboratory and field studies of environmental heat stress and task performance, and selected results were used as the basis for a set of iso-decrement curves of performance against temperature and time on specific task categories. The selection criteria were ready categorisation of type of task, and ambient conditions data which could be reduced to a common single parameter, viz Wet-Bulb Globe Temperature (WBGT). They noted that it was primarily an operational or managerial decision for a predicted performance decrement to be considered of practical significance. (The same applies to an actual decrement.) In view of the statements above in this section, Ramsay and Morrissey's curves may not be reliable guides unless the circumstances of interest are comparable with those present when the original data were collected. It may not be easy or even possible to make the comparisons.

3. PERSONAL THERMAL CONDITIONING

In actual military situations, it is not always possible or practicable to provide adequate control of the thermal environment. Consequently under conditions of prolonged or continued thermal stress, operator performance may be degraded or the task even abandoned. In extreme cases, syncope or hyperthermia may occur without the operator being fully aware of his degraded or worsening physiological and psychological states.

One method (and in many cases, the only practicable method) of dealing with this type of problem is to provide individuals with personal cooling systems (see Burton and Collier 1964, Nunneley 1970). Typically, these systems provide some means of removing metabolic heat at or close to the skin surface.

3.1 Air Ventilated Garments

In the air ventilated suit, cool air at a slight excess pressure is passed through long lengths of flexible porous tubing sewn into a garment which is worn close to the skin. Cooling is by means of evaporation of sweat, and heat flow to the air from the skin. This type of device functions even when the wearer has partly or fully impermeable clothing, as in the case of protective clothing designed to cope with a hazardous chemical or microbiological environment. However, air ventilated systems have unpopular characteristics, apart from the cumbersome nature of the garments, viz:

(i) they tend to be noisy;
(ii) it is usually not easy to provide the mass flow and temperature combination required for cooling while maintaining an acceptable level of comfort;
(iii) unless the system is fitted with a water condenser or absorber to remove evaporated sweat, the working fluid usually cannot be recirculated, so that air has to be used as the working fluid and purification/decontamination of the inlet air may be difficult or expensive; and
(iv) subjects tend to complain of discomfort from uneven cooling.

3.2 Liquid Conditioned Garments

In this case, the working fluid is liquid and this has several advantages compared with air as the working fluid: smaller pumping power required, ease of recirculation, quietness, and less subject discomfort. The simplest systems are vest-like garments capable of holding a few kilograms of water which is initially fully or mostly frozen. More complex systems have the fluid circulating in flexible tubing sewn into undergarments and skull caps, with thermoelectric heat exchangers or other refrigerating equipment to remove the metabolic heat transferred to the circulating fluid. Precise control of the fluid flow rate and garment inlet temperature is sometimes incorporated. The simplest systems have been used by mine workers and the most complex, by astronauts. Systems of complexity intermediate between these extremes have been or could be used by, for example, firefighters, stokers, furnace workers, surgeons (to inhibit sweating during operations), military pilots, and persons wearing impermeable protective clothing. Where controlled heating as well as cooling is required and is made available by the system, the term 'liquid conditioned' is apposite; otherwise, 'liquid cooling' is appropriate. The actual liquids used are usually water or water with anti-freeze additives such as ethylene glycol.

It is important to note that garments intended for civil use may not be satisfactory in some aspects of military use, particularly combatant duties. This explains the 'non-combatant' distinction in the title of this document.

4. LABORATORY INVESTIGATION

4.1 Aim of Investigation

The aim of the practical part of this study was indicated by the requesting agency as the determination of whether specific liquid cooled vests (supplied by the agency from commercial sources) would be suitable for alleviating heat stress effects on non-combatant sedentary personnel in thermally stressful conditions.

4.2 Method

4.2.1 Facilities and Equipment

Planning for the practical aspects of this study was governed initially by the facilities and equipment available.

By agreement with the Commanding Officer of the Royal Australian Air Force Institute of Aviation Medicine (IAM), Point Cook, Victoria, the IAM environmental chamber was made available for this study, and the CO also accepted medical responsibility for experimental subjects at IAM. For the temperature and humidity values used in the heat stress exposures, the environmental control within the chamber was expected to be within limits of $\pm$ 1°C (dry bulb) (Tdb) and 3% relative humidity (RH), respectively.

The chamber was sufficiently large for accommodating at least six subjects, and a window allowed continuous observation of the subjects by the experimenter. An intercommunication system allowed conversation between subjects and the experimenter. A Gilson Polygraph (Model R612) was available for recording of physiological data. Thermistors used with the Polygraph for temperature measurement were calibrated and checked for linearity before use, using the standard method in the Gilson operating manual. A Light Laboratories Minilab WBGT Index Meter Mk 5 was available for environmental measurements of Tdb, Wet-Bulb Temperature (Twb) and Small Black Globe Temperature (Tsg).

An insulated container capable of holding 50 kg of an ice-water mixture was fitted with a centrifugal pump to provide an external supply of coolant liquid for one of the vests to be evaluated. Inlet and outlet temperatures to this reservoir could be monitored with mercury-in-glass thermometers to within ± 0.1°C under calibrations traceable to National Measurements Laboratory. A Five-Choice Task (Leonard 1959) previously used in an ARL experiment (White and Clark 1975) and psychological tests from the Australian Council for Educational Research (ACER) were available for subject performance testing. Of these ACER tests, one called the Number Comparison Test was judged suitable for use in the evaluation. Platform scales for subject mass determinations were also available.

The garments supplied for evaluation were both from the same foreign manufacturer* and were of identical size. Each consisted of a vest constructed from flexible sheet urethane-coated nylon, with interconnected front and rear compartments of equal areas. Vest 1 was fitted with a battery driven submerged centrifugal pump to circulate water through passages in and between compartments. Vest 2 had the same arrangement of circulation passages as Vest 1, but was connected via flexible tubing to the cooled liquid (water) supply. A detachable hood with circulation passages inbuilt could be attached to either vest for additional cooling via the wearer's head.

4.2.2 Subjects

As the primary purpose of the study was to solve a pressing practical problem, the requesting agency initially agreed to provide sufficient potential user personnel to meet the requirements of a properly designed controlled experiment. Unfortunately and at short notice, the agency advised that workload pressures would allow only three volunteer subjects to attend and only for a few days at that. As potential user judgement of the acceptability of the vests was an important part of the study, substitution/complementation of subjects by 'outsiders' was rejected, quite apart from the difficulty of arranging substitutes at short notice.

Prior to the exposures in the chamber, a briefing about the purpose and conditions of the evaluation was read to the subjects who each then consented to take part. The subjects were aged between 26 and 33 years. Their frequent and lengthy exposures to high ambient temperatures in their occupational environment had presumably rendered them heat acclimatised before the present trial. They each performed better than the population age norm on a standard step test, indicating good physical fitness.

4.2.3 Exposure conditions and protocols

The choice of exposure conditions was governed by a desire to reproduce the most severe environment likely to be encountered by the users, viz Tdb about 55°C and RH about 55%, corresponding to about 40°C WBGT in the absence of additional radiant heat load. A two-hour exposure was planned as a compromise: the subjects' actual shift times at high temperatures are usually longer, but longer exposures in the chamber would have increased difficulties with subject scheduling.

Continuous recording of each subject's electrocardiogram (ECG), skin temperatures and core temperature was planned. Apart from the value of

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* Details available to qualified requestors from Director, Aeronautical Research Laboratories.

these data as results, they also provided a means of monitoring the subject's fitness for continuing the exposure. The following criteria were set for premature termination of the exposure:

(i) core temperature (Tb) > 39°C or more than 2°C above value immediately before exposure or rate of rise greater than 1°C/h; or
(ii) heart rate (HR)> 140 beats/minute; or
(iii) at the direction of the medical observer; or
(iv) at the request of the subject.

Because of the small number of subjects, balancing was not possible. Order effects would therefore be ignored, with exposures ordered for each subject as No Vest, Vest 1, and Vest 2.

4.2.4. Procedure

Immediately before heat exposure, the subjects were weighed without clothing. Skin-temperature transducers (thermistors) were then attached at the following locations: upper chest (T1), upper arm (T2), and thigh (T3). ECG leads were attached to monitor cardiac activity. Subjects then inserted a temperature-sensing (thermistor) rectal probe to a distance of approximately 120 mm past the anal sphincter. The subjects donned shorts, and when appropriate, either Vest 1 or Vest 2. The subjects then entered the chamber and sat at a table where the Five-Choice Task apparatus was placed. Light reading matter was also provided. Temperature-sensor and ECG leads were fed through a hole in the chamber wall and were connected to the Gilson polygraph when the subjects were seated. The hole was then plugged with foam rubber to prevent the exit of warm air from the chamber. At this point timing for the exposure began.

In the case of Vest 1, it had been determined that an initial fill of 3 kg of an ice-water sludge would take about 15 minutes to reach 33°C. It was therefore decided that refilling with the ice-water mixture would have to take place every 10 minutes, and an attempt was made to maintain this schedule throughout the exposures with Vest 1. Note that there was no control of coolant flow rate or temperature with this vest.

For Vest 2, connection was made to the coolant liquid supply as soon as the subject was seated. The vest inlet coolant temperature was maintained at approximately 20°C, and inlet and outlet temperatures could be monitored to 0.1°C.

Measurements of environmental parameters in the chamber were made using the Minilab system. The sensor tree (small black globe, wet bulb and dry bulb sensors) was placed at face level as close to the subjects as practicable. The sensor lead passed out of the chamber along with the physiological leads. Values of WBGT were calculated from the measured Tsg, Tdb and Twb values rather than from the WBGT scale. This avoided some of the inaccuracies in WBGT measurement that are inherent in this device (Ross 1982).

The Number Comparison Test and the Five-Choice Task were administered soon after each subject entered the chamber. Originally the plan was to administer the tests again when body temperature had risen 1°C above its initial value, but this protocol was not followed when the observed temperature rise was less than 1°C in several cases. Here the tests were re-administered before the subject left the chamber. (No record of actual time of or between tests was available to the second author.) When it was becoming apparent that any particular exposure would have to be terminated prematurely on the criteria given in section 4.2.3, the tests were administered before the subject left the chamber. One specific exception to this is mentioned in section 4.4.2.1.

Subjects had been requested in the briefing to follow their normal diet and have at least their normal fluid intake prior to the exposures. No drinking was allowed during the exposures. At the completion of each exposure, subjects left the chamber, were weighed immediately (with vest removed if they had been using one), showered, and were encouraged to rehydrate. Opinions of how subjects felt about effects of the exposure on their task performance and what they thought of the vests if they had just used one were requested in an informal debriefing after each exposure.

It did not prove possible to follow the order of exposures planned, particularly because of difficulties with subject availability and limitations of the environmental chamber control system which caused delay in commencing exposures. The actual order of exposures for the individual subjects was:

Subject 1	No Vest	Vest 1	Vest 2	No Vest
Subject 2		No Vest	Vest 2	Vest 1
Subject 3		No Vest	Vest 1	Vest 2

The first of the Subject 1 exposures was disregarded in the results because the chamber temperature was about 45°C Tdb, 45% RH, WBGT 35°C and therefore markedly lower than planned. Thus the actual order of exposures was neither constant nor varied systematically. Furthermore (for reasons not known to the second author), the last exposure of Subject 3 (which was the seventh of the ten exposures) included the use of the hood with Vest 2.

All exposures were terminated prematurely, four for excessive heart rate or body temperature rise and the other five for reasons apparently not recorded and not known to the second author (see Table 1). The pre-exposure thermal conditions were not standardised and were apparently not recorded except in one case (Subject 3, Vest 2) when the day was unusually hot (> 40°C).

TABLE 1

Exposure duration (minutes) and reason for termination of exposure

	CONDITION		
SUBJECT	NO VEST	VEST 1	VEST 2
1	45 HR>140/min	110 HR>140/min	90 (NR)
2	30 Tb rise>1°C/h	60 (NR)	60 (NR)
3	60 HR>140/min	60 (NR)	70* (NR)

(NR): Apparently no record of reason for premature termination of exposure

* Vest 2 plus hood

Furthermore, it did not prove possible to have each exposure at the same time of day: some were in the morning, and others were after lunch. No subject was used twice on the one day, but the intervals between successive exposures ranged from 1 day to 13 days.

Temperature and humidity fluctuations within the chamber during the exposures were about double the expected values mentioned in section 4.2.1.

4.4 Results

4.4.1 Physiological results

4.4.1.1 Body temperature rise rate

In the No Vest (control) condition, all subjects had a marked rise in body temperature (Table 2). Rate of rise of body temperature was rapid (> 1.0°C/h) and in the case of Subject 2 this rate (1.6°C/h) exceeded the limiting value suggested as safe by Stribley & Nunnelev (1978). Continued exposure to these experimental conditions would have resulted in an unacceptably high body temperature, syncope and hyperthermia in all subjects.

Under the severe heat stress conditions of this experiment the wearing of a liquid cooled vest did not prevent body temperature of subjects from increasing above the pre-chamber entry values. For all subjects, the wearing of a liquid cooled vest reduced the rate of rise of body temperature. Rate of rise of body temperature was less with Vest 2 than with Vest 1. The statistical significance of these results is not testable because of uncertainty about and variation in the experimental conditions. The difference between the two vests most probably reflects the fact that the inlet water temperatures to Vest 2 were generally lower than to Vest 1. Vest 1 had to be drained of water and recharged with ice at frequent intervals, and low temperatures of the circulating water were maintained only for relatively short periods after recharging.

TABLE 2

$$\frac{\text{Final - initial body temperature (°C)}}{\text{Exposure duration (h)}}$$

	CONDITION		
SUBJECT	NO VEST	VEST 1	VEST 2
1	1.0	0.4	0.2
2	1.6	0.6	0.5
3	1.0	0.6	0.3*

* Vest 2 plus hood

4.4.1.2 Mass loss rate

The rate of mass loss, effectively the sweat rate, is shown in Table 3.

TABLE 3

$$\frac{\text{Final - initial body mass (kg)}}{\text{Exposure duration (h)}}$$

SUBJECT	CONDITION		
	NO VEST	VEST 1	VEST 2
1	1.44	0.50	0.59
2	1.90	0.49	0.49
3	2.04	0.86	0.59*

* Vest 2 plus hood

4.4.1.3 Heat storage rate

The heat storage rate S was calculated with the following formula derived from one given by Slonim (1974):

$$S\ (\text{watt}) = \frac{0.84 \times \text{final body mass (kg)} \times \text{rise in body temperature } (^\circ\text{C})}{\text{exposure duration (h)}}$$

Values of S are shown in Table 4.

TABLE 4

Heat storage rate (watt)

SUBJECT	CONDITION		
	NO VEST	VEST 1	VEST 2
1	73	33	12
2	118	43	36
3	77	44	19*

* Vest 2 plus hood

4.4.1.4 Heart rate change

Final and initial values of heart rate are given in Table 5, together with the exposure durations from Table 1.

TABLE 5

Final - initial heart rate (beats/min)
Exposure duration (min)

	CONDITION		
SUBJECT	NO VEST	VEST 1	VEST 2
1	$\frac{140-90}{45}$	$\frac{130-110}{110}$	$\frac{120-110}{90}$
2	$\frac{120-100}{30}$	$\frac{110-100}{60}$	$\frac{130-90}{60}$
3	$\frac{150-70}{60}$	$\frac{100-80}{60}$	$\frac{90-80*}{70}$

* Vest 2 plus hood

4.4.2 Performance results

4.4.2.1 Five-Choice Task

The results from the Five-Choice Task were lost before preparation of this version of the account of the evaluation. (The circumstances of this loss are unknown to the second author.) However, the summary of the results from earlier drafts provided the following information (with editing by the second author indicated by square brackets):

"Under the heat stress conditions of this experiment, this task was found to be an insensitive measure of performance. These results are essentially similar to those reported by White and Clark (1975) although response rates in these trials were higher than those of the previous study. No general trends could be established because of curtailed (missing) data. The Five-Choice equipment malfunctioned under the extreme environmental conditions during the first occasion on which it was used. Also, [when] subject 2 was prematurely removed from the heat chamber on his control trial because of an unacceptably high rate of rise of body temperature [the Five-Choice Task was not done]. Overall there was no [statistically significant] effect of heat stress or wearing of a vest on number of responses (total, correct or incorrect). There did however appear to be a slight practice effect within subjects from trial to trial at the same time of testing."

It is understood by the second author that the task was performed for a fixed time, which was either two or three minutes.

4.4.2.2 Number Comparison Test

The results of the Number Comparison Test are summarised in Table 6. A comparison of subject performance on the Number Comparison Test at the beginning and end of each experimental session revealed that there was a general performance decrement over all conditions. For the control condition the performance decrements (defined as the percentage decreases from first to second testing) for Subjects 1, 2 and 3 were 9.1%, 10.3%, and 9.1% respectively. The number of incorrect responses was generally greater on the second testing as compared with the first testing. Given the experimental paradigm it is impossible to distinguish if this reflects the effects of heat stress, exposure duration or a temperature-time interaction.

The average performance decrement was 9.5% for the control condition and 5.9% for the conditions in which subjects wore a cooling vest. No conclusions can be drawn from the results to distinguish between the effectiveness of Vest 1 and Vest 2. Again, given the way in which the experiment was performed, it is not possible to test the statistical significance of the trends.

4.4.3 Subjective comments

All subjects expressed positive attitudes towards wearing the vests and the benefits they thought the vests provided with respect to alleviating heat stress. All subjects expressed the view that they felt "better" when wearing a liquid conditioned vest during heat exposures in the chamber.

In the control condition all subjects stated that they were willing to stay in the chamber for longer periods despite the fact that by the end of an exposure they were observed to have difficulty in concentrating on reading matter and in coordinating eye-hand movements. All subjects did not seem to be fully aware of their deteriorating physiological and psychological condition. Additionally, all subjects expressed the view that their performance was much better than their scores indicated.

Vest 1 was reported as subjectively cold and unpleasant to wear. All subjects expressed some concern at the prospect of wearing these vests in a real world situation. The vests were heavy when filled with coolant, and were awkward to don and uncomfortable to wear. (Subsequent correspondence indicated that the subjects did indeed decline to use the vests in their usual working environment.) During the evaluation it was noticed by the experimenters that air locks occasionally formed in the delivery tubes and thereby reduced or prevented the flow of water through the vests. Regular checks for air locks had to be introduced as the subjects were often unaware that the water had stopped circulating.

5. DISCUSSION

5.1 Physiological Aspects

Despite the faults in the evaluation procedure, the results give a clear indication that the vests reduced the physiological strain. With the vests, the rate of rise of body temperature (and hence heat storage rate), the

TABLE 6

Results of Number Comparison Test

	RESPONSES				
	TOTAL	CORRECT	INCORRECT	SCORE	HEAT STORAGE RATE
SUBJECT 1 NO VEST	initial 18 final 17	18 16	0 1	18 15	38
VEST 1	initial 18 final 17	18 17	0 0	18 17	28
VEST 2	initial 18 final 17	18 16	0 1	18 15	14
SUBJECT 2 NO VEST	initial 18 final 19	17 16	1 3	16 13	99
VEST 1	initial 28 final 25	26 24	2 1	24 23	25
VEST 2	initial 24 final 26	22 22	2 4	20 18	37
SUBJECT 3 NO VEST	initial 18 final 19	18 17	0 2	19 15	98
VEST 1	initial 18 final 17	18 15	0 2	18 13	40
VEST 2*	initial 19 final 19	18 18	1 1	18 18	20

initial = first testing in chamber
final = final testing in chamber

TOTAL RESPONSES refers to the total number of number comparison pairs attempted.
CORRECT RESPONSES refers to the total number of number comparison pairs correctly identified.
INCORRECT RESPONSES refers to the total number of number comparison pairs incorrectly identified.
HEAT STORAGE RATE refers to the rate of heat storage of the subjects in watts, measured between the times of initial and final testing. Note that the heat storage rates in Table 4 are for different time intervals.

* Vest 2 plus hood

sweat rate and circulatory strain were all reduced by amounts of practical significance.

Because of the way that thermoregulatory sweating is governed by local skin temperature, sweating was inhibited over the skin areas cooled by the vests. It appeared that the vests did not cause any marked interference with vasodilative heat exchange and sweating in the distal parts of the body, and this agrees with results from other evaluations of liquid cooled vests (Brown and Roberts 1981, Edwards and Harrison 1978).

Perhaps the most important advantage of wearing these vests was that the mass loss of subjects due to thermoregulatory sweating was reduced to less than 50% of that of the control condition, despite the limited amount of body surface area that was covered. Without a liquid conditioned vest or other means of removing metabolic waste heat, subjects given continued exposure to WBGTs of about 40°C or more would tend to suffer rapid, clinically significant dehydration. Such dehydration would interfere with sweating and reduce work capacity through secondary effects on circulatory adjustments. Even if partial relief is given by means of liquid cooled vests, significant dehydration may still occur if subjects are exposed to heat stress conditions (comparable with conditions in this trial) for extended periods. Such reservations have been expressed in other studies (Edwards and Harrison 1978) and may be of practical or applied significance in those industrial situations where liquid conditioned vests are worn to reduce heat storage rate and thereby extend task duration (Del Rosa and Stein 1977, Lind 1962). Under such circumstances, when an equilibrium body temperature has been established at a higher than normal level, dehydration rather than heat storage rate may be the most limiting factor in determining duration of exposure (Lind 1962).

Vest 2 appeared to reduce physiological stress to a greater extent that Vest 1, presumably because of the better maintenance of low inlet coolant temperatures to Vest 2. It is also interesting to note that the heat storage rate for subjects in the No Vest condition (see Table 4) was more than double the basal metabolic heat production rate for a 70 kg man.

5.2 Psychological Aspects

From the literature surveyed, it seems that marked degradation in simple, well-practised task performance as a consequence of heat stress occurs only when physiological collapse is imminent (e.g. Hancock 1981, 1982). Any earlier, more subtle degradation (or even improvement) is not easy to demonstrate, especially for the well practised and familiar tasks used in this evaluation. Heat stress degradation of performance appears to be more likely and more important in the complex, novel or emergency situation. The absence of positive findings about heat stress effects on task performance in this evaluation, even in the No Vest condition, much less any differential effects between conditions, can be ascribed to:

(i) removal of subjects from the chamber well before marked physiological distress could occur;
(ii) tasks being insufficiently complex;
(iii) insufficient time on tasks;
(iv) insufficient numbers of subjects in the experiment; and
(v) shortcomings in the experimental procedure.

If it should be necessary to carry out evaluations of similar garments in future, these points would need to be considered fully. Detailed information about the actual working conditions of the users would need to be available beforehand so that the chamber WBGT could be more confidently set to equal or approach the users' worst case conditions. Having the conditions too severe is counterproductive as it leads to premature removal of the subjects and confounded results. Furthermore, exposures equal to the working shift length are highly desirable and in any case, exposures of two hours or more are probably required in order to fit in sufficiently long times on the various performance tasks. For instance, if the Five-Choice Task were used again, not only should the apparatus be required to function well in the chamber conditions, but it should be used for 10-minute sessions and preferably it should incorporate a 'gap' counter. Gaps or lapses in attention have been mentioned by others as a useful measure of performance. Subject response time of greater than say 1.5 s would appear to be suitable for counting as a gap. Tasks of greater complexity might be introduced, but if the user situation does not make similar demands the results might be of limited value. The other factors in the list above, relating to experimental design and procedure, should be overcome by better planning and in the light of experience.

More positively, subjects did say they felt better able to tolerate the heat when wearing the vests, even though they later rejected the vests in practice because of the discomfort of wearing them. If the discomfort problems can be overcome sufficiently, then the prospects of mental or psychomotor task performance degradation are lessened. Presumably the problems could be alleviated by insulating the vest inner surface to limit the fall in the underlying skin temperature (see Harrison and Belyavin 1978), and by insulating the outer surface to limit the waste of cooling capacity which currently occurs. Less waste would mean less ice-water quantity and hence less weight for a given endurance time.

5.3 Ethical and Legal Aspects

During the rewriting of this document in June 1984, a press release from the Queensland Institute of Technology, published by 'The Age' newspaper in Melbourne, drew attention to experiments on rats which indicated adverse effects of severe heat stress on spermatogenesis. The findings were extrapolated to man in the newspaper account. This will raise ethical and legal aspects if it is shown in due course that occupational heat stress or short-term but severe experimental heat stress in man does indeed have adverse longer term effects on male reproductive ability or results. One consequence could be enforced limits on occupational heat exposure, and this would be of particular significance in the military environment where environmental temperatures, tasks, equipment and clothing (especially protective clothing) combine on occasions to produce working conditions considerably beyond levels that are tolerated in the civil industrial system.

Further information on this topic was sought by the second author who spoke to the researcher concerned (Dr D.J. Allen) in August 1984. Dr Allen confirmed the report but had no further information available. He was hoping to extend his research to human subjects. He cited Setchell (1978) as a standard reference on the topic. Setchell (p 361) stated "It has been found that temperatures above 37°C are effective [in producing heat-induced histological changes in the testis] in most animals, and that the higher the temperature, the shorter the exposure needed [20 references]. Repeated applications of heat produce progressive damage [2 refs]...Damage to the testis can also be produced by insulating the scrotum, so as to prevent normal heat loss [8 refs] or by heating the whole animal [27 refs] when indirect effects can be mediated through nervous, metabolic or hormonal pathways as well as direct effects on the testis itself."

In view of the above, investigations into similar adverse effects in humans would appear to be worth supporting, and data gathering exercises with human subjects in thermally stressful operational military settings might usefully include scrotal temperature.

6. CONCLUSIONS

The liquid cooled vests examined ameliorated some of the physiological effects of exposure to extreme ambient temperatures. Although shortcomings in the experimental design and procedure prevented application of the statistical tests usually performed in this type of experiment, the trends appear to give a reasonable indication that using the vests, compared with not using them, in 40°C WBGT conditions resulted in practically useful reductions in the subjects' heart rate, rate of rise of body temperature, heat storage rate, and rate of mass loss due to thermoregulatory sweating. For a mental test, there was a trend in the results for performance to be worse near the end of a chamber exposure than at the beginning but there were no obvious differences between the scores for vest and no-vest conditions.

Subjects felt better when wearing the vests in the hot conditions of the chamber during the experiment but declined to use the vests in their usual work places. As there is substantial evidence that complex task performance decreases with the discomfort felt in hot conditions, the reasons why the users rejected practical application of the vests should be investigated further and overcome if possible. Insulating garments both under and over the vests may assist in their practical acceptance.

If the practical problems of acceptance and the logistics of coolant supply can be overcome, vests such as those evaluated may be useful in providing increased subjective comfort, maintaining task performance and reducing the physiological risks in occupational heat stress when environmental control is not possible or practicable. Application to specific non-combatant situations and extension to combatant situations requires further investigation.

It is possible that current research elsewhere may indicate adverse effects of occupational or severe experimental heat stress on male reproductive ability and results. If so, serious ethical and legal aspects may arise concerning the levels of heat stress encountered by military personnel.

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Fatigue (Physiology)
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Heat stress
Comfort

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16. Abstract

A laboratory experiment was used to assess the value of two commercial liquid cooled vests in alleviating some of the physiological and psychological effects of heat stress on human performance. For conditions of 35°C (dry bulb) and 55% relative humidity, both vests reduced the rate of rise of body temperature, heat storage rate, and mass loss due to thermoregulatory sweating of three subjects. All subjects stated that the vests provided some relief from heat stress, but no effects of heat stress on performance were demonstrated. It is suggested that for non-combatant personnel, vests like those tested may provide a practical and economical way of alleviating some of the discomfort and adverse physiological effects of heat stress when environmental control is not practicable.

This paper is to be used to record information which is required by the Establishment for its own use but which will not be added to the DISTIS data base unless specifically requested.

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