

University of Wollongong - Research Online

Thesis Collection

Title: The interaction of the thermal environment, clothing and auxiliary body cooling in the workplace

Author: Joanne Caldwell Odgers

Year: 2008

Repository DOI:

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Research Online is the open access repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

2008

The interaction of the thermal environment, clothing and auxiliary body cooling in the workplace

Joanne N. Caldwell
University of Wollongong, joc@uow.edu.au

Follow this and additional works at: <https://ro.uow.edu.au/theses>

University of Wollongong

Copyright Warning

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site.

You are reminded of the following: This work is copyright. Apart from any use permitted under the Copyright Act 1968, no part of this work may be reproduced by any process, nor may any other exclusive right be exercised, without the permission of the author. Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material.

Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

Unless otherwise indicated, the views expressed in this thesis are those of the author and do not necessarily represent the views of the University of Wollongong.

Recommended Citation

Caldwell, Joanne Nellie, The interaction of the thermal environment, clothing and auxiliary body cooling in the workplace, MSc-Res thesis, School of Health Sciences, University of Wollongong, 2008.
<http://ro.uow.edu.au/theses/765>

Research Online is the open access institutional repository for the University of Wollongong. For further information contact the UOW Library: research-pubs@uow.edu.au

NOTE

This online version of the thesis may have different page formatting and pagination from the paper copy held in the University of Wollongong Library.

UNIVERSITY OF WOLLONGONG

COPYRIGHT WARNING

You may print or download ONE copy of this document for the purpose of your own research or study. The University does not authorise you to copy, communicate or otherwise make available electronically to any other person any copyright material contained on this site. You are reminded of the following:

Copyright owners are entitled to take legal action against persons who infringe their copyright. A reproduction of material that is protected by copyright may be a copyright infringement. A court may impose penalties and award damages in relation to offences and infringements relating to copyright material. Higher penalties may apply, and higher damages may be awarded, for offences and infringements involving the conversion of material into digital or electronic form.

THE INTERACTION OF THE THERMAL ENVIRONMENT,
CLOTHING AND AUXILIARY BODY COOLING
IN THE WORKPLACE

A thesis submitted in partial fulfilment of the
requirements for the award of the degree

Masters of Science (Research)

from

University of Wollongong

by

Joanne Nellie Caldwell, BSc.

School of Health Sciences

2008

I, Joanne Nellie Caldwell, declare that this thesis, is submitted in partial fulfilment of the requirements for the award of Masters of Science (Research), in the School of Health Sciences, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Joanne Nellie Caldwell

Date: _____

THE INTERACTION OF THE THERMAL ENVIRONMENT, CLOTHING AND AUXILIARY BODY COOLING IN THE WORKPLACE

Abstract

Extensive research into the physiological impact of wearing thermal protective clothing has been conducted for many years. However, the current literature does not provide a consensus concerning the interaction of heat strain and cognitive function. This project sought to investigate the problems associated with personnel working in uncompensable environmental conditions while wearing Australian Defence Force (ADF) protective clothing. Four separate investigations were conducted. The first was a field based study evaluating the thermal influences of operating a helicopter simulator. The second was a laboratory study evaluating the impact of wearing body armour on physiological and cognitive function. Thirdly, a theoretical evaluation of, the problems associated with performing work in an uncompensable heat stress environment and, the physical characteristics of various coolants and cooling systems were investigated. Finally, a laboratory investigation on the physiological and cognitive consequences of wearing a personal protective ensemble while performing exercise with and without an activated liquid-cooling garment. A significant reduction in flying performance was evident when pilots were heated to a mean skin temperature (\bar{T}_{sk}) of $\sim 39^{\circ}\text{C}$ compared to the other two conditions ($\sim 33^{\circ}\text{C}$ and 37°C , $P < 0.05$), using a water perfusion garment to achieve these target \bar{T}_{sk} . However no obvious detriments in cognitive performance were observed for the two laboratory based studies even though subjects were exposed to a significant thermal load, as determined by increases in T_c , \bar{T}_{sk} and f_c ($P < 0.05$). For the final study, where thermal strain was significantly higher in the hot-dry trial without cooling ($P < 0.05$), resulting in a terminal rectal temperature that was 1.6°C higher than the thermoneutral condition, the liquid-cooling garment (water temperature 15°C) successfully prevented all detriments in physiological function observed during the hot-dry trial without cooling. It can therefore be concluded from this investigation that, individuals exposed to extreme environmental conditions while wearing protective ensembles, are at risk of developing increased thermal strain that may lead to heat illness. In terms of cognitive function assessment, this project failed to determine specifically, which areas of cognitive function are in fact adversely affected. However, a reduction in thermal strain can be achieved with the use of an auxiliary cooling device.

Acknowledgements

I would like to thank the following people who have helped me along the long road to completing this thesis:

- Associate Professor Nigel Taylor for his ongoing excellent supervision and advice throughout my research degree. He has provided outstanding support and guidance from which I have developed many skills and knowledge.
- My secondary supervisor, Dr Mark Patterson from Defence Science and Technology Organisation for his continued collaboration throughout all of these studies.
- Cass Haley, Christopher Gorden, Christiano Christiano Machado-Moreira and all the visiting Dutch students for their assistance in learning the thermal laboratory skills required to complete this research and for their assistance throughout the data collection periods.
- The subjects who willingly gave up their time to participate in this project. Their contribution to science research was invaluable.

Finally, I would like to thank friends and family, especially Dougie, for their support throughout my research.

TABLE OF CONTENTS

| | |
|---|------------------|
| Abstract | Page i |
| Acknowledgments | Page ii |
| TABLE OF CONTENTS | Page iii |
| LIST OF FIGURES | Page viii |
| LIST OF TABLES | Page xii |
| CHAPTER ONE: INTRODUCTION | Page 1 |
| 1.1 Introduction | Page 1 |
| 1.2 Mechanisms of heat exchange | Page 1 |
| 1.3 The nature of the problem | Page 4 |
| 1.4 The consequences of this problem | Page 6 |
| 1.5 A possible solution | Page 7 |
| 1.6 Aims and hypotheses | Page 9 |
| 1.7 References | Page 10 |
| CHAPTER TWO: THE INTERACTION OF TRANSCUTANEOUS HEATING AND HELICOPTER FLIGHT SIMULATOR PERFORMANCE | Page 12 |
| 2.1 Introduction | Page 12 |
| 2.1.1 Aims of the study | Page 13 |
| 2.2 Methods | Page 13 |
| 2.2.1 Subjects | Page 13 |
| 2.2.2 Experimental conditions | Page 13 |
| 2.2.2.1 Determination of water temperature for the water perfusion garment | Page 13 |
| 2.2.3 Experimental procedures | Page 15 |
| 2.2.3.1 Experimental standardisation | Page 16 |
| 2.2.3.2 Flight simulation | Page 16 |
| 2.2.4 Data collection procedures | Page 17 |
| 2.2.4.1 Physiological measures | Page 17 |
| 2.2.4.2 Psychophysical measures | Page 21 |

| | |
|---|---------|
| 2.2.4.3 Independent flight performance scores | Page 24 |
| 2.2.5 Statistical analysis | Page 24 |
| 2.3 Results | Page 25 |
| 2.3.1 Gastric temperature | Page 25 |
| 2.3.2 Skin temperature | Page 25 |
| 2.3.3 Mean body temperature | Page 28 |
| 2.3.4 Cardiac frequency | Page 28 |
| 2.3.5 Psychophysical responses | Page 28 |
| 2.3.5.1 Thermal sensation and discomfort | Page 28 |
| 2.3.5.2 Perceived flight performance measures | Page 34 |
| 2.3.6 Independent flight performance scores | Page 37 |
| 2.3.7 Inter-relationships between physiological and psychophysical responses | Page 37 |
| 2.4 Discussion | Page 37 |
| 2.4.1 Evaluation of the thermal stimulus | Page 37 |
| 2.5 Conclusion | Page 42 |
| 2.5. References | Page 44 |

CHAPTER THREE: THE THERMAL CONSEQUENCES OF WEARING BODY

| | |
|--|----------------|
| ARMOUR DURING EXTENDED EXERCISE IN THE HEAT | Page 46 |
| 3.1 Introduction | Page 46 |
| 3.1.1 Aims of the Study | Page 50 |
| 3.2 Methods | Page 50 |
| 3.2.1 Subjects | Page 50 |
| 3.2.2 Experimental conditions | Page 50 |
| 3.2.3 Experimental procedures | Page 50 |
| 3.2.3.1 Experimental standardisation | Page 51 |
| 3.2.4 Data collection procedures | Page 51 |
| 3.2.4.1 Physiological measurements | Page 55 |
| 3.2.4.2 Psychophysical measures | Page 56 |
| 3.2.4.3 Cognitive-function indices | Page 59 |

| | |
|--|---------|
| 3.2.5 Statistical analyses | Page 61 |
| 3.3 Results | Page 62 |
| 3.3.1 Core temperature | Page 62 |
| 3.3.2 Skin temperatures | Page 62 |
| 3.3.3 Cardiac frequency | Page 66 |
| 3.3.4 Whole body sweat and evaporation | Page 66 |
| 3.3.5 Psychophysical indices | Page 66 |
| 3.3.6 Cognitive function | Page 68 |
| 3.4 Discussion | Page 74 |
| 3.4.1 Core temperature | Page 74 |
| 3.4.2 Skin temperatures | Page 74 |
| 3.4.3 Cardiac frequency | Page 75 |
| 3.5 Conclusion | Page 75 |
| 3.6 References | Page 77 |

CHAPTER FOUR: A FIRST-PRINCIPLES EVALUATION OF AUXILIARY

| | |
|--|----------------|
| COOLING FOR ADF PERSONNEL | Page 82 |
| 4.1 Introduction | Page 82 |
| 4.1.1 Purpose | Page 82 |
| 4.2 Modelling the problem | Page 82 |
| 4.2.1 Two-dimensional analyses | Page 82 |
| 4.2.2 Three-dimensional analyses | Page 89 |
| 4.2.2.1 Predicting cooling requirements | Page 93 |
| 4.3 Modelling coolants and cooling system | Page 93 |
| 4.3.1 Modifying the work rate | Page 93 |
| 4.3.2 Modifying clothing | Page 95 |
| 4.3.3 Modifying the interface between the person and environment | Page 95 |
| 4.3.3.1 Conductive heat removal | Page 101 |
| 4.3.3.2 Convective heat removal | Page 102 |
| 4.3.3.3 Combination cooling methods | Page 103 |
| 4.3.4 Concluding comments | Page 103 |
| 4.4 Physiological considerations | Page 106 |

| | |
|--|----------|
| 4.4.1 Regional versus whole-body cooling | Page 106 |
| 4.4.1.1 Concluding comments | Page 111 |
| 4.4.2 Cutaneous vasoconstriction and heat extraction | Page 111 |
| 4.4.2.1 Concluding comments | Page 113 |
| 4.4.3 Intermittent versus continuous cooling | Page 113 |
| 4.4.3.1 Concluding comments | Page 115 |
| 4.5 Cooling systems | Page 115 |
| 4.5.1 A general overview of cooling systems | Page 115 |
| 4.5.1.1 Ice cooling systems | Page 115 |
| 4.5.1.2 Water-perfusion systems | Page 116 |
| 4.5.1.3 Air cooling systems | Page 117 |
| 4.5.1.4 Phase-change cooling systems | Page 118 |
| 4.6 Recommendations | Page 120 |
| 4.6.1 General recommendations for the selection of cooling systems | Page 121 |
| 4.6.1.1 Selecting the appropriate coolant | Page 121 |
| 4.6.1.2 Selecting the surface area to be cooled | Page 123 |
| 4.6.1.3 Selecting the optimal coolant temperature | Page 124 |
| 4.6.1.4 Selecting the desired coolant flow | Page 124 |
| 4.6.1.5 The selection of cooling systems | Page 125 |
| 4.6.1.6 Environmental considerations | Page 125 |
| 4.6.1.7 Operational considerations | Page 126 |
| 4.6.1.8 Cooling system considerations | Page 130 |
| 4.6.1.9 An auxiliary cooling system matrix | Page 131 |
| 4.7. References | Page 137 |
| CHAPTER FIVE: THE PHYSIOLOGICAL AND COGNITIVE CONSEQUENCES OF WEARING NUCLEAR, BIOLOGICAL AND CHEMICAL PROTECTIVE CLOTHING WITH AND WITHOUT AUXILIARY COOLING | |
| 5.1 Introduction | Page 146 |
| 5.1.1 Aims of the study | Page 147 |
| 5.2 Methods | Page 147 |
| 5.2.1 Subjects | Page 147 |

| | |
|--|-----------------|
| 5.2.2 Experimental conditions | Page 148 |
| 5.2.2.1 Determination of water temperature for liquid-cooling garment | Page 148 |
| 5.2.2.2 Environmental conditions | Page 151 |
| 5.2.3 Experimental procedures | Page 151 |
| 5.2.3.1 Experimental standardisation | Page 151 |
| 5.2.4 Data collection procedures | Page 153 |
| 5.2.4.1 Physiological measurements | Page 153 |
| 5.2.4.2 Psychophysical indices | Page 154 |
| 5.2.4.3 Cognitive function measures | Page 157 |
| 5.2.5 Statistical Analysis | Page 158 |
| 5.3 Results | Page 159 |
| 5.3.1 Core temperature | Page 159 |
| 5.3.2 Skin temperature | Page 161 |
| 5.3.3 Cardiac frequency | Page 162 |
| 5.3.4 Whole body sweat and evaporation | Page 165 |
| 5.3.5 Psychophysical Indices | Page 165 |
| 5.3.6 Cognitive function parameters | Page 168 |
| 5.4 Discussion | Page 168 |
| 5.4.1 Core temperature | Page 173 |
| 5.4.2 Skin temperature | Page 173 |
| 5.4.3 Cardiac frequency | Page 173 |
| 5.4.4 Psychophysical indices | Page 176 |
| 5.4.5 Cognitive function | Page 177 |
| 5.5 Conclusion | Page 177 |
| 5.6 References | Page 179 |
| CHAPTER SIX: CONCLUSION | Page 183 |
| 6.3 Recommendations | Page 185 |
| 6.2 Future research | Page 186 |
| APPENDIX A: EQUATIONS USED FOR MATHEMATICAL MODELLING | Page 187 |

LIST OF FIGURES

| | |
|---|---------|
| 1.1 The agents and host factors of heat illness relevant to military personnel..... | Page 8 |
| 2.1 Clothing configuration: (a) water-perfusion garment (upper left); (b) flight clothing (upper right) and (c) nuclear, biological and chemical clothing (bottom)..... | Page 18 |
| 2.2 Core temperatures during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 27 |
| 2.3 Mean skin temperatures during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 29 |
| 2.4 Mean body temperatures during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 30 |
| 2.5 Cardiac frequencies during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 31 |
| 2.6 Thermal sensation (range: 0-13) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 32 |
| 2.7 Thermal discomfort (range: 0-5) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 33 |
| 2.8 Flight simulator perceived performance quality (range: -5 to +5) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 35 |
| 2.9 Flight simulator perceived performance effort (range: 0-5) during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 36 |
| 2.10 Flight simulator performance ratings (scores ranged: 0-8) as evaluated by an independent flight simulator training officer (26 y as flight instructor), | |

| | |
|---|---------|
| during three, two-hour flight simulations comprised of eight flight circuits (labelled 1-8), performed under three levels of thermal strain..... | Page 38 |
| 2.11 The correlation between perceived flight performance effort and mean body temperature during three, two-hour flight simulations, performed under three levels of thermal strain:..... | Page 40 |
| 2.12 The correlation between perceived flight performance quality and mean body temperature during three, two-hour flight simulations, performed under three levels of thermal strain:..... | Page 41 |
| 3.1 Core (auditory canal) temperature changes during steady-state walking at two speeds in a hot-humid environment..... | Page 63 |
| 3.2 Mean skin temperatures during steady-state walking (two speeds) in a hot-humid environment..... | Page 64 |
| 3.3 Scapular, chest and arm skin temperatures during steady-state walking at two speeds in a hot-humid environment..... | Page 65 |
| 3.4 Cardiac frequency during steady-state walking (two speeds) in a hot-humid environment..... | Page 67 |
| 3.5 Mass changes and evaporation during steady-state walking (two speeds) in a hot-humid environment..... | Page 70 |
| 3.6 Perceived exertion (effort sense) during steady-state walking (two speeds) in a hot-humid environment..... | Page 71 |
| 3.7 Psychophysical responses during steady-state walking (two speeds) in a hot-humid environment..... | Page 72 |
| 3.8 Change in cognitive function during steady-state walking (two speeds) in a hot-humid environment..... | Page 73 |
| 4.1 Heat exchange during nude, resting exposures..... | Page 84 |
| 4.2 Heat exchange during unclothed, resting and exercising exposures..... | Page 86 |
| 4.3 The impact of clothing on resting heat exchange..... | Page 87 |
| 4.4 The interaction of clothing and exercise on heat exchange..... | Page 88 |
| 4.5 The three-dimensional surface for resting exposures to combinations of clothing insulation and air temperature..... | Page 90 |
| 4.6 The three-dimensional surface (70 Watts of external work) for exposures to | |

| | |
|--|----------|
| combinations of clothing insulation and air temperature..... | Page 91 |
| 4.7 Three-dimensional surface (200 Watts): clothing insulation and air temperature..... | Page 92 |
| 4.8 Three-dimensional surface for heat exchange across ranges of external work rates and air temperatures, when wearing ADF camouflaged, combat fatigues (insulation $0.29 \text{ m}^2\text{K}\cdot\text{W}^{-1}$)..... | Page 94 |
| 4.9 The impact of coolant (water) inflow temperature upon heat removal..... | Page 98 |
| 4.10 The impact of coolant contact surface area (water at 15°C) upon heat removal..... | Page 99 |
| 4.11 The impact of coolant (water at 15°C) flow upon heat removal..... | Page 100 |
| 4.12 Heat removal capabilities of three hypothetical cooling systems..... | Page 105 |
| 4.13 Body segments and stature of the model..... | Page 108 |
| 4.14 An electron micrograph of phase-change material within a fabric..... | Page 119 |
| 4.15 Flowchart to guide the selection of auxiliary (microclimate) cooling systems..... | Page 129 |
| 5.1 Auditory canal temperature (A) and mean skin temperature (B) responses for one subject during pilot testing to determine a suitable temperature for liquid-cooling garment during low intensity exercise (30 watts) on the cycle ergometer..... | Page 150 |
| 5.2 Core temperatures (mean of auditory canal and rectal temperatures) during an exercise protocol when exposed to a temperate environment (control), hot-dry inactive cooling or hot-dry with an activated cooling system..... | Page 160 |
| 5.3 Mean skin temperatures during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials. Values are means with standard error of the means..... | Page 163 |
| 5.4 Cardiac frequency during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials..... | Page 164 |
| 5.5. Body mass change ($\text{kg}\cdot\text{h}^{-1}$) during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials..... | Page 166 |

| | |
|---|----------|
| 5.6 Ratings of perceived exertion during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials..... | Page 167 |
| 5.7: Psychophysical responses during an exercise protocol when exposed to a temperate environment (control), hot-dry, inactive cooling or hot-dry, active cooling trials..... | Page 169 |
| 5.8 Cognitive function: Vigilance, three term reasoning, filtering, verbal working memory, divided attention and perceptual reaction time before and after an exercise protocol when exposed to a temperate environment (control), hot-dry with inactive cooling or hot-dry with active cooling trials..... | Page 172 |

LIST OF TABLES

| | |
|--|--------------|
| Table 2.1 Physical characteristics of the RAN pilots..... | Page 14 |
| Table 2.2 Experimental time line..... | Page 19 |
| Table 2.3 Flight simulator operational faults, graded by difficulty..... | Page 20 |
| Table 2.4 Overall physiological responses during three, two-hour flight simulations, performed under three levels of thermal strain..... | Page 26 |
| Table 2.5 Overall correlation coefficients for perceived performance quality and effort, and overall flight performance scores (assessed by flight officer) during three flight simulations..... | Page 39 |
| Table 3.1 Subject characteristics..... | Page 52 |
| Table 3.2 Experimental time line..... | Page 53 |
| Table 3.3 Body mass changes during steady-state walking in a hot-humid environment with three clothing configurations: camouflage uniform (control), uniform with body armour, and uniform with armour and helmet..... | Page 69 |
| Table 4.1 Assumed operational indices for use in mathematical modelling..... | Page 83 |
| Table 4.2 Physical properties of standard coolants at the operating temperatures indicated..... | Page 96 |
| Table 4.3 Morphometric data for ten body segments..... | Page 109 |
| Table 4.4 Major blood vessels within 3 cm to the skin surface..... | Page 110 |
| Table 4.5 Contact surface areas for water-perfused tubes and ice packs..... | Page 122 |
| Table 4.6 Environmental conditions for which auxiliary cooling is not required... | Page 127 |
| Table 4.7 Environmental conditions for which auxiliary (microclimate) cooling may be required..... | Page 128 |
| Table 4.8 Auxiliary cooling systems..... | Page 131-136 |
| Table 5.1 Physical characteristics of subjects..... | Page 149 |
| Table 5.2 Experimental timeline..... | Page 152 |
| Table 5.3 Psychophysical indices for individuals required to perform work during rest and at completion of exercise when exposed to three different heat stress environments. | Page 170 |
| Table 5.4 Cognitive function measures for individuals required to perform work | |

| | |
|--|----------|
| during rest and at completion of exercise when exposed to three different heat stress environments..... | Page 171 |
|--|----------|