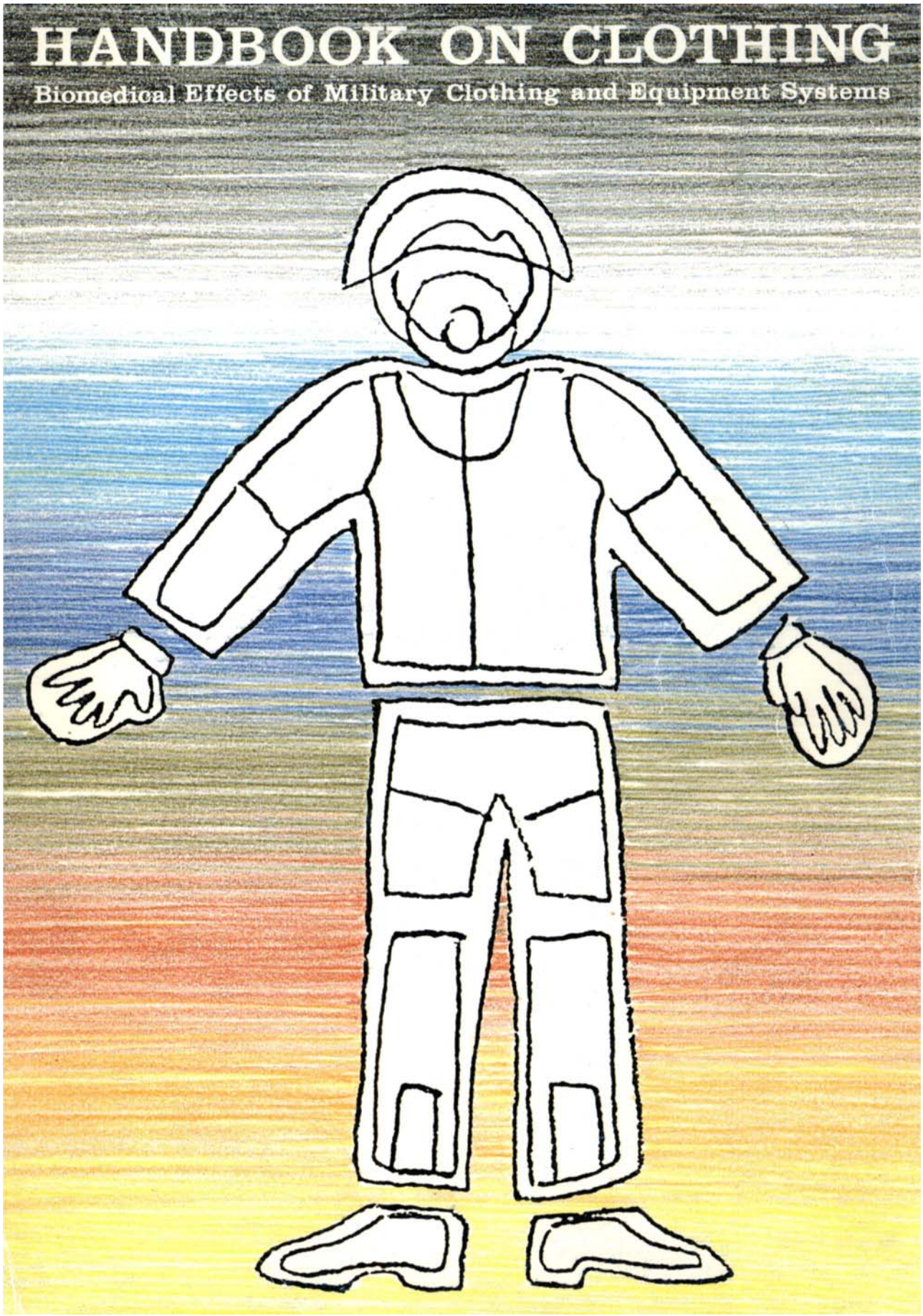
HANDBOOK ON CLOTHING

Biomedical Effects of Military Clothing and Equipment Systems



2nd Edition Ralph F. Goldman, Bernhard Kampmann 2007

This book is dedicated to my grandson, Daniel A Goldman, and all others who are interested in joining “this small band of brothers” and sisters (< 50), who operate the small (± 200) unchartered and unsponsored, free-floating meetings known as

“The International Conference of Environmental Ergonomics”.

Chag Sameach (unto you, be strength)

Preface 2nd edition

The verse "No man is an island" by the 15th century English poet John Donne, is particularly applicable to scientists. All of us build on the works of our predecessors, often without knowing who they were. This is as true for Environmental Ergonomics as it is for any other science. One of the first reports of heat stroke appears in the Bible (Book of Ruth). Xenophon's The Anabasis relates the effects of heavy wicker armor in about 500 BC, while a suggested essential role of a woolen wrap to protect the kidneys from the effects of cold appears in German literature as recently as the 1920s.

Although climatic chamber studies of human heat transfer date to the 1770s (Blagden & Fordyce) our progenitor Society, the Ergonomics Research Society, did not exist prior to 1950. World War II was the first time large numbers of men, and some women, had been transported rapidly from familiar surroundings to arctic, desert, jungle, or high terrestrial elevation, i.e.,environmental extremes requiring customizations, acclimatization and/or specialized protective clothing. The information gained in the United States on the latter was summarized in "Physiology of Heat Regulation and the Science of Clothing," (L.H. Newburgh, ed.), Saunders, Philadelphia, 1949. When Captain Leif Vanggaard of Denmark proposed NATO Research Study Group 7 (under NATO Panel VIII) in 1980 on "The Biomedical Effects of Clothing, a number of international groups had been meeting on various aspects of the problem for almost 20 years. Dr. Goldman had been involved in:

a) The Standing Working Group on Clothing and Equipment (#4), Quadripartite Standardization Program meetings: in Natick, MA (1961), Ottawa, Canada (1962), London, England (1963), Melbourne, Australia 1965;

b) The Commonwealth Conferences on Operational Combat Clothing & Equipment meetings: in Melbourne, Australia (1965), Delhi, India (1975), Nairobi, Kenya (1968), Kingston, Ontario, Canada (1971), Accra, Ghana (1978), Kuala Lumpur, Malaysia (1981);

c) NATO Combat Clothing and Equipment Working Group (1970 –1978), and chaired its Subcommittee on Allied Publication "Heat Transfer & Physiological Evaluations of Clothing," 1974 -1978;

Dr. Goldman thus knew, and was known by, most of the members and was asked to serve as Chairman for NATO Research Study Group 7, Biomedical Aspects of Military Clothing, Panel VIII. He accepted on condition that, rather than write yet another STANAG (Standardization National Agreement), the RSG would be tasked to write a Handbook on The Biomedical Effects of Clothing. Drafting a topical outline, he agreed to write the first two, introductory Chapters, and then assigned two members to author each remaining Chapter; he attempted to balance the most knowledgeable individuals on a given topic with a Committee member who might have less expertise on that topic. The RSG met in: Farnborough, U.K. (1981), Koblenz, FRG (1982), Soesterberg, Netherlands (1984), Natick, MA, USA (1985) and Lyon, France (1986). Dr. Goldman always intended publishing the Handbook in the open literature, to compile the knowledge added to the literature since Newburgh's 1949 opus, but he left the government in 1985 (rather than run a study on human subjects he felt was outside his area of expertise). Others completed the final editing at US ARIEM, and only a few dozen copies were issued. Dr. Bernhard Kampmann accepted the major task of reformatting the original to MS Word, and he and Dr. Goldman completed the revisions to make it available to the public through the ICEE Web site.

HANDBOOK ON CLOTHING

Biomedical Effects of Military Clothing and Equipment Systems

prepared by

Research Study Group 7 on Bio-Medical Research Aspects
of Military Protective Clothing

FOREWORD

This handbook on military clothing was conceived by Dr. Ralph Goldman, when he chaired Research Study Group 7 of NATO's AC/243(Panel 8) on the Defence Applications of Human and Bio-Medical Sciences, as an alternative to writing the usual STANAG (Standardization National Agreement) produced by such Study Groups. It summarizes the knowledge (to ~1985) in the field of biophysical principles applied in military clothing design. It was recognized by the participating countries that there was a need, not only for giving clothing developers a tool to substantiate some of the problems in human biomedical engineering, but also to convey to the user, the military system, a possibility to gain insight in the problems behind applied clothing design.

It was furthermore intended that the handbook should furnish the military decision makers with guidelines describing the interactions between the person, clothing, military task and environment.

The person, clothing, task and environment all interact to a degree, but it is in the clothing system that they meet, and the clothing system is often the only changeable factor. The handbook thus does not only deal with clothing, but to a high degree also with compatibility of clothing and the military tasks.

Military clothing has to meet a multitude of requirements, and it is well recognized, that the military clothing in many ways also sets the standards for clothing development in the civilian society. A combat uniform, for example, is and has to be a multipurpose clothing system, but this means that its design has to take into consideration many different aspects. Many of these are also relevant in the design of civilian working clothing.

It is the hope that this handbook might find use also outside the military circles (perhaps as a fundamental one of clothing properties) although it necessarily deals with some of the problems particular to the military scenario.

The Research Study Group 7 which took on the task of producing the book wishes to thank all those who during the life of the group have contributed to its contents, feeding information into the respective group members.

In preparing the manuscripts for the final report to Panel 8, the RSG.7 is indebted to Dr. Richard Gonzalez for his hard work in bringing the many different manuscripts and authors into a common format. In this work, Mr. J.R. Breckenridge has offered the working group a very essential help with his profound knowledge of all aspects of the subject. The RSG.7 is indebted to Ms. Dorothy Buell for her painstaking technical help in preparation of the text. Finally, the United States Army Research Institute of Environment Medicine has acted as the coordinator for the group, and RSG.7 wishes to express its gratitude to the Institute, particularly the two commanders (Col. Brendan E. Joyce, MSC and Col. David D. Schnakenberg, MSC) during the time when this book was being written, and all the Institute's staff for the help and good will they have rendered the project.

(Signed) LEIF VANGGAARD

Chairman

MEMBERS OF RESEARCH STUDY GROUP 7

on

Biomedical Effects of Military Clothing and Equipment Systems

Canada
G.T. Holmes
P.L. Marsh

Denmark
L. Vanggaard (Chairman)

France
J. Doucet

Germany
F.W. Behmann
G. Schaad

Netherlands
W.A. Lotens

United Kingdom
M. Haisman
R.A. Scott

United States
K.B. Pandolf
R.F. Goldman (Initial Chairman)

Besides the nominated members of the Research Study Group, many others from the different research establishments have participated in the work and, when appropriate, in specific meetings of the group.

Meetings of NATO Research Study Group 7,
Biomedical Aspects of Military Clothing, Panel VIII, 1981 - 1986

1981	Farnborough, U.K.;
1982	Soesterberg, Netherlands
1983	Koblenz, FRG
1984	Natick, MA
1986	Lyon, France

TABLE OF CONTENTS

CHAPTERS

Dedication

Preface 2nd edition

Foreword

Members of Research Study Group 7

1. Historical Review of Developments in Evaluating Protective Clothing

2. Biomedical Effects of Clothing on Human Thermal Comfort and Strain

3. Predictive Thermal Modeling

4. Clothing Materials - Their Required Characteristics and Their Impact on Biomedical Factors

5. Cold Weather Clothing Systems: Recent Progress and Problems for Future Research

6A. The Practical Aspects of Sleeping Systems

6B. Biomedical Effects of Sleeping Systems

7A. Protection of Hands and Feet

7B. Footwear and Blister Incidence

8. Immersion Suits

9A. Physiological Aspects of Auxiliary Heating and Cooling

9B. Auxiliary Cooling: Experimental Results

10. Biomedical Effects of Underwear

11. Biomedical Aspects of NBC Masks and Their Relationship to Military Performance

12. Protection Against Flames and Radiant Heat

13. Load Carriage

14. Personal Protective Body Armor

15. Military Performance of Clothing

16. Field Evaluation Methods

17. Optimal Design Principles for Clothing Systems

Appendix. Conversion Units Common to Biomedical Research on Military Clothing

CHAPTER 1

HISTORICAL REVIEW OF DEVELOPMENTS IN EVALUATING PROTECTIVE CLOTHING

R.F. Goldman

CONTENTS

SUMMARY

THE 1940's: INSULATION OF CLOTHING AND AIR COOLING CONCEPTS

2. INSULATION ESTIMATION AND MEASUREMENT

3. IMPORTANCE OF EXTREMITY INSULATION

4. THE 1960's

5. THE 1970's

6. THE FUTURE

7. REFERENCES

SUMMARY

The evolution of some of the important studies that have been made since World War II is addressed in this chapter. Clothing insulation is modified by thickness, weight and air permeability and several methods are introduced towards qualification of these parameters.

Key Words: Copper manikins, clothing, insensible and sensible heat loss, clothing permeation and heat transfer factors.

THE 1940's: INSULATION OF CLOTHING AND AIR COOLING CONCEPTS

Gagge, Burton and Bazett's (1) development of the clo unit* from 1941 on as a measure of clothing insulation, coupled with the heated copper manikins that Belding arranged to have fabricated in the mid-1940's, provided a basis for direct measurement of the resistance of clothing to sensible ("dry") heat transfer. This heat transfer by radiation and convection took place between the skin of the wearer and the ambient environment, through the clothing and its associated internal and external "still" air layers. Winslow, Herrington & Gagge also presented information on the alteration of the external air layer insulation as a function of ambient air motion (2). The history of this subject has been reviewed (1a). Availability of these concepts, together with the ability to measure the heat transfer properties of clothing on the heated copper manikin, and of materials on a heated flat plate, allowed rapid advances to be made in the science of protection of man against cold weather by clothing. Burton in Canada and Edholm in U.K. provided additional theoretical and practical information (3), and an extensive series of clothing items and ensembles were measured during the late 1940's and early 1950's in US Army, Navy and Air Force laboratories; the conclusions from much of this work were summarized by L.H. Newburgh (4). Siple, a geographer for the US Army Quartermaster General, applied this information and principles of climatic geography to identify appropriate cold weather clothing ensembles for various areas on world maps; he also advanced the concept of characterizing the cooling power of an environment by a "wind chill index" (5).

INSULATION ESTIMATION AND MEASUREMENT

By 1955 most of the copper men had been relegated to storage, after extensive tables of clothing insulation values, and maps delineating their zones of use, had been obtained. Also, by then it was recognized that the insulation of a clothing material tended to be a linear function of its thickness; measured insulation values generally could be estimated as 1.57 clo units per centimeter of clothing thickness. A variety of simple techniques have since evolved for estimating the insulation of clothing, as worn by a human. One technique simply used the thickness calculated from increases in circumference of various body segments, with an adjustment when the space between layers occupied only by trapped air was greater than 0.5 centimeters (6). Another suggested that, for most practical purposes, the total insulation could be estimated simply from the number of layers of clothing worn (4). A third indicated that, since thickness tended to be a linear function of fabric weight for conventional clothing materials, total insulation could be estimated from clothing ensemble weight; a relationship of 0.35 clo per kg of clothing weight was suggested (7). An "additive" technique, summing the insulation of each clothing item has been incorporated in the most recent Comfort Standard (7) promulgated by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, Inc. (ASHRAE). None of these simple techniques yields precise values for clothing insulation, but may be acceptable when one considers the variation in effective insulation produced by individual fit and sizing.

---

*1 clo is that insulation of the typical 1940 business suit which limits heat transfer to 6.45 watts per square meter of surface area per °C difference between skin and air temperatures; two clo allows half that heat transfer, etc.

IMPORTANCE OF EXTREMITY INSULATION

It also had been generally recognized that the problems of protecting man in a cold environment were not those of providing adequate insulation to the torso but to the extremities; any footwear had to be of minimal weight (since one kg of footwear was roughly equivalent to five kg of torso load in the energy cost of walking), and handwear required minimal degradation of manual performance. The latter problem was compounded by the rapidly increasing surface area for heat loss associated with increasing the thickness of insulation around such relatively thin cylinders as the fingers (8) since heat exchange is a linear function of surface area. A factor (f) for adjusting the external air layer insulation for the ratio of clothed to nude body surface areas was developed; Gagge has suggested an increase in surface area of 15% per clo unit of clothing insulation (7) but, recently, McCullough et al. (9) reported this value seemed low. In one study, carried out at the Arctic Aeromedical Laboratory by Veghte (10), subjects given four "pillows" of insulation had much greater cold tolerance when the four pillows were used around the extremities than when they were used to protect the torso per se. The focus for cold weather environments therefore shifted from protective clothing for the torso, to extremity protection. Goldman (11) has suggested auxiliary heating as the only practical means to maintain the extremities of a relatively inactive individual at functional ($T_{finger} \geq 15$ °C) or safe ($T_f \geq 5$ °C) temperatures. Various physiological mechanisms and use of hot cayenne pepper inside the socks next to the skin and yoga meditation were explored, and auxiliary heated gloves, socks and wristlets became the subject for studies involving cold weather protection. While Belding had noted the decrease in insulation of heavy clothing with wearer motion (12), with the loss of insulation while walking amounting to 50%, little or nothing was done to modulate this effect since the extremities were recognized as the real problem in the cold.

THE 1960'S: HOT WEATHER PROTECTION, SWEAT EVAPORATION AND MOISTURE PERMEABILITY CONCEPTS

The role of clothing in hot environments received little scientific attention prior to the 1960's, although some studies on the benefits of wearing clothing as a barrier against solar radiant heat had been carried out by Douglas Lee in the Yuma desert (13). Gagge, early in his studies exploring the use of the clo value for characterizing the radiation and convection heat exchanges of clothing, had utilized the human heat balance equation; from this he identified a new parameter, the percent wetted skin area (14), as a key element in characterizing comfort in warm conditions. The required evaporative cooling (E_{req}), derived from the heat balance equation by summing the heat production and the radiant and convective heat gain or loss (R+C), allowed estimation of the percent sweat wetted area simply as the ratio of the required evaporative cooling (E_{req}) to the maximum evaporative cooling (E_{max}) allowed by the clothing in any given environment. Independently, Belding working with Hatch at Pittsburgh, had developed a Heat Stress Index (HSI) which was formulated in an identical manner (E_{req}/E_{max}). They also suggested that the evaporative heat transfer coefficient from the body, with or without clothing, was roughly twice the convective heat transfer coefficient (15). However, there was no way to measure the evaporative heat transfer characteristics of fabrics or clothing. Woodcock, working first in Canada and subsequently at the US Army Laboratories in Natick, had developed a theoretical index to characterize the moisture permeability of fabrics (16). This index (i_m) is simply the ratio of the

maximum evaporative cooling, at a given ambient vapor pressure, from a 100% wetted surface through a fabric, to the maximum evaporative cooling of a psychrometric wet bulb thermometer at the same vapor pressure. However, there was no way to utilize this index for practical clothing applications until copper manikins were resurrected from storage and outfitted with a thin, tailored cotton skin which could be 100% wetted by spraying it with water; it was possible to measure the maximum evaporative heat transfer and, thereby, simulated a "sweating" human wearing a given clothing ensemble. This procedure allowed calculation of the total Calories that a man, wearing a given clothing ensemble which partially (or fully) covered his body, would be able to exchange with his environment by both sensible and insensible heat transfer for a given skin temperature and percent skin wettedness. Gagge and Nishi, and other associates at the J.B. Pierce Foundation Laboratory in New Haven, introduced a clothing permeation factor (F_{pcl}) (32) with similar modifications to maximum evaporative heat loss.

A 1959 field evaluation of the effects of chemical protection clothing on the wearer, in which troops collapsed within the first hour of a march in a relatively temperate climate, dramatically increased the demand for understanding of the effects of reduced permeability in clothing. An extensive series of copper manikin evaluations of chemical protective clothing ensembles, body armor, and rain suits were carried out (17); these were supplemented with studies of human volunteers wearing these items in a variety of temperate, warm or hot conditions in the large climatic chambers at Natick or in the field (18). Combining these biophysical measurements of clothing ensembles on the heated, sweating copper manikins, and the physiologic measurements on volunteers resting and working in the same ensembles, it became possible to rank order garments in terms of the relative heat tolerance of the wearer, simply by characterizing the garment ensemble by its insulation (clo) and its moisture permeability index ratio (i_m/clo) (19).

THE 1970's: AIR AND BODY MOTION "PUMPING" COEFFICIENT CONCEPTS

It soon became apparent, from a study of raincoats in which a poncho was compared with a standard raincoat, that still another factor had to be considered (20). Measured values of i_m/clo on the copper manikin indicated that the poncho, which covered more area, should be a much hotter garment during work than the standard impermeable raincoat; however, when the data from the human subjects wearing these items were examined, quite the reverse proved to be the case. The pumping of air produced by wearer movement in the relatively loose-fitting poncho dramatically increased the opportunities for evaporative, as well as convective, transfer within the poncho. In contrast, there was only limited air exchange within the relatively close-fitting, impermeable raincoat. Accordingly, a pumping coefficient (V_{eff}) was evolved to characterize the changes in both insulation and clothing permeability as a result of "effective air motion" (21). Given the insulation and permeability characteristics of the materials, and the body area coverage of a clothing ensemble, at present all remaining factors involved in "functional clothing design" appear to be characterizable in terms of such pumping coefficients; these describe the slope of the change of insulation (clo) and of permeability (i_m) with increasing "effective air motion" (V_{eff}). Originally, the pumping coefficient for permeability was considered identical to that for insulation, but this may not prove correct; more data are needed. Currently, V_{eff} is considered to be the air motion generated by wind and/or by wearer motion. Thus, pumping coefficients can characterize: the weight of the

materials; the cut, fit and drape of the ensemble; the air permeability (primarily that of the outermost layer); the apertures; the number of layers within the ensemble and the extent to which they can move independently; and the like.

THE FUTURE: PREDICTION MODELING OF CLOTHING EFFECTS

Using just these three parameters (clo, i_m and V_{eff}), Givoni and Goldman developed a system of equations to characterize the resultant rectal temperature (21), heart rate (22) and skin temperature (unpublished), of wearers of a given ensemble in any cool to very hot environment as a function of the interaction between the body's heat production and the non-evaporative and evaporative exchanges with the environment allowed by the clothing. Subsequent modifications have been made for such physiologic factors as the degree of acclimation of the wearers to heat (23) and the level of dehydration (24). Breckenridge and Goldman have also presented models for including the effects of solar load on the heat balance (25), and the group at US Army Research Institute of Environmental Medicine (ARIEM) at Natick, have provided formulations to predict: the effects of clothing and load weight (26), and placement on the body (27), on heat production; the sweat production (28); and the physiological effects of clothing and solar load in combination (29). Water immersion protection clothing has also been measured, and its physiologic effects modeled (30). Another branch of physiological models deals with heat flow within the body as controlled by physiological mechanisms (Stolwijk and Hardy, 1966) and is elaborated in Chapter 3. A 1983 workshop in Texas (Wissler) compared a number of the models for predicting physiological responses to the environment; the values predicted by the formulae of the ARIEM group, which simply assume a value of 35 °C or 36 °C for skin temperature, gave at least as good agreement with the actual data points in the studies used for these comparisons as several, more physiologically sophisticated models. (33).

REFERENCES

1. Gagge, A.P., A.C. Burton, and H.C. Bazett. A practical system of units for the description of the heat exchange of man with his environment. Science, 94: 428-430, 1941.

1a. Gagge, A.P. The science of clothing, a short history from a physiologist's viewpoint. Aspects Medicaux et Biophysiques des Vetements de Protection. Centre de Researches du Service de Sante des Armees, Lyon, 13-21, 1983.

2. Winslow, C.E.A., L.P. Herrington, and A.P. Gagge. The influence of air movement upon heat losses from the clothed human body. Am. J. Physiol., 127: 505-518, 1939.

3. Burton, A.C. and 0.G. Edholm. Man in a Cold Environment. Edward Arnold & Co., London, 1955.

4. Newburgh, L.H. Physiology of Heat Regulation and the Science of Clothing. W.B. Saunders Co., Philadelphia, 1949.

5. Siple, P.A. and C.F. Passel. Measurements of dry atmospheric cooling in subfreezing temperatures. Proc. Am. Philos. Soc. 89: 177-199, 1945.

6. Estimation of the thermal insulation of clothing by measuring increases in girth of the wearer. U.S. Army Air Forces, Air Technical Service Command. Memo Rpt TSEAL-5H-5-241. May 1945, 20 pp.

7. American Society of Heating, Refrigerating and Air Conditioning Engineers, ASHRAE Standard 55-81, Thermal environmental conditions for human occupancy, Atlanta, 1981.

8. Van Dilla, M., R. Day, and P.A. Siple. In: Physiology of Heat Regulation and the Science of Clothing. W.B. Saunders Co., Philadelphia, 1949; pp. 374-388.

9. McCullough, E.A., B.W. Jones and PJ. Zbikowski. The effect of garment design on the thermal insulation of clothing. ASHRAE Trans. 89, Part II; 327-352, 1983.

10. Veghte, J.H. Human physiological response to extremity and body cooling. Aerospace Med. 33: 1081-1085, 1962.

11. Goldman, R.F. The arctic soldier: possible research solutions for his protection. Proc. 15th AAAS Alaskan Science Conf. 15:114-135, 1964.

12. Belding, H.S., H.D. Russell, R.C. Darling and G.E. Folk. Analysis of factors concerned in maintaining energy balance for dressed men in extreme cold; effects of activity on the protective value and comfort of an arctic uniform. Am. J. Physiol. 149: 223-239, 1947.

13. Lee, D.H.K. and J.A. Vaughan. Studies on thermal effects of solar radiation in transportabie solar chamber. ASME paper 60-WA-251, 1961.

14. Gagge, A.P. A new physiological variable associated with sensible and insensible perspiration. Am. J. Physiol. 120: 277-287, 1937.

15. Belding, H.S. and T.F. Hatch. Index for evaluating heat stress in terms of resulting physiological strains. Heating, Piping and Air Conditioning J. 27: 129, 1955.

16. Woodcock, A.H. Moisture transfer in textile systems. Textile Res. 3. 32: Pt 1, 628-632; Pt 11, 719-723, 1962.

17 Breckenridge, J.R. and R.F. Goldman. Effect of clothing on bodily resistance against meterological stimuli. Progress in Biometeorology, Vol. 1, Part 111, Section 19, 194-208, Chap. 7, 1977.

18. Goldman, R.F. Tolerance time for work in the heat when wearing CBR protective clothing. Mil. Medicine, 128: 776-786, 1963.

19. Goldman, R.F. and J.R. Breckenridge. Etude Des Effets Physiologiques du Vetement en Rapport avec Ses Proprietes Biophysiques. Cahiers de l'Association Francaise de Biometeorologie. 3: 33-36, 1970.

20. Goldman, R.F. Clothing design for comfort and work performance in extreme thermal environments: Transactions, New York Academy of Sciences 36: 531-544, June 1974.

21. Givoni, B. and R.F. Goldman. Predicting rectal temperature response to work, environment and clothing. J. Appl. Physiol. 32: 812-822, 1972.

22. Givoni, B. and R.F. Goldman. Predicting heart rate response to work, environment and clothing. J. Appl. Physiol. 34: 201-204, 1973.

23. Givoni, B. and R.F. Goldman. Predicting effects of heat acclimatization on heart rate and rectal temperature. J. Appl. Physiol. 35: 875-979, 1973.

24. Pandolf, K.B., R.L. Burse, B. Givoni, R.G. Soule and R.F. Goldman. Effects of dehydration on predicted rectal temperature and heart rate during work in the heat. Med. Sci. Sports 9: 51-52, 1977.

25. Breckenridge, J.R. and R.F. Goldman. Solar heat load in man. J. Appl. Physiol. 31: 659-663, 1971.

26. Givoni, B. and R.F. Goldman. Predicting metabolic energy cost. J. Appl. Physiol. 30: 429-433, 1971.

27. Soule, R.G. and R.F. Goldman. Energy cost of loads carried on the head, hands or feet. J. Appl. Physiol. 27: 637-690, 1969.

28. Shapiro, Y., K.B. Pandolf and R.F. Goldman. Predicting sweat loss response to exercise, environment and clothing. Eur. J. Appl. Physiol., 48: 83-96, 1992.

29. Pandolf, K.B., Y. Shapiro, J.R. Breckenridge and R.F. Goldman. Effects of solar heat load on physiological performance at rest and work in the heat. Fed. Proc. 38, Part II:1052, 1978.

30. Strong, L. and R.F. Goldman. A linearized, time dependent model of the heat transfer and thermoregulatory responses occurring upon immersion in cold water. U.S. Army Research Institute of Environmental Medicine, Tech. Rpt. T7/82, 1982, 53 pp.

31. Stolwijk, J.A.J. and J.D. Hardy. Temperature regulation in man - a theoretical study. Pfluegers Arch Ges Physiol 291: 129-162, 1966.

32. Nishi, Y. and A.P. Gagge. Moisture permeation of clothing - a factor governing thermal equilibrium and comfort. ASHRAE Transaction 76: 137-145, 1970.

33. Wissler, E.H. A mathematical model of the human thermal system. Bull. Math. Biophys. 26: 147-166, 1964.

CHAPTER 2

BIOMEDICAL EFFECTS OF CLOTHING ON THERMAL COMFORT AND STRAIN

R.F. Goldman

CONTENTS

SUMMARY

1. COMFORT AND STRESS
2. KEY FACTORS INVOLVED IN THERMAL COMFORT
3. THE HEAT BALANCE EQUATION
4. CLOTHING INSULATION AND WATER VAPOR PERMEABILITY
5. PHYSIOLOGICAL RESPONSES TO HEAT AND COLD
6. COMFORT SENSATION
7. HEAT TOLERANCE

REFERENCES

SUMMARY

Human comfort, discomfort and thermal strain are affected by the balance between produced and dissipated heat. Many factors are involved, including climatic variables, metabolic heat production and clothing parameters. The physiological response to a thermal imbalance is apparent by vasomotor action, shivering and sweating, accompanied by sensations of discomfort and, ultimately, limited thermal balance.

Key Words: thermal stress, thermal comfort, clothing insulation, evaporative cooling, clothing thermal exchanges, physiological response, human heat tolerance.

1. COMFORT AND STRESS

Any investigation of comfort must begin with recognition that comfort is a state of mind. It is extremely difficult to identify the myriad factors which affect comfort; the interaction between the physical demand imposed upon the individual, his physiological status and his psychological attitudes must be considered in interaction with social customs, tactile perceptions and the like. Even if we choose to restrict our comfort investigation to the area of thermal comfort, we still must recognize that we are in a subjective area and that it is impossible to satisfy all individuals with a given simple environmental specification. Indeed, thermal comfort depends on the interaction between three sets of factors: environmental factors, clothing factors and physiological factors.

The usual air temperatures associated with thermal comfort fall in the temperature range from 15 to 28 °C (60 to 81 °F). However, the human body has a much narrower "physiological" comfort range, i.e., that temperature range where human temperature regulation can be achieved: 1) without shivering, or even uncomfortably cool toes and fingers (as a result of the reduced circulatory heat input by blood flow from the body core to the skin, termed "vasoconstriction") and 2) without sweating to the point where the skin must exceed a 20% skin wettedness to obtain the evaporative cooling required. Indeed, the American Society of Heating, Refrigerating and Air Conditioning Engineers specifies that the space being conditioned for occupants wearing the usual long-sleeved shirt and trousers (which provide 0.6 clo of intrinsic insulation) should be maintained between 22.2 to 25.5 °C (72 to 78 °F). This suggests that the human comfort zone for "physiological" regulation of body temperature has a band width of roughly 3.3 °C (6 °F) as discussed later in this chapter. Thermal comfort outside this zone of "physiological" regulation from 22.2 to 25.5°C with normal (U.S.) indoor clothing is provided by "behavioral" temperature regulation by adding or removing clothing. Each change of 0.18 clo units of clothing insulation compensates for a 1 °C change in air temperature. Thus, at 15 °C a resting individual would need about 1.9 clo to be comfortable (i.e., 0.6 + 0.18 (22.2 - 15)), while at 28 °C only about 0.15 clo (e.g., shorts) should be worn (i.e., 0.6 - 0.18 (28 - 25.5) clo).

At ambient air temperatures below about 15 °C (59 °F), ill clad, chronically under-nourished individuals are susceptible to hypothermia. They do not have enough body fat stores to provide energy to sustain shivering and they lack enough clothing insulation to reduce their body heat loss to match their limited heat production. Even well fed troops will be shivering violently if they remain inactive for more than a few hours below about -30 °C (-22 °F), despite the best extreme cold weather protective clothing. Troops can successfully carry out military operations at temperatures below –55 °C (-67 °F), given good training and once cold acclimated. Under such extreme ambient conditions, it is, however, extremely difficult if not impossible to achieve thermal comfort; clothing, and training in how to use it, become essential elements in survival.

Heat stress for the soldier, an old problem, has been increased to new dimensions by the demands for increased protection in the event of chemical warfare. Even light mission activity demands become intolerable within a few hours in the desert for men completely encapsulated in chemical protective clothing systems, especially inside crew compartments with minimal ambient ventilation, e.g., in the "buttoned-up tank" mode. Providing air conditioning for the entire occupied space represents an unachievable logistic load for most

combat vehicles. Studies conducted in Yuma, AZ during September, 1980 demonstrated that, even under modest operational conditions in the desert, severe heat stress was experienced by combat crewmen in the fully encapsulated state when the vehicle ventilation system was shut down and all hatches closed. The internal humidity build-up in this condition was dramatic, produced performance decrements within 30 minutes, and limited tolerance to 2 hours or less.

2. KEY FACTORS INVOLVED IN THERMAL COMFORT

Air temperature, air motion, ambient air relative humidity (or more appropriately vapor pressure) and mean radiant temperature represent the four key environmental parameters in defining thermal comfort. These four are key parameters because they directly affect the heat transfer from the body. The rate of convective heat transfer is a linear function of the difference between skin temperature and the ambient air temperature. It is also affected by air velocity, with the relationship being a function of the air motion to the 0.6 power. Evaporative heat transfer is similarly affected by air motion, but is a linear function of the difference between the vapor pressure of sweat at skin temperature and the ambient vapor pressure. Finally, radiant heat transfer is independent of air motion but is a power function of the difference between the mean radiant temperature and skin temperature.

Another major element which must be considered to fully define a comfort state is the amount of metabolic heat produced by the individual. Heat production at rest or at work is an essential element in the comfort balance; it is appropriate to use a time weighted average since the body mass provides a damping of response and is sufficient to eliminate any observed effect of short term peaks in heat production on the order of ten minutes or less.

The final key element in comfort is the clothing worn. There are three aspects of the clothing that should be considered. Obviously, the insulation (clo units) provided by the clothing represents a direct barrier between the skin and air and therefore directly influences, in an inverse and linear manner, the convective heat exchange between the skin and the environment. One can also define a permeability index (i_m) reflecting any interference with the normal moisture permeability of the clothing. Thus, evaporative transfer through clothing turns out to be an inverse linear function of the length of the diffusion path, since the insulation is a linear function of the thickness of the clothing and associated trapped air layers. Therefore, one can define the actual maximum evaporative transfer, per millimeter of difference between vapor pressure of sweat at the skin and ambient vapor pressure, as the ratio of the intrinsic moisture permeability to the insulation (i.e., i_m /clo). The insulation and permeability of clothing are usually measured in static state on a heated manikin. A few representative values for military clothing in calm (0.3 m/s) air are given in Table 1. Obviously, such functional clothing design elements as the cut and fit of clothing, weight of material, nature of apertures, and the like, serve to alter insulation and permeability when the clothing is moved by wind or pumped by wearer motion; a pumping coefficient has been derived specifically to assess such changes in insulation and permeability when the individual wearing the ensemble is exposed to an external air motion or generates air and/or clothing movement by activity.

Table I

BEST AVAILABLE VALUES FOR TYPICAL U.S. MILITARY CLOTHING

(0.3 m/s air motion)

CLOTHING	i_m	clo	i_m/clo
Cold-Dry	.43	4.30	.10
Cold-Wet	.40	3.20	.13
Utility Fatigues	.41	1.40	.29
Battle-Dress Uniform	.41	1.34	.31
Chem. Prot. Overgarment			
(without mask,hood,gloves)	.34	1.97	.17
(MOPP IV with mask, hood and gloves)	.30	2.44	.12
(MOPP IV, plus body armor, ground troops)	.29	2.20	.13

Source: USARIEM copper manikin measurements

3. THE HEAT BALANCE EQUATION

The body's interaction with its environment has been described by a fundamental "heat balance equation" where the interaction between the metabolic heat production of the individual (M), and his heat exchanges by convection (C), radiation (R) and evaporation (E) describe whether or not the heat being produced by the individual can be balanced by the exchanges with the environment. If it cannot, then there must be a change in the body heat content; a heat debt (in the cold) or heat storage in any environment where heat losses are less than heat production and gains.

Essentially, if the metabolic heat production can be offset by the non-evaporative heat exchanges by radiation and convection (i.e., R + C) then there is no change in body heat content and, in addition, no requirement for evaporative exchange. One can express this by the following simple equation:

$$M \pm (R + C) + E = \Delta S \qquad \text{Equation 1}$$

where ΔS, the change in body heat storage, is calculated from the change in mean body temperature (ΔT_b) times the mass of the body and its specific heat. The specific heat of human body tissues (c_p) is generally taken as 0.83 kcal/kilogram·C; thus, for a 70 kilogram (154 lb) standard man, a change of 58 kcal in body heat content corresponds to a change of 1 °C (i.e., 0.83 x 70) in mean body temperature. When M is less than (R + C), ΔS obviously reflects a heat debt. If, on the other hand M is greater than (R + C) the relationship defines the required evaporative cooling (E_{req}) to achieve thermal balance. The required evaporative cooling is often achievable: a) if the body can produce enough sweat (the sustainable sweat rate is often the order of 1 liter per hour); b) the ambient water vapor pressure in the environment is low enough to facilitate evaporation; and c) the clothing is sufficiently porous to allow it to be transferred from the skin to the ambient environment as a vapor rather than being wicked into the clothing and evaporated at the surface of the clothing, then the body can lose 0.58 kcal per milliliter (~ one gram) of sweat evaporated.

Heat production (M) at rest is about 1 MET (defined as 50 kcal of metabolic heat production per square meter of body surface area per hour); i.e., for an average adult man (who has 1.8 m^2 of body surface area), heat production at rest is about 90 kcal/hr or 105 watts. Normal work can double this heat production level and hard work can triple it. The sustainable "voluntary hard work" level of M is about 5 MET (425 kcal/hr or 500 watts), while 6 or 7 MET will prove exhausting for the average man if sustained for over a few hours.

Usually, about 12% of the resting heat production is eliminated from the lungs by respiration; another 12% is eliminated as a result of evaporation of body water diffusing through the skin. The remainder (about 76%) of resting metabolic heat production is eliminated from the body by convection and radiation in a comfortable environment; the relative proportion of convective to radiation losses is controlled by the ambient air motion. With minimal clothing in still air, about 60% of the resting heat production is lost by radiation. Elimination of the increased heat production during work is facilitated by the extra convective air motion generated by body "pumping", but in a warm environment most of the increased

heat production is lost by production of sweat and its subsequent evaporation; even in a cold environment, about 42% of working heat production may be lost by evaporation of skin moisture (diffusion and sweat).

4. CLOTHING INSULATION AND WATER VAPOR PERMEABILITY

One clo unit of clothing and air insulation is defined as allowing 5.55 kcal/m^2·hr of heat exchange by radiation and convection (R + C) for each °C of temperature difference between the skin (at an average skin temperature $\overline{T}_s$) and ambient adjusted bulb temperature (T_{adb} = 1/2 (air temperature plus mean radiation temperature)). Since the average man has 1.8 m^2 of surface area, his (R + C) can be estimated as

$$(R + C) = (10/clo)\,(\overline{T}_s - T_{adb}) \qquad \text{Equation 2}$$

Thus, a 0.8 clo "still" air layer by itself limits the heat exchange by radiation and convection for a nude man to about 12.5 kcal/hr (i.e. 10/0.8) for each °C of difference between skin and air temperature.

A typical value for clothing insulation is 1.57 clo per centimeter of thickness (4 clo per inch), although it is difficult to extend this generalization to very thin fabric layers, or to fabric layers like underwear, which may simply occupy an existing still air layer of maximum thickness (0.5 cm). The underwear makes little contribution to the intrinsic insulation (i.e. excluding the external air layer insulation) unless there is: a "pumping" of the clothing layers by body motion; compression of the clothing layers overlying clothing or combat equipment or by external wind; or penetration of some of the wind into the trapped air layer. Table II presents a listing of the intrinsic insulation contributed by adding each of the listed items of civilian clothing. Note that the total intrinsic insulation is not taken to be the sum of the individual items, but as 80% of their total insulation value; this allows for an average loss of 20% of the sum of the individual insulation items to account for the compression of one layer by the next. This average 20% reduction is, of course, an approximation which is highly dependent on the nature of the fibre, the weave, the weight of the clothing fabric, use of foam or other non-fibrous layers, the clothing fit and cut, etc.

Insulation is generally a function of the thickness of the clothing ensemble and this, in turn, is characteristically a function of the number of clothing layers. Thus, each added layer of clothing will tend to exert a characteristic increase in total insulation. This is why most two-layer clothing ensembles exhibit quite similar insulation characteristics, most three layer systems are comparable, etc., regardless of some rather major differences in fiber selection, fabric type or layer thickness.

Table II

INSULATION FOR INDIVIDUAL ITEMS OF CIVILIAN CLOTHING AND FORMULAE FOR OBTAINING TOTAL INTRINSIC INSULATION*

(CLO UNITS)

	Light	Heavy	
Undershirt			
"T"	.09		
sleeveless	.06		
long underwear	.20		
fishnet	.10		
Shirt			
short sleeve	.18	.25	
long sleeve	.22	.29	
Sweater			
short sleeve	.18	.33	
long sleeve	.20	.37	
turtle neck	.24	.43	
Vest			
Jacket			
short ski jacket (waist)	.22	.49	
long ski jacket (hip)	.33	.73	
Pants			
Long pants	.26	.35	
knickers	.18	.23	
overpants	.30	.40	
ski overalls	.40	.53	
long underwear	.20	.30	
Socks			
ankle	.04	.08	
knee	.08	.13	
tights	.06	.11	
Ski Boots		.08	.11

Total I = 0.8 (individual items + external air layer (0.8))

*Adapted for skiwear from clo list developed at the Kansas State University by Sprague and Munson.

Water vapor permeability

Evaporative heat transfer through clothing tends, similarly, to be affected linearly by the thickness (i.e., insulation) of the ensemble. The moisture permeability index (i_m) defined by Woodcock is a dimensionless unit, with a lower limit value of 0 for an impermeable layer and an upper value of 1 if all the moisture that the ambient environment can take up (as a function of the ambient air vapor pressure) can pass through the fabric. Values of i_m approaching 1 should only be found with high wind and no clothing, since moisture vapor transfer is a diffusion process limited by the characteristic value for diffusion of moisture through "still" air. A typical i_m value for most permeable clothing ensembles in "still air" is a bit less than 0.5. Water repellent treatment, very tight weaves and chemical protective impregnations can reduce the i_m value significantly. However, even impermeable layers seldom reduce the i_m value to 0, since an internal evaporation - condensation process is set up between the skin and the inner surface of the impermeable layer which effectively transfers some heat from the skin to the vapor barrier; this shunting, which bypasses the intervening insulation layers, can be reflected as an i_m value of perhaps 0.08 even for a totally impermeable overgarment.

A few fibre treatments have been found to improve the i_m index value of fabric layers; surfactants, which somehow improve wicking, appear to improve the i_m value of a fabric as measured on a heated, sweating flat plate.

Note that the ultimate evaporative heat transferred from the skin, through the clothing and external air layers, to the environment is not simply a function of the permeability index (i_m), but is a function of the permeability index to insulation ratio (i_m /clo). The maximum evaporative heat exchange with the environment can be estimated, in a manner analogous to Equation 1 for the (R + C) of man with 1.8 m^2 of surface area, as:

$$E_{max} = 10\ i_m/clo \times 2.2(\overline{P}_s - Ø_a P_a) \qquad \text{Equation 3}$$

where the constant 2.2 is the Lewis number (from physics) to indicate that a one mmHg vapor pressure change is equivalent to a 2.2 °C temperature difference if one wishes to express the evaporative heat transfer coefficient (h_e) as a function of the convective heat transfer coefficient (h_c), i.e., $h_e = 2.2\ h_c$; $\overline{P}_s$ is the vapor pressure of sweat (water) at skin temperature $\overline{T}_s$; $Ø_a$ is the fractional relative humidity and P_a is the saturated (100% RH) vapor pressure of the ambient air at air temperature T_a. Thus, the maximum evaporative transfer tends to be, at best, a linear inverse function of insulation even if not further degraded by the various chemical agent protective treatments, which range from, at worst, total impermeability to, at best, water repellent treatments to disperse agent droplets.

5. PHYSIOLOGICAL RESPONSES TO HEAT AND COLD

Vasomotor effects

Having thus defined the relationship between the environmental parameters, the clothing, and the heat dissipation from the body, it becomes appropriate to look at the physiological responses of the body. As shown in Table III, these can be divided into some five zones. Despite attempts to identify a single temperature with thermal comfort the comfort zone has been found better represented as a band roughly 3.3 °C (6 °F) wide; the central point is a function of activity and clothing and also of air motion, relative humidity and mean radiant temperature. The subjective comfort band corresponds, in part, to the physiological state shown in Table III as the vasomotor control zone. The body's first line of defense against conditions where metabolic heat production is greater than heat losses by radiation and convection, is to increase the flow of blood from the body's core to the skin. The resultant increase in skin temperature helps increase non-evaporative heat losses and/or reduce convective and radiant heat gains. If metabolic heat production is less than heat loss by radiation and convection from the body, then the blood flow to the skin is reduced by vasoconstriction; the resultant fall in skin temperature helps reduce heat losses. Vasoconstriction is most effective at reducing the circulatory heat input to the extremities, particularly since the reduction in heat input is aided by a counter-current heat flow exchange; the warm blood flowing in the arteries to the extremity is pre-cooled by the juxtaposed venous return. The limited circulating blood which eventually does reach the extremity is already reduced in temperature by this exchange mechanism. Since heat transfer is a linear function of surface area, the fingers and toes which have relatively large surface areas available for heat loss but only low mass from which to lose heat, suffer the greatest drops in extremities temperatures, the drop in their temperatures usually signals the onset of thermal discomfort in the cold. The net result is that, even within the vasomotor control zone, extremity cooling and in particular cold toes and fingers lead to onset of thermal discomfort.

Table III

5 ZONES OF HUMAN THERMAL EFFECT

I INCOMPENSABLE HEAT ZONE

(E_{req}/E_{max})

100%

80

f(CLOTHING PERMEABILITY (I_M/CLO); VAPOR PRESSURE GRADIENT ($\overline{P}_s$ - P_a); WIND)

60

40

hot

---------- ..20

warm

0 II. SWEAT EVAPORATION COMPENSABLE ZONE (700 WATT = E_{MAX})

VASODILATATION

comfortable III VASOMOTOR CONTROL ZONE

VASOCONSTRICTION

cool

---------- EXTREMITY COOLING

cold

SKIN COOLING

0

100

200 IV SHIVERING COMPENSABLE ZONE (525 WATT = M_{MAX})

300 f(CLOTHING INSULATION (CLO); TEMPERATURE GRADIENT ($\overline{T}_s$ - T_a); WIND)

400 Watt

($M - H_R + C$) V INCOMPENSABLE COLD ZONE

Metabolic Effects

As cold discomfort increases, the body's second line of defense against cold is to increase its heat production, first by muscle tensing (i.e., imperceptible increases in motor tone) and, ultimately, by frank shivering; both muscle tensing and shivering increase heat production. Sometime between the imperceptible increases in muscle tone and the onset of shivering, the development of "gooseflesh" can be noted. The maximum increase in heat production associated with shivering is about 525 watt (450 kcal per hour). Whether any of that added heat production is actually effective in raising body temperature is determined by the external clothing insulation, the ambient air motion, and the difference between the skin temperature and the air temperature. Indeed, a lightly insulated or unclothed individual might increase his heat loss to such an extent while shivering, that he could wind up with a greater heat debt than he would have had if he had not shivered; i.e., the extra heat production associated with shivering is not conserved because the increased heat loss to the environment associated with the movement of the external clothing and air layers, coupled with a decrease in vasoconstriction during shivering, results in an increase in heat loss greater than the increase in heat production by shivering. Under any circumstances, shivering cannot be considered comfortable, and an individual who is shivering at anything near the maximum 450 kcal per hour is functionally unable to do much else; the incompensable cold zone thus represents a large area of failure in terms of physiological regulatory responses. Behavioral temperature regulation, i.e., putting on more clothing or moving to a warmer environment is the only workable solution for man in a cold environment.

Sweating Response

Table III shows that vasodilation, which raises the body skin temperature, is inadequate to produce the required heat losses to balance heat production. As the skin temperature rises to above 35 °C (95 °F) sweat production is initiated. A little sweating is not uncomfortable; sweating at a level to produce 20% or less skin wettedness is still "comfortable" although perhaps perceived as slightly warm.

A maximum limit to sweat evaporative cooling is imposed by the one liter per hour sweat rate sustainable by the average individual. While two or three times this rate can be achieved for an hour or two, this one liter per hour sustainable rate corresponds to an evaporative cooling potential of 700 watts (or 600 kcal per hour). It is the evaporated sweat rather than the produced sweat which determines a limit of tolerance.

The percent sweat wetted surface area ($\%SW_A$) that will be required for eliminating heat from the body can be estimated simply as the ratio of the required evaporative cooling (E_{req}) by Equation 1, and the maximum evaporative cooling (E_{max}) by Equation 3; i.e.

$$\%SW_A = E_{req}/E_{max} \qquad \text{Equation 4}$$

The threshold for a sensation of discomfort is a skin wettedness of about 20%. Discomfort is marked with between 20 and 40% of the body surface sweat wetted ($\%SW_A$) and performance decrements can appear; they become increasingly noted as $\%SW_A$

approaches 60%. Sweat begins to be wasted at 70%, dripping rather than evaporating, while physiological strain becomes marked between 60 and 80% SW_A; increases above that level result in limited tolerance even for fit, heat acclimatized, young men. From the above arguments, it should be clear that any conventional chemical protective clothing will pose severe tolerance limits since its i_m /clo ratio is rarely above 0.20. The basic problem is that skin temperature ($\overline{T}_s$) must be maintained at least 1 °C below deep body temperature (T_{re}) if the body is to be able to transfer heat from the body core (where it is produced by metabolism at rest and during work) to the skin, whence it can subsequently be eliminated to the environment, through the clothing.

6. COMFORT SENSATION

The three sets of factors involved with comfort (environmental factors, clothing, and human responses) have now been identified and the question of what is comfortable can be addressed. Cold fingers and toes, or cold skin are associated with cold discomfort, while discomfort in the heat will increase as the sweat wettedness of the surface increases. Comfort studies have been conducted in which a group of individuals has been assembled, wearing the standard 0.6 clo ensemble in a climatic chamber, and voted their thermal comfort and their temperature sensation while seated at rest. A standard comfort ballot has been used, a 7 point scale where a temperature sensation of neutral corresponded to a comfort vote of 4, slightly warm 5, warm 6 and hot 7, with slightly cool corresponding to a vote of 3, etc. as shown in Table IV. These temperature sensations can be roughly related to environmental temperatures using the new effective temperature scale (ET*) where ET* corresponds to a standard environment, at the stated Effective Temperature*, with 50% relative humidity and air movement of 0.15 m/s when wearing standard long sleeve shirt and trousers (0.6 clo intrinsic). Comfort sensations differ slightly from temperature sensations, but can similarly be related to the Effective Temperature index ET*. A neutral temperature sensation occurs at a 27°C ET*. At this point average skin temperature is between 33 and 34 °C and the body is considered to be roughly 6% wetted, simply as a result of the diffusion of moisture through the skin. This ET* 27 °C comfort temperature appears to be relatively invariant across cultures, ages or sex, but is clearly modifiable by clothing as well as by activity. Increasing temperature to ET* 30 °C will result in a comfort vote of slightly warm and a temperature sensation of slightly warm, as skin temperature approaches 35 °C; further increases in ET* result in increasing comfort votes and temperature sensations going from warm to hot, etc., corresponding to increases in sweat wetted area. As ET* drops below 27 °C, comfort votes decrease as temperature sensations shift, initially in response to cooler fingers and toes and, ultimately, to colder mean weighted skin temperatures. Thus, as shown in Table IV, comfort can be predicted based on the interactions between the three sets of key factors presented previously (clothing, environment and physiological response) for a standard condition at rest, wearing a standard long sleeve shirt or trousers, with standard air movement and relative humidity.

Table IV

COMFORT VOTE AND TEMPERATURE SENSATION

VOTE		TEMPERATURE SENSATION	ET*(4)	COMFORT SENSATION	$\overline{T}_s$ (5)	% A_{sw}(6)
(1)	(2)	(3)				
		1 Very Cold	10 °C	Uncomfortable	30 °C	
1	-3	2 Cold	15 °C		30.5 °C	
2	-2	3 Cool		Slightly Uncomfortable	32 °C	
			20 °C			
3	-1	4 Slightly Cool			32.5 °C($T_{fingers/toes}$)	
			25 °C	Comfortable		
4	0	5 Neutral			34 °C	6
5	+1	6 Slightly Warm	30 °C		35 °C	
6	+2	7 Warm	35 °C	Slightly Uncomfortable	—	20
7	+3	8 Hot			—	40
			40 °C	Very Uncomfortable		60
		9 Very Hot			—	80
			45 °C	Limited	(T_{core}-$\overline{T}_s$)	100

(1) Classic ASHRAE comfort scale

(2) Fanger modification

(3) Rohles modification

(4) Air temperature (T_{db}) at 50% RH with air movement = 0.14m/s wearing standard long sleeved shirt or trousers (1.4 clo total).

(5) Mean Weighted Skin Temperature

(6) Percent of skin area sweat wetted = Skin relative humidity = E_{req}/E_{max}

Relative importance of environmental factors.

An extensive series of studies, involving well over 3000 subjects over the years, has lead to the recognition that trade-offs can be made between these six key parameters: air temperature, air motion, vapor pressure, mean radiant temperature, clothing, and heat production, although these trade-offs only operate within finite limits. An alteration of heat production by an individual obviously would change the temperature sensation and relative comfort; each increase of roughly 30 watts (25 kcal per hour) in the heat production of an individual, which is a relatively slight increase in activity, allows the comfort temperature to be dropped by about 1.7 °C (3 °F). This is a key factor in keeping people comfortable in the cold; one could solve most cold discomfort simply by being more active. Because of the limitations on maintaining comfort when differences in surface and mean radiant temperature are more than 11 °C (20 °F), i.e., asymmetric or non-uniform radiation, it is much easier to keep warm while cutting firewood than it is standing in front of a roaring fire with one side exposed to high radiant temperature and the other side radiating to a relatively cold ambient environment. Increases in mean radiant temperature can be used to compensate for decreases in air temperature in roughly a 1 to 1 proportion, with each decrease of 1 °C in air temperature being offset by 1 °C rise in radiant temperature. However, as pointed out above, an asymmetry of more than 11 °C in radiant temperature is not comfortable even if the appropriately adjusted dry bulb temperature (i.e., (mean radiant temperature + air temperature) /2), would still produce a condition falling within the comfort range. Other trade-offs can be made; each 0.18 m/s increase in air motion roughly corresponds to an increase of 1 °C in allowable comfort temperature. Again, there is a limit to the extent to which increasing air motion can compensate for increased air temperature; the maximum comparable temperature increase is roughly 2.8 °C, which would be associated with an increase of 0.5 m/s. A change of roughly 36% in relative humidity corresponds approximately to a 1 C change in the comfort temperature, with increasing humidity being associated with decreasing temperatures and vice versa. All these offset factors are relatively small, except for the change in heat production by the individual, compared to the very dramatic increases in comfort which can be obtained simply by putting an additional clothing as temperatures decrease, with each added 0.2 clo of intrinsic insulation roughly producing comfort at a 1 °C lower air temperature. Such increases in clothing to offset falling temperatures can be carried much further, and more easily effected than any changes in the other six parameters but, to achieve thermal comfort at very low temperatures, the distribution of the additional clothing must be carefully addressed, with appropriate attention to head and extremities.

7. HEAT TOLERANCE

The metabolic heat transferred to the skin per unit time can be seen to be limited, ultimately, by the cardiac output and by the extent to which mean skin temperature ($\overline{T}_s$) can be maintained below deep body temperature (T_{re}). T_{re} is a function of metabolic heat production (T_{re} = 36.7 + 0.004M) in the absence of any restrictions on heat loss as a result of clothing, high ambient temperatures or vapor pressures, or very low air motion; i.e., at rest (M = 105 watts) T_{re} is about 37.1 °C. Normally, under the same conditions of unlimited heat loss, skin temperatures are about 3.3 °C + (0.006M) below T_{re}. Thus at rest, when T_{re} is 37 °C, the corresponding $\overline{T}_s$ is about 33 °C; (i.e. 37 - (3.3 + 0.6)). This 4 °C difference between T_{re} and

$\overline{T}_s$ indicates that each liter of blood flowing from the deep body to the skin can transfer about 4 kcal of heat to the skin. Since T_{re} increases and T_s decreases with increasing M, it becomes easier to eliminate body heat with increasing work since the difference between T_{re} and $\overline{T}_s$ increases by about 1 °C per 100 watts of increase in M (i.e., T_{re} changes 0.004 °C, and $\overline{T}_s$ -0.006 °C, per Watt of M). Thus, at a sustainable voluntary hard work level (M = 500 watts), each liter of blood flowing from core to skin can transfer about 9 kcal to the skin, more than double the amount at rest.

Unfortunately, any clothing interferes with heat loss from the skin and skin temperature rises, predictably, with increasing clothing. Core temperature (T_{re}) also rises when clothing is worn, as a function of the insulation induced rise in $\overline{T}_s$ and the resultant, limited, ability to transfer heat from the core to the skin. There is an even greater interference with heat loss from the skin when sweat evaporation is required (E_{req}) but this is lirnited by either high ambient vapor pressure ($Ø_aP_a$), low wind, or low clothing permeability index (i_m /clo) (cf. Eq.3). As E_{req} approaches E_{max}, skin temperature increases dramatically and deep body temperature begins to increase exponentially. Deep body temperatures above 38.2 °C are considered undesirable for an average industrial work force.

At a deep body temperature of 39.2 °C, associated with a skin temperature of 36 or 37 °C (i.e. $\overline{T}_s$ converging toward T_{re} and approaching a 1 °C limiting difference where one liter of blood can only transfer 1 or 2 kcal to the skin) there is about 25 % risk of heat exhaustion collapse in fit young males. At a similarly elevated $\overline{T}_s$, and T_{re} of 39.5 °C there is a 50% risk of heat exhaustion collapse, and as T_{re} approaches 40 °C, with elevated skin temperatures, almost all individuals are highly susceptible; in practice, most laboratories will terminate experiments well below these limits. Finally, T_{re} levels above about 42 °C are associated with heat stroke, a life threatening, major medical emergency. The competition for cardiac output is sorely exacerbated by dehydration (limited stroke volume), by age (limited maximum heart rate), by reduced physical fitness (lower stroke volume) and these mission limiting and potentially deadly deep body temperature levels are reached more rapidly when any of these three factors is involved.

In essence, mission performance will be seriously degraded by protective clothing worn during heavy work in moderately cool environments, or at low work levels in warm conditions. It is also suggested that little improvement in the heat stress problem is likely with any two layer protective ensembles, or any effective single layer vapor barrier system for protection against CW agents, unless some form of auxiliary cooling is provided.

Tolerance in CW Clothing

Figure 1 is a 1963 Chart of "Predicted Time to 50% Unit Heat Casualties" when troops wear a CW protective ensemble in either open (MOPP III) or closed (MOPP IV) state. This is expressed as a function of the environmental Wet Bulb Globe Temperature (WBGT) index, a combination of 10% of air temperature, 20% of the 15.4 cm (6") Black Globe Temperature (representing the radiant heat load received by a man) and 70% of the naturally convected (i.e. non-ventilated or non-psychrometric) Wet Bulb Temperature. The latter term is more applicable to a soldier, who only has the available air motion to evaporate whatever sweat he produces, than would be some expression of the conventional relative humidity or wet bulb

temperature, which uses a ventilated wet bulb thermometer. If hard work is involved, tolerance time to 50% unit heat casualties is between 1 and 2 hours, whether in MOPP III or MOPP IV, and almost without regard to ambient heat stress. For moderate work, little problem would be anticipated with WBGT in the 20 °C (68 °F) range for closed suit or below 25 °C (77 °F) for open suit, while for light work, the WBGT would have to reach 32 °C (90 °F) for MOPP IV and about 36 °C (97 °F) for MOPP III in order to incur 50% unit heat casualties in 5 to 6 hours.

PREDICTED TIME TO 50% UNIT HEAT CASUALITIES

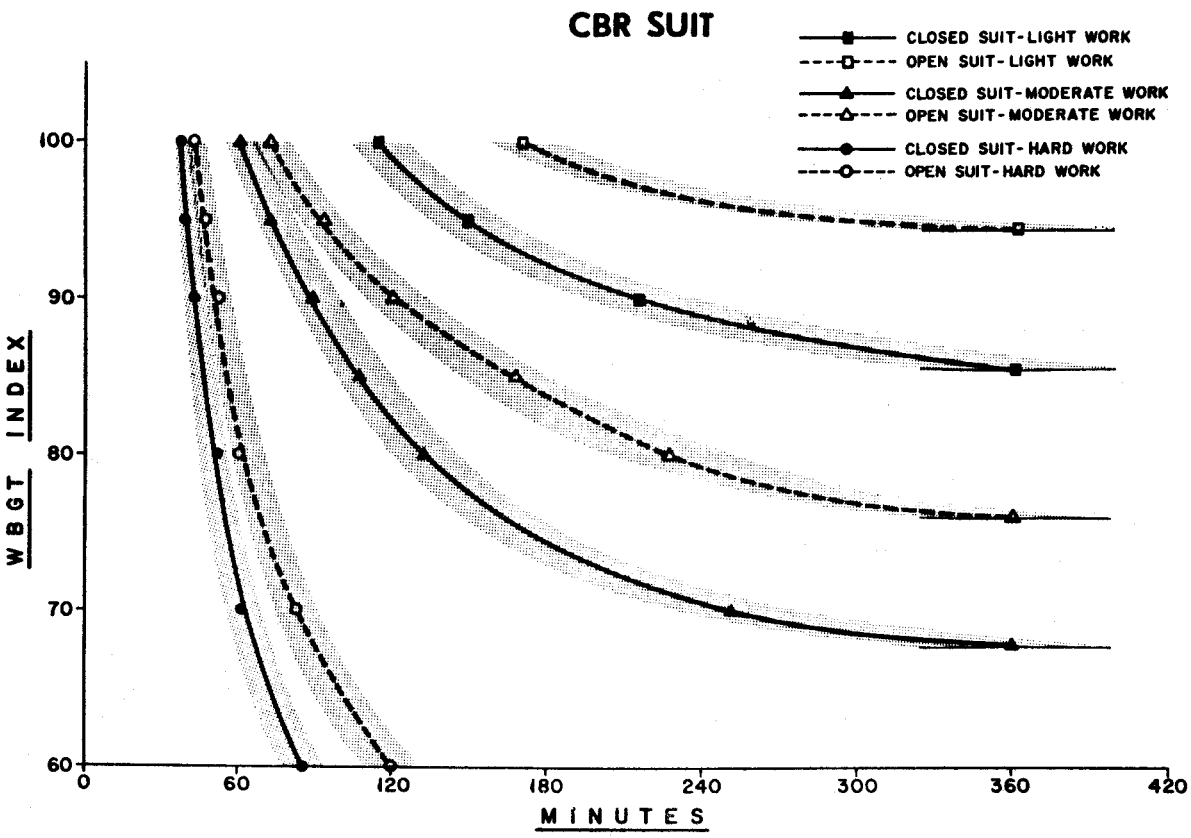


Fig 1. Predicted time to 50% unit heat casualties

REFERENCES

Thermal Environment:

Burton, A.C. and Edholm, O.G. Man in a Cold Environment, Edward Arnold, Ltd., London, 1955.

Gagge, A.P., J.A. J. Stolwijk and Y. Nishi. An effective temperature scale based on a simple model of human physiological regulatory response. ASHRAE Trans. 77(1):246-262, 1971.

Newburgh, L.H. Physiology of Heat Regulation and the Science of Clothing. W. B. Saunders, Philadelphia, 1949.

Physiological Responses:

Burton, A.C. The application of the theory of heat flow to the study of energy metabolism. J. Nutr. 7:497-533, 1934.

DuBois, E.F. Fever and the Regulation of Body Temperature. CC Thomas, Springfield, 1948.

Gagge, A.P. A new physiological variable associated with sensible and insensible perspiration. Am. J. Physiol. 120:277-287, 1937.

Selle, W.A. Body Temperature. CC Thomas, Springfield, IL., 1952.

Winslow, C. E.A., L.P. Herrington and A.P. Gagge. Physiological reactions of the human body to varying environmental temperatures. Am. J. Physiol. 120:1-22, 1937.

Clothing:

Fourt, L. and Hollies, N.R.S. Clothing Comfort and Function. Marcel Dekker, Inc., New York, 1970.

Gagge, A.P., A.C. Burton and H.C. Bazett. A practical system of units for the description of the heat exchange of man with his environment. Science. 94:428-430, 1941.

Hollies, N.R.S. and Goldman, R.F. Clothing Comfort. Ann Arbor Science, Michigan, 1977.

Sprague, C.H. and D.M. Munson. A composite ensemble method for estimating thermal insulation values of clothing. ASHRAE Trans. 80(1):120-129, 1974.

Woodcock, A.H. Moisture transfer in textile systems, Part I. Text. Res. J. 32:628-633, 1962.

Comfort:

ASHRAE. Handbook of Fundamentals, Chapter 8. American Society Heating, Refrigerating and Air Conditioning Engineers, New York, 1977.

McIntyre, D.A. 1974, The determination of individual preferred temperatures. Electricity Council Research Centre Note ECRC/N729, Capenhurst, U.K, 1974.

Winslow, C.-E.A., and Herrington, L.P. Temperature and Human Life. Princeton Univ. Press, Princeton, N.J., 1949.

CHAPTER 3

PREDICTIVE THERMAL MODELING

W.A. LOTENS

CONTENTS

SUMMARY

1. INTRODUCTION
2. PHYSICS OF CLOTHING (1-2)
3. PHYSIOLOGICAL MODELS
4. DATA REGRESSION MODELS (1-3)
5. PERFORMANCE CRITERIA (3-4)
6. THERMAL SENSATION MODELS (2-4)
7. VALIDATION

REFERENCES

SUMMARY

The various kinds of predictive thermal models are classified according to the calculation steps involved, in the chain: environment - skin heat transfer - physiological strain - performance. Each class of model is discussed, including validity and differences between representative examples.

Key Words: thermoregulation, mathematical model, mass and heat transfer, clothing, thermal physiology, performance criteria, thermal sensation

1. INTRODUCTION

It was perhaps Burton in 1934 who first published a mathematical model to predict temperature response. Many models have been developed ever since at an exponentially growing rate. Only few of those have been put into use by people other than the authors, for various reasons. Lack of understanding, lack of confidence, lack of input data and lack of ready-to-use program files are probably the main reasons. It is the purpose of this chapter to touch on various models, explain the context and differences and to go into some more detail regarding the most popular models, in an attempt to remove some of the obstacles mentioned.

The general scheme of Fig. 1 may serve as a means for classification of the various models. In this scheme, the environmental conditions are related to operational performance by means of a long process that starts with the heat exchange between the skin and the environment. This is in fact pure physics, but by no means a static process. The heat and moisture transfer depends on the ventilation due to motion and wind, the properties of the clothing change with wetting of the clothing, and, due to posture and behaviour, the exposed surface area may change.

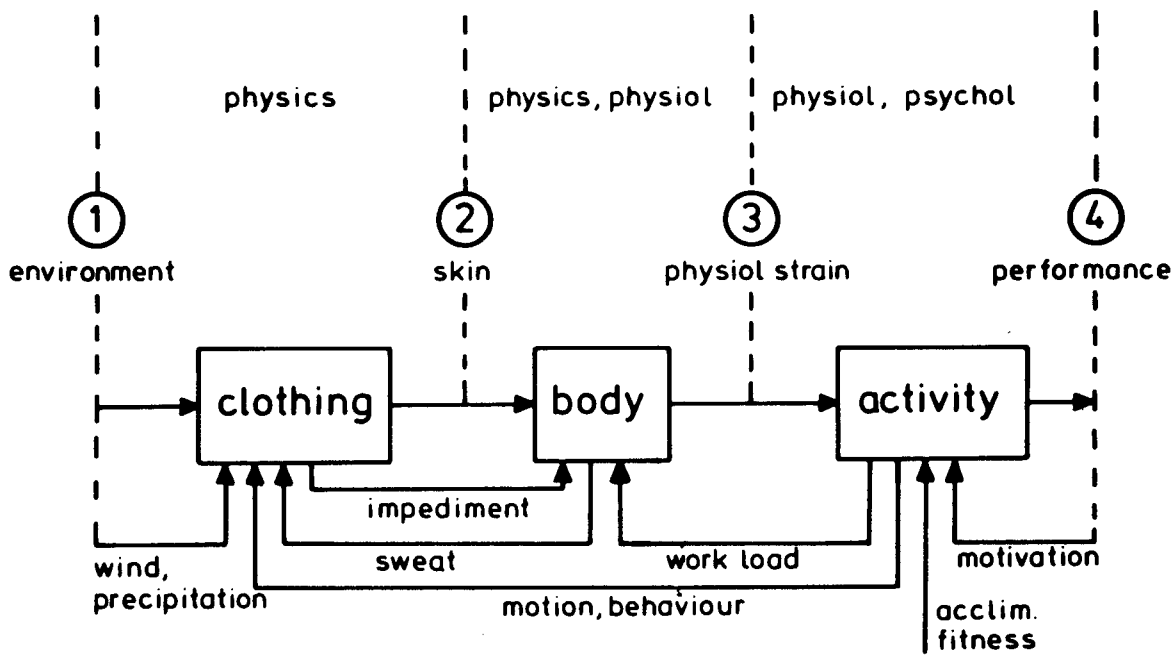


Fig. 1 A general scheme of calculation steps to relate environmental conditions to operational performance.

The next step, from skin to physiological strain, is partly physical and for a large part physiological. In the tissue of the body, heat is transferred by conduction and circulatory convection. The heat flow is controlled by the physiological processes of sweating, shivering, vasomotor action and metabolic heat production. The latter depends on the work load evolving from the task and the impeding effect of the clothing. The resulting effect of the physiological system is called the physiological strain. Physiological strain is not represented by a unique parameter, but rather shows itself in many more or less related variables such as

heart rate, blood pressure, sweat production, body temperature, metabolic waste products, etc. The main physiological system involved is probably the circulation, including body fluids, but the nervous system (pain, muscle control) is important as well.

In the third step in Fig. 1 the physiological strain, or better the spare capacity in the physiological system, is used as a criterion to decide whether a task can still be continued. In general, the strain will increase in the course of time until the maximum of the individual is reached. The maximum is dependent on the individual's state of acclimatization, fitness and various other factors of minor importance. Mental aspects play a role as well. Due to motivation, the performance may be kept level until it breaks down completely. With less motivation the performance will decrease gradually.

The various existing models may be classified according to the calculation steps involved. Some do one step only, some take two or more, either implicitly or explicitly. Some are mechanistic, taking an engineering view on the matter. Others do not deal with the processes that are going on, but relate results to input conditions in an empirical approach. In the next sections, this classification will be made, but first a few remarks on models in general.

Considerations in modeling

Models increase in value when they take verifiable steps. Verifiable means in this respect that the results can be checked with experimental methods, methods that preferably do not require difficult techniques like invasive measurements. Some investigators may have access to the required facilities, but the majority do not and consequently difficult-to-check models will otherwise be of disputable value for many potential users. The argument for verifiable steps demands a block building concept of models. Any block should deal with a single or a few coupled variables only and have a clearly defined interface of input and output variables. Another advantage is that blocks of various models may be coupled and give room for investigators to play with them.

A related topic is the availability of input data. Any model will require input data, at least about the environmental conditions, the clothing and the activity. Some require many more parameters, dealing with the shape and thermal properties of the body and with physiological control functions. A model can run only when all input parameters are available. In default of actual measured values, literature or even estimated values have to be used. These are usually provided by the author of the model. It is tempting, however to fit the model to experimental data by changing those parameter values in the expectation that the model will be improved. What it really boils down to is that a <u>different</u> model has been used and moreover, it becomes a one shot model, for just one experiment. If every investigator acts this way, chaos results in the literature, if not in his own archives. The utmost care has to be exercised in this matter.

Few authors will claim that their model is close to reality. In fact, it is rather a mathematical description of observed phenomena than a representation of the real process. However, the assumption underlying the model, together with the fit of the data give confidence to interpolations and some extrapolation. The non-expert user of the model is not so aware of the limitation to the validity of the model and will apply it to his problem, which

might be well outside the validity range. Moreover, he will probably believe that the results are as good as reality. It is advisable, therefore, to accompany a model with a definition of the validity domain and the level of validation. A typical correct use of a model would be the estimation of the range of conditions for an experiment.

Types of models

The various types of models will be classified according to the included steps, referring to Fig. 1. Class 1-2 are the models dealing with the physics of clothing only. Class 2-3 are the purely physiological models and class 3-4 the performance criteria. Models that do not make the separation between physics and physiology, jumping directly from environment to physiological strain are data regression models (class 1-3). Models that use the skin condition to predict performance are relatively rare, but thermal sensation models fall into this class (2-4). Models that predict performance directly from the environmental conditions, without clear steps in between, are unknown to the author.

The mentioned classes will be discussed in more detail in the following sections. It must be emphasized that this is not a complete inventory of existing models, however.

2. PHYSICS OF CLOTHING (1-2)

Usually, the transfer of heat and moisture through clothing is described by two simple equations:

$$\text{Dry} = (h_{T,c} + h_{T,r})\,\Delta T \qquad (W/m^2) \qquad (1)$$

and

$$\text{Evap} = hp\Delta p \qquad (W/m2) \qquad (2)$$

Dry consists of convective as well as convective and radiative heat transfer. Conduction and convection are lumped together in the heat transfer coefficient $h_{T,c}$ and radiation is represented by $h_{T,r}$ (W/m^2K). Equation (1) is only correct when the radiation temperature of the environment equals the air temperature.

Evap is the evaporative heat transfer, proportional to the vapour pressure gradient Δp (Pa) and the vapour transfer coefficient h_p (W/m^2Pa).

In general, there is a link between convective and evaporative heat transfer. It has been experimentally determined that for air layers:

$$L_a = \frac{h_p}{h_{T,c}} = 0.0165 \text{ K/Pa} \qquad (= 2.2\ °C/mmHg) \qquad (3)$$

L_a is the so-called Lewis constant. This constant is independent of the air velocity, except when the airflow turns over from laminar into turbulent; in that case L_a takes the value of 0.015 K/Pa (2.0 °C/mmHg), sometimes called the psychrometric constant.

Lewis relations may be found for all kinds of layers. Woodcock (1962) qualified the vapour transmission of a fabric, including the adjacent air layer, by the moisture permeability index i_m, which gives the vapour transmission, relative to that of a pure convective air layer of the same heat transmission:

$$i_m = \frac{L_{lay}}{L_e} \qquad \text{(n.d.)} \qquad (4)$$

where L_{lay} is the Lewis constant for clothing plus air.

By definition i_m takes the value of 1.0 for air layers and between zero and unity for other layers, depending on the obstruction to vapour transfer.

Substituting (3) and (4) into (2) yields:

$$\text{Evap} = i_m \, L_a \, h_{T,c} \, \Delta p \qquad (2a)$$

In many papers, a slightly, but significantly, different version of this equation is used:

$$\text{Evap} = i_m \, L_a \, (h_{T,c} + h_{T,r}) \, \Delta p \qquad (2b)$$

In clothing layers, where the fibers are so densely packed that radiation is intercepted many times, $h_{T,r}$ does not play an important role and the difference between (2a) and (2b) is not large. But for air layers, $h_{T,r}$ may be the largest of the two and a serious error results when i_m is taken to be unity. However, when a different definition of i_m is used, the error is compensated for:

$$i_m' = \frac{h_{T,c}}{h_{T,c} + h_{T,r}} \; i_m \qquad (5)$$

This means that for pure air, or fabric plus air assemblies a significantly lower value for i_m' results than for i_m.

Instead of the heat transfer coefficient in equations (1) and (2b), frequently heat resistance units are used (clo, 1 clo = .155 m^2 K/W, Gagge et al., 1941).

$$h_{T,c} + h_{T,r} = \frac{1}{.155 \text{ clo}} = \frac{6.45}{\text{clo}} \qquad (6)$$

where clo is the number of clo units, somewhat confusingly.

Equations (1) and (2) thus take, in the Woodcock description the form:

$$\text{Dry} = \frac{6.45}{\text{clo}} \; \Delta T \qquad (1a)$$

$$\text{Evap} = i_m' \, \frac{6.45}{\text{clo}} \; Le_a \; \Delta p \qquad (2c)$$

Nishi (1970) used a slightly different version of equations (1) and (2), expressing the effect of clothing as the factor with which the dry and evaporative heat transfer changed compared to the nude situation. A standard value for the permeability of the clothing was included, but Lotens and Van de Linde (1983), showed that the mentioned factor is at least a factor of 2 too large to agree with a vast amount of data on fabrics.

So far, only transport equations of the type (1) and (2) have been discussed. These are valid only when heat and vapour transport are independent and as long as there is no storage of heat and moisture in the clothing. During transient conditions, however, due to changes in workload or environment, the heat capacity and particularly the moisture absorption in the clothing make the equations fail. Thus, only steady state conditions are to be described by (1) and (2). Another limitation is that condensation is not allowed. During condensation, heat is

produced. Consequently, part of the evaporative heat transfer is converted into dry heat transfer, proving that the equations are not adequate in this case.

An exact solution of heat of vapour transport, including time dependency, is to be found in any textbook on heat transfer (for example Shitzer and Eberhart, 1985). Coupling of the equations is explained by Farnworth (1980) and Lotens and Van de Linde (1983). Exact solutions require the specifications of any layer in an assembly, regarding insulation, permeability and absorption. For many typical clothing assemblies the model may be simplified to include the most relevant parameters only. Such models are currently being worked out and validated by the author for absorbent clothing, semi-permeable and impermeable clothing, and ventilated clothing.

Neither the Nishi nor the Woodcock description allows the calculation of the properties of an assembly from those of the separate layers. For any assembly, new parameter values have to be determined. When, however, the parameters are assigned to single layers, instead of one or more layers including adjacent air, the addition is rather straightforward, provided the clothing is uniform over the area:

$$\text{Dry} = \frac{1}{\Sigma \frac{1}{h_{c,i} + h_{r,i}}} \Delta T \qquad (1b)$$

$$\text{Evap} = \frac{Le}{\Sigma \frac{1}{i_{m,i}\ h_{c,i}}} \Delta p \qquad (2d)$$

where the subscript i denotes the i-th layer of the assembly.

From Flat Plate to Human Shape

The permeability of clothing is usually measured on a sweating hot plate or comparable apparatus. For insulation measurements, flat plates are available as well as heated manikins. Measurement of permeability and insulation on subjects is possible, but difficult.

The values obtained with those various methods are different for three main reasons:

- on a flat plate there are usually no enclosed air layers;
- when a flat material is curved to shape a garment, the insulation changes;
- on a manikin and humans there are uncovered skin areas.

These three factors may be accounted for, to estimate the insulation, in the following way:

Clothing materials do not vary widely in specific resistance (m K/W). For various materials (without air layers) a specific insulation of 25 m K/W is reported (about 4 clo/inch, Burton and Edholm, 1955). The measurements of Van Bruggen and Wammes, (1984) average 21 m K/W; the difference may be caused by differences in internal radiation transfer in the samples. The inclusion of air layers will decrease the specific resistance. Typically, a pure air gap of 10 mm width will have a specific resistance as low as 13 m K/W due to the

radiative heat transfer. Clothing assemblies will be somewhere in between those limits, depending on the enclosed air layers (tight or loose fit).

Clothing is not a flat slab, but consists of more or less cylindrical parts like sleeves, trunk, trousers etc. Due to the curvature of the clothing, the layers will have a larger surface area than the skin. When the same heat flow goes through a specific clothing layer as it leaves the skin, the apparent resistance R' of the clothing is:

$$R' = \frac{\text{skin area}}{\text{clothing area}} R \qquad \text{(m K/W)} \qquad (7)$$

where R is the specific resistance of the flat material. The specific resistance thus decreases with increasing thickness and increasing curvature of the assembly.

These assumptions have been put into a model (CLOMAN) that calculates various insulations for clothed man. A human is represented schematically as 19% nude (head, feet, and hands), 35% trunk (cylinder, radius 15 cm) and 46% extremities (cylinder, radius 5 cm). Fig. 2 shows some results. In Fig. 2a the difference in intrinsic insulation[1] is given as a function of the thickness of the clothing, both for tight fit (no enclosed air layers) and loose fit (mostly air layers). The levelling off of the curves is mainly due to the exposed skin. For extremely thick clothing, all heat will pass there. Fig. 2b shows the calculated difference between the insulation on a flat plate, when the material is bent to the shape of a sleeve, and for a whole garment, like on a thermal manikin. It is clear that the difference between flat plate and manikin values is due in the first place to exposed skin, but for thicker clothing also due to the increasing clothing surface.

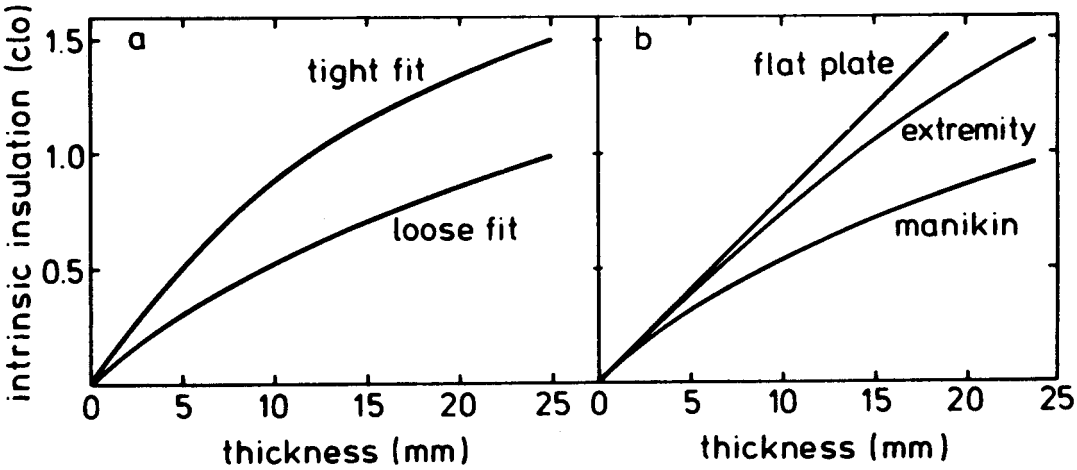


Fig.2 a. Calculated intrinsic insulation as a function of assembly thickness.

b. Calculated insulation of the same material on a flat plate, as a sleeve and on a manikin (for loose fit).

[1] Intrinsic insulation is the insulation of clothing only.

Wind and Pumping

The main difference between manikin results and results on humans is presumably due to external wind and motion-induced pumping.

The Nishi description does not allow easy account of varying wind speeds, since the relevant factors change with the air insulation; this description was designed, however, for indoor climates with generally slight air motion.

The Woodcock description was modified by Givoni and Goldman (1972) to take into account the pumping effect of motion and the effect of wind by the formulas:

$$V_{eff} = V_a + .004\ (M - 105) \qquad \text{(m/s)} \qquad (8)$$

$$clo = clo_o\ V_{eff} - \alpha \qquad (9)$$

$$i_m = \text{constant}$$

where V_{eff} = effective wind speed (m/s)
clo_o = insulation at V_{eff} = 1 m/s
α = coefficient depending on clothing item (0.1 – 0.3)
V_a = wind speed (m/s)
M = metabolism (W)

From a theoretical point of view, i_m should change with wind speed. In a later paper (Goldman, 1984), indeed i_m is reported to increase with V_{eff}. V_a in (8) evokes the wind effect and the term with the metabolism M the effect of pumping. Nielsen (1985), Olesen and Madsen (1983) and Havenith (1985) all found a decrease in insulation of about 35% for moderate work, compared to standing, which is considerably more than the 21% calculated with (8) and (9) for standard fatigues (α = 0.25). The effect of wind only (2 m/s) on various garments amounted to a 26% decrease in total insulation (Havenith, 1985), compared to a predicted 16%. Apparently, the prediction is on the low side. There is good agreement on the combined effect of wind and pumping. Measurements of Nielsen (1985), the prediction by (8) and (9), as well as direct measurements on ventilation (Lotens, 1986a) agree that the combined effect of wind and pumping is less than the sum of the separate effects.

3. PHYSIOLOGICAL MODELS (2-3)

Physiological models usually consist of a controlled part (the body) and a controller (the neural network), which together form a feedback system (see Fig. 3). The temperature sensors are connected to an integrating system, located primarily in the hypothalamus, that sends out efferent signals to activate the vasomotor system, the sweat system or the shivering muscles. The strength of the efferent signals depends on the comparison between the integrated afferent signals and a reference value.

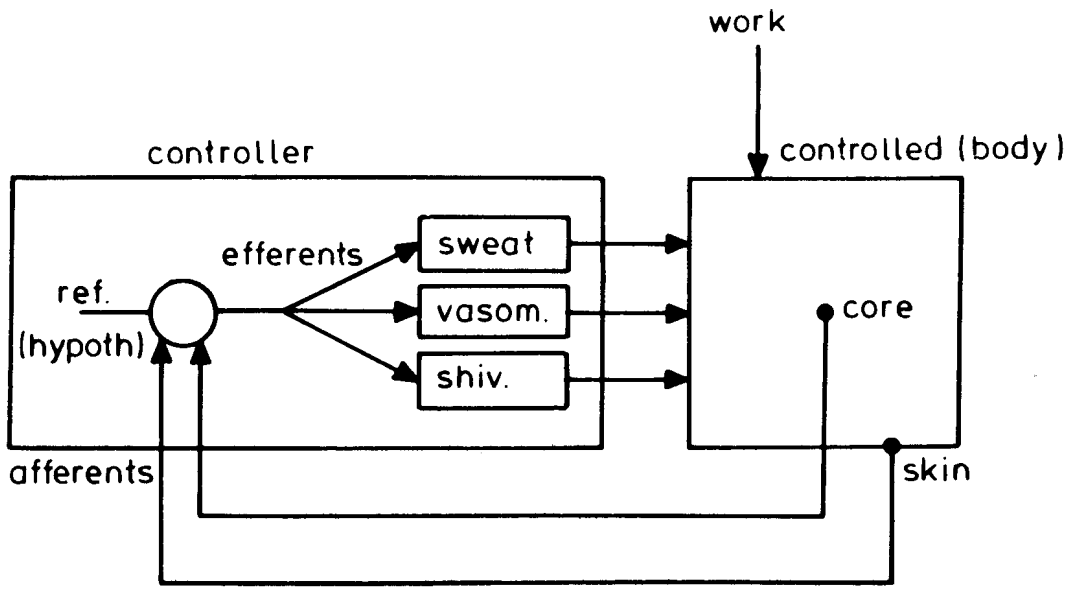


Fig. 3. Feedback control system, consisting of a controller and a controlled part. Core and skin thermal signals serve as a feedback loop to the controller, which compares the actual value with a reference value. The differential signal drives the thermoregulatory motor functions.

In this view, high sweat activity is for example caused by a large offset of the central temperature. The feedback loop insures that the sweating no longer increases when thermal equilibrium is reached. Models of this type may be simple or sophisticated, according to the realism of the body simulation, the types of physiological sensors involved and the sophistication of the neural network.

The simulation of the body evolved from one homogeneous cylinder into multilayered cylinders of various sizes for separate body parts, connected by a circulatory blood flow. The layers are deduced from anatomical differences in body tissue: skin, fat, muscle and core. The heat flow between the layers may either be calculated by exact mathematical solutions of the heat conservation equation or the layers may be treated as if they have a uniform temperature. In the latter approximation, the computation involved is much easier. Gordon and Roemer (1975) pointed out that the resulting errors are small in the heat but larger in the cold, where more layers are required due to the larger temperature gradients.

A special area is the simulation of the extremities. A major effect may result here from the blood flow control. The blood flow is not simple, however. Starting at fingertips and toes, the venous system splits into two layers of veins, a central layer which is relatively constant in flow, and a superficial layer, that is effectively controlled. The anatomy is thus more complicated than that of the rest of the body. Questions to be asked are whether blood brings heat from one layer to the next (or from one body part to the other) without returning first in the venous pool and whether or not countercurrent heat exchange between arteries and veins takes place, thus decreasing the effective heat transport. Aschoff and Wever (1958) developed a countercurrent extremity model. However, Mitchell and Meyers (1968) argue that countercurrent heat exchange rarely sets in. The close contact between arteries and veins required is to be found only in capillaries that usually are embedded in the same layer.

An evolution in modeling controllers is to be seen as well. The early models worked with just one variable, the average body temperature. And even that temperature was not really controlled, because no relationships were included between body temperature and effectors such as vasomotor or sudomotor system. These models (Machle and Hatch (1947), Kerslake and Waddell (1958), Wyndham and Atkins (1960)) were in fact passive systems only. It was not until the early sixties that physiological control functions were introduced (Crosbie, Hardy and Fessenden, 1961, 1963), at first as a function of body temperature and later based on central, muscle and skin temperature (Stolwijk and Hardy, 1966). In particular, the control of blood flow became a theme with variations. Wyndham and Atkins (1960) used a regression model for skin conductance (implicitly depending on skin blood flow), Kitney (1974) applied a non-linear (bang-bang) controller and Hsia (1975) used blood pressure and arterial resistance instead of direct flow control.

The described principles have been implemented in various models with a real deal of refinement. Wissler started in 1959 with expansion of Pennes' (1948) model for a forearm only, and next improved Wyndham and Atkins, (1960) model (Wissler (1963, 1964)), to arrive in 1982 at a very detailed model including physiological control functions that requires a long execution time on a large computer.

The most popular model, however, became that of Stolwijk (1971), produced for NASA. Stolwijk put a lot of effort in the statement of the controller, which was much more detailed than any preceding one. Sweat rate, vasoconstriction, vasodilation and chilling are controlled by networks of similar type, shown in Fig. 4. The inputs for the controller (ε) are signals that represent the deviation of skin and core temperature from a set point value. The rate of temperature change is included as well, however. The importance of temperature transients is emphasized by Mitchell et al. (1972) who think that the rate of change might be even more important than the temperature per se. This was confirmed by Libert et al. (1979) and in later models (Wissler, 1982) more explicitly processed. The coefficients $\beta 1$ and $\beta 3$ in Fig. 4 define a linear output, both for core and skin temperature, while $\beta 2$ adds a non-linear component. Although the controllers for all the effector outputs have the same format, $\beta 2$ equals 0 for the sweating, dilatation and constriction output whereas for the chilling output $\beta 1 = \beta 3 = 0$. Thus, the first three are assumed to be strictly linear and the last one purely multiplicative.

These controlled functions meant a tremendous step forward, although it was not tried to include every bit of physiological knowledge. In particular, the sweat control lacks an exercise input. Mitchell (1971), Gisolfi and Robinson (1970) and Robinson et al. (1965) agree that there is a quickly rising, long sustaining effect of exercise on the gain of the sweat control. The general concept, however, was in fair agreement with the thoughts of Bligh, who gradually developed control networks. Fig. 5 shows the model of Maskrey and Bligh (1972), cited in Bligh (1972).

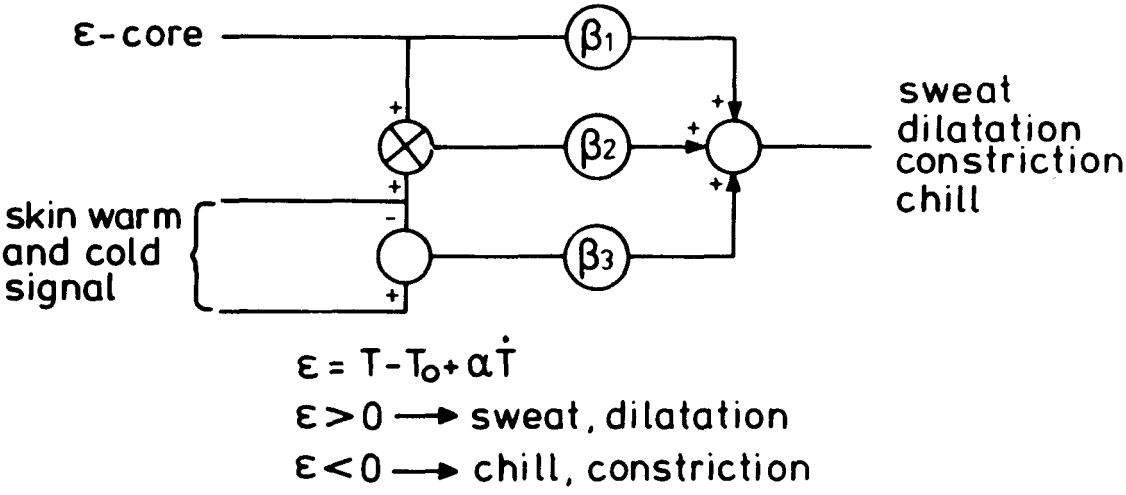


Fig. 4. The general form of the controller of Stolwijk (1971).

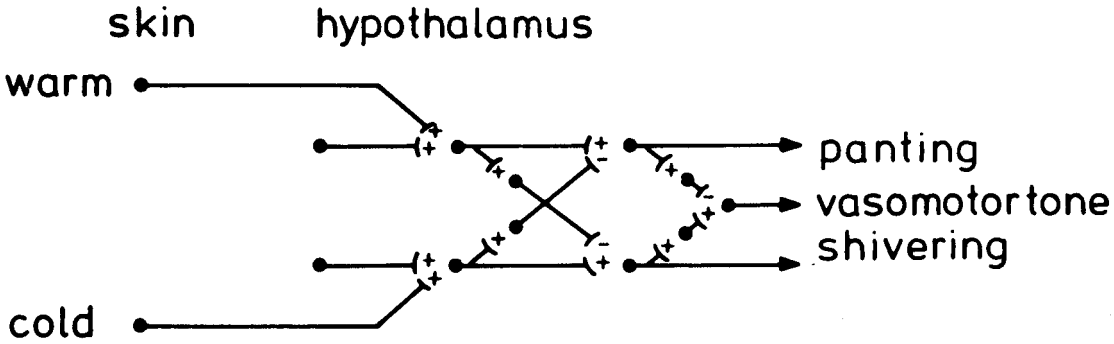


Fig. 5. The network for thermal control developed by Maskrey and Bligh (1972).

In Stolwijk's model, blood flow, metabolism and sweat production are functions of the above efferent Signals for any Segment:

$$\text{blood flow} = \frac{(\text{BFB} + \text{dilat})}{(1 + \text{stric})} \; 2^{\varepsilon / q_2} \tag{10}$$

$$\text{metabolism} = \text{MB} + \text{work} + \text{chill} \tag{11}$$

$$\text{sweat prod.} = \text{SPB} + \text{sweat} \cdot 2^{(T - T_0)/q_2} \tag{12}$$

where the extension B stands for basal

ε is the local error function

q_2 is the temperature difference that doubles the activity

By means of the power terms, the local temperature modifies the signal, either to enhance or to suppress the local blood flow or sweat production.

This controller has been connected by Stolwijk to a six compartment (head, trunk, arms, hands, legs, feet), four layer (skin, fat, muscle, core) model with a central blood pool.

The Stolwijk model has been a source of inspiration to other investigators. Gordon (1976) expanded Stolwijk's model from 6 to 14 compartments and from 4 to 11 layers. In the controller, allowance for heat flux sensors is made. Wissler's model (1982) is also an expansion of Stolwijk's, to even 15 compartments and 15 layers, while the controller is enhanced with explicit processing of rate of temperature changes and a refinement of shivering control. The principles of the pulmonary model of Grodins et al. (1967) are included as well. Section 7 deals with the achieved improvement in terms of accuracy.

Gagge et al. (1971) developed another quite influential model, probably not independent of Stolwijk's, although significantly different. In contrast to the former investigators, Gagge simplified the model down to just core and shell compartments, connected to a simple controller, with the aim to develop a useful tool for comfort calculations. The blood flow is basically the same as in equation (10) but chilling (eq. (11)) is not considered and sweat production is governed by a non linear equation ($\beta_3 = 0$ in Fig. 4).

Few attempts have been made to incorporate differences between individuals. In a comprehensive literature study, Havenith (1985) concluded that acclimatization, fitness, hydration, anthropometric measures and time of day have (in decreasing order) an effect on temperature control. Sex and age are considered secondary variables which depend on the variables already mentioned. Of these variables, the anthropometric measures could be taken into account with a Stolwijk type model, but the most important variables acclimation, fitness and hydration need to be incorporated explicitly.

An added complication is a coupling between acclimatization and fitness. Acclimatization has an effect on the sweat system, as well as on the cardiovascular system. Those are not strongly related, since acquisition and decay show different behaviour for the two systems. Fitness enhances the cardiovascular aspect of acclimatization by cardiovascular training.

Only the model of Konz (1979) includes some individual factors: females are supposed to have a lower sweat capacity and cardiac stroke index decreases with age. Height, weight and fat may be entered. Fitness is used to estimate stroke volume and acclimatization shows in maximum sweat rate. Konz reports varying success in simulating individuals.

Specific models at the cold side of thermoregulation deal with the heat production due to shivering and non-shivering thermogenesis (Hayward et al., 1977) and with the heat loss in cold water. The fat layer is considered a major variable in these models (Timbal et al. 1976) and Montgomery (1974).

Looking back at the development of physiological models, three milestones may be distinguished. The first is the application of heat diffusion mathematics to a biological problem (Pennes, 1948) and the attempt to model the whole body (Machle and Hatch, 1947). The second milestone is the inclusion of control functions into a model by Crosbie, Hardy and

Fessenden (1963) and Wyndham (1962) and the third is the publication of a much improved Controller by Stolwijk and Hardy (1966), enabling wide application of the model. Since then, in 20 years time, relatively little progress had been made. This is the era in which mathematical models have to wait for the much more laborious analysis of the highly complicated thermal control system. In fact, mathematical models could be a powerful tool in this analysis, but the extensive publications on models suggest that models are often more a goal in themselves than a tool to understand the physiology.

4. DATA REGRESSION MODELS (1-3)

The oldest data regression models are the climatic indices. It has been tried in a great many ways to simplify the production of heat strain by at least taking the climatic variables (temperature, humidity, radiation and wind) together into a single variable. A condition is of course that this new variable relates in a unique way to perceived strain. Here, no intermediary is involved, dealing with the heat flow through the skin: the relationship is directly between environment and strain.

The oldest index is probably the Wet Bulb Temperature of Haldane (1905) and many others followed. Still well known indices are the Katathermometer (Hill et al., 1916), Effective Temperature (Houghton and Yaglou, 1923), Windchill (Siple, 1945), Corrected Effective Temperature (Bedford, 1946), Predicted 4 Hour Sweat Rate (McArdle et al., 1947), Heat Stress Index (Belding and Hatch, 1955), Wet Bulb Globe Temperature (Yaglou and Minard, 1957) and Botsball Temperature (Botsford, 1971).

These indices take into account the climatic variables in various levels of sophistication. What they have in common, is that the clothing is either unspecified or specified as semi-nude or standard clothing (often 0.6 clo). There are numerous papers on the evaluation of these indices. In particular, the WBGT index is discussed extensively and this is probably the most important one, since it has penetrated into the industrial hygiene legislation in many countries. WBGT has been shown to be a valuable rough estimator of strain, but in a recent study (Lotens, 1986b) it is calculated that variations in industrial protective clothing are causing intolerable discrepancies between actual and recommended exposure limits. It is clear that clothing must be appropriately taken into account, to arrive at realistic exposure limits. Since any manageable system of tables or nomograms will fail to do so, for WBGT as well as for other climatic indices, straightforward modeling is a better alternative. Gagge et al. (1971) used such a model to define the Humid Operative Temperature, but this is putting the cart before the horse: the user must have the model available, not some specific results.

Goldman and associates took a different approach, that will be explained in more detail. Based on ample laboratory data, Givoni and Goldman (1972) stated empirical equations to relate the rectal temperature response to clothing (clo, i_m), metabolism and environment (T_a, r.h., wind). The response includes time pattern and final value, for rest, work and recovery. The equations assume the skin temperature to be 35 °C and the skin vapour pressure 44 mmHg, fully wet skin. This is not necessarily the actual skin condition, but a model construct. Understanding of the procedure is important: the insulation of the clothing is measured on the copper man, e.g. standing still, including the overlying air later. The i_m value is either determined on a flat plate during moderate air flow or on a copper man with a wet "skin".

These are the values to be put into the model. The model predicts the average rectal temperature for groups of young healthy men.

In later papers, many other aspects of thermal strain are covered, such as heart rate response (Givoni and Goldman, 1973a), acclimatization (Givoni and Goldman, 1973b), solar heat load (Breckenridge and Goldman, 1972), sweat production and water requirement (Shapiro et al., 1982) and skin temperature (the actual skin temperature this time, unpublished). All these aspects have been integrated into one model: the heat stress model. Berlin et al. (1975) published a computer program that covers part of it. Goldman (personal communication) has also incorporated a thermal comfort model, deduced from Fanger's model.

As it stands, the heat stress model does not cover other areas, such as cold. To this purpose, different models were stated. An extremity cooling model deals with mainly finger cooling and its modulation by gloves. In this model tissue mass, surface area, insulation, wind and heat input determine the time constant of the cooling response. The model is stated to be valid from 10 down to -100 °C. Wilson and Goldman (1970) deal with the effect of temperature and wind on time to freezing. Molnar et al. (1973) investigated the effect of wetness and Wilson et al. (1976) determined the actual finger temperature at which freezing starts.

A third model deals with whole body cooling, involving heat production, subcutaneous fat and mass/surface ratio. Dependent on wind and clothing, the model is valid for water immersion between 5 and 30 °C, air exposure between 20 and 0 °C during rest and much lower as long as work and clothing prevent the extremities from becoming the limiting factor. The model is described in Strong et al. (1985). This model is somewhat more mechanistic than for instance the heat stress model, since it consists of core, fat, skin and clothing compartments, with assigned heat productions and conductances.

Individual variability is not included in these models, except for the cold model, where skinfold thickness is a major parameter. Thus, these models are suited only for group average estimations. In fact, the largest variability may be found in the comfort zone, where physiological control is prevailing. For severe circumstances, the physics of the heat transport is dominating and individual variability is not large there; agreement between predictive models and experimental results is hardly supportive to the model under those circumstances, and the physiological part of the model cannot be reliably tested.

5. PERFORMANCE CRITERIA (3-4)

This step in the general scheme of Fig. 1 is probably the most complicated one, since understanding of the relationship between physiological strain and functional performance involves the knowledge of all physiological processes in full extension, including interrelations and interactions with motivational aspects. It is not tried here to acquire insight in this process, but a collection of data is given instead, that relates physiological values to apparent failure of subjects to perform. The data are adapted from a great number of experiments, which are not referred to here, but an important source is USARIEM, Natick. The data were compiled by R.F. Goldman and, for a minor part, by the author. A compilation is given in Table 1.

Table 1. Approximate Thermal Strain Criteria

Strain	comfort	discomfort	performance degradation		tolerance		damage
mean skin temp. (°C)	33	< 31 > 35		30 36		25	< 15 > 45 (time dependent)
local skin temp. (°C)					pain:	45	
finger temp. (°C)	27-34	< 20		< 15		5	-2 « 15 (time dependent)
toe temp. (°C)	24-34	< 17		< 13		5	-2 « 15 (time dependent)
rectal temp. (°C)	37	38	working:	> 38.2	standing: work-1 hr: work-2 hr:	> 38.0 > 39.5 > 38.8	41-42 (time dependent)
				< 36.0		< 35	28
sweat rate (l / hr)	.03	–	accl, 4hr: unac, 4hr:	1.5 .75		3 2	–
fraction wet skin (n.d.)	.06	.3	accl: unac:	.9 .7		–	–
Water loss (% body weight)	0	2		4		5-6	15-20
heat storage (J/g)	0	3		5	work: rest:	10 8	14
heat loss (J/g)	0	4		6		12 (depending on cooling rate)	20
metabolic rate (W)	120	350		500	1 hr:	700	–
heart rate (min^{-1})	70	100	8 hr: 8 hr, fit:	110 120	2 hr: 4 hr: rest, 4 hr:	160 140 120	1 hr: 220-age

The limit values for various physiological variables are given, as a function of performance. The performance is split into five levels, ranging from comfort to damage. The criteria given do not pretend to be physiologically perfect, since the cause of failure depends on the specific condition, but should be regarded as a general guideline instead.

6. THERMAL SENSATION MODELS (2-4)

At least two models exist that relate the heat exchange of the skin directly to strain. Both are dealing with comfort. Nishi and Ibamoto (1969) developed a heat exchange model, in which a Model Skin Temperature was calculated that would keep a resting person in thermal equilibrium. The skin humidity is supposed to be low. Comparison with actual skin temperature shows a moderate correlation but over a large range of Model Skin Temperatures the correlation with thermal sensation votes is rather good: on a 10-point scale, ranging from unbearably cold to very hot, any step corresponds to a 1.8 °C increase in Model Skin Temperature. Thus, in an analytical way the thermal sensation vote may be calculated, taking into account the insulation and permeability of the clothing.

Fanger (1970) did not try to predict thermal sensation votes during rest, but comfort conditions during various levels of activity. He also took an analytical approach, but did not need to know the permeability of the clothing. This touches the gist of the matter. Fig. 6 shows the basic assumptions of his model. At "comfort" the mean skin temperature drops with increasing metabolic rate, and the evaporation increases. Comfort is obtained during these tests by decreasing the air temperature in accordance with the metabolic rate. When clothing is added, the temperature of the air must be lowered again, to account for the temperature gradient through the clothing as well. It may be easily calculated that for normal permeability of the clothing this gradient is sufficient to pass the vapour. But a consequence is that the method holds only for normal permeabilities.

As may be seen in Fig. 6, the correlation between metabolic rate and evaporative heat loss is not so close. This already gives an indication of the individual variability in comfortable conditions. Deviations from the regression line of up to 50% in evaporation rate may be found. The deviating subjects are not in thermal equilibrium, but are storing or losing heat. Fanger found correlations as well between the rate of heat storage and the mean comfort vote (which is basically the same as Nishi and Ibamoto (1969) uncovered).

From the fact that all subjects voted "comfortable", whereas most of them were not in equilibrium and thus should vote differently, it may be concluded that for any specific environment, subjects will disagree about the comfort. This results even in an optimal climate in a certain percentage of dissatisfied subjects. The model predicts the percentage dissatisfied persons, but is validated for lightly clothed persons only. The criterion that Fanger chose for dissatisfaction is rather wide: 2 steps on the comfort scale. Goldman reports that extension of the vote scale far beyond Fanger's range still provides useful information.

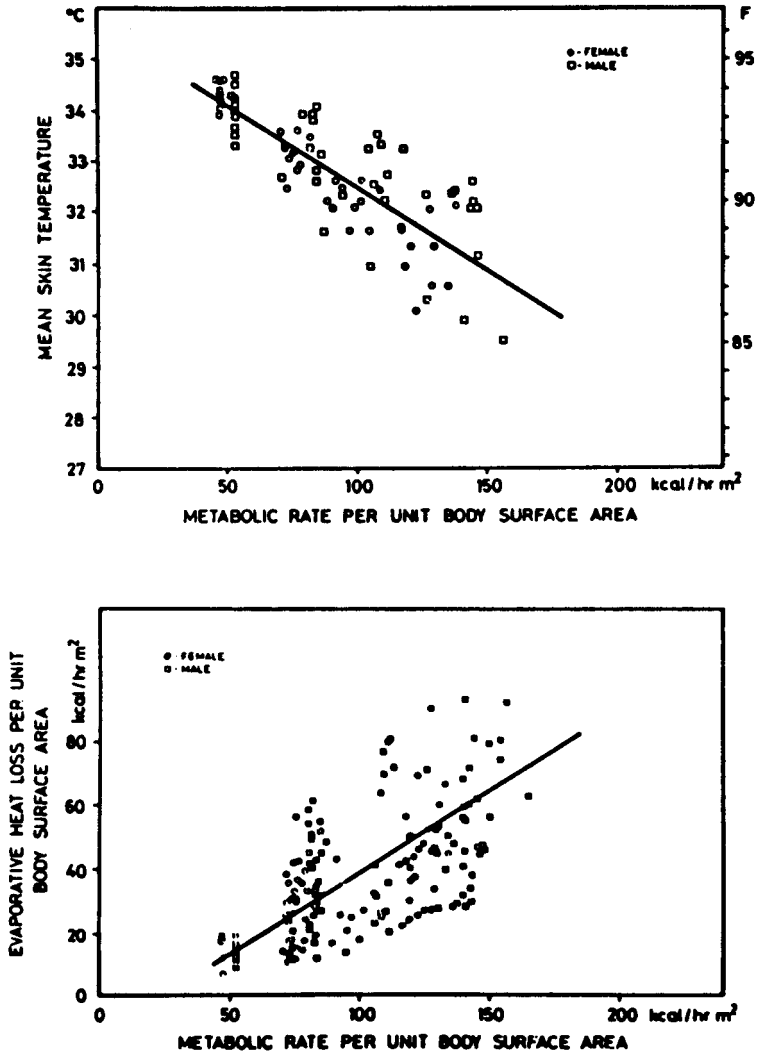


Fig 6. Correlation between, respectively, mean skin temperature as well as evaporative heat loss, and metabolic rate (Fanger, 1970).

7. VALIDATION

Most reviews on models are restricted to the explanation of features and differences (e.g. Hwang and Konz (1977), Fan et al. (1971), Witherspoon and Goldman (1974)); some are critical (for instance Mitchell et al. (1972)) but few are validating models. Validation is a tedious job, in particular for mathematical models with their many variables. A good example, however, is the report of Wissler (1982) on a Workshop held in Austin, TX, where various models have been run for a wide range of experiments. The models successfully run were Goldman's heat stress and whole body cooling model, Stolwijk's model and Wissler's model, all equipped with the same clothing description. The results are summarized in Table II.

For work in various temperatures and rest in the heat, Goldman's heat stress model (though only providing metabolism and rectal temperature) and Wissler's model perform well. Wissler's esophageal temperature is systematically too high and the skin temperature

appears to be out of phase with the work/rest cycle in some occasions. Stolwijk's model has a consistently low rectal temperature and the time pattern is not always right.

In cold situations (water immersion) all modes show deficiencies, in particular Stolwijk's. Wissler's model suffers from inaccurate rectal and tympanic temperature and, in Goldman's model, rectal temperature is inconsistent.

A general impression is that Wissler improved Stolwijk's model to a considerable extent, but that he did not outmatch Goldman's data regression approach in accuracy. The synthetic model, true enough, is more versatile.

In one of our own studies, we compared the Stolwijk model, the Goldman heat stress model and the Gagge model, all with the same clothing description, for a range of conditions (.2/.8 clo, 30/35/40 °C, 30/90% r.h., 200/400 W). (The models used are those from 1971 and 1972; a more up-to-date model from Gagge et al was published in 1986).

This comparison deals with the final rectal temperature (Goldman's vs. Stolwijk's vs. Gagge's) and the sweat production (P4SR vs. Stolwijk's vs. Gagge's). In Fig. 7 the main results are shown. Gagge's model predicts the lowest rectal temperatures, actually much lower than Goldman's. Since Goldman's model is run for acclimatized subjects, whereas Gagge's is for unacclimatized, the real difference is even larger. Stolwijk's prediction of rectal temperatures is systematically 0.5 °C higher, but still does not match those of Goldman, in particular in the heat stress area.

The accumulated four hour sweat rate is low as well for Stolwijk's and particularly Gagge's model. As far as Stolwijk's model is concerned, this compares to the results of Table II.

Table II. Deviations of four models based on seven sets of experimental data (data adapted from Wissler, 1982)

Conditions	Wissler model	Stolwijk model	Goldman models (rectal temp and metabolism only)
work/rest cycles in 10 °C air	evaporation a bit low	low evaporation, low rectal and esophageal temp.	
work/rest cycles in 20 °C air	high rectal and esophageal temp, phase shift in skin temp	high skin temp, low rectal temp, low evaporation	
work/rest cycles in 30 °C air	high rectal and esophageal temp, high skin temp and phase shift	high skin temp, low rectal temp	high rectal temp
step change to warm/wet air	high esophageal temp	low rectal, esophageal and skin temp, too early levelling off	
step change to hot/dry air	high esophageal temp	same as above	
water immersion 18 °C	low rectal temp, varying tympanic temp	high metabolism, initial drop and too early levelling rectal temp	low rectal temp
water immersion 24 °C	varying rectal temp, varying tympanic temp, high metabolism	same as above	same as above
water immersion 29 °C	high tympanic temp, low metabolism	same as above	high rectal temp, low metabolism

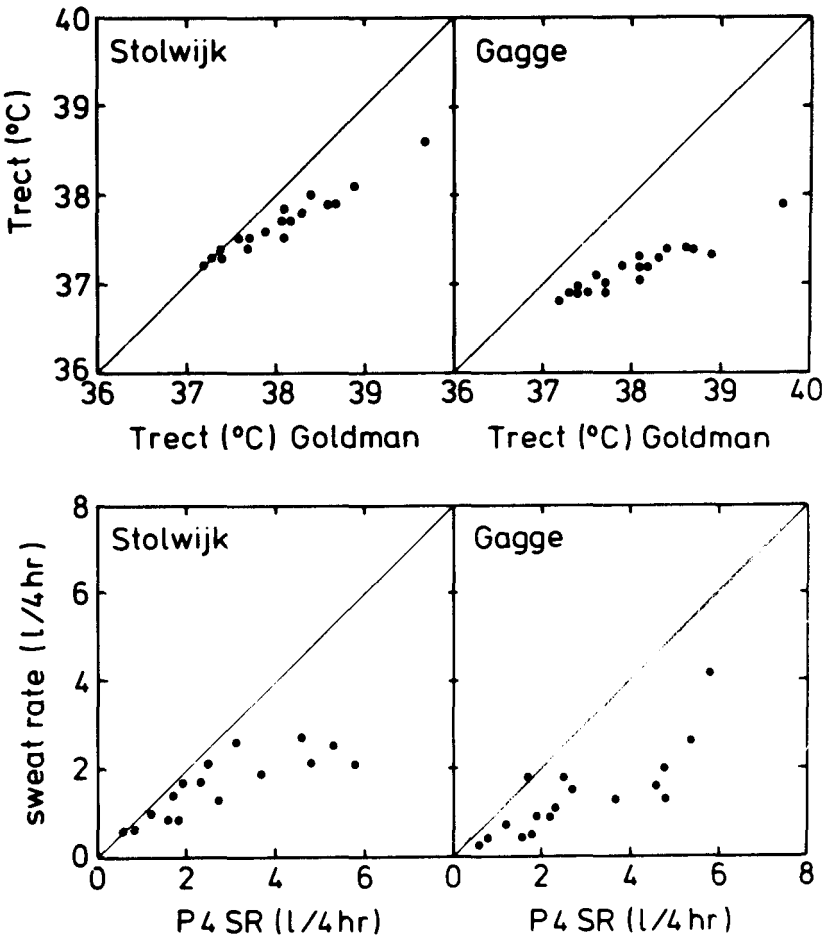


Fig. 7. Comparison of predicted final rectal temperature (Stolwijk's and Gagge's model against Goldman's) and four hour sweat rate (against P4SR).

One cannot disapprove of some model because it may produce incorrect results. The model may be designed for specific purposes and serve that purpose well. The conclusions of this section rather emphasize the point about validity range and the awareness that models are no reality.

An anecdote, probably from a Canadian source, may moderate overly serious considerations on modeling. A farmer, worried about his cow giving no milk, consulted a veterinarian surgeon, but nothing abnormal was found. Then he unsuccessfully tried, in sequence, a biochemist, a dietician, and an animal psychologist. In despair, he applied to a physicist, who studied the cow. The farmer anxiously waited for the report, and when it finally came, it started with the words: "Consider a spherical cow..." .

REFERENCES

1. Aschoff, J. and R. Wever (1958). Modellversuche zum Gegenstrom-Wärmeaustausch in der Extremität. Z Gesamte Exp. Med. 130(4): 385-395.

2. Bedford, T. (1946). Environmental warmth and its measurement. Med. Res. Council War, Memo 17, HMSO, London.

3. Belding, H.S. and T.F. Hatch (1955). Index for evaluating heat stress in terms of resulting physiological strain. Heat., Piping and Air Cond. 27: 129-136.

4. Berlin, H.M., L. Stroschein and R.F. Goldman (1975). A computer program to predict energy cost, rectal temperature and heart rate response to work, clothing and environment. ED-SP-75011, Edgewood Arsenal, Aberdeen Proving Ground, MD.

5. Bligh, J. (1972). Neuronal models of mammalian temperature regulation. In Essays on Temperature Regulation. Bligh and Moore (Eds.), North-Holland Publ. Co., p. 105-120.

6. Botsford, J.H. (1971). A wet globe thermometer for environmental heat measure ment. Am. Ind. Hyg. Assoc. J. 32, 1-10.

7. Breckenridge, J.R. and R.F. Goldman (1972). Human solar heat load. ASHRAE Transactions 78: 110-119.

8. Bruggen, E.J.G. van and L.J.A. Wammes (1984). Warmtedoorlaatbaarheid van enkle isolatiematerialen. Report Institute for Perception IZF, 1984-M25.

9. Burton, A.C. and O.G. Edholm (1955). Man in Cold Environment. Edward Arnold, Ltd., London.

10. Burton, A.C. (1934). The application of the theory of heat flow to the study of energy metabolism. J. Nutr. 7: 497.

11. Crosbie, R.J., J.D. Hardy and E. Fessenden (1963). Electrical analog simulation of temperature regulation in man. In: Temperature Its Measurement and Control in Science and Industry, Part III, Hardy (Ed.) Reinhold, N.Y.

12. Fan, L.T., F.T. Hsu and C.L. Hwang (1971). A review of mathematical models of the human thermal system. IEEE Trans. Biomed. Eng. 18: 218-234.

13. Fanger, P.O. (1970). Thermal Comfort. McGraw-Hill Book Co.

14. Farnworth, B. (1979). Calculations of heat and vapour transport in clothing: transient effects in hygroscopic materials. Defence Research Establishment Ottawa, Technical Note 80-25.

15. Gagge, A.P., A.C. Burton and H.C. Bazett (1941). A practical system of units for the description of the heat exchange of man with his environment. Science 94: 428-429.

16. Gagge, A.P., A.P. Fobelets, and L.G. Berglund (1986). A standard predictive index of human response to the thermal environment. ASHRAE Trans. 92: 709-731

17. Gagge, A.P., J.A.J. Stolwijk and Y. Nishi (1971). An effective temperature scale, based an a simple model of human physiological regulatory response. ASHRAE Trans. 74: 242-262.

18. Gisolfi, C. and S. Robinson (1970). Central and peripheral stimuli regulating sweating during intermittent work in men. J. Appl. Physiol. 29: 761-768.

19. Givoni, B. and R.F. Goldman (1972). Predicting rectal temperature response to work, environment and clothing. J. Appl. Physiol. 32: 812-822.

20. Givoni, B. and R.F. Goldman (1973a). Predicting heart rate response to work, environment and clothing. J. Appl. Physiol. 34, 201-204.

21. Givoni, B. and R.F. Goldman (1973b). Predicting effects of heat acclimatization on heart rate and rectal temperature. J. Appl. Physiol. 35: 875-879.

22. Goldman, R.F. (1984). Biophysical evaluation of relative heat stress of four chemical protective mask/hood systems. Report Multi-rech Corp. C028/MT 21-84, Natick, MA.

23. Gordon, R.G. and R.B. Roemer (1975). The effect of radial nodal spacing on finite difference calculations of temperatures in living tissue. IEEE Trans. Biomed. Eng. 22: 77-83.

24. Gordon, R.G., R.B. Roemer and S.M. Horvath (1976). A mathematical model of the human temperature regulatory system - transient cold exposure response. IEEE Trans. Biomed. Eng. 23: 434-444.

25. Grodins, F.S., J. Buell and A.J. Barb (1967). Mathematical analysis and digital simulation of the respiratory control system. J. Appl. Physiol. 22: 260-276.

26. Haldane, J.S. (1905). The influence of high air temperatures. J. Hygiene 5: 494-513.

27. Havenith, G. (1985). Individual parameters in thermoregulatory control; a review. Report Institute for Perception IZF 1985-26.

28. Havenith, G. and H. van Middendorp (1985). Thermische eigenschappen van het gevechtskledingsysteem uit de PSU-80. Report Institute for Perception IZF 1985-C21.

29. Hayward, J.S., J.D. Eckerson and M.L. Collis (1977). Thermoregulatory heat production in man: prediction equation based on skin and core temperature. J. Appl. Physiol. 42: 377-384.

30. Hill, et. al. (1916). The Measurement of the Rate of Heat-Loss at Body Temperature by Convection, Radiation, and Evaporation. Phil. Trans. Sec. B 207: 183-220.

31. Houghton, F.C. and C.P. Yaglou (1923). Determining equal comfort lines. J. Am. Soc. Heat. Vent. Eng. 29: 165-176 and 515-536.

32. Hsia, T.C. (1975). A prototype segmental model for blood flow and heat transfer in the limb. Comp. Progr. Biomed. 4: 219-225.

33. Hwang, C.L. and S.A. Konz (1977). Engineering models of the human thermoregulatory system; a review. IEEE Trans. Biomed. Eng. 24: 309-325.

34. Kerslake, D.Mc.K. and J.L. Waddell (1958). The heat exchanges of wet skin. J. Physiol. 141: 156-163.

35. Kitney, R.I. (1974). The analysis and simulation of the human thermoregulatory control system. Med. Biol. Eng. Jan. 74, 57-65.

36. Konz, S.A. (.1979). Computerized prediction of physiological responses to work environments. SAE Trans. 88: 1123-1128.

37. Libert, J.P., V. Candas and J.J. Vogt (1979). Effect of rate of change of skin temperature on local sweating rate. J. Appl. Physiol. 47: 306-311.

38. Lotens, W.A. and F.J.G. van de Linde (1983). Insufficiency of current clothing description. Int. Conf. Med. Biophys. Aspects Prot. Clothing, Lyon.

39. Lotens, W.A. and G. Havenith (1986a). Ventilation of rainwear determined by a trace gas method. Report Institute for Perception IZF 1986-21.

40. Lotens, W.A. and H. van Middendorp (1986b). How well does WBGT predict heat strain? Estimates from a mathematical model. Report Institute for Perception 1986-C12.

41. Machle, W. and T.F. Hatch (1947). Heat: man's exchanges and physiological responses. Physiol. Rev. 27: 200-227.

42. McArdle, B., W. Durham, H.E. Holling, W.S. Ladell, J.W. Scott, M.L. Thomson and J.S. Weiner (1947). The prediction of the physiological effects of warm and hot environments: the P4SR index. Med. Res. Council RNP 47/391, London.

43. Mitchell, D., A.R. Atkins and C.H. Wyndham (1972). Mathematical and physical models of thermoregulation. In: Essays an Temperature Regulation, Bligh and Moore (Eds.), North-Holland Publ. Col., p. 37-54

44. Mitchell, D. (1971). Human surface temperature: its measurement and its significance in thermoregulation. Ph.D. Thesis, Univ. of Witwatersrand, Johannesburg.

45. Mitchell, J.W. and G.E. Meyers (1968). An analytical model of the countercurrent heat exchange phenomena. Biophysics J. 8: 897.

46. Molnar, G.W., A.L. Hughes, O. Wilson and R.F. Goldman (1973). Effect of skin wetting on finger cooling and freezing. J. Appl. Physiol. 35: 205-207.

47. Montgomery, L.D. (1974). A model of heat transfer in immersed man. Ann. Biomed. Eng. 2: 19-46.

48. Nielsen, R., B.W. Oleson and P.O. Fanger (1985). Effect of physical activity and air velocity on the thermal insulation of clothing. Ergonomics 28: 1617-1632.

49. Nishi, Y. and A.P. Gagge (1970). Moisture permeation of clothing - a factor governing thermal equilibrium and comfort. ASHRAE Trans. 75: 137-145.

50. Nishi, Y. and K. Ibamoto (1969). Model skin temperature - an index of thermal sensation in cold, warm and humid environments. ASHRAE Trans. 75: 94-107.

51. Olesen, B.W. and T.L. Madsen (1983). Measurement of the thermal insulation of clothing by moveable manikin. Int. Conf. Med. Biophys. Aspects Prot. Clothing, Lyon.

52. Pennes, H.H. (1948). Analysis of tissue and arterial blood temperatures in the resting human forearm. J. Appl. Physiol. 1: 93-122.

53. Robinson, S., F.R. Meyer, J.L. Newton, C.H. Ts'ao and L.O. Golgersen (1965). Relations between sweating, cutaneous blood flow and body temperature in work. J. Appl. Physiol. 20: 575-582.

54. Shapiro, Y., K.B. Pandolf and R.F. Goldman (1982). Predicting sweat loss response to exercise, environment and clothing. Eur. J. Appl. Physiol. 48: 83-96.

55. Shitzer, A. and R.C. Eberhart (Eds.) (1985). Heat Transfer in Medicine and Biology, Plenum Press, New York, London.

56. Stolwijk, J.A.J. and J.D. Hardy (1966). Temperature regulation in man - a theoretical study. Pflugers Arch. 291: 129-162.

57. Stolwijk, J.A.J. and J.D. Hardy (1971). A mathematical model of physiological temperature regulation in man. NASA contractor report CR 1855.

58. Strong, L.H., G.K. Gee and R.F. Goldman (1985). Metabolic and vasomotor insulative responses occurring on immersion in cold water. J. Appl. Physiol. 58: 964-977.

59. Timbal, J., M. Loncle and C. Boutelier (1976). Mathematical model of man's tolerance to cold using morphological factors. Aviat. Space Env. Med. 47: 958-964.

60. Wilson, O. and R.F. Goldman (1970). Role of air temperature and wind in the time necessary for a finger to freeze. J. Appl. Physiol. 29: 658-664.

61. Wilson, O., R.F. Goldman and G.W. Molnar (1976). Freezing temperatures of finger skin. J. Appl. Physiol. 41: 551-558.

62. Wissler, E.H. (1964). A mathematical model of the human thermal system. Bull. Math. Biophys. 26: 147-166.

63. Wissler, E.H. (1982). An evaluation of human thermal models. Report on a workshop, Austin, TX Dec. 13-15.

64. Wissler, E.H. (1963). An analysis of factors affecting temperature levels in the nude human. In: Temperature its Measurement and Control in Science and Industry, Part IV, Hardy (Ed.), Reinhold, N.Y.

65. Witherspoon, J.M. and R.F. Goldman (1974). Indices of thermal stress. ASHRAE Bulletin 10-73-8.

66. Woodcock, A.H. (1962). Moisture transfer in textile systems. Text. Res. J. 32: 628-723.

67. Wyndham, C.H. and A.R. Atkins (1960). An approach to the solution of the human biothermal problem with the aid of an anologue computer. Proc. 3nd Int. Conf. Med. Electr., London.

68. Wyndham, C.H. and A.R. Atkins (1962). A physiological scheme and mathematical model of temperature regulation of man. Pflügers Arch. 303: 14-30.

69. Yaglou, C.P. and D. Minard (1957). Control of heat casualties at military training centers. Arch. Ind. Health 16: 302-316.

CHAPTER 4

CLOTHING MATERIALS - THEIR REQUIRED CHARACTERISTICS AND THEIR IMPACT ON BIOMEDICAL FACTORS

G.T. Holmes, P.L. Marsh, R.B. Barnett, and R.A. Scott

CONTENTS

SUMMARY

INTRODUCTION

SYSTEM REQUIREMENTS VERSUS BIOMEDICAL CONSIDERATIONS
- Durability of Physical and Chemical Properties
- Water Resistance
- Flame Resistance
- Ballistic Protection
- Protection from Thermal Effects of Weapons
- Camouflage
- Insect Repellency
- Ease of Movement
- Comfort
- Other Characteristics

FIBRE PROPERTIES

FABRIC PROPERTIES

CONCLUSIONS

REFERENCES

SUMMARY

Military clothing systems demand a variety of characteristics in order to meet their functional purpose. The means of achieving these characteristics are reviewed and the advantages and physiological penalties are discussed. The range of natural and synthetic textile fibres available to the clothing designer is presented and the salient properties of different fibres are outlined. An examination is made of fabric properties and of the biophysical effects that may result from their selection to meet specific operational requirements. The chapter concludes by indicating directions for future work.

Key Words: Textile fibres, Textile fabrics, Synthetic textiles, Flame-resistant textiles, Waterproof/ vapour permeable textiles, Thermal insulation materials, Weight of clothing and textiles, Bulk of clothing and textiles, Stiffness of clothing and textiles, Combat clothing materials/incompatibilities

INTRODUCTION

Textile materials are the basic building blocks with which protective clothing systems are built. Textile fibres can be natural or man made. They can be in short staple or continous filament form. The fibers are formed into yarns which are then formed into woven or knitted fabric constructions. Loose fibres can also be formed into non woven fabric structures. The essential characteristics of a protective system can be attained through careful choice of fiber and fabric. These fabrics can also be finished to provide extra properties such as shrink resistance, flame resistance, crease resistance, water repellency, wettability, rot resistance, and coloring. Finishing processes are means of improving some of the inadequacies of the fibres or fabrics. This utilization of the good together with the compensatory provisions made for the poor is an imperfect method of meeting functional and protective requirements. It is an acknowledgement that the ideal fibres and manufactured materials for the provision of military protection do not exist, nor are they likely to be developed in the foreseeable future. It must be clear that, at present, the level of desired protection must be, more times than not, compensated by some acceptable level of undesirable biomedical condition.

The objective of current materials research and development should therefore be the meeting of as many of the critical requirements as possible without creating new problems in incompatibilities between two or more requirements, or types of behavior. A solution to one problem could well create another problem resulting in little or no overall gain. This matter has been discussed at length by Holmes (1) and a review of that paper reveals that many of the incompatibilities identified in 1965 are still not resolved in a satisfactory manner. (See Fig. 1)

An examination of the prime characteristics of operational clothing materials will demonstrate that many of the solutions to the individual protection problems are not only incompatible with each other but they intensify the biomedical problems which already exist.

SYSTEM REQUIREMENTS VERSUS BIOMEDICAL CONSIDERATIONS

Durability of Physical & Chemical Properties.

If physical durability is achieved by increase in mass, the individual will be burdened by increased weight and bulk which results in greater stress under conditions of activity, increased difficulty in achieving adequate moisture vapour transmission and a loss of body and limb dexterity.

The achievement of durability without increased weight and bulk is usually the result of using high tenacity synthetic fibres (for example polyester and nylon). Most of these fibres have low internal moisture absorption and some are almost completely hydrophobic. These materials cause problems because they could impede low weight and bulk absorption of moisture vapour. Conversely such hydrophobic fibres can assist the wicking, which is the transport of liquid through capillaries and crevices at contact points.

The combined requirement for durability and low weight and bulk leads the developer to the use of high strength fibre/fabric combinations, and the problems regarding hydrophobic fibres have already been discussed.

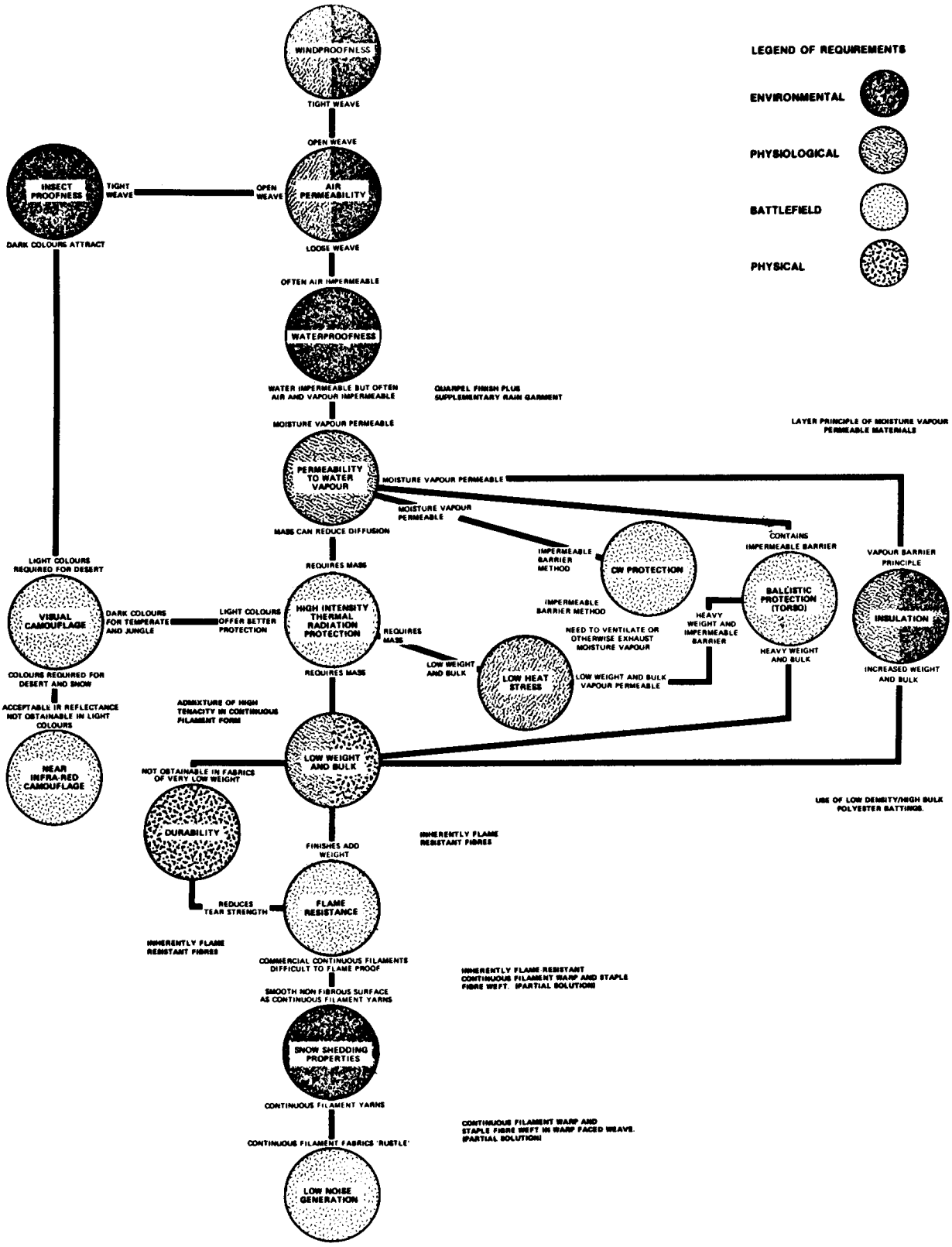


Fig. 1. Incompatibilities in combat materials systems.

Water Resistance

The means of preventing the entry of moisture into and through the clothing layers must not prevent the exhaustion of moisture vapour from the body. This may be accomplished through the use of poromeric and vapour permeable membranes or coatings. A secondary benefit of providing water resistance is to prevent absorption of water by the clothing, thereby increasing the weight and causing discomfort. Note that increased weight will contribute to heat stress. (Table I and Table IV)

Flame Resistance

The application of flame-retardant finishes to textile materials such as the PROBAN treatment for cotton and the borax/boric acid treatment for wool not only tends to lower the tensile properties, they usually result in a significant weight increase and additional stiffness. The added weight does not contribute to the reduction of the heat stress risk, while the loss of flexibility impedes limb and joint movement.

Ballistic Protection

In the area of ballistic protection, current research and development achievement has been limited to the use of flexible body armour as an additional item to be worn. This results in considerable extra weight to be carried. It also has an adverse effect on the transfer of heat and moisture vapour and causes physical impedance. These can also be turned to advantage in that body armour can help to keep the wearer warm or provide insulation against heat and flames.

Protection from thermal effects of weapons

Protection from the thermal effects of weapons can be achieved by providing a flame resistant textile shell fabric together with underlying layers of thermal insulation utilizing a combination of new polymers, fibre selection, fabric construction and inherent mass. Thermoplastic fibres (nylon polyester, polypropylene and PVC) can constitute a particular melt hazard if worn near the skin by military personnel exposed to heat, flames and flash. The behavioural effects of each contributing factor are influenced by the level of protection required, and the need for multi-shot protection. Although all components of the means of protection can play a role in the decrement of human performance and behaviour, it is the increased load provided by the insulation which could be the prime concern. (See Table II)

Protection from Chemical Warfare Agents

Current technology is capable of defeating the known Chemical Warfare (CW) hazards using one of the three general approaches:

a. impermeable barriers such as butyl rubber coated fabrics or laminates.
b. permeable scavenging and neutralizing materials systems; such as those based on activated charcoal.
c. total encapsulation with a built-in life support system.

TABLE I

PROPERTIES OF WATER-RESISTANCE AND WIND PRESSURE

MATERIAL WATER-RESISTANCE

CATEGORY	WATER ENTRY PRESSURE
WATER REPELLENT	< 0.5 psi
SHOWERPROOF	to 15 psi
WATERPROOF	> 25 psi
RAINPROOF	to 30 psi
STORMPROOF	> 30 psi

WIND PRESSURE - MULLEN EQUIVALENT

WIND SPEED (mph)	4	31(BREEZE)	54(GALE)	72(STORM)
PRESSURE (psi)	3.5	9	25	50

TABLE II

BURNING CHARACTERISTICS OF TEXTILE FIBRES

FIBRE	IGNITION TEMP °C	FLAMMABILITY
Cotton	205	Burns readily, chars, afterglow
Rayon	215	Burns very rapidly, chars, no afterglow
Acetate	260	Burns, melts ahead of flame
Nylon 6	276	Supports combustion slightly, melts, drips
Nylon 66	278	Supports combustion, melts and drips
Triacetate	282	Burns readily, melts ahead of flame
Acrylic	293	Burns readily, melts and sputters
Modacrylic	199	Does not support combustion or melt
Polyester	232	Burns readily with soot, melts
Polypropylene	299	Burns slowly
Wool	315	Flame resistant, melts ahead of flame
Nomex	370*	Will not support combustion
Kevlar 29	500*	Will not support combustion
PBI	560*	Will not burn in air
Thermoglass	–	Will not burn

*Decomposes

From: Morris, G.J. The thermal properties of textile materials. J. Text. Inst. 44(10): T449-476,1953.

TABLE III

THERMAL INSULATION MATERIALS

FIBRE TYPE		EXAMPLES	APPLICATIONS			COMMENTS
			Clothing	Sleeping Bags	Underwear	
a.	Polyester Solid Fibre	Polarguard			100% form or in blends	fibrous batting
		Dacron				
		Trevira	X	X	X	materials
b.	Polyester Hollow Fibre	Hollofil	X	X		Tubular fibre
		Superloft				Tubular fibre
		Quallofil		X		4 hole structure
c.	Polyester Microfibre	Dacron	X			"Thin" insulator
				Sliver Knit Pile		
d.	Acrylic Fibre	Teklan	X	X	X	Modacrylic fibre
		Orlon				
		Dunova				Sintered fibre
e.	Polyolefin	Lifa			X	Can be blended with nylon or wool. Low melting point
f.	Polyolefin Microfibre	Thinsulate	X			Thin insulation
		Elzack				materials.
g.	Wool		Knitted or pile fabrics			
			X		X	Can be blended with other fibres nylon, polyester.
h.	Cotton or Viscose Rayon	Vincel			X	Can be blended with polyester.
i.	Polyvinylidene Chloride	Damart Thermolactyl			X	Low melting point. Can be blended with acrylic fibres.
j.	Down & Feathers	Natural source duck or fowl	X	X		Very expensive. Good warmth for mass. High compressibility.

TABLE IV

COMPARISONS OF CURRENT WATERPROOF TEXTILE MATERIALS

* = POOR * * * * * = Best

MATERIAL CATEGORY	WATER VAPOUR TRANSMISSIONPROPERTY	WATER PROOFNESS	RELATIVE COST	GENERAL NOTES
Polyurethane coated Nylon	Impermeable	* * *	= 1 Control Comparison	Widely used. Lightweight.
PVC Coated Nylon	Impermeable	* * * * *	x 1.5	Heavy duty. Stiffens at low temperature.
Neoprene Coated Nylon	Impermeable	* * * * *	x 2	Heavy duty. Flame resistant.
Microporous PTFE Laminates	* * * *	* * * * *	x 5	Expensive. Can be stiff & noisy. Can delaminate.
Microporous Polyurethane Coatings or Laminates	* * to * * * *	* * *	x 2 to x 3	Wide range available. Good handle. Some prone to hydrolysis.
Hydrophilic Solid Film Polyurethane Coated Fabrics	* *	* * *	x 1.5	Cheap. Easy to produce.
Microporous Polypropylene	* * *	* * * *	x 2 to 3	Rather stiff. Still under development
Microporous Polyamino-Acid	* * * *	* * *	x 2 to 3	Very light. Prone to hydrolysis.
Tightly Woven Non-coated Fabrics (Ventile Cotton) (Fine Polyester)	* * * * *	*	Ventile x 5 Others x 2	Water repellent treatment affected by laundering. Air permeability high.

An impermeable barrier prevents the transmission of moisture vapour and, because of heat stress risk, the activities of the wearer are extremely limited. While complete encapsulation with a filtered air supply could provide an acceptable systems approach to both body and respiratory protection, the combat effectiveness of the wearer in terms of body movement, speed, use of weapons and accessibility to his equipment is seriously impaired. He would need to expend much more energy to operate and additional weight of the system would result in penalties. This then leaves the permeable scavenging/neutralizing approach followed by many NATO countries at present. The ensembles transmit moisture vapour but not at a rate which will allow the protective ensemble to be worn at a level of individual effectiveness equal to that of conventional combat clothing. There are numerous records of the heat stress experienced while wearing CW protective ensembles under conditions of normal and high activity. (2,3,4)

Insulation

The provision of insulation against the cold environment has been traditionally achieved by resorting to the multi-layer system. By the use of several clothing layers the bulk of material for a given insulation will be less than that of a single layer system. In addition, a multilayer offers a greater thermal range and the individual layers could carry specific protective properties. Approaches such as the use of a vapour barrier, reflective layers or auxiliary heating have been attempted but have not been successful in the operational environment of the combat soldier. Insulation is discussed at length in Chapters 2 and 5. (See Table III)

Windproofness

If wind-proofness is achieved by the use of a tightly constructed woven fabric, there should be no adverse biomedical implications. If wind-proofness is attained through the medium of applying a coating to a fabric substrate, all the physiological problems caused by impermeable barrier layers will prevail.

Camouflage

Provided the personal camouflage can be achieved without the wearing of an additional garment which will add to the load, there should be no additional biomedical effects attributable to camouflage. However, dark camouflage colours tend to attract insects. Printed colours may be allergenic.

Insect repellency

The two prime approaches to the provision of insect repellency are the use of repellents applied to exposed skin and the wearing of a repellent-impregnated lightweight net jacket. This latter item is completely air and moisture permeable, and the effect on heat load is minimal. Physiological effects of repellents contacting the skin has recently been studied but

until any conclusive evidence comes forth, it is assumed that insect repellents do not contribute to biomedical problems.

Ease of Movement

Ease of movement includes total body movement across ground, and limb and joint dexterity. They are both adversely affected by fabric properties such as weight, thickness and stiffness, and by system properties such as total number of layers, overall thickness and systems design.

Comfort

Wearing comfort has been described by Mecheels (5) as a measure of how well the clothing assists the functioning of the body, or at least impairs it to a minimum degree. There is no single determination of comfort: a number of researchers have emphasized that thermal resistivity and moisture dissipation in all their forms play a significant role in providing overall comfort (5, 6, 7, 8, 9, 10, 11). Other contributing factors are surface characteristics such as scratchiness and harshness of coarse wool fibres or the wet cling associated with synthetic filament fabrics. Propensity for electrostatic charging, shrinkage of cotton, felting of wool causing tightness of garments, all contribute to wearing discomfort. Comfort thus is not a factor in itself but a subjective weighting of all the different properties of clothing.

Other Characteristics

There are innumerable other materials characteristics which are included in requirements for military clothing. They include the series of colourfastness requirements, micro-biological and actinic degradation, snow shedding, low noise generation, and others which have little or no biophysical action or reaction.

FIBRE PROPERTIES

No one fibre possesses all the properties desirable for military, operational and protective clothing.

If an essential fabric property can be obtained by incorporating it into the fibre there are advantages to be gained over the approach of applying finishes in that there are no penalties to be incurred in terms of increased weight, increased stiffness, lower physical properties and lack of durability of the property. An excellent example of this is in attainment of flame-retardance where the inherent flame-resistant property of aramid fibers can be translated into a fabric property without any significant loss of other desirable characteristics.

Although the properties of natural fibres can be modified (e.g., de-scaling of wool fibre for shrink-resistance), it is considered that the possibility of success favours the synthetic fibres. In recent years there have been tremendous advances in polymer chemistry that makes possible the development of new fibres with specific characteristics. Whether or not these fibres would be commercially or economically viable is another consideration.

Examples of some of the more recent technology advances in fibres include the development of hollow fibres which may eventually have a place in the structuring of new insulation media with lower density and higher resilience factors; another development which has found its own place in technology and in the commercial market are the high tenacity aramid fibres which offer advances in ballistic protection. They provide similar levels of protection as HT nylon but with a significant reduction in mass or a much higher level of protection for the same mass.

Fibre technology which may be of increasing importance in the 1985-2000 time-frame includes:

a. bi-component or multi-component fibres obtained either by polymer blending or graft polymerization; for example, bi-component polyester fibres with low melting point sheath for heat bonded insulated battings.

b. inherent fibre colouration with a high degree of colour fastness. Up to present, this has posed considerable problems when applied to fibres produced by hot melt spinning; incorporation of pigments in Nomex aramid fibres, for example, is now possible.

c. sheathed fibres which are essentially hollow fibres with a filled core or a core fibre spun with a sheath for protection or enhancement of the core properties; for instance, glycol based fillings which buffer heat changes (12).

d. fibres whose basic properties have been modified by irradiation; for example, increasing the melting point of polyester fibres (13).

If approaches such as those briefly discussed cannot give the fibre designer or the clothing developer the fibre properties needed to provide more complete protection with fewer physiological penalties, we must then look to the polymer chemists for the development of new polymers, or co-polymers. The synthetic fibre industry is dominated by large multi-national corporations that are naturally interested in returns on research and development investment. Unless a multi-purpose fibre created for military consumption has extensive civilian applications, it would not be cost-beneficial for any one national company to proceed with development and pilot plant production.

As the majority of synthetic fibre producers are multi-national, it is possible that a multi-national approach to nations could provide the break-even production run for one plant. Provided that preliminary inquiries with industry indicate that a multi-national approach is feasible, the first requirement would be for participating NATO nations to identify and agree upon the fibre properties required.

FABRIC PROPERTIES

An examination of the biophysical effects that could be caused by meeting other materials requirements for military protective and operational clothing, indicates that the following fabric properties should be the subject of concentration;

a. moisture vapour transmission
b. flame and heat protective materials
c. thermal insulation
d. wicking and absorbency
e. weight
f. stiffness

While it is necessary to ensure that additional weight must be kept to a minimum, the provisions of protection against the environmental and enemy-imposed hazards is essential. It is therefore difficult to set weight limitations. It is necessary to meet the essential protective levels and ensure that this is being accomplished with the practical minimum weight.

The various means of attaining decreased weight have been examined in detail by Holmes (14). He established that the use of lightweight materials is but a part of the whole process. Various other means of achieving this aim, such as the use of multi-layer design, are currently available.

There is still a great deal to learn regarding the relationship between material stiffness and physiological behaviour. The two extremes of the continuum are a high level of resistance to bending which results in impedance of body and limb movement particularly at the joints, such as that associated with body armour, and a low level of resistance which produces an objectionable clinging sensation, magnified when the material is wet, as instanced by some underwear materials.

Little has been done to examine the threshold levels of stiffness between the two extremes of the continuum, in relation to the various activities to be carried out by the wearer. The object is to prevent a dramatic elevation in the physical effort required to combat material stiffness, without falling into the area where lack of stiffness is in itself an undesirable form of behaviour.

Kaswell (15) has synoptically discussed stiffness and drape. While he does not provide any solutions to the establishment of threshold levels, his descriptions of behavioural patterns and test methods are most pertinent, despite the 1953 date of publication. See also Chapter 10.

All other factors being equal, the thermal insulation properties of a fabric are dependent upon the symbiotic relationship between the mass of fibres (thermal conductors) in a given volume and the amount of entrapped (dead) air (thermal regulators) in the same volume. That is to say that, for two fabrics of identical mass and thickness, the fabric with the greater amount of entrapped air will have the higher insulation value. For example, the insulation value of steel wool is only about 15% less than the same thickness of a textile fibre batting.

Similarly, the transfer of water vapour through a textile material is mainly by diffusion through the air contained in the pores of the structure. There are other means of water vapour transfer as discussed earlier. See Chapter 2.

In order to determine thermal conductivity and water vapour transfer of textile structures, it is therefore necessary to know the volume percent fibre. A limited search shows that standard test methods to determine this property do not exist in many countries, largely because it is a research test and not an acceptance test.

Crow (16) has developed a test method that will be used in pertinent Canadian research and development programs. There is a possible need for a standardized test method for use by participating allied nations.

At one time more emphasis was placed upon the water absorptive capacity of the fibre as a prime factor in the dissipation of moisture from the body. Thus, fibres with low moisture regain were avoided. In 1957 Leach (6) of E.I. Du Pont de Nemours & Co referred to the experimental work of Weiner and Kennedy of US Army Natick Laboratories, which indicated that wettability or wicking could be more important than regain. If the prime objective is to remove moisture from the skin surface and pass it to the ambient atmosphere it is not essential that the moisture be stored in the fibre for a period.

Mehrtens and McAlister (7) also of the Du Pont company reported on fabric comfort studies in 1962 and one of their conclusions was that fabric wickability had no detectable influence on comfort under the test conditions (90 ^{0}F and 80% RH).

The fact that dissimilar statements have been raised from the same source is not a matter for concern but it does exemplify the paucity of data on the significance of wicking in the study of biophysical effects. As late as 1983 Dolhan (17) conducted experiments on eight winter undergarment fabrics produced from a number of fibre constructions ranging, in terms of moisture regain, from 100% cotton to 100% polypropylene. Dolhan found that knitted structures made from these two fibres had much better wicking ability than the other samples which included a polyester/cotton blend, three samples which contained 85 % Thermolactyl chlorofibre and a two-layer combination of 100% cotton and 65% cotton/25% wool/10% nylon blend. Despite the marked differences in moisture regain of cotton and polypropylene, the two samples showed water absorption performance of a similar magnitude, as were also the thermal resistance measurements. See also Chapter 10.

In the face of these data, Dolhan still has some doubts as to the value of wicking and she stresses this point in her findings and conclusions.

It would appear that the function of wicking (wettability) and moisture absorption is worthy of further study using both underwear materials and clothing fabrics produced from a variety of fibres and blends.

It is difficult to discuss moisture vapour transmission and heat transfer properties in terms of a material behaviour alone. In the operational situation the problems of moisture and heat transfer are concerned with the interaction between the body and all clothing layers, the carried load, activity levels, the resultant micro-climate and ambient environment. There are numerous contributing factors such as the size of the spaces between layers, the insulation values of the components and the composite, the convection effects, the presence of a full or partial vapour barrier (as in rainwear) and the design features of the clothing items. There are too many variables to be able to predict with any accuracy the behaviour of the man/load/activity on the basis of laboratory evaluation of the component materials. In spite of this it is necessary to obtain information on the materials in order to determine their contribution to the total behaviour of the clothing ensemble, and also to achieve comparisons between materials systems during the early research and development stages.

There is no difficulty in conducting heat and/or water vapour transfer tests on single fabric layers and through multiple layers, simulating the spacing effect. The various

conditions of temperature and humidity can be obtained with absorption and condensation of water taking place in the layers. However, some of these determinations are taken under static conditions. There are many types of thermal resistance apparatus, with the sweating hot plate and moving copper manikins reflecting the current level of sophistication. Similarly, in most countries there are various methods and apparatus for the measurement of moisture vapour diffusion.

The NATO Document ACCP-1, Heat Transfer and Physiological Evaluation of Clothing, outlines the methodology available to determine heat and moisture transfer in materials but observes that the apparatus may not be readily available to all nations. The measurement of thermal resistance is expressed in units of:

m^2 K / W (square metre Kelvin per watt)

where 1 m^2 K / W = 6.45 Clo.

The moisture permeability index is expressed in i_m:

$$i_m = B \times R_c / R_e$$

where

R_c = thermal resistance in m^2 K / W
R_e = water vapour resistance in m^2 mbar / W
B = 0.6 mbar / K (B is the inverse of the Lewis factor, cf Chapt 2).

The range in i_m is from 0 (impermeable) to 1 (ideal).

Water vapour resistance can be measured by a number of devices, provided that the surface is wetted. For example, sweating hot plates and manikins.

In order that true comparisons can be made of results it is necessary to ensure that there is correlation between methods. It would greatly facilitate comparison if international standardization of methodology and apparatus could be achieved and this would be worthy of further study. Included in the study should be the feasibility of modifying the selected test methods by the inclusion of a controlled dynamic condition by forced convection or other means. The inclusion of the wicking action should also be a variable that could be added at will.

CONCLUSIONS

This chapter has attempted to relate fabric properties to biomedical reaction. The study is by no means complete. Special materials requirements such as those that provide ballistic protection carry their own penalties because the desired level of protection must not be compromised and the current state of technology has no viable alternative solutions.

The provision of materials to meet military requirements is still a compromise situation and no one property should be examined in isolation nor should any form of behaviour be regarded as pertaining to materials alone. The ultimate evaluation is that which is directed to

the man/load/activity combination and any tests on materials merely contribute to that objective (except in the case of acceptance testing against specifications).

In seeking gaps in knowledge, this chapter has identified future areas of fibre and fabric development, the need for standardization of methodology and the requirement for modified methodology. There are no doubt many other requirements that would be examined under the aegis of general problem areas but these are beyond the parameters of this discussion.

In attempting to solve some of these non-biomedical problems, care must be taken to ensure that the solution is not creating other problems, particularly physiological problems.

The matter of incompatibilities between requirements or solutions must always be kept in mind. This indicates that future materials programs should be approached on a team basis with fabric designers, clothing designers and human factors scientists being members of the team. Further benefits would be ensured if the team could be international in composition as the requirements, the problems and the current state of technology are common to all allied countries.

REFERENCES

1. Holmes, G.T. Incompatibilities in requirements for combat materials systems. Dept of National Defence, Canada. Paper presented at 8th Commonwealth Defence Conference on Clothing and General Stores, 1965.

2. Goldman, R.F. Tactical implications of the physiological stress imposed by chemical protective clothing systems. US Army Research Institute of Environmental Medicine, Natick, MA, 1970.

3. Henane, R., Bittel, J., Viret, R., and Morino, S. Thermal strain resulting from protective clothing of an armoured vehicle crew in warm conditions. Aviation Space Environmental Medicine. 50(6): 599-603, 1979.

4. Defence Research Establishment Ottawa. Heat stress from protective clothing. Canadian Status Paper prepared for Fourth Meeting of TTCP WP E-1.

5. Mecheels, J. Körper-Klima-Kleidung-Textil. Melliand Textilberichte. 58: 773-776, 857-860, 942-946, 1977.

6. Leach, L.L. Fibres, fabrics and body comfort. Canadian Textile Journal. 74: 59-65,1957.

7. Mehrtens, D.G. and McAlister, K.C. Fibre properties responsible for garment comfort. Textile Research Journal. 32: 658-665, 1962.

8. Fourt, L. and Hollies, N.R.S. The Comfort and Function of Clothing (United States Army Natick Laboratories Report No. 69-74-CE). Harris Research Laboratories, Rockville, Maryland, USA, 1969.

9. Umbach, K.H. Evaluation of comfort characteristics of clothing by use of laboratory measurements and predictive calculations. Proceedings of International Conference on Protective Clothing Systems, Stockholm, Sweden, 141-149, 1983.

10. Vittorio, P.V., Cattroll, S.W. and Nolan, R.W. A physiological evaluation of the stress imposed by protective clothing. Defence Research Establishment Ottawa Report No. 738, 1976.

11. Goldman, R.F. et. al. CW protective clothing; the nature of its performance degradation and some partial solutions. 13th Commonwealth Defence Conference on Operational Clothing and Combat Equipment, Kuala Lumpur, Malaysia, 1981.

12. Virgo, T.L. and Frost, C.M. Filled hollow fibres. Textile Research Journal. 56: 737-743, 1985.

13. Elton, S.F. Investigation into the burning behavior of cross-linked and irradiated polyester fibres. Ministry of Defence, SCRDE Technical Memo SCRDE/85/6, October 1985.

14. Holmes, G.T. The problem of reduction of weight and bulk in clothing and equipment. Dept of National Defence, Canada. A paper presented at 6th Commonwealth Defence Conference on Clothing and General Stores, 1959.

15. Kaswell, E.R. Textile Fibres, Yarns and Fabrics. Reinhold Publishing Corporation, New York, 1953, pp.425-462.

16. Crow, R. A method to determine volume percent fibre in a fibrous material. Defence Research Establishment Ottawa.

17. Dolhan, P.A. Wicking ability, water absorption and thermal resistance of several thermal undergarment fabrics. Defence Research Establishment Ottawa, Canada, 1982.

CHAPTER 5

COLD WEATHER CLOTHING SYSTEMS: RECENT PROGRESS AND PROBLEMS FOR FUTURE RESEARCH

L. Reed, R.J. Osczevski and B. Farnworth

CONTENTS

SUMMARY

INTRODUCTION

HEAT AND VAPOUR TRANSFER IN CLOTH MATERIALS
- Theoretical Models
- Application to Wet Insulation
- Effects of Wind
- Limitations of Existing Models

PHYSIOLOGICAL RESEARCH
- Thermal Models of the Human Body
- Hands and Feet

DESIGN OF CLOTHING SYSTEMS
- Designing for the Active Wearer
- Interaction of Design Requirements
- Powered Systems

CONCLUDING REMARKS

REFERENCES

SUMMARY

Factors affecting the design of clothing systems for cold weather are discussed. There have been recent advances in understanding the details of the physics of heat transport in fibrous battings and of the interaction of heat and water vapour flow within a variety of materials used for clothing. There is however a continuing requirement to investigate the effects of wind and of bellows ventilation. Additional physiological research is also required to be able to formulate more useful models of the thermal properties of the human body including the special cases of the hands and feet. Important design problems still require solutions. These include the need to provide protection appropriate to widely varying exercise levels; the need to ensure that improvements in cold weather clothing is not made at the expense of mobility, tactility, dexterity, or other aspects which affect the capabilities of the wearer; and the need to include simultaneous protection from various hazards, e.g., ballistic protection and chemical protection.

Key Words: Cold weather clothing, clothing energy exchange, clothing insulation, fibre battings, thermal exchange models, bellows ventilation, thermal physiology.

INTRODUCTION

The ideal role of a cold weather clothing system is to maintain the thermal balance of the user in spite of any large variations in environmental conditions and enormous variations in the user's metabolic rate. If the system is well designed, there will be minimum interference with the various tasks that the user must undertake and no major incompatibility with other clothing or equipment required by the user. It is important for the reader to integrate many considerations (e.g. the topics discussed in the chapter dealing with materials, hand-wear, footwear, and headwear) in any detailed design studies of cold weather clothing.

Clothing research and development is, by its very nature, multidisciplinary. The properties of fibres, fabrics, air spaces and people are all important in the interaction between a clothing system and the person wearing it. A large part of this R/D effort is devoted to evaluating the performance of clothing. A comprehensive system for this evaluation has been described by Goldman (1974) and by Umbach (1983) and in Allied Publication (ACCP-1). Five levels of analysis have been proposed: physical heat transfer studies of fabric; instrumented manikin studies of clothing ensembles; physiological trials in controlled climate chambers; small-scale field trials; and full-scale field trials held in cooperation with user units (see Fig 1). An important feature of this approach is stage-by-stage analysis and application of the information gained to the plans for succeeding stages.

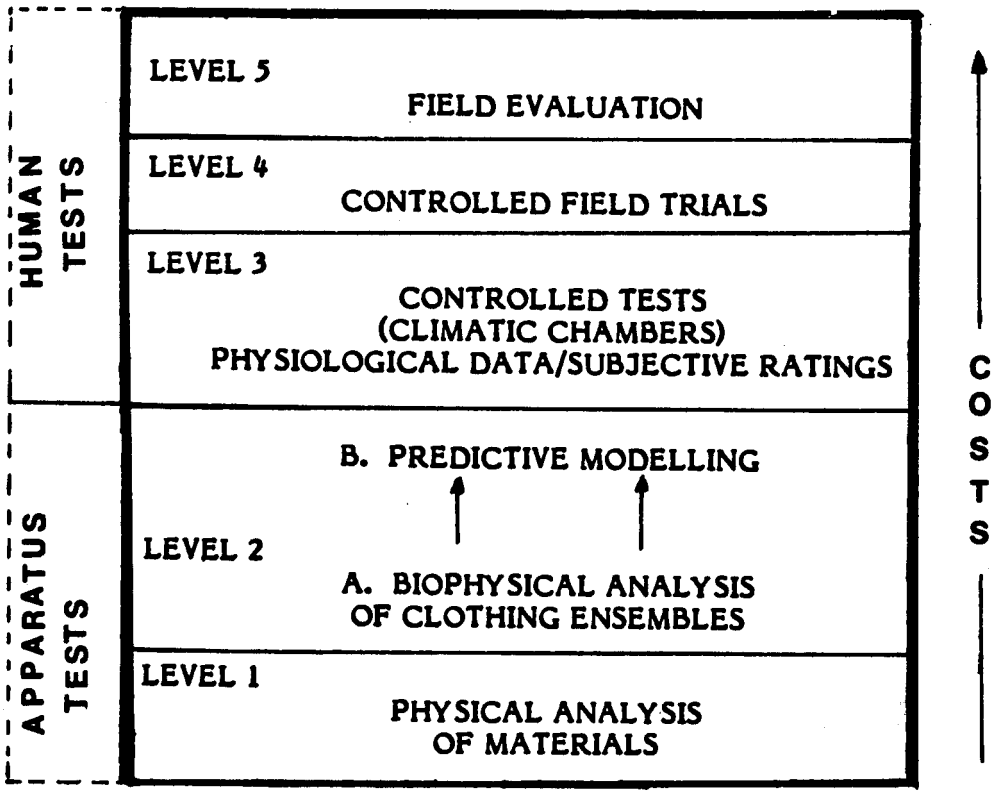


Fig. 1. The 5 levels of clothing testing

New experimental techniques and detailed theoretical models of the basic processes both of heat transfer in the human body and of heat and water transport in clothing materials are forming additional bases for advances in clothing design.

In the sections that follow, various gaps in research knowledge in the areas of heat and water vapour transfer, physiology, and clothing design will be discussed briefly together with some mention of related advances. Several of these gaps have been long-lived and are described in early publications in the field. For additional information relating to cold weather clothing, the reader is referred to the texts of Burton and Edholm (1955), Newburgh (1949), Fourt and Hollies (1970), and Hollies and Goldman (1977) and to the protective clothing bibliographies published by the US National Technical Information Service (e.g. Kenton (1980)).

HEAT AND VAPOUR TRANSFER IN CLOTHING MATERIALS

Theoretical Models

One of the research gaps cited by Burton and Edholm (1955) was the need for studying the physical factors that determine the thermal insulation of a given substance. There has been a need to progress beyond the rule of thumb that the thermal resistance of a particular clothing ensemble is unchanging and is determined primarily by its thickness.

Farnworth (1983) has also presented a theory of combined radiative and conductive heat flow in battings. The success of the model in predicting the thermal conductivity of a variety of battings, including microfibre battings, leads to the conclusion that convection is not a factor in heat flow through battings of normal density for clothing. The theory may be useful in designing new insulation materials. It has been used to predict the usefulness of metal-coated layers in reducing heat flow in clothing materials. Breckenridge (1978) has reviewed the attempts to use such materials since the 1940's and their lack of success. By physical analysis and experimentation he concluded that they would be of some use when separated by thin layers of low density battings, where radiative transfer from inner to outer surface is direct. This is in agreement with the prediction model.

Recently, Farnworth (1980) devised a numerical model of transient heat and water vapour transfer through multiple layers of clothing materials that allows for condensation, evaporation, absorption, and desorption of water within hygroscopic layers. The model gives good agreement with the experimental results obtained earlier by Woodcock (1962) and by Farnworth and Nordli (1982) and supports the conclusions of Pratt et al. (1956) that hygroscopic insulation such as wool is likely to be disadvantageous to a soldier whose work rate changes frequently. This is because hygroscopic materials reduce the heat loss during periods of active sweating (compared to weakly hygroscopic materials) and prolong the period of evaporative cooling (i.e. increase the heat loss) after sweating stops or when sweat rates are reduced (after-exercise chill).

Application to Wet Insulation

Farnworth and Dolhan (1986) have been able to explain the variations in heat flow in wet insulating layers as a combination of water vapour diffusion, radiation and conduction of

heat by the fibres and the enclosed still air. Some experiments were undertaken to examine the supposed superiority of synthetic battings compared with down or down-and-feather mixtures in wet-cold conditions. Significant differences in water uptake and heat loss during drying on a guarded hot plate were observed, but a choice between the two for wet cold conditions was not clearcut. In either case, no insulation is really effective when it is wet. The superior drying properties of synthetics are an advantage in cold-wet situations.

Effects of Wind

In addition to being highly insulating, the thermal protection offered by clothing for cold conditions must not be degraded by wind. Wind affects heat loss in several ways: by penetrating the clothing and cooling the body; by reducing the thermal resistance of external air layers by pressing clothing layers together; by compressing insulating materials; and by causing the clothing to flap and thus promote air exchange between layers and with the environment. In arctic clothing, a tightly woven outer shell is used to prevent penetration by the wind, but compression can still cause increased heat loss from areas where insulation is provided by air layers between thin clothing layers.

Ideally, it should be possible to predict the heat flow in clothing in any combination of wind and temperature on the basis of the properties of the materials from which they are composed. This is not yet possible. Although some research has been carried out on the effects of wind (see, for example, Burton and Edholm (1955), Fonseca (1975), and the review by Breckenridge (1977)), most work has involved experiments with simple physical models, evaluation of existing clothing, and the derivation of empirical relations. The value of such relations is limited in that they apply, strictly speaking, only to the specific clothing used in the specific conditions for which the relations were derived, and they contribute little towards an understanding of what is actually happening.

Limitations of Existing Models

The theoretical models of the details of heat flow in insulating materials have a limitation in that they can, as yet, only be applied to flat samples of materials in the absence of wind. Nevertheless, they do lead to some understanding of the processes that occur in clothing and can therefore assist the designer in making some estimate of the behavior of candidate materials in actual clothing systems.

Estimates of heat loss from a non-sweating stationary man can be made with a fair degree of accuracy from a knowledge of his clothing. Sweating complicates the matter greatly as the major mode of heat transfer is by evaporation or by a series of evaporation, condensation and conduction. Body movement introduces a further complication through the effects of bellows ventilation.

In summary, the prediction of clothing performance under all sets of weather conditions and activity is a goal that has yet to be achieved.

PHYSIOLOGICAL RESEARCH

Thermal Models of the Human Body

In their list of problems for future research, Burton and Edholm (1955) included the difficulties encountered in calculating total body heat exchange using measured skin and core temperatures and they suggested the need for much additional work involving simultaneous direct and indirect calorimetry. The difficulties continue. Various models for the human body have been proposed (see for example the work of Stolwijk (1970) and the review by Hwang and Konz (1977)), and various weighting factors have been used in calculating mean body temperatures. It is apparent that these weighting factors are affected by changes in heat storage and, therefore, by changes in mean body temperature itself, hence the difficulty (Livingstone (1967)). It is for this reason that Myles and Livingstone (1975) devised a physiological protocol for measuring insulation which involved the selection and use of an ambient temperature at which the subject (protected by the item to be tested) could maintain relatively constant body temperatures. By this means it is possible to minimize errors arising from uncertainties in body heat storage but since near steady state is difficult to achieve, the method can be time-consuming. Additional work is still needed especially for application to situations in which body temperatures are varying.

Hands and Feet

Protection of the hands and feet is discussed in other chapters but it is important to note, in general terms, some of the aspects that affect cold weather protection for the extremities. It has been known for many years that peripheral blood flow is markedly affected by warming or cooling the body as a whole (see for example, Burton and Edholm (1955) and the report by Meehan (1957)). Vanggaard (1983 (cf Chpt 7)) has emphasized that there is a serious requirement to analyze the importance of arterio-venous anastomoses in the thermoregulatory changes in peripheral blood flow. He maintains that these "shunts" exert considerable control of blood flow in the hands and feet, and that it will therefore be impossible to produce adequately insulating gloves or boots for a person threatened by hypothermia during cold exposure. Goldman (1975) has also identified a related requirement for physiological research to provide the additional information required for use in developing prediction models of extremity cooling and whole body cooling. Of course, in an ideal clothing system, the body would remain thermally neutral and such physiological responses would not occur.

DESIGN OF CLOTHING SYSTEMS

It is probably true that clothing has evolved by a process akin to natural selection. To design clothing it is necessary to be able to predict performance under any specified set of conditions so that optimum decisions on materials and design features can be made before constructing prototypes.

It is a fairly simple matter to design a cold weather clothing system for an inactive person. Most of the heat transfer will be "sensible", and the thickness of insulating layers that are required will therefore be easy to calculate from the thermal conductivity of the materials

and the allowable heat loss rate. The total protection need only be variable by a factor of two in response to weather changes.

Design for the Active Wearer

The real challenge is in the development of clothing for an active person. The protection value must be variable by a factor of ten in response to activity changes. Sweating will be unavoidable, and evaporative heat loss will be the major heat loss mechanism. Water or ice will build up on clothing as little work can be done at cold temperatures without reaching the point where the rate of sweat production exceeds the rate of sweat escape (Behmann 1971). How much of a problem does this actually present in both the short and long term? Much of the training given soldiers on this point results from experience with clothing systems which were developed before the advent of synthetic, non-hygroscopic, materials. A wet fur or wool parka resembles a suit of armour when frozen. The problem is to choose designs and materials which minimize the effects of water or ice and which have fast drying properties. There is some value in the use of micro-porous materials in wet-cold clothing derived mainly from the drying of clothing rather than the avoidance of heat stress, but is it worth their cost?

Burton and Edholm (1955) cited overheating during exercise in the cold (and after-exercise chill) as the greatest problem of protection in the Arctic. Designers of clothing usually resort to a system of clothing that has a number of layers. In theory, layers can be removed or added to regulate heat loss. As it is usually the inner layers that are added or removed, the system works best in response to changes which occur slowly and infrequently, such as weather changes. It is much more difficult to regulate heat loss in response to changes in work rate, which occur frequently and often suddenly. Severe weather conditions further limit the adaptability of such systems, as adding or removing inner layers would involve the removal of the outer windproof and water repellent layer, allowing exposure to the elements. In conditions of high winds and blowing snow, changes of inner layers will rarely occur without access to some kind of shelter.

As an individual will usually dress to be warm at low activity levels, additional cooling will be required as work rates increase. It is important to examine how to produce this cooling most effectively, simply, and in a manner which is most compatible with military activities and ancillary equipment (e.g., load carrying systems). Attention to design aspects such as optional openings and seals and the ability to remove an outer windproof layer can help reduce the problem of overheating.

Studies for cold weather clothing could be undertaken to determine where changes in insulation will have the most effect in reducing the tendency to overheat an active soldier. In addition, subjective perception of heat and cold in different body areas influences the consideration of locations at which cooling should be enhanced. This also needs further study.

In considering the problem of overheating during exercise, Gilling (1972) has concluded that, short of a radically new concept, the basis for arctic clothing with existing materials must continue to depend on the variable layer system, despite its operational problems, and on garment design to provide additional ventilation during activity. The idea of using "bellows ventilation" (caused by motion of the clothing) to reduce overheating during exercise has

been of interest since Belding (1947) showed that the apparent thermal resistance of a particular set of clothing was halved during walking as compared with standing. As Burton and Edholm (1955) have pointed out, the increase in heat dissipation caused by bellows ventilation in most clothing systems is less than the increase in heat production during exercise. Various investigators have evaluated the effects of body motion on heat loss from a variety of clothing systems (Nishi and Gagge (1970), Mecheels (1971), Mecheels and Umbach (1977), Vokac et al. (1973), Breckenridge and Goldman (1976), and Shivers et al. (1977)). Osczevski (1981) recently described the design of a prototype cold weather ensemble involving features that were designed to emphasize bellows ventilation and help to maintain thermal balance at different levels of exercise. Bellows ventilation is attractive, as it should automatically increase heat loss with an increase in heat production. Efforts should be devoted to finding ways of enhancing this mechanism in cold weather clothing.

Interaction of Design Requirements

In a recent listing of problems requiring further research, Holmes (1981) has referred to the challenge of ensuring that improvements in cold weather clothing are not made at the expense of mobility, tactility, dexterity or individual effectiveness. The increased energy cost of wearing some cold weather ensembles is also of concern. (See, for example, the work of Teitlebaum and Goldman (1972)). It is important to minimize incompatibilities between the components of any complete clothing system. An additional concern is the potential interference that items such as load-carrying equipment could cause in the intended pathways for ventilatory air.

The problem of combining protection against both cold weather and chemical agents presents particular challenges to the designer. In addition to problems that may be associated with cold weather operation of chemical warfare protective (CW) ensembles themselves (e.g. misting of eyepieces, icing of valves, stiffening of elastomers), there are problems which can arise from the interactions of the cold weather and CW ensembles. The requirement to be able to maintain thermal balance may be frustrated by a requirement to leave the CW protective layer and any enclosed insulating layers undisturbed, or by the requirement to wear a respirator. Tight-fitting respirators and gloves could interfere with skin blood flow and lead to frostbite. The combination of stiffened elastomers, friction between clothing layers, and other interferences between the two ensembles can readily lead to increased times required to don or doff CW equipment. Loss of mobility, dexterity, and tactility when wearing both cold weather and CW ensembles can lead to additional problems associated with the use of other equipment (e.g. rifles, radios, and vehicles). There is therefore an important requirement for the designer of military cold weather clothing systems to know (or even to influence) the characteristics of the other clothing items with which his designs will interact.

Powered Systems

Various authors have suggested that there may be a need for powered types of cold weather protective clothing systems including, for example, auxiliary heating systems and controlled microclimate systems similar to those used in space suits (e.g., Goldman (1974)). However, before resort is made to systems that require auxiliary power or are prone to mechanical or electrical failure, it should be ensured that the problem cannot be solved by passive means such as appropriate application of additional insulation.

CONCLUDING REMARKS

Some progress has been made in understanding the basic mechanisms of heat transfer in clothing materials. This new understanding will prove to be of value in the design of new materials. It also provides useful background to designers of cold weather clothing so that rational decisions regarding clothing materials can be made.

Bellows ventilation to enhance pumping effects deserves more attention. Lack of knowledge of these effects limits the application of predictive models based on theoretical considerations. In addition, Bellows ventilation may provide a convenient way to reduce heat stress in active individuals.

The difficulties involved in calculating heat storage in human subjects have limited the accuracy of physiological evaluations of clothing. An understanding of how heat storage and body temperatures are related is a requirement in the development of models of the human thermal system and thus of schemes for the prediction of clothing performance and the development of optimum designs. Until such models are available, clothing design will depend on the slow process of evolution from previous designs through changes, trials, and redesign. This process will benefit from information gleaned from experiments on simple physical models, from theoretical models of simple systems, and by the intuition and experiences of the designers. Optimum solutions to the problems of cold weather clothing design will therefore be difficult to find.

Major research problems related to cold weather clothing systems are still outstanding. A systems approach is required to ensure that the basic sciences, the user's needs, the user's activities, and interactions with other equipment and clothing systems are all considered in research and development of new cold weather clothing ensembles.

REFERENCES

1. Behmann, F.W. Maximum of evaporative heat loss in relation to clothing thickness. Journal de Physiologie 63:201-203, 1971.

2. Belding, H.S., Russell, H.D., Darling, R.C., and Folk, G.E. Analysis of factors concerned in maintaining energy balance for dressed men in extreme cold; effects of activity on the protective value and comfort of an arctic uniform. American Journal of Physiology 149:223-239, 1947.

3. Breckenridge, J.R. and Goldman, R.F. Clothing, the interface between man and his environment: resistance against meteorological stimulus. Progress in Biometeorology Volume 1, Lisse, Netherlands: 1976.

4. Breckenridge, J.R. Effects of body motion on convective and evaporative heat exchanges through various designs of clothing. Clothing Comfort: Interaction of Thermal Ventilation Construction and Assessment Factors. (Edited by N.R.S. Hollies and R.F. Goldman) Ann Arbor, Michigan, 1977.

5. Breckenridge, J.R. Insulating effectiveness of metalized reflective layers on cold weather clothing systems. United State Army Research Institute of Environmental Medicine, Report No. T 2/78, 1978.

6. Burton, A.C. and Edholm, O.G. Man in a Cold Environment. Edward Arnold, Ltd, (Publishers), London, 1955.

7. Campbell, G.S., McArthur, A.J. and Monteith, J.L. Wind speed dependence of heat and mass transfer through coats and clothing. Boundary Layer Meteorology 18: 485-493, 1980.

8. Farnworth, B. Calculations of heat and vapour transport in clothing: transient effects of hygroscopic materials. Defense Research Establishment Ottawa Technical Note No. 80-25, 1980.

9. Farnworth, B. and Dolhan, P.A. Heat loss through wet clothing. Defense Research Establishment Ottawa Technical Note No. 82-28, 1982.

10. Farnworth, B. and Nordli, B. Measurement of the combined heat and water-vapour flow through clothing under transient conditions. Defense Research Establishment Ottawa Technical Note No. 82-13, 1982.

11. Farnworth, B. The mechanisms of heat flow through clothing insulation. Textile Research Journal 53:717-727, 1983.

12. Farnworth, B. A numerical model of the combined diffusion of heat and water vapour through clothing. Textile Research Journal. 56: 653-665, 1986.

13. Fonseca, G.F. Sectional dry-heat-transfer properties of clothing in wind. Textile Research Journal 45:30-34, 1975.

14. Fourt, L. and Hollies, N.R.S. Clothing: Comfort and Function. Marcel Dekker, New York, 1970.

15. Gilling, D.F. Some aspects of the assessment of cold weather clothing. Army Personnel Research Establishment Memorandum No. U/4, 1972.

16. Goldman, R.F. Clothing design for comfort and work performance in extreme thermal environments. Transactions of the New York Academy of Sciences 36:531-544, 1974.

17. Goldman, R.F. Predicting the effects of environment, clothing and personal equipment on military operations. US-1, Eleventh Commonwealth Conference on Operational Clothing and Combat Equipment, India, 1975.

18. Hollies, N.R.S. and Goldman R.F. Clothing Comfort: Interaction of Thermal, Ventilation, Construction and Assessment Factors. Ann Arbor Science Publishers, Inc., Ann Arbor, Michigan, 1977.

19. Holmes, G.T. Combat clothing in the 1985-2000 time frame. CDA-15, Thirteenth Commonwealth Defence Conference on Operational Clothing and Combat Equipment, Malaysia, 1981.

20. Hwang, C.L. and Konz, S.A. Engineering models of the human thermoregulatory system - a review. IEEE Transactions on Biomedical Engineering BME 24:309-325, 1977.

21. Kenton, E. Protective clothing: arctic and tropical environments. Springfield, VA: National Technical Information Service, Microfiche P380-809635, 1980.

22. Livingstone, S.D. Calculations of mean body temperature. Canadian Journal of Physiology and Pharmacology 46:15-17, 1967.

23. Mecheels, J. Die Messung der funktionellen Wirkung der Kleidung auf den Menschen. Melliand Textilberichte 52 No 7, pp. 843-849; No 8, pp. 967-974; No 9, pp. 1215-1221; 1971.

24. Meehan, J.P. General body cooling and hand cooling. Protection and Functioning of the Hands in Cold Climates (Edited by R. Fisher) National Research Council, National Academy of Sciences, Washington, D.C., 1957.

25. Myles, W.S. and Livingstone, S.D. A method of measuring clothing insulation. Defense and Civil Institute of Environmental Medicine Report No. 75-X-19, 1975.

26. Newburgh, L.H., ed. Physiology of Heat Regulation and the Science of Clothing. Saunders, Philadelphia, PA, 1949.

27. Nishi, Y. and Gagge, A.P. Direct evaluation of convective heat transfer coefficient by napthalene sublimation. Journal of Applied Physiology 29:830-838, 1970.

28. Osczevski, R.J. Experimental cold-weather clothing. Defence Research Establishment Ottawa Technical Note No. 81-13, 1981.

29. Pratt, R., Fonseca, G., and Woodcock, A. Some aspects of the absorbency of clothing materials. U.S. Army Natick Q.M.R. and D. Center Research Study Report BP-3, 1956.

30. Stolwijk, J.A.J. Mathematical model of thermoregulation. Physiological and Behavioural Temperature Regulation (Edited by J.D. Hardy, A.P. Gagge, and J.A.J. Stolwijk), Springfield, Illinois, 1970.

31. Teitlebaum, A. and Goldman, R.F. Increased energy cost with multiple clothing layers. Journal of Applied Physiology 32:743-744, 1972.

32. Umbach, K.H. Evaluation of comfort characteristics of clothing by use of laboratory measurements and predictive calculations. International Conference on Protective Clothing Systems (Edited by K. Amundin, C. Brunius and A. Brand-Persson), Stockholm, Sweden, 1983.

33. Vanggaard, L. Protection of the hands. International Conference on Protective Clothing Systems (Edited by K. Amundin, C. Brunius, and A. Brand-Persson), Stockholm, Sweden, 1983.

34. Vokac, Z., Kopke, V., and Keul, P. Assessment and analysis of the bellows ventilation of clothing. Textile Research Journal 43:474-482, 1973.

35. Woodcock, A.H. Moisture transfer in textile systems Part II. Textile Research Journal 32:719-723, 1962.

36. ACCP-1, Heat transfer and physiological evaluation of clothing. NATO, April 1984.

37. Mecheels, J.H. and Umbach, K.H. Thermoregulation properties of clothing systems. Melliand Textilberichte, 1142-1146, December, 1976.

CHAPTER 6a

THE PRACTICAL ASPECTS OF SLEEPING SYSTEMS

L. Vanggaard

CONTENTS

SUMMARY

INTRODUCTION

BASIC REQUIREMENT FOR A SLEEPING SYSTEM

HEAT LOSS FROM THE HEAD

PERSPIRATION

SLEEPING COMFORT

CONCLUSIONS

REFERENCES

SUMMARY

Sleeping bags are a modern concept not known to the people living in the cold, the Lapps and eskimos. The changing thermal need of the body during sleep is the most important problem in sleeping bag design. The effect of training is of utmost importance to obtain necessary undisturbed sleep.

Key Words: temperature regulation in sleep, sleeping bags, sleeping bag design, CO_2 buildup, sleep ergonomics.

INTRODUCTION

Although it is comparatively easy to establish the thermal insulation required of a sleeping system from theoretical considerations, practice shows that the comfort of a sleeping system is dependent upon other factors than simply its thermal protection.

It should not be forgotten that native northern populations, e.g., the eskimos and the Lapps, have developed clothing systems comparable to what modern technology and materials can produce, but never "invented" a sleeping bag; they used furs or blankets (2). The sleeping bag was invented by the early polar explorers to serve a special need; optimal thermal protection with a minimum of weight. This is still the main objective of a military sleeping system.

BASIC REQUIREMENT FOR A SLEEPING SYSTEM

The basic requirement for a sleeping system is to allow the user a period of recuperative, relatively undisturbed sleep or rest. However, several factors counteract this, the most important of which is the unchangeable insulation value of a sleeping bag. When a person first enters the sleeping bag, his metabolic heat production is slightly higher than when he falls asleep, when his metabolism falls to the 0.8 MET (40 kcal/m^2hr, or 72 kcal/hr for the average man) of sleep. He may also have a positive heat storage, i.e., some extra heat not yet lost from the activities prior to the rest period. However, during the night, the environmental temperatures of most climates show marked changes, their minimum coinciding with that of the lowest body temperature at about 3 to 4 a.m. in the morning.

The best solution to these thermal problems would necessitate a sleeping system with a variable insulation, more or less regulated by instinctive but learned (for instance by training) reflexes of the user.

It is well known that even a very young infant regulates heat dissipation from the body during sleep by changes in body posture; when warm and covered, the baby positions itself with the extremities stretched out from the body, offering a large heat surface for heat loss to the environment; when exposed to even moderate cooling, the baby curls itself up, offering a much reduced surface for heat loss to the surroundings. In adults, these reflexes are modified by the sleeping system, whether this consists of loose blankets, furs or down comforters. By unconscious changes in body position, and by exposing more or less of the skin surface to the environment, heat exchange is accomplished without hampering undisturbed sleep. These are perhaps the reasons why none of those cultures which live a greater part of their life under conditions comparable to military "field conditions", have ever evolved or invented a sleeping bag.

HEAT LOSS FROM THE HEAD

Heat losses from the unprotected head poses a special problem; as indicated earlier in this chapter, they are very high due to the high blood flow to the scalp and the brain (1). This blood flow is relatively independent of the individual's thermal status even though enough heat is lost to lead to cold stress. There is some evidence that sufficiently slow but steady

heat loss, e.g., from an unprotected head, might not trigger the normal physiological responses to lowering of body temperature.

Only very few sleeping bags have solved the problem of how to give free movement for the head while providing it with ample insulation. Often, the user of a sleeping bag will cover his head by dragging the sleeping bag up over the head. This creates a situation where respiration might be influenced by the exhaled carbon dioxide (CO_2) build up around the face; even low concentrations of CO_2 (> 0.5%) in the inspired air may produce a throbbing headache in susceptible individuals after only a few hours of exposure. (3).

PERSPIRATION

During the night the body will lose water by perspiration through the skin, i.e., the insensible water loss associated with the 6% humidity of a non-sweating skin. This will result in a moisture build up within the sleeping system of about 25 ml/hour. This moisture will condense inside the covering surface of the sleeping bag in a cold environment. The design of a sleeping system should thus be such that, after use, the cover could be removed from the insulating part of the sleeping bag and dried out separately. In an arctic environment, the condensed water will freeze as "hoar frost" and it must then be beaten out.

As a sleeping bag often is used as a bivouac, the protective cover should be impermeable to water from the ground below while the upper part of the cover should be permeable to water vapour but able to withstand rain.

SLEEPING COMFORT

Undisturbed sleep not only depends upon proper heat exchange between the user and the environment, but also demands certain bodily comfort; i.e., movements of the extremities should not be too restricted. Many sleeping bags are too tight, and such tightness also reduces the thermal insulation of the bag at those points where it is compressed from the inside; areas of special importance are the shoulders, hips and knees.

During sleep most of the heat production takes place in the trunk of the body and only to a very slight degree in the extremities. This leaves these to cool rapidly if the heat loss from the sleeping bag does not completely balance the heat production of the sleeping user. Sleeping bags should therefore be designed in a way that allows the user free access to his feet so he can massage and warm these with his hands.

Sleeping bags designed for use in very cold climates should perhaps be constructed and sized in such a way that, in an emergency, two people could be accommodated within one bag. This would reduce their total heat loss surface by 50% and thus increase survival time considerably. In a cold survival situation, where the feet are in especially great danger of developing frostbite, the optimal solution is to use a double-ended zipper, so the two people can keep each others feet warm by entering the bag from opposite ends. Such a double working zipper would also allow the sleeping bag to be used as a casualty bag, giving access to the lower extremities for treatment, control, and bandaging without exposing the total body surface. The zipper also gives the ability to alter clothing ventilation.

When sleeping on hard surfaces the body's weight is transferred to the ground at certain pressure points; head, shoulders, hips, and knees. At these points, extra bulk or compression resistance should be added to the lower side of the bag in order to obtain a softer undercover and to help maintain insulation below the body. One approach, tried by the U.S. Army with good results prior to the introduction of foam ground pads, used an insulating batt material on the inside of the top surface of the inflatable ground pad used at that time.

CONCLUSIONS

A military sleeping system should offer ample thermal protection, but ideally be designed to allow varying the overall insulation during sleep. It should offer thermal protection of the head and at the same time not impose undue restraint on head movements. Incompressibility should be highest below the body pressure points with the ground. The sleeping bag should allow freedom of movement for the extremities. Its cover should be detachable, water impermeable below and weatherproof on the upper surface. It should have a double working zipper to accommodate two people in emergencies and also to meet requirements for use as a casualty bag.

A number of other design criteria for military sleeping systems can be added to these "physiological" demands; washability, easy drying and cleaning cnaracteristics, and more operational criteria such as ease in donning and doffing. In combat areas the soldier requires a system that allows him to get out of the bag quickly if the necessity arises.

Finally, any sleeping system requires training in its use; a soldier must therefore be well trained in the proper use of the system if it is to offer him the required undisturbed sleep and comfort.

REFERENCES

1. Froese, G., and A.C. Burton. Heat loss from the human head. J. Appl. Physiol. 10:235-241, 1957.

2. Rodahl, K. personal communication.

3. Stephenson, L.A., B.C. Cadarette and K.L. Speckman. Physiological testing of experimental chemical warfare agent protective patient wraps. USARIEM Technical Report T2/86, 17 p, 1986.

CHAPTER 6b

BIOMEDICAL EFFECTS OF SLEEPING SYSTEMS

R.F. GOLDMAN

CONTENTS

SUMMARY

THERMAL REQUIREMENTS

ADEQUACY OF INSULATION

ACHIEVABLE INSULATION

RELATING INSULATION TO USER THERMAL COMFORT

INSULATION OF BLANKETS

SUMMARY

The functional demand on a sleeping system is to enable the user to obtain a specified period of sleep in a given thermal environment. The required insulation bears a linear relationship to the environmental temperature (~ 4 clo/20 °C decrease in environmental temperature). An insulation of about 8 clo is at present accomplished in heavy arctic sleeping bags.

Key Words: sleeping systems, sleeping bag insulation, sleep requirements.

THERMAL REQUIREMENTS

Three definitions, precise or approximate, are the key to understanding the biomedical effects of any item of protective clothing and personal life support equipment. One must define:

1. the functional demands placed upon an item;
2. the corresponding relevant functional capabilities, and interactions, of the user of the item; and
3. the degree of mismatch which is incompatible with user tolerance, unimpaired performance or continued comfort.

The effects of a sleeping system are presented in this chapter of the Handbook, not because a sleeping system is an item of primary military importance, but because it is probably the simplest item of protective clothing and personal equipment to characterize in terms of its biomedical effects.

The functional demands (i.e., Required Operational Characteristics) on a sleeping system can be defined quite precisely; i.e., the sleeping bag must allow some specified number of hours of comfortable sleep (usually 4 to 6 hours) down to some specified temperature (frequently, although unattainably, -40 °C). The user's interaction with the system is minimal; the relevant capability of the user is his heat production level. Heat production can be defined in terms of body size (for all practical purposes without other concern for height, weight, age or gender) as 0.8 MET units while asleep, i.e., 40 kilocalories/m^2 of body surface area per hour, or 57 W/m^2; any variation with body motion is minimal, short of shivering which falls outside the definition of comfortable sleep. Finally, the loss of body heat which is incompatible with continuing to sleep can be defined as an accumulated heat debt of 80 kcal (i.e., 44 kcal/m^2) for an individual who is not totally overcome by exhaustion or hypothermia (i.e., body temperature below 35 °C) before falling asleep.

Consider a soldier of average size; i.e., weight of 70 kg and height of 173 cm, which corresponds to a total body surface area of 1.8 m^2. Such an individual produces about 72 kcal/hr while sleeping (i.e., 0.8 MET) and loses about 25% of this amount from the body by respiration and evaporation of the body water diffusing through the skin, which typically maintains a minimum 6% wettedness; i.e., a skin relative humidity of .06. This leaves 54 kcal/hr to be lost by the body by non-evaporative heat loss through the sleeping system to the ambient environment if body heat content is to remain unchanged.

Figure 1 graphically relates the required clo units of insulation for a "comfortable" sleeping system as a function of ambient air temperature. One clo unit of insulation can be defined as that insulation which not only allows, but requires the transfer of 10 kcal/hr for an average man (1.8 m^2) for each °C difference between his mean skin temperature (T_s, which can be defined for comfort at 32 °C) and ambient temperature. Therefore, at an ambient air temperature of 0 °C the non-evaporative heat loss will be 320 kcal/hr with a 1 clo sleeping system; it will be 160 kcal/hr with a 2 clo sleeping system, etc.

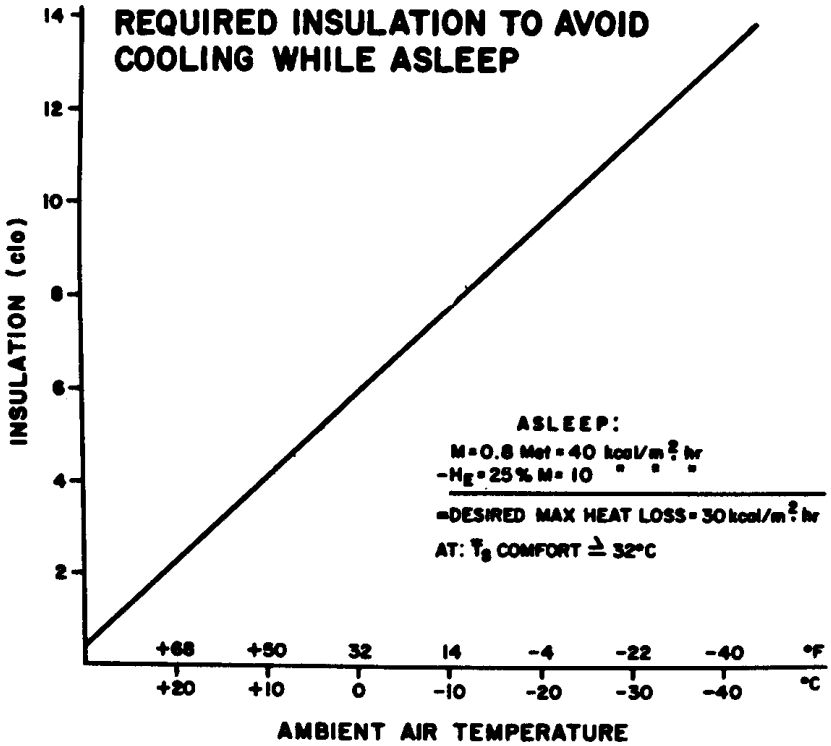


Fig 1. Required insulation to avoid cooling while asleep.

ADEQUACY OF INSULATION

Two definitions can be used for "adequacy" of a cold-weather sleeping system: (1) "comfort", which implies that the sleeping soldier loses just the 54 kcal/hr by non-evaporative avenues, i.e., can maintain heat balance without shivering or sweating; or (2) "six hours of restful sleep", which allows him to incur a total body heat debt of 80 kcal during a six-hour sleeping period and, therefore, to lose 67.3 kcal/hr, i.e., 54 + 80/6. In addition to the criterion that heat debt beyond 80 kcal is generally incompatible with continued sleep, average mean weighted skin temperature should not be below 32 °C. Indeed, some data exists (Goldman, unpublished) to support the hypothesis that waking while asleep under cold conditions is triggered by the sudden fall in the temperature at a skin site suddenly exposed to a cold surface as a result of body movement during sleep. In any event, the lowest ambient air temperature for "comfort" T_a (min) while asleep with a given insulation can be calculated as:

$$T_a \text{ (min)} = 32 - 5.4 \text{ (clo)} \qquad \text{Equation 1}$$

where the number of clo is the insulation of the sleeping system (bag + pad + clothing, if any) expressed in clo units.

Using the "six hours of restful sleep" criterion (i.e., allowing a total heat debt of 80 kcal during six hours of sleep), the minimum ambient temperature can be defined as:

$$T_a \text{ (min)} = 32 - 6.7 \text{ (clo)} \qquad \text{Equation 2}$$

Table I gives examples of protective systems providing between 1 and 12 clo units of insulation, and relates those insulation levels to the minimum ambient air temperature for both "comfortable sleep" and "six hours of restful sleep".

Table I
Lowest Ambient Air Temperatures for Comfort or 6 Hours Rest while Asleep

Insulation (clo)	Example of System	"COMFORT" (°C) $T_{a,min}$	(°F)	6 hrs REST (°C) $T_{a,min}$	(°F)	Zone
	Clothing					
1	Swim Suit	26.6	80	25.3	77.6	Temperate
2	Business Suit	21.2	70.2	18.5	65.3	
3	Outdoor Cold Weather Ensemble	15.8	60.5	11.8	53.3	
	Sleeping Systems					
4	Synthetic (dacron fill)	10.4	50.7	5.1	41.3	Cold-Wet
5	"Mountain" 60/40 chicken feather & down fill	5.0	41.1	-1.6	29.1	
6	Commercial: 100% prime goose	-0.4	31.3	-8.4	17.0	
7	"Intermediate Cold" poly; 60/40 in outer channels	-5.8	21.6	-15.1	4.9	
8	"Extreme Cold" poly; 100% down in outer channels	-11.2	11.9	-21.8	-7.1	Cold-Dry
	Sleeping Systems and Additions					
9	"Extreme Cold" above + insulated pad, clothing, hood & poncho liner	-16.6	2.2	-28.6	-19.4	
10	All 9 clo above + warm gloves & bootees	-22.0	-7.5	-35.3	-31.5	
11	Not achieved - auxiliary heat required?	-27.4	-17.3	-42.0	-43.6	Extreme Cold
12	Not achieved - auxiliary heat essential	-32.8	-26.0	-48.7	-55.6	

ACHIEVABLE INSULATION

Note that the highest insulation values obtained to date for a sleeping system, ca. 8 clo (for the U.S. Army's Extreme Cold LINCLOE, sleeping system when used by a man sleeping in clean long underwear and socks with the insulated air mattress), can be extended by adding additional clothing items to achieve a 9 clo level. It was possible to approach a 10 clo level of sleeping system insulation when the most sensitive and heat loss prone areas of the body, i.e, the hands and feet, were provided with supplementary warm sleeping gloves and bootees. Conversely, much lower values of insulation were obtained when just the long underwear and socks were worn and the extreme cold LINCLOE sleeping bag was used on bare ground, without the insulated air mattress which is part of the sleeping system; on a bare cement floor, the insulation dropped from about 8 clo to less than 6 clo.

Almost all the measured values for sleeping bags were made with new, unlaundered bags. In one study (Mil Erg/ARIEM, E18-81), after a single laundering there was a loss of from 0.1 to 0.3 clo in the insulation of a small series of experimental cold weather bags whose insulation, on a foam pad, ranged from 6.33 to 7.77 clo before laundering; after three launderings insulation losses ranged up to 0.6 clo or about 10%. However, losses with continued use <u>without</u> cleaning are substantially higher.

RELATING INSULATION TO USER THERMAL COMFORT

All these measurements of sleeping system insulation have been obtained using a heated, copper manikin. It would be impossible to obtain such precise measurements of sleeping insulation using human subjects; the changes in human body heat storage have been used to estimate the insulation of a sleeping system, with 5-10% accuracy, when an appropriate test design was used. An appropriate test design requires low enough ambient temperature and long enough duration of exposure to accumulate a significant heat debt, but not enough to induce severe shivering.

Figure 2 presents the measured mean heat debt of human subjects resting/sleeping after three hours at -34 °C, as a function of sleeping bag insulation for 12 different sleeping systems. The correlation between the heat debt, as calculated from the change in each subject's mean body temperature ($T_b = (2\ T_{re} + T_s)/2$), and the sleeping bag insulation, as measured by a heated, copper manikin, was $r = -0.89$; this implies that 80% (i.e., r^2) of the body heat debt can be accounted for by the insulation of the sleeping system.

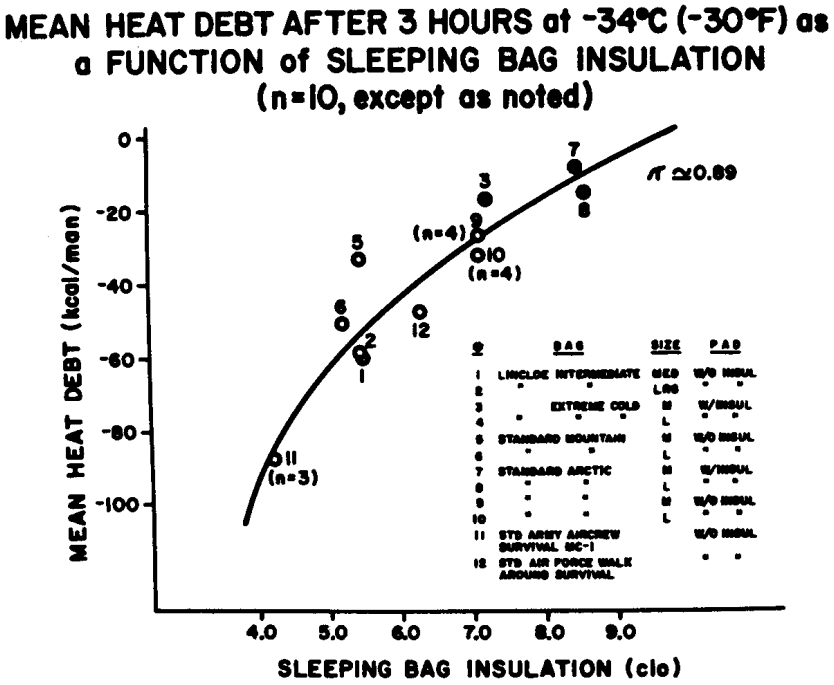


Fig 2. Mean heat debt after 3 hours at -34 °C (-30 °F) as a function of sleeping bag insulation (n=10, except as noted).

Note also that differences in the size of the bag used by the subjects generally produced very small changes between the insulation measured by the copper manikin, as well as very small differences in mean heat debt measured for this group of subjects. However, the surface area for heat loss in a sleeping bag is a function of the sleeping bag size, and the heat production of a smaller individual is lower than that of a large individual, so that a small individual in a sleeping system which is unnecessarily large, probably will not be as comfortable as when the proper size bag is used. This inference, derived from the physics of heat transfer and the physiology of heat production, appears to be validated by reports from the field that female troops using the standard, medium size, sleeping systems, found them much less comfortable than did their male counterparts.

INSULATION OF BLANKETS

Turning from field sleeping systems to the more typical situation using a blanket, in bed or on the ground, copper manikin evaluations have been conducted to determine the effective insulation (clo) value of these items. Results of these measurements, and the corresponding "comfort" temperatures, are summarized in Table II. The tabulated differences between the values in bed and the values on the ground, include the use of a manikin head cover for all on-ground measurements; clo values ranging from 0.3 to 0.9 clo units higher were obtained in bed when the manikin head was similarly covered. These higher values produced comfort temperatures up to 5 °C lower than indicated; the higher the insulation provided the body, the more important the heat lost from the uncovered head. This finding would not be unique to a heated, copper manikin, which has a controlled skin temperature, since a human exhibits little or no regulation of the heat lost from the head in the cold. Non-

evaporative heat loss from the head represents about 25 % of the total body non-evaporative heat loss at +20 °C, about 40% at 10 °C, 50% at 0 °C and 80% at –20 °C. Thus, protection of the head against heat loss should be a major focus for sleeping system design.

Table II

Insulation with Blankets and Predicted "Comfort" Temperatures

State	Insulation clo	Heat Loss kcal/m^{2}hr °C	Comfortable to
A. In bed			
sheets only	2.2	2.5	20 °C (68 °F)
one blanket	3.1	1.8	15 °C (59 °F)
two blankets	3.8	1.5	12 °C (53 °F)
three blankets	4.3	1.3	9 °C (48 °F)
B. On ground*			
one blanket	2.6	2.1	18 °C (64 °F)
two blankets	3.6	1.5	13 °C (55 °F)
three blankets	4.6	1.2	7 °C (45 °F)

*Manikin wrapped in blankets, with head covered; no ground cloth or sleeping pad.

CHAPTER 7a

PROTECTION OF HANDS AND FEET

L. Vanggaard

CONTENTS

SUMMARY

INTRODUCTION

HANDS AND FEET IN THERMOREGULATION

ERGONOMICS OF HAND FUNCTION

DESIGN PROBLEMS IN HANDWEAR

FUNCTIONAL (NON THERMAL) DEMANDS ON HANDWEAR

THERMAL CONSIDERATION IN HANDWEAR

TESTING OF HANDWEAR

ACCLIMATIZATION OF HANDS TO COLD

REFERENCES

SUMMARY

Local temperatures of hands and feet are limiting to man's ability to perform in severe cold. The arteriovenous anastomoses play an important role in the local thermoregulation of hands and feet. The design of handwear should mimic the physical characteristics of the hand, the palmar side reflecting the mechanical properties of the hand grip, while the dorsal side should allow for heat dissipation with the surroundings.

Testing procedures should refer the restraint of a given glove or mitten to the normal function of the hand.

Key Words: hand-foot protection, hand-foot thermoregulation, hand-foot blood flow, arteriovenous anastomoses, hand-foot cooling, hand ergonomics, handwear design, hand acclimatization, trenchfoot.

INTRODUCTION

In cold climate conditions, the thermal protection of hands and feet becomes of utmost importance. Hands and feet are essential in the general thermal regulation of the body. In the heat, the large surface of the hands and feet, plus arms and legs, plays a paramount role in ensuring a sufficient heat loss from the body. In cold, the body protects its deep temperature by diminishing the blood supply to hands and feet, thus minimizing the total heat loss. This protects the deep body temperature and thus is essential in survival, when man is threatened by a fall in deep body temperature. But this reflex also raises the problem of keeping hands and feet sufficiently warm in a cold surrounding. In cold, the local temperatures of hands and feet in resting man will thus depend on the local insulation, i.e., the hand- and footwear.

A low local temperature impairs the proper function of hands (arms) and feet (legs). If the temperature falls further, complete incapacitation may arise, and later cold injuries (non-freezing cold injury (trench-foot) and frostbite) occur. Besides these serious consequences of a lowered extremity temperature, the feeling of cold in hands and feet might lead to a degree of discomfort which may severely reduce the subject's motivation to carry out his tasks.

In most military campaigns in cold climate, cold injury has been a stronger adversary than the enemy. Trench foot and frostbite may constitute a very large number of the casualties, and as these lesions always occur among the frontline soldiers, their logistic importance cannot be overstressed.

The lesson learned in the trench warfare in WW I was forgotten in WW II, and in the Korean War the toll of cold injury again was large (7). In the recent campaign in the Falklands, cold injury contributed heavily to the casualty lists. The equipment, boots and gloves, have often been blamed, but it should be recognized that even the best foot-wear will not be able to keep a cold man's feet warm, nor will the best gloves keep his hands functioning.

Footwear and handwear function intimately together with the rest of the clothing. A man may develop incapacitating cold injury even at a normal body temperature if his local protection is insufficient, or (which is equally important) if he does not recognize and therefore does not react to the very feeble signs and symptoms of impending cold injury. Thus, even the best clothing does not give any insurance against cold injury.

To understand the problems of hand- and footwear, a basic understanding of the underlying thermophysiological principles is necessary.

HANDS AND FEET IN THERMOREGULATION

In human temperature regulation, hands and feet play almost the same role. The extremities constitute a significant part of the total body surface. This means that a large part of the heat exchange with the environment takes place here. Heat exchange from the body core can be seen as a heat flow from the deeper structures to the skin surface, from where it is given off to the surroundings. This can also be visualized as a cooling of the surface.

The heat transport within the body takes place either by simple (conductive) heat flow or transported by the blood (convective) heat flow. As the simple heat flow is determined only by temperature differences, and as these are fairly constant within the body, it is the convective

heat transport by the blood, from the deeper heat-producing tissues to the heart and then through the arteries to the skin, that forms the most important part in the regulated heat exchange with the environment. Thus, by increasing or decreasing the blood flow to the skin, the overall heat exchange is altered.

The only part of the skin where changes in blood flow have any capacity for major change in the heat loss from the body is at the extremities. Over the trunk and head, blood supply to the skin is fairly constant. This is easily demonstrated by the changes in temperature seen over areas where the subcutaneous fat is more abundant. Here the skin temperature is lower than over areas with less fat. When sweating, this becomes more evident. Due to the evaporation of sweat, the temperatures of these skin areas fall far below those of the more lean areas.

The changes in blood flow to the skin of the extremities are determined by the arteriovenous anastomoses (AVAs), which are small, artery-like vessels situated in the tips of the fingers and toes. These small vessels (with an internal diameter of around 30 to 60 microns) convey warm arterial blood from the arteries to the veins lying just under the skin of the hands, feet, arms and legs.

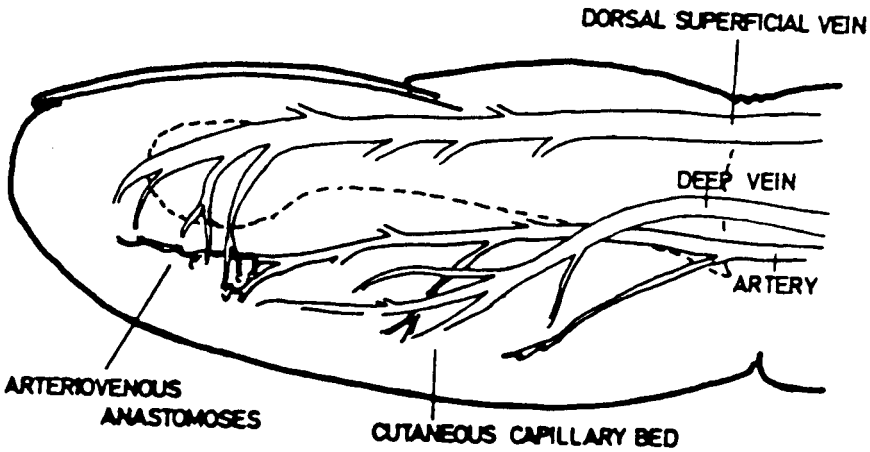


Figure 1. From the arteries of the finger, the returning venous blood either passes centrally from the nutritive capillary bed or passes through the arteriovenous anastomoses. Blood from the AVAs passes centrally through the superficial veins of the extremity, while blood from the nutritive capillary bed is conveyed mainly through the deep veins.

In the passage of blood backwards to the body, heat is given off to the surroundings. The arteriovenous anastomoses convey around 90% of the blood flow in the hands when this is at its highest.

The arteriovenous anastomoses (AVAs) are regulated from the thermoregulatory center in the brain (hypothalamus). They open and close on direct command from this center; their function is thus parallel in hands and feet. When the thermoregulatory center senses that the body is in positive heat balance, the center will order the AVAs to open, thus increasing the heat loss from the blood. This can be followed in the skin temperatures of the hands and

forearm (and in the feet). The local temperatures will rise. The highest temperatures of the extremities will then be at the fingertips and in the toes, where the AVAs are situated. Up along the forearms, the temperature will be higher around the superficial veins and fall centrally as the blood is cooled up along the arm.

In the warm person, the AVAs and superficial veins thus form an important heat exchange mechanism.

This mechanism could be described as a separate thermoregulatory organ. Its function is specific (control of heat dissipation), its localisation is well defined as it is only found in the acral parts of the extremities, it has a specific innervation (sympathetic cholinergic nerves govern the closure of the AVAs; histologically, AVAs are distinct from other vessels.

When a person is cold, that is, when the temperature regulating center senses a threatening fall in body temperature, the command to the AVAs is to close. This means that the hands (and feet) will give off more heat than they gain, and the local temperature will fall.

The fall in local temperature is so marked, that the fall in hand temperature after cold exposure (= "threatening body cooling") is the same as that seen after applying a tourniquet around the arm, thus abolishing all blood flow to the hand.

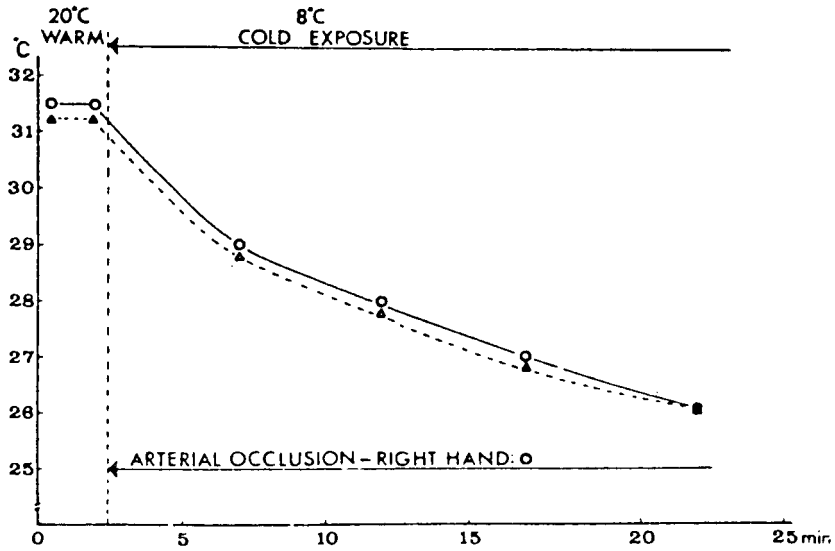


Figure 2. Temperature drop at dorsum of the hands during cold exposure. Right hand (○) was occluded by application of a blood pressure cuff maintained at 200 mm Hg from the onset of cold exposure. Left hand (▲) had an undisturbed blood supply (1).

The fall in hand (or foot) temperature upon general cooling cannot be avoided. It is due to the closure of the AVAs and the cessation in heat inflow from arterial blood. The rate of fall in hand temperature will depend upon the insulation around the hand (and the foot). With a good pair of gloves or boots, it might take a long time for the temperature to reach dangerously low levels. But it is essential for the understanding of the problems in hand- and footwear to realize that, in a cold man, it is only a matter of time before the temperature of hands and feet will reach low levels. Steady state is only to be reached when the temperature of hands and feet approaches that of the environment. Insulation of hands and feet thus merely introduces a time factor when we are dealing with cold exposed man. This can, of course, be counteracted by a voluntary increase in total heat production, as seen during muscular work. But it demands voluntarily increased heat production to keep the AVAs open, and thus the hands (and feet) warm. In a resting (but not sleeping) cold exposed man, this will not occur.

If one should give a modern definition of thermoneutrality in man, it is that situation where heat production and heat loss are equal and body temperature is constant when viewed over a period of time. This definition would imply that the arteriovenous anastomoses are open and the hands and fingers warm.

One could state that the body's thermal response is only fulfilled when hands and feet are warm (AVAs open). This is not to stretch matters too far; man's ability to live, produce and thus survive is more than anything else dependent upon whether he can maintain optimal function in his extremities.

This is even more evident in the animals, where proper and optimal function determines whether the captor can catch his prey, or whether the prey can escape its predator.

ERGONOMICS OF HAND FUNCTION

The hand is a unique instrument not equalled in any other species. The opposition of the thumb makes it into a powerful instrument for gripping and manipulating objects. The strength of the fingers and the hand depends on its muscles and tendons. These muscles are placed proximally in the forearm, so it tapers into the hand, thus providing minimal interference with the functioning of the hand itself.

The functioning of this extremely fine instrument is dependent upon the neuromuscular responses. On one side are tactile and proprioceptive sensors, and on the other side the motor innervation of the muscles. These neuromuscular functions are directly dependent on the local temperatures. With decreasing local temperature there is a linear decrease in nervous conduction velocity and neuromuscular transmission.

At a local temperature of 7 °C the motor and sensory nerves are completely blocked. At this temperature, the hand (or foot) will be without sensation ("sleeping sensation"), and the muscles will not convey any impulses; the hand is paralyzed.

This fact is of very high importance in the training of soldiers. In a cold climate, one must never accept numbness, as this implies that the local temperature is below 7 °C. From this point onwards there will not be any sensations that give warning of impending cold injury (2). This concurs with the observation that cold injuries such as trenchfoot or frostbite

very often are first recognized when function is impaired, which occurs much later than the tissue lesions.

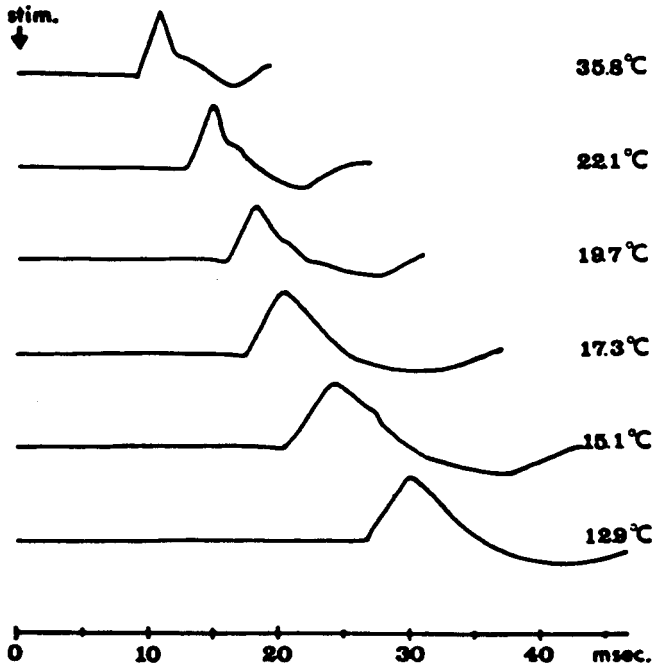


Figure 3. Oscilloscope tracings of the muscular action potential during cooling, showing the increased latency and the stretched appearance of the potential with decreasing temperatures.

DESIGN PROBLEMS IN HANDWEAR

As stated above, insulation of the hands tends both to minimize the heat loss from upper extremities and to keep the hands warm as long as possible when man is exposed to cooling. Both these functions demand insulation. On the other hand, insulation means bulkiness, as insulation in clothing always is due to a trapped air layer, and bulkiness is associated with impaired function. This controversy cannot be fully overcome in the design, but it is necessary to analyze the different functions a given handwear must fulfill.

Here much can be learned from an analysis of the functions in the hand itself. The different designs in handwear should imitate the hand itself. A glove is an extension of the skin, and much can be gained from studying how evolution has solved the problems. The hand's functions can be divided into two main groups. On one side, the hand is able to carry out very fine movements without hindrance. The skin is therefore very loose at the back of the fingers and the hands, and offers no resistance to bending. On the palmar side, the skin is tightly adhering to the underlying structures corresponding to the joint and to the palm itself. This ensures that when the hand is gripping an object, this is held in a tight and secure grip, as the skin cannot move. In addition to this, the fat pads in the fingertips and between the joints are of a nature that ensures that the forces originating from gripping an object are distributed to the largest possible area. The skin forms itself around the object. At the same

time the finer details of the skin surface consist of ridges and grooves which increase friction between skin and object. Furthermore, this effect is enhanced by the small ducts from the sweat glands which moisten the ridges and thus prevent an object sliding in the grip. This structure is most prominent at the fingertips. Sweat glands in the palm of the hand are especially active during psychological apprehension which might play a role. The sweat glands on the back of the hand are abundant. These sweat glands are especially activated in thermoregulatory sweating in contrast to the adrenergic (psychological) sweating in the palm of the hand. This is in concordance with the above mentioned role of the superficial veins in the extremities. Here the blood flow is large when the subject is in positive heat balance and, due to the high flow of warm "arterial" blood, the heat dissipation from the back of the hand, with its large surface, is important in the regulation of the body temperature.

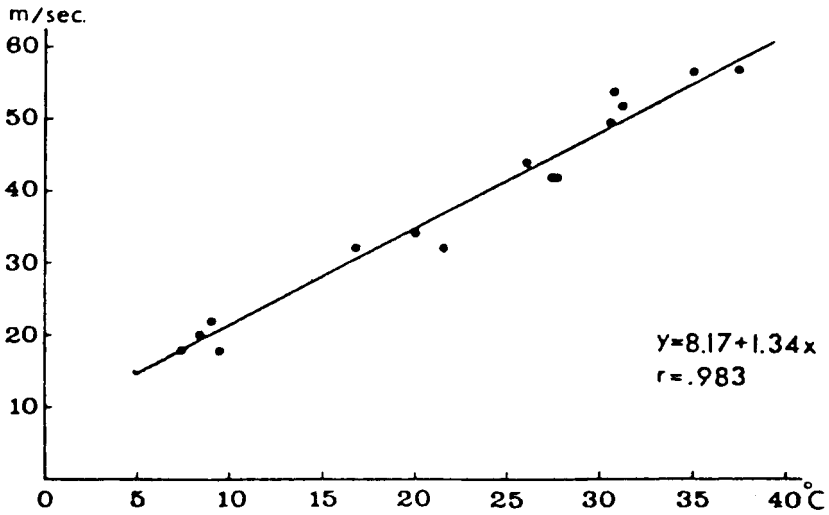


Figure 4. Conduction velocity of the ulnar nerve at different nerve temperatures.

This can be seen in the construction of some pilot's gloves where the palmar side of the gloves consists of thin leather, imitating the skin of the palm, whereas the back is of a light woven material that allows sweating to take place. A similar construction is seen in gloves especially made for automobile drivers.

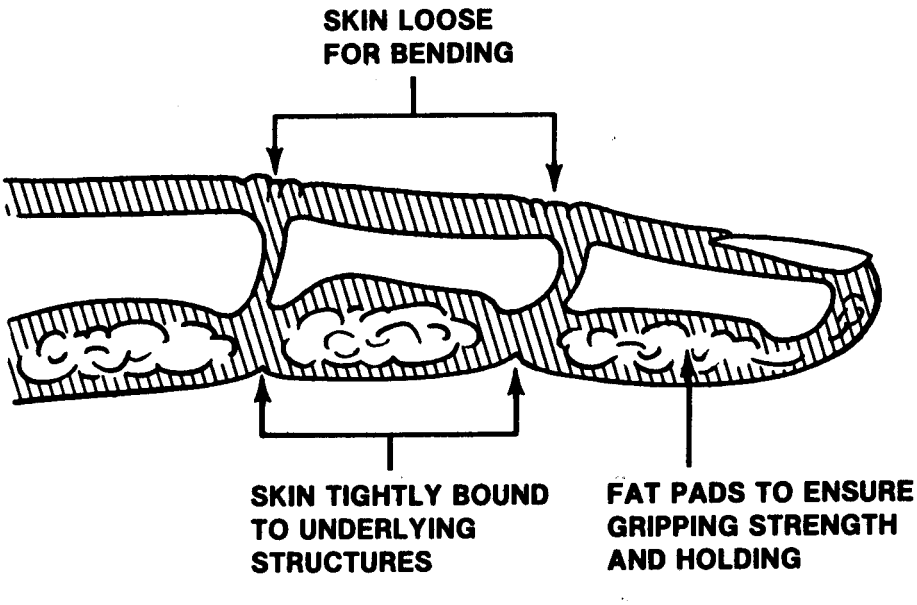


Figure 5. The details of the ergonomics of a finger.

FUNCTIONAL (NON THERMAL) DEMANDS OF HANDWEAR

The glove or mitten should be designed in accordance with the ergonomic requirements of the wearer and the job. In cold climates, this may mean that the glove has to be divided into a thermal protective outer-glove combined with an inner glove. For work in extreme cold, the inner glove might consist of an anti-contact glove to prevent the moisture on the skin from freezing to cold objects, which might give rise to serious skin abrasions.

Design criteria: (These might not all be met, and in many cases a compromise has to be found.)

The palmar side of the handwear:

1. The material of the glove should function in close contact with the skin. It should to the least degree hamper the tactile information to be transmitted to the touch sensors of the skin. Special attention should be given to the fingertips of the glove.
2. The design should be such that the glove fits, in order to ensure a good grip on objects relevant to the job to be performed by the wearer.
3. The glove should have a form that corresponds to the "normal" position of the fingers in the relaxed hand. This is especially important for cold weather gloves, where a bad fitting glove might give rise to "cold spots", i.e., areas where the glove constricts and thus interferes with the normal blood supply to the finger.

The dorsal side of handwear:

1. If the palmar side of a glove is impermeable to water vapour, the dorsal side should have good water vapour transmitting qualities.
2. In extreme cold weather, a soft (fiber pile) material should be placed at the dorsal side of gloves and mittens to relieve the wearer of the problems of a "running nose". (In cold weather, water vapour from the exhaled air will condense in the front of the nasal cavity and drip off the nose.).

Other aspects

The handwear should be constructed in such a way that it fits the other parts of the clothing system. A glove should have a sleeve that fits with the jacket, and which does not leave a part of the wrist naked when the wearer moves his hand.

When insulation is added to a glove, the bulkiness of the glove or mitten should be at the back, while the palmar side should be soft, thin and flexible. In cold, man will clench his fist in order to present as small a surface to the surroundings as possible. In this situation, the insulation built into the back of the hand will help protect him.

String through the arms of the jacket will prevent the loss of gloves in an arctic environment, where loss could be fatal.

THERMAL CONSIDERATIONS IN HANDWEAR

The most comprehensive and still highly relevant monograph on protection and functioning of the hands in cold is given in Fisher (2).

It has been stated above that, when threatened with cold, the body reacts with a drastic reduction of blood, and thus heat inflow to the hands. In this situation, the problem in hand protection is to preserve the heat contained in the hand, its muscles and nerves, for as long as possible. Function will decline linearly with local temperature (1).

Man "threatened by cold" means a person whose heat loss is greater than the heat production. In the arctic, even at very low temperatures, man is very often faced with a situation where he is "overprotected" by his arctic clothing system. He is very often actually threatened by a high heat storage, which leads to sweating and warm hands. In this situation, heat might be given off from the hands. This can be accomplished by simply removing the handwear. If this is not done, sweat will accumulate in the gloves, a situation which first becomes dangerous when he, at a later time, might come into negative heat balance where the blood supply to the hand will be shut off and the local temperature will fall. The moisture in the handwear will seriously reduce the insulation and the temperature will drop to a level where the danger of freezing injury is imminent.

At temperatures far below freezing, there is a need for an anti-contact glove that will prevent the bare skin from freezing to cold surfaces. This glove is thin and has itself little insulative value, but is a necessity for finer manual tasks.

The time that man can work with unprotected fingers in cold is given by Molnar et al (4).

When exposing hands (and feet) to a cold environment, the effects of the so called CIVD (Cold Induced VasoDilatation) should be mentioned. This effect is the sudden opening of blood vessels (AVAs) in hands and feet when exposed to a cold environment. This effect, however, can only be elicited in a comfortably "warm" man, never in a cold-threatened person.

A cold weather hand wear presents the designer with two conflicting interests. On one side, thermal protection means that the glove should present as small an area to the surrounding as possible - on the other side, hand functioning demands that the hand and the fingers can be used effectively, which inevitably will lead to a design with a large surface.

This is reflected in the most used types of arctic handwear. Here the mittens ("two-finger" glove) give the best protection. As the demand for better manual function is increased, the number of fingers in the mitten is increased; a three-finger mitten is the most used alternative. It is interesting that the Eskimos also used a three-finger mitten, but this was based upon a mitten that had two thumbs, giving a possibility for using the mittens on either hand. This design has seldom been tried in modern mittens. Modern three-finger mittens give accomodation for the first and second finger separately, while the third, fourth, and fifth finger are shielded by a common insulation.

The five finger glove presents its own problems. It is a well established fact that small diameter cylinders cannot gain a higher degree of thermal protection by increasing insulation (10), due to the accompanying increasing surface area.

An optimally designed glove is expensive in protection, but it should not be forgotten that the harsh reality is that man does not function at all if he cannot keep a reasonably high local temperature in hands (and in feet).

As stated above, all protection of hands and feet involves a time factor. The handwear extends the time man can function, but ultimately the hands have to be rewarmed. This can be done by voluntary work or by passive rewarming. Passive rewarming is done when hands are being heated not by an increase in blood flow, but by being placed in a warm environment. In arctic clothing such a shielded warm environment can be made available by proper design of pockets that allow hands easy access to the warmer environment inside the clothing assembly. Such pockets should have a good insulation against the outside, and a poorer one against the inside. In really cold conditions, the body is the only available heat source.

TESTING OF HANDWEAR

As optimal manual functioning is the aim of clothing design, the evaluation and testing of different gloves is highly relevant.

Several methods have been designed for the testing of manual tactility, dexterity, and strength. Many of these methods are meant for the testing of the bare hand, but can easily be redesigned to serve the testing of gloves.

A relevant way to present the results of such testing is by quantifying the difference between the bare hand at normal temperatures and the hand wearing the handwear to be tested (5.2).

ACCLIMATIZATION OF HANDS TO COLD.

It is a generally observed fact that people who habitually are exposed to cold climates, like fishermen, cold stores workers, etc., seem to adapt themselves to a cold environment. This is, for instance, demonstrated in their ability to sustain lower extremity temperatures than newcomers to an arctic environment (6). But this "adaptation" is more a psychological than a physiological adaptation. Hellstrom (8) investigated possible signs of physiological changes in hand/finger blood flow in workers in the fishing industry and found no sign of changes in this group compared with non-exposed controls.

Vanggaard (9) found in exposure trials in Danish military personnel in Greenland that, during the night, temperature of seasoned troops' feet fell at the same rate as newcomers. But in seasoned troops this fall in local temperature did not wake them from sleep, whereas newcomers woke up when temperatures reached around 10 °C. Local temperatures tended to stabilize at this temperature, which was the temperature of the air inside the sleeping bags.

There is only scanty evidence of man's ability physiologically to adapt to cold. Thus, physiological adaptation of hands and feet is not likely to occur as the function is temperature dependent, placing importance on the insulation of hands and feet. To a certain degree, man may learn psychologically to accept a higher degree of cooling of the hands, but this should not be confused with adaptation.

REFERENCES

1. Vanggaard, L. Physiological reactions to wet-cold. Aviation, Space, and Environmental Medicine. 46(1):33-36, 1975.

2. Fisher, F.R. Protection and functioning of the hands in cold climates. National Academy of Sciences - National Research Council. Washington, 1957.

3. Goldman, R.F. The arctic soldier: possible research solutions for his protection. Science in Alaska-1964, G. Dahlgren, ed. Alaska Division, American Association for the Advancement of Science, March 1965.

4. Molnar, G.W., A.L. Hughes, O. Wilson and R.F. Goldman. Effect of skin wetting on finger cooling and freezing. J. Applied Physiology, 35:205-207, 1973.

5. Sperlin, L., N. Jonsson, I. Holmer, and T. Lewin. Test program for arbetshandskar. Arbetarskyddsstyrelsen, Stockholm, 1980.

6. Burton, A.C. and O.G. Edholm. Man in a Cold Environment. Edward Arnold, London, 1956.

7. Coates, J.B. and E.M. McFetridge. U.S. Army in WW II. Cold injuries, ground type. Office of the Surgeon General, Dept. of the Army, Washington, D.C., 1958.

8. Hellstrom, B. Local effects of acclimatization to cold in man. Universitetsforlaget, Oslo, 1965.

9. Vanggaard, L. Unpublished data.

10. VanDilla, M., R. Day and P.A. Siple. Special problems of hands. Physiology of Heat Regulation and the Science of Clothing, L.H. Newburgh, ed. W.B. Saunders Co., Philadelphia, PA., 1946.

CHAPTER 7b

FOOTWEAR AND BLISTER INCIDENCE

D. Cooper

CONTENTS

SUMMARY

INTRODUCTION

GAPS IN KNOWLEDGE

PREVENTIVE MEASURES

FIELD OBSERVATIONS

REFERENCES

SUMMARY

The biomechanical aspects of combat footwear are discussed with particular emphasis on the familiar problem of foot blisters. Progress of studies to determine the cause of foot blistering are reported.

Key Words: blisters, combat boots, boot ergonomics, march injuries.

INTRODUCTION

Technology, during this century, has brought the quality of life to an unprecedented high level which is perhaps most evident from the attention given to such consumer interests as recreational activities to achieve more meaningful leisure, and to raise the level of individual physical health and social morale. In the work-place, technology to improve conditions of personal health, safety and overall efficiency is a universally high priority for industrial management. In turn the demand which this type of social progress creates, is seen to be met by the respective consumer industries in their increasing attention to designing their products to specific functional requirements. For the purpose of this paper, the chosen example is in the field of footwear where national safety standards exist for protecting against all hazardous operations, and industrial accident legislation ensures that management carries out its obligations to that end. The military user would appear to be at least as well catered for as his civilian counterpart from the point of view of the quality of the manufactured item; indeed, the combat boot of the day surpasses any civilian equivalent industrial version since its engineering is directed entirely by criteria of military performance requirements. Notwithstanding such excellence of the product in meeting the stresses and strains of battle, the infantry soldier still falls victim to his equipment through foot blisters causing serious impairment of his mobility and operational effectiveness, both in carrying out his assigned mission and in surviving after it.

GAPS IN KNOWLEDGE

Only a few predisposing factors have been studied which are linked to blister formation. Some of those involve moisture buildup and shearing forces.

There are numerous accounts of infantry exercises in which foot blister problems of a disabling severity, commonly affecting between 10 and 30 percent of participants, are available (Stokes 7). Such records date back to 1895 and refer to UK forces. The account given for 1895 is of particular interest for those who hold the view that before armies were mechanized to the degree which is normal today, soldiers did not suffer blistered feet. On that occasion, 824 cases of blistered feet were recorded.

In 1976, the US (Bensel 11) in a report by the U.S. Army Natick Laboratories states that 73 percent of all treated cases for foot disorders in peace time were for blisters.

PREVENTIVE MEASURES

Recourse to so called preventive measures against blisters varies from hardening the skin to interposing a nylon stocking between the foot and the army sock. A reduction in foot moisture on the one hand and reduced friction on the other are also variants within the general belief and practice in blister prevention. The latter, involving dusting the feet with a dessicant (foot powder), produces the reverse effect by introducing an abrasive third agent once the dessicant has solidified in combination with sweat salination (Allan 9, Comaish 12). Similarly the use of potassium alum as an astringent to reduce sweat secretion may be associated with a potential secondary complication in hyperhidrotic cases where sweating provides the necessary vehicle for discharging waste products. Potassium permanganate (a

powerful oxidising agent) has been used in dermatology for many years and has been used sporadically to 'toughen' soldiers' feet. Used experimentally, at a higher than normal concentration, laboratory tests were able to discriminate between treated versus untreated cases but the results favouring the treated cases were not significant (Comaish 12). Dermatologists have employed glutaraldehyde over a number of years as an antiperspirant and this prompted its inclusion in the series of laboratory tests. From these tests, it is likely that a reduction in the incidence of blisters may be possible by an application of 5-10 percent glutaraldehyde in a 10 percent aqueous solution with 1.65 percent sodium bicarbonate 24 hours before marching. Over a prolonged period, retreatment at 2 or 3 day intervals would provide a continuing protection (Comaish 12).

FIELD STUDIES

In Canada in 1977 a study was made of the problem of blisters, their frequency of occurrence and location, using a march of 35 miles as the established test march for candidates undergoing commissioning training. The conditions for the march were ideal, a night march in July in Gagetown, New Brunswick with each man carrying his rifle and water bottle. All men wore the same order of combat dress (summer weight) and the combat boots were the men's own (not specially issued). Of a total of 110 men, 90 were measured to compare the foot size with the size of boot being worn both before and after marching. Where discrepancies in size of boot worn was found, this was recorded only; no boots were exchanged.

Blisters to the heel region of the foot were the most frequently observed (58 percent), with those at the tips of the toes next (23 percent) and the remainder (19 percent) distributed at the outer edge of the mid-foot region. The size in length of each individual's worn boots when checked against his initial foot length measurements showed that 21 of the 30 blister cases were correctly fitted to within an error of $\pm$ 3.0 mm and 9 were incorrectly fitted to within an error of greater than $\pm$ 3.0 mm. For the remaining 40 individuals who did not develop blisters, 34 were correctly fitted to within an error of $\pm$ 3.0 mm and 6 were incorrectly fitted to within an error greater that $\pm$ 3.0 mm. The correctness or otherwise of the fit of boots in width and girth at the joint, once they are well worn, is less accurately determined; however, all subjects appeared to be either satisfactorily or slightly generously fitted in width.

In regard to whether or not the foot changes in its dimensions or shape as a result of stress when marching, this survey indicated that at the maximum circumference of the foot, measured at its widest point, both before and after marching, the range in variation for 70 out of the 90 soldiers surveyed was $\pm$ 9.0 mm with 49 percent in the plus group, 28 percent in the minus group and 23 percent who showed no change. Unfortunately, this statistic could not be obtained for the remaining 20 men due to the exigencies of the course itself, which prevented a correlation to be made with the blister and non-blister groups.

For data on service women's foot health problems, there has yet to be a comparable study to that for men made in Canada. A report was recently distributed from the US on recruits' foot disorders during basic training which contains a reference to women's foot problems far exceeding (in number) those for men. Moreover, on reception, women recruits display a lower standard of foot health than their male counterparts (Bensel and Kish 14).

Physical conditioning within the military is associated with many other types of lower extremity disorders peculiar to the program of training, which has undergone drastic changes since the mid 1970s. Trainees in particular are currently susceptible to unusually prolonged periods of aerobic development activities in which running, on paved surfaces, is responsible for most injuries excluding ankle and knee sprains of the game playing variety. The more common of these involve the load stress receptors of the leg and foot and their articulations. Such medically related losses in training person-hours might conceivably present a strong challenge to the long established theory that combat troops should always train outdoors in their combat boots.

To summarize the problems thus far:

a. In the advancing of military footwear design engineering since World War II, the problem of protection against functional foot disorder remains unsolved.

b. Correctness-of-fit tolerance of high activity footwear such as combat boots, by either actual foot measurement or subjective preference does not ensure freedom from blister and similar lesions. To date all practical results are obtained with footwear sized to the Imperial (English) system as distinct from the current Mondopoint (metric) system.

c. No conclusive evidence exists that a particular anatomical classification of foot type is either more or less prone to develop lesions.

d. Further work is required to complete the study to the point of making recommendations likely to seriously impact upon the design engineering of operational army footwear.

REFERENCES

1. WHITTINGHAM P.G.V. Exercise Orthopod I. Effects of marching in flying boots. RAF Institute of Aviation Medicine (UK) FPRC Report 729, December 1949.

2. WHITTINGHAM, P.G.V. Exercise Orthopod II. Effects of marching in flying boots. RAF Institute of Aviation Medicine (UK) FPRC Report 751, January 1951.

3. HUDSON, G. An investigation into the problem of foot casualties in the army. Army Operational Research Group Report No. 9/54, 1954.

4. NAYLOR, P.F.D. The skin surface and friction. Brit. J. Derm. 67: 239-248, 1955.

5. NAYLOR, P.F.D. Experimental friction blisters. Brit. J. Derm. 67: 327-342, 1955.

6. STOKES, A.W. Trials of Boots, Ankle, Improved General Service (I.G.S.) and Boots, Ankle, Direct Moulded Sole (D.M.S.). Ministry of Supply, Directorate of Physiological and Biological Research Clothing and Stores Experimental Establishment Report No. 64, 1956.

7. STOKES, A.W. Military footwear and the occurrence of foot blisters. 8th Commonwealth Defence Conference on Clothing and General Stores, Paper U.K. 6, 1965.

8. QUINN, J. The effects of two new foot powders on the incidence of foot infection and blisters in recruits during basic training. Army Personnel Research Establishment Research Memorandum P/6, 1964.

9. ALLAN, J.R. A study of foot blisters. Army Operational Research Establishment, Research Memorandum 1/64, 1964.

10. ALLAN, J.R. and A.L. MacMILLAN, The immediate effects of heat on unacclimatised paratroops (Exercise Tiger Brew II), (Physiological and Medical Findings). Army Operational Research Establishment, Research Memorandum, 16/62, 1962.

11. BENSEL, C.K. The effects of tropical and leather combat boots on lower extremity disorders among US Marine Corps recruits. Report No. CEMEL 154, 1976.

12. COMAISH, J.S. The study of friction blisters in man (undated).

13. COOPER, D.S. Research into foot lesions among Canadian field forces. 13th Commonwealth Defence Conference on Operational Clothing and Combat Equipment, Paper CDA II, 1981.

14. BENSEL, C.K. and R.N. KISH. Lower extremity disorders among men and women in army basic training and effects of two types of boots, 1983.

CHAPTER 8

IMMERSION SUITS

L. Vanggaard

CONTENTS

SUMMARY

INTRODUCTION

THERMAL DEMANDS OF IMMERSION SUITS

TYPES OF IMMERSION SUITS

REQUIRED INSULATION

WATERTIGHTNESS

SIZING

ERGONOMIC DESIGN CRITERIA

COMPATIBILITY WITH FLOTATION AIDS

TESTING PROCEDURES

REFERENCES

SUMMARY

The Eskimos knew of the importance of protection against immersion in cold water. The first immersion suits date back to the 15th century. The SOLAS conventions describe the thermal and technical demands for an immersion suit.

Water ingression greatly reduces the insulative capabilities of an immersion suit. Ergonomic design criteria are discussed. The compatibility with other flotation aids is of special importance. Testing procedures have been established for immersion suits, but those based upon the SOLAS resolutions should be changed as they may lead to erroneous evaluation results.

Key Words: immersion suit insulation, immersion suit leakage, immersion suit testing, immersion suit evaluation.

INTRODUCTION

The role of immersion suits is to protect the wearer against cooling during water immersion. Different principles have been used to accomplish this protection. Passive suits are either based upon maintaining an insulative layer of still air around the body as in the dry-suits, or an insulating air trapped within the fabric of a closed cell foam. In "active" suits, the thermal protection is due to a combination of insulation in the suit and auxiliary heating. In this article, only the dry suits and their properties will be dealt with. For survival use, most immersion suits are based upon the "dry" principle. In diving suits, the tendency has been to adopt the wet suits, which have many advantages as long as the water pressure does not influence the insulating properties of the closed-cell foam.

Immersion suits have been used since early times by the Eskimos, who used a so-called "spring-pels" which consisted of sealskin or seal gut stitched together, forming a complete covering, only opening up at the hands and the face. The wearer entered the suit by an opening on the front side. The suit could be inflated to increase insulation and to improve the buoyancy of the wearer when in water. The suit was used when hunting whales, and gave a completely waterproof protection. These suits were known as far back as the 16-17th century. The suits worn by the Eskimos when sailing in their kayaks were very similar, offering the hunter full protection (1).

Figure 1. Eskimos "spring-pels" used for whale hunting.

The modern concept of immersion suits dates back to WW II, when it was first realized that cold, not drowning, was the essential threat to survival when man was accidentally immersed in cold water while wearing a life-jacket.

In the last decade, the IMO (The International Maritime Organization) has advocated the use of immersion- or survival suits, and in the 1983 Amendments to the International Convention for the Safety of Life at Sea- 1974 (SOLAS) (2) are defined the specifications which shall apply to ships after July 1986. The convention deals with merchant ships but the safety demands of naval ships, and of aircrews operating over open water, are similar and most navies operating in cold waters have introduced immersion suits. Some of these suits are of the type called "quick-don" survival suits, i.e., watertight suits which only offer the wearer protection against immersion, but do not have any intrinsic insulating capacity. The thermal protection of the wearer is thus dependent upon the clothing worn under the suit. Such suits can be packed relatively compact, in order not to interfere with the user's other duties until the moment where he is to don the suit. The insulating immersion suit is bulky, most types have to be individually sized, and demand much room for storage, a problem difficult to overcome in warships.

THERMAL DEMANDS OF IMMERSION SUITS

The above mentioned SOLAS convention in its Chapter III (Regulation 34) gives the requirements for immersion suits. These requirements apply to insulated as well as uninsulated immersion suits. Although given in a civilian context, they are equally applicable to other situations where protection against cold water immersion is essential.

Regulation 33

Immersion suits

1 General requirements for immersion suits

1.1 The immersion suit shall be constructed with waterproof materials such that:

.1 it can be unpacked and donned without assistance within 2 min, taking into account any associated clothing*, and a life jacket if the immersion suit is to be worn in conjunction with a life jacket;

.2 it will not sustain burning or continue melting after being totally enveloped in a fire for a period of 2 s;

.3 it will cover the whole body with the exception of the face. Hands shall also be covered unless permanently attached gloves are provided;

.4 it is provided with arrangements to minimize or reduce free air in the legs of the suit;

---

*Reference is made to paragraph 3.1.3.1 of the "Recommendation on testing of life-saving appliances" to be submitted to the Assembly of the Organization at its thirteenth session for adoption.

.5 following a jump from a height not less than 4.5 m into the water there is no undue ingress of water into the suit.

1.2 An immersion suit which also complies with the requirements of regulation 32 may be classified as a lifejacket.

1.3 An immersion suit shall permit the person wearing it, and also wearing a lifejacket if the immersion suit is to be worn in conjunction with a lifejacket, to:

.1 climb up and down a vertical ladder at least 5 m in length;

.2 perform normal duties during abandonment;

.3 jump from a height of not less than 4.5 m into the water without damaging or dislodging the immersion suit, or being injured; and

.4 swim a short distance through the water and board a survival craft.

1.4 An immersion suit which has buoyancy and is designed to be worn without a lifejacket shall be fitted with a light complying with the requirements of regulation 32.3 and the whistle prescribed by regulation 32.1.6.

Chapter III- Reg. 34

1.5 If the immersion suit is to be worn in conjunction with a lifejacket, the lifejacket shall be worn over the immersion suit. A person wearing such an immersion suit shall be able to don a lifejacket without assistance.

2 <u>Thermal performance requirements for immersion suits</u>

2.1 An immersion suit made of material which has no inherent insulation shall be:

.1 marked with instructions that it must be worn in conjunction with warm clothing;

.2 so constructed that, when worn in conjunction with warm clothing, and with a lifejacket if the immersion suit is to be worn with a lifejacket, the immersion suit continues to provide sufficient thermal protection, following one jump by the wearer into the water from a height of 4.5 m, to ensure that when it is worn for a period of 1 h in calm circulating water at a temperature of 5 °C, the wearer's body core temperature does not fall more than 2 °C.

2.2 An immersion suit made of material with inherent insulation, when worn either on its own or with a lifejacket, if the immersion suit is to be worn in conjunction with a lifejacket, shall provide the wearer with sufficient thermal insulation, following one jump into the water from a height of 4.5 m to ensure that the wearer's body core temperature does not fall more than 2 °C after a period of 6 h immersion in calm circulating water at a temperature of between 0 °C and 2 °C.

2.3 The immersion suit shall permit the person wearing it with hands covered to pick up a pencil and write after being immersed in water at 5 °C for a period of 1 h.

3 Buoyancy requirements

A person in fresh water wearing either an immersion suit complying with the requirements of regulation 32, or an immersion suit with a lifejacket, shall be able to turn from a face-down to a face-up position in not more than 5s.

Although immersion suits have much in common with divers suits, and many of the physiological parameters of the immersion suit also apply to diving suits, the main difference is that most immersion suits, when not individually sized, will be bulky and not constructed to allow the wearer the freedom of the diving suit.

TYPES OF IMMERSION SUITS

The general concept of the immersion suit is given by the SOLAS definition: "A protective suit which reduces the body heat loss of a person wearing it in cold water". The way this is accomplished might vary from one design to another. The basic considerations to be covered are:

1. Required insulation.
2. Minimum water ingress into the suit.
   a. due to leakage through the fabric and seams.
   b. due to ineffective closure at openings.
3. Sizing. One size that fits all or different sizes.
4. Ergonomic design to fulfill the functional requirements.
5. Compatibility with flotation aids.
6. Testing procedures.

REQUIRED INSULATION

The basic equation for man's heat exchange with the environment applies for immersed man:

$$C = \frac{H}{(T_s - T_w) \cdot A} \qquad W \cdot m^{-2} \cdot °C^{-1}$$

Where C = Conductance of clothing system.

H = Heat production (watts).

T_s = Temperature of the skin (°C)

T_w = Temperature of the water (°C).

A = Body surface (m^2).

The insulation (I) is given by the reciprocal of the conductance.

Allan (3) has calculated the time to cool the deep body temperature to 34 °C for a thin individual.

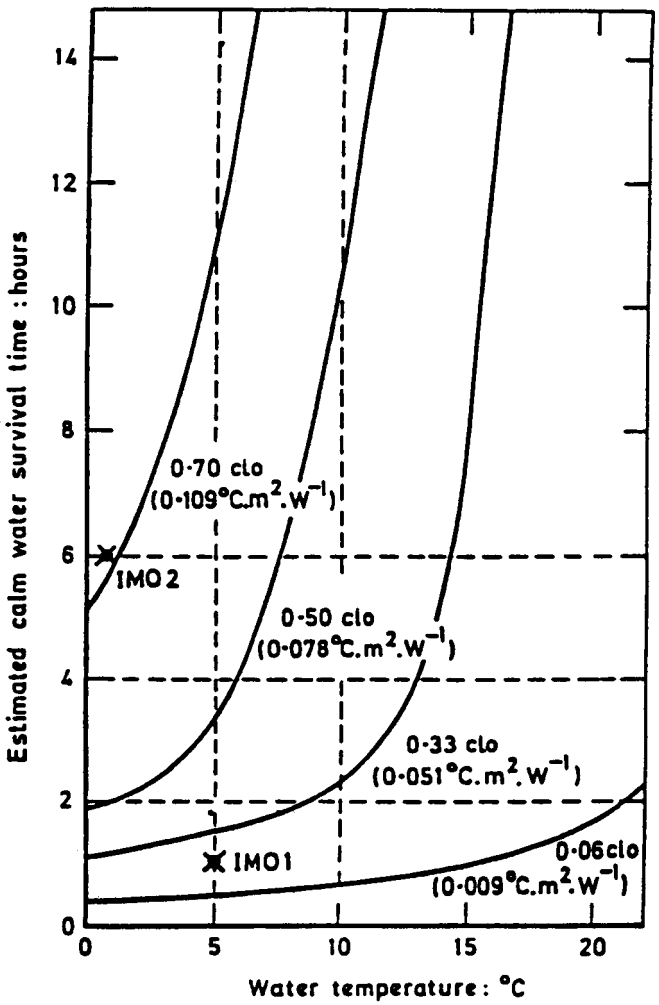


Fig. 2 Model estimates of time to cool to a deep body temperature (arterial) of 34 °C for 10th percentile thin individuals (mean weighted skinfold thickness 6.7 mm, body weight 66.6 kg) plotted against water temperature. The four lines represent four levels of immersed clothing insulation. IMO 1 is the design point equivalent to the IMO specifications for uninsulated suits. IMO 2 is the design point equivalent to the IMO specification for insulated immersion suits. (2).

It should however be noted that the requirements for maintaining a sufficiently high body temperature not only apply to the deep body temperature, but also to the temperature of hands and feet. According to the SOLAS convention, no local temperature should drop below 15 °C during the described conditions. This is a criterion which cannot be met if the testing of a suit is carried out in realistic low temperatures. At very low water temperatures, the local temperatures of hands and feet will fall close to that of the water, and although unpleasant and in cases limiting to the time of endurance tolerated at evaluation procedures, this will not influence the survival time in a given suit. However, low extremity temperatures indicate that the person is in a situation where his manual dexterity might be seriously impaired, and insulating gloves should always be included in an immersion suit.

WATERTIGHTNESS

Water might enter the suit, either due to leakage through the material, for instance due to faulty production, or to wear due to storage or use (4), or due to water ingress through the opening in the suit, when the wearer enters the water (jumping into the water) or by the action of waves or swimming.

The effect of water ingress upon the total insulation of a suit has been evaluated by Hall & Polte (5) and Allan (5,10).

The recommended amount of acceptable water ingress has been set to 200 ml after an initial jump from 4.5 m and a further 200 ml after 20 minutes of slow back-swimming (Allan (5).

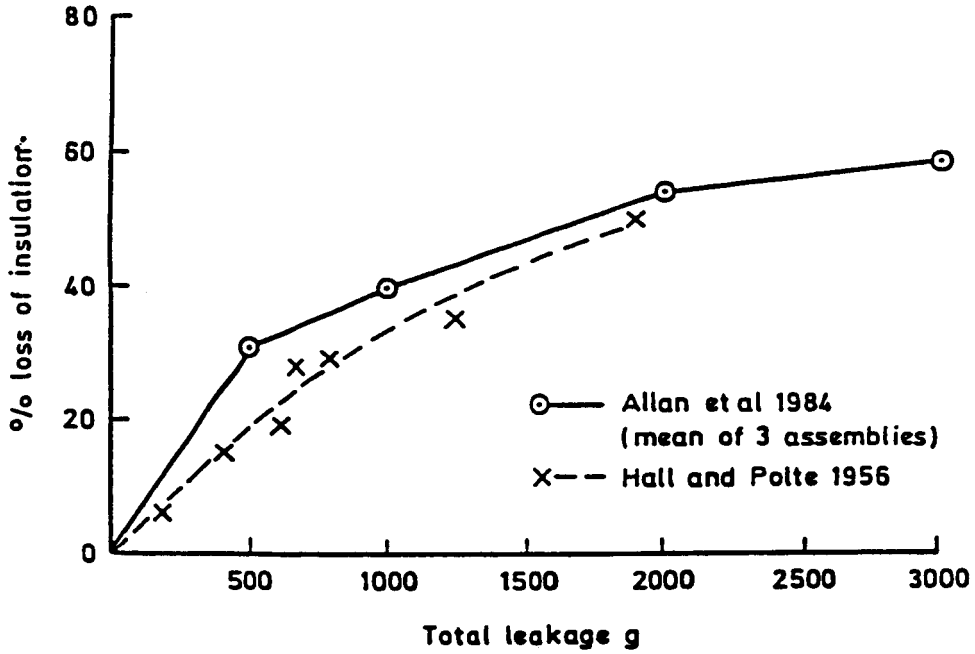


Fig. 3. Percent loss of insulation plotted against leakage.

As water ingression thus highly affects the thermal characteristics of an immersion suit, any functional testing of a suit should include a realistic way of imitating the situation of a survivor in open water (see below).

SIZING

As immersion suits are designed to be used in emergency situations, where time is limited, and where no proper sizing can be carried out, the requirements are that an immersion suit should suit any wearer. This is not possible in every case, as even within the normal range of human stature large differences exist. This creates great design problems, and no practical solution has yet been given. A suit which is too large for the wearer will be very bulky and thus contain a large amount of air. The air content of a suit does increase the insulation of the suit, but it also influences buoyancy of the suit, which might lead to a

situation where the wearer cannot maintain the upright position in the water and thus runs the risk of drowning, when not being able to keep the face above water (see later). Another problem arising from sizing is that a small person in a large suit, when jumping into the water, might be displaced within the suit. Even in individually designed suits, the wearer often will "disappear" into the suit when hitting the water. This situation will give rise to water ingress and thus diminish the thermal protection.

ERGONOMIC DESIGN CRITERIA

The SOLAS convention regulations givecertain design criteria that should be fulfilled. These have partly been described above. The demand for quick-donning without help interferes with the demand for the insulation of the hands. If gloves are part of the suit, this simplifies the problem of watertightness and donning but interferes with the demand that the wearer should be able to perform even simple manual tasks.

The most difficult problem in the design of immersion suits is to ensure a watertight sealing at the neck and around the face.

Certain types of immersion suits are not designed to meet the problems of an emergency, but are working suits for personnel that have to carry out work which might result in accidental water immersion. These suits will have to meet the requirements peculiar to the work they are designed for. The insulation in such suits is normally only due to the insulation inherent in the clothing worn under the suit.

COMPATIBILITY WITH FLOTATION AIDS

An immersion suit protects against cold water immersion. Most of the suits produced today will give ample protection against even very cold water, which then leaves the problem of the protection against drowning as the major concern. As the thermal protection in immersion is due to the amount of trapped air inside the suit, this air will influence the buoyancy of the suit. Most suits are designed to be used in connection with life-vests or life-jackets, but the characteristics of the flotation aid may be severely hampered or even counteracted by the buoyancy inherent in the immersion suit.

The SOLAS regulations concerning the life-vests demand that these should have a self-righting effect within 5 seconds on floating man, in order to ensure that the airways of even an unconscious subject are kept above water level. The freeboard is defined as 120 mm, and the position in the water of the body of an unconscious person as inclined backwards at an angle of not less than 20 degrees and not more than 50 degrees from the vertical position (SOLAS, Chapt. III, Reg. No 32).

The immersion suit in itself has the flotation inbuilt but, even so, most existing immersion suits will not allow the wearer to maintain the position described in the convention. The demand for insulation of the feet is almost incompatible with the buoyancy requirements.

It might be discussed, whether an immersion suit should give the wearer the same position in water as that required by a life-vest without a suit. The air within the suit will give the wearer a near-horizontal floating position, high in the water. In this position, the survivor may have the advantage of being able to steer himself with the feet against the incoming

waves, thus making them break before they reach his face (7). Golden (8) has demonstrated the risks of drowning of man when only wearing a life-vest. After the passage of just two medium sized waves, the face of the survivor will be turned against the incoming sea. Cold water in the face gives rise to a reflex causing unavoidable inspiration, which in unprepared and untrained persons might lead to sudden inhalation of seawater, resulting in uncontrollable coughing and drowning.

The position of the survivor wearing an immersion suit can counteract this by the wavebreaking effect of the high floating legs.

Whether the survival value of an immersion suit might benefit from the use of a sprayshield to protect the face from the cooling and drowning effect of the water should be considered (Golden 8).

A negative effect of the high floating position in water is that, in nearly all commercially available immersion suits, it is very difficult for even a conscious person to turn himself over if he is positioned in the water with his face downwards.

The introduction of survival suits might thus have solved the problem of heat loss in the survivor, but at the same time have increased the dangers of drowning.

TESTING PROCEDURES

Testing procedures for immersion suits might be inferred from the SOLAS convention. Additional testing instructions have been given in the resolutions to the convention.

These resolutions give the details of the testing procedures (9).

One of the main points which has given rise to criticism on ethical grounds is that the tests shall be carried out on persons immersed, clothed in the suit to be tested, exposed to water temperatures of 0 to 2 °C, according to the type of suit. It is stated that the procedure should follow that laid down by the Helsinki declaration about "informed consent" but, as these tests often will be carried out on a commercial basis and not as a scientific experiment, it is not obvious that the declaration of Helsinki can be applied. Thus the testing of survival suits implies ethical considerations, which might lead to more reasonable testing involving manikins (Allan, 10). Such measurements have been made on diving suits, and the results are in agreement with the results obtained in human trials.

A test for water leakage through materials, seams, etc., has been devised by Allan (4). The test is based upon determining by weighing the amount of water that in a 20 minute period leaks out of a water filled suit. This amount should not exceed 100 g. This method is easy to use and can be applied for the periodical checks of suits.

A functional test for water ingression due to design and manufacturing characteristics is to measure the amount (weight) of water ingression following a jump of 4.5 m into water followed by 20 minutes of backswimming. Backswimming can be replaced by a more standardized exposure in a water tank. Allan (6) found good correlation between these two methods.

Additional specifications of a test for flame resistance is given in SOLAS (Assembly Resolution A 521 (14) "Recommendations on Testing of Life-saving Appliance ".

It is foreseeable that, in the future, these SOLAS testing recommendations will be changed due to ethical considerations and new research in testing methods.

Over the years, a number of trials have been performed comparing the insulation of different suits and weighting them against each other (12,13). Most of these tests have involved human exposure to cold water, preferably around 0 °C. The insulative properties have then been given by the rate of fall in deep body (core) temperature. When a constant rate of fall in temperature has been obtained, the expected survival time for a given suit can be calculated by extrapolation. The main objection to such simple tests is that they cannot in any reliable way be corrected for the very large individual responses to cooling. If the initial fall in deep body temperature or the peripheral cooling is sufficiently slow, this response might not give rise to any increase in metabolic heat production (shivering). This could lead to the paradoxical situation that a suit with good insulative characteristics might give erroneously low calculated insulative values.

The use of a thermal manikin is the only method which will give reproducible figures, as here the individual differences can be ruled out. Studies involving thermal manikins have been carried out by Allan (14), Bynum et al. (15) in U.S. and at the Institute of Occupational Health in Helsinki (16).

The problem to be solved is the standardization of a thermal manikin which will yield results that can be correlated to the situation of man immersed in cold water. The main obstacle is that our knowledge of the cooling characteristics of man is scarce. The main problem is how extremity cooling shall be included in the cooling characteristics of a manikin. The extremities constitute nearly 50% of the total body surface and about 1/3 of the total body mass.

With the revision of the SOLAS convention and its annexes, it is expected that these problems will be addressed.

The existing recommendation satisifies neither the user's demand of proper guidance when accepting a suit nor the producer's demand for a reliable, reproducible, test method.

REFERENCES

1. Birket-Smith, K. Ethnography of the Egedesminde district. Copenhagen, 1924.

2. 1983 Amendments to the international convention for the safety of life at sea. 1974, Vol 1, Internation Maritime Organization, London, 1984.

3. Allan, J.R. Functional performance tests for immersion suits. Royal Aircraft Inst. of Aviat. Med., Proceedings of Robert Gordon Inst. of Technology, Aberbeen meeting on safety at sea, 1985.

4. A simple test of the watertight integrity of immersion suits. Royal Aircraft Inst. of Aviat. Med., Aircrew Equipment Group Report No. 478, Dec 1982.

5. Hall, J.F. and J.W. Polte. Thermal insulation of air force clothing. WADD Tech. Report 60-597, Wright Air Development Division, Sept. 1960.

6. Allan, J.R. Royal Airforce Inst. of Aviat. Med., Aircrew Equipment Group Report No. 504, June 1984.

7. Davidson, A.F., F.S.C. Golden and W.J. Blake. Trial of flotation characteristics of subjects wearing general service life jackets and "once only" survival suits. Institute of Naval Medicine, Report No. 13/75, 1975.

8. Davidson, A.F., F.S.C. Golden and W.J. Blake. Futher trials of a prototype general service life jacket with face screen and increased buoyancy (Phase I and II).

9. Annex to 14 Assembly Resolution A521. Recommendations for test procedures to ensure compliance with IMO Regulation 33.

10. Allan, J.R. and P.A. Hayes. The specification and testing of the thermal performance of immersion suits. Royal Airforce Inst. of Aviat. Med., Aircrew Equipment Report No. 512.

11. Allan, J.R., C. Higgenbottom and P.J. Redman. The effect of leaking on the insulation provided by immersion protective clothing. Royal Airforce Inst. of Aviat. Med. Aircrew Equipment Report No. 511.

12. Ilmarinen, R., A. Paasche and S. Gordon. Thermal properties of wet versus dry emergency suits. NUTEC (Norwegian Underwater Technology Center). Report No. 43,84, 1984.

13. Hayward, J.S., P.A. Lisson, M.L. Collins and J.D. Eckerson. Survival suits for accidental immersion in cold water. Design concepts and their thermal protective performance. University of Victoria, Dept. of Biology, Jan 1978.

14. Allan, J.R., C. Higgenbottom and P.R. Redman. Measurements of survival clothing insulation using an immersed manikin. Royal Airforce Inst. of Aviat. Med. Aircrew Equipment Group Report No. 475. Oct 1982.

15. Bynum, G.D., R.F. Goldman and J. Stewart. Whole body cooling with protective clothing during cold water immersion. USARIEM Report No. T1/80. United States Army Res. Inst. of Env. Med., Natick, MA 1980.

16. Ilmarinen, R. Personal Communication.

CHAPTER 9a

PHYSIOLOGICAL ASPECTS OF AUXILIARY HEATING AND COOLING

L. Vanggaard, R.R. Gonzalez, and J.R. Breckenridge

CONTENTS

SUMMARY

INTRODUCTION

AUXILIARY HEAT EXCHANGE

REFERENCES

SUMMARY

This chapter focuses on a few physiological factors which should be considered along with external heating or cooling aids used to extend human work performance under adverse thermal environments. One consideration is the extent of blood flow to the trunk region and to the extremities, each with variable capacities for heat exchange. Manual dexterity is strongly affected by local temperature (and blood flow) to the lower arms, hands, and fingers with arteriovenous anastomoses (AVAs) serving as fine controllers of their vascular bed. Some mention is made of techniques such as the use of phase change material in the coolant of auxiliary devices and microwave heating applicable to auxiliary devices.

Key Words: auxiliary heating, local heating/cooling, physiological properties, microwave heating

INTRODUCTION

Heat exchange between humans and the environment has to take place over the body surfaces. Although the airways have been proposed as useful heat exchangers in rewarming hypothermic victims (Lloyd, 1966), the principal site of external (auxiliary) heat exchange with the environment is the skin. Inside the body, the conductive heat transfer with the blood is the main avenue for heat distribution, although conductive heat transfer is responsible for the transfer of heat over small distances. The regulation of heat dissipation from the body to the surroundings can only be accomplished by alterations in the skin blood flow since the conductive heat transfer over the subcutaneous tissues is a passive, non regulated property of heat transfer.

The blood supply to the skin may be generally divided into the amount distinguished as nutritive blood flow, as found in all skin areas, and the specific blood flow as found in the acral parts of the body, most evident in the extremities.

It is normally envisaged that the blood flow to the skin is regulated according to the body's need for heat conservation or heat dissipation. During steady-state exercise the blood flow to the sweating skin is strongly associated to that necessary for dissipating the heat lost by evaporation (Nielsen, 1969) particularly when the whole body surface is considered. However, during steady sweating, the skin temperature over the trunk region often falls confirming that vasoconstriction may exist along with heat dissipation occurring with evaporation of sweat as it cools the skin. In one experiment in which nude resting persons were exposed to cooling in a climatic chamber held at 15 °C, the skin temperature over the trunk region fell to values which, in comparison to the values obtained at a higher temperature, would be expected to occur if the skin insulation in these parts were constant. Thus, over the trunk, there is limited evidence of peripheral vasoconstriction playing any role in the protection against heat loss. In the same experiments, the temperature of the hands and feet fell, paralleling similar cooling curves for the occluded extremities, thereby suggesting the importance of the extremities dominating role in the body's protection against heat loss. A threatening fall in deep body temperature leads to a physiological "amputation" of the extremities, causing a drastic reduction in the effective body surface areas and body volume which are susceptible to excessive heat loss (Vanggaard, 1965).

AUXILIARY HEAT EXCHANGE

During the processes of auxiliary heating or cooling, effective heat transfer within the body is accomplished by heat exchange between the surrounding (heating or cooling) media and the circulating blood in the skin. Augmented heating and cooling over the skin of the body trunk often influences the overall heat exchange of the body with the surroundings, but this loss occurs only if a large enough temperature gradient can be established in the subcutaneous tissues. Thus cooling or heating devices situated over such areas become limited by the ability of such devices to raise or lower skin body temperatures. Furthermore, large deviations from normal (comfortable) skin temperatures are not often compatible with comfort (Gagge and Stevens, 1968).

The only body surface areas where heating and cooling can be accomplished without excessively larger fluctuations in skin temperature is in the extremities, in which the blood

flow is of a magnitude that the blood temperature over a wide range will maintain normal or close to normal skin temperatures. Thus, auxiliary heating and cooling applied to the extremities is an acceptable solution provided that it can be applied with technical ease.

The capacity for heat exchange, whether it involves cooling or heating, is high in the extremities where optimal arteriovenous shunting of blood can take place in the anastomoses localized distally in fingers and toes. From such arteriovenous anastomoses, blood is drained centrally to the body core via the superficial venous rete, which allow excellent possibilities for heat exchange with the surrounding media.

Some unpublished data indicate that the heat exchange capacity for cooling corresponds to that of heating, as long as the surrounding medium is kept above the temperatures where cold induced vasodilation first appears (15 °C). It has further been demonstrated that the heating and cooling capacity exhibited by hands is equalled by the feet. This is one rationale for treating cold exhaustion by immersing hands and feet in hot water as used by the Royal Danish Navy. Thus, principles of auxiliary heating or cooling should, as far as possible, follow the normal physiological routes for heat exchange.

Manikin studies which operate on the principle of measuring heat loss from areas with fixed and maintained temperatures reflect the heat exchanged between manikin and the auxiliary heating system, but can only reflect to a limited degree the physiology involved. Manikin studies thus should always be checked against results obtainable along with those derived from human experimentation.

Auxiliary heating has two objectives. One is to maintain a sufficiently high local temperature to enable a person to carry out appropriate tasks as is required to carry out repairs under arctic conditions. Here local heating, for instance to the hands, might enable a person to work for a prolonged period in extreme cold where, otherwise, rapid cooling of hands and fingers would result in a very limited time of endurance. Local heating of the hands often presents an unaccounted increase in overall heat loss as reported by Goldman (1965), but this disparate heat loss might be accepted as a minor inconvenience.

Secondly, auxiliary heating or cooling might be useful in order to maintain proper overall function of man for prolonged periods in normally intolerable cold or warm environments as evident when confined in a tank operating in hot climates, or when exposed to high levels of radiant heat stress, as found in the cockpit of an airplane or helicopter.

A number of studies have been carried out to establish the effect of auxiliary heating or cooling systems (see Chapter 9b for a detailed evaluation). Most cooling systems are based upon using convective heat transfer by circulating aqueous glycol solution, water or air, while others have employed melting ice as the cooling media. Most auxiliary heat exchange systems are limited to use of energy sources close at hand to accomplish a sufficient heating or cooling effect. Only a few systems can be used efficaciously by persons operating away from a fixed power source. One such system has been developed in Norway based upon a small charcoal burner and using a small battery driven fan to drive hot air to the target area (Rustad, 1984).

For casualty handling in cold climates, auxiliary heating of patients is a necessity. Experience from the Korean war showed that a large proportion of cold injuries (frostbite) occurred in wounded under the care of the medical services.

Immobilized individuals in severe cold will not, even when well insulated, be able to maintain thermal equilibrium without vasoconstriction of the extremities. Hands might be kept passively warm when held close to the body, while the feet will exhibit falling temperatures and, in severe cold, become susceptible to frostbite if not heated by operational devices (Goldman, 1965).

While acceptable systems do exist for pilots and tank crews, these are often too cumbersome and theoretically "unphysiological". In some cases these also create some degree of discomfort not only due to unphysiological skin temperatures but also because they are not readily controllable. To date, an acceptable system for the infantryman and for use by the medical services does not exist.

In most auxiliary heating and cooling systems, the time-lag of the system offers the greatest problem. The sluggishness of the control system to obtain rapid cooling or heating leads to a situation whereby the user often has to maintain a constant working rate in order to induce a sufficient endogenous load owing to the thermal demands of the system. Alternatively, excessive engineering damping has to exist in the system to account for "overshooting" when the wearer changes the temperature of the auxiliary system. The only feasible approach for further research is to construct a system in which the heat transfer from the system to the wearer is based upon rapid exchange between a system and circulating blood. This is, with the existing technology, possible only with auxiliary devices on the extremities and head/neck areas.

Individualized auxiliary heating and cooling units attached to CW protective garments entail additional special problems, because the demand for physical performance in such suits becomes additive with the burdens present during normal combat stress. The CW protective suit impedes thermal and mass transfer due to the chemical protective layer. On the other hand, the use of a vest of waffled polymeric laminate design through which coolant is passed also has its problems. The specific heat of the coolant entails that inlet temperature should be very low to eliminate excessive coolant flow rate. However, too low entry temperatures often cause cold discomfort in upstream areas of the vest and localized condensation of moisture. One attractive possibility is the use of phase change material, which can exist as microspheres in the coolant. These are typically hydrocarbons (n-octadecane) which can absorb and liberate large quantities of heat without marked temperature changes by utilization of more optimal heat of fusion than glycol (McMahon et al., 1984). Additionally, in CW suits the respiratory mask poses an added thermal and psychological strain on the wearer (See Chapter 11). Only limited man-carried systems have been developed with dubious success (Cosimini et al., 1985).

Microwave heating of deeper structures is a feasible alternative to microclimate heating in the future. For example, electromagnetic heating of tissues could be done in three ways: a) radiation emitted by ultra-high (UHF) and microwave frequencies; b) by the induction of eddy currents in the tissue of deep structures; and c) by application of diffused microwave radiation (Pound, 1980). As an auxiliary device the latter technique is a possibility. Berglund (1983), predicted a situation in which thermal comfort for sedentary persons wearing 1.2 clo (light winter troop clothing) would be possible in a 10.5 °C environment with diffuse microwave radiation at the currently permitted 10 $mW \cdot cm^{-2}$ (American National Standards Institute) level. However, use of microwave heating is still at best only a futuristic concept.

REFERENCES

1. Berglund, L.G. Characterizing the thermal environment. In Microwaves and Thermoregulation. E. Adair (ed) Academic Press, N.Y. pp 15-31, 1983.

2. Cosimini, H., J. Cohen, B. DeCristofano, R. Goff, V. Iacono, M. Kupcinskas, T. Tassinari, N. Pimental, B. Cadarette, W. Holden, L. Levin, K.B. Pandolf, and M.N. Sawka. Determination of the feasibility of two commercial portable microclimate cooling systems for military use. Technical Report. Natick/TR85/033L, March 1985.

3. Gagge, A.P. and J.C. Stevens. Thermal sensitivity and comfort. In: The Skin Senses. D.R. Kenshalo (ed). C.C. Thomas, Springfield. pp 345-457, 1968.

4. Goldman, R.F. The Arctic Soldier: possible research solutions for his protection. In: Science in Alaska G. Dahlgren (ed). Alaska Div. AAAS. pp 401-419, 1965.

5. Lloyd, B.B. The interactions between hypoxia and other ventilatory stimuli. In: International Symposium on the Cardiovascular and Respirator Effects. Effects of Hypoxia. J.D. Hatcher and D.B. Jennings (eds.) Basel, Karger, 1966.

6. McMahon, W.A., W.W. Harlowe, Jr., D.J. Mangold. Feasibility study of utilizing phase change coolant for protective garments. Technical Report. Natick/TR-85/013L, December 1984.

7. Nielsen, B. Thermoregulation in rest and exercise. Acta Physiol. Scand. (Suppl). 323:1-74, 1969.

B. Pound, R.V. Radiant heat for energy conservation. Science. 208:494-495, 1980.

9. Rustad, S. Cold climate field heating - final report FFI/Rapport-84/4006, Norwegian Defence Research Establishment, 1984.

10. Vanggaard, L. Physiological reactions to wet-cold. Aviat. Space Env. Med. 46:33-36, 1975.

CHAPTER 9b

AUXILIARY COOLING: EXPERIMENTAL RESULTS

K. B. Pandolf, A. E. Allan, R. R. Gonzalez, M. N. Sawka,
L. A. Stroschein and A. J. Young

CONTENTS

SUMMARY

1. INTRODUCTION

2. METHODS

3. RESULTS AND DISCUSSION

REFERENCES

SUMMARY

The major factors which contribute to the increased thermal burden imposed by chemical warfare (CW) protective clothing are the insulation characteristics (clo) and the evaporative impedance (i_m) of the material and the increased levels of energy expenditure for performing physical exercise while wearing these clothing systems. An approach to alleviating heat stress is through the use of auxiliary cooling. A number of prototype microclimate cooling systems which employ either air-cooled or liquid-cooled vests have been shown to be effective in reducing soldier heat strain during exercise while wearing CW protective clothing in hot environments. A prediction of the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in CW protective clothing in a wide variety of environmental conditions is discussed.

Key Words: CW protective clothing, microclimate cooling, manikin studies, human studies, prediction modelling.

INTRODUCTION

Performance of muscular exercise in hot environments has been shown to be influenced by aerobic fitness (1), acclimation state (2) and hydration level (3). An aerobically fit individual who is exercise-heat acclimated and fully hydrated should experience less body-heat storage and enhanced performance while exercising in the heat (3). However, it is questionable whether these three factors would have major impact in reducing the added thermal burden imposed by wearing low permeable or impermeable protective clothing during exercise-heat stress of prolonged duration.

Chemical protective clothing characteristically has high thermal insulation and low moisture permeability. These clothing characteristics place severe limitations on the body's usual heat dissipating mechanisms, namely the evaporation of sweat. Auxiliary cooling has been suggested to be essential in industrial and military settings when exercising in hot environments while wearing low permeable or impermeable protective garments (4,5,6). Effective auxiliary cooling is dependent on active sweating for evaporative cooling (6).

This paper will briefly review our biophysical test observations concerning the auxiliary cooling provided by five water-cooled undergarments in association with chemical protective clothing as directly evaluated on a life-size, sectional copper manikin. The report will then review recent findings from our Institute[1] demonstrating that auxiliary cooling significantly reduces physiological strain and increases tolerance time of soldiers exercising in protective clothing in hot environments.

2. METHODS

2.1 Experiment 1

An electrically heated copper manikin capable of individual sectional evaluations of the head, torso, arms, hands, legs and feet was used for these experiments. The environmental conditions were either 29.4 °C (85% relative humidity) or 51.7 °C (25% relative humidity). The five water-cooled undergarments which were tested included: (a) a water-cooled cap for head cooling; (b) a water-cooled vest for torso cooling; (c) a water-cooled cap and vest for head and torso cooling; (d) a short water-cooled undergarment for upper arms, upper legs and torso cooling, and, (e) a long water-cooled undergarment for upper and lower arms, upper and lower legs, head and torso cooling. None of these water-cooled undergarments provided cooling to the hands or feet. Cooling water inlet temperature varied over the range of 7 to 28 °C. The components of the combat vehicle crewman (CVC) ensemble and the chemical protective suit were worn over these water-cooled undergarments. A more detailed explanation of these methods can be found in a previously published report (7).

---

[1] Portions of this report were presented at the "Proceedings of the Annual International Industrial Ergonomics and Safety Conference" in Miami, FL, 9-12 June 1987, Trends in Ergonomics/Human Factors IV, S.S. Asfour (Ed.), Elsevier Publ. (North Holland), 1987.

2.2 Experiment 2

In these experiments, water-cooled, air-cooled and ambient air-ventilated auxiliary cooling vests were evaluated in a hot-wet climate (35 °C, 75% relative humidity) and a hot-dry climate with added infrared radiation (49 °C, 20% relative humidity, 68 °C black globe temperature). Twelve male volunteer soldiers, dressed in full chemical warfare uniforms, attempted 120 min of exposure to each combination of climate and cooling vest. Total exercise was 20 min and rest time 100 min which resulted in a mean time weighted metabolic rate of 180 W. The results concerning the ambient air-ventilated auxiliary cooling vest will not be presented in this report but can be found with a more detailed explanation of these methods in a previously published paper (6).

2.3 Experiment 3

After being heat acclimated for five consecutive days, four male volunteer soldiers dressed in CVC uniform and full chemical protective clothing attempted 300 min heat exposures (49 °C, 20 °C dp) at two different metabolic rates (175 and 315 W) each with five different auxiliary cooling combinations. The 175 W metabolic rate involved 45 min of rest and 15 min of walking (1.01 $m \cdot s^{-1}$) per hour while the 315 W metabolic rate involved 45 min of walking at this same speed and 15 min of rest per hour. At each of these two metabolic rates, five combinations of dry bulb and dew point temperatures that ranged from 20-27 °C db and 7-18 °C dp were supplied to an air-cooled vest at 15 scfm. During each of the two control tests, the subjects did not wear the air-cooled vest; however, the face piece to the mask was ventilated with 3 scfm of ambient air. A more detailed description of these methods can be found in a soon to be published report (5).

2.4 Experiment 4

In these field observations, physiological responses of tank crew members inside the armored vehicle were evaluated while wearing an air-cooled vest under the standard CVC uniform and full chemical protective clothing in tropic (Tropic Test Center, Republic of Panama) and desert (Yuma Proving Grounds, AZ) environments. Six male volunteer tank crewmen participated in the tropic test while four different male volunteer crewmen were evaluated during the desert tests. During the tropic test, ambient temperature ranged from 27-36 °C db and relative humidity between 40-81% while during the desert tests the ambient temperature ranged from 23-38 °C db and relative humidity from 20-64%. These crewmen performed continuous operations for up to 12 hours. A more detailed description of these methods can be found in a recently published report (4).

3. RESULTS AND DISCUSSION

Figure 1 presents the range of cooling in watts provided by each of the five water-cooled undergarments as a function of the cooling water inlet temperature from Experiment 1. These findings illustrate that at a cooling water inlet temperature of about 10 °C the water-cooled cap could not provide 100 W of cooling; however, both the short and long water-cooled undergarments provided approximately 400 W of cooling. A "comfortable" cooling water inlet temperature of 20 °C was shown to provide 46 W of cooling for the water-cooled cap, 66 W for the water-cooled vest, 112 W for the water-cooled cap and vest, 264 W for the

short water-cooled undergarment and 387 W for the long water-cooled undergarment (7). As expected, these results support the conclusion that cooling in watts increases with greater body surface coverage from the water-cooled undergarment and illustrates the importance of biophysical assessments of the heat transfer characteristics concerning prototype auxiliary cooling systems using heat copper manikins.

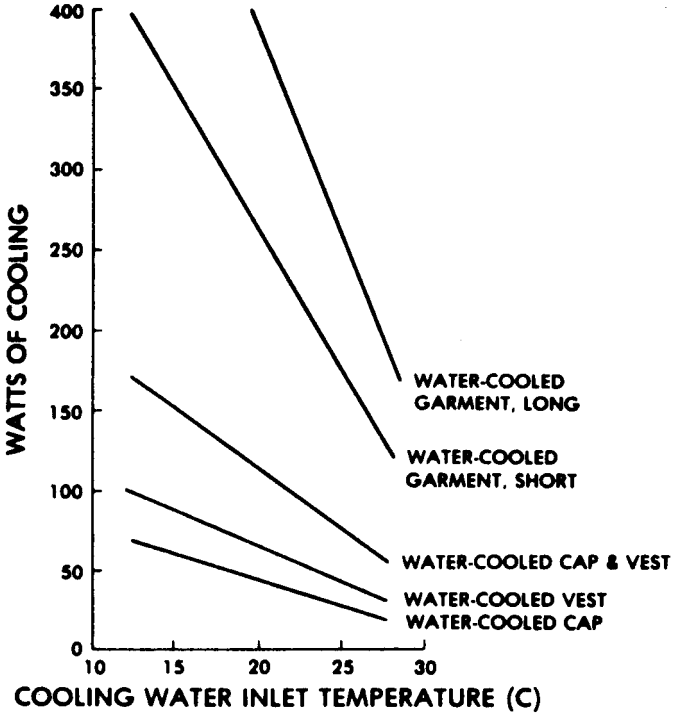


FIGURE 1. Watts of cooling provided by five water-cooled undergarments as a function of the cooling water inlet temperature for a completely wet (i.e., maximal sweating) skin condition (7).

Table 1 shows a summary of the thermoregulatory trends between auxiliary cooling (water-cooled and air-cooled vests) and no auxiliary cooling during both hot-wet and hot-dry exposures from Experiment 2. In the hot-wet condition, the water- and air-cooled vests displayed better thermoregulatory status than predicted for these subjects without auxiliary cooling: greater than 1 °C lower rectal temperature (T_{re}); 2.5 to 3.5 °C lower mean skin temperature ($\overline{T}_{sk}$); 10 to 20 b·min^{-1} lower heart rate (HR); about one tenth the heat storage (ΔS); and one third less sweating ($\dot{m}_{sw}$). When compared to no auxiliary cooling (predicted), the evaporative sweat rate ($\dot{E}_{sw}$) was lower for the water-cooled vest but slightly higher for the air-cooled vest. Comparing the air- and water-cooled vests, no differences ($p>0.05$) were found for T_{re}, $\overline{T}_{sk}$, ΔS and $\dot{m}_{sw}$; however, HR was lower ($p<0.05$) and $\dot{E}_{sw}$ was higher ($p<0.05$) for the air-cooled vest. In the hot-dry condition, the water- and air-cooled vests again showed better thermoregulatory responses than no auxiliary cooling (predicted): 1 °C lower T_{re}; 1 to 2 °C lower $\overline{T}_{sk}$; 30 b·min^{-1} lower HR; and one third the ΔS. Compared to no auxiliary cooling (predicted), $\dot{m}_{sw}$ was the same for both vests but $\dot{E}_{sw}$ appeared greater.

The $\dot{E}_{sw}$ was greater ($p<0.05$) for the air-cooled vest when contrasted to the water-cooled vest. These authors concluded that an air-cooled vest can be used with the same efficiency as a water-cooled vest, and both are clearly superior to no auxiliary cooling under hot-wet or hot-dry conditions (6).

Table 1. Summary of thermoregulatory trends between auxiliary cooling and no auxiliary cooling during hot-wet and hot-dry exposures.

	HOT-WET			HOT-DRY		
	WATER-COOLED VEST	AIR-COOLED VEST	DIFFERENCE	WATER-COOLED VEST	AIR-COOLED VEST	DIFFERENCE
T_{re} (°C)	↓	↓	ns	↓	↓	ns
$\overline{T}_{sk}$ (°C)	↓	↓	ns	↓	↓	ns
HR ($b \cdot min^{-1}$)	↓	↓	–	↓	↓	ns
ΔS (W)	↓	↓	ns	↓	↓	ns
$\dot{m}_{sw}$ ($g \cdot m^{-2} h^{-1}$)	↓	↓	ns	=	=	ns
$\dot{E}_{sw}$ ($g \cdot h^{-1}$)	↓	= or ↑	+	↑	↑	+

↓, auxiliary cooling (water- or air-cooled vest) is lower than no auxiliary cooling (predicted);
↑, auxiliary cooling (water- or air-cooled vest) is higher than no auxiliary cooling (predicted);
=, no difference between auxiliary cooling and no auxiliary cooling;
ns, not significant;
+, air-cooled greater than water cooled ($p< 0.05$);
–, air-cooled less than water cooled ($p<0.05$).

Figure 2 displays the T_{re} responses over time for the four subjects in Experiment 3 during the control test which involved no air-cooled vest but full chemical protective clothing at the low metabolic rate of 175 W. All subjects show a rapid rate of rise in T_{re} during this test and were unable to complete the proposed 300 min heat exposure. Average endurance time was 118 min. The rapid rate of rise in T_{re} which is associated with an increased rate of body heat storage has been implied to be a good prognosticator of exercise-heat tolerance (8).

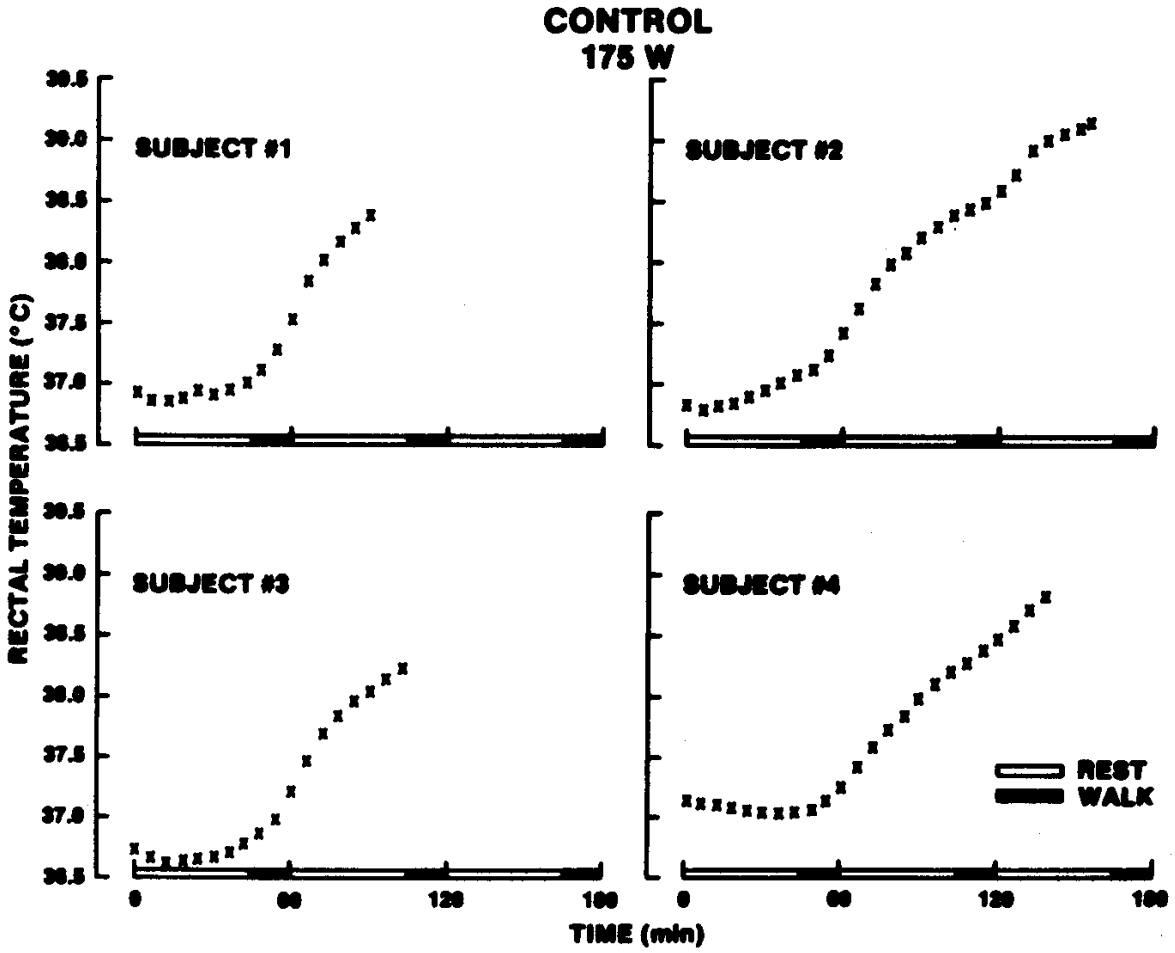


FIGURE 2. Rectal temperatures over time for four subjects during periods of rest and treadmill walking (1.01 $m \cdot s^{-1}$) while wearing full chemical protective clothing but no air-cooled vest (unpublished from 5).

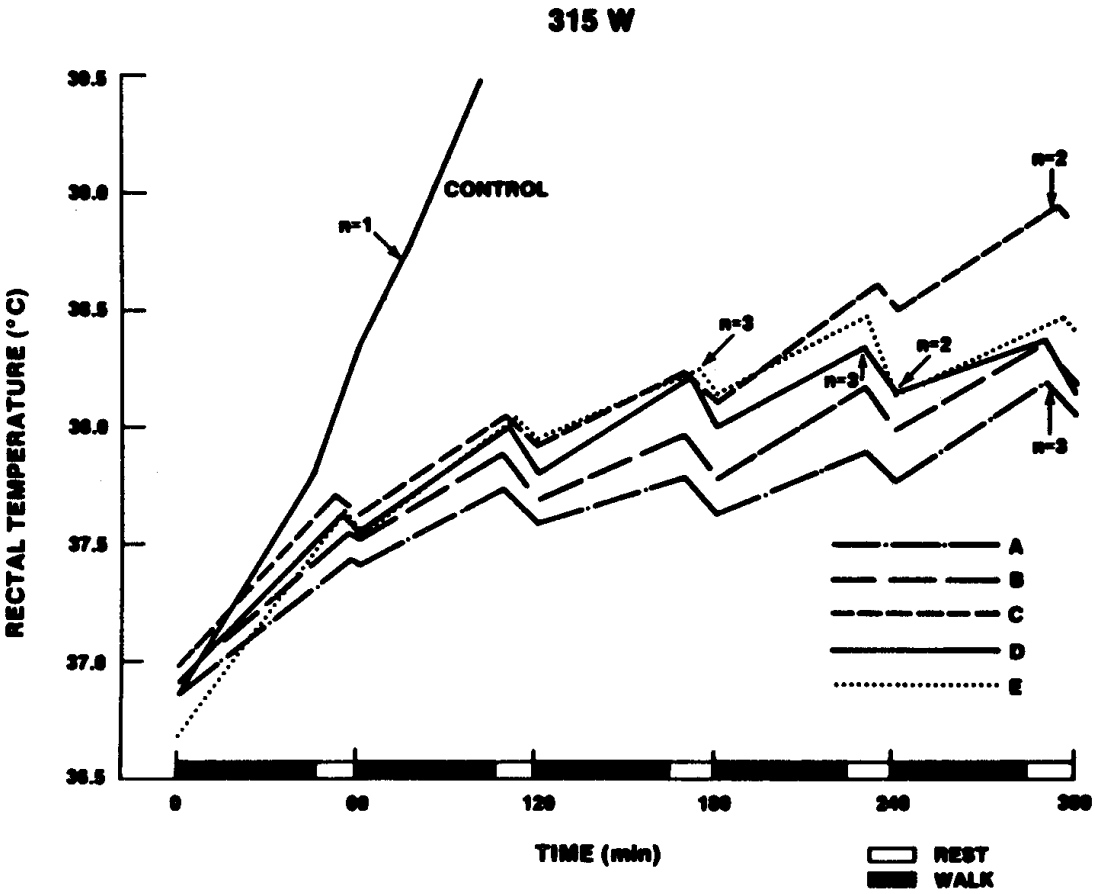


FIGURE 3. Rectal temperatures over time for the five cooling combinations (A,B,C,D and E provide 687, 631, 620, 564 and 498 total watts of cooling, respectively) and the control test at 315 W (5).

In contrast to the T_{re} values for the control test at 175 W in Experiment 3, all five cooling combinations allowed for the maintenance of a near constant body temperature while in full chemical protective clothing (5). In addition, there were no significant differences in T_{re} responses among the five cooling combinations during the various rest or exercise periods ($p>0.05$). However, at the higher metabolic rate of 315 W also evaluated in Experiment 3, the air-cooled vest at all five cooling combinations was less effective in maintaining T_{re} as illustrated in Figure 3. With all five cooling combinations, T_{re} decreased during the various rest periods but also increased significantly over time ($p<0.05$). After the fourth exercise bout (about 235 min), peak T_{re} averaged 38.0 for A (n=4), 38.2 for B (n=4), 38.3 for D (n=3), 38.5 for E (n=3) and 38.6 °C for C (n=4). Nevertheless, all five cooling combinations were more effective in lessening the rate of rise in T_{re} than no cooling (control).

Figure 4 presents the endurance times for each of the five cooling combinations and for the control tests at metabolic rates of 175 and 315 W. At 175 W, all subjects were able to complete the 300 min heat exposure for all five cooling combinations; however, without the cooling vest (control) endurance time was limited to an average of 118(±27,SD) min. At 315 W, endurance times did not differ significantly ($p>0.05$) between the five cooling combinations (range, 242-300 min); however, with no auxiliary cooling the endurance time averaged only 73(±19,SD) min.

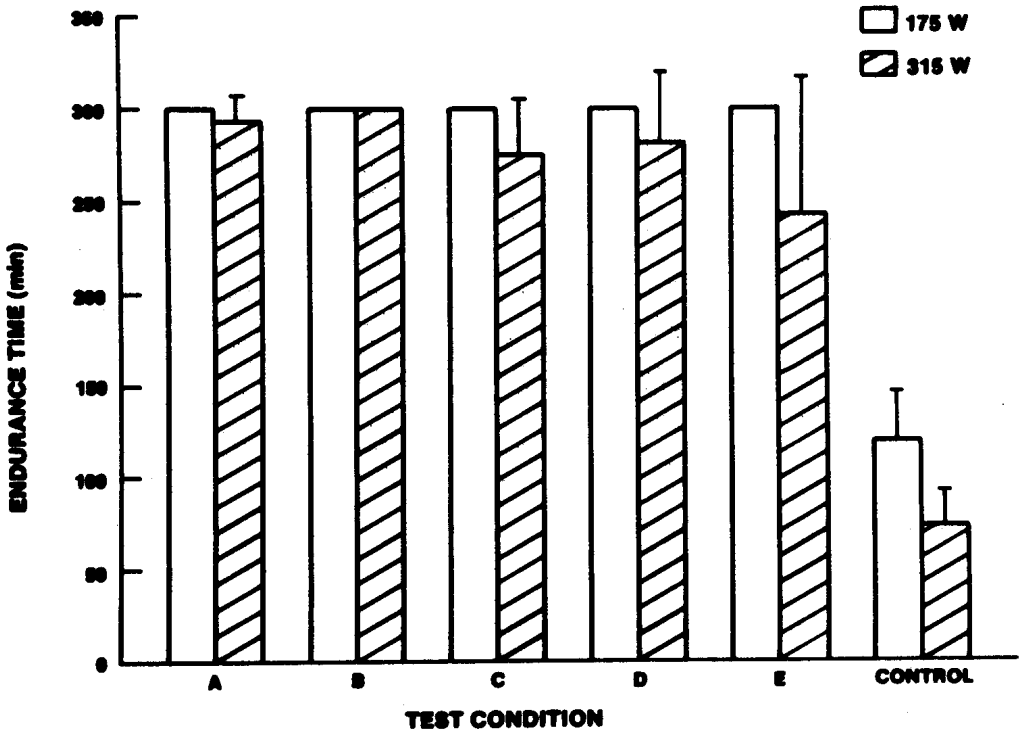


FIGURE 4. Endurance times for each of the five cooling combinations and control test at either 175 or 315 W (5).

Figure 5 shows the mean T_{re} responses for the four tank crewmen during the 12-hour tropic test of Experiment 4. These crewmen displayed a group decrease in T_{re} during the first hour in the tank followed by a mean increase in T_{re} of 0.5 °C over the next 11 hours. While not approaching our physiological safety limit, T_{re} did show a statistically significant increase ($p<0.05$) over this 12-hour test (4). Mean T_{re} at the start and end of this tropic test were 37.2±0.5 and 37.4±0.4 °C, respectively. However, at this low metabolic rate, the air-cooled system appears to have helped increase the evaporative cooling capabilities of these subjects during extended operations in the tropics. Similar results were observed during extended operations in desert environments (4).

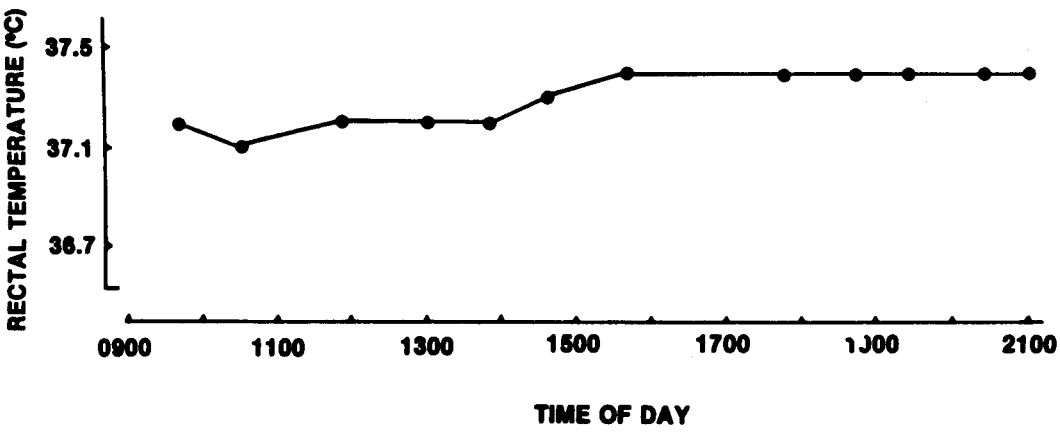


FIGURE 5. Mean rectal temperature of the four tank crewmen during a 12-hour extended operations field test in the tropics (4).

The Military Ergonomics Division of our Institute has developed the ability to predict the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in CW protective clothing in a wide variety of environmental conditions. This comprehensive heat stress prediction model encompasses a series of predictive equations for deep body temperature, heart rate and sweat loss responses for clothed soldiers performing physical exercise at various environmental extremes (9). Our model includes a clothing menu which incorporates a variety of low permeable protective clothing ensembles. Currently, our prediction model is programmed on both a desk-top computer and hand-held calculator and with some possible minor adjustments should be quite applicable for industrial use.

4. CONCLUSIONS

Over the last decade, our Institute has maintained an active research program evaluating the thermal burden imposed by wearing chemical warfare (CW) protective clothing during exercise-heat stress. Through the use of a sectional copper manikin which is life-size, measurements can be made of the insulation characteristics (clo) and evaporative impedance (i_m /clo) of low permeable or impermeable clothing ensembles. In addition, the cooling power in watts at a given cooling water inlet temperature has been shown to increase with greater body surface area coverage by a water-cooled undergarment. Except for the separate use of a water-cooled cap, a collection of five water-cooled systems, singularly or in combination, have the potential to remove the metabolic heat produced in the sedentary state (about 80 W; water-cooled vest, water-cooled cap and vest) or in a highly active state (about 400 W; short or long water-cooled undergarment). A number of prototype microclimate cooling systems involving both air-cooled and liquid-cooled vests have been shown to be effective in alleviating heat stress in soldiers during light exercise while wearing CW protective clothing in hot-wet or hot-dry environments. Microclimate cooling while wearing CW protective clothing in armored vehicles has also been shown to be effective in alleviating heat stress during sustained 12-hour operations involving light exercise in tropic or desert environments. For soldiers performing exercise in CW protective clothing, the most important factor affecting thermal strain appears to be the level of metabolic energy expenditure. We have demonstrated that when moderate to heavy exercise is

performed in hot environments, some soldiers cannot tolerate these conditions for prolonged periods of time even with the inclusion of an air-cooled vest. Possibly, a greater body surface area coverage by microclimate cooling would help solve this problem. Finally, our Institute has developed the ability to predict the thermal strain, water requirements, tolerance time and optimal work-rest ratios for soldiers exercising in CW protective clothing or other low permeable clothing ensembles in a variety of hot environments.

REFERENCES

1. Pandolf, K.B., Effects of physical training and cardiorespiratory fitness on exercise-heat tolerance: recent observations, Med. Sci. Sports 11:60-65, 1979.

2. Nadel, E.R., Pandolf, K.B., Roberts, M.F. and Stolwijk, J.A.J., Mechanisms of thermal acclimation to exercise and heat, J. Appl. Physiol. 37:515-520, 1974..

3. Sawka, M.N., Francesconi, R.F., Young, A.J. and Pandolf, K.B., Influence of hydration level and body fluids on exercise performance in the heat, JAMA 252:1165-1169, 1984.

4. Cadarette, B.S., Pimental, N.A., Levell, C.A., Bogart, J.E. and Sawka, M.N., Thermal responses of tank crewmen operating with microclimate cooling under simulated NBC conditions in the desert and tropics, Tech.Rpt. T7/86, U.S. Army Research Institute of Environmental Medicine, Natick, MA, 1986.

5. Pimental, N.A., Cosimini, H.M., Sawka, M.N. and Wenger, C.B., Effectiveness of an air-cooled vest using selected air temperature and humidity combinations, Aviat. Space Environ. Med. 58:119-124, 1987.

6. Shapiro, Y., Pandolf, K.B., Sawka, M.N., Toner, M.M., Winsmann, F.R. and Goldman, R.F., Auxiliary cooling: comparison of air-cooled vs. water-cooled vests in hot-dry and hot-wet environments, Aviat. Space Environ. Med. 53:785-789, 1982.

7. Fonseca, G.F., Effectiveness of five water-cooled undergarments in reducing heat stress of vehicle crewmen operating in a hot-wet or hot-dry environment, Tech.Rpt. T2/81, U.S. Army Research Institute of Environmental Medicine, Natick, MA, 1981.

8. Pandolf, K.B. and Goldman, R.F., Convergence of skin and rectal temperatures as a criterion for heat tolerance, Aviat. Space Environ. Med. 49:1095-1101, 1978.

9. Pandolf, K.B., Stroschein, L.A., Drolet, L.L., Gonzalez, R.R. and Sawka, M.N., Prediction modeling of physiological responses and human performance in the heat, Comput. Biol. Med. 16:319-329, 1986.

CHAPTER 10

BIOMEDICAL EFFECTS OF UNDERWEAR

R.F. Goldman

CONTENTS

SUMMARY

1. INTRODUCTION

2. WARMTH

3. TACTILITY PROPERTIES

4. MOISTURE HANDLING

    a) WICKING

    b) WATER UPTAKE

    c) DRYING

5. IDEAL CHARACTERISTICS REFERENCES

REFERENCES

SUMMARY

Underwear can play a major role in a clothing system, as much as a result of its tactile and moisture handling properties (water uptake, drying and wicking) as of its thermal properties. The constant relationship between the uncompressed thickness of a material and its insulation values is demonstrated, despite the heavily advertised claims for superiority of one material over another; any such superiority must be associated with the material's insulation per unit weight, its aforementioned moisture handling properties or its ability to retain thickness when wet. The ideal underwear would be "soft", have extremely high wicking characteristics, should be able to rapidly absorb large amounts of sweat, and should dry rapidly, while being as thick, non-compressible and light weight as possible.

Key Words: underwear, wicking, underwear water uptake, fabric tactility, underwear insulation

1. INTRODUCTION

The biomedical effects of underwear are relatively unique among clothing items. While its insulation tends to be of less importance than that of most clothing items, its tactile properties, and the way in which it handles moisture, are of much greater concern since underwear is in direct contact with the skin. Perhaps this intimate contact accounts for the folklore which has grown up about the properties of underwear; the stated importance of flannel for the prevention of rheumatism, the need to wear a spine pad to protect the spine against the actinic rays of the sun, the importance of a stomacher of flannel to serve as a protective belt against cholera, and the need for wool around the kidney area to protect against kidney disease, regularly appear in the military clothing literature throughout the 18th and 19th centuries and, indeed, are occasionally resurrected as questions today.

2. Warmth

The warmth of any clothing item is directly related to its thickness; the intrinsic insulation (clo_i) as defined in Chapter 1, when measured using a heated, flat plate apparatus is almost always closely related to the intrinsic insulation predicted on the basis of thickness. The few discrepancies between underwear thickness and measured insulation values could be associated with errors in thickness measurement. The usual American Society of Testing Materials (ASTM) method for thickness measurement requires compressing the material by 0.7 g/cm^2 (.01 psi). This very mild level of compression is still sufficient to compress the fibrils at the surface of the material and these, although very compressible, do contribute to trapping additional surface air film thickness. If one uses a method where thickness is measured without any compression, the measured intrinsic insulation can almost always be matched against the insulation predicted using 1.57 clo per centimeter (4 clo per inch).

The insulation of underwear is seldom a major consideration in thermal comfort, since it lies within an already trapped still-air layer between the skin and the outerwear (3). Indeed, static copper manikin measurements of a clothing system frequently give the same insulation measurement with or without underwear. Nevertheless, a thicker underwear will contribute warmth in the presence of wind or body motion, particularly if the outerwear is not windproof, the closures are not tight, or the clothing is compressed by the weight of outer clothing layers or load carriage systems (1); then the insulation over the torso will generally be close to that approximated from the full thickness of the underwear, because of the air gaps between the underwear and the clothing worn over the torso. However, the insulation over the arms and the legs will be closer to that suggested by the compressed (ASTM) thickness measurement as a result of the closer fit of the outer garments and, hence, their compression of the underwear over the limbs. In essence, underwear with superior warmth will feature looseness of fit, the greatest thickness whether by fiber selection, weave or as a result of napping, will exhibit the least loss of thickness with compression and will have the least tendency to take a compression set whether dry or wet (7).

Table I presents data on twelve different underwear samples arranged in thickness from 1.5 to 2.6 mm uncompressed, and from 1.14 to 2.26 mm when compressed to 0.7 g/cm^2. The insulation values, as indicated above, are predicted based on thickness and compare quite favorably with their measured values in most cases.

TABLE I. Physical Characteristics of Twelve Representative Underwear Materials

MATERIAL	THICKNESS		INSULATION	DRYING TIME	WATER ABSORPTION				WICKING		
	Full	ASTM	Pred.		1 Min	5 Min	20 Min	1 Min Squeeze	Horiz.	Vert.	Flat
	(mm)		(clo)	(%Wgt/hr)	(%Wgt/hr)					(seconds)	
DOUBLE FOLDS											
85% Vinyon	2.64	2.26	.42	111	613	630	633	620	YES	YES	1
15 % Acrylic											
100% Polypropylene	2.50	1.78	.39	125	307	336	340	315	YES	YES	21
Inner – 100% Cotton Outer – 50% Cotton 40% Wool 10% Nylon	1.83	1.42	.29	153	14	45	191	573	NO	NO	80
Inner – 100% Polypropylene Outer – 55% Polypropylene 45% Wool	1.60	1.19	.25	149	480	480	480	500	YES	YES	6
SINGLE LAYER											
100% Cotton	2.06	1.40	.32	100	429	443	445	440	YES	YES	1
50% Cotton/50% Polyester	2.03	1.98	.29	118	237	408	408	380	YES	YES	12
100% Polypropylene	1.88	1.78	.28	120	409	427	430	381	YES	YES	18
40% Wool 50% Trevira 10% Nylon	1.80	1.47	.28	134	12	288	420	464	NO	NO	80
85% Polypropylene 15% Nylon	1.65	1.52	.26	128	444	456	485	476	YES	YES	2
60% Dunova/40% Wool	1.52	1.19	.24	125	29	347	532	508	NO	NO	27
85% Wool/15% Nylon	1.47	1.14	.23	82	21	35	352	400	N0	NO	17

3. TACTILITY

The contact characteristics of underwear have not been well worked out, although a significant percentage of the population has a true, genetically based, allergic dermatitis when wearing wool underwear. In even more cases, the discomfort produced by underwear contact is an irritant dermatitis, rather than an immunological (i.e., allergic) dermatitis.

The Japanese have become the world leaders in exploring the "hand" properties of fabrics (6). They have identified eight qualities of a fabric to characterize tactile, i.e., "hand", sensations as shown in Table II. Clearly smoothness as opposed to roughness, and silkiness as opposed to scratchy, are relevant properties for underwear tactile comfort, as probably is softness as opposed to hardness. However, there appear to be wide differences in individual sensitivities and also these tactile sensations change dramatically with moisture uptake of the fabrics in contact with the skin.

TABLE II

Characterization of Tactile ("Hand") Properties of Fabric

Japanese Expressions:

			Winter/Summer or Both
1.	KOSHI	Stiffness (to bending)	B
2.	NUMERI	Smoothness	W
3.	FUKURAMI	Fullness and Softness	B
4.	SHARI	Crispness	S
5.	HARI	Anti-drape Stiffness	S
6.	KISHIMI	Silky	S
7.	SHINAY AKASA	Flexibility and Softness	S (- thin)
8.	SOFUTOSA	Soft	W (- medium thick)

Fabric Thickness (0.5 g/cm^2 pressure): thin .131 to 1.460 mm ($\bar{x}$ = 0.445 mm);
medium 0.323 to 2.490 mm ($\bar{x}$ = 0.974 mm)

4. MOISTURE HANDLING

The sweat handling properties of underwear are probably far more important for comfort than their contact sensations. Individuals can characterize the actual water content of a fabric in contact with the skin with good repeatability, using a subjective scale of fabric wetness where a value of "1" is considered dry, "2" slightly damp, "3" moderately damp, and "4" is perceived as wet (5). Hollies reported that the actual water content for cotton, expressed as percent of dry weight added as water, increased by 1 subject unit for every 25% of additional weight of fabric added as water. In another study (Goldman, unpublished), it was necessary to use a five point scale for subjective discrimination of fabric wetness.

As water content increased from 8% to 40%, subjective comfort fell exponentially for a variety of cotton-and-polyester blend materials with little regard for the relative percentage composition of cotton to polyester. Obviously, the openness of the weave, which affects the amount of material in contact with the skin, is another significant factor; it may account for the high acceptability reported for the open, fisherman's net underwear known as a "brynje string vest" (2,8).

Regardless of the absolute level of water content reached, non-wicking fibers or fabrics are probably undesirable for underwear whenever heavy activity is involved since any liquid sweat would tend to remain in direct contact with the skin. A desirable aspect of comfort is keeping the skin wettedness as low as possible. Less than 20% skin wettedness, or equivalently < 20% skin relative humidity, is generally perceived as comfortable while 60% skin wettedness (or 60% relative humidity of the skin) is generally the upper limit compatible with continued exposure in a civilian workforce.

a) Wicking

There are three ways to characterize wicking: 1) with the material in a "vertical" position so that wicking is against the pressure of gravity; 2) with the material in a "horizontal" position so that wicking is a matter of capillary attraction and surface wetting, with no gravitational limit; and 3) with the material placed "flat" on the surface of a pool of water or with a drop of water placed on the material. Representative wicking curves are shown in Figure 1.

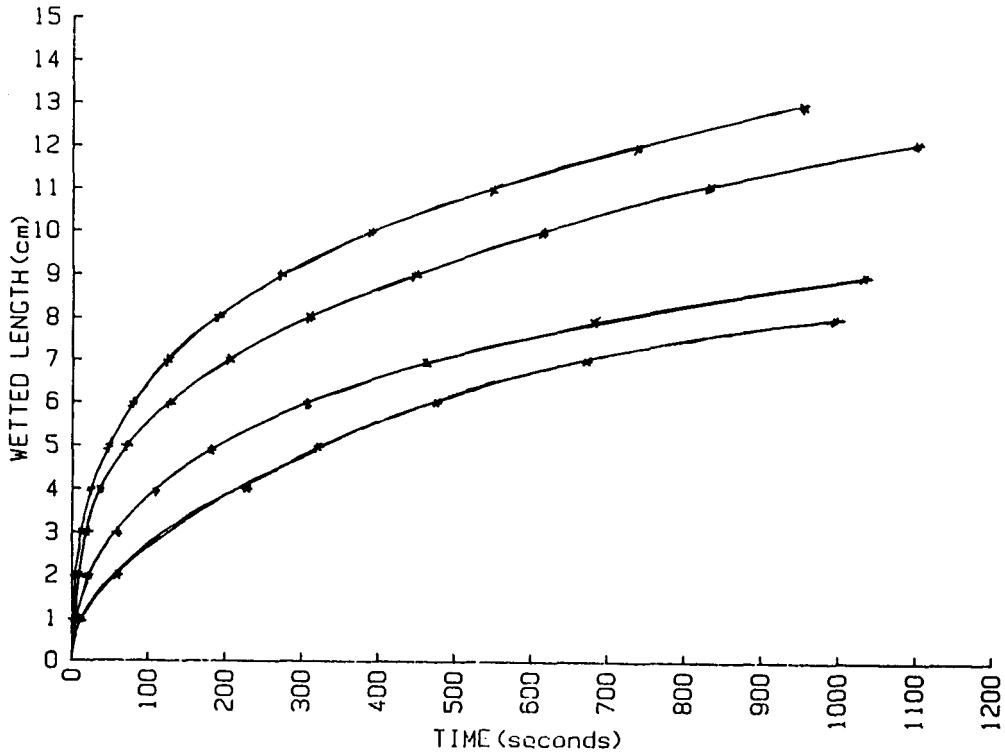


Fig. 1: Wetted length vs. time from vertical wicking trial

A faster initial wicking is associated with more rapid removal of water from the skin and this implies greater comfort during wear while sweating.

b) Water uptake

The amount of water that can be absorbed by the material is obviously another important characteristic; this is expressed as a percent of dry weight of material and is given (in Table I) at the end of 1 minute, 5 minutes and 20 minutes of immersion, and after 1 minute during which the material is repeatedly squeezed during immersion. The water absorption characteristics, as shown in Table I, generally appear to parallel the wicking characteristics, with non-wicking materials generally picking up less than 30% of their weight as water after 1 minute of immersion, compared to 613% for the double-layer, 85% Vinylidene Chloride/15% acrylic fiber underwear and to 400% for most of the other wicking materials, unless squeezed during the 1-minute immersion to force water into the material. The ability to pick up and hold more sweat, thus helping blot the skin dry, should enhance the comfort of an underwear system; however, if the material loses its thickness (i.e., "slumps"), or takes longer to dry out, this water absorption capability may actually detract from comfort. There appears to be a reasonable relationship between the amount of water picked up in the first minute and the wicking characteristics of the materials, and also between the amount of water picked up within 5 minutes and the flat wicking measurement. While the water picked up as a result of squeezing the material during immersion would appear to be relevant to the wetting of underwear, there seems to be little relationship between wicking characteristics and the water taken up as a result of squeezing the material during a 1-minute immersion.

c) Drying

Drying time, again expressed as percent of the dry material weight of water lost per hour, ranged from a slow 82% of wet weight per hour, to a little more than twice that, 176% of wet weight per hour; a sample drying curve is shown in Figure 2.

In theory, the faster a material dries, the more comfortable it should be. This will be particularly the case in avoiding the "post-exercise" chill which occurs when the sweat accumulated in the underwear during exercise, continues to evaporate and provide cooling after the body's level of heat production has returned to resting levels. It would appear far better for comfort if the post-exercise evaporation is as rapid as possible, preferably while the body still has some surplus heat storage as a result of its exercise.

5. IDEAL CHARACTERISTICS:

These projections as to the interaction between the water handling characteristics of underwear fabrics, as measured by a variety of wicking, water absorption and drying tests, all require further confirmation against human perceptions. Nevertheless, it appears that the ideal underwear would be "soft", have extremely high wicking characteristics, should be able to absorb sweat in an amount of 400% of its dry weight or more in a minute or less, and should dry extremely rapidly despite being as thick, non-compressible and lightweight as possibly. Melting and flammability properties should also be considered and these aspects are discussed in Chapter 12.

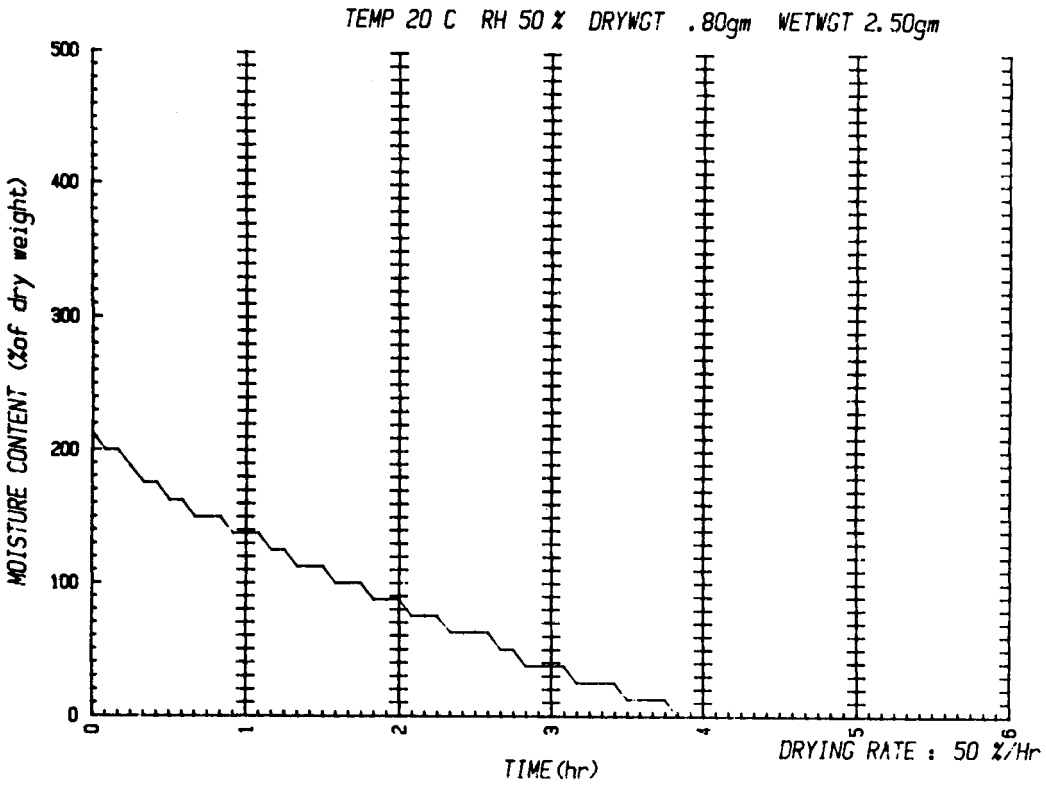


Fig 2: Moisture content as a function of drying rate

REFERENCES

1. Cassie, A.B.D., Underwear fabric characteristics for warmth. J. Textile Inst. 40: 444-453, 1949.

2. Darling, R.C. and G.E. Folk. Physiological effects of two types of brynje vests as an additional garment in the cold. Underwear Net (Brynje Vest) Project 268-43 Test HEL 101. OQMG Report No. 32, Fatigue Laboratory, Harvard University, September 30, 1944.

3. Fonseca, G.F. Heat-transfer properties of ten underwear-outerwear ensembles. Textile Res. J. 40: 553-558, 1970.

4. Hoge, H.J. and G.F. Fonseca. The thermal conductivity of a multilayer sample of underwear material under a variety of experimental conditions. Textile Res. J. 34:401-410, 1964.

5. Hollies, N.R.S. The comfort characteristics of next-to-skin garments, including shirts. In: Proc. Intl. Seminar on Textiles for Comfort, Shirley Inst., Manchester (England) 1971.

6. Kawabata, S. The Standardization and Analysis of Hand Evaluation (2nd Edition). The Textile Machinery Society, Japan, OSAKA, July 1980, pp. 97.

7. Rodahl, K., F.A. Giere, H. Staff, and A.B. Wedin. A physiological comparison of the protective value of nylon and wool in a cold environment. The Institute of Work Physiology, Oslo, Norway.

8. Wedin, B. Heat Insulating and Ventilating Garment. U.S. Patent No. 3,122,754 awarded March 3, 1964.

CHAPTER 11

BIOMEDICAL ASPECTS OF NBC MASKS AND THEIR RELATION TO MILITARY PERFORMANCE

S.R. Muza

CONTENTS

SUMMARY

INTRODUCTION

1. ADDED RESISTANCE TO BREATHING

   Resistance Standards for NBC Masks
   Respiratory Responses to Loaded Breathing
   Cardiovascular Responses to Loaded Breathing Exercise
   Performance Limitations

2. EXTERNAL DEAD SPACE

3. THERMAL STRESS OF THE NBC MASK AND HOOD

   Physical Effects
   Physiological Effects
   Psychological Effects

4. VISUAL LIMITATIONS

   Visual Field Restrictions
   Dynamic Visual Acuity
   Dark Adaptation
   Altered Space Perception

5. SPEECH TRANSMISSION AND RECEPTION

   Speech Transmission
   Sound Reception Ambient
   Ambient Noise

6. NBC MASK FORCES ON THE HEAD

7. PSYCHOLOGICAL PROBLEMS CONCLUSIONS

8 COMPLICATIONS OF LONG-TERM WEAR

REFERENCES

SUMMARY

The function of a nuclear, biological and chemical protective mask (NBC mask) is to protect the respiratory system from nuclear, biological and chemical warfare agents and, in concert with a hood, protect the face, eyes and head from percutaneous agents and skin contamination. While accomplishing these functions, the NBC mask and hood frequently impose a variety of physiological as well as psychological burdens on its user. Foremost of these burdens is the added resistance to breathing. Although modern NBC masks have relatively low levels of air flow resistance, several studies have shown that mask wear will reduce exercise endurance and intensity. This reduction in exercise performance may be manifested by both physiological as well as psychological responses. NBC mask wear increases the work load on the respiratory muscles and consequently the potential for development of muscle fatigue. The perception of effort during exercise while wearing a NBC mask is increased and unpleasant respiratory sensations, such as breathlessness, may develop which can cause a soldier to stop performing work. Wear of the NBC mask and hood may also increase the heat stress imposed on the soldier which can degrade performance of military tasks by increasing their physiological and psychological strain.

The face and head contain the principal sensory (eyes, ears, nose) and communication (mouth) structures of the body. Since the NBC mask and hood encapsulates these structures in order to protect them from contamination, impairment of sensory reception and vocal communication may occur. The degree of degradation observed is dependent upon the specific task and the conditions under which it is accomplished. For example, tasks requiring a large visual field are degraded by mask wear whereas tasks utilizing a small visual field might not be affected. Also, due to the rich sensory ennervation of the face and head, almost everyone who wears a NBC mask experiences some discomfort. Long-term wear of the NBC mask and hood can accentuate the distress experienced by a soldier by interfering with basic facial hygiene, eating and sleeping. The result could be lower morale, increased physiological and psychological strain and loss of military effectiveness.

Key Words: NBC masks, breathing resistance, muscle fatigue, exercise, heat stress

INTRODUCTION

Soldiers are provided with individual protective garments to guard them from nuclear, biological and chemical (NBC) contamination. A key item of these protective garments is the NBC protective mask (NBC mask). NBC masks can provide respiratory protection against radioactive particles and field concentrations of all known chemical and biological agents in both vapor and aerosol form.

The first employment of NBC masks in warfare was during World War I (17). Initially, German soldiers were equipped with the "face mask of the Ghent zone." This mask consisted of a cotton dressing sewn to a cloth the size of a handkerchief; the cotton dressing was soaked in alkaline sodium thiosulfate prior to use and the mask had to be kept moist during use. After the first major attack with Chlorine gas at Ypres (Ieper), Belgium in April 1915, the German Army issued the forerunner of the modern gas mask. It consisted of an oiled leather, bag-shaped mask with a filter which screwed to the body of the mask. Straps held the mask against the face. The British developed and issued their Small Box Respirator, which consisted of a rubber face-piece holding two glass eyepieces and a breathing tube which was connected to a filter-box. The French developed their own filter-box respirator called the Tissot. The U.S. Army was mainly equipped with the British Small Box Respirator but, owing to its high resistance to breathing, the U.S. modified the French mask, and late in the war issued the lower resistance American Tissot mask.

Concurrent with the employment of the NBC mask, the physiological and psychological burdens of NBC mask wear began to emerge. The most important parameters affecting military work performance with a NBC mask include: 1) the additional inspiratory and/or expiratory breathing resistance; 2) increased external dead space; 3) thermal stress of the mask and hood; 4) restriction of functional vision; 5) hindrance of speech transmission and reception; 6) weight, bulk and pressure on the face and head of the respirator and its straps; 7) claustrophobic reactions and 8) sleep loss and lack of water and nutrient intake associated with long-term wear.

The chapter's objective is to present a review of these factors, and how they can degrade the soldier's ability to perform military tasks. Although focused on research, development, test and evaluation efforts conducted by the United States, the findings appear to be applicable across the spectrum of NATO NBC masks.

1. ADDED RESISTANCE TO BREATHING

Resistance Standards for CB Masks. The healthy adult has an average airway resistance of 0.8 $cmH_2O \cdot liter^{-1} \cdot s^{-1}$. By contrast, the typical modern NBC mask produces about a four-fold increase in the resistance to breathing. Although an early recognized limitation of the NBC mask was its inspiratory and expiratory resistance, the development of standards for acceptable levels of breathing resistance of NBC masks did not occur until World War II. Several studies by Silverman et al. (57,58) investigated the effects of breathing against added resistance while working at various rates on a cycle ergometer. Healthy male subjects exercised for 15 minute periods at work rates ranging from 68 to 180 watt (W) with added inspiratory resistances ranging from 0.4 to 7.5 $cmH_2O \cdot l^{-1} \cdot s^{-1}$. (NBC mask airflow resistance is typically measured at an airflow of 85 $l \cdot min^{-1}$. However, many of the resistances reported in

this text were measured between 30 to 100 $l \cdot min^{-1}$ airflows). Increases in the resistance to breathing resulted in decreased submaximal oxygen uptake and minute ventilation at work rates above 135 W. Most subjects were able to tolerate the increased resistance provided the total respiratory work required to breathe through a mask (usually calculated by integration of the instantaneous product of pressure and flow) did not exceed 0.41 W at the low workloads and 2.2 W at the high workloads. These data have provided the basis for most modern military NBC mask design criteria and certification tests.

In 1960, Cooper (10) suggested standards of resistance which he expressed as the rate of respiratory work done on a breathing apparatus per minute ventilation. The maximum respiratory work rate done on a mask expressed in $kgm \cdot min^{-1}$ was arbitrarily set at one-fourth of the minute ventilation expressed in $l \cdot min^{-1}$ (e.g., if the minute ventilation is 40 $l \cdot min^{-1}$, then the maximum rate of respiratory work done on a mask should not exceed 10 $kgm \cdot min^{-1}$ (1.6 W)). Since Silverman et al. (57) had suggested lower levels of respiratory work, Cooper acknowledged that this standard may represent an excessive resistance and that the ideal mask may have a resistance one-half of this standard. However, Cooper believed that with training in breathing against resistance and improved physical condition, subjects could tolerate this level of respiratory work. Thirteen years later, Bentley et al. (6) re-evaluated tolerance to added resistance to breathing in 158 mine rescue workers during exercise. The exercise consisted of a 30-minute walk on a treadmill with the work rate altered between subjects to obtain a wide range of minute ventl$_i$lations. The added inspiratory resistance ranged from 2.4 to 21.0 $cmH_2O \cdot l^{-1} \cdot s^{-1}$. After completion of the exercise, each subject selected one of four statements which most closely described his sensation of the effect of the resistance on his breathing. The results indicated that both the peak inspiratory pressure and the inspiratory work rate per liter of inspired air were closely correlated with the sensation of dyspnea (shortness of breath). From these data, Bentley et al. (6) formulated a standard for acceptable resistance such that 90% of the population tested would not experience dyspnea. They determined that the level of external respiratory work done on a mask should not exceed 1.7 $J \cdot l^{-1}$ of inspired air. Regardless of flow patterns, under steady flow conditions, the pressure drop across the inspiratory valve and filter should not exceed 17.0 cmH_2O. This level of tolerable external respiratory work is below those suggested by Cooper (10), but above those derived by Silverman et al. (57).

Given the pressure-flow characteristics of several different NBC masks (U.S. M17A1, M25, XM40; British S6 and Netherlands C-3) and applying Bentley et al. (6) results one can predict that discomfort in breathing would be experienced by 10% of the wearers at minute ventilations ranging from 55 to 89 $l \cdot min^{-1}$. These minute ventilation levels are commonly attained during moderate to heavy intensity exercise and may represent the threshold above which the widespread development of dyspnea may impair soldier work performance.

<u>Respiratory Responses to Loaded Breathing.</u> The physiological mechanism(s) by which added resistance to breathing impairs work performance is potentially complex. Several studies (9,18,28) have investigated the effects of added resistance applied to inspiration and/or expiration during exercise at various intensities. With increasing added resistance to breathing, minute ventilation and endurance time decreased at each level of exercise. The reduction in ventilation was directly proportional to the increase in resistance. Hermansen et al. (28) noted that ventilatory rates were lower with the NBC mask on and rose to only 30 $breaths \cdot min^{-1}$ during exercise. Maximal oxygen uptake ($\dot{V}O_{2max}$) was reduced, but the

relationship between oxygen uptake and sub-maximal workload (>75 percent of $\dot{V}O_{2max}$) was not altered. However, there was no clear evidence that an additional shift to anaerobic metabolism occurred. When breathing through added resistance, the relative hypoventilation resulted in an increase of alveolar carbon dioxide, which may impair the capacity for work (via a mixed metabolic and respiratory acidosis). Cerretelli et al. (9) also observed that at the highest levels of exercise the work could no longer be tolerated when the intra-thoracic pressure difference between inspiration and expiration exceeded 100 cmH_2O. They speculated that when intra-thoracic pressure swings approach this level, some protective mechanism intervenes to limit the respiratory work.

Demedts and Anthonisen (18) observed that at each level of added resistance, maximum exercise ventilation was about 70 percent of the 15 sec maximum voluntary ventilation measured with that resistance. Second, in four of the five subjects they examined, an important relationship was observed between these individuals' ventilatory response to CO_2 and the degree of their respiratory effort while breathing against added loads. When breathing was opposed by added resistance, subjects with low CO_2 sensitivity minimized their ventilatory effort and let their alveolar CO_2 rise; in contrast, those subjects who were most sensitive to CO_2 increased their respiratory work and maintained alveolar CO_2 near normal. Consequently, by increasing their minute ventilation, the latter subjects' exercise intensity and duration were more limited by the added resistance. The authors concluded that the exercise limitation imposed by added resistance to breathing depends both on the ventilatory limitations produced by the resistance and on the CO_2 responsiveness of the individual.

Several investigators (14,30) have shown that this limitation of ventilation during exercise results from attempts to minimize the total respiratory work by reducing the expiratory time duration (T_E) in order to prolong the inspiratory duration (T_I) of each breath. Since the NBC mask produces its greatest resistance to breathing during inspiration, this strategy reduces inspiratory work while letting expiratory work increase slightly. Johnson and Berlin (30) demonstrated in 10 subjects that a minimum T_E of 0.66 s corresponded to the voluntary termination of exercise. However, Stemler and Craig (62) observed a variable T_E at the termination of exercise. They suggested that the minimal T_E attained is more a function of expiratory resistance than a general limitation on expiratory performance. Expiratory resistance of NBC masks can be increased by hood designs which increase protection against agent penetration by incorporating a "neck dam". Still, when wearing a NBC mask, minute ventilation can increase in response to the metabolic demands of the exercise until a minimum T_E is reached. Thereafter, minute ventilation falls below the metabolic needs of the individual and impairs continued exercise performance.

When breathing is opposed by resistance loads, the ventilatory responses are regulated by the combined actions of mechanical load compensation intrinsic to the respiratory muscles and neural load compensation which are extrinsic to the muscles (3). In conscious humans, the ventilatory response to resistive loading is also modulated by neural responses mediated by conscious perception of the added load (3,65). The NBC mask opposes breathing by applying a non-linear, phasic, flow-resistive load. It is further defined as a passive load since the respiratory muscles must develop forces to overcome the load. Axen et al. (3) analyzed ventilatory responses to 10 consecutively loaded (range 10-45 $cmH_2O \cdot l^{-1} \cdot s^{-1}$) inspirations. The first breath response to the added resistance was an increased duty cycle (T_I/T_T) due to

a lengthened T_I, and a decreased mean inspiratory flow (V_T/T_I) caused by the reduction of V_T. Consequently, minute ventilation was reduced. During subsequent breaths, minute ventilation progressively increased toward control levels due principally to augmentation of mean inspiratory flow (increased V_T), suggesting an increase in neural drive to the respiratory muscles. These ventilatory adjustments to added resistance probably represent the combined action of intrinsic muscle properties, extrinsic neural load compensation, and consciously mediated responses as well as the chemical drive for ventilation.

Minute ventilation is dependent upon the transformation of central respiratory drive into muscle force which acts upon the chest wall. The chest wall is divided into two parts, the rib cage and abdomen. Three principal muscle groups act upon the rib cage and abdomen to displace them: the inter-costal muscles, the diaphragm and the abdominal muscles. A recent study (40) reported that the rib cage contribution to tidal volume increased significantly, from 68% during quiet breathing to 78% when inspiring through added resistance. The authors suggested that there was a greater recruitment of the rib cage inspiratory muscles than the diaphragm during resistive loading, although intrinsic properties of the chest wall musculature may also have contributed.

A potential consequence of prolonged work while wearing a NBC mask is respiratory muscle fatigue. During exercise with no opposition to breathing, ventilatory muscle endurance does not appear to constitute a limitation to exercise performance (7). However, the work of breathing increases as the resistance increases. The greater the fraction of the maximum inspiratory muscle force developed to breathe across a resistance, the greater the energy demands of the muscle. Several studies have found that development of diaphragm fatigue was dependent upon both the relative tension developed (53) and the duration of the contraction (5). More recently, McCool et al. (38) determined that the velocity of muscle shortening, as characterized by inspiratory flow, also influences the endurance of the inspiratory muscles. Although it has been speculated that respiratory muscle fatigue is a limiting factor of work performance when wearing NBC masks, this relationship has not been demonstrated.

As stated earlier, in conscious humans the ventilatory response to mechanical loading is also modulated by neural responses mediated through conscious perception of the added load (3). Using the psychophysical technique of scaling, it is possible to assess subjects' performance in judging the magnitude of respiratory sensations (47). Results of several studies suggest that signals related to respiratory muscle force generation (2) and motor command (8) contribute to the sensation of respiratory loads.

Perceptual performance during a scaling task is very reproducible within a given subject, but varies greatly between different subjects (33). Little is known concerning the important question of whether or not an individual's sensitivity to respiratory sensations influences how he regulates ventilation when breathing is opposed. Two studies (23,46) have demonstrated a relationship between subjects' sensitivity to respiratory sensations and ventilatory load compensation. Their results suggest that subjects who have a greater sensitivity in scaling added inspiratory loads are better able to preserve their ventilation when unexpectedly confronted with an added load. The wide range of perceptual performance observed in the healthy adult population may account for the reported variability between

subjects in the degree of discomfort felt and the tolerance to exercise under similar conditions of physical stress while breathing through a NBC mask.

Cardiovascular Responses. Several studies have evaluated the cardiovascular responses to loaded breathing. Hermansen et al. (28) reported that average heart rates during submaximal exercise were higher when wearing the U.S. NBC mask, but were similar at maximum exercise intensity to those obtained without added resistance to breathing. Conversely, Van Huss et al. (63) reported reduced exercise heart rates with NBC mask wear. Furthermore, the exercise heart rates were inversely related to the magnitude of the added resistance to breathing. Lerman et al. (36) observed similar heart rate responses during short duration, high intensity exhausting exercise. As the magnitude of the inspiratory resistance increased from 0.3 to 4.6 $cmH_2O \cdot l^{-1} \cdot s^{-1}$, the heart rates at the end of each run decreased from 190 ± 2 to 185 ± 2 $beats \cdot min^{-1}$. Other studies (45,51) have reported no differences in exercise heart rates associated with NBC mask wear. The physiological mechanism(s) responsible for the heart rate alterations is not clear. Possibly, the larger intrathoracic pressures occurring with NBC mask wear enhance venous return and therefore stroke volume resulting in lower heart rate via the baroreflex.

Blood pressure responses during exercise appear to be unaltered by NBC usage. Two studies (36,51) reported no significant differences in systolic blood pressure measurements during short-term fatiguing exercise. However, in a third study (61) a 24 percent increase in recovery systolic blood pressure was reported when wearing NBC mask during a Harvard Step Test. This result suggests increased cardiovascular stress during exercise with NBC mask usage.

Exercise Performance Limitations. Many studies have investigated the exercise performance decrement that can be attributed to NBC mask wear. With tasks that demand a high percent of maximal aerobic power, performance seems to be dependent on breathing resistance (31). Cummings et al. (15) reported that wearing a NBC mask increased the time to accomplish a one-half mile run by 11%. Lotens (37) found a 16% performance decrement during 400 m and 3 km runs while wearing the C-3 respirator and he notes that similar results were obtained during British studies of their S-6 respirator. Several studies (12,20,36) have demonstrated that any amount of added resistance to breathing causes a decrease in exercise endurance and performance. Most studies have tested work performance of men wearing masks using both fixed task-variable rate and fixed rate-variable time end points. A different approach to evaluating work performance is the use of perceived exertion or sense of effort to set and adjust exercise intensity.

Pandolf and Cain (49) demonstrated that when subjects maintain exercise at a constant sense of effort, they decrease the intensity of the exercise over time. The relationship between exercise intensity and exercise duration is known as a constant effort function. Recently, we studied constant effort dynamic cycle exercise (for 20 minutes) in order to learn whether the constant-effort functions were affected by added inspiratory resistance (5.8 $cmH_2O \cdot l^{-1} \cdot s^{-1}$). Preliminary results demonstrate that with minimal inspiratory resistance (1.0 $cmH_2O \cdot l^{-1} \cdot s^{-1}$) the constant-effort functions declined approximately 20% during the initial eight minutes of exercise and then remained relatively constant. With the added inspiratory resistance, the constant-effort functions followed a similar pattern for the initial eight minutes but then continued to decline throughout the exercise period reaching a power output that

was approximately 30% below the starting level. The subjects also performed maximal exercise tests with the same minimal and increased inspiratory resistances levels. Although increased inspiratory resistance caused a significant reduction of peak minute ventilation, the maximal oxygen uptakes and peak power output levels were not altered. These data suggest that while this level of inspiratory resistance may not diminish achievement of maximal power output and aerobic capabilities for short durations (>10 minutes), it does enhance the subjects' perceived sense of effort during prolonged exercise. Consequently, while wearing NBC masks, individuals engaged in military tasks requiring high levels of physical exertion for sustained durations are subject to performance degradation. This is consistent with the observations of Lotens (37), who observed that performance is dependent on the magnitude of the breathing resistance as well as the duration of the task.

2. EXTERNAL DEAD SPACE

Effective gas exchange in the lungs requires an adequate amount of fresh air entering the alveoli with each breath. Consequently, each tidal volume is composed of an anatomical dead space volume (the air in the airways at the end of expiration) and an alveolar volume. In a normal adult male the anatomical dead space has an internal volume of about 150 ml. The alveolar volume is increased or decreased depending on the metabolic needs of the subject. The external dead space is an extension of a subject's anatomic dead space. It is the volume of expired air contained within the mask which during the next inspiration must be moved into the alveoli before any fresh, filtered environmental gas can enter. When a soldier dons a NBC mask, he artificially increases his dead space volume. If the soldier does not increase his tidal volume, then the volume of fresh air entering the alveoli will decrease for a given breath. Bartlett et al. (4) found that minute ventilation increased when the external dead space exceeded 50 ml. They also observed a nearly linear relationship between external dead space volume and ventilation during submaximal exercise. When the external dead space is increased (e.g., by wearing a NBC mask) the soldier initially inspires a larger fraction of carbon dioxide enriched gas. As the alveolar CO_2 increases, so does the arterial partial pressure of CO_2 (P_aCO_2). The stimulus to increase minute ventilation in response to added external dead space is this elevation in arterial CO_2 termed "hypercapnic drive". The increased P_aCO_2 stimulates the peripheral and central chemoreceptors, which increase ventilatory drive via the respiratory control centers in the brainstem. Since the ventilatory sensitivity to CO_2 varies greatly between individuals, a given volume of external dead space can produce a wide range of ventilatory responses.

Modern NBC masks are designed to minimize the size of the external dead space. However, dead spaces between 300-500 ml are common to NBC masks. Furthermore, a poor seal of the mask's nose cup or internal partitions with the wearer's face can result in internal mask leaks, which may increase the volume of the external dead space. Craig et al. (13) have shown that an increase in inhaled CO_2 is not well tolerated when combined with increased resistance. Since the effect of increased dead space is increased minute ventilation, tasks requiring aerobic performance can be degraded by the sustained increase of ventilation and the additional work of breathing. Furthermore, specialized tasks which require precise control over breathing motions (i.e., sharpshooting, etc.) can be hindered by the responses to external dead space.

3. THERMAL STRESS OF THE CB MASK AND HOOD

The NBC mask will have to be worn in a variety of environmental extremes. In warm environments, the addition of a NBC mask and its associated hood to the NBC protective overgarment will increase the heat stress level imposed on the soldier. This increased heat stress can limit the soldier's performance of military tasks by increasing physiological and psychological strain.

Physical Effects. The transfer of heat from the body via the head is simply a function of the surface area available. Since the head constitutes less than 10% of the body surface area, the proportion of the total body heat loss by the head is generally relatively small. However, when any clothing, and in particular chemical protective overgarments, are worn the relative contribution of the head to total body heat loss increases as the other areas of the body are covered. Consequently, wearing a NBC mask and hood over the head can seriously reduce the already limited heat loss capability of the body. In a study done by the U.S. Army (19) with an air motion of 0.3 $m \cdot s^{-1}$, the insulating air layer around a bare head was reported as 0.64 clo units. The evaporative moisture permeability (i_m) was 0.62 yielding a permeability index ratio (i_m/clo) value of 0.97; i.e., sweat evaporation cooling from the bare head is only 3 percent less than the maximum evaporative cooling capacity of the environment. When the standard U.S. M-1 helmet was worn, the i_m/clo value dropped to 0.43 indicating greater than a fifty percent reduction in heat transfer from the head.

Subsequently an evaluation of the U.S. M17 mask, alone and with the M6 protective hood, was conducted (23) to discriminate the heat stress effects of a protective hood from the heat stress effects of the NBC mask. In still air, the standard U.S. helmet and M17 NBC mask on a sweating sectional manikin head yielded an i_m/clo value of 0.13; with the addition of the impermeable M6 hood, the permeability index ratio decreased to 0.02 i_m/clo. Assuming that a soldier is wearing a helmet, donning a NBC mask without a hood can reduce heat transfer from the head by approximately 70 percent and adding the hood can make the total decrease in heat transfer greater than 90 percent. Furthermore, the M6 hood also covers the shoulders and seals the opening at the jacket's collar, thus reducing evaporative heat transfer from the torso area by about 25%. If the body is already having difficulty in meeting its requirements for heat loss (i.e., if protective garments are being worn) this loss of heat transfer from the head and torso could result in significantly increased core temperature and decreased work performance as a result of the increased body heat storage.

A soldier wearing a NBC mask in direct sunlight may gain heat in the area of his face by the mask's "green house effect". Belard (personal communication) has shown that radiant energy entering through the mask's lenses can cause the temperature within the mask to rise several degrees. NBC masks with large lenses or transparent facepieces collect more radiant energy. However, the ventilatory induced air motion within the mask attenuates this green house effect. Heat gain via this pathway maybe a problem, or at least a nuisance, during tasks requiring minimal movement and subsequently low ventilatory rate (e.g., manning an observation post, etc).

Physiological Effects. Several studies have attempted to evaluate the effect of NBC mask wear on the physiological responses during exercise in the heat. Robinson and Gerking (52) studied, in two heat acclimated subjects, the effects of NBC masks on sweat rate, heart rate and body temperature in both hot/wet (T_a = 30.5 °C, T_{dp} = 27.7 °C) and hot/dry (T_a = 45

°C, T_{dp} = 26 °C) environments. In both environments the subjects wore jungle fatigues, and exercised for two hours (~350 W). Wearing a NBC mask and impermeable hood elevated sweat rate by about 28% above the no mask and hood controls in the hot/wet and by about 16% in the hot/dry environment. Mean skin temperature was increased, but core temperature was not further elevated when the mask and hood were worn. Finally, heart rate tended to be higher with the mask on.

Similar results were obtained in a British study (39) in which the heat stress of an S6 respirator was evaluated in four heat acclimated subjects in a test environment of T_a = 34.0 °C and T_{dp} = 25.5 °C. The exercise consisted of 120 minutes of bench stepping, which yielded a work rate of ~230-350 watt. The subjects were tested with and without the S6 NBC mask wearing an Army tropical khaki uniform or the same uniform with the UK No. I, Mk 1, NBC protective overgarment and neoprene gloves. Final exercise sweating rates and heart rates were significantly elevated when wearing the NBC mask compared to the no mask condition. However, the NBC mask had a significant effect on final exercise rectal temperature only when the NBC protective overgarment was worn; with both uniforms, wearing the mask elevated skin temperature. The authors also demonstrated that as the total sweat loss increased, that portion attributed to wearing the mask decreased. However, as rectal temperature increased, the effect on rectal temperature attributed to the mask significantly increased. Finally, the authors concluded that the elevated heart rate measured during mask wear was due to the mask and could not be attributed to an elevation in core temperature.

James et al. (29) recently evaluated the effects of two industrial respirators on physiological responses to work in the heat. Five unacclimatized subjects wearing trousers and long-sleeved shirts performed one hour treadmill exercise tests at two work rates (58 and 116 W) and in two environmental conditions (T_a = 25 °C, T_{dp} = 14 °C and T_a = 43.3 °C and T_{dp} = 14 °C). These four tests were conducted with the subjects wearing either a half face or full face air-purifying respirator or a Collins large mouthpiece and nose clip ("no mask" condition). No hood was worn with any of the masks. When compared to the "no mask" condition, both masks significantly elevated heart rate, by about 9 percent. Core (oral) temperature was significantly elevated (0.33^0C) during the 116 watt exercise while wearing the full facepiece respirator compared to the no mask condition. Likewise, the full facepiece respirator increased minute ventilation about 18 percent compared to the no mask control. The authors attributed this minute ventilation elevation to the large dead space of the full facepiece mask. Neither mask had any effect on whole body sweat rate or metabolic rate in either the comfortable or the hot dry environment which should not be surprising in view of the clothing worn and the low ventilatory demand of the work. However, the authors concluded that the greater dead space volume and surface area covered by the full facepiece mask is associated with a greater physiological strain than when the half-mask type of respirator is used. Belard (personal communication) has observed that sweating under the NBC mask and hood causes an uncomfortable accumulation of liquid which soaks the chin. Also, it has been reported that sweat may penetrate the filter elements in NBC masks which contain the filters within the mask facepiece (e.g., U.S. M17). This can cause meaningfully increased inspiratory resistance and degrade the filter's protective function.

Psychological Effects. Aside from the actual physiological strain imposed by wearing NBC masks in warm environments, there exists the psychological acceptability of a NBC

mask in these environments. Factors such as the dry bulb temperature and dew point of the air inside the NBC mask, and facial skin wettedness, affect the temperature and comfort sensations for the whole body. In a recent study by Gwosdow et al. (25), six subjects wearing ventilated masks during rest and exercise in a wide range of environmental conditions were asked to rate their whole body thermal sensation and perception of breathing effort. Increasing the dry bulb or dew point temperatures in the mask decreased whole body thermal acceptability. The whole body thermal sensations were directly correlated with upper lip skin temperature. Moreover, the subjects perceived breathing to be more difficult with increasing intra-mask temperature and humidity. NBC mask acceptability and the capacity to perform essential military tasks may be severely degraded by the interaction of soldiers' psychological acceptability of the NBC mask and the increased physiological strain due to NBC mask wear. In military vehicles containing microclimate cooling systems, consideration should be given to the temperature and humidity control of the cooling air ventilating the facepiece.

4. VISUAL LIMITATIONS

The successful employment of surveillance and weapon systems on a modern battlefield, requires minimal interference with a soldier's functional vision. Wearing a NBC mask can significantly degrade a soldier's vision, resulting in substandard performance of military tasks (11,41). Degradation of functional vision can be the result of several factors, including: 1) visual field restrictions; 2) reduced dynamic visual acuity; 3) dark adaptation; and 4) altered space perception. Also, it should be noted that, under certain circumstances, NBC mask wear can contribute to the development of conjunctivitis; masks which are ventilated by a blower can produce a flow of dry air across the eye which could cause irritation of the surface of the eyeball.

Visual Field Restrictions. Standard clinical procedures employing Projection Perimeter apparatus have been used to obtain visual field measurements. Usually, the visual field measurements made when wearing a NBC mask are compared to the "no mask" (unrestricted) measurements. A NBC mask reduces the wearer's visual field; the magnitude of the reduction is dependent upon the design of the facepiece and its fit on the subject's face. Three basic lens designs are usually used in NBC masks. These include: 1) two separate binocular lenses; 2) a single piece windshield lens; and 3) a single full facepiece (panoramic) lens. Masks using the two binocular lenses (U.S. M-17, British S6) generally demonstrate the greatest decrement in visual field. This style of lens particularly restricts the inferior medial and inferior oblique portions of the visual field (22,64). All styles of lenses tend to restrict the inferior visual field. This common observation can probably be attributed to NBC masks incorporating a voicemitter assembly and/or exhalation valve on the exterior of the oral-nasal portion of the facepiece; this exterior assembly blocks the wearer's inferior visual field.

A second factor which can affect the wearer's visual field is proper fit of the mask on the user. For example, if the surface of the lens is positioned far ahead of the eyes, then the visual field is further restricted. An additional factor which may affect the wearer's visual field is the wear of corrective lens. Most NBC masks provide for the use of spectacle inserts which provide eyeglass wearers with the necessary refractive power to maintain normal vision when wearing a NBC mask. The potential exists for users of spectacle inserts to experience further

degradation of their visual field due to the interference with peripheral vision normally attributed to corrective lens wear. Finally, the visual field can be further reduced by fogging of the respirator's lenses or accumulation of opaque material (dirt, frost) on the lenses.

Alignment of the eye with weapon and surveillance systems optical sights can be hindered by the size and shape of a NBC mask. This could decrease the effectiveness of these systems. However, performance of certain tasks may be enhanced by NBC mask wear. The narrower field of view may eliminate distractions and help the soldier concentrate on his task. Hand-eye coordination tasks may be degraded by respirator wear. However, a recent study by Johnson et al. (31) showed that wearing a gas mask and hood (M17A1) did not impair the manual dexterity of soldiers performing the O'Connor Five Finger Dexterity Test or the Purdue Pegboard Assembly Test. Since both of these tests only require a small field of vision, they are probably not good measures of manual dexterity tasks which occur over a large visual field.

Dynamic Visual Acuity. NBC mask wear has been shown to reduce the dynamic visual acuity of the wearer (64). The typical test of dynamic visual acuity requires the subject to track a target at a constant rate across the visual field, while the target angular size and direction of travel are randomly varied. In a study done by the U.S. Army (64), when wearing a NBC mask the target angular size had to be increased by 7-38% over "the no mask" condition to achieve a 95% detection criterion. These results indicate that NBC mask wear interferes with the wearer's ability to detect and then track a rapidly moving target. This loss of performance may be attributed to the scattering of light by the mask lens. This degradation of dynamic visual acuity can hinder a soldier's ability to detect moving targets, or the ability of an operator of a moving combat vehicle (air or ground) to avoid obstacles.

Many military tasks require the detection of visual events or signals occurring anywhere in the visual field. Kobrick and Sutton (35) developed a laboratory device for measuring the voluntary response time to such visual stimuli. The task required the subject to monitor stimulus lights distributed about the visual field and to depress a handheld push-button switch whenever the onset of a signal light was detected. Average response time was tabulated as a function of the stimuli location within the visual field. In a subsequent study, Kobrick and Sleeper (34) compared the effects of wearing NBC protective clothing (U.S. Army MOPP IV) on the ability to detect visual signals throughout the visual field. Tests were conducted while the subjects wore the U.S. Army battledress uniform or the NBC protective ensemble including the M17A1 mask for a continuous 8-hour period.

With no NBC mask on, significant increases in response times for visual signal detection occurred with peripheral displacement of the target. These impairments became substantially greater when the subjects were wearing the NBC mask while encapsulated in NBC protective garments. With no mask, the mean response times also increased with visual stimulus locations in the superior and inferior visual field areas, and were shortest with targets along the horizontal axis of view; again, wearing the NBC mask and protective overgarment significantly increased these response times. There was no progressive cumulative effect of wearing the protective overgarment and NBC mask over the daily 8-hour testing session. These results indicate that wearing a NBC mask and protective overgarment seriously limits functional vision. Furthermore, this limitation occurs with the donning of the protective ensemble and remains undiminished for at least eight hours.

Dark Adaptation. The transmission of light through the lenses of NBC masks is reduced by the material comprising those lenses. This may interfere with the soldier's ability to detect targets which have low Illumination at night. In a test (64) of the effect of NBC mask wear on visual sensitivity following 40 minutes of dark adaptation, mask wear degraded visual sensitivity approximately 1 log unit. Hence, the apparent brightness and information content of images transmitted through the NBC mask is reduced. The reduced transmission of light through the lens of NBC masks could also reduce the definition of images by shifting the operation of the visual system from the area of central vision (fovea centralis) to the periphery of the retina. The fovea centralis consists only of specialized nerve endings called cones. The cones are responsible for the high optical efficiency of the fovea centralis. Although the cones do adapt to the dark, their threshold shift is not nearly as extensive as that of the rods (21). Consequently, when wearing a NBC mask at night, vision may become totally dependent on the activity of rods, and thus will be degraded.

Altered Space Perception. The proper perception of space and distance is a basic requirement for the successful performance of tasks requiring good depth discrimination. Proper space perception when wearing a NBC mask depends upon minimizing the prismatic power of the lens material. Prismatic power alters the normal convergence of the incident light thereby changing the convergence demand of the oculomotor system (64). Excessive prismatic power could upset the balance of the accomodative and convergence components of the eye, resulting in degradation of functional vision and development of ocular distress (eye strain). The utilization of spectacle inserts by soldiers requiring corrective lenses can also alter space perception. In many NBC masks, spectacle inserts can become loose, thus displacing the alignment of the lenses with the eyes. This may cause altered space perception, eye strain and optical distortions which could further reduce the visual field and visual acuity. Consequently, the ability to perform military tasks can be greatly degraded, even if not made impossible to accomplish.

5. SPEECH TRANSMISSION AND RECEPTION

A key element in the successful accomplishment of military tasks is clear verbal communications. The physical transmission and reception of audio signals are significantly degraded by wear of a NBC mask and hood. This hindrance of audible signals by the NBC mask and hood is primarily the result of three factors: 1) degradation of speech transmission; 2) attenuation of sound reception; and 3) increased ambient noise.

Speech Transmission. Most NBC masks are equipped with a voicemitter assembly which permits the transmission of speech by the wearer of the mask. Typically, the voicemitter is located in the masks nose cup area in front of the soldier's mouth. In some NBC masks, a smaller auxiliary voicemitter is located on a side of the mask beside the nose cup. This additional voicemitter permits the normal use of telephone style communications handsets. As sound passes through the voicemitter, the transmission quality is degraded and the signal volume is reduced. In a 1967 study of speech amplifier systems for protective NBC masks, Abbagnaro et al. (1) found that the M17 mask alters normal speech response by producing a roll-off of the speech energy above 1000 Hz. This roll-off at high frequencies gives the speaker's voice a bassy, muffled quality and reduces the speech intelligibility by hindering transmission of consonant sounds.

Sound Reception. Sound reception is not impeded by the wear of a NBC mask which does not cover the ears. However, the hood which is normally worn in conjunction with a NBC mask can hinder sound reception. The degree to which sound reception is degraded is probably dependent upon the hood material, the fit of the hood over the head, and the tightness of the hood's seal to the other garments. The U.S. M6 impermeable hood, which is coated with butyl rubber, muffles sound. On the other hand, the British NBC smock and attached hood are made of permeable materials. This style of hood has been shown to produce negligible attenuation of sound below 2 kHz (54).

Numerous tests of NBC mask wear on the performance of individual combat skills have demonstrated large degradation of verbal communication task performance (11,16,41). In a stressful combat environment with both the speakers and listeners wearing NBC masks, it is very likely that voice commands will be severely hindered or completely impossible. The use of hand signals will be essential. However, previously discussed restrictions on functional vision may also degrade this form of communication.

Ambient Noise. Although wearing a NBC mask and hood muffles sound reception, it simultaneously increases the level of background sound or noise heard. The primary source of increased noise is the soldier and his garments and equipment. When wearing a NBC mask and hood, the soldier is more likely to hear sounds associated with his breathing and with movement of his clothing. This increased level of ambient noise can reduce the soldier's ability to detect external sounds and their source. Consequently, performance of surveillance-type tasks which depend upon auditory clues may be degraded.

Operators of air and ground combat vehicles wear noise attenuating communications headsets. The headset provides the soldier communications and hearing protection from the operational environment. A British study (54) evaluated the effect of wearing the NBC hood under an AFV Crewman's Helmet on noise attenuation. The results indicated that wearing the hood under the helmet increased the level of noise reaching the soldier's ear. Thus, the hearing protection afforded by the helmet was decreased when wearing the NBC hood. Similarly, recent U.S. Army studies (44,48) found that the wear of several models of NBC masks under the SPH-4 aviator helmet significantly reduced the noise attenuation function of the helmet at all frequencies evaluated. It was determined that the mask’s straps passing near the ears created a leakage path for the noise. This loss of protection can aggravate hearing loss among crew members and adversely affect communications. Future NBC mask and hood designs should be integrated with the combat crewman's helmet and headset to maintain adequate hearing protection and communications.

6. NBC MASK FORCES ON THE HEAD

Wearing a NBC mask requires it to be supported by the head. Furthermore, the efficiency of the NBC mask in preventing agent penetration of the respiratory tract is dependent upon establishing an adequate facial seal. Force is transmitted to the face and scalp in the process of attaining a reliable seal. The combination of forces applied to the head, face and scalp by a respirator certainly affects the soldier's personal comfort and the masks acceptability. Moreover, these forces may have numerous physiological effects including fatigue of head and neck muscles and restriction of cutaneous and facial muscle blood flow.

Generally, NBC masks weigh less than 1 kg. However, due to their displacement far anterior of the Occipito-Atlantal articulation, the weight of a NBC mask could produce forces causing flexion of the head. In order to maintain a heads-up posture, a soldier has to overcome the force of the mask by increasing the activity of muscles that produce extension of the head (i.e., the Rectus capitis posticus major and minor, the Superior oblique, the Complexus, Splenius and the upper fibers of the Trapezius). Consequently, the potential exists for accelerated development of fatigue in these muscles. Even in the absence of muscle fatigue, the constant load on this muscle group could result in the development of pain, tenderness, a stiff neck, backache or headache. These symptoms have been reported by soldiers during wear of NBC masks (16,26).

When a NBC mask is properly worn, pressure is applied against the skin of the face and scalp by the peripheral edge of the mask and by the straps and buckles which secure it to the head. Under these pressure points, irritation and abrasion of the skin has been reported (16,26,59). Belard (personal communication) reported that contact pain appeared within 2-5 hours under the forehead and temples. The extent of damage done to the skin is related to the magnitude of the force applied, the hardness (durometer) of the mask's periphery and the surface area covered by the seal or straps. Damage to the skin can be minimized by reducing the force against the skin (60), constructing the mask's periphery of lower durometer material and increasing the seal's surface area to better distribute the forces (22). The restriction of cutaneous and muscle blood flow and drainage of the lymphatic vessels is affected by the same mechanical factors listed above. Restriction of lymph drainage from the scalp results in the formation of edema, which has been observed during wear of NBC masks (16). Development of skin abrasions and edema could result in the soldier experiencing discomfort and irritability of sufficient magnitude to degrade the successful accomplishment of military tasks. Stemler and Craig (62) found that wearing a US M9 NBC mask with the lenses, voicemitter, valves and filter, removed still resulted in a significant reduction of exercise duration. These results indicate that the forces applied to the head by the NBC mask can degrade the performance of military tasks requiring aerobic activity.

7. PSYCHOLOGICAL PROBLEMS

In a recent article (42) Morgan reviewed several of the psychological problems associated with the wearing of protective respirators. Among these problems are NBC mask discomfort, claustrophobia and development of anxiety and hyperventilation.

Mask discomfort depends on a variety of factors. A number of these have already been reviewed (pressure points of the head and face, sensations of breathing difficulty, temperature and humidity inside the mask, limits on vision, speech and hearing). Additionally, there is the individual's perception of the degree of stress each of these factors imparts. Recently, Morgan and Raven (43) tested the hypothesis that an individual's likelihood of experiencing distress when exercising while wearing a mask, could be predicted from their level of trait anxiety. They tested 45 male subjects by first administering Spielberger's trait anxiety scale and then giving three submaximal exercise tests while the subjects wore a self-contained breathing apparatus with an inspiratory resistance of 6.07 $cmH_2O \cdot l^{-1} \cdot s^{-1}$. Spielberger's model of trait anxiety predicts that high scoring individuals would be more likely to experience anxiety attacks when performing physically hard work while breathing through a mask. Morgan and Raven (43) predicted that subjects with trait anxiety scores one standard deviation or greater above the group mean would experience respiratory distress during the exercise while wearing the breathing apparatus. The results confirmed their hypothesis. Based on the trait anxiety scores, the "hit" rate for predicting distress was 83 percent and their accuracy for predicting no respiratory distress was 97 percent. These results demonstrated that trait anxiety was effective in predicting the development of respiratory distress during exercise while wearing a breathing apparatus.

A recent series of studies (50) by the U.S. Army, assessed the capability of soldiers to conduct sustained military field operations while wearing full chemical clothing ensemble. The 81 soldiers were administered a battery of psychological tests (including subjective symptoms and a coping strategy inventory) prior to and after the field operations. Soldiers who failed to complete the 72-hour operation were classified as casualties. The single symptom which maximized the difference between the survivors and casualties was that the latter quit because it "hurts to breathe". Consequently, the perception of respiratory discomfort could compromise the performance of military operations.

The manifestations of an anxiety attack while wearing a NBC mask include the psychophysiological consequences of hyperventilation, which can lead to decrements in military task performance (42). Hyperventilation can produce symptoms including dyspnea, tachycardia, dizziness, blurred vision, paresthesia, trembling and tetany; full-blown attacks can result in convulsions and disturbances of consciousness. Psychomotor performance is impaired by hyperventilation; the degree of psychomotor deterioration appears to be inversely related to the alveolar P_{CO_2} In most individuals, hyperventilation does not manifest all these symptoms. However, some individuals are apparently more sensitive to the effects of hyperventilation. Individuals possessing this sensitivity are characterized as susceptible to the hyperventilation syndrome (42); such individuals may be more prone to experience respiratory distress while wearing a NBC mask and performing physically demanding military tasks.

8. COMPLICATIONS OF LONG-TERM WEAR

The potential exists for the employment of chemical warfare agents on the modern battlefield for prolonged periods of time. Accordingly, soldiers may have to remain in their individual protective equipment for extended periods. This requirement places on the soldier's protective equipment the need to accommodate such normally routine, physiological

functions as eating, drinking, elimination of body waste and sleep. Of these functions, the NBC mask interferes with the soldier's ability to drink fluids, eat food and sleep.

The latest NBC masks (U.S. M17A1, British S10) incorporate a drinking system which permits the consumption of beverages from the soldier's canteen with little difficulty. The principal problem associated with their use is the manipulation of the system while wearing the bulky protective gloves. Under the stressful conditions of combat, the soldier may forgo drinking because of the perceived increased effort to accomplish the task. Consequently, the soldier may become hypohydrated. Hypohydration will reduce physiological work performance in soldiers in comfortable environments. Since the soldier may be under a thermal stress imposed by the wear of an NBC overgarment, hypohydration would substantially increase his physiological strain and reduce military work performance (56).

Current NBC masks do not permit the soldier to take in nutrients other than what may be contained in beverages, and difficulties with cleaning the drinking attachment suggest it should be limited to ingestion of water. During extended periods of encapsulation, lack of nourishment could realistically cause a degradation in performance. Henschel et al. (27) evaluated the effect of starvation on exercise performance in 12 men. They observed a significant decrease (~32%) in the endurance of the men to perform high intensity work after the second day of starvation. The combination of starvation and NBC mask and protective garment wear may degrade the ability of soldiers to perform such high intensity tasks as combat vehicle rearming, rapid runway repair and sustained artillery fire. Providing the soldier with the capability to eat while wearing a NBC mask may help maintain his physical strength and will certainly improve morale. The result could be more effective execution of military tasks.

Soldiers encapsulated in protective garments for extended periods would, when sleep was possible, have to do so in their protective equipment. The wear of the NBC mask can interfere with the soldier's ability to sleep (16). There are primarily four factors, previously discussed, which affect the soldier's ability to sleep while wearing a NBC mask: resistance to breathing, external dead space, forces on the head and psychological stress. Soldiers sleeping while wearing NBC masks have reported waking and feeling short of breath. In some cases, the soldier may partially or completely occlude the inlet valve of the mask by rolling onto the NBC mask during sleep. It is also possible that, with the lower minute ventilation during sleep, the ratio of total dead space to tidal volume may increase. This would cause a lower alveolar ventilation rate and a subsequent increase in arterial carbon dioxide; this hypercapnia could wake the soldier. The pressure of the NBC mask on the face and development of pressure points as the soldier's head changes position during sleep, could produce irritation and pain sufficient to wake the wearer. Finally, some soldiers may be fearful of sleeping in a contaminated environment because they believe that the masks seal may leak as they move during sleep. No matter what the specific cause of the sleep loss, sustained sleep deprivation can seriously degrade effective performance of military tasks (26). Sleep loss can also impair a soldier's ability to thermoregulate (55). Since soldiers wearing NBC masks would likely be wearing NBC protective garments, the combination of sleep loss and increased heat stress will likely result in elevated physiological strain and reduced exercise performance. Sleep loss can be expected while wearing NBC masks, and this factor should be considered during the planning of military operations.

REFERENCES

1. Abbagnaro, L.A., A.J. Rosenheck and A.L. DiMattia. Development of a speech amplifier system for protective masks. Tech. rpt. 1089-CLD-1776, U.S. Army Edgewood Arsenal, Maryland, Dec. 1967.

2. Altose, M., A. Dimarco, S. Gottfried and K. Strohl. The Sensation of respiratory muscle force. Am. Rev. Respir. Dis. 126:807-811, 1982.

3. Axen, K., S. Haas, F. Haas, D. Gaudino and A. Haas. Ventilatory adjustments during sustained mechanical loading in conscious humans. J. Appl. Physiol. 55:1211-1218, 1983.

4. Barlett, H.L., J.L. Hodgson and J. Kollias. Effect of respiratory valve dead space on pulmonary ventilation at rest and during exercise. Med. Sci. Sports 4: 132-137, 1972.

5. Bellemare, F. and A. Grassino. Evaluation of human diaphragm fatigue. J. Appl. Physiol. 53:1196-1206, 1982.

6. Bentley, R.A., O.G. Griffen, R.G. Love, D.C.F. Muir and K.F. Sweetland. Acceptable levels for breathing resistance of respiratory apparatus. Arch. Environ. Health 27:273-280, 1973.

7. Bye, P.T.P., G.A. Farkas and C.H. Roussos. Respiratory factors limiting exercise. Ann. Rev. Physiol. 45:439-451, 1983.

8. Campbell, E.J.M., S.C. Gandivia, K.J. Killian, C.K. Mahutte and J.R.A. Rigg. Changes in the perception of inspiratory resistive loads during partial curarization. J. Physiol. (London) 309:93-100, 1980.

9. Cerretelli, P., S. Rajinder and L. Farhi. Effect of increased airway resistance on ventilation and gas exchange during exercise. J. Appl. Physiol. 27:597-600, 1969.

10. Cooper, E.A. Suggested methods of testing and standards of resistance for respiratory protective devices. J. Appl. Physiol. 15:1053-1061, 1960.

11. Cox, T.J. and A.R. Jeffers. Ground crew chemical defense equipment performance task-time degradation test. Tech. Rpt. 81-5003, U.S. Air Force Aeronautical Systems Division, Dayton, Ohio, May 1981.

12. Craig, F.N., H.L. Froehlich and W.V. Blevins. Inspiratory resistance as a limiting factor in exhausting work. Tech. Rpt. 4230, U.S. Army Edgewood Arsenal, Maryland, Oct. 1968.

13. Craig, F.N., W.V. Blevins and E.G. Cummings. Exhausting work limited by external resistance and inhalation of carbon dioxide. J. Appl. Physiol. 29:847-851, 1970.

14. Craig, F.N., W.V. Blevin and H.L. Froehlich. Training to improve endurance in exhausting work of men wearing protective masks: A review of some preliminary experiments. Tech. Rpt. 4535, U.S. Army Edgewood Arsenal, Maryland, July 1971.

15. Cummings, E.G., W.V. Blevins, C.M. Greenland and F.N. Craig. Effects of protective masks on soldier's ability to run a half mile. Tech. Rpt. 2254, U.S. Army Edgewood Arsenal, Maryland, 1958.

16. Cummings, E.G., J. Marrero and E. Bird. Seventy-two hour outdoor wearing trial of individual CBR protective clothing with M17 mask and E33 hood under simulated combat conditions. Tech. Rpt. 3097, U.S. Army Chemical Research and Development Laboratories, Maryland, Sep. 1967.

17. Davis, R.H. Breathing in Irrespirable Atmospheres. The Saint Catherine Press LTD., London, 1947.

18. Demedts M. and N.R. Anthonisen. Effects of increased external airway resistance during steady-state exercise. J. Appl. Physiol. 35:361-366, 1973.

19. Fonseca, G.F. Heat transfer properties of military protective head gear. Tech. Rpt. 74-29, U.S. Army Research Institute of Environmental Medicine, Natick, MA, Jan. 1974.

20. Gamberale, F., I. Holmer, A.S. Kindblom and A. Nordstrom. Magnitude perception of added inspiratory resistance during steady-state exercise. Ergonomics 21:531-538, 1978.

21. Geldard, F.A. The Human Senses, 2nd Edition. John Wiley and Sons, Inc., New York, pp 28-32, 48-51, 1972.

22. Goldberg, M.N., D.H. Mangelsdorf, R.E. Jones, T.P. Crooks and F.W. Mazy. Individual respiratory protection against chemical and biological agents. Contract DA 18-035-AMC-286(A), U.S. Army Edgewood Arsenal, Maryland, Oct. 1966.

23. Goldman, R.F. Biophysical evaluation of relative heat stress of four chemical protective mask/hood systems. Rpt. C-028/MT21-84, Multi-Tech Corp., Natick, MA, Dec. 1984.

24. Gottfried, S.B., M.D. Altose, S.G. Kelsen and N.S. Cherniack. Perception of changes in airflow resistance in obstructive pulmonary disorders. Am. Rev. Respir. Dis. 124:566-570, 1981.

25. Gwosdow, A.R., R. Nielsen, L.E. Berglund and A.B. Dubois. Effect of thermal conditions on the acceptability of respiratory protective devices on humans at rest. Am Ind Hyg Assoc J.;50:188-195; 1989.

26. Haslam, D.R. Sustained operations with special reference to operational clothing and combat equipment. 13th Commonwealth Defense Conference on Operation Clothing and Combat Equipment, Malaysia, 1981.

27. Henschel, A., H.L. Taylor and A. Keys. Performance capacity in acute starvation with hard work. J. Appl. Physiol. 6:624-633, 1954.

28. Hermansen L., Z. Vokac and P. Lereim. Respiratory and circulatory response to added air flow resistance during exercise. Ergonomics 15:15-24, 1972.

29. James, R., F. Dukes-Dobos and R. Smith. Effects of respirators under heat/work conditions. Am. Ind. Hyg. Assoc. J. 45:399-404, 1984.

30. Johnson, A.T. and E.G. Cummings. Mask design considerations. Am. Ind. Hyg. Assoc. J. 36:220-228, 1975.

31. Johnson, A.T. and H.M. Berlin. Exhalation time characterizing exhaustion while wearing respiratory protective masks. Am. Ind. Hy. Assoc. J. 35:463-467, 1974.

32. Johnson, R.F. and L.A. Sleeper. Effects of chemical protective handwear and headgear on manual dexterity. Human Factors (In Press).

33. Killian, K.J., C.K. Mahutte and E.J.M. Campbell. Magnitude scaling of externally added loads to breathing. Am. Rev. Respir. Dis. 123:12-15, 1981.

34. Kobrick, J.L. and L.A. Sleeper. Effect of wearing chemical protective clothing in the heat on signal detection over the visual field. Aviat. Space Environ. Med. 57:144-148, 1986.

35. Kobrick, J.L. and W.R. Sutton. Device for measuring voluntary response time to peripherally placed stimuli. Percep. Mot. Skills 30:255-258, 1970.

36. Lerman, Y., A. Shefer, Y. Epstein and G. Keren. External inspiratory resistance of protective respiratory devices: effects of physical performance and respiratory function. J. Am. Ind. Med. 4:733-740, 1983.

37. Lotens, W.A. Physiological Strain: Clothing, physical load and military performance. In: Aspects medicaus et biophysiques des vetements de protection. Centre de Recherches du Service de Sante des Armees, Lyon, pp 268-279, 1983.

38. McCool, F.D., D.R. McCann, D.E. Leith and F.G. Hoppin, Jr. Pressure-flow effects on endurance of inspiratory muscles. J. Appl. Physiol. 60:299-304, 1986.

39. Martin, H. deV. and S. Callaway. An evaluation of the heat stress of a protective face mask. Ergonomics 17:221-231, 1974.

40. Mengeot, P.M., J.H.T. Bates and J.G. Martin. Effect of mechanical loading on displacements of chest wall during breathing in humans. J. Appl. Physiol. 58:477-484, 1985.

41. Montague, W.E., R.D. Bakner and A.H. McClure. The effects of wearing the CBR protective mask upon the performance of selected individual combat skills. Tech. Rpt. 57, The George Washington University Human Resources Research Office, Washington, D.C., 1959.

42. Morgan, W.P. Psychological problems associated with the wearing of industrial respirators: A review. Am. Ind. Hyg. Assoc. J. 44:671-676, 1983.

43. Morgan, W.P. and P.B. Raven. Prediction of distress for individuals wearing industrial respirators. Am. Ind. Hyg. Assoc. J. 46:363-368, 1985.

44. Mozo, B.T. and L.J. Peters. Effects of chemical protective and oxygen masks on attenuation and intelligibility when worn with the SPH-4 helmet. Tech. Rpt. 84-5, U.S. Army Aeromedical Research Laboratory, Ft. Rucker, AL, Mar. 1984.

45. Muller, K. The effects of the CBR protective mask on the magnitude of ventilatory or gas-metabolic function while at rest and under working stress. Technical Translation FSTC-HT-23-952-70, U.S. Army Foreign Science and Technology Center, Alexandria, VA, Dec. 1970.

46. Muza, S.R., S. McDonald and F.W. Zechman. Relationship between perceptual performance and load compensation responses to added inspiratory resistance. Fed. Proc. 42: 331, 1983.

47. Muza, S.R. and F.W. Zechman. Scaling of added loads to breathing: Magnitude estimation vs. handgrip matching. J. Appl. Physiol. 57:888-891, 1984.

48. Nelson, W.R. and B.T. Mozo. Effects of XM-40 chemical protective mask on real-ear attenuation and speech intelligibility characteristics of the SPH-4 aviator helmet. Tech. Rpt. 85-2, U.S. Army Aeromedical Research Laboratory, Ft. Rucker, AL, Feb. 1985.

49. Pandolf, K.B. and W.S. Cain. Constant effort during static and dynamic muscular exercise. J. Motor Behavior 6:101-110, 1974.

50. Rauch, T.M., I. Munro, W. Tharion and L.E. Banderet. Subjective symptoms, human endurance and cognitive interventions. Psychology in DOD Symposium. U.S. Air Force Academy, Colorado Springs, Apr. 1986.

51. Raven, P.B., A.T. Dodson and T.O. Davis. The physiological consequences of wearing industrial respirators. A review. Am. Ind. Hyg. Assoc. J. 40:517-534, 1979.

52. Robinson, S. and S.D. Gerking. Heat stress imposed by gas masks. (Report #26). Office of Scientific Research and Development, U.S. War Research Agency, Washington, D.C., 1945.

53. Roussos, C. and P.T. Macklem. The respiratory muscles. New Eng. J. Med. 307:786-796, 1982.

54. Savill, M.W. and M.R. Forrest. The effect of NBC clothing on the noise attenuation of the AFV crewman's helmet. Rpt. No. 11/76, Army Personnel Research Establishment, Farnborough, England, Jun. 1976.

55. Sawka, M.N., R.R. Gonzalez and K.B. Pandolf. Effects of sleep deprivation on thermoregulation during exercise. Am. J. Physiol. 246:R72-R77, 1984.

56. Sawka, M.N., A.J. Young, R.P. Francesconi, S.R. Muza and K.B. Pandolf. Thermoregulatory and blood responses during exercise at graded hypohydration levels. J. Appl. Physiol. 59:1394-1401, 1985.

57. Silverman, L.G., A.R. Yancey, L. Amory, L.J. Barney and R.C. Lee. Fundamental factors in the design of protective respiratory equipment: A study and an evaluation of inspiratory and expiratory resistances for protective respiratory equipment. (Report #5339). Office of Scientific Research and Development, U. S. War Research Agency, Washington, D.C., 1945.

58. Silverman, L., G. Lee, T. Plotkin, L.A. Sawyers and A.R. Yancey. Air flow measurements on human subjects with and without respiratory resistance at several work rates. Ind. Hyg. Occup. Med. 3:461-478, 1951.

59. Singler, R.T. Early environmental test phase, (Cold Regions Phase) E2G prototype of the XM30 new protective mask, protective hood, and combat spectacles. U.S. Army Cold Regions Test Center Interim Letter Report, May 1981.

60. Snook, S.H., W.C. Hinds and W.A. Burgess. Respirator comfort: subjective response to force applied to the face. Am. Ind. Hyg. Assoc. J. 27:93-97, 1966.

61. Spioch, F.M., R. Kobza and S. Rump. Effects of respirators on some physiological reactions to physical effort. Acta Physiol. Polonica 13:542; 637-649, 1962.

62. Stemler, F.W. and F.N. Craig. Effects of respiratory equipment on endurance in hard work. J. Appl. Physiol. 42:28-32, 1977.

63. Van Huss, W.D., F. Hartman, F.N. Craig and A.H. Steinhaus. Respiratory burden of the field protective mask under exercise load. Fed. Proc. 26:721 1967.

64. Wiley, R.W., I. Behar, W.C. Chiow and F.F. Holly. Visual and optical analyses of XM-29 and M-24 protective masks. Tech. Rpt. 77-14, U.S. Army Aeromedical Research Laboratory, Ft. Rucker, AL, Jun. 1977.

65. Zechman, F.W. and R.L. Willey. Afferent inputs to breathing: Respiratory sensations. Handbook of Physiology Section 3, The Respiratory System, Vol II Control of Breathing. Ed. N. S. Cherniack and J.G. Widdicombe, Am. Physiol. Soc., 1986.

CHAPTER 12

PROTECTION AGAINST FLAMES AND RADIANT HEAT

F.W. Behmann

CONTENTS

SUMMARY

I. CONVENTIONAL AND COMBAT CLOTHING

SOURCES OF DANGER
HEAT TRANSFER TO MAN
TISSUE DAMAGE
PROTECTION BY CLOTHING
INFLUENCE OF CLOTHING CONSTRUCTION
A) Fiber Selection
B) Yarn and Fabric Structure
C) Finish
D) Shape and Layers of Clothing
E) Other Factors
TEST OF BURNING PROPERTIES
A) General
B) Thermal-Manikin
ESTIMATION OF CASUALTIES

II. SPECIAL FIRE PROTECTIVE CLOTHING

OCCUPATIONAL AND FIREFIGHTING DANGER
CLASSIFICATION OF FIRE PROTECTIVE CLOTHING
CONSTRUCTION OF FIRE PROTECTIVE CLOTHING
A) Materials
B) General Work Clothing
C) Safety Equipment
D) Local Heat Protection
E) Light Protective Ensembles (Approach Suits)
F) Heavy Protective Ensembles (Proximity Suits)
G) Respirators
TEST AND EVALUATION METHODS
A) Physical Methods
B) Physiological Methods
COMPARISON OF COMMERCIAL PROTECTIVE ENSEMBLES
LIMITS OF FIRE PROTECTION

REFERENCES

SUMMARY

Flames and radiant heat may occur sporadically, e.g. by accident or in war, and they are characteristic properties of some work places, e.g. in industry or while firefighting. Part I describes the different elements of textile construction to realize an optimal protection against sporadic heat. Further, a method is reported to estimate the relative number of casualties. Part II describes the construction principles for heat protective clothing used in industry or firefighting. Further, a comparison of commercial protective clothing is given which demonstrates that, in the case of heavy protective suits, remarkable improvements are possible.

Key Words: Fire protective clothing, burn casualties, burn tissue damage, clothing flammability factors, textile burning properties

Part I: CONVENTIONAL AND COMBAT CLOTHING

SOURCES OF DANGER

In protection against flames and heat radiation, two cases have to be distinguished: first, flames and heat may occur sporadically and unexpectedly, e.g. in accidents or in war; second, they are characteristic of many work places, e.g. in smelting-works or rolling mills, during fire-fighting or rescue operations. As a start, the danger of fire from accidents or on the battle field will be considered.

The probability of risk of being burned can be only estimated. Considering the civilian sector, the number of burn injuries (USA) are about 1.1% of population per annum; 40 % of these happen in industry and 35 % in a domestic situation. In industry, burn-injuries mostly occur in factories working with molten materials; burn-injuries in the domestic setting mainly involve children and older people (2,12).

In war the number of casualties due to burns is much higher; for conventional warfare it is estimated to be 0.1 to 0.4% of the effective strength per day (9,26). The risk of burns is greater for air crews than for tank crews, and the risk for the latter is greater than for infantrymen. The kind of weapons is also important; for example, it is estimated (10) that in the case of a nuclear explosion (20 kiloton, open terrain, 100 men/km^2) of all casualties about 25% will be killed, 35% will be severely injured by radiant heat, and the rest will have minor injuries. In the case of a napalm attack, according to a Russian source (22) 35% of the soldiers would be killed and 60% burned seriously.

HEAT TRANSFER TO MAN

Heat transfer in the case of burns mostly happens by touching hot surfaces, by radiation or by direct contact with the flames. Given the temperature of the heat source, T (°C) (Table 1), and the time of exposure, t (sec), one can estimate the amount of heat transferred, Q (cal/cm^2), by the following equations (constant properties combined to a numerical factor):

TABLE I

Characteristic Values of Dangerous Heat Sources.

K = matter constant (non-dimensional), v = buoyant velocity (m/sec). Exploding gas values are for fumes of aliphatic hydrocarbons (calculated). Napalm bomb values are for burning phase (16).

Heat Source	Temperature T (°C)	Emission e (%)	Other parameters
Hot brickwork	50...1000	76...88	k = 0.39
Molten aluminum	700.....750	4.....7	0.94
Molten iron	1200...1500	74...86	0.88
Molten glass	1200...1400	72...86	0.44
Burning buildings	700... 900	4...12	v = 9.4
Burning fuel	900...1100	10...12	10.4
Exploding gases	60.....120	10...12	3.1
Napalm bomb	600.....800	10...12	8.7

A) Contact heat transfer: The contact heat transfer (Q_{cont}) can be estimated (13) as:

$$Q_{cont} = 0.278\ kT \cdot t$$

where k is a non-dimensional factor resulting from the thermal properties of skin and the material (Table 1).

B) Radiation heat transfer: The radiant heat transferred from surfaces and flames can be estimated (13) as:

$$Q_{rad} = \frac{1.37\ e}{1+(s/D)^2} \cdot \frac{(273+T)^4}{1000}\ t$$

where e is the emission (Table 1), s (m) is the distance and D (m) is the diameter of the radiation source, which is assumed to be semicircular.

C) Heat transfer by continuous contact with flames: Flame contact heat transfer can be estimated (13) as:

$$Q_{flame} = (1.37\ e \cdot \frac{(273+T)^4}{1000}\ t \cdot 2.05 \cdot 10^{-4}\ T \cdot v/d)\ t$$

where v (m/sec) is the flame velocity (Table I) and d (m) is the diameter of the exposed parts of body.

D) Heat from nuclear weapons: The heat delivered to a surface by the flash of nuclear weapons can be estimated (11) as:

$$Q_{flash} = 2.65 \cdot 10^6 \cdot W/s^2$$

where W (kiloton TNT) is the explosive energy, s (m) is the distance and absorption by the atmosphere is neglected.

E) Heat from non-nuclear explosions: With explosion flames the time of exposure is so short (< 20 msec), that normally no burns are caused by the explosion itself. However, if burnable materials are ignited (e.g. napalm-bomb fuel), or the remaining hot fumes persist for a while (e.g., after a mine gas explosion), an estimation of the heat transfer can be made using the equation for continuous flames.

TISSUE DAMAGE

The mechanism of biological damage is the same in all cases. The amount of heat delivered causes an increase of skin temperature. Above 44 °C the cells become damaged by degradation of tissue proteins; the rate and depth of this damage increase with temperature (24).

Burns can be classified into three categories according to depth of damage:

1st degree: Erythema, dilatation of capillaries; a normal reaction, with no damage.

2nd degree: Separation of epidermis, formation of edematous blisters; painful but reversible.

3rd degree: Necrosis of skin and deeper tissues, largely pain free; scar formation unavoidable.

First-degree burns can be ignored but second- and third-degree burns cause further severe injury to the entire organism; the traumatic irritation of all cutaneous nerves frequently produces a circulatory collapse. The loss of the water barrier function of the skin allows large losses of water by evaporation, so that further circulatory complications follow. The toxic products of protein degradation load the kidneys. A large number of pathological micro-organisms colonize on the unprotected tissues.

The severity of these secondary burn symptoms is determined mainly by the extent of the destroyed skin surface, so that lethality increases progressively (Fig. 1); for burns of more than 50 % of the body surface the chance to survive is low. However, even non-lethal burns require long and intensive treatment (about 60 days). Frequently, secondary surgery is necessary and often deforming scars remain, burdening the injured person psychologically. Therefore burns are among the most severe injuries known, and everything must be done to reduce them to a minimum.

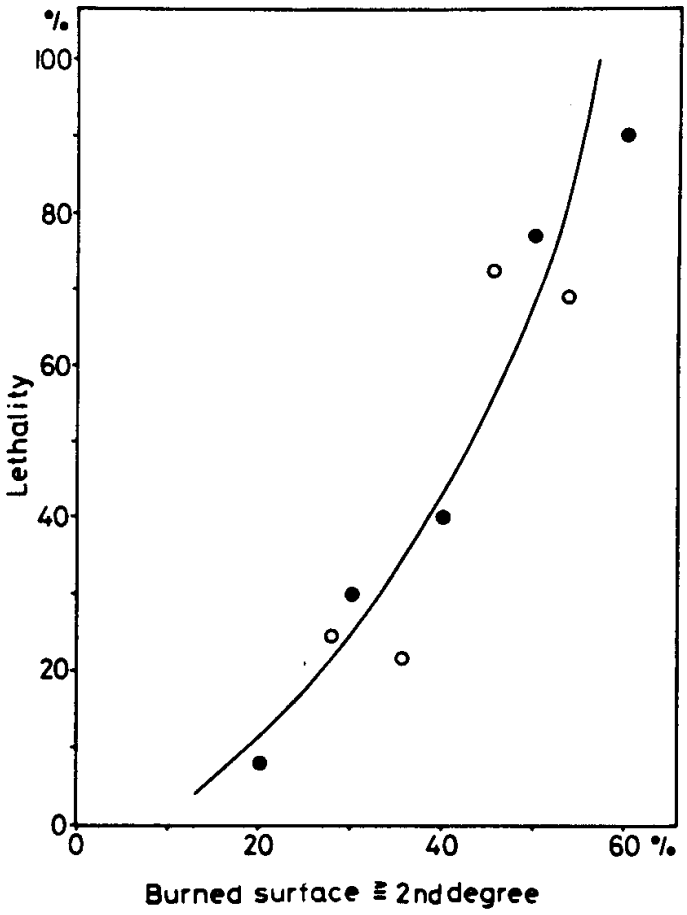


Fig. 1: Lethality as a function of the burned body surface. Dots: 359 patients (20); Circles: 4 coal mine ignitions with 66 persons in total (25).

PROTECTION BY CLOTHING

Clothing influences the occurrence of burns in two ways. All clothing has a certain heat insulation; this delays the heat transfer to the skin so that, for the same exposure time, the depth of skin damage is lower. On the other hand, the clothing itself may be set on fire by a relatively small heat source (e.g., an adhering napalm-splash) so that the burned area of the skin may be larger than it would be without clothing.

However, insulation generally cannot be utilized to increase the protective effect; conventional or combat clothing is worn permanently and the desired extent of their insulation is determined by the climate and work conditions (see Chap. 2). Therefore the only practical possibility is to reduce the inflammability of the clothing, thus reducing the additional inherent danger.

The inflammability of clothing depends on numerous factors. If textiles come in contact with a flame, one has to distinguish three cases: the fabric catches fire and continues to burn; the flame dies after removal of the heat source; or the fabric does not inflame at all. But even a non-inflammable fabric may melt, drip hot molten material, shrink or lose its mechanical strength, so that different properties have to be considered.

TABLE II

Burning Properties of Some Textile Fibers (8,19,21).
Values are variable depending on fabrication and preconditioning.

	Fiber damage °C	Flash point °C	Burning point °C	Burning heat kcal/g	Other characteristics
Cotton	215	225	255	3.89	Crumble ashes
Wool	195	285	570	4.90	Foamy carbonization
Polyamide 6.6	220	350	425	7.91	250 °C melting drops
Polyester	210	370	485	5.71	260 °C melting drops
Polyacrylonitrile	230	245	465	7.59	240 °C decomposition
Nomex	310	500	600	?	370 °C decomposition

INFLUENCE OF TEXTILE CONSTRUCTION ON INFLAMMABILITY

A) Fiber Selection

All organic fibers are more or less combustible; Table 2 shows the characteristic values of some frequently used textile fibers. As the temperature is raised, the molecular structure decomposes, combustible gases are emitted and fiber damage results. When the temperature reaches the flash point, the emitted gases are inflamed, but the flames go out if the ignition source is removed, because the amount of gas released is not sufficient. Only at the burning point is enough heat produced to release more gas than is necessary for heating up more fiber to the flash point, so that burning now maintains itself.

Another property must be mentioned for synthetic fibers. As shown in Table II, they will melt or decompose before the temperature reaches the flash point. By dripping off, or shrinking of the material, they withdraw from the range of contact with the ignition flame, so that a non-inflammability may be supposed. If, however, the molten material touches the skin, burns may be produced by contact heat transfer.

B) Yarn and Fabric Structure

The combustibility of textiles, however, is not determined only by the material. If the density of yarn and fabric is increased, the heat storage capacity also is raised, so that even with the same heat flow it takes a longer time to reach the burning point. Also, after ignition a longer time is required until the material near the flame is heated to the burning point, so that the rate of burning is lowered also.

By raising the weight of the textile material, the process of ignition and burning is retarded, so that the textiles become "more difficult to ignite" and can resist a smaller heat source for a limited time. The areal weight of normal clothing, however, cannot be raised

above 300 to 350 g/m^2 in practice because the textiles get too heavy and too stiff, so that the utilization of increased weight of material to reduce burns is limited as well.

C) Finish

Inflammability also can be reduced by applying chemical finishes. Numerous processes have been developed. For clothing, however, the only suitable finishes are those which are sufficiently washproof and which do not adversely affect such essential textile properties as weight, strength, vapor permeability, etc. Only a few finishes of this kind are known and they are mainly applicable only to cotton and cellulose fibers.

As examples, the PROBAN-finish (phosphonium chloride derivate) and the PHOSPHONATE-finish (phosphonic acid derivate) may be mentioned (1). The PROBAN-finish can be rated as a little more favorable in regard to its effects on tensile strength and abrasion resistance, while the PHOSPHONATE-finish is better in terms of its effects on weight, feel and air permeability. The mechanism of flame suppression is the same for both finishes and can be attributed to the fact that free radicals occurring during burning processes (e.g. H^+, OH^-, (27)) are bound, so that the chain reaction in the flame is interrupted.

D) Shape and Layers of Clothing

The insulation of clothing is fixed but this insulation can be realized by different constructions. To obtain optimal protection against burns: 1) the covered part of the body surface should be as large as possible; and 2) the thickness of air layers inside the clothing should be about 4 mm (24), because below this value, insulation decreases, and above this value, free convection heat flow increases inflammability. In the case of the normal clothing which is worn regularly, the face and hands (about 12% of the surface) cannot be covered. Also the second requirement above cannot be met, because the mobility of joints is not sufficient if the inter-clothing air layers are limited to 4 mm. To keep the risk low in spite of these facts, the clothing should consist of two layers. Furthermore, a construction combining relatively small internal air layer width with a great freedom of movement should be selected, so that a two-piece, closed dress should be preferred.

E) Other Factors

In practice, blends of different fibers often are used. Synthetic fibers already melt at relatively low temperatures (Table II). However, if withdrawing from the ignition flame is prevented by some kind of "scaffold", they burn more intensely than cotton because of a greater heat of combustion. Such a scaffold-effect may be produced by a blend with flame-resistant fibers, by the combustion residues of other materials, by a water-repellent finish or by pigments which lower the surface tension of the melt (15).

Further effects occur with continued wear. Clothing soiled by oil (e.g. tank crew overalls) burns rapidly. In laundering, incrustations like calcium-soap may be deposited, which cause a scaffold-effect. Moreover, it may be mentioned that the radiation of nuclear weapons includes the visible range, so that light-colored fabrics may reflect a considerable part (11) of the incident radiant heat.

TESTS OF BURNING PROPERTIES

A) General

A number of standardized methods are available for testing burning properties. Their common principle is the ignition of a specimen under defined conditions and the measurement of burning time and other parameters. The results are reproducible and can be used for a comparison of fabrics. However, the quantitative results of the different methods do not agree. Furthermore, the results cannot be transferred to practical conditions, because the ignition depends on the heat source and the exposure time, while the burning rate depends on the air inflow and the angle between the flame and fabric.

If only a comparison between fabrics is desired, a method with a good differentiating quality should be employed. An adequate arrangement is to use a strip of material hanging down, vertical to an ignition flame; the time of contact between the strip and flame is raised step by step (like the US HLT-15 test). If the material is not ignited within a set time (30 sec or more), the area of charring, the time of smoldering and the loss of strength may be used as criteria.

B) Thermal-Manikin

In order to have a method yielding results transferable to man, the author in 1968 used a wooden manikin covered with asbestos (4). Within the manikin, 48 small heat sensors were installed, each corresponding to a defined area of the skin. This model was dressed with the clothing under test. The area around the knees was exposed to a continuous flame and the heat transferred to the various sensors was measured. The areas where heat inflow exceeded 2 cal/cm^2 were assumed to represent areas of 2nd degree burn or more (24) and the burned part of the body surface was calculated from the sum of these areas as shown below.

Independent of this, a so-called "thermal-man" was developed in the USA in 1973 (14). This thermal-man was constructed of a heat resistant material and a higher accuracy was obtained by use of 125 sensors. A computer connected with the thermal-man calculated the areas of the body surface with 2nd and 3rd degree burns and plotted them on an outline drawing of a human body. This method is the most advanced to date and shows the weak points of a clothing ensemble at a glance.

An example using flame resistant outer and under wear is given as a demonstration of this method. The burned part of body surface is shown in Fig. 2 for a two-layer, cotton work-clothing ensemble. In case A, both layers were inflammable; in case B the underwear and in case C the outerwear was treated to be flame-resistant with PROBAN. In all cases the clothing system was set afire, but with an impregnated layer the burning velocity was smaller. In particular, the protective effect of the flame-resistant outerwear was clearly higher than the effect of a flame-resistant underwear, because with flame resistant outerwear the air flow to the inflammable underwear was restrained.

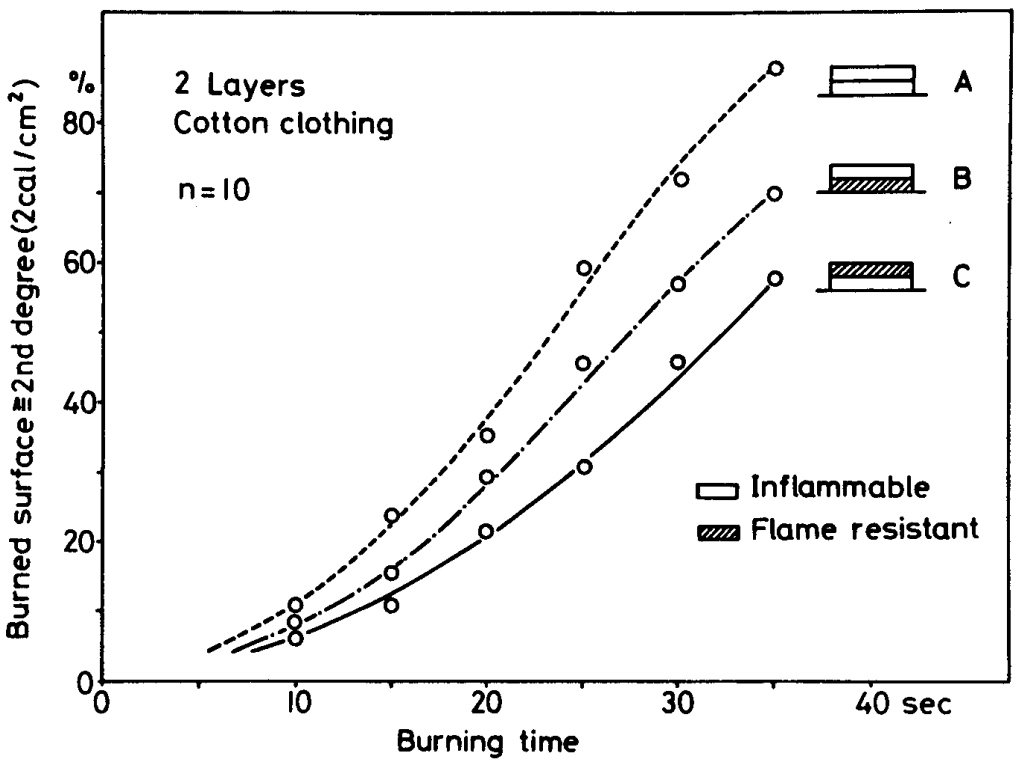


Fig. 2: Percentage of burned surface ≤ 2nd degree as a function of burning time (4). Model experiments with a two-layer work clothing of cotton; outside a 280 g/m^2 twill, inside a 230 g/m^2 tricot.

This experiment clearly demonstrated a protection effect. However, one can see also that the difference is very small for short exposure times (up to 10 sec). On the other hand, at longer times (about 35 sec) there is a clear difference between the graphs. But even with a flame-resistant outerwear the burns are very serious (see Fig. 1), so that the physical protection required for longer times has no biological significance. Therefore, a question arises, as to the practical importance of flame-resistant clothing.

ESTIMATION OF CASUALTIES

The number of persons and the time of heat exposure cannot be predicted for a real accident; a calculation of the absolute number of casualties therefore is impossible. In practice, however, the question is to what extent casualties can be reduced by flame-resistant clothing in comparison to inflammable clothing. This can be answered, if the graphs of lethality and fabric burning are combined, as shown in Fig. 3.

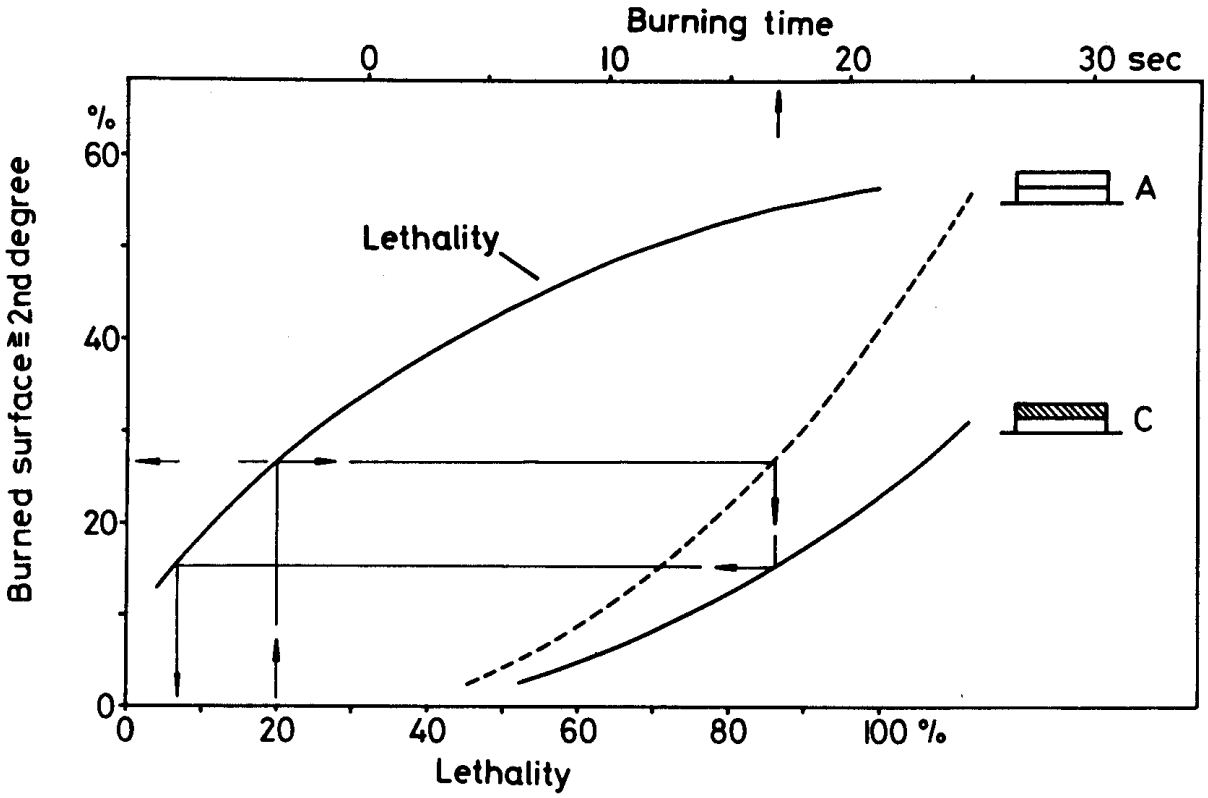


Fig.3: Example for estimation of casualties. Given: Sample A, lethality 20%; required: Lethality wearing sample C under same conditions.

Assuming for example, that inflammable clothing (model A) is worn in a certain accident and that 20% of the persons are killed and 80% injured, these casualties would correspond to an exposure time of about 17 sec; wearing a flame-resistant outerwear (model C), with the same exposure time only 7% of the people would be killed and 93% injured, so that the fatalities would be reduced to 35% of the original amount.

Assuming further that, in case of a fire catastrophe, the distribution of injuries were as follows (similar estimations see (14)):

20% heavy burns (36-60% of body surface), survival only with optimal therapy

50% medium burns (16-35% surface); supine transport

30% light burns (up to 15% surface), usually able to walk

and then the percentage of persons injured at each of the three degrees also can be estimated (example in Table III).

TABLE III

Estimation of the Casualties with Inflammable (A) and Flame Resistant Clothing (B, C). (The percentage of persons killed in the case of clothing A was assumed)

Clothing	Killed	Burned (% Pers)		
	(% Pers)	Heavy	Medium	Light
A	20	16	40	24
B	12	18	44	26
C	7	19	46	28
A	40	12	30	18
B	22	16	39	23
C	13	18	43	26

The values given in Table III are only an estimate from which the burning properties of a given clothing could be expressed in terms of the percentage of expected casualties. This estimation neglects the variability of both the fire and the position of the people; it also neglects the age of victims and the depth of burns, which would raise the lethality. It neglects the fact that in the case of small area burns, these mostly affect the face and that burns of the face are more severe because they are frequently combined with burns to the respiratory tract. Finally, it neglects the additional victims that are caused by toxic gases and that the extent of casualties also depends upon the available medical care. Most of these factors, except for the depth of burns and the complications in the head area, do not depend on the clothing so that, although the observed values may be inaccurate, the relative relationships between an inflammable and a flame-resistant clothing are nearly correct.

Part II: SPECIAL FIRE PROTECTIVE CLOTHING

OCCUPATIONAL WORK AND FIREFIGHTING DANGER

At many work places man is endangered by heat. At first, one tries to lower this danger by technical means but as these are exhausted, special protective clothing becomes necessary. In contrast to normal or combat clothing, this protective clothing is not worn permanently and can be designed to meet the actual risk.

This risk is very variable. It will be outlined, first, for some industrial work places (17). During welding, splashes of fused metal may inflame the clothing. In mines, the temperature increases with depth (2 to 3 °C per 100 m of depth below the surface) and the risk of mechanical injuries is relatively high. At most of the hot work places (e.g. on furnaces, steel-works, rolling-mills, glass-factories, etc.), the increased air temperature is accompanied by a one-sided exposure to fluctuating radiation (up to 1800 kcal/m^{2}h) and the worker is also endangered by molten materials. Protection against thermal radiation, molten splash and injury is needed which still permits sufficient sweat evaporation to prevent body temperatures from rising.

Similarly, the conditions in firefighting are variable (23). Burning buildings can be fought from an adequate distance. In underground facilities and ships we find smoldering fires with toxic gases and an oxygen deficit. At crash landings of aircraft, fuel often is set afire and heat radiation (up to 8000 kcal/m^{2}h) and darting flames (up to 1000 °C) may occur. The rescue time for a person, however, is limited to about 1 min, so that short-term heat reflective protection with high mobility is needed. At burning fuel tanks, the radiation increases up to 30,000 kcal/m^{2}h (18), so that the reflective cover has to be supplemented by an insulation layer. At catastrophes, e.g. like the area conflagrations of World War II, we find similar values of radiation (6) combined with darting flames, toxic air-contamination and falling fragments, so that complete protection against radiation, flames, toxic gases and mechanical injuries is required.

CLASSIFICATION OF FIRE PROTECTIVE CLOTHING

The demands on a fire protective ensemble are numerous. Therefore, it seems appropriate to distinguish 5 protection classes (Table IV):

TABLE IV

Class	Type of Clothing	Main Feature	Use
1	Work clothing	Flame Resistant	Sporadic heat
2	Safety equipment	For head, hands etc.	Accidental risk
3	Partial heat protection	Permits evaporation	One-sided radiation
4	Light protection suit	Reflection, mobility	Quick saving actions
5	Heavy protection suit	Additional insulation	Hardest condition

Class 1 consists of normal work clothing made of a flame-resistant material. It is worn as the basic protection in all cases of heat danger and can be supplemented by the equipment of class 2 to 5 as required. Class 2 includes the safety equipment for head, hands and feet against heat and mechanical injuries. Class 3 comprises the partial heat protection for the different body parts; these have been widely used and proved successful in industry. Class 4 comprises light protection suits for short rescue-operations, and Class 5 are the heavy protective suits for the most severe conditions.

The equipment of class 1 to 3 is assigned for operational times up to 8 hours, so that sufficient sweat evaporation for cooling has to be ensured. Suits of class 4 and 5 are worn only for a short time (up to 30 min), so that sweat evaporation is less important and an impermeable outer-layer can be used. For extended operations under severe heat, special protective suits have been developed which are cooled by air or by water, but these will not be discussed here.

CONSTRUCTION OF FIRE PROTECTIVE CLOTHING

A) Materials

Flame-resistant textiles of cotton or synthetic fibers (200 - 400 g/m^2) are sufficient for low heat loads (up to 200 °C). For more severe conditions, non-inflammable textiles of asbestos-, glass- or synthetic fibers (500 – 1200 g/m^2) are used. In case of mechanical strain (cuts, abrasions, splashes of molten materials, etc.) low shrinking leather is also used; however, this is sensitive to chemical fire extinguishing agents.

These materials are covered with a thin film of aluminum, copper or a teflon-foil metallized in vacuum, for reflection of heat radiation. The reflection of these fabrics when new may be 90 to 95%, but the coatings are very sensitive to abrasion, flames and splashes and they are impermeable to sweat.

B) General Work Clothing (Class 1)

This is normal working clothing made of flame-resistant textiles. The flame resistance has to be launder-proof. The construction should have no open pockets, and no cuffs or folds in which splashes of molten material may be caught.

C) Safety Equipment (Class 2)

Metallized helmets of fiberglass-polyester have proven successful for head protection (17), since large molten metal splashes may melt through helmets of aluminum. Visors made of wire-gauze or metallized plastic panes are in use as face protection (17). The wire-gauze, however, restricts vision, and the plastic panes may alter their shape and transparency in the heat.

Gloves are offered in many different models (17). Often the palm of the hand is made of leather, and the back of a reflecting insulation layer. The insulation value depends on the curvature of hand and the mobility required, but cannot be increased to more than 1.8 clo (7).

Heavy shoes, with steel-caps inserted and thick soles, are used to protect the feet (17). The upper part should be smooth, so that splashes flow off. A reflective cover is needed, when heat radiation is present.

D) Local Heat Protection (Class 3)

Partial heat protection is provided by a multitude of different items such as aprons, gaiters, oversleeves or backside-open overcoats (17). These are put on over the normal work clothing, protecting the endangered parts of body against heat and other risks, while the uncovered parts ensure a sufficient sweat evaporation and mobility for the required work.

E) Light Protective Ensembles (Class 4)

Light protective suits are made of non-inflammable, reflecting textiles. The fit should be comfortable and ensure optimum mobility. The face is protected by a hood, which has a large metallized pane and is worn over a helmet. The hood should allow all-directional head movements, a sufficient visual field and should not slip when running and stooping; these demands, however, are not always met in practice. The suit consists of two or three pieces, so that the hood and jacket can be taken off during longer stand-by periods.

F) Heavy Protective Ensembles (Class 5)

A heavy protective suit is a one-piece ensemble, constructed with a reflecting outer-layer, an insulating middle-layer and a smooth lining, all non-flammable. The outer-layer should be impermeable to water and burnable fluids. The insulation layer should be fortified at the curved and stretched sites at the shoulder and thigh. The cut of the clothing should be such that its weight is carried by the shoulders near the neck. Further, the cut should allow sufficient mobility and should have an enlargement at the back for placement of a respirator. The head is protected by an attached hood, worn loosely over a helmet, which should allow free movements of the head and offer sufficient space for a breathing mask. Heat-conducting junctions between the outside and inside of the clothing must be avoided. Fasteners should be shielded by a flap and parts with more heat capacity should be placed near the outside surface. Moreover, the wearer should be able to take the suit off quickly, without assistance, because stored heat may continue to flow to the inside of clothing even after withdrawing from the fire. These multiple demands, however, are not always met in practice (5).

G) Respirators

When toxic gases occur or when there is a lack of oxygen, a respirator is needed. Recirculating devices can be used for longer periods (about 5 hours), because the expired, but unused oxygen is recycled, but the absorption of carbon dioxide causes an unpleasant heating of the breathing air. In compressed-air devices, although the air is cooled by expansion, the operational time is limited to about 30 min because cylinders with a larger volume are too heavy to be portable.

TESTING AND EVALUATION OF FIRE PROTECTIVE CLOTHING

A) Physical Methods

For the initial characterization of a fire protective clothing, its physical properties such as strength, inflammability and burning-through of molten metal splashes are determined; these values are sufficient to evaluate the accident risk. The methods are described in standard regulations, so that only the degree of heat protection provided needs to be considered here.

To test these qualities, a specimen of the textiles is exposed to a defined flame, or radiation source, and the increase of temperature or heat flow at the backside is measured as function of time. This method can be used for a comparison of textiles to select the best. However, the values can not be equated with the protection provided to a man because the insulation of clothing during wear depends on such factors as air gaps, folds, curves and pressure; these vary over the body surface and change with body movements, so that the protection limit is established by the weakest point.

B) Physiological Methods

Experiments with subjects are required to determine the actual protection of clothing as worn. The subjects must perform a dynamic, standardized work routine in front of a radiation panel and the time is measured until the first pain occurs somewhere on the skin. This time is measured in both the dressed (t) and the undressed state (t_o) with the same radiation and the same work. A heat protection factor (P) can then be calculated as follows (5):

$$P=(R\cdot t)/(R\cdot t_0) =(t/ t_0) \quad \text{if} \quad R = \text{constant}$$

This protection factor is nearly independent of the experimental conditions; it simply gives the tolerance time as a multiple of the tolerance time in the undressed state. Further, if the product of radiation and time unprotected (e.g., $(R\cdot t_0) \approx 100$ kcal·m^2) is known, then the tolerance time for any other radiation level may be calculated. It is also possible to ask the subject to identify the weakest point i.e. where the first pain occurs on the skin, and to improve the clothing in a systematic way.

In addition to heat protection, the physical load imposed by the clothing is important. It can be described by a loading factor $L = M/M_0$, where M is the metabolic rate in the dressed, and M_0 in the undressed state at a fixed activity level. The increase in energy consumption is caused by the weight of clothing and its resistance against rubbing and deformation upon movement. Further details concerning the effects of the physical load are given in Chap. 13.

TABLE V

Characteristic Values of Commercial Fire Protective Clothing (5). Rhythmical work, radiation 6800 kcal/m^{2}h. M = metabolic rate (S.D. ± 10.8 %); t = time until pain occurs (S.D. ± 15.4 %); L = loading factor; P = heat protection factor; index 0 represents nude values. Means of 5 subjects.

Clothing		Weight (kg)		Measurements		Characteristics	
Prot. Class	Type (Suit No.)	Respi-rator	Suit	$M\left(\frac{kcal}{min}\right)$	t (sec)	$L\left(\frac{M}{M_0}\right)$	$P\left(\frac{t}{t_0}\right)$
–	Nude (1)	–	0	2.44	61	1.00	1.0
1	Work clothing (2)	–	3.1	2.63	136	1.08	2.2
2	Helmet, gloves (3)	–	7.3	2.80	176	1.15	2.8
3	Long apron (5)	–	8.2	2.86	237	1.17	3.9
3	Free back coat (8)	–	9.7	2.94	396	1.20	6.5
4	Light protection (10)	–	11.6	3.04	428	1.25	7.0
4	Light protection (13)	16.3	11.8	3.62	441	1.48	7.2
5	Heavy protection (15)	16.3	15.8	4.16	647	1.70	10.6
5	Heavy protection (19)	16.3	13.8	3.79	994	1.55	16.2

COMPARISON OF COMMERCIAL PROTECTIVE ENSEMBLES

The data for some commercial fire protective clothing are given in Table V as examples. As one can see, the heat protection factor P (last column) of normal work clothing (including underwear and shoes) is about 2.2; with additional safety equipment (helmet, visor and gloves) it is increased to 2.8. A protective coat open at the back (No 8) nearly reaches the value of a light protective suit (No 10) while for heavy protective suits (No 15, 19), values of 10.6 to 16.2 were found so that differences up to 50 % exist. The additional load (next to last column) is practically negligible for protection Classes 1 to 3. For light protective suits (Class 4), the influence of a respirator is clear (No 10, 13) while for heavy protective suits an additional load of 70% was found in one case (No 15) although another model (No 19) showed only a value of 55%.

The best heat protection factor for twelve heavy ensembles tested was 16.2. However, it could be shown (5) that, as a result of laboratory tests employing subjects, this factor can be increased to 25.2 . This increase was obtained by some minor modifications without a change of the physical load, so that in the range of heavy protective suits remarkable improvements are possible.

LIMITS OF FIRE PROTECTION

The number of burn-accidents could be reduced substantially by the use of heat protection clothing as described above; further, it was possible to perform safety-work and rescue-operations under severe heat. Nevertheless, there are still limits to fire protection which cannot be overcome at the present time:

1. In the case of a sporadic heat impulse, a flame-resistant clothing can provide remarkable protection, but this protection is limited to the covered body surface, so that burns of the face and hands are not avoidable.
2. At a given heat load, the tolerance time is determined by the point of lowest insulation. However, since the insulation of gloves cannot be increased to more than 1.8 clo, the tolerance time of even the heaviest protective suits is limited by this value.
3. Modern fibers have sufficient heat resistance. However, the reflecting covers are destroyed quickly in the heat, so that direct contact with flames must be avoided. Therefore, the use of fire protective clothing is limited mainly to protection from the high levels of radiant heat associated with fire.

REFERENCES

1. Aenishanslin, R. Possibilities for rendering cotton textiles flame resistant. In: Duttweiler Inst. (Ed.): Textile flammability and consumer safety. Ruschlikon 1969, p 120.

2. Artz, C.P., Yarbrough, D.R. Present status of the treatment of burns. N.Y. Acad. Med. 43: 627, 1967.

3. Wright-Patterson AFB. Instrumented thermal manikin. Report ASD-Rf-73-33, Jan. 1973.

4. Behmann, F.W. Unpublished experiments, 1968.

5. Behmann, F.W. Evaluation of heat protection clothing for firefighters. In: Aspects medicaux et biophysiques des vetements de protection. Lyon, Service de Sante des Armees, 1983, p 55.

6. Buettner, K. Conflagration heat. In: German aviation medicine, World War II. Washington, US Gov. Print. Off. 1950, p 1167.

7. Dilla, M.V., Day, R., Siple, P.A. Special problems of hands. In: Newburgh, L.H.: Physiology of heat regulation and the science of clothing. Philadelphia, Saunders 1949, p 374.

8. Falkai, B.V. Synthesefasern. Weinheim, Chemie 1981, p 450.

9. Ganzoni, N. Die Schussverletzung im Krieg. Wien, Huber 1975, p 181.

10. Gessener, H. Die Abschaetzung der Verlusterwartung bei Atombombeneinsaetzen. ViertJahrSchr Schweiz. SanOff 34:344, 1957.

11. Glasstone, S. The effects of nuclear weapons. Washington, US Atomic Energy Commission 1957, p 302 ff, 335.

12. Iskrant, A.P. Statistics and epidemiology of burns. N.Y. Acad. Med. 43:636, 1967.

13. Krischer, O. Die Wissenschaftlichen Grundlagen der Trocknungstechnik. Berlin, Springer 1963, p 70-90, 118, 132, 135.

14. Krupp, S. Die Behandlung des Verbrennungsschocks unter Katastrophenbedingungen. Schweiz. Z. Milit. Med. 51:61, 1974

15. Kruse, W. The combustibility and flame-resistant finishing of mixed textiles. In: Duttweiler Inst. (Ed.): Textile flammability and consumer safety. Ruschlikon 1969, p 137.

16. Meyer-Noack, L. Vorbeugender Brandschutz gegen Großfeuer. Kampftruppen 1979, 1.

17. Ordinanz, W. Hitzearbeit und Hitzeschutz. Düsseldorf, Stahleisen, 1968.

18. Richter, K.H. Wärmebelastung bei Treibstoffbränden, Werksarzt 11:30, 1964.

19. Rieber, W. The inflammability of synthetic textiles. In: Duttweiler Inst. (Ed.): Textile flammability and consumer safety. Ruschlikon 1969, p 28.

20. Roding, H. Objektive Erfolgsbeurteilung der Behandlung thermischer Schädigungen. Zbl. Chir. 95:1313, 1970.

21. Schiecke, H.E. Wolle als textiler Rohstoff. Berlin, Schiele u. Schon, 1979, p 168.

22. Schukow, G.A. Napalmverletzungen in Vietnam (in Russian). Voennomed. Zh. 1971, No 8 p 85. Reported in: WehrMed. Mschr. 16:57, 1972.

23. Simms, D.L., Hinkley, P.L. Protective clothing against flames and heat. Fire Res. Rep. 3, London 1960.

24. Stoll, A.M., Chianta, A.M. Thermal protection principles. In: Hardy, J.D.: Thermal problems in aerospace medicine. Agard 111, NATO 1968, 89.

25. Tempest, M.N., Atkins, J.B. The influence of clothing on the pattern and severity of burns studied in some recent colliery fire-damp ignitions. Brit. J. industr. Med. 15:147, 1958.

26. Tikka, S. Schaden durch Verbrennung. WehrMed. Mschr. 22:175, 1978.

27. Vogel, J. Flammfestmachen von Kunststoffen. Heidelberg, Hüthig 1966,

CHAPTER 13

LOAD CARRIAGE

M. Haisman

CONTENTS

SUMMARY

INTRODUCTION
- Load Actually Carried by the Infantry Soldier
- Methods Used in the Assessment of Load Carriage Systems and Load Carrying Ability
- Factors Affecting Load Carrying Ability

LOAD FACTORS
- Maximum Weight of the Load
- Dimensions of the Load
- Load Placement

PHYSICAL CHARACTERISTICS OF THE SOLDIER
- Body Weight
- Anthropometric Dimensions

PHYSIOLOGICAL FACTORS
- Maximum Aerobic Power
- Maximum Anaerobic Power and Muscle Strength
- Body Composition
- Gender
- Age
- Perceived Exertion

ENVIRONMENTAL FACTORS
- Climate
- Terrain
- Grade

OTHER FACTORS
- Sleep Loss
- Protective Clothing

PREDICTION OF PHYSIOLOGICAL STRAIN INVOLVED IN LOAD CARRIAGE

LOAD CARRIAGE AND MILITARY PERFORMANCE

CONCLUSIONS

REFERENCES

SUMMARY

Interest in the individual load carried by the soldier goes back over many years. Physiological aspects of load carriage have been reviewed with particular reference to the relationship between desirable maximum load and body weight. These physiological aspects include age, anthropometry, aerobic and anaerobic power, muscle strength, body composition, perceived exertion and gender, together with other relevant factors such as the dimensions and placement of the load, nature of the terrain and its gradient, and the effect of climate.

In reviewing the many studies which have been done it is important to distinguish between those which assess the load carrying capacity, i.e., the soldier in a "pack-horse" role, and those which examine load carrying ability whilst the soldier retains at least a minimum level of military effectiveness.

The energy cost of walking with loads has been found to depend primarily upon the walking speed, body weight and load weight, together with terrain factors such as gradient and surface type; several equations exist which allow the prediction of energy expenditure from these variables. Such equations (e.g. Givoni and Goldman 1971) can provide a valuable guide in assessing the physical severity of proposed military operations. Other factors such as the degree of environmental heat stress and protective clothing worn would have to be taken into account, but the level of energy expenditure (or heat production) of the soldier assumes central importance as it is related to physical exhaustion, to heat exhaustion and also, albeit less directly, to the efficiency of performance of military tasks.

Renbourn (1954c) documented the loads carried by the soldier through history; he noted the inevitable increase in weight carried during wars and concluded that "the load carried by the soldier will probably always be a compromise between what is physiologically sound and what is operationally essential". Recent experience in the British Army endorses this view.

Key Words: load carriage, load placement, energy cost, personal equipment, load weight.

INTRODUCTION

Interest in the military aspects of individual load carriage is longstanding and was recorded in such reports as the British Royal Commission of 1858, quoted in a historical review of the subject by Renbourn (1954a). There are a number of reviews which cover various aspects of load carriage, for example: energy expenditure studies, Passmore and Durnin (1955) and Redfearn et al. (1956); physiological limitations of the soldier and load carriage development reviewed by Kennedy, Goldman and Slauta (1973); effects of load carriage on military performance examined by Lotens (1982).

The literature available on the physiological assessment of individual load carriage is vast. Consequently it is important to circumscribe this paper; reports which are concerned with load carried on the trunk, hands or head and appear to have some military relevance are of greatest interest, whereas the problems of lifting in a static position, (e.g., Legg & Pateman, 1984), and also the use of mechanical devices such as wheels, (Haisman et al., 1972) have not been considered. Rather the aim is to draw together the main physiological factors that affect load carriage itself, and the impact on the performance of military tasks as this is of prime importance to the soldier.

Load Actually Carried by the Infantry Soldier The extent of the load carriage problem is often not fully appreciated, either because it is believed that mechanised transport will always be available, or that the complexity of the equipment involved in different orders of battle obscures the very considerable total weights involved. Table 1 shows the loads the British infantryman has to carry, starting from the skin and working outwards. Consideration of Table 1 indicates that the basic clothing assembly weighs 7 kg and the Assault Dress (including weapon, ammunition and NBC ensemble) takes the total to over 26 kg. It is easy to see that, with the addition of support weapons, radios and extra equipment, the total weight carried can rapidly escalate to the very high figures which have been quoted for military operations; e.g., 45-60 kg in the Falklands operation and similar loads in Viet-Nam operations.

Methods Used in the Assessment of Load Carriage Systems and Load Carriage Ability Having established that the soldier does indeed have a load carriage problem, the main factors which affect load carrying ability can be examined. Various methods of assessing the physiological aspects have been used in the laboratory or in the field; e.g., marching at a fixed speed or during selfpacing (Winsmann & Goldman (1976)). In addition to physiological measures of energy expenditure, heart rate, body temperature, and sweat loss, use has been made of subjective rating scales such as the RPE scale (Rated Perceived Exertion) of Borg (1970). Effects of load placement on back muscle activity have been investigated by Bobet & Norman (1984). Other methods of evaluating load carriage systems can include short duration runs after cross-country marches (Knowles, 1984), agility course performance (Wynne, 1974), performance studies (Bensel & Lockhart, 1975), or troop trial, that is during evaluation in service use over an extended period of time, e.g., one year (Hopkinson et al., 1980).

Table I

Clothing and Personal Equipment Carried by a British Infantryman

			Weight kg	Total Weight kg
A. Dress	Underclothes, shirt, combat smock and trousers, jersey, socks, boots, gloves field dressing, cap, Camouflage, helmet			
			6.97	6.97
B. Assault Dress	Clothing, etc. as in A; rifle and sight, 6 x 30 rounds ammunition, 1 x 150 rounds, 2 x grenades, NBC ensemble, webbing (pouches, belt, yoke), full water bottle, mug and carrier, digging tool.			
			19.40	26.37
C. Combat Order	Dress and equipment as in A & B; main 2 meals, cooker and spoon, warm clothing (combat liner and waterproof jacket)			
			3.65	30.02
D. Marching Order	Clothing and equipment as in A, B & C; underclothes, shirt, socks, long johns, boots, polish and brush, towel, foot powder and water sterilising kit, washing and shaving kits, rations (24 hour pack, remainder of main meal), mess tin, sleeping bag, 2nd NBC ensemble rucksack, protective sheet.			
			10.16	40.18
E. Additional Equipment that can be added.		LAW 66mm	2.2	
		MAW 84mm	16.36	
		4xMAW rounds	10.45	
		51 mm mortar and wallet	7.60	
		6 x 51 mm mortar bombs	7.60	
		Individual weapon sight	3.20	
		Radios of various types	2.10 7.40 12.60	
		Binoculars	1.18	
		Torch	0.30	
		Rope	0.65	
		Body armour	2.50-4.32	
		16mm flares pack	0.24	

A United States infantryman, according to Kennedy et al. (1973), has an assigned basic load of 17 kg. Adding body armour, CW protection and basic existence load takes it up to 27.8 kg; a machine gunner would carry 32 kg, and radio operators or mortar men carry loads in

excess of 35 kg. These peace time loads are routinely increased during actual combat operations (Kennedy et al. (1973) Fig. 17).

Factors Affecting Load Carrying Ability Factors affecting load carriage have been examined in order to assess their relative importance, to determine the situations in which load carrying ability may be reduced to an unacceptable level and to establish how any reductions in performance could possibly be alleviated.

LOAD FACTORS

1) Maximum Weight of Load

There have been numerous attempts to define the upper limit of weight to be carried by the soldier. World War I did not necessitate much movement and, as a result, the soldier became grossly overloaded. Cathcart et al. (1923) describe the problem of an initially heavy load of 60 lbs (27.3 kg) being increased to 94 lbs (42.7 kg) because of water and mud soaking into the clothing and equipment. With the much greater use of water resistant materials today this problem of water uptake has been minimised, but that extra load has now been replaced by a diversity of weaponry and equipment as illustrated in Table 1. Marshall (1950), describing the experience of US troops, cites training loads of about 60 lbs (27.3 kg) being increased in combat by more rations and munitions. In terms of the load carriage capacity of man, Soule et al. (1978) showed that the constancy of measured energy expenditure per kg of load (or body weight) extended up to loads of 70 kg provided the load was well balanced and close to the center of the body. Daniels (1956) reported observations of loads of up to about 180 kg being carried with a Korean A frame. On the other hand there is evidence (Durnin & Passmore (1967)) that the physiological efficiency of load carriage falls at high load weights. There is clearly a case for setting an upper limit to the absolute weight carried by the soldier and, if the load is not going to impair the soldiers' efficiency to a marked extent, this weight limit ought to be in the region of 30 kg. While it is more logical to relate the load to the body weight of the soldier, as it is obvious that a 30 kg load is a very heavy one for a 57 kg soldier (5 percentile for British Infantry, Gooderson, 1982) but a reasonable load for a 92 kg soldier (95th percentile), it may however be quite impractical to attempt to tailor an individual soldier's load to his body weight.

2) Dimensions of the Load

Missile systems often present the soldier with awkward shapes of load to carry. Amor & Vogel (1974) compared three methods of carrying a missile of 35 kg in weight and 1.2 m in length; they found no difference in energy cost between the methods but the subjects preferred to carry the missile in a horizontal position on the back. Torre (1973) studied the effects of weight and length of an anti-tank system on performance and found that the soldier was reluctant to carry loads longer than 31" (at 8 lbs), when added to his current fighting load. There is also the problem of the load interacting with other items of the soldier's equipment, for example a shovel carried center back can conflict with the back of the helmet in the prone firing position.

3) Load Placement

Soule & Goldman (1969) showed that the energy cost of carrying loads on the head, hands and feet were, in comparison to a no load condition, in the ratio of 1.2X for the head, 1.9X for the hands and 4-6X for the feet (up to 6 kg on each foot). Strydom et al. (1968) however concluded that, provided the boot weight was no more than 4-6 lbs per pair, there was no increase in oxygen consumption. Datta & Ramanathan (1971) compared seven methods of carrying loads of 30 kg; a double pack (front and back) proved to be the best, and the hands the worst in terms of physiological efficiency. Legg & Mahanti (1985) compared five methods of carrying a load of 35% body weight on the trunk and found that there were no significant physiological differences between them. The front/back pack combination and a load carrying jacket were subjectively rated as more comfortable than the back packs, with or without a frame; on the other hand the front/back pack was reported to be the hardest to don and doff and was associated with a restrictive type of ventilatory impairment.

PHYSICAL CHARACTERISTICS OF THE SOLDIER

1) Body Weight

That the maximum comfort load should be related to body weight is an idea of long standing. According to Renbourn's review (1954b) the weight carried by the infantry soldier steadily increased during Worid War I until it often amounted to 85% of body weight. Much work on the energy expenditure of load carriage was undertaken in the years after World War I, notably by Cathcart et al. (1923); on the basis of the "costliness" of load carriage, which rose steeply above 40% of body weight; they recommended that under laboratory conditions the maximum load for the maintenance of efficiency and health should be 40% body weight, and for service conditions they accepted the traditional limit of one-third body weight. Pandolf et al. (1977) suggested that the energy cost of standing with a back load increased as the square of the ratio of load weight to body weight. Marshall (1950) cites British and other studies to recommend an optimal marching load for the average man of not more than one-third of body weight. Therefore, individuals with a high body weight can carry greater loads but, as will be discussed later, the constituent proportions of body weight, whether muscle or fat, will be important. Indian porters appear to be an exception to any generalisations about the advantages of high body weight in load carriage; Nag & Sen (1978) studied porters of 53 kg mean body weight who carried loads up to 100 kg on the treadmill; they were, however, very lean (body fat 8.3%) and had a high $\dot{V}O_{2max}$ (ml/kg-min).

2) Anthropometric Dimensions

The design of load carriage equipment must take into account the range of dimensions in key anthropometric variables in the population to be fitted. Experience has shown that back length and waist circumference are important and that those individuals having very small dimensions will have great difficulty in fitting a back frame correctly or in accommodating the full complement of pouches on the waist belt (Kennedy et al., 1973). Furthermore, small and large extremes in the range may find that the load is not bearing on the anatomical points that the designer intended, although this problem may be partially alleviated if there is an adequate range for adjustment of the straps.

PHYSIOLOGICAL FACTORS

1) Maximum Aerobic Power ($\dot{V}O_{2max}$).

$\dot{V}O_{2max}$ is much used as an index of cardio-respiratory performance (Astrand, 1956; Shephard, 1968) and also as an index of ability to perform maximal work (Taylor et al., 1955; Mitchell et al., 1958). It follows that factors which will raise $\dot{V}O_{2max}$ will improve the ability to carry loads, and the converse will also be true. It has been shown by a large number of studies that aerobic physical training will increase $\dot{V}O_{2max}$. Saltin (1969) showed that the absolute improvement in $\dot{V}O_{2max}$ ranges up to 50% starting from a post 3 weeks of bed rest level, but the improvement is highly dependent upon the initial level of $\dot{V}O_{2max}$ and may be about 25% for average, non exercising individuals. A number of factors have been associated with a decrease in $\dot{V}O_{2max}$, for example: increasing age (Astrand, 1960); semi-starvation with consequent loss of lean body mass (Keys et al., 1950); bed-rest (Taylor et al., 1949); loss of blood (Rowell et al., 1964); high altitude (Pugh et al., 1964); and dehydration (Buskirk et al., 1958). Factors such as these will, therefore, tend to lower the <u>maximal</u> load carriage capacity or slow the march rate at which it can be carried. Another important consideration is that a well trained man cannot be expected to work all day at a work level equivalent to more that 50% of his $\dot{V}O_{2max}$ without becoming fatigued (Astrand, 1956), so that the $\dot{V}O_{2max}$ will be a major determinant of the size of load carriage task which can be sustained for a prolonged period. Since $\dot{V}O_{2max}$ is usually correlated with body weight, and in particular with muscle mass, individuals with a high $\dot{V}O_{2max}$ (l/min) and large load carriage capacity will also tend to have higher than average body weight or muscle mass.

Shoenfeld et al. (1977) used the size of the decrement in $\dot{V}O_{2max}$ after load carriage to assess the maximum load which should be carried for 20 km; they concluded that for individuals in good physical condition this should not exceed 25 kg, i.e., just over one third of the body weight of a 70 kg man.

2) Maximum Anaerobic Power and Muscle Strength

Anaerobic power and muscle strength are important for activities of high intensity for brief periods of time, i.e., less than 2 minutes. According to surveys of the tasks

which soldiers undertake in the US Army, a considerable proportion require anaerobic power and muscle strength; e.g., handling heavy weights such as artillery shells, pulling, pushing and throwing (Vogel, 1984, personal communication). Methods of measurement of anaerobic power are available, e.g., the Wingate ergometer test (Bar-Or et al., 1980) and some of these methods have been compared recently (Patton & Duggan, 1985). Muscle strength can be measured during isometric contractions using strain gauge dynamometers (Hermansen et al., 1972) or isokinetically using equipment such as the Cybex II dynamometer (Thorstensson, 1976). However, only fair to poor relationships have been found between the isometric strength of various muscle groups and $\dot{V}O_{2max}$ (Toft, 1981) and, although it seems likely that dynamic muscle strength (as measured isokinetically) will relate to load carrying ability, the studies do not appear to have to been done. Patton & Duggan (1985) found that peak torque on both the Cybex and the Wingate tests of anaerobic power correlated with field tests of anaerobic performance (sprinting and stair climbing).

3) Body Composition

The main body composition factors to affect load carriage are firstly the size of the lean body mass (i.e. bone, muscle and water content) and secondly the proportion of the total body weight which is fat. Lean body mass is highly correlated with $\dot{V}O_{2max}$ (Buskirk & Taylor, 1957) and is a positive factor in load carriage ability. Conversely, excess body fat is dead weight in the performance of work and degrades the performance of physical tasks involving movement of the body and external load, and thus the utility of expression $\dot{V}O_{2max}$ in terms of ml of oxygen uptake per kilogram of body weight per minute as an expression of aerobic fitness. A soldier weighing 85 kg (88th percentile of British Army), with 25% of body fat is carrying 21 kg of body fat; assuming he need only have about 9 kg of fat (i.e., about 10% of body weight) for good health, this represents about 12 kg less of external load which he can carry.

4) Gender

Snook & Ciriello (1974a) compared males and females on various tasks including six carrying tasks. Women handled significantly less weight than men but experienced similar or higher heart rates. Generally speaking, women will be at a disadvantage in load carriage tasks because, compared to men, they tend to have lower body weight, higher body fat, lower $\dot{V}O_{2max}$ and lower muscle strength, particularly in the arm muscles (Vogel & Patton, 1978).

5) Age

It has already been mentioned that $\dot{V}O_{2max}$ decreases with age. The decrease is about 10% per decade from age 20 (Hermansen, 1978); this effect of aging is likely to be associated with the decline in maximal heart rate with increasing age (Robinson, 1938) as well as with the increase in fat as a percent of body weight with age.

6) Perceived Exertion

Borg (1970) studied the relationships between the physiological responses to different levels of work and the subjective rating of the work load. The rating scale used has come to be known as "the Borg scale" and, in general, correlates roughly with the heart rate. It is a useful tool for evaluating the severity of a load carriage task, or for comparing different methods of carrying a load since, simply by having the individual select a number on the scale (which ranges between 6 and 20), we gain insight on the ratio of the actual energy expended to the individual, $\dot{V}O_{2max}$.

ENVIRONMENTAL FACTORS

1) Climate

Kamon & Belding (1971) found no difference in the metabolic cost of load carriage in hot climates (35 & 45 °C) compared to a temperate climate, but heart rate was found to increase by 7-10 beats/min for each l0 °C rise in air temperature, presumably because of increasing difficulty in eliminating the metabolic heat production at higher temperatures. Snook & Ciriello (1974b) showed that load carrying ability was reduced by 11% in a hot environment (WBGT=27 °C), with significantly higher rectal temperature and heart rate. Durnin & Haisman (1966) investigated the effects of hot-dry and hot-wet climates on load carrying in acclimatised subjects and found that the metabolic rate, heart rate, sweat rate and body temperature were all elevated in the hot climates. In cold climates the effect of reduced air temperature does not appear to increase the energy cost of walking at standard speeds with loads (Haisman, 1977). It has been shown (Amor et al., 1973) that the energy cost of walking in multi-layer clothing is increased by up to 20% over the same task when wearing shorts with the weight of the multi-layer clothing carried on the belt. Thus, should higher levels of energy expenditure be found in cold climates, the extra energy expenditure is more likely attributable to the weight, hobbling and restrictive effects of multi layer clothing than to the effects of the cold itself.

2) Terrain

Strydom et al. (1966) showed that carrying loads over sandy surfaces required an energy expenditure 80% greater than over a firm surface. Soule & Goldman (1972) investigated a variety of terrains including smooth and dirt roads, light and heavy brush, as well as swamp and sand, and they compared the results with control conditions of walking on a treadmill. Pandolf et al. (1976) examined the effects of walking in various snow depths and found that the energy cost was increased by 5X with a footprint depth of 45 cm in the snow. Thus, combining the snow depth effect with the effect of multi layered cold weather clothing already mentioned, it can be seen that this is an activity which results in very high rates of energy expenditure and the production of large amounts of heat. The cost of carrying a given load for various terrains, in comparison with a treadmill at the same walking speed (of 1.6 m/s) are shown in Table 2.

TABLE II

Energy Cost of Walking (watts) at a Given Speed (1.6 m/s) for Various Level Terrains (70 kg man with no load)

Terrain	Blacktop	Dirt Road	Light Brush	Hard Snow	Heavy Brush	Swampy Bog	Loose Sand	Soft Snow footprint depth (15cm)	Soft Snow footprint depth (25cm)
Energy cost	374	401	428	454	508	589	669	777	992

from Pandolf et al. (1977)

3) Grade

Gordon et al. (1983) compared the effects of added load (up to 50% body weight) on walking subjects, with unloaded walking at the same velocity for gradients up to 20%; they found that added loads brought about larger increases in heart rate and RPE (rating of perceived exertion) than did unloaded walking on grades for equivalent increases in power. The effects of increased grade when walking with loads of 0, 20 and 40 kg at a constant speed of 1.34 m/s are shown in Table 3, taken from Pandolf et al. (1977).

TABLE III

Energy Cost of Walking (watts) at a Given Speed (1.34 m/s) for Loads of 0, 20 and 40 kg at Various Grades (70 kg man)

Grade (%)		0	4	8	12	16
Load	0	294	425	556	687	819
(kg)	20	362	531	700	867	1037
	40	473	679	886	1092	*

*exceeds the physiological range for soldiers. (From Pandolf et al., 1977)

OTHER FACTORS

1) Sleep Loss

In a series of studies on the effects of reduced sleep on military performance, Haslam (1984) has shown that the tasks worst affected are those requiring cognitive ability, especially sustained attention; physiological function, particularly in the performance of physical work, appears to be little affected.

2) Protective Clothing

A series of experiments has been conducted to study the effects of wearing chemical protective clothing with military loads in a range of temperate to hot environments (Gooderson, 1981); the results have been integrated to provide a Commanders Guide for NBC Dress Discipline which allows an appropriate work rate to be selected for a particular NBC Dress in different levels of climatic stress. As might be anticipated, the increased heat production associated with heavier, or inefficiently carried, loads exacerbates the potential heat stress when wearing such clothing.

PREDICTION OF PHYSIOLOGICAL STRAIN INVOLVED IN LOAD CARRIAGE

The energy cost of walking with loads has been found to be dependent primarily upon the speed of walking, and the weight of the body and the load, together with the gradient. There are now several equations available which allow prediction of energy cost from those variables. For example, Goldman and Iampietro (1962) combined data from their own subjects with those from the literature to produce a graph for prediction of energy cost of walking at speeds from 2.4 - 6.4 km/h, on grades 0-9%, with loads up to 30 kg; they concluded that the energy cost per unit weight is essentially the same whether the weight is of the body or the load. Durnin and Passmore (1967) reviewed the older literature and derived an equation for walking on level ground.

Givoni and Goldman (1971) used data from Goldman's studies and from the literature to derive an empirical equation using body and load weights, walking speed, slope and a terrain factor. A wide range of speeds and grades was included; viz: walking 2.6 - 9 km/hr and up to 25% grade, running from 8-17 km/hr up to 10% grade, and loads up to 70 kg. Modifying coefficients were suggested for terrains other than the treadmill, for load placement if not carried on the trunk and for very heavy levels of work. The mean standard error of estimate over all conditions was 29 kcal/hr.

Since 1971 there has been considerable development of the method to improve accuracy. Soule and Goldman (1972) investigated terrain coefficients and Pandolf et al. (1977) modified the equation to include walking speeds down to 0.2 m/s and standing still. This equation is:

$$M = 1.5W + 2.0\,(W+L)\,(L/W)^2 + n(W+L)\,(1.5V^2 + 0.35\,VG)$$

M = metabolic rate (watts).
W = subject weight (kg); L = external load (kg).
V = speed of walking (m/s); G = grade (slope %)
n = terrain coefficient (n=1.0 for level treadmill or paved road)

Using this equation the relationship between energy expenditure, march rate and load weight can be seen from the figures in Table IV.

TABLE IV

Metabolic Rate (Watts) as a Function of March Rate on Level Black Top Road (for 70kg man carrying 30kg load including clothing).

March Rate (m/s)	0.69	0.83	0.97	1.11	1.25	1.39	1.53	1.67	1.81
Metabolic Rate (watt)	213	245	283	327	376	431	493	560	633

Other physiological parameters besides the energy expenditure of load carriage have also been estimated. Givoni & Goldman (1972) developed a series of equations to predict the rectal temperature responses to work, environment and clothing. These predictions of rectal temperature were, in turn, used to estimate heart rate (Givoni & Goldman, 1973). Generally the metabolic heat production is a major contributor to the problem of maintaining acceptable levels of deep body temperature and heart rate, particularly when evaporative skin cooling is limited by protective clothing or high ambient vapour pressures.

LOAD CARRIAGE AND MILITARY PERFORMANCE

The ultimate question that must be addressed is how the load carried affects the performance of a military task. Renbourn (1954b) noted an extreme example that prevailed at Cambrai in November 1917 when the British infantry, exhausted by their great loads, were unable to consolidate the positions opened for them by the first, and historic, mass attack by tanks. Marshall (1950) described similar problems with American troops. Bensel & Lockhart (1975) examined the effects of load carriage equipment and body armour on a number of performance criteria including rate of movement and body flexibility; both the equipment and body armour degraded performance compared with a control condition, with body flexibility particularly affected. Williamson & Kindick (1975) used the time required to complete a 4 km jungle course, a navigation test and an arm-hand steadiness test to assess the effects of carrying 25 to 55 lbs loads. Lotens (1982) reanalyzed studies by Leopold and Derrick (1963) and Haisman & Crotty (1975) to confirm the view that performance decrement due to carried load is dependent on weight, and that the method of suspension (within limits) is of minor importance. Performance decrement was of the order of 1.5 - 3.0% per kg of load weight carried.

The effect of increasing load weight on military performance in terms of rate of progression when self pacing on a 6.4 km march can be seen in Table V, taken from the data of Hughes & Goldman (1970); as the load weight increases, the speed decreases proportionately. The average energy cost per unit distance marched was found to be lowest for 30-40 kg of load.

TABLE V

Weight of Load, Energy Cost and Speed when Self Pacing over 6.4 km
(Hughes & Goldman 1970)

Weight of Load (kg)	0	20	30	40	50	60
Speed (km/hr. approx.)	8.0	6.5	5.8	5.2	4.3	3.7
Energy cost (kcal/hr.)	587	469	457	448	395	386
Energy cost per unit distance (kcal/kg.m)	1.04	0.83	0.79	0.79	0.84	0.84

CONCLUSIONS

Various physiological aspects of load carriage have been reviewed with particular reference to those studies of military relevance and the findings that allow prediction of the effects on military performance. Renbourn (1954c) having documented the loads carried by the soldier through history, noted the inevitable increase in weight during war and observed that "the load carried by the soldier, and the personal load carriage equipment, will probably always be a compromise between what is physiologically sound and what is operationally essential". Some thirty years later, after more load carriage systems have been developed and many more studies undertaken, we can but agree.

REFERENCES

1. Amor A F & Vogel J A, 1974: Energy cost of man-packing the Swingfire Missile. Army Personnel Research Establishment Report 5/74.

2. Amor A F, Vogel J A & Worsley D E, 1973: The energy cost of wearing multi layer clothing. APRE Tech Memo 18/73.

3. Astrand P O, 1956: Human physical fitness with special reference to sex and age. Physiol. Rev. 36, 307-335.

4. Astrand I, 1960: Aerobic work capacity in men and women with special reference to age. Acta Physiologica Scandinavica Vol. 49, supplementum 169. 1-92.

5. Bar-Or O, Dotan R, Inbar O, Rothstein A, Karlsson J & Tesch P, 1980: Anaerobic capacity and muscle fibre type distribution in men. Int. J. Sports Med 1, 82-85.

6. Bensel C K & Lockhart J M, 1975: The effects of body armour and load carrying equipment on psychomotor performance. Natick Tech Report CEMEL-141.

7. Bobet J & Norman R W, 1984: Effects of load placement on back muscle activity in load carriage. Eur. J. Appl. Physiol. 53, 71-75.

8. Borg G, 1970: Perceived exertion as an indicator of somatic stress. Scand. J. Rehab. Med. 2(3), 92-98.

9. Buskirk E R, Iampietro P F & Bass D E, 1958: Work performance after dehydration, effects of physical conditioning and heat acclimatisation. J. Appl. Physiol. 12(2), 189-194.

10. Buskirk E R & Taylor H L, 1957: Maximal oxygen intake and its relation to body composition, with special reference to chronic physical activity and obesity. J. Appl. Physiol. 11(1), 72-78.

11. Cathcart E P, Richardson D T & Campbell W, 1923: On the maximum load to be carried by the soldier. J. Roy. Army Med. Corps 40, 435-443. and 41, 87-98 and 41, 161-178.

12. Daniels F, 1956: Observations on the Korean A frame. The Physiology of Load-carrying XI. Natick QRDL Rpt. EP-29.

13. Datta S R & Ramanathan N L, 1971: Ergonomic comparison of seven modes of carrying loads on the horizontal plane. Ergonomics 14 (2), 269-278.

14. Durnin J V G A & Haisman M F, 1966: The effects of hot environments on the energy metabolism of men performing standardised physical work. APRE Memo N/3.

15. Durnin J V G A and Passmore R, 1967: Energy, Work and Leisure. London, Heinemann.

16. Givoni B & Goldman R F, 1971: Predicting metabolic energy cost. J. Appl. Physiol. 30(3), 429-433.

17. Givoni B & Goldman R F, 1972: Predicting rectal temperature response to work, environment and clothing. J. Appl. Physiol. 32, 812-822.

18. Givoni B & Goldman R F, 1973: Predicting heart rate response to work, environment and clothing. J. Appl. Physiol. 34 (2), 201-204.

19. Goldman R F and Iampietro P F, 1962: Energy cost of load carriage. Journal of Applied Physiology. 17 (4), 675-676.

20. Gooderson C Y, 1981: The measurement of thermal penalties associated with NBC and other protective clothing. 13th Commonwealth Defence Conference on Operational Clothing & Combat Equipment.

21. Gooderson C Y 1982: Final Report. The ADRE anthropometry survey of the British Army 1972-1977. APRE Memo 82R003.

22. Gordon M J, Goslin B R, Graham T and Hoare J, 1983: Comparison between load carriage and grade walking on a treadmill. Ergonomics 26(3), 289-298.

23. Haisman M F, 1977: Physiological aspects of protective clothing for military personnel. Chapter 2 in Clothing Comfort (eds. Hollies N R S & Goldman R F) Ann Arbor Science, Michigan.

24. Haisman M F & Crotty J, 1975: Problems associated with body armour. Paper presented to the 11th Commonwealth Defence Conference on Operational Clothing and Combat Equipment. Delhi, India

25. Haisman M F, Winsmann F R & Goldman R F, 1972: Energy cost of pushing loaded hand carts. J. Appl Physiol 33(2), 181-183.

26. Haslam D R, 1984: The military performance of soldiers in sustained operations. Aviat. Space Environ. Med. 55(3), 216-221.

27. Hermansen L, Ericksen O & Larsen C, 1977: Apparatus for rating of isometric muscular strength. J. of Norwegian Medical Assoc. 4, 1-8.

28. Hermansen L, 1978: Assessment of physical performance capacity in human subjects. Proceedings of the RSG4 Physical Fitness Symposium DCIEM Canada, NATO. DS/DR(78)98 pp 7-19.

29. Hopkinson W I, Knowles D J & Haigh P M, 1980: Troop trials of the 58 pattern Mk II Webbing & Rucksack GS, Personal Load Carriage Equipment. APRE Report 80007.

30. Hughes A L & Goldman R F, 1970: Energy cost of "hard work". J. Appl. Physiol. 29(5), 570-572.

31. Kamon E & Belding H S, 1971: The physiological cost of carrying loads in temperate and hot environments. Human Factors 13 (2), 153-161.

32. Kennedy S J, Goldman R F, & Slauta J, 1973: The carrying of loads within an infantry company. Natick Tech Report 73-51-CE.

33. Keys A, Brozek J, Henschel A, Michelson O & Taylor H L, 1950: The Biology of Human Starvation, Vol. I. University of Minnesota Press, Minneapolis, Minnesota.

34. Knowles D J, 1984: A human factors assessment of a weapons carrier for general purpose use. APRE Working Paper 9/84.

35. Legg S J & Mahanty A, 1985: Comparison of five modes of carrying a load close to the trunk. Ergonomics 28,1653-1660.

36. Legg S J & Pateman C M, 1984: A physiological study of the repetitive lifting capabilities of healthy young males. Ergonomics 27, 259-272.

37. Leopold R S, Derrick L G, 1963: The effects of wearing body armour of different designs, materials and weights in conjunction with two designs of packs and suspenders on the performance of the Marine. US Naval Med. Field Research Lab. North Carolina, Vol. XIII, No. 8.

38. Lotens W A, 1982: Clothing design and its relation to military performance. Institute of Perception TNO. IZF 1982-34.

39. Marshall S L A, 1950: The soldier's load and the mobility of a nation. Marine Corps Assoc., Quantico, Virginia.

40. Mitchell J M, Sproule B J & Chapman C B, 1958: The physiological meaning of maximal oxygen uptake test. Journal Clin. Invest. 37, 538-547.

41. Nag P K, Sen R N & Ray U S, 1978: Cardio-respiratory performances of porters carrying loads on a treadmill. Ergonomics 22(8) 897-907.

42. Pandolf K B, Givoni B & Goldman R F, 1977: Predicting energy expenditure with loads while standing or walking very slowly. J. Appl. Physiol. 43(4), 577-581.

43. Pandolf K B, Haisman M F & Goldman R F, 1976: Metabolic energy expenditure and terrain coefficients for walking on snow. Ergonomics 19(6), 683-690.

44. Passmore R & Durnin J V G A, 1955: Human energy expenditure. Physiological Reviews, 35, 801-840.

45. Patton J F and Duggan A, 1985: The evaluation of tests of anaerobic power. APRE Memo 85M503.

46. Pugh L G C E, Gill M B, Lahiri S, Milledge J S, Ward M P & West J B, 1964: Muscular exercise at great altitudes. J. Appl. Physiol. 19, 431-440.

47. Redfearn J W T, Crampton R F, William T D & Mitchell B, 1956: The metabolic cost of load carrying - a discussion of experimental findings. AORG Report 4/56.

48. Renbourn E T, 1954a: The knapsack and pack. An historical and physiological survey with particular reference to the British Soldier. J. Roy. Army Med. Corps. 100, 1-15.

49. Renbourn E T, 1954b: The knapsack and pack Part II. J. Roy. Army Med. Corps. 100 (2), 77-88.

50. Renbourn E T, 1954c: The knapsack and pack Part III. J. Roy. Army Med. Corps. 100, 193-200.

51. Robinson S, 1938: Experimental studies of physical fitness in relation to age. Arbeits-physiologie 10, 251-323.

52. Rowell L B, Taylor H L, & Wang Y, 1964: Limitations to prediction of maximal oxygen intake. J. Applied Physiology 19(5), 919-927.

53. Saltin B, 1969: Physiological effects of physical conditioning. Med. & Sci. in Sports 1(1), 50-56.

54. Shephard R J, 1968: Methodology of exercise tests in healthy subjects and in cardiac patients. Can. Med. Ass. J. 99, 354-359.

55. Shoenfeld Y, Shapiro Y, & Portugeeze D, 1977: Maximal back pack loads for long distance hiking. J Sports Med. Phys. Fitness. 17(2), 147-151.

56. Soule R G & Goldman R F, 1969: Energy cost of loads carried on the head, hands or feet. J. Appl. Physiol. 27(5), 687-690.

57. Soule R G & Goldman R F, 1972: Terrain coefficients for energy cost prediction. J. Appl. Physiol. 32(5), 706-708.

58. Soule R G, Pandolf K B and Goldman R F, 1978: Energy expenditure of heavy load carriage. Ergonomics 21(5), 373-381.

59. Snook S H & Ciriello V M, 1974a: Maximum weights and work loads acceptable to female workers. J. Occup. Med. 16(8), 527-534.

60. Snook S H & Ciriello V M, 1974b: The effects of heat stress on manual handling tasks. Amer. Industr. Hyg. Assoc. J. 35(11), 681-685.

61. Strydom N B, Bredell G A G, Benade A J S, Morrison J F, Viljoen J H & Van Graan C H, 1966: The metabolic cost of marching at 3 mph over firm and sandy surfaces. Int. Z. Angew. Physiol. einschl. Arbeitsphysiol. 23, 166-171.

62. Strydom N B, Van Graan C H, Morrison J F, Viljoen J H & Heynes A J, 1968: The influence of boot weight on the energy expenditure of men walking on a treadmill and climbing steps Int. Z. Angew. Physiol. einschl. Arbeitsphysiol. 25, 191-197.

63. Taylor H L, Buskirk E & Henschel A, 1955: Maximal oxygen intake as an objective measure of cardio-respiratory performance. J. Appl. Physiol. 8, 73-80.

64. Taylor H L, Henschel A, Brozek J and Keys A, 1949: Effects of bed rest on cardiovascular function and work performance. J. Appl. Physiol. 2(5), 223-239.

65. Toft R J, 1981: Maximal oxygen uptake and muscle strength of well trained men. APRE Memo 81M501.

66. Torre J P Jr. 1973: The effects of weight and length on the portability of anti-tank systems for the infantrymen. US Army Human Engineering Lab. Aberdeen Md. Tch Memo 20-73.

67. Vogel J A & Patton J F, 1978: Evaluation of fitness in the US Army. Proceedings of RSG4 Physical Fitness Symposium DCIEM Canada. NATO DS/DR(78)98, pp 29-35.

68. Williamson R L & Kindick C M, 1975: Human Performance in the Tropics II. A pilot study on load carrying test methodology. Army Tropic Test Centre USATTC -7511001.

69. Winsmann F R & Goldman R F, 1976: Methods for evaluation of load carriage systems. Percept. Motor Skills 43(3), 1211-1218.

70. Wynne R W, 1974: Effect of weight carried on performance over agility course. APRE Memo 20/74.

CHAPTER 14

PERSONAL PROTECTIVE BODY ARMOUR

E. van de Linde and W. Lotens

CONTENTS

SUMMARY

1. INTRODUCTION

2. SOURCES OF STRAIN

3. TYPES OF BODY ARMOUR AVAILABLE

4. FUNCTIONAL OBSTRUCTION

5. PHYSIOLOGICAL IMPAIRMENT

6. GENERAL DISCUSSION

REFERENCES

SUMMARY

Benefit (protection) and drawbacks (functional obstruction, physiological impairment) of body armour are discussed. The mechanism of physiological impairment seems to be rather straightforward and can be explained by an impairment of heat exchange. However, protection and functional obstruction are still subject to dispute, mainly where the conversion of experimental individual data to overall military performance is concerned.

Key Words: Body armour; ballistic protection, heat stress, military performance, human load carriage.

1. INTRODUCTION

Originally, body armour was intended to protect the wearer against weapons with a relatively low penetration, and a leather jacket or a coat of mail was sufficient to prevent severe injury caused by a sword or a knife. At the time that weapons with higher impact became in vogue (lances, e.g.), body armour gained weight as well. Soon it became necessary mechanically to hoist a knight upon his horse. With the increasing use of firearms, starting at the beginning of the 16th century, the use of body armour decreased because with the available materials it was not possible to attain sufficient protection and preserve agility. It was not until the end of World War II that body armour came into regular use on a small scale, for the aircrew of military aircraft. Later on, in Korea, body armour was used for ground troops on a fairly large scale because of a break-through in the use of flexible materials, such as nylon or nylon/doron. Nowadays it is more commonly thought that every soldier should possess his own ballistic protection, although to date few armies have body armour issued for general war. At this moment the helmet is the only ballistic protective item regularly worn. Nevertheless, the increasing use of body armour is foreseen. Therefore, again the question arises how to deal with the increased physiological strain resulting from use of body armour.

2. SOURCES OF STRAIN

In Fig. 1 a diagram is shown that displays a simplified view of the interaction between task, body armour and performance. The main properties of body armour are distinguished. First of all, the protection factor determines the type and severity of wounds, given a specific battlefield. (This protection factor will be dependent of course upon the material used and the covered body surface area in m^2, with specific interest to protection of vulnerable areas).

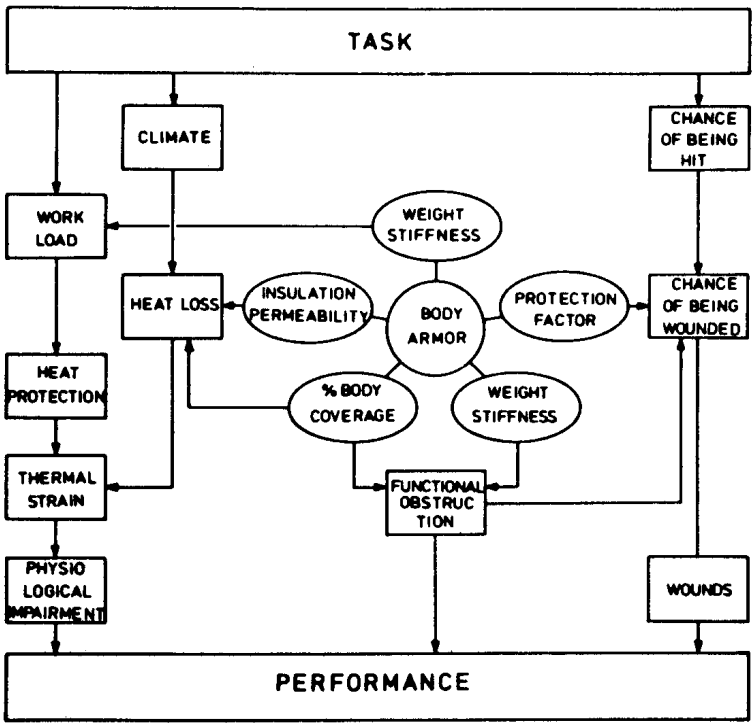


Fig. 1. The interaction of task, body armour and performance

On the other hand, heat loss is affected by the material used (insulation, permeability) and the covered body surface area as well. Work load is mainly affected by weight and stiffness of the body armour. Finally weight, stiffness and relative body coverage cause functional obstruction, also through incompatibility with other clothing and equipment items. In summary, body armour may have three main effects:

– a decrease in number and severity of wounds

– an increase in – physiological impairment
– functional obstruction.

It is clear that the first effect is beneficial for the wearer, whereas the latter two are disadvantageous. Such a situation can only be resolved by compromise. Therefore we need to know the magnitude of the effects and the relative importance of the causes. Once again, we distinguish the following causes:

Material factors: weight, stiffness, insulation, permeability

Design factors: body coverage, fit, compatibility with other equipment .

3. TYPES OF BODY ARMOUR AVAILABLE

Body armour comes in three different types, with increasing protection offered:

1. Spall protective
2. Shell fragmentation protective
3. Bullet protective

These three categories refer mainly to the origin of the ballistic threat. Spall, coming from armour when hit, is lowest in energy. Typical figures range from 0.25 to 1.00 kJ. Shell fragmentation may reach an energy of up to 10 kJ, with fragments to almost 100 g and speeds more than 1000 m/s. In between are bullets, with .5 to 3.5 kJ. Of course, not only is energy important, but also the shape of the projectiles. Although shell fragmentation is highest in energy, protection against that threat is easy compared to bullets because of low penetration. So, although the names of the three categories refer to the origin of the ballistic threat, the classification is in conformity with increasing protection, too .

In general, increased protection keeps pace with increased weight and relative body coverage. As technology reduces weight required for a particular protection level, there is a tendency to seek higher levels of protection. Modern body armour is mostly made from aramid panels (ed. note ~ 1980). The more panels, the more protection one gets. But also: the more panels, the more weight, the more insulation, the more stiffness, and the less water vapour permeability.

Spall protective vests are only worn by personnel under armoured protection. They protect the wearer only against splinters coming off the armour when it is hit. Shell fragmentation protective vests offer better protection, preventing grenade shell fragments from penetrating. To stop the more penetrating bullets such a huge amount of aramid panels would be needed that additional protection such as steel composite or ceramic plates are the only solution at this time. It is beyond doubt that, with bullet protective vests as they are now, physical work is only possible at a considerable physiological cost. The shell fragmentation

protective vest is the most currently worn type. This is not surprising, since most casualties are caused by grenades (75%) (Homes et al., 1954; Jameson et al., 1975). The shell fragmentation protective vest is also most frequently described in the literature. This affords the opportunity to take a closer look at this type of body armour.

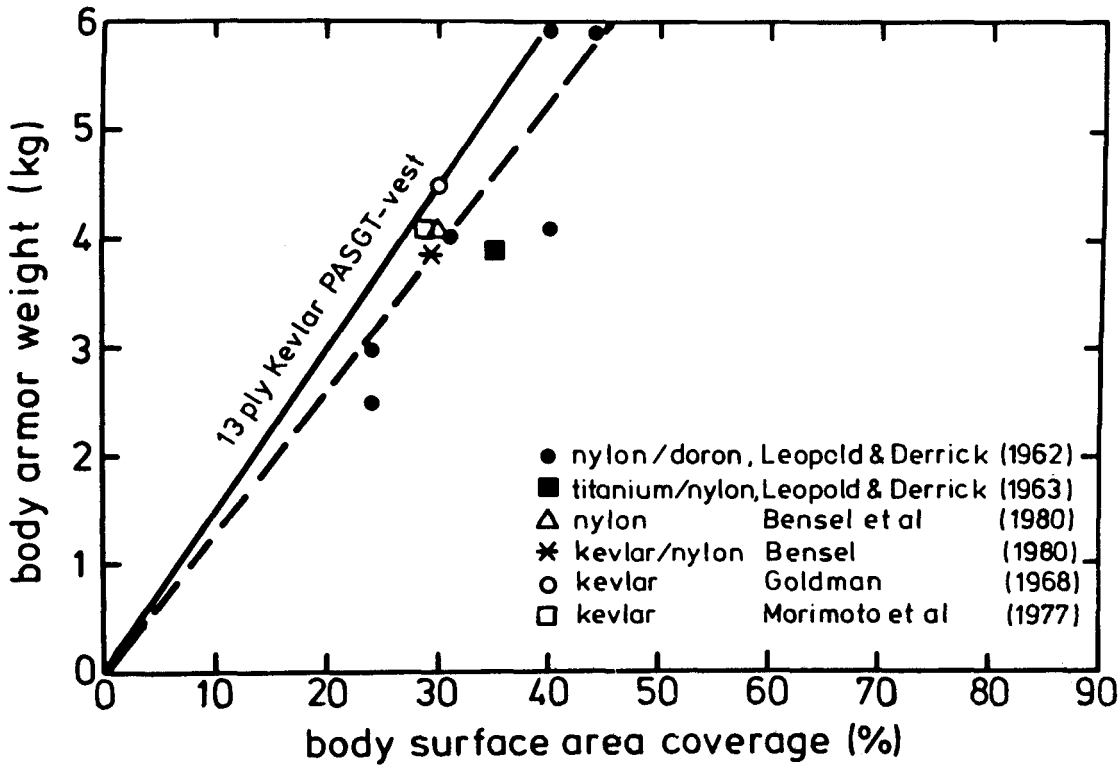


Fig. 2. Relationship between weight and % covered body surface area of various types of body armour. Straight line: 13 ply aramid PASGT. Dotted line: regression, drawn by hand, through data of general vests described by the authors cited.

In Fig. 2, the relation between covered body surface area and weight is constructed from data from several authors. Bensel et al. (1980) stated these properties quite precisely for the PASGT vest (Personal armour system for ground troops (USA)). For this 13 ply aramid vest the specific weight is 8 kg/m^2, or, for an average man with a skin surface area of 1.9 m^2, 150 g/% body coverage (This particular vest is covering 30% of body surface area).

Other authors are less precise but give nevertheless a fairly accurate description. If we combine their data (Fig. 2), a regression of 130 g/% body coverage results (under the forcing condition that the regression runs through the origin). The variation is rather small, indicating that the various designs and materials have not, until the present moment, resulted in a drastic decrease in specific weight. (It might well be, though, that protection has increased). In the rest of this chapter we may therefore take 150 g/% as a reasonable figure. With this figure we may easily calculate the weight of body armour, depending upon the area covered.

Fig. 3 shows 7 hypothetical designs of body armour. Of these, weight and relative body coverage are listed in Table I.

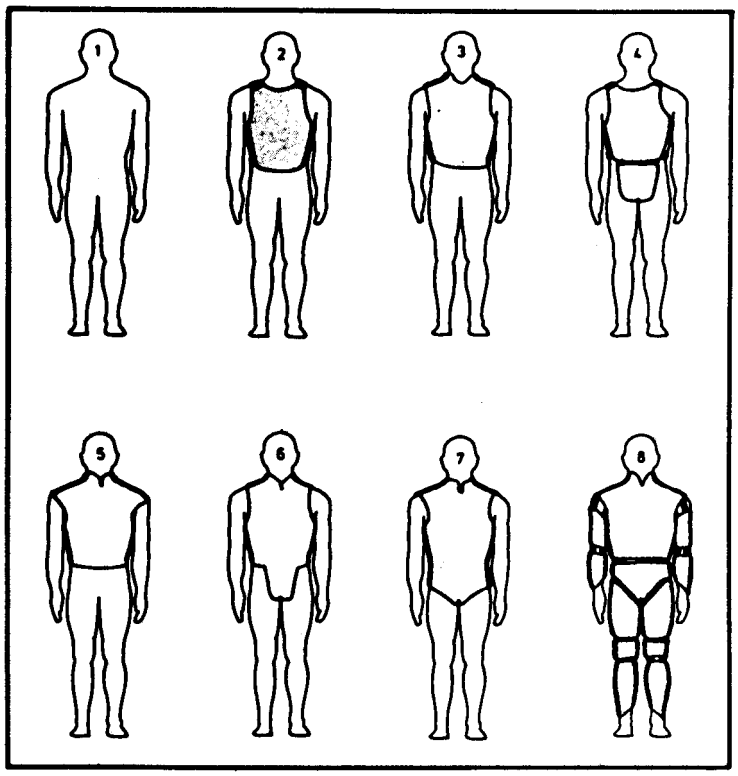


Fig. 3. Some hypothetical versions of body armour with increasing body coverage. Description in Table I.

Table I. Weight and relative body coverage of the hypothetical body armour types shown in Fig. 3. All figures are for an average man (skin surface area 1.9 m).

type nr.	description	% body coverage	weight (kg)
1	nude	0	0
2	upper torso	25	3.75
3	upper torso	30	4.50
4	upper/lower torso	30	4.50
5	upper torso+shoulder	35	5.25
6	upper/lower torso	35	5.25
7	upper/lower torso	40	6.00
8	total	75	11.25

Assuming that more relative body coverage offers more protection, we might easily conclude that protection is proportionately paid for by weight. However, this assumption is not that obviously valid. Homes et al. (1954), evaluating Korea casualties, report that 30% of the non-lethal wounds of soldiers not wearing body armour were on the thorax, but soldiers wearing body armour still suffered 19.5% non-lethal thorax wounds. Furthermore, for an explosion distance of 10-25 meters, they calculated that 25% of all shell fragmentation hits (being by far the largest ballistic threat) penetrate the vest. These findings suggest that reduction of thorax wounds is not directly proportional to the area covered.

Jameson et al. (1975) did statistical work on fragmentation hits by M26 grenades in Vietnam. From the size of the wounds, they concluded that wounded soldiers wearing body armour are closer to grenade explosions (average: 4.5 meters) than soldiers not wearing body armour (average: 8.5 meters). Therefore, wounded soldiers that had worn the vest had a greater average number of wounds (12.5) than soldiers that had not worn the vest (9.2). Of all hits, body armour wearers had 34% on the chest. Soldiers without body armour had 27.5% hits on the chest.

The work discussed above indicates that wearing body armour does not evidently result in a proportional decrease in the number of wounds. The authors explain that this might be due either to the soldiers taking higher risks, or to loss of agility by functional obstruction. The average figure of 30% wounds on the thorax suggests, however, that the chance for the thorax to be hit is indeed proportional to its surface (chest surface area is about 30% of total skin surface area). So, although the opinion may still hold that relative body coverage is proportional to theoretical protection, effective protection seems to be at least influenced by soldier behaviour.

In conclusion, we may ascertain the following:

1. The chance for a specific part of the body to be hit seems to be proportional to its relative surface area.

2. Interaction between body armour and wearer's behaviour influences effective protection, in such a way that the number of wounds is greater than theoretically would be expected.

4. FUNCTIONAL OBSTRUCTION

Design, weight, stiffness, fit and compatibility problems can all be attributed to loss of agility. By definition, this functional obstruction is an ergonomic problem that should be investigated in short-duration trials to eliminate confounding with heat-associated problems. The latter will be discussed separately as physiological impairment. Commonly, functional obstruction is defined as the loss of performance at individual tasks. It is subject to discussion, however, whether the figures for individual loss* are also valid in large scale military manoeuvres

* "loss" is defined as

$$\frac{\text{treatment - control}}{\text{control}} \times 100\% \quad \text{for increasing scores}$$

and

$$\frac{\text{control - treatment}}{\text{control}} \times 100\% \quad \text{for decreasing scores.}$$

(Lotens, 1983/1). Gruber et al. (1964) selected a series of individual tasks with highest military importance. In priority order they were:

1. Fire and reload
2. Manoeuvre
3. Grenade course
4. Digging fox holes
5. Reconnaissance

These tasks were selected on the basis of expert opinion, but a critical evaluation in a field trial showed that several of these tasks were not particularly suited to obtain significant differences (Lotens, 1983/1). Therefore, functional testing of body armour has been done under a great diversity of conditions, having only a relative short duration in common (< 1 minute).

In particular, the work of Derrick et al. (1983) seems to be suitable to relate weight and covered body surface area to loss of performance. We therefore take a closer look at the results for the "grenade throw" and a "dash through combat town". If we plot performance against the product of surface area (m^2) and weight (kg), a correlation shows up (Fig. 4) that is distinctly better than when plotting performance against weight or covered surface area alone. This indicates that weight and covered body surface area both have a specific influence upon functional degradation.

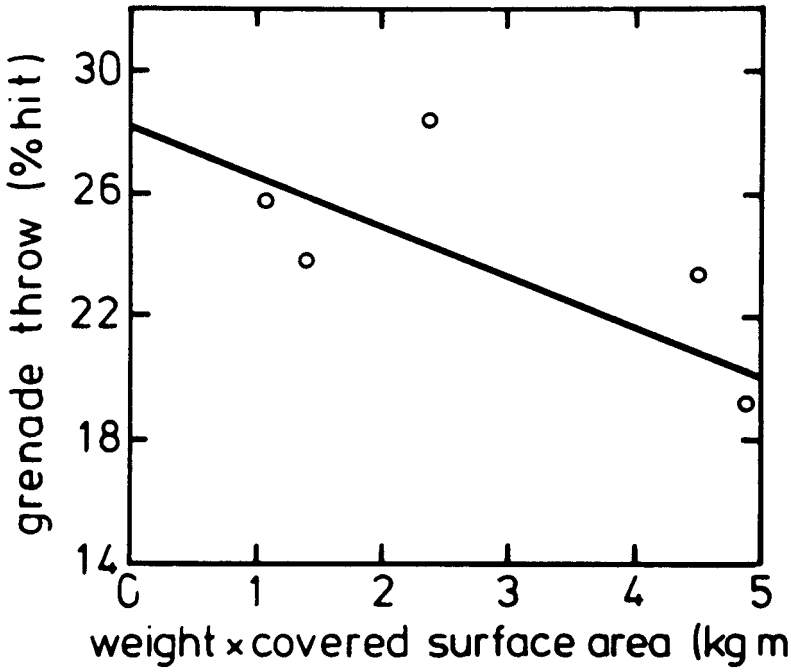
Several authors have included control measurements in their experiments. Sometimes the controls are just subjects dressed in fatigues, but also experiments are done in which the controls were weight compensated, i.e. the subjects wore a belt the weight of which was equal to the body armour. Thus, only the effect of stiffness was measured. We have compared four investigations in Table II.

Table II. Average loss of performance (%) by wearing shell fragmentation protective body armour. Comparison of the results of various authors. Average (military type) task shorter than one minute.

Author		Weight-compensated control	Not-weight compensated control
Corona et al.	(1974)		37%
Haisman and Crotty	(1975)	14 %	
Morimoto et al.	(1977)	3.7%	
Derrick et al.	(1963)		23.9%

Of course, since different types of body armour were used in the various experiments, only a rough comparison of the figures of Table II is possible. We may, nevertheless, conclude that weight seems to be the most important obstructional factor. Stiffness plays a second but still important role. Summarizing, it is not unrealistic to state that the functional

obstruction by the average shell fragmentation protective vest (weight 4.5 kg, % body coverage 30%) results in 30% loss of performance.



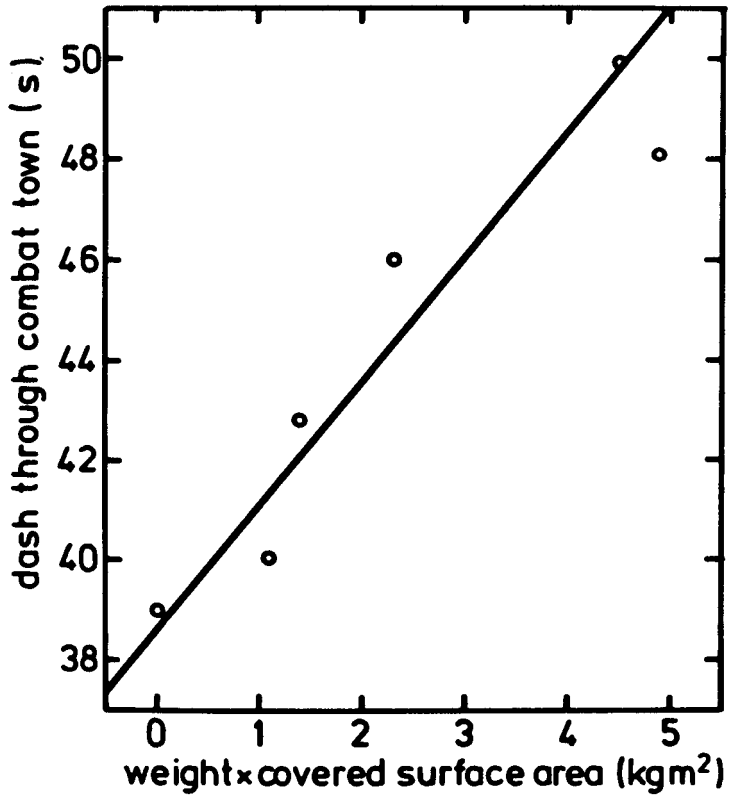


Fig. 4. Performance related to the product of weight and covered surface area ($kg \cdot m^2$). Data from Derrick et al. (1963) for both the "grenade throw" and the "dash through combat town".

The above described loss of performance is in agreement with observations on the battlefield. Spicely (1967), discussing performance in (warm?) Vietnam, reports that body

armour (weighing only 2.3 kg) was far too heavy for foot patrol. Winecoff found performance to be even 75% worse, and also stated that "military behaviour" (agility, reconnaissance) was affected very badly. On the other hand, some authors claim almost the opposite. From observations in Korea, Homes et al. (1954) report no problems whatsoever, even finding an increase in performance. Crampton, conducting an experiment in 1954, found only a very small decrease. According to Martorano and Gallagher (1963), performance of the Marines was hardly affected in a field experiment with total equipment weight of 24.5 kg.

Specific obstruction by poor compatibility is not very well documented, although it may play a considerable role. The most pronounced problem seems to be interaction with the helmet when firing in prone position. Also, interaction with load carriage equipment is a topic of demanding interest.

In conclusion, performance decrement by functional obstruction caused by the average shell fragmentation protective vest may reach the considerable value of 30%. This effect, however, is not unanimously confirmed in the field. Weight is the most obstructing factor.

5. PHYSIOLOGICAL IMPAIRMENT

In this chapter we will deal with long-term physiological effects of body armour. The problems are caused by interaction with production and liberation of heat.

First of all, since it is necessary to carry the body armour around, wearing requires metabolic power. It is not easy to say precisely what amount of additional metabolic power is needed, since tasks differ a great deal. During sedentary tasks the influence of metabolic power will not be all that great, whereas, for instance, during running uphill, there will be a tremendous rise in metabolic demand.

The available literature deals only with walking or marching. All authors agree that the weight of body armour is fairly well balanced around the point of gravity. Therefore, the additional weight can be regarded as being combined with body weight. Of course, this only holds for upper and lower torso body armour.

Required metabolic rate may be calculated with the equation of Pandolf et al. (1977); one may thus calculate that, for level walking at 5 km/h, the average body armour (4.5 kg, 30% covered surface area) requires an additional 20 W or so for weight of armour alone.

$$M = 1.5W + 2.0\,(W+L)(L/W)^2 + n\,(W+L)\,(1.5\,V^2 + 0.35\,VG)$$

with:
- M = metabolic rate (W)
- W = subject weight (kg)
- L = load carried (kg)
- V = walking speed (m/s)
- G = grade (%)
- n = terrain factor (1.0 for treadmill walking).

Weight is not the only factor that may raise metabolic power. Stiffness may also have a significant effect. For aramid and nylon shell fragmentation protective vests, a 1-1.5% increase is found (Yarger et al., 1969; Goldman, 1969; Haisman and Goldman, 1974).

Incorporating the effect of stiffness, the additional metabolic demand for walking 5 km/h with the average body armour comes to slightly less than 25 W. A useful rule of thumb may therefore be 5 W per kg of body armour. Second, body armour partly inhibits heat exchange with the environment. Made to be ballistically impermeable, the material is also virtually impermeable to water vapour. Therefore, part of the body is covered with "clothing" with a very low permeability index. The only means to allow sweat to evaporate underneath the body armour is to take advantage of pumping effects. However, Rasch et al. (1965) report that soldiers preferred a 10 lb vest instead of a 7 lb vest because the former was more tightly fitting. A loose fit to allow forced convection underneath body armour therefore seems to be a bad solution. Given the assumption that there will nevertheless be some forced convection underneath the body armour, a permeability index of i_m = 0.2 is quite reasonable. Also, body armour offers some insulation. For this, we may well take an insulative value of 0.25 $m^2 \cdot °C/W$. Having thus characterized the thermal properties of body armour, we may now calculate thermal load in relation to covered body surface area. In this particular situation, it is convenient to express thermal load as the residual cooling capacity. According to Leithead and Lind (1964) men have the ability to produce 0.75 to 1.25 liters of sweat per hour for a period of several hours, depending upon the level of acclimatization. If all this sweat were evaporated from the skin, a maximum cooling power of 500-850 Watt would result. Clothing, work and ambient conditions may considerably decrease this figure. The smaller the residual cooling power, the less the risk of heat disorders.

In Fig. 5 residual cooling power is given for three hypothetical climatic conditions:

moderate	15 °C, 40% r.h.
hot, wet	30 °C, 85% r.h.
hot, dry	40 °C, 25% r.h.

The straight lines are computed for the following conditions:

The wearers are physiologically characterized as follows:

max. sweat rate 1.0 l/hr, body surface area 1.9 m^2 , weight 75 kg., equipment 25 kg and body armour 150 g/% body coverage; metabolic power (predicted according to Pandolf, et al. (1977)) with walking speed = 5 km/h, level grade and terrain factor = 1; $I_{cl\ (body\ armour)}$ = 0.25 $m^2 \cdot °C/W$, $I_{cl\ (rest\ of\ the\ man)}$ = 0.155 $m^2 \cdot °C/W$, i_m (body armour) = 0.2, i_m (rest of the man) = 0.6.

The following formulas have been used:

$$Dry = \frac{A \cdot \Delta T}{I_{cl}}$$

and

$$Evap = \frac{i_m \cdot 2.2 \cdot \Delta P \cdot A}{I_{cl}}$$

with Dry = "dry" heat exchange (W)
A = body surface (m^2)
ΔT = temp. difference between skin and environment (°C)
I_{cl} = insulation ($m^2 \cdot °C/W$)
Evap = "wet" heat exchange (W)

i_m = permeability index
2.2 = Lewis factor (°C / mmHg)
ΔP = vapour pressure differences between skin and environment (mmHg).

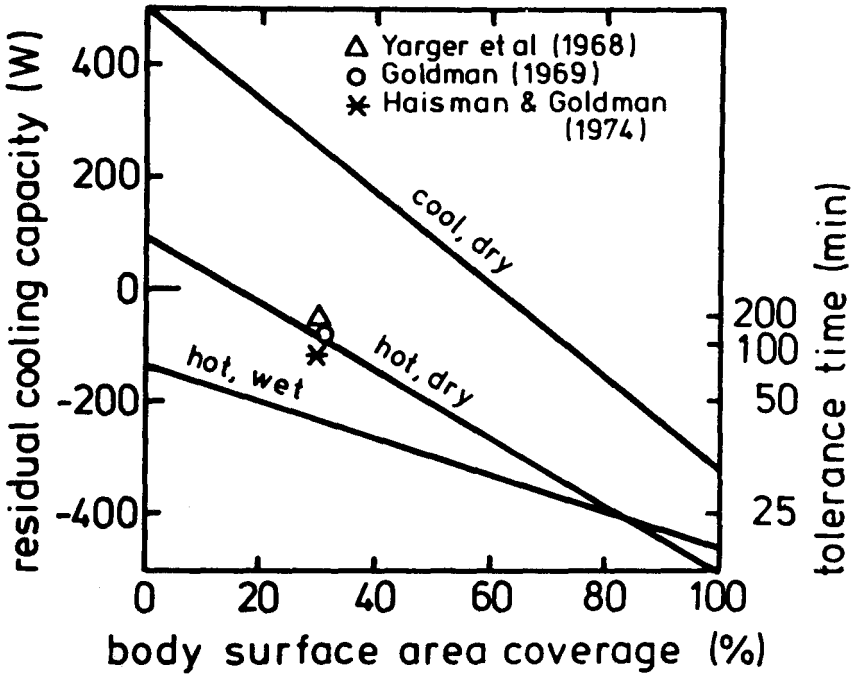


Fig. 5. Calculated residual cooling capacity and tolerance times for three hypothetical climates, in relation to % body surface area covered by body armour (for additional conditions see text); data of 3 authors are shown for the hot, dry climate.

Negative residual cooling power leads to body heat storage. This again leads to tolerance times (based on the heat load criterion of 8 joule per gram body weight (Lotens, 1983/2)) that are also shown in Fig. 5.

The data of Yarger et al. (1968), Haisman and Goldman (1974) and Goldman (1969) for a hot, dry environment fit well within the calculation. The calculations show that even with average body armour (4.5 kg, 30% body surface coverage), tolerance time is limited for the hot, dry climate (100 min) and for the hot, wet climate (40 min). With such body armour there will be no heat problems in the cool, dry environment. But apparently there will be heat problems in the hot, wet climate (tolerance time 70 min) even without body armour.

Therefore we come to the conclusion that, since clothing and equipment already impose a considerable heat stress upon the military, body armour may very quickly lead to severe heat problems. This is in close agreement with several reported findings. Yarger et al. (1968) found that only 40% of the soldiers wearing body armour in a hot, wet climate were able to complete a 90 min march, whereas without body armour this figure was 70%. Goldman (1969), experimenting under comparable circumstances (28 °C WBGT), witnessed heat casualties after 75 minutes. He suggested a 5 °F addition to the WBGT index to account for body armour, as a simple way to describe its thermal influence. When NBC clothing is worn additionally, risks may not just simply add, but interact with each other, resulting in even higher strain than expected from simply combining both limitations.

6. GENERAL DISCUSSION

As shown in Fig. 1, task, body armour and performance do heavily interact. However, the mechanism is not always clear. In the case of physiological impairment by heat stress, the relationship seems to be rather straightforward: the more body surface area that is covered with material of a high insulation and a low permeability, the higher the risk of physiological impairment. Indirectly, weight also causes a certain stress, although small in comparison with the imposed obstruction of heat exchange.

Functional obstruction (loss of agility) is less easy to quantify, mainly because the various authors do not always agree on that matter. Especially it seems that experimental findings (average 30% loss of agility) are less easy to quantify, mainly because the various authors do not always agree on that matter.

Furthermore it is not clear how to convert individual functional obstruction into overall loss of military performance during large scale manouvres. Although vital for a precise balancing of benefits and drawbacks, we may well leave this subject to the field of operations research.

Most confusing is the effective protection offered by body armour. Theoretically, there should be no doubt: the more coverage, the more protection. However, the chance of being hit is affected by alteration of the soldier's behaviour. It has been suggested that soldiers wearing body armour tend to take higher risks and lose a great deal of their agility. This means that a most delicate, balanced judgement has to be made; the extremes are: no protection, high military output, full protection, low military output.

REFERENCES

1. Derrick, L.G., H.R. Henn and G.H. Malone (1963). The influence of body armour coverage and weight on the performance of the marine while performing certain simulated combat type tasks. Nav. Med. Field Res. Lab. Vol. XIII No. 29.

2. Gruber, A., J.W. Dunlap and G. Denittis (1964). Development of methodology for measuring effects of personal clothing and equipment on combat effectiveness of individual soldiers. USATECOM No. 8-3-7700-01.

3. Haisman, M.F. and R.F. Goldman (1974). Physiological evaluation of armoured vests in hot-wet and hot-dry climates. Ergonomics 17: 1-12.

4. Haisman, M.F. and J. Crotty (1975). Problems associated with body armour. Paper at the 11th Commonwealth Defence Conference on Operational Clothing and Combat Equipment, Delhi, India

5. Jameson, J.W., J.M. Merkler and M.C. Kohn (1975). Analysis of WDMET M26 grenade cases for armour vest protective effect. Edgewood Arsenal report EB-TR-75402.

6. Leopold, R.S. and L.G. Derrick (1962). The effect of wearing body armor of different designs, materials and weights on the performance of the Marine. Nav. Med. Field Res. Lab. Vol. XII, No. 12.

7. Leopold, R.S. and L.G. Derrick (1963). The effect of wearing body armor of different designs, materials and weights in conjunction with two designs of packs and suspender on the performance of the Marine. US Navy Med. Field Res. Lab. Vol. XIII, No. 8.

8. Martorano, J.J. and T. Gallagher (1963). Physiological and psychological evaluation of vest-type load-carrying systems. Nav. Med. Field Res. Lab. Vol. XIII, No. 1.

9. Morimoto, W.S., M.D. Lanning and D.W. Jones (1977). Operational test of Personnel Armor System for Ground Troops. Final Report-TRADOC ANC 18452.

10. Homes, R.H., W.F. Ener and J.C. Beyer (1954). Medical aspects of body armor used in Korea. J.A.M.A. 155: 1477-1478.

11. Lotens, W.A. (1983/1). How much protective clothing? DRS Seminar on the human as a limiting element in military systems, Toronto, 1983.

12. Bensel, C.K., D.S. Fink and S.A. Mellian (1980). The psychomotor performance of men and women and wearing two types of body armor U.S. Army Natick Res. and Devel. Command. Rep. No TR-80/014.

13. Crampton, R.F. (1954). The influence of body armor on fighting efficiency. UK user trials, 1953. Q.O.R.G. report No. 3/54.

14. Lotens, W.A. (1983/2). Heat stress, heat strain and risk of heat disorder. In: Proc. Int. Conf. on Prot. Clothing Syst., Stockholm 1981, Ed. by K. Amundin, C. Branious and A. Brand-Pusson.

15. Yarger, W.E., B.D. Litt and R.F. Goldman (1969). Body armor in a hot humid environment; Part II, studies in heat acclimatized men. US Navy Med. Field Res. Lab Vol. XIX No. 1.

16. Leithead, C.S. and A.R. Lind (1964). Heat Stress and Heat Disorders. Cassell and Company, Ltd., London.

17. Rasch, P.J., P.C. White and R.J. Morton (1965).The effects of two types of body armor on body temperature. N.M.F.R.L. Vol. XV. No. 24.

18. Pandolf, K.B., B. Givoni and R.F. Goldman (1977). Predicting energy expenditure with loads while standing or walking very slowly. J. Appl. Physiol. 43(4): 577-581.

Annex to Chapter 14.

Head Protection Check List

I. The Cost of Head Protection

Vision	Communication	Respiratory Burden
Recognition	Speech	Smell
Mobility	Hearing	Fire
		Other

II. Types of Protection:

(1) Thermal – Cold/Hot
Trigger Areas

(2) Wind – H as f(wind)
non-V.C. – cold injury sites- ear/nose/mentum
ear/nose/mentum/malar
surface area/mass
time constants (minutes)

Head as a source of heat loss (B+F. H at T_a)
Caps/earlaps/scarves
Hoods
Hood rim/tunnel
Face Masks
Respiratory Heat Loss
Respiratory Heat Exchange
Eye dazzle-goggles - motorcyclists/cornea/heat-dust/
corneal abrasion by snow/ice crystals
Burn and Respiratory Tree
Windchill/Heat Stress - normal heat loss
from head as % of body

(3) Radiant Energy

Sunburn	Offset Display (Holographic Display)
Lasers	Flash Blindness

(4) Humidity – headbands – eye stinging; neck scarves

(5) Noise – ear defenders, ear plugs, foam fitting sizing,
commo sets, OSHA legislation?

(6) Helmets – History

Weight-balance-as a hanger	Support/nape strap
Night Vision	Offset
Squad Radios	Special: Eyes
Center of Gravity	Ears
Sizing	Thermal insulation/
	heat loss added

(7) Bump – padding, soft helmets

(8) Crash helmets – cyclists'

(9) Riot Helmets
- Shields
- Visors

(10) Ballistic Helmets

Weight	Carriage
Protection	Liners
Other Uses	Metal/Other

CHAPTER 15

MILITARY PERFORMANCE OF CLOTHING

W. Lotens

CONTENTS

SUMMARY

1. INTRODUCTION
2. ENERGY COST
3. PERFORMANCE DECREMENT
4. SUBJECTIVE EVALUATIONS
5. TYPICAL VALUES AND FINDINGS
    1. Body Armour
    2. CW-Protective Clothing and Respirator
    3. Load Carriage Systems
    4. Arctic Clothing
6. DISCUSSION
7. REFERENCES

SUMMARY

Protective clothing is associated with protection on one hand, but with increased energy cost and loss of physical performance on the other hand. For a variety of clothing and equipment, including body armour, CW protective clothing, respirator, load carriage systems and arctic clothing, the physical loss of performance is analyzed and typical values of loss of performance are given.

Key Words: energy cost, physical performance, functional performance, subjective evaluation, body armour, CW clothing, load carriage.

1. INTRODUCTION

Although a majority of biomedical problems with clothing are related to heat or cold stress, the non-thermal characteristics are equally worth considering. Within the boundary conditions of thermal comfort there is a drive for ease of wear, the latter depending on weight, bulkiness and motion restriction of the clothing item.

Since subjects trying various designs of a clothing item easily indicate an order of preference, it should also be possible to find objective methods to evaluate design features. Possible measures for this purpose are energy expenditure, functional obstruction, fatigue and decrement of performance. The best evaluation ought to emerge from a field trial during actual military employment but, because of the practical difficulties involved, most scientists use more artificial tests, varying from abstract tests up to large scale manoeuvres. The major question then is the validity of the test method for prediction of military performance.

In this paper methods will be discussed, and typical figures will be given for various clothing and equipment items, to serve as a design aid for future developments.

2. ENERGY COST

A convenient laboratory test is the measurement of the energy cost of the use of a specific clothing or equipment item, compared to the semi-nude condition. Energy cost is dependent on various aspects of the clothing item, such as its weight, number of layers and motion restriction related to the demands.

There is good agreement in the literature on the weight factor, weight being linearly related with energy cost, just like body weight (Soule and Goldman, 1969). When walking at a speed of 5 km/h energy expenditure amounts to 5 W/kg. This only holds for weight carried close to the center of gravity of the body or having its center of gravity near that of the body. Soule and Goldman (1969) point out that weight carried on the extremities may cost more, varying from an increase of 30% on the head to 100% on the hands and as much as 500% on the feet. The values are dependent on the activity (walking), the speed (about 5 km/h) and the eccentric mass (about 6 kg).

Martorano and Gallagher (1963) found no difference in physiological responses (although they did not measure the energy expenditure) between three types of load carriage systems as worn with various garments and carrying various loads.

The bulkiness of clothing, often expressed as the number of clothing layers, has great influence on energy expenditure. Teitlebaum and Goldman (1972) compared a 1-2 layer suit with a 6-7 layer suit, balanced to equal weight. Metabolism with the latter was 18% higher when walking at a speed of 5.6 km/h and 14% higher at a forced speed of 8 km/h. Amor et al. (1973) got comparable results from an experiment with 0-1, 2-3 and 4-6 layer clothing, the latter two raising energy cost by 8 and 21% respectively at various walking speeds (3.6-6 km/h). The results of both experiments may well be summarized by the rule of thumb that energy cost increases by 4% for each clothing layer at marching speed, and 3% per layer at slow pace, as may be seen from Fig. 1. The actual source of this effect is not very well understood: friction between clothing layers and hobbling gait are both possible explanations.

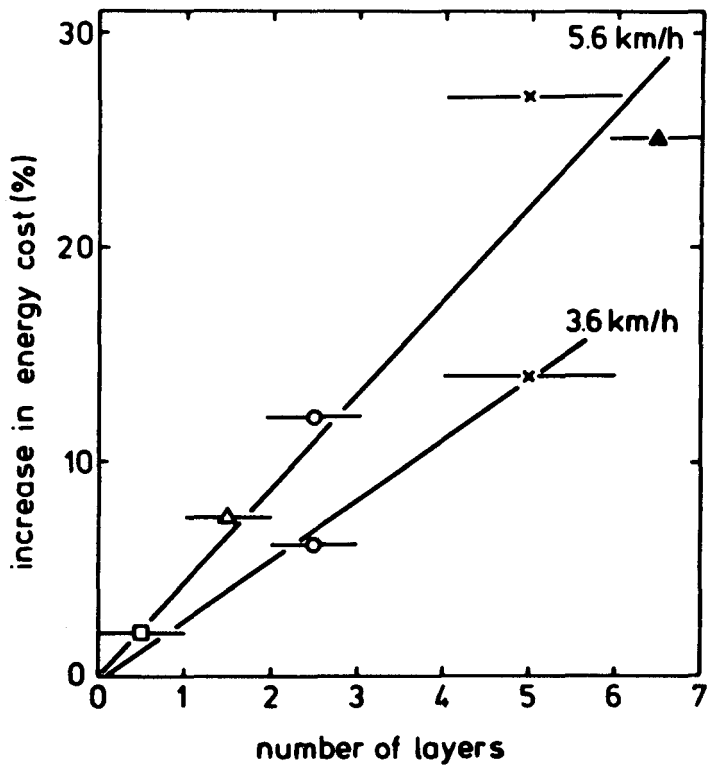


Fig. 1. Increased energy cost resulting from addition of clothing layers.

Energetic effects of motion restriction are hard to measure for experimental reasons. Exercise in the laboratory is often limited to bicycle riding and treadmill walking, exercises not very well suited for motion restriction measurements. It seems a logical, though yet unproven, hypothesis that motion restriction does raise energy cost considerably. In the next section this problem will be dealt with in terms of performance decrement.

3. PERFORMANCE DECREMENT

For the military, one of the most relevant aspects of clothing is the decrement in performance that might be expected during operations. However, the relationship between clothing design and operational performance is a very complicated one and virtually impossible to assess due to lack of control of some variables involved. All trials have therefore been carried out with more or less artificial procedures, varying from short coordination tests up to combat-like activities.

Gruber et al. (1964) identified 6 tasks as the most relevant for success in combat:

- rifle firing and loading
- manoeuverability
- marching and moving
- grenade throwing
- digging foxholes
- reconnaissance and camouflage

A United Kingdom choice of combat-like tests essentially suggested the same activities. Gruber et al. (1964) and Lotens (1981) agree that firing on a range does not discriminate between garments, or the conditions with or without a respirator. When using sudden appearing targets and putting the subject under stress, differences in speed may be found, especially for short distance targets. British data show larger performance decrements than those of Gruber et al. (1964).

Manoeuvre courses are very well suited for the measurement of performance decrement. Performance should be measured, however, for every obstacle separately. Gruber et al. (1964) found that the debarkation net, the crawl, and the jump discriminate well between various packloads. Leopold et al. (1962) mentioned a dash through a "combat town" as one of the best suited tasks and British data show "individual movement" to be a very good discriminator.

In general, manoeuvrability is highly discriminating but tasks should either be short and uncomplicated or very well trained. Although combat-like activities appear to be very representative for military application, they essentially consist of elementary movements that can be measured separately. Often the results of those elements have high correlation. This brought Lotens (1979) to test clothing using short activities, such as running 100 m, Sargent's jump (a coordination test in which standing height is compared to maximal jump height) and a figure 8-track (running 8-shaped laps while stooping each time underneath a bar). These tests proved to be highly sensitive to clothing, not only discriminating between different kinds of protective clothing, but between different designs of the same kind as well (Lotens, 1979, 1986). It may be doubted whether the more complicated combat-like activities have the same discriminating power (Corona et al., 1974).

Self-paced individual marching, on blacktop roads as well as cross-country, proved to have only average discriminating power in experiments of Gruber et al. (1964) and Leopold et al. (1962). The problem with this activity is that the subjects need a lot of experience in all the garments in order to be able to distribute their energy over the whole course. For this same reason, short runs (100 m) are preferable to medium distance runs (400-1000 m).

Grenade throwing may be separated into accuracy, speed and distance tests. In experiments of Lotens (1979, 1981, 1986) distance significantly discriminated between CW protective garments and between body armour, expressing the mobility of the upper body. Accuracy was only of average discriminating power in experiments of Gruber et al. (1964), but accuracy and speed together provided a useful criterion (Leopold, 1962, 1963). It is not unlikely that the latter improvement is partly due to the introduction of a manoeuverability element.

Digging foxholes did discriminate between with/without respirator conditions in experiments of Gruber et al. (1964). Well prepared or consistent soil should be considered as a condition for successful discrimination.

Reconnaissance and camouflage is very difficult to define and thus to measure in terms of performance. It tends to be a test for the observer instead of for the subject and the discriminating power is weak.

In general, all tests show a dependency of performance on clothing and load weight, as anticipated. The effect of bulkiness of clothing cannot be analysed from the available data and is confounded with motion restriction or other impeding effects.

The above mentioned tests seem to form a useful test-battery, with the simple "average performance decrement" being a handy measure for comparing garments or equipment items. It seems not worthwhile to standardize to a welldefined course because comparison of results would still be dependent on fitness, weather condition, motivation, etc. When expressed as a percentage performance decrement, the results may well be comparable, even if the covered tests were not exactly the same. Average performance decrements for body armour amount to 2.4 %/kg (Leopold et al., 1962), 3 %/kg (Leopold et al., 1963), 3.5 %/kg (Derrick et al., 1963), 2.9 %/kg (Lotens, 1981) and 2.9 %/kg (Haisman and Crotty, 1975). Marching shows smaller performance decrements (= 1.5 %/kg) than agility courses, or manoeuvrability courses and sprinting 100 m shows even smaller decrements.

The effect of wearing a respirator is rather specific and the above tests are not all fit to measure it. Of course, the main interference will happen with firing and tasks that make demands on the aerobic system. Lotens (1980) found reductions in performance on 400 m and 3 km runs as shown in Fig. 2. Performance seems to be dependent on breathing resistance and duration of the task. The 22% loss of performance found in British experiments with the S-6 respirator compares well with the data of Lotens (1980) with the C-3 respirator. Tests that do not demand maximum pulmonary performance show less performance decrement. Thus, the detrimental effect of the S-6 respirator is 6 to 7% while marching on roads and cross-country. This comparison must be made with some care, however, because the garment assembly worn was different from those in Fig. 2. This might be important because Lotens (1982b) measured a strong interaction between respirator effect and garment effect on performance. Fig. 3 shows that the additional effect of the respirator is smallest for the most impeding garment.

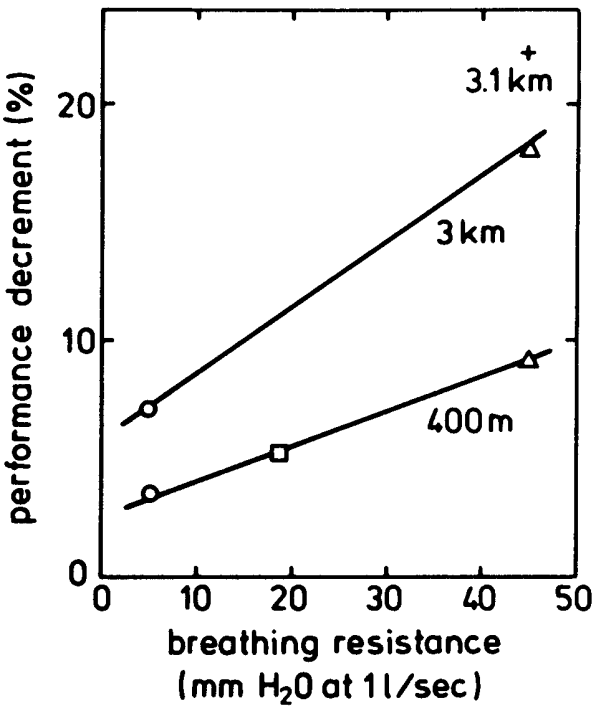


Fig. 2. Performance decrement for 400m and 3km runs as function of respirator breathing resistance.

A possible explanation could be that respirator and garment act on different mechanisms, the limitation of the one mechanism causing idle capacity in the other mechanism, which makes the limitation of the latter less severe. In this view, effects that act on the same system should be additive. Lotens (1986) investigated the effects of combined degradation in more detail, showing that degradation will generally add up, but indeed CW equipment is an exception to this.

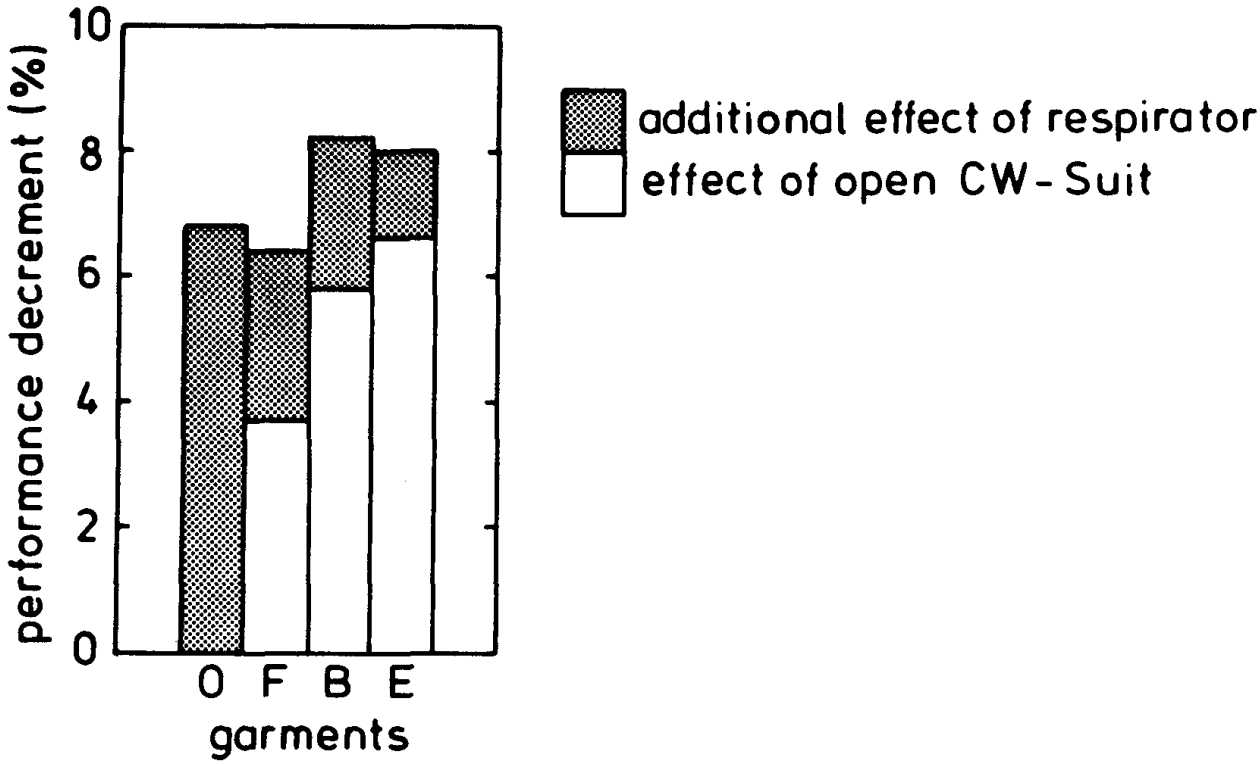


Fig. 3. Interaction between performance decrement due to a respirator and the decrement caused by garment impedance to motion.

Another exception is the combination of load carriage and weapon carriage. Both exceptions show less degradation than the sum of the separate effects. Table I lists the performance degradation for various articles, as mentioned with the earlier mentioned test battery. From this table of the effects of Dutch clothing and equipment it may be concluded that performance degradation in comparison to sportswear is considerable, even under mild weather (10 %). With added CW-gear this increases up to 15 % more (Lotens, 1986).

Table I. Performance degradation due to separate items, in comparison to sportswear, averaged over a test battery (n = 10 subjects) (Lotens, 1986).

LOSS OF PERFORMANCE

Article		Degradation (%)
1.	fatigues	1
2.	overgarment	4
3.	insulative liner	0
4.	combat boots	4
5.	helmet	2
6.	CW suit	6
7.	CW overboots	4
8.	respirator	5
9.	webbing	15
10.	weapon in hand	8
11.	weapon suspended	8

Loss of performance can be defined as:

$$\frac{\text{treatment} - \text{control}}{\text{treatment}} \times 100\% \quad \text{for increasing scores}$$

and

$$\frac{\text{control - treatment}}{\text{treatment}} \times 100\% \quad \text{for decreasing scores}$$

4. SUBJECTIVE EVALUATIONS

For many applications, performance measurements are much too time-consuming or too laborious to go through; subjective evaluations may then be very cost-effective. In contrast to the general mobility, as tested with the above methods, specific functions may demand specific clothing characteristics. Lotens (1981) evaluated four different designs of small fragment protective vests on subjects, testing 14 functions on various armoured vehicle crewmen (driver, gunner, commander, etc.). Each function was examined on six aspects and scores were averaged. Fig. 4 shows the cumulative distribution of scores. With this new method, clear cut differences are found between the vests, the rank order correlating nicely with the number of complaints and the subjective preferences. When demanding that the score should at least be "fair", vest A4 is acceptable for all 14 functions, whereas A1 is just acceptable for 3 out of 14. This method, though based on subjective data, yields reasonably firm results. Another approach, very often taken, is use of a questionnaire after field trials. This method, however, does not discriminate too well between designs, particularly when

control groups are lacking. The same holds when observers and referees are asked to score the result of a realistic exercise, aiming for the evaluation of fighting capability under CW threat. All statistically examinable effects deal then with development of variables in time; this gives no information about the effect of wearing CW protection per se. It is recommended that a control group be included whenever possible.

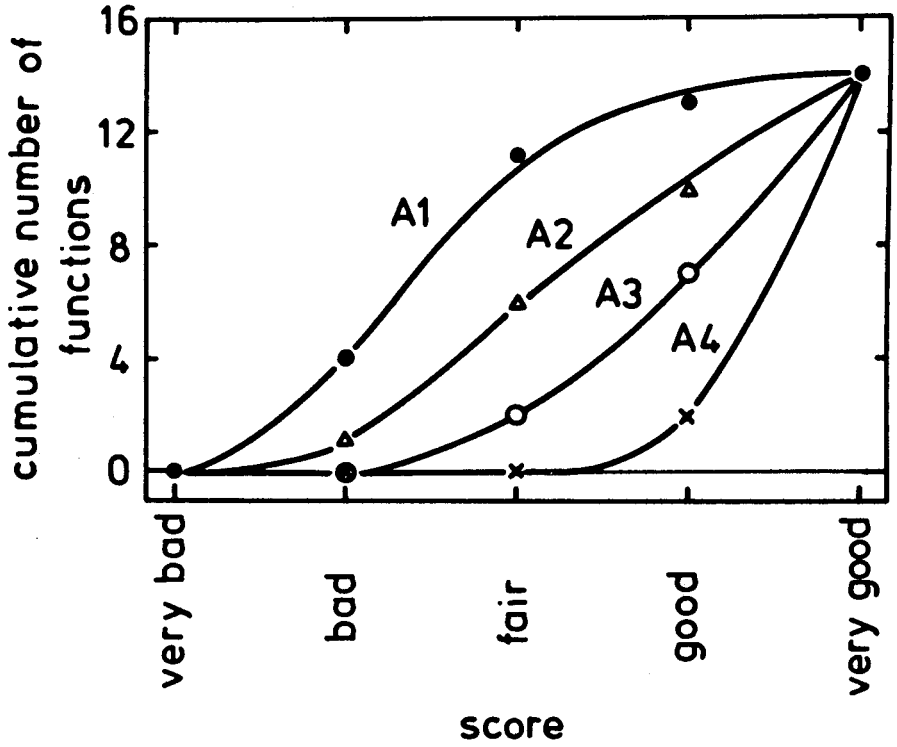


Fig. 4. Cumulative distribution of performance scores for four different small fragment protective vests (A1 to A4).

5. TYPICAL VALUES AND FINDINGS

In this section the foregoing results and methods are applied to various clothing and equipment items. The items will not be very well defined, because data are collected on various clothing designs, evaluated with various methods and, therefore, only typical values are available for performance decrement, energy cost, subjective judgements, etc. Specific clothing and equipment items covered here are: body armour, CW-protective clothing and respirator, load carrying systems and arctic clothing.

5.1 Body Armour

Leopold et al. (1962, 1963), Derrick et al. (1963), Haisman et al. (1975) and Lotens (1981) all found performance decrements for various designs of about 3 %/kg. Morimoto et al. (1977), evaluating the PASGT vest concluded there was only a 1 %/kg performance decrement, whereas Corona et al. (1974) indicated 6 %/kg. The differences are as yet unexplained.

Energy cost of wearing body armour may be estimated when body armour is seen as half a clothing layer. Increase in energy cost for a 5 kg vest amounts to 5 kg x 5 W/kg for the weight plus 7 W for a half a layer, together 32 W, while walking at about 5 km/h.

Functional obstruction by vests was scored by Morimoto et al. (1977) and Lotens (1981). Morimoto found very few complaints when trying a vest on various functions and Lotens got comparable results with a very similar vest. During manoeuvres, perhaps due to the prolonged wearing times, there were many complaints. Lotens (1982a) mentions 15% reported seriously hampered function, and 40% discomfort and complaints about heat, weight and chafing at neck and armpits. Haisman et al. (1975), questioning personnel with experience in internal security duties, noted 60-70% of the men dissatisfied with obstruction, functional ability and shooting performance.

Typical compatibility problems, found by Lotens (1981) and Haisman and Crotty (1975) as well as Corona et al. (1974), involve collar and helmet contact and slipping of the butt when shouldering rifles. Another, more general problem concerns the sizing of layers in a multilayer protective clothing system, worn in various assemblies.

5.2 CW-Protective Clothing and Respirator

Performance decrement with CW-protective clothing worn open was 4-6%, depending on the design, in experiments of Lotens (1982b) and 7.5% for the U.K. Mk III. When worn closed and with respirator, Lotens (1982b) found decrements of 7% for short duration tasks; U.K. data suggest the much larger figure of 19% for longer tasks. The difference in magnitude is quite understandable from Fig. 2, which indicates that the performance decrement is larger the longer is the task. Haisman and Crotty (1975) obtained a decrement of about 15% with overboots but carrying the respirator. Data from Goldman (Military Effectiveness in a Toxic Environment, METOXE, data; see Chapter 15 Appendix) collected during large scale troop trials give even higher decrements, the value of 36% being the average of various military units and activities; it is hard to trace back the reasons for this excessive decrement. Goldman's data are probably the most realistic ones currently available. It is not quite sure, however, how these individual or group decrements work out in loss of objective of the whole manoeuvre. The British observed less performance decrement in a comparative large trial; on the contrary, there was a higher rate than during comparable manoeuvres. They consider it unlikely that loss of individual performance would lead to failure to take an objective; it appears there is a critical gap in knowledge. Another noteworthy result from Goldman is that the performance decrement is much smaller when the clothing was worn open, without gloves, etc. but with respirator. The figure then is 16% which compares well with the forementioned 19%.

The increase in energy cost due to CW-protective clothing is not large. It may be estimated as 10 W for the weight and 14 W for the additional layer, a total together of 24 W.

Functional obstruction is not large for well designed suits. Lotens (1982b) obtained the qualification "good" for the best design, which compared to a loss of 3%; "only average" corresponded to a loss of 7% in performance. Prolonged wear may lead to many detrimental effects. Sleep deprivation and decreased physical condition, attitude to the task, alertness

and morale may result. However, a major part of these problems is associated with the respirator.

Compatibility problems with clothing are the gas tightness at the junction with the respirator, the changing of the suspension of the helmet and the general sizing problem.

5.3 Load carrying systems

In general the performance decrement due to carried load is dependent on the weight, the way of suspension being of minor importance. The performance decrement due to the weight was 3 %/kg according to Leopold et al. (1963) but Haisman and Crotty (1975) found smaller values, 1.5 %/kg on the average. It is not unlikely that the performance decrement of weight per se is less than that of body armour (3%) causing both weight and motion restriction.

Martorano et al. (1963), in physiological experiments with 3 kinds of pack, combined with 2 kinds of garments, found that the physiological parameters all turned out to be independent of the pack. It is not likely therefore that energy cost was different. This is in agreement with Soule and Goldman's finding that load located near the center of gravity of the body, has an energy cost independent of weight distribution.

5.4 Arctic clothing

Allen et al. 1973) measured the performance decrement caused by arctic clothing during a short movement task and found a decrement of 10% in comparison with fatigues. They did not measure the energy cost, but non-significant differences in post exercise heart rate and ventilation suggest that during performance tasks, energy expenditure is independent of garment. Amor et al. (1973) and Teitlebaum and Goldman (1972) found increases in energy cost due to the arctic clothing as in Fig. 1, typically 4 %/layer at 5.8 km/h and 3 %/layer at 3.5 km/h.

6. DISCUSSION

A gap in current knowledge is the translation of individual performance on standardized tests into unit performance in military operations. The available data are confusing and it should be anticipated that controlled experiments in this field will be extremely difficult and expensive.

Although performance decrement and increase in energy cost have been dealt with separately, they are not unrelated. A quantitative relationship, however, has never been established. In Figure 5, an attempt to establish such a relationship is made. The loss of performance on a physical test battery is plotted against the increase in energy cost during walking. The graph suggests a correlation of 1.1% loss of performance for each % increase in energy cost. Some data points seem to deviate considerably from this line, dealing with arctic clothing and load carriage, respectively. There could be various explanations for this deviation, but data for a confirmation are lacking. The correlation of Fig 5 should therefore be considered as a rough guess.

It was shown that the loss of performance due to various clothing articles just adds when they are worn as an assembly. In those cases where an interaction was found, the actual loss of performance was less than the sum of the constituents. This suggests that such clothing articles are causing different types of load for the body, such that the one type of load is creating a spare capacity for the other type of load. This may be illustrated by the interaction between CW clothing and respirator. The performance while wearing the clothing might be limited by the maximum force that the muscles can exert during motion. The respirator will, due to aerobic restrictions, force the subject to a slower pace, which demands less muscular forte. Thus, the extra load due to the clothing becomes evident only when the maximum muscular force is reached again. In this view, the loss of performance with clothing articles that load the same systems simply adds up, whereas articles that load different systems show a regressive interaction in loss of performance.

A very basic question is the extent to which protective clothing is actually an advantage; in other words, at what point does loss of mobility become a greater danger than the threat the clothing protects against. Apparently this question is easier to answer for CW-protective clothing than for body armour. When unprotected against chemical agents, an attack with a few tons of chemical ammunition will disable a majority of the personnel and it is not likely that their mobility will save them. Such a disaster will not happen so easily when the threat has a ballistic character. Mobility will give personnel a chance to show good military behaviour. However, in many situations, for instance during an assault or when entering a booby-trapped area, body armour is most likely to be advantageous. Jameson et al. (1975), when analyzing M26 grenade casualties in Vietnam, found the remarkable result that troops wearing body armour had a greater average number of wounds than those without body armour. The explanation might well be that men in body armour tend to take greater risks. This hypothesis is supported by the fact that the average explosion distance was 3.84 m without the vest and only 2.05 m with vest. This kind of compensatory behavior is a common finding, for instance, in road traffic research. The extent to which the higher risk was paid back in military effectiveness is unknown.

Winecoff, considering body armour from a user's point of view, observed that wearers when on patrol in Vietnam did not have a mind to leave flat tracks and showed little movement and lateral shield. In general, the attitude was passive instead of active. Winecoff recommended body armour at night in booby-trapped areas, or for infantry at a fire base, but certainly not during daytime heat, on long route marches or on foot patrol. In his opinion, better patrol technique and less fatigue make body armour superfluous.

Although the choice of protective clothing is a commander's prerogative, it seems necessary to gather more information about this complicated matter in order to provide him with practical rules of thumb.

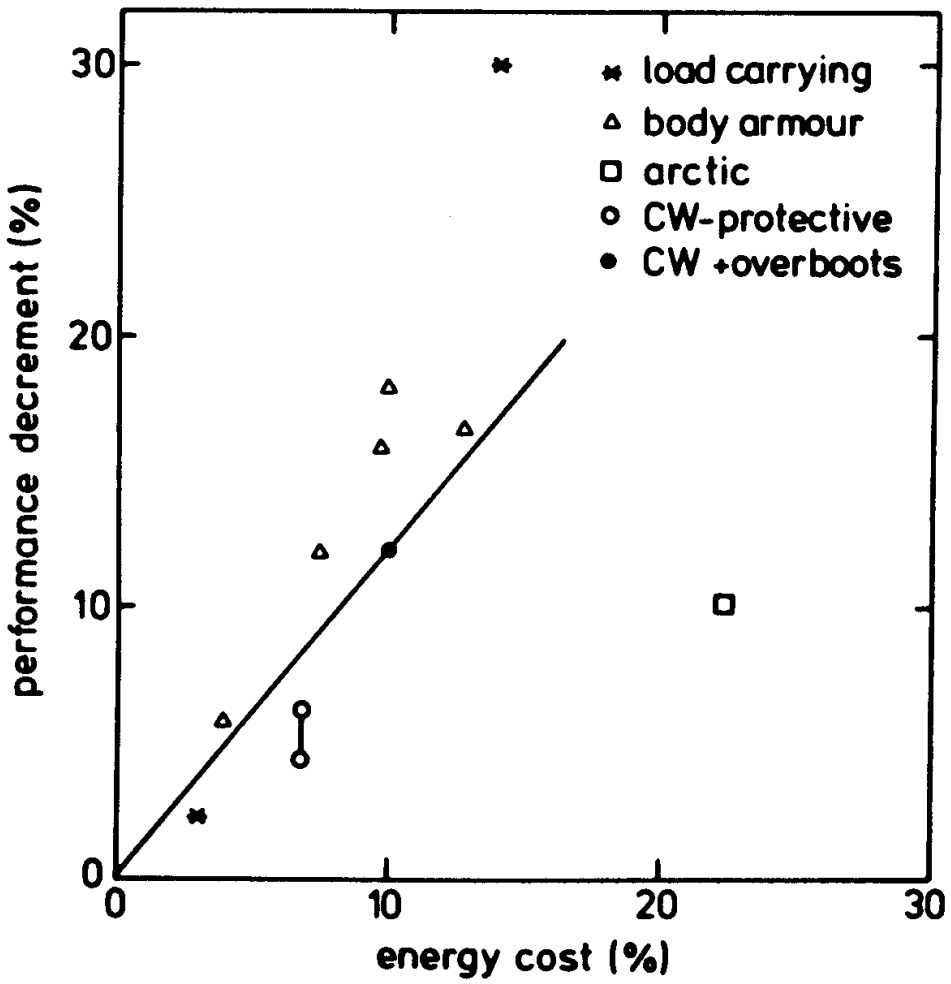


Fig. 5. Correlation between performance decrement and increased energy cost.

REFERENCES

1. Allen, C.L. and S.D. Livingstone (1973). Effect of arctic clothing on a short-duration task. Report DCIEM, no. 73-R-974.

2. Amor, A.F., J.A. Vogel and D.E. Worsley (1973). The energy cost of wearing multilayer clothing. Report APRE 18/73 (TM).

3. Corona, B.M., R.D. Jones, R.B. Randall, P.H. Elli and R.S. Bruno (1974). Human factors evaluation of two proposed army infantry/marine fragmentation protective systems. Aberdeen Proving Ground Tech. Memo 24-74.

4. Derrick, L.G., H.R. Henn and G.H. Malone (1963). The influence of body armor coverage and weight on the performance of the Marine while performing certain simulated combat type tasks. Nav. Med. Field Res. Lab. Vol. XIII no. 29.

5. Gruber, A., J.W. Dunlap and G. Denittis (1964). Development of methodology for measuring effects of personal clothing and equipment on combat effectiveness of individual soldiers. USATECOM no. 8-3-7700-01.

6. Haisman, M.F. and J. Crotty (1975). Problems associated with body armor. Paper at the 11th Commonwealth Defence Conference on Operational Clothing and Combat Equipment.

7. Jameson, J.W., J.M. Merkler and M.C. Kohn (1975). Analysis of WDMET M26 grenade cases for armor vest protective effect. Edgewood Arsenal report EB-TR-75042.

B. Kennedy, S.J., R.F. Goldman and J. Slauta (1973). The carrying of loads within an infantry company. Clothing & Personnel Life Support Equipment Lab. Technical Report. 73-51-CE.

9. Leopold, R.S. and L.G. Derrick (1962). The effect of wearing body armor of different designs, materials and weights on the performance of the Marine. Nav. Med. Field Res. Lab. Vol. XII, no. 32.

10. Leopold, R.S. and L.G. Derrick (1963). The effects of wearing body armor of different designs, materials and weights in conjunction with two designs of packs and suspenders on the performance of the Marine. Nav. Med. Field Res. Lab. Vol. XIII, no. 8.

11. Lotens, W.A. and E.J.M. Smienk (1979). A comparative test of A2-clothing I. Wearability. Report. Institute for Perception, IZF 1979-20 (in Dutch).

12. Lotens, W.A. (1980). Evaluation of chemical protective facelets and comparison of four prototypes. Report Institute for Perception, IZF 1980-15 (in Dutch).

13. Lotens, W.A. (1981). Selection of body armor for the Royal Dutch Army I. Functional characteristics. Report Institute for Perception, IZF 1981-17 (in Dutch).

14. Lotens, W.A. (1982a). Selection of body armor for the Royal Dutch Army II. Inquiry after field trials. Report Institute for Perception, IZF 1982-23 (in Dutch).

15. Lotens, W.A. (1982b). Selection of CW-protective garments for the Royal Dutch Army I. Usability and impediment of movement. Report Institute for Perception IZF 1982-21 (in Dutch).

16. Lotens, W.A. (1986) Loss of performance due to military clothing and equipment. Report Institute for Perception 1986-13.

17. Martorano, J.J. and T. Gallagher (1963). Physiological and psychological evaluation of vest-type load-carrying systems. U.S. Nav. Med. Field Res. Lab. Vol. XIII, No. 1.

18. Morimoto, W.S., M.D. Lanning and D.W. Jones (1977). Operational test of Personnel Armour System for Ground Troops. Final Report-TRADOC ACN 18452.

19. Soule, R.G. and R.F. Goldman (1969). Energy cost of loads carried on the head, hands or feet. J. Appl. Physiol. 27: 687-690.

20. Teitlebaum, A. and R.F. Goldman (1972). Increased energy cost with multiple clothing layers. J. Appl. Physiol. 32: 743-744.

APPENDIX 1

OPERATIONAL DEGRADATION WITH CW PROTECTION WITHOUT HEAT STRESS*

	FIREPOWER			COMMUNICATIONS			MOBILITY			SUPPORT		
MOPP	I	II	III	I	II	III	I	II	III	I	II	III
INFANTRY	Rounds per hit			Messages unanswered			Road march time			Time to get medic		270%
M-14	5.4	5.9	8.6	4	–	10	–	–	12%	M-14 maintenance		14%
(%)	–	9	59	Time to install wires			March rate					
M-60	10	5.7	10.7	15'	25'	26 min	–	>4%	10%	CBR recon		
(%)	–	43	7	Getting specific man			Assault time			4 min	-	9.5 min
M-79	5.3	3.0	8.4	1-2'	–	4+ min	–	<10%>	100%	Ammo resupply		
(%)	–	43	58	Voice versus signals			platoon leader		142%	13 min	30%	47%
				–	–	50%	first man		197%			
							last man		102%			
ARMOUR: N.B. - MOPP III also required closed hatch												
1-73	Rounds per hit			Target identification			Road march time		9%	Boresight	1 min	
	–	NSD	–	# missed			March rate		13%	Complaints		
1-85	–	6%	104%	1	7	25	Attack time		20%	Gloves:		33%
05	–	0.3r	0.6r	13%	28%	42%	Attack difficulty		3X	maintenance		
	Zero main gun			# of transmissions							27% loading	
	–	1 min 13 min		–	19	28				Mask/Hood 20% vision		
				duration of transmissions						CBR suit: 14% movement		
				–	12%	4%						
ARTILLERY:												
Time from receipt at FDC to battery order				In firing sections			Last unit			Filling sandbags		
				responses			across SP		192%	22 min	25'	35'
Area adjust.	–	27%	137%	26 OK	11%	24%	Clear hasty			Wire splicing		
Registration	–	100%	75%	Accuracy			position		45%	5.5 min	7.75'	8'
Transfer	–	33%	94%	> 95%	–	45%	Enter-to all					
Target location							ready		31%			
F.O. i.d. to call for fire				F.O. i.d. to end of mission								
	90 sec	114 sec	183 sec	27 min	-	40 min						

ENGINEER: road repair, bridge building, demolition - NSD; voice commands repeated 2X as often in MOPP III.

*The extent of operational degradation, in the absence of heat stress, for combat units wearing NBC protection in MOPP II (i.e. mask and "open" garment) or MOPP III (mask, hood, gloves and "closed" overgarment in comparison to the normal combat clothing, (MOPP I) for four categories of military activity (Data from METOXE studies).

CHAPTER 16

FIELD EVALUATION METHODS

F.W. Behmann

CONTENTS

SUMMARY

1. INTRODUCTION

2. TECHNICAL EVALUATION

3. PHYSIOLOGICAL FIELD TRIALS

4. TROOP TRIALS

   4.1 Questionnaires
   4.2 Test Execution

APPENDIX

REFERENCES

SUMMARY

New clothing and equipment requires field evaluation. A summary of the methods involved, in terms of practical recommendations, is hard to find. Therefore, in this chapter the most important field evaluation methods are discussed: 1) Technical Evaluation, 2) Physiological Field Trials, and 3) Troop Trials.

The technical evaluation, as a last step in the development process, is not problematic, but the physiological and troop trials, involving severe environmental stress and subjective ratings, respectively, require specific methods. The theoretical considerations on these methods are illustrated by examples, taken from many field trials, in particular explaining the importance of the design of questionnaires.

Key Words: troop trials, technical evaluation, clothing and equipment, field trials, questionnaire, physiological evaluation.

1. INTRODUCTION

Three phases may be distinguished during the development of clothing and equipment: 1) the determination of the requirements, 2) the technical development, including the manufacturing of prototypes and 3) the qualification by the user, resulting in a final selection.

In the first phase, the requirements are stated by the user. These should be as detailed as feasible, since ambiguities lead to difficulties during the development. The priorities of the various requirements and the prevailing climatic conditions should be specified. In the second phase, a number of fabrics are manufactured and tested for their technical qualities, including wear and tear strength, color fastness, launderability, etc. The next step is the production of prototypes. Heat insulation and water vapour permeability may be measured on a manikin, and the psychrometric range or comfort range determined. These may be verified by environmental chamber tests with subjects. The results obtained only pertain to limited work load and environmental conditions. The third phase comprises field trials, which are the topic of this chapter. Field trials may consists of various tests, including:

- technical evaluation, serving the optimization of the ergonomic properties.
- physiological evaluation, providing realistic tolerance limits under relevant environmental stress.
- troop trials, exposing the clothing to the widest variety of conditions and collecting the user's subjective opinion.

The NATO countries have rather different procedures for evaluation. Consequently, the above procedures will not generally apply. But whatever the procedure might be, the methods to obtain field data should be sound. A good deal of attention will be paid, therefore, to the methodological rules, explaining the points by practical examples.

2. TECHNICAL EVALUATION

The technical evaluation is usually both the first step in testing and the last step in the development. It serves the optimization of design, sizing, ease of use and compatibility. Often these properties are hard to measure so that subjective evaluation is indicated. Since the shortcomings do not relate to specific environmental conditions, the observations are rather straightforward and may be carried out in a short time.

There are no special requirements as to the number of tested items. Generally 15 to 20 subjects are sufficient, performing various activities. Fit and mobility are tested by means of various body postures (see also Chapter 17), while the ease of donning and doffing should be tested under normal as well as under difficult conditions, for instance, in confined spaces or in the dark. Displacement of the clothing may be determined during running or jumping. An important condition for all these tests is that the size of the clothing is carefully chosen for any participating individual.

Faults are not likely to pass these tests unnoticed. When testing the compatibility, sometimes a specific combination is forgotten. Furthermore, it may happen that fashionable constructions are not regarded sufficiently from the functional point of view. The inclusion of highly experienced subjects may prevent this type of imperfections.

Usually, the clothing can easily be modified to eliminate climatic drawbacks. The best points of various models may even be integrated in one new model. By virtue of the technical evaluation no unsuitable model has to be subjected to further testing. The technical evaluation is not an adequate means to select the best model, however, as may be shown by the following example.

> In a test of rainwear for construction workers, three models -- a coat, a two piece suit and an overall -- were submitted for technical evaluation. On all three there was criticism, but for the overall there was no way to cater for the faults. Therefore, the overall was discarded. Of the other two garments, the coat evoked considerably more negative comments that the suit. A wear test with modified garments showed, however, that the suit was so difficult to don or doff that it was worn almost continually, with consequent sweat accumulation. Due to this discomfort the coat was preferred, despite the worse rain protection and the larger impediment.

3. PHYSIOLOGICAL FIELD TRIALS

General

This kind of evaluation is used to compare various test samples under identical conditions. The conditions should be well defined in order to make the test meaningful. Consequently, all variables that are not deliberately included in the test design should be kept constant.

Physiological trials may produce objective (physiological) data as well as subjective data (ratings). The procedures for obtaining physiological data are described in detail in NATO ACCP-1 (6).

Subjective data are easier to acquire than physiological data, but the required number of subjects for significance is usually larger.

Test Samples and Subjects

No more than four test samples should be examined in the same test, always including the current model in service. The required number of subjects is a-priori unknown. It depends on the standard deviation of the data and the magnitude of the relevant differences between samples. Often, a pilot experiment is done to estimate the required size of the test. The author proposes a new technique for this problem in Appendix A. Adequate statistical testing is unconditional for this kind of evaluation and the designer of the test must consider this in advance, with one method or the other.

Subjects should be in good health, participate on a voluntary basis and give their informed consent. Motivation plays an important role in the results and the subjects should therefore be aware of the purpose of the test. Experienced subjects are preferred.

> Often the importance of motivation is underestimated. During a test of body armour, 28 military subjects participated in a maneuver until tolerance limits were

reached. Subjects with an incentive showed longer tolerance times than those without an incentive. With increased weight of the body armour, the tolerance times decreased dramatically, but the effect of the incentive increased, becoming very relevant for the heaviest armour.

Environmental Conditions and Activities

The clothing should be examined during the periods with the highest climatic stress, usually during winter and summer. The air temperature, solar radiation, humidity and wind velocity should be monitored close to the test site. Also the kind and quantity of precipitation and the nature of the terrain should be recorded.

The most stressful work conditions should be included, rest in the cold and hard work in the heat. Activities should be militarily relevant and preferably standardized, including hiding in a foxhole, marching and maneuvering. The more standardized the activity is, the more significant the test result will be, but monotony should be avoided as it reduces motivation.

The level of stress may be so chosen that either an equilibrium in physiological strain is reached or the tolerance limit will be surpassed. Equilibrium in strain has the advantage that mean values for performance may be determined, but the variance in the performance is often so large that the difference between the samples does not become significant.

Therefore, conditions of limited tolerance are preferred. When fatigue, body temperature or extremity temperature reach a limit value the test is discontinued. With this type of test, the variance is usually smaller, the experimental sessions are shorter and the results are militarily relevant. Too stressful conditions, however, tend to mask the differences between samples.

During a test of three types of CW-protective clothing, heart rate and sweat loss did not differ very much, but the rate of increase of rectal temperature and the tolerance times showed a distinct advantage for the garment with the highest vapour permeability. By taking the ratio of the rates of temperature rise, a convenient relative figure for heat exhaustion risk was obtained.

Test Design

The strain perceived or the performance observed are both highly dependent on inter-individual differences and fortuitous weather conditions. It is therefore necessary to have each subject test each item or to use matched groups. Furthermore, all items should be tested at the same time to be sure the environmental conditions are the same. This may be done by applying a Latin Square design (Fig. 1). The number of samples determine the number of subjects (or groups of subjects) and the number of experimental sessions.

Period	1	2	3
1. Group	A	B	C
2. Group	C	A	B
3. Group	B	C	A

Fig 1. Example of a Latin Square design. There are as many groups and periods as there are samples (here are three: A, B and C). During each period all samples are worn and each group wears all samples successively.

On planning a test, sufficient time for familiarization, instruction, donning and doffing, rest, repairs and unpredictable events should be scheduled in addition to the actual experimental sessions.

Physiological variables

The physiological measurements must be limited to a few easy-to-measure variables. These should be relevant stress indicators and clear tolerance values should be applied. At least the following variables should be included:

- During cold stress, the temperature of the big toe or little finger. Criterion value 5 °C.
- During heat stress, the rectal temperature. Criterion value 39.5 °C.
- Heart rate. It includes the effects of work and heat on the circulation. Criterion value 180 beats per minute for young males.

Other variables may be metabolic heat production, sweat production (weight loss), and convergence of rectal and skin temperature, (1 °C difference indicates possible onset of heat collapse), peripheral blood flow and skin hydration. For all these variables, the required instrumentation should be more sturdy than the normal laboratory equipment.

Data Acquisition

Data acquisition may be performed by telemetry or portable data loggers, either on magnetic tape or in solid state memory. Telemetry allows continuous monitoring but the equipment is expensive and susceptible to malfunction. Data loggers do not allow continuous monitoring and medical supervision. An alternative is to accompany each subject by a monitor who performs the measurements, but may be tasked with organization, trouble shooting and observation at the same time.

Observations

Observation of subjects is essential. Medical problems like dizziness, weakness, nausea and heat cramps may be noticed immediately and the subject can be treated

appropriately. Observations also provide the level of unsystematic information that will not be covered by the measurements. Finally, observations are an adequate means for the determination of behavioural variables, such as work efficiency, alertness, attitude to a task or handling of the outfit.

> Three helmets of different weights and protection were tested during an 8-hour military exercise. Measurements showed that both speech intelligibility and firing performance decreased with increasing helmet weight. Neither of these effects was statistically significant, however. Observers counted the number of corrections that the subjects made to the position of the helmet. These increased significantly with helmet weight, reflecting the acceleration forces on the head during running and jumping.

Interviews

After completion of the test, the subjects should be asked for their opinion on e.g., thermal sensations, impediment, appreciation, etc. These ratings are complementary to the measurements and observations, but reveal unexpected comments as well. Preferably, a psychologist should have interviews with the subjects, rather than having the subjects fill out a questionnaire.

Report

The report should deal first with the facts, supported with sound statistical analysis. Next, these facts should be discussed with regard to their relevancy for the use of the clothing, considering the following points of view:

- how relevant were the test conditions
- which were the factors limiting the tolerance time
- which clothing evoked the least physiological strain
- which modifications to the clothing are recommendable
- can the tolerance time be extended by other means
- which aspects need special attention in the troop trial.

4. TROOP TRIALS

General

By means of a troop trial, the military user judges the test samples in a wide variety of circumstances. The suitability of samples is a complex composition of observed facts and subjective ratings, balanced to each other. Probably the only way to analyze the opinions is to question the subjects. This might look easy, but the reality is that the techniques used in interviews or questionnaires determine to a high degree the outcome of the investigation (12). If one considers that the decisions taken on the basis of this outcome have large financial consequences, it becomes clear that methodological faults must be eliminated. This section deals with the traps and difficulties, involved in subjective data collection.

4.1 QUESTIONNAIRES

Compilation of Questions

As a first step, the topics of the questionnaire are put on a key word list. There will usually be a distinction between technical and physiological topics. The topics should be treated with as much detail as possible, to avoid uncertainties about the aim of the question. First, the topics are classified and then the questions within a class are dedicated to single features. Examples of classes are:

Technical	Design and Pattern	Fit sleeve and leg length pockets
	Ease of Use	donning and doffing fasteners
	Compatibility	with other clothing with other equipment with weapons
	Durability	material aging wearability damage repairability

Questions on technical topics are largely material dependent and are fairly standard for all clothing, with slight modifications for special clothing articles. This is not possible for the questions on physiological topics, since work and climate are involved as well.

Physiological	Comfort	increased effort insufficient cold protection skin irritation
	Performance	mobility functional loss of performance
	Health	injuries frostbite burns heat collapse

Time Frame of Questionnaires

Before a question can be answered, enough experience must have been gained by the subjects. On the other hand, a question should not be asked after such a long time that the experience has faded away. Thus, questionnaires should be filled out several times during the trial. Questions may be classified as follows according to the time frame requirements:

– features that can be determined at any time (handling, compatibility). One questionnaire at any time is sufficient.

– features that can only be determined after prolonged use (damage, wear and tear, material aging). One questionnaire at the end of the trial.

– features depending on the weather or special activities (impediment during maneuvers, temperature sensation). Repeated questionnaires at suitable times (discussed later).

Each questionnaire should not comprise more than 20 questions, since a larger number is, by experience, not paid the required attention. All questions that might be answered in other ways, for instance by routines and annotations of the Commander or consulting medical or accident reports, should be omitted.

Absolute or Relative Judgements

It must be decided whether an absolute or a relative evaluation should be made. In the absolute evaluation, the subjects wear only one sample and compare their perceived sensation with an individual internal scale. In a relative judgement, the subjects compare all test samples on their own internal scale, so that the reference is the same. This might provide more accurate comparisons, but only so when the time between the experiences is short enough to generate fresh impressions and, in particular, ensures that samples are not mentally confounded. A disadvantage of relative judgements is that even the "best" sample might be limited in function, essential information that gets lost.

During a field trial on 2 types of CW clothing, the compatibility with other equipment was rated. Absolute judgements as well as relative judgements showed, with statistical significance, that one garment was more compatible than the other. However, only the absolute judgements revealed that the majority of subjects were still not satisfied with the compatibility of the best garment.

Complex or Simple Questions

Complex questions allow the evaluation of features that involve more than one factor at the same time. This requires a complicated internal weighing of the relative importance of these factors, complicated even more by incomplete recollection of these factors. Thus, the variance in answers becomes larger when the complexity of the questions increases.

Simple questions, on the other hand, are answered in a relatively reliable way, but reveal only small details. Therefore, it is useful to combine complex and simple questions in the questionnaire.

In a field trial on combat clothing, the wearer comfort was evaluated. The unspecified question as to wearer comfort showed no significant difference between positive and negative responses. When the question was split up into mobility, cold protection and rain protection, however, these particular aspects were brought into memory. Mobility proved significantly positive and rain protection significantly negative.

Forced Choice and Open Questions

Open questions allow the discovery of unforeseen aspects. However, often hints are required to evoke responses.

Forced Choice questions allow a choice out of a limited number of answers. The frequency of easy answers may be determined and used for statistical analysis. Thus, both types of questions have their specific advantages and it is useful to combine them.

During a field test of rainwear, the spots were identified where leakage occurred first. With a purely open question, only 10 responses out of 100 subjects were obtained. When the same question was put, but enhanced with four suggested specific locations, no less than 76 responses were obtained. In both cases, the shoulders and thighs were identified as the main problems, but in the combined question, other spots were also identified such as the back and under the belt. The open question at the end ("other spots") gathered more responses than the single open question above.

Forced Choice Response Scales

As a next step, response scales have to be introduced for the forced choice questions. A distinction should be made between nominal and ordinal scales. A nominal scale represents independent factors, such as various locations on the body, environmental factors, etc.

Ordinal scales are often used to express the strength of feelings. The calibration points on the scale are provided by verbal descriptions, preferably not more than five since finer details cannot be distinguished during field trials.

Often, the point of interest is the number of responses beyond a certain limit (uncomfortable, impossible, unbearable). In that case, the five point scale may be replaced by a simple two-alternative forced choice question (yes/no).

During a test of cold weather footwear, the temperature of the feet of subjects in manholes was rated on a five point scale as a bit colder than "very cold" on the average. More important, however, was the fact that 12% of the test population voted "unbearably cold". Since the latter category is representative for future complaints, the question could be simplified to "was the cold still bearable?". The actual answers obtained with this question were close to those for the former, more complicated, rating scale.

Obtaining an Overall Judgement

An overall judgment must be based on the various judgments on distinguishing features. These features have completely different units, however, that are not easily equated to one positive or negative "user opinion". It is recommended that the questions be put in such a way that the answers compare to a profit scale, for all features. There are various possibilities to combine features in one total judgement:

1. If any of the features is statistically judged to be unreliable, the sample is rejected. This works well during a technical test, using a checklist.

2. The average percentage of positive judgements over all features is calculated. This may give a rank order of the samples but does not account for the difference in subjective importance of the features.
3. Weighting factors are assigned to the features in addition to procedure 2. These weighting factors have to be determined in some way, for instance, by expert opinion, but will not be the same for any subject and thus lead to errors.

> The wear comfort of combat boots was evaluated, including bending stiffness, weight, slipping, stability, mobility, waterproofness, cold protection and blister formation. Three features were significantly positive and two were significantly negative. Applying procedure 1 would lead to rejection, but the overall opinion was significantly positive. Both procedures 2 and 3 led to about equal proportions of negative and positive opinions, which is apparently too pessimistic.

The basic problem here is that too little is known about the basis of the formation of an overall opinion by the subjects. A practical solution is to decide upon the suitability of any test sample by means of method 1, but to select the best sample based on procedure 2.

Interviews or Questionnaires

Fact finding can be executed in several ways. The most easy way is to task the Commander with the collection of experiences. The Commander decides then on the way he gets his information and consequently his report is a mix of his personal opinion and those of his personnel.

A better way is to have interviews with the actual users, standardized by means of a checklist. If carried out consistently, the answers may be used for statistical evaluation without further processing. An advantage over the use of questionnaires is that wrong understanding of questions can be corrected. Interviews are time consuming, however, involving more than one interviewer. Since skilled interviewers are not always available, there is a danger that various interviewers evoke various responses. In this case, questionnaires may be more reliable.

> During a field trial of combat suits, the cold protection was evaluated in four different ways: report by the Commander, interviews by psychologists, interviews by different ranking military staff, and questionnaires. The Commanders all reported that the cold protection was sufficient. The psychologists obtained close results, neither positive nor negative, while the various ranking military obtained rather different results. The questionnaires, finally, showed a slight but consistent majority for insufficient cold protection. The conclusion from this experiment is that if no skilled interviewers are available, questionnaires are a better solution than leaving the procedure up to the military.

The Structure of a Questionnaire

On examining a clothing system, the questions have to be grouped for each clothing article separately. In each group, topics are distinguished, worked out in single questions. The last question may deal with the subjective opinion on the topic as a whole and could be enhanced with an open question. Questions should be arranged in a logical order to enable the buildup of a reasonable judgement. It is recommendable as well to start with simple questions, and to save the more complex questions for the end when recollection is nearly complete.

The questionnaire should be split into at least three parts, according to the time frame, as explained earlier. The last part should include a call for suggested improvements of the clothing and of the test procedure as well. The latter serves to motivate the subjects.

Final questions deal with the subjective opinion about the suitability of the articles not only during peacetime, but the prospects for combat conditions as well. The article could be so basic that inherent problems are taken for granted. Answers to these questions should be classified separately because they represent expectations rather than facts.

Formulating Questions

Questions should be formulated very precisely, in plain clear words that correspond to the vocabulary of the subjects. Global and, in particular, abstract notions should be avoided. Also, qualifications without a clear reference (average, big, bad) are undesirable. Questions like "Is the new model better than the current, in-service, model" are suggestive and evoke a bias. Questions should instead be formulated in a neutral way. "Don't know" as a response category should be avoided, since it allows the subject to escape from a decision.

Preliminary Check

The first draft of a questionnaire is often imperfect. Some questions may be superfluous because the test samples do not differ in that specific feature. Other questions may be confusing or should be concerned with special properties of a sample. It is recommended that the questionnaire be checked by the clothing designer, a military consultant, a psychologist and a physiologist.

The next step is a preliminary test by about 15 subjects who have used the test samples for about a week. An open interview with these subjects reveals the difficulties.

> During a test of rainwear for construction workers, the original questions dealing with global notions such as mobility, design, ventilation, suitability and waterproofness were specified in clearly understood sub-questions. The average proportion of positive responses dropped as dramatically as from 67% to 38%, revealing specific problems with ladder climbing, collar design, sweat wetted back, water protection of the hands, and cold feet. This example illustrates the point of complex and simple questions as well as the value of a pilot test.

Subjects

For subjective evaluations more subjects are needed than in physiological trials, to obtain statistically significant results. A rough estimate is that 70 valid votes are required (Appendix A). By experience, about 30 non-valid answers may be anticipated and about 20 pieces of missing data, so that 120 subjects should participate. Large trials, e.g., 1000 men or more, may be impressive but bring little advantage and are a lot more work. In such large trials, the deficiencies of the questionnaire, rather than real effects of the clothing, become apparent.

Subjects should be randomly selected. In reality, however, an organizational unit is appointed. This is not a serious problem as long as the unit is representative with respect to environmental conditions, work load and fitness. Elite corps, such as marines or rangers, are often willing to tolerate more than normal troops, giving a distorted idea of the general acceptance.

Motivation of the subjects is an essential point which is the commander's responsibility. Stress due to additional services for participating personnel should be avoided if possible.

Climatic Conditions

Each appropriate season should be included in the test period. Usually, 2 months of wear during each season is sufficient. To avoid wrong conclusions, due to deviations from the anticipated weather conditions, daily maximum and minimum temperatures as well as precipitation should be recorded.

Questioning Intervals

As already discussed, the moments for inquiries about observable topics are determined by beginning and ending of the test. For the collection of random subjective experiences, a short dedicated inquiry should repeatedly be held. Experience shows that this should not be done too frequently, because subjects will become reluctant to fill the questionnaire out again and again. Too long intervals, on the other hand, cause loss of information due to incomplete recollection. Somewhere in between these is an optimal interval, estimated as approximately one week.

A test for optimal inquiry intervals was held by asking three groups of subjects, respectively daily, weekly and once during a four week period, whether their combat suit was sufficiently water repellent. The responses were checked with an objective measurement of water absorption. Fig 2 shows that the group with weekly intervals gave quite consistent answers, whereas both the daily interval and a single inquiry caused degradation of the quality of the responses.

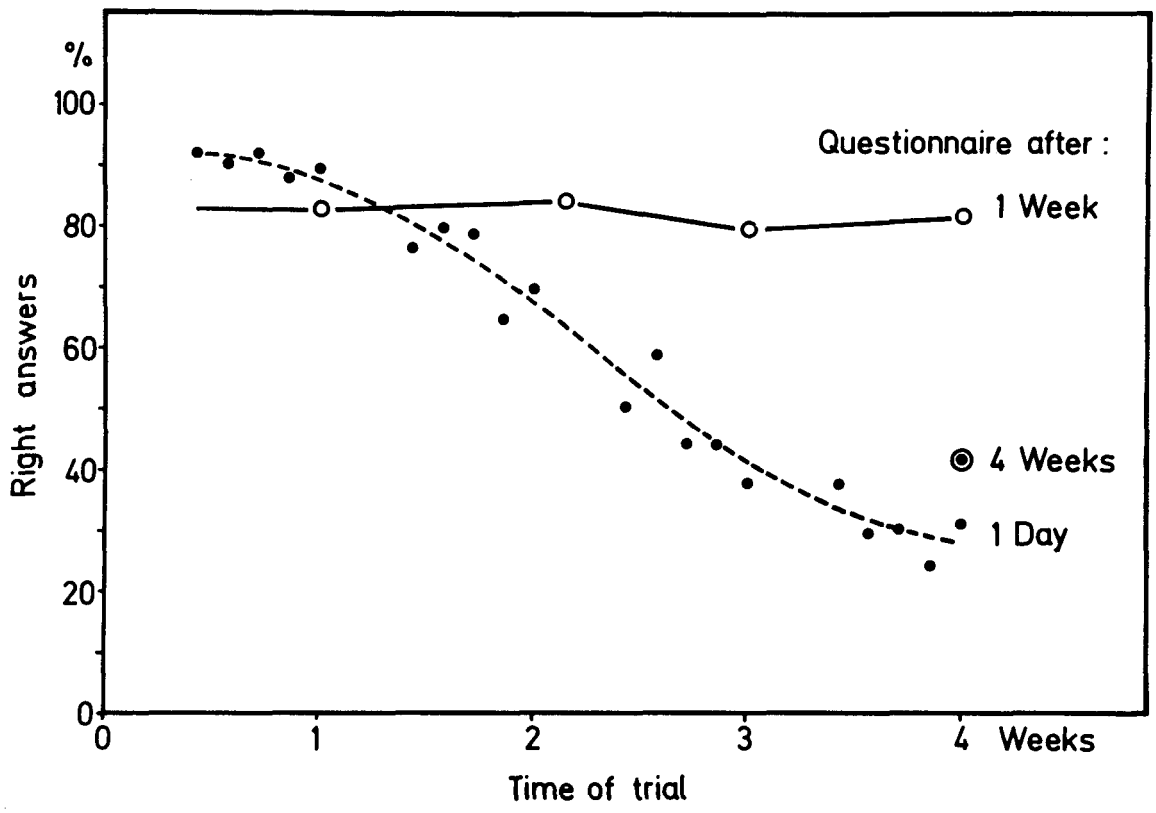


Fig 2. Reliability of answers as a function of questionnaire interval (1 day, 1 week, 4 weeks). Both too often and too few causes degradation of the reliability (here defined as the correlation between observations and a physical test on water repellency.

The number of test samples

The evaluation of a certain number of test samples may be executed with basically two test designs. Within a subject design, each subject wears all samples successively. This is time consuming but allows relative evaluation. When the test takes long, due to a large number of samples, the recollection of former experiences is incomplete and the discriminating power of the test accordingly is lost.

The second design is between subjects. In this case, the subjects are divided in groups and each wears just one sample. Here, only absolute evaluations are possible, that have to be compared between the groups. Therefore, the groups must be matched with respect to the relevant characteristics.

For both types of tests, the distinction between any two samples becomes more difficult when a larger number of samples is included. For significance, an accordingly larger number of subjects is required, which increases the effort progressively. Therefore, the number of samples should be limited, typically to three.

A compilation of 73 tests was made, with various clothing and equipment articles. In these tests, from 2 to 7 different samples were included. Each test was evaluated by questionnaires dealing with an average of 40 questions each. Ideally,

each question should provide significant differences between all samples, but in reality, the number of significant differences is lower, of course. When the ratio of the real number of significant differences to the ideal number is calculated, the following table results:

# Samples	# Tests	Fraction of significant differences	# Significant differences
2	17	.50	.50
3	12	.56	1.1
4	11	.47	1.4
5	16	.43	1.7
6	12	.36	1.8
7	7	.31	1.9

This table shows that the number of significant differences slightly increases with the number of samples, but not in proportion by far.

It is good practice to include the in-service model in the test, leaving room for 2 new models. If, despite the technical evaluation, more models have to be included in the troop trial, a two step procedure is recommended.

The necessity of inclusion of the in-service model in the test, instead of comparing the test data on the new model with former experiences with the in-service model may be obviated with the following example:

During a trial of apparently identical safety shoes, three experimental groups of subjects were included. The first group wore both the new and the old shoes, the second group wore only the new shoes and compared those in thought with the old shoes, and the third group wore the old shoes, being presented as the new type. In the first group, no difference between the shoes was found, but both in the second and the third group the model presented as new was significantly preferred. Apparently new is strongly associated with better, fulfilling its own prophecy.

Test order

Since the weather is a continually changing factor during a test, having a strong impact on the fraction of dissatisfied subjects, it is absolutely necessary to have the various test samples worn at the same time by different groups. When only an absolute evaluation is required each group has to wear one sample only (between-groups design). In that case, the groups must be matched according to activity, exposure to the weather, etc.

For relative evaluation, the samples must be permuted over the groups, each group wearing all samples (within the group design). The way to do this is called a Latin Square design; in Fig 1 such a design was shown for three groups and three samples.

Violation of the condition leads to erroneous results as in the following example:

> During a field test of long underwear, the average air temperature dropped from 6 °C in the first week to 3 °C in the second week. Two groups were involved, grenadiers and radio operators. The latter group showed more dissatisfaction at any time. Three types of experimental design were applied at the same time, a between-groups design, a within-groups Latin Square design, and a design in which both groups wore one type of underwear in the first week and the other type in the second week. The first two designs gave identical results, while in the third design, where type of underwear and environmental temperature were confounded, the difference between the types of underwear was highly exaggerated.

When more factors become involved (tolerance, weather, type of work, additional equipment), the design becomes more complicated. In that case, more groups should be employed at the same time, but always as a Latin Square.

4.2 TEST EXECUTION

Test conditions

During field trials, a wide range of activities may be performed, but these will be limited to medically safe conditions. Conditions that may evoke injuries could be very relevant for military operations, however, like cold injury conditions. In testing clothing, one should be aware of the incompleteness of the troop trial data. Even more so, the troop trial data may be misleading.

> During a trial of cold weather socks, the feet of subjects felt equally cold in both the tested samples, despite the fact that the heat insulation was different in a physical test. Another finding in the trial was that the best insulating socks evoked significantly more numbness of the feet, which might be related to the lower moisture absorption of these socks. Another trial with rats showed that indeed these socks caused higher hydration of the skin leading to tremendous tissue damage upon rewarming after cold exposure. In summary, the warmest socks in a physical test were equally cold in a wear trial and would cause increased injury in cold wet conditions. The moisture absorption would have been a relevant parameter.

Instruction and Supervision

Before the troop trial, the subjects have to be informed about the purpose of the test and its importance. Test samples should be shown and their use explained. The questionnaire should be dealt with in detail and remaining problems cleared. This procedure shows also the motivation of the subjects and, equally important, their superiors.

When questionnaires are completed, the subjects should be allowed to give their independent opinion, free from pressure by strong personalities in the group. Ample time should be provided to fill out the form. This should not be at the expense of their leisure time.

During the test, a visit should be paid to the troops. It serves both the purpose of solving remaining problems and showing interest. The visit should take place immediately after the first questionnaire.

Evaluation of the Results

The essential questions to be answered by means of the troop trial are:

– Is the clothing suited?
– Which model is best?
– What shortcomings of the best model have to be corrected?

By means of the procedure explained in Obtaining an over-all judgement, a judgement for each topic (wear comfort, ease of use, etc. is obtained. A further step would be to combine these judgements into a single statement about the suitability of the test sample. Asking the subjects is unreliable because they are not likely to oversee such a complicated matter and, moreover, they will be reluctant to reject a sample. Therefore, the decision has to be based on the various topical qualities.

The judgements on the various topics may be significantly positive, significantly negative or indecisive. An easy statistical test for the significance is the sign test (Appendix A), which involves the number of positive and negative responses only. A test sample may fall in one of the following three classes:

– All topics are significantly positive. The sample is accepted.
– One or more of the topics are undecided. The sample might be acceptable, but needs modifying.
– One or more of the topics is significantly negative. The sample is rejected.

The best of the acceptable samples may be selected on the average percentage of positive judgements over all topics. This method implies that all topics are of the same weight in modifying the over-all judgement as discussed in 4.1. The deficiencies of even the best model are easily found by going back to the single features of the least appreciated topics. Both the single features and the topical judgements thus play an essential role in the evaluation and can not be omitted.

The Commander's Report

In addition to the questionnaire, the Commander should submit his own report, representing his point of view on the samples. Often the commanding officers have a different idea about required comfort and the interference of the sample with fighting power.

Final Report

The facts should be presented first in the report, then followed by a discussion of their relevance for the military use, taking into account:

– Were the climate and the activity representative of the intended use?
– Which findings were unexpected?
– What is the recommended sample?
– Were the results significant?
– Suggested modifications?
– Have the problems with current equipment been solved?
– What disadvantages must be accepted?
– What precautionary measures are proposed?

The questionnaire, the answers and the Commander's report should be included to enable the decision maker to check the recommendations.

REFERENCES

In this chapter, many topics have been discussed that are of interest to executing staff. For clarity, it was illustrated with examples, rather than with scientific proof. Those who wish to go into more detail regarding one or more of the topics may find useful references in the following list.

1. Andrews, T.G. Methods of Psychology. New York 1947.

2. Armstrong, D.M. Perception and the Physical World. London 1961.

3. Atkinson, J.W. An Introduction to Motivation. Princeton 1964.

4. Bendig, A.W. The reliability of self-rating as a function of the amount of verbal anchoring and of the number of categories on the scale. J. Appl. Psychol. 37, 146 (1953).

5. Boehringer, H. Trageversuche als Grundlage der Gebrauchswertprüfung. In: Siebel, E. (ed), Handbuch der Werkstoffprüfung, Bd. V. Berlin 1960.

6. Bruner, J.S. Beyond the Information Given. New York 1973.

7. Bruner, J.S., Goodman, C.C. Value and need as organizing factors in perception. J. abnorm. soc. Psychol. 42, 33 (1947)

8. Brunswick, E. Perception and the Representative Design of Psychological Experiments. Berkeley 1956.

9. Cantrill, H. Experiments in the wording of questions. Public Opinion Quarterly 4, 330 (1940).

10. Cantrill, H. Gauging Public Opinion. Princeton 1947.

11. Clauss, G. Zur Methodik von Schätzskalen in der empirischen Forschung. Probl. Erg. Psychol. 26, 7 (1968).

12. Cochran, W.G., Cox, G.M. Experimental Design. New York 1962.

13. Cronback, L.J., Gleser, G.C. Psychological Tests and Personal Decision. Urbana 1965.

14. Dicken, C. Good impression, social desirability, and acquiescence as suppressor variables. Educ. psych. measurement 23, 84 (1963).

15. Dixon, W.J., Mood, A.M. The statistical sign test. J. Amer. Statist. Assoc. 41, 557 (1946).

16. Dixon, W.J., Massey, F.J. Introduction to Statistical Analyses. New York 1957.

17. Draper, J. Planning trials of clothing and equipment. Commonwealth Defense Conference, Canada 1956.

18. Dukes, W. Psychological studies of value. Psychol. Bull. 52, 24 (1955).

19. Ebbecke, U. Über Reflexempfindungen, insbesondere Kitzel- und Juckempfindungen. Pflügers Arch. ges. Physiol. 248, 220 (1944).

20. Ekman, G., Bratfisch, O. Subjective distance and emotional involvement. Acta psychol. 24, 430 (1965).

21. Ferber, R., Wales, H.G. Detection and correction of interviewer bias. Public Opinion Quarterly 16, 107 (1952).

22. Festigner, L., Katz, D. Research Methods in the Behavioral Science. London 1954.

23. Fisher, R.A. The Design of Experiments. Edinburgh 1960.

24. Fisher, R.A., Yates, F. Statistical tables for biological, agricultural and medical research, Edinburgh 1963.

25. Fuzek, J.F., Ammons, R.L. Techniques for the subjective assessment of comfort in fabrics and garments. In: Hollies, N.R.S., Goldman, R.F. (Eds), Clothing Comfort. Ann Arbor 1977.

26. Gallup, G. A Guide to Public Opinion. Princeton 1948.

27. Geldard, F.A. The Human Sense. New York 1972.

28. Gibson, E.J. The development of perception as an adaptive process. Amer. Scientist 58, 98 (1970).

29. Glanzer, M., Cunitz, A.R. Two storage mechanisms in free recall. Jour. verb. Learning a verb. Behavior 5, 351 (1966).

30. - - - - Heat transfer and physiological evaluation of clothing. ACCP-1, NATO, Febr 1980.

31. Guilford, J.P. Psychometric Methods. New York 1954.

32. Gulliksen, H., Messick, S. (Eds.): Psychological scaling: Theory and Applications. New York 1966.

33. Herzberg, A.M., Cox, D.R. Recent work on the design of experiments. J. Roy. Statist. Soc. 132A, 29 (1969).

34. Hicks, C.R. Fundamental Concepts in the Design of Experiments. New York 1973.

35. Hofstaetter, P.R. The actuality of questions. Int. Jour. Opinion and Attitude 4, 16 (1950).

36. Hollies, N.R.S. Psychological scaling in comfort assessment. In: Hollies, N.R.S., Goldman, R.F. (Eds); Clothing Comfort, Ann Arbor 1977.

37. Jacoby, L.L. Encoding processes, rehearsal and recall requirements. Jour. verb. Learning a. verb. Behavior 12, 302 (1973).

38. Kenshalo, D.R. The Skin Senses. Springfield 1968.

39. Kohler, I. Interne und externe Organisation in der Wahrnehmung. Psychol. Beitr. 6, 426 (1962).

40. Kornhauser, A. The problem of bias in opinion research. Int. Jour. Opinion and Attitude 1, 1 (1947).

41. Lienert, G.A. Testaufbau und Testanalyse. Weinheim 1961.

42. Lindsay, P.H., Norman, D.A. Human Information Processing. New York 1977.

43. Loftus, G.R., Loftus, E.F. Human Memory: The Processing of Information. Hillsdale, New York 1976.

44. Mandler, J.M., Johnson, N.S. Remembrance of things passed. Cognitive Psychol. 9, 111 (1977).

45. Marsh, S.E., Perris, F.A.C. An experimental study of the rating scale technique. J. Abnorm. Soc. Psychol. 19, 310 (1925).

46. Merrill, R.M. The effect of pre-experimental and experimental anxiety on recall efficiency. Jour. Exp. Psychol. 48, 167 (1954).

47. Miller, G.A. The magical number seven, plus or minus two: Some limits on our capacity for processing information. Psych. Review 63, 81 (1956).

48. Moskowitz, H.R., Scharf, B., Stevens, J.S. (Eds): Sensation and Measurement. Boston 1974.

49. Neisser, U. Cognitive Psychology. New York 1967.

50. Newman, J.W. Motivation Research and Marketing Management. New York 1957.

51. Nisbett, R.E., Wilson, T.D. The halo effect: Evidence for unconscious alteration of judgements. J. pers. soc. Psychol. 36, 250 (1977).

52. Nisbett, R.E., Wilson, T.D. Telling more than we can know: Verbal reports on mental processes. Psych. Review 84, 231 (1977).

53. Osgood, C.E., Suci, G.J., Tannenbaum, P.H. The Measureinent of Meaning. Urbana 1957.

54. Powell, F.A. Open- and closed-mindedness and the ability to differentiate source and message. J. abnorm. soc. Psychol. 65, 61 (1962).

55. Ramsay, D.A., Nelms, J.D. Practical aspects of simplified field testing. Commonwealth Conference on Operational Clothing. Ghana 1978.

56. Reenpaa, Y. Allgemeine Sinnesphysiologie. Frankfurt a.M. 1962.

57. Rosenthal, R., Rosnow, R.L. The Volunteer Subject. New York 1975.

58. Sachs, L. Angewandte Statistik. Berlin 1978.

59. Schachter, S., Singer, J.E. Cognitive, social and physiological determinants of emotional state. Psych. Review 69, 379 (1962).

60. Schank, R.C., Abelson, R.P. Scripts, Plans, Goals and Understanding. Hillsdale, New York 1977.

61. Schniederman, M.A. The proper size of a clinical trial. Jour. of New Drugs, 1964, 3.

62. Sixtl, F. Messmethoden der Psychologie. Weinheim 1967.

63. Skramlik, E.V. Psychophysiologie der Tastsinne. Arch. Psychol., Erg. Bd. 4, Teil 1 und 2. Leipzig 1937.

64. Smith, H., Hyman, H. The biasing effect of interviewer expection on survey results. Public Opinion Quarterly, 14, 491 (1950).

65. Sprung, L., Sprung, H. Zur Theorie und Methodik der Fragebogenkonstruktion. Probl. Erg. Psychol. 66, 5 (1978), 67, 5 (1978).

66. Stanley, L.P. The art of asking questions. Princeton 1951.

67. Sternberg, S. High speed scanning in human memory. Science 153, 652 (1966).

68. Thurstone, L.L. The Measurements of Values. Chicago 1959.

69. Torgerson, W.S. Theory and Methods of Scaling. New York 1960.

70. Tulving, E., Donaldson, W. (Eds): Organization and Memory. New York 1960.

71. Weiner, B. Motivational factors in short-term retention. Psych. Reports 20, 1203 (1967).

Appendix A.

Method to determine the required number of subjects

Usually, the difference between samples and the standard error of the results are not known in advance of a test. This is sometimes estimated during a pilot test in order to determine the required number of subjects in a test, to make sure that interesting differences become significant.

The kernel of the problem lies in the adjective "interesting". The decision as to what difference is interesting is sometimes defined by the operational decision makers. A definition in terms of the percentage of wearers that must favor the new model is very helpful in this respect.

When two samples A and B are compared, and N_A subjects prefer A, while N_B subjects prefer B, the excess probability may be defined as:

$$\Delta p = \frac{N_B - N_A}{N}$$

where N is the total number of subjects. Once Δp is given, the required number of subjects (N) can be read from Table AI or from Fig A1, upper curve. Both are based on the sign test for two alternative forced-choice responses.

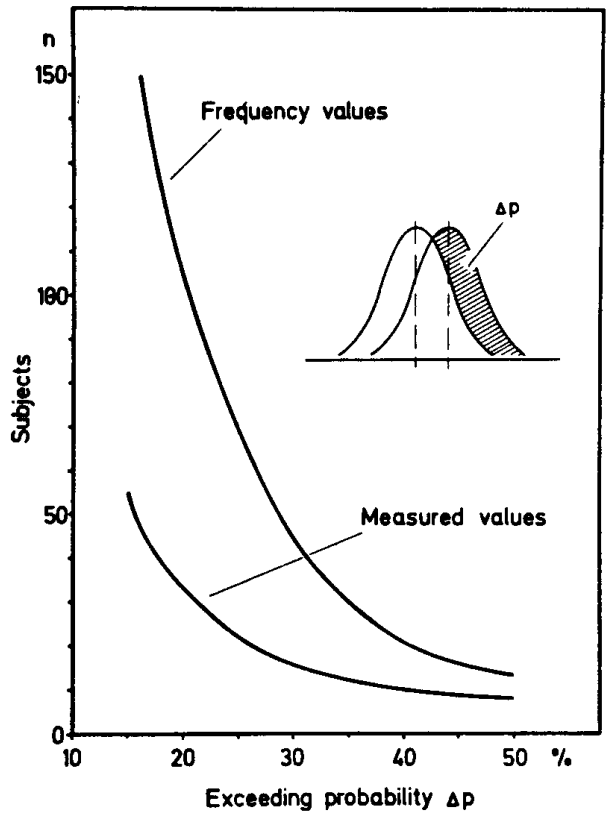


Fig A1. Relationship between the exceeding probability (the fraction that a sample is more preferred that an alternative sample) and the number of subjects that is required for the effect to become significant at 0.05 levels. The upper curve is for the sign test (used for yes/no responses) and the lower curve for the t-test (used for measurements on an interval scale). The upper curve compares to Table AI.

When measurements are taken, these will usually be expressed on a continuous scale, instead of on separate response categories. In this case, the t-test is more appropriate. When the excess probability is defined in the same way as before, graphically shown in the insert in Fig A1, the lower curve of this figure is obtained. Obviously, for this higher quality type of data, fewer subjects are required for a defined level of Δp.

Table AI

Significance limits for the design-test, $\alpha = 0.05$ (58). - The total of the found values $n_1 + n_2 = N$ was found and examined, whether n_1 and n_2 are situated within the limits given. On reaching or surpassing these limits the effect is significant.

N	n_1 n_2	N	n_1 n_2	N	n_1 n_2	N	n_1 n_2
1	–	31	9-22	61	22-39	91	35-56
2	–	32	9-23	62	22-40	92	36-56
3	–	33	10-23	63	23-40	93	36-57
4	–	34	10-24	64	23-41	94	37-57
5	–	35	11-24	65	24-41	95	37-58
6	0-6	36	11-25	66	24-42	96	37-59
7	0-7	37	12-25	67	25-42	97	38-59
8	0-8	38	12-26	68	25-43	98	38-60
9	1-8	39	12-27	69	25-44	99	39-60
10	1-9	40	13-27	70	26-44	100	39-61
11	1-10	41	13-28	71	26-45	101	40-61
12	2-10	42	14-28	72	27-45	102	40-62
13	2-11	43	14-29	73	27-46	103	41-62
14	2-12	44	15-29	74	28-46	104	41-63
15	3-12	45	15-30	75	28-47	105	41-64
16	3-12	46	15-31	76	28-48	106	42-64
17	4-13	47	16-31	77	29-48	107	42-65
18	4-14	48	16-32	78	29-49	108	43-65
19	4-15	49	17-32	79	30-49	109	43-66
20	5-15	50	17-33	80	30-50	110	44-66
21	5-16	51	18-33	81	31-50	111	44-67
22	5-17	52	18-34	82	31-51	112	45-67
23	6-17	53	18-35	83	32-51	113	45-68
24	6-18	54	19-35	84	32-52	114	46-68
25	7-18	55	19-36	85	32-53	115	46-69
26	7-19	56	20-36	86	33-53	116	46-70
27	7-20	57	20-37	87	33-54	117	47-70
28	8-20	58	21-37	88	34-54	118	47-71
29	8-21	59	21-38	89	34-55	119	48-71
30	9-21	60	21-39	90	35-55	120	48-72

CHAPTER 17

OPTIMAL DESIGN PRINCIPLES FOR CLOTHING SYSTEMS

W.A. Lotens

CONTENTS

SUMMARY

FACTORS IN DESIGN

PROTECTION

COMFORT

MOBILITY

COMPATIBILITY

EASE OF USE

CLOTHING AS A SYSTEM

THE MOST OPTIMAL DESIGN PRINCIPLE

REFERENCES

SUMMARY

The main factors in the design of clothing systems are identified: protection, comfort, mobility, compatibility and ease of use. Each of these factors requires the compromising of various design options and, moreover, the different factors have to be compromised to each other as well. Once decisions are made about the priorities, the design may be optimized in a rational way. The considerations involved, together with a good deal of practical experience, are reflected in this chapter.

Key Words: clothing design, comfort range, clothing systems, protection, mobility, clothing and equipment compatibility.

FACTORS IN DESIGN

Protective clothing has to meet numerous - often incompatible - requirements, between which an optimal balance should be held. One well known contradiction is comfort versus protection. Every designer will meet the problem of designing clothing for those rare hazardous events, although he knows that the clothing will be worn mainly in harmless situations. What will have priority then, the comfort that is appreciated all the time or the protection that only is rewarding during emergencies? Another contradiction is between protection and loss of functional ability, where the latter is a risk in itself. A third example of incompatible requirements is protection and an imposing appearance, in particular for uniforms. The functional design of the clothing is a factor in protection that cannot be neglected in favour of the styling.

Obviously, it is not up to the designer to answer these questions. What he can do, is pose the question explicitly. It is the user who should provide the answers, but unfortunately their answers are seldom very decisive; due to lack of methods such advantages and disadvantages cannot be compared. The designer might be helpful here in not only pointing out the problems, but in supporting proposed solutions as well with estimates of risk, protection level, strain imposed on the wearer and loss of functional ability.

Although attempts have been made to interrelate these issues this is still an open research area. Here, no such attempt will be made, but the main factors in design and their optimization will be discussed.

These main factors are perceived as:

- protection
- comfort
- mobility
- compatibility
- ease of use

PROTECTION

Generally, protection will be located in the outer layers of clothing. Protection from fire, rain, wind, abrasion or detection by instrumented vision will be seriously affected, if not completely cancelled, when it is not located in the outermost layer. Consequently this layer has to consist of very special material, unifying hardly compatible properties.

It has been tried many times to upgrade protection by applying a unique finish to otherwise conventional materials. This will generally work for just one kind of finish and even then to a limited extent. Treatments are notorious for their mutual incompatibility and their fast degradation.

A far better solution is the use of inherently protective materials, resulting in higher protection levels, slow degradation and compatibility with other characteristics like tear strength, abrasion resistance and vapour permeability. Requirements of minor importance may interfere with this strategy. A disrupted camouflage pattern, for instance, that may give marginally better camouflage than plain colour, requires print-dyeing, a finish, whereas the plain colour could be intrinsic to the (artificial) fibre. This example shows that requirements should be scrutinized for their necessity.

Usually, the protection level will be determined in the laboratory, using standard tests as a guideline. This is understandable since in development reproducible test procedures are indispensable. The validity of the test results for field conditions is often rather questionable however. Hydrostatic water column, for instance, may be an easy laboratory method to determine waterproofness, but it is not predictive for clothing. The correlation between hydrostatic head and waterproofness is weak in this application, necessitating alternative or additional tests for reliability. Similar problems exist with the determination of wear resistance, flammability, heat flash protection and even heat and water vapour transmission (Lotens, 1983). The designer should try to get feedback from a variety of tests, including simulated field tests involving the whole clothing assembly, while also testing fabric and its construction.

Although most attention in the literature is dedicated to fabric properties, the impact of the construction of the clothing on the protection is far from negligible. Fire protection will be taken as an example. There is a distinct difference between edge and surface ignition, the latter requiring the highest temperature. Consequently cuffs, lying collars, flaps and to a lesser extent seams, catch fire relatively easily and should be omitted or strengthened by additional fabric layers. Obviously, upward edges are not as dangerous as downward facing edges. Folds in the fabric, like hanging curtains, take fire more easily as well.

Seams deform when exposed to heat, protecting the thread, but increasing the shrinkage of the garment that already suffers from the shrinkage of the exposed fabric. When this leads to a break open of embrittled fabric, the protection is lost. If high protection is required, a double layer garment could be considered, since two layers of light fabric show better fire protection than one heavy layer of the same total weight. The second layer will stay intact longer and decrease the danger of a break open.

A fire protective garment should not be too close fitting, not only for the risk of a break open, but for the protection from skin burns during motion as well; the joints are particularly,involved. Extra insulation and extra space at knees (both front and back side), buttocks, elbows and upper back will enable the wearer to move easier in a hot garment and to undo the garment without help. Finally, attention should be paid to fastenings, to avoid both heat bridges and dysfunction. Unshielded zippers may jam due to melting and shrinkage of the tape.

THERMAL COMFORT

In theory, any clothing assembly is comfortable only at a single temperature for any work rate. Due to physiological adjustments to heat and cold, this single temperature may be extended to a comfort zone, but the comfort will gradually decrease when approaching the boundaries between comfort and discomfort; how will such boundaries be defined? Comfort is a psychological state, instead of a physiological one, with undefined limits, subject to motivation and acceptance. The physiological state is more or less a non-psychological mirror image of comfort, as perceived in laboratory or field conditions.

One can try to find a correlation between the sensation of comfort, expressed on a rating scale, and the physiological state in terms of core and skin temperature, both on trunk

and extremities, skin humidity and sweat production. Havenith and Van Middendorp (1985) did a factor analysis on such data and found two relationships between temperature and humidity sensation on one hand and extremity temperature (T_{extr}) and skin humidity (RH_{sk}) on the other hand:

$$\text{temperature sensation} = .16\ T_{extr} + 0.02\ RH_{sk} - 5.7$$

$$\text{humidity sensation} = 0.015\ RH_{sk} - 0.08$$

These equations explain over 75% of the variance for clothed subjects, both during rest and work, in the wind as well as in still air. The other mentioned physiological variables did not add significantly to the explained variance. The limits of comfort are defined in these equations by "uncomfortably warm" (1.0), "uncomfortably cold" (-1.0) and "slightly wet" (1.0).

Apparently in the cold the extremity temperature was associated with the comfort, whereas in the heat, where the extremity temperature may reach a plateau, the skin humidity is dominant. During this test, esophageal and rectal and trunk skin temperature did not cover a range large enough to become significant.

By means of these relationships a comfort range may be determined for any clothing assembly. Should the climate range be larger than the psychrometric range, then additional assemblies will be necessary to cover it. The ranges of the various assemblies should show considerable overlap, however, in order to avoid temperature shocks when changing assemblies. Fig. 1 gives an example of the comfort range of four successive clothing assemblies, during rest as well as during work. Typically the range is 20 °C wide for fatigues, and up to 30^{0}C wide for cold weather garments.

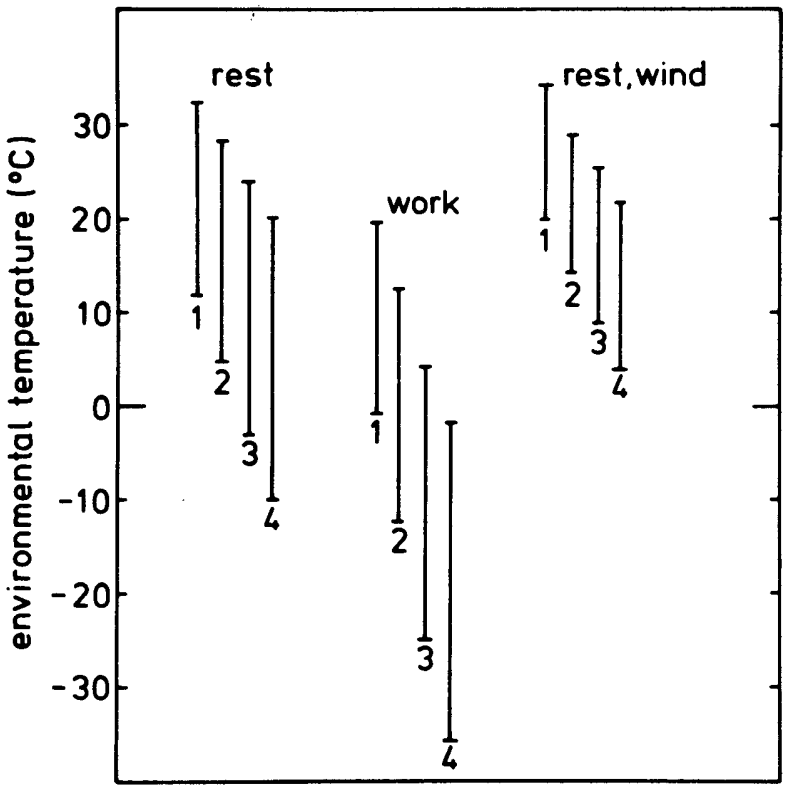


Fig. 1 Comfort range for four clothing assemblies measured during rest as well as during exercise. (Literally adopted from Havenith and Van Middendorp, 1985).

During work, the range shifts down on the temperature scale due to the increased heat production, which requires a larger gradient for the increased heat dissipation. This increased production is compensated partly, since the insulation value of any assembly will decrease during work, due to motion induced wind, but most of all due to increased convection inside the assembly. This is a feature that should be cultivated carefully, because it partly solves the problems of heat stress and moisture storage when starting work, and of post-exercise chill when ceasing work. The designer should be aware that windbreak layers in the middle of multilayer cold weather assemblies seriously reduce the internal convection. Typically, insulation during body motion may be reduced by 30% due to internal convection.

No matter how advantageous internal convection may be, it seldom will compensate entirely for increases in heat production during activity. Behavioural adjustment of clothing insulation (e.g., ventilation) will be necessary. Many attempts have been made to ventilate clothing by means of pumping effect, chimney effect or wind, using zippers, adjustable legs and sleeves or meshed ventilation holes. All of these features may help, but a good rule of thumb is that only big features help considerably.

Ventilation is mainly dependent on pumping (body motion) and wind, the latter being the strongest of the two. Unfortunately, wind is independent of the required cooling. Lotens (1985a), Crockford et al. (1972), and Shivers et al. (1977), using tracer gas techniques to measure ventilation of various types of garments, showed that about 100 $l/m^2 \cdot min$ is a practical maximum for pumping-induced ventilation. Wind may cause far more ventilation but intentional control will be required. The famous chimney effect (natural convection) hardly exists, but air space underneath the clothing makes ventilation due to pumping or wind more effective (Lotens, 1985a).

Some types of protective clothing should not be ventilated at all (e.g. CW-protective wear), whereas others may show some incompatibility between protection and ventilation. Rainwear, for instance, is difficult to ventilate while maintaining waterproofness; in this type of clothing, however, aspects of thermal comfort, heat stress and moisture storage are evidently involved. Vapour permeability of the fabric may augment the limited ventilation to transport vapour to the environment, increasing the comfort. Lotens (1985b) showed in a theoretical study that condensation inside the rainwear is difficult to avoid, when the work rate increases. Using both optimal permeability and ventilation, rainwear may stay dry up to moderately heavy work. Decreasing the heat stress will require more evaporation than currently can be achieved under these conditions.

Another aspect of comfort is the tactile property of the fabric. It is a general, but erroneous, belief that absorption of sweat is a main determinant of tactile comfort. Many non-absorbing materials such as polypropylene, polyester and polyamid may give better comfort than the highly absorbing, but slack, cotton fibre. In general, resilient fibres give the best comfort, when the structure is fine enough. In particular, microfibres will meet this requirement. Up to date, double faced underwear, consisting of a wicking but non-absorbing layer facing an absorbing layer, give surprisingly good comfort as well.

MOBILITY

The freedom of motion of clothed persons is dependent both on fabrics and construction.

Heavy fabrics will show their impact in several ways. The weight of the garment has to be carried and increases the energy cost. Weight on the extremities of the body has to be accelerated and decelerated at every step, causing an even higher increase in energy cost (Soule and Goldman, 1969). A considerable part of the weight of the clothing rests on the shoulders, being carried by the trapezoid shoulder muscles, causing a similar strain to a shoulder suspended backpack.

For these reasons weight should be as light as possible and, when inevitable, be concentrated on the trunk. This has particular significance for the distribution of insulation over the body. Preferably, the trunk should have higher insulation than the extremities, not only for the weight argument, but for reasons of cold protection as well. Exposing a subject to cold, with higher insulated trunk than extremities, the latter will cool rapidly, due to a shut off of extremity blood circulation, saving the heat for the trunk, however. As long as the extremities are not too cold to function properly, this may be an uncomfortable, but safe condition.

If the designer had distributed the insulation equally over the body, the subject would have cooled down slowly, the relatively high extremity temperature giving an impression of comfort, but with a slowly cooling trunk. At the moment of shutdown of the blood circulation, the extremities would finally start cooling, despite the insulation, leaving the subject eventually with both low extremity and trunk temperature.

When exercising in cold weather clothing, the extremities will become relatively hot, due to the disproportionate increase of the blood circulation trying to dissipate excess heat. In this case as well, low insulation at those spots will be an advantage, showing that also during heat stress uneven distribution of insulation is desirable.

For insulation, bulk is needed. Insulative materials should be regarded in this respect as a means to produce a still air layer, no matter what the nature of the material is. In this view the best material is the one that gives the highest bulk with the lowest possible fabric weight. Physically, this means that the areal density (D, kg/m^3) should be low. Density is calculated by:

$$D = \text{fabric weight/thickness}, \quad kg \cdot m^{-2} \cdot m^{-1}$$

Although insulative materials do not vary widely in specific insulation (R_{spec}, $m^2 \cdot °C \cdot W^{-1}$), there is a relationship with the density, as shown in Fig. 2. Although there are marked differences between various types of insulative material, all of them tend to higher specific insulation when increasing the density. The lower transfer of radiation as well as of convective heat with increasing density are a plausible explanations for this effect.

Dependent on the specific application, the designer could prefer high specific insulation, taking the weight for granted, or low weight, accepting the bulk of the less insulative material. For the producer, the amount of insulation that he gets out of a certain mass of raw materials is more relevant. In particular for the latter, the ratio between R_{spec} and D is a useful indicator of a material, called efficiency (Eff, $m^5 \cdot {}^{\circ}C \cdot kg^{-1} \cdot W^{-1}$):

$$Eff = R_{spec}/D$$

Table I gives a few typical figures for various materials. Efficiency values of about 1.5 should be regarded as very good.

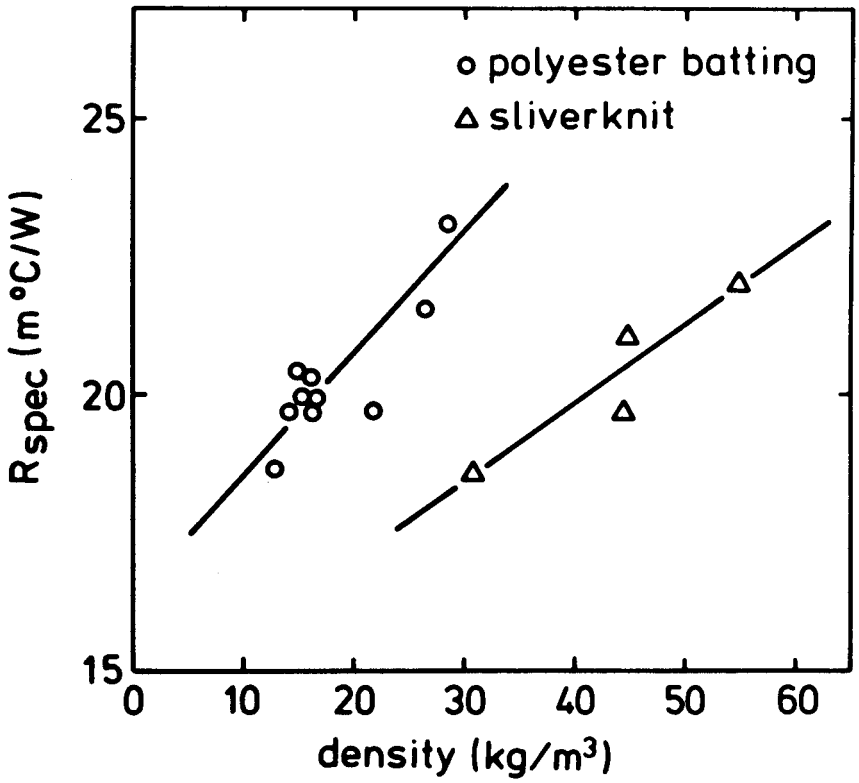


Fig. 2. Dependency of specific insulation on density for two types of insulative material (Adopted from Van Bruggen et al., 1984.)

Table I

Values for Various Materials

	R_{spec} ($m^2 \cdot {}^\circ C/W$)	D (kg/m^3)	Eff ($m^5 \cdot {}^\circ C \cdot kg^{-1} \cdot W^{-1}$)
Polyester batting	19-20	15-25	0.8-1.3
Sliverknit (pile)	18-22	40-50	0.4-0.6
Microfibre batting	26-28	15-25	1-1.5
Plain weave	30	400-500	0.1
Polyurethane foam	30	28	1

Bulk in itself is an impeding factor, like weight is. Typically, energy cost will increase by about 4% for each clothing layer, due to hobbling gait and internal friction between layers. The latter may be controlled by means of smooth liners, not only decreasing the impediment, but being easier to don and doffas well.

So far, the relation between fabric properties and mobility has been discussed. The other factor, the construction of the clothing is equally important, though of different nature. Here, the limitation of extreme movements is at issue. The impeding effect originates from the inability of the fabric to meet the stretch of the skin. When joints are bent, body tissue is stretched, the more so, the further the distance to the axis of the rotation. Obviously, the extension of the clothing must correspond to the stretch of the skin. This accomodation must be greater when the clothing is remote from the skin. Fig. 3 shows a few typical positions that might be used to check mobility, while the insert provides typical figures for the stretch of the skin in the shown positions, relative to the standing position. These figures are obtained from relatively lean young males and could considerably be exceeded with fat persons.

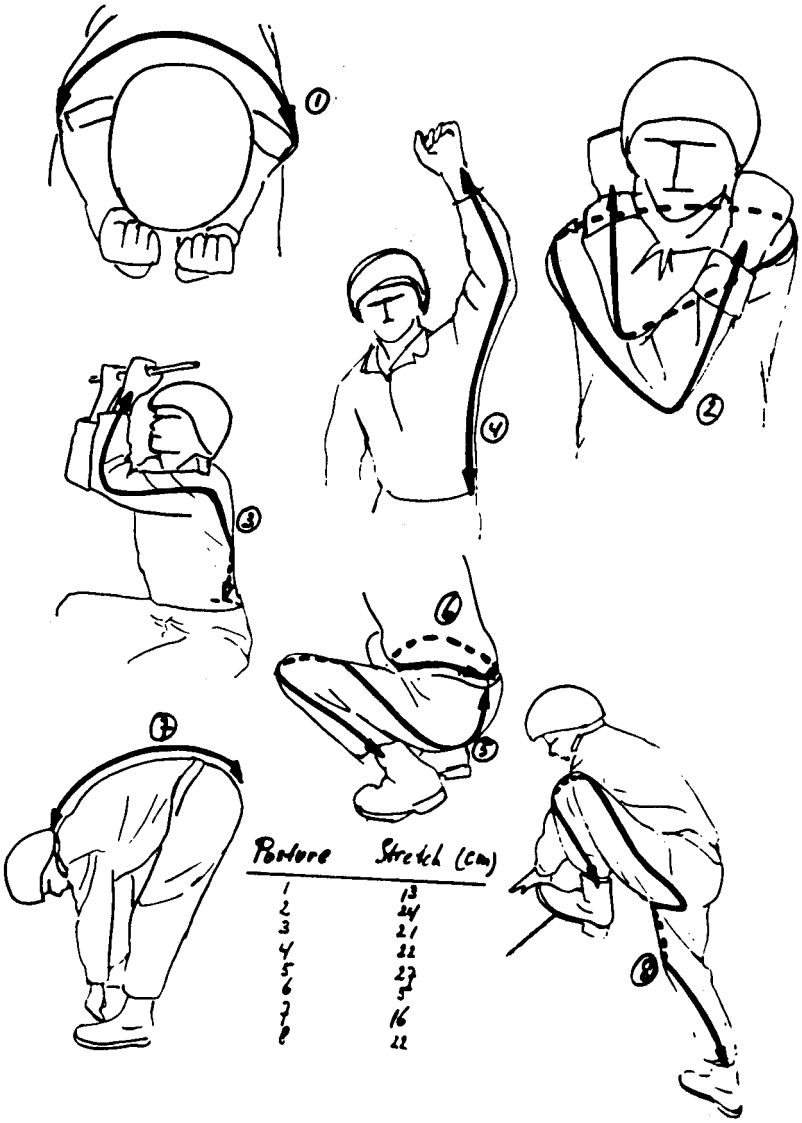


Fig. 3. Positions to check motion limitation.

The required stretch is only achievable with knitted fabrics, which is why underwear and sportswear almost invariably are made from tricot. Woven fabrics, however, demand well designed features in the clothing, that provide the required extensions in default of elasticity. It is not only the required dimension of the fabric that counts, but extra length should be available at the right spots as well. An overlength trouser-leg, for instance, will not allow squatting down, although the required total length is available: at the bended knees, the fabric is locked, blocking the necessary upward shift. This blocking is enforced by close fit and by damp textile. Fig. 4 gives some ideas for practical solutions to the motion limitation problem.

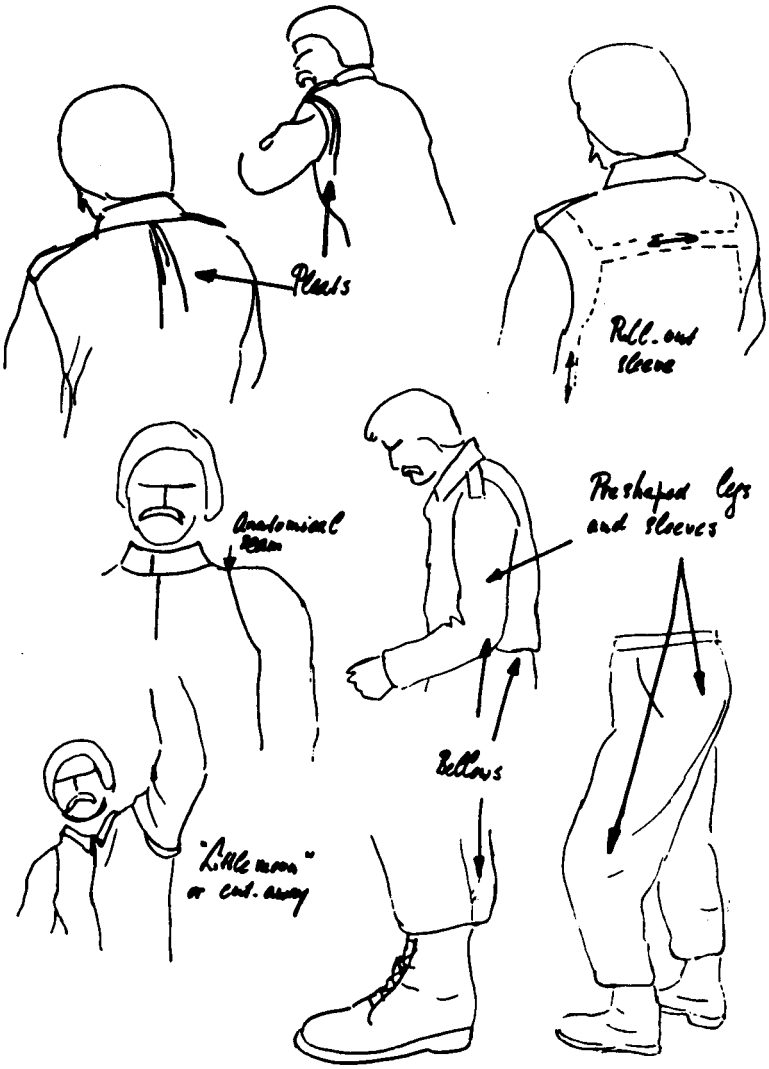


Fig. 4. Some solutions for the motion limitation problem, providing the required over-length at the right spots.

COMPATIBILITY

Clothing or equipment articles should not spoil the fine design of other articles, when worn in an assembly. This is basically what compatibility means, referring to virtually all aspects of the clothing. When selecting fabrics, this means that flexibility, weight, absorption, vapour permeability and probably some other characteristics of the various layers in an assembly should be carefully tuned. In particular, the moisture management is a complicated

matter that requires either extensive practical experience or physical simulation models (Farnworth, 1979; Lotens, 1985b), to optimize the process of wicking, absorption, evaporation and condensation inside the assembly. Such models allow the prediction of concomitant heat and moisture transmission, if necessary, even during continuously changing environmental and work conditions.

For the construction of clothing, compatibility means that the dimensions of any clothing article are adjusted to what might be worn underneath. This might be illustrated by the example of putting an insulating liner into a parka. The circumference of the body increases strongly due to the liner, typically more than six times its thickness. This should be matched in the parka, either by some size adjustment, or by inserting an extra strip of outer surface along with the liner. In general, putting clothing somewhere underneath causes problems in the design, not only for the sizing, but also for rapid alterations in insulation and donning and doffing procedures. This is particularly true when including CW protection.

The size system of the clothing should be as simple as possible. When clothing is properly designed for mobility and compatibility, it is so flexible that the number of sizes could be limited to six, covering 95% or more of the population. Trousers could come in four waist sizes, the two smaller waists in two leg lengths, the jackets in four shoulder widths, the two middle widths in two lengths. An additional merit will be that all clothing that is compatible, may have the same size number, simplifying the logistics greatly.

Typical compatibility problems at the detail level are the ventilation when wearing webbing, reaching into pockets of underlying garments, the handling of garment fasteners when wearing gloves (zippers, buttons), the stacking of collars in multilayer clothing and the junctions of gloves and boots with the garments.

EASE OF USE

All features of clothing and equipment that make the use of it easy and efficient belong to this design factor. Donning and doffing is an important aspect of handiness. Generally, two-piece garments are easier to use than overalls, since they give more freedom of motion when donning the upper piece. Anorak type jackets, that must be pulled on over the head, are less handy than jackets with a front fastening, particularly when a helmet or a respirator is worn.

Donning trousers with boots on might be attractive for over-garments, but the legs must have over-width to let the boots pass. With zippers this over-width may be eliminated, but the zip puller should be fairly large then, becoming a potential breaking point. Preferably, the zippers will be located laterally at the backside of the legs, for easy handling and minimal damage.

When applying zippers, the designer should consider the maintenance and renewal, which cannot be carried out at the first echelon. The same holds more or less for many synthetic fasteners, press buttons, hook and loop tape etc. Also, such handy materials may lose their function under snow or ice conditions. In particular, hook and loop tape may grow filthy, due to ice, dirt and loose fibres in the laundry. Fasteners of cold weather must be robust enough to be handled by gloved hands.

Pockets are a much discussed topic. Users often require more pocket space than strictly necessary. In addition to the functional pack load, personal things have to be packed up, such as notebook, pencils, drivers license, passport, handkerchief, keys, glasses, tobacco, lighter and often larger things such as a pocket heater, manual, light, etc. The designer should only cater to these wishes as long as there are no large or heavy things involved. Those ought to find their place in a load carriage system, not in the clothing where it impedes and bumps. Some armies have no other recourse than to carry pouches with ammunition in the pockets of the trousers.

A few of the best places for pockets are shown in Fig. 5. Slit pockets at the hip are not considered useful because their space is limited, while the access is blocked when sitting.

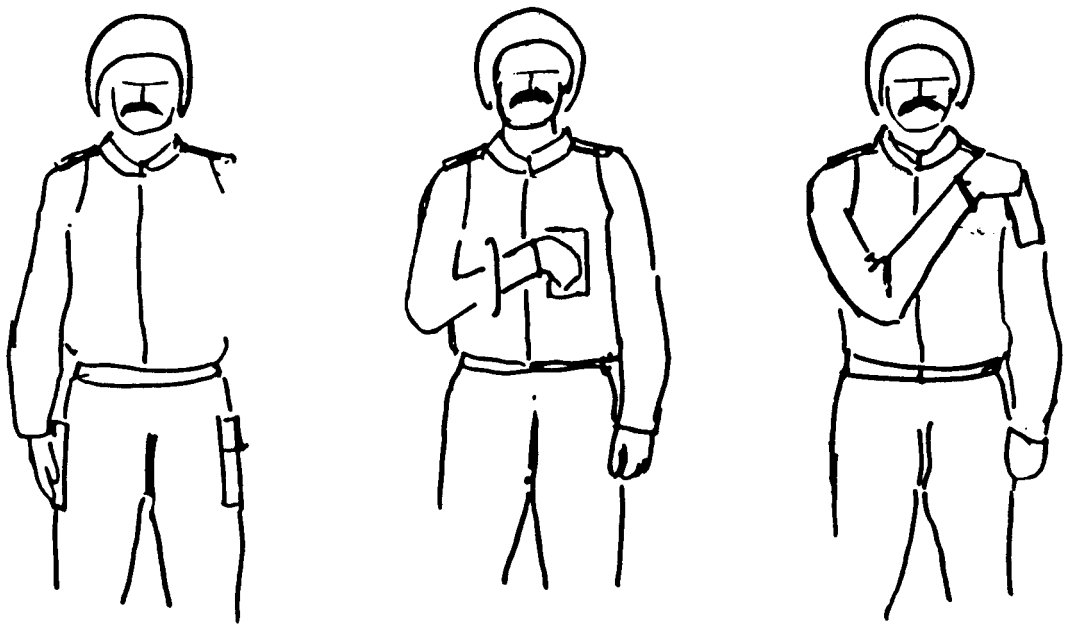


Fig. 5 Ergonomically optimal places for pockets.

When putting on additional garments, the pockets of the inner layers should still be within reach, preferably by openings in the outer layers. These could be protected from wind by means of a zipper. These zippers should open upwards for maximal protection from damage. The opening may serve to keep the hands warm as well.

Serious consideration should be given to packing, storage and carriage of clothing. Rainwear may be packed in one of its own pockets, inside out, or mounted to the belt. Other garments may be too bulky to be carried in such manner. Consequently, they should find their place in the backpack of marching infantry or in the vehicle of mechanized troops. Since in both cases the storage space is severely restricted, the number of articles of clothing as well as their compressed volume need to be small.

CLOTHING AS A SYSTEM

It is easily discerned that clothing should not be developed as separate articles, but as a system instead. Reality shows, however, that this is hard to achieve if not all articles are being redesigned at the same time. This is seldom the case, often the most out of date articles being facelifted. The compatibility problem, arising by redesigning clothing and equipment piece by piece is a major obstacle to ergonomic progress.

What must be the premise when setting up a clothing system? The forementioned design factors play an important role. Generally, the protection will be located in the shell of the assembly, the insulation in the middle and the (tactile) comfort in the innermost layer. Protection should be assured in any sensible clothing assembly, composed of the system articles. This will generally mean that the shell of any article that could be worn at the outside should meet the protection demands. This holds particularly for flammability, abrasion resistance, camouflage pattern, infrared protection, etc.

Comfort, at least the thermal aspect of it, is dependent on the right choice of the assembly for the prevailing weather. Therefore, the assemblies should be composed, as to kind of articles and insulation, based on the weather statistics. Fig. 6 gives the temperature distribution for the West-German plains as an example.

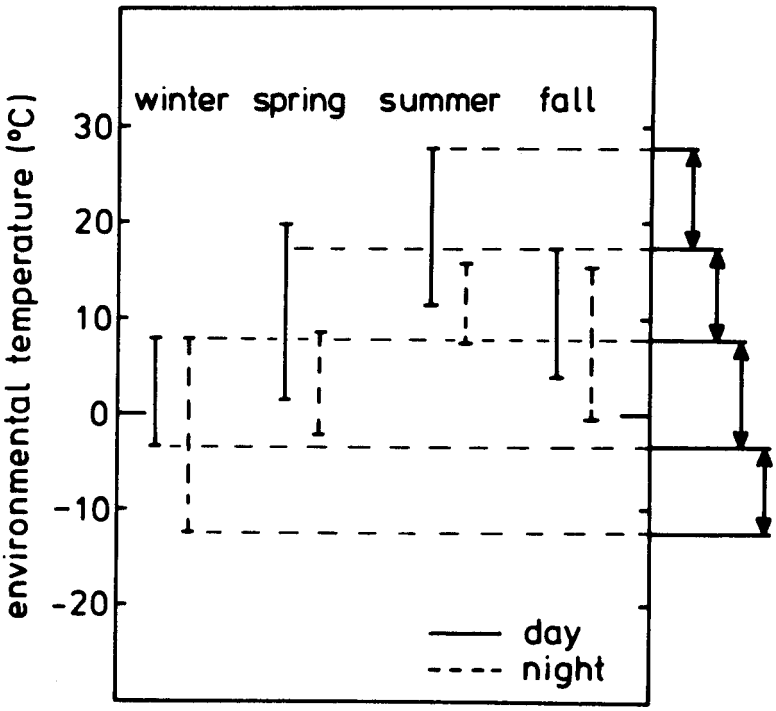


Fig. 6 Temperatures for the West-German plains during the seasons, both for day and night, divided in four ranges.

The total temperature range requires several assemblies but too many assemblies should be avoided, both because of the inconvenience of changing and of the storage problem of clothing that is not in use. The temperature distributions of Fig. 6 are cut into four

temperature ranges, corresponding with four clothing assemblies, that will seldom require more than one change over a short period. Of course, other weather aspects (precipitation, wind, sun) and the changes in work rate both have their impact on the required kind of clothing articles as well as on their design. In particular ventilation of early responding sweat areas (armpits, torso) and cooling of wrists and ankles, optimal ways for adjustment of heat loss, should be considered and, if applied, not be hampered by additional clothing of other assemblies.

The latter aspect already belongs to the compatibility. A major determinant here is the sizing. When clothing is worn, the outer layers must give room to the inner layers, without being oversize when worn separately. Since bulky outer layers demand more stretch in extreme positions than central layers, the sizing problem is even more acute. Often, adjustable sizing is required. Other typical compatibility problems are, in addition to the already mentioned stack of collars and junctions at wrist and ankle, the bulk in the armpit and crotch, and the use of hoods.

Various clothing system models may meet the specified requirements more or less. Roughly, there are three basic models:

– Onion model. In any new assembly, layers are added at the outside. The advantage is that there is no size problem and that changing is easy. However, in cold weather assemblies internal convection will be hampered and impediment of motion will be likely due to the stack of protective shell fabrics.

– Substitution model. Any assembly consists of just one article; i.e., it interchanges for another when changing assemblies. Here, the design for ventilation and freedom of motion could be optimal, but there is a storage as well as a change problem. Should be restricted to use at fixed locations.

– Binary model. Layers are combined in any way to give the correct insulation. This model adds the disadvantages of the two preceding models to the lack of free choice of psychrometric range for any assembly. It has the big advantage, however, that an extremely small number of clothing articles is required when many assemblies are necessary, for instance in a typical land climate. Required number of clothing articles is two for three assemblies, three for up to seven assemblies, compared to three for three assemblies and seven for seven assemblies in the other models.

Of course, intermixing of these models and variations (putting clothing underneath) are possible. The presented models give firstly an idea for the large framework.

THE MOST OPTIMAL DESIGN PRINCIPLE

In this paper many problems have been addressed which attempt to convey an understanding of physiologic and ergonomic problems relating to optimal design principles. Some problems are small and easy to overcome, others are almost unsolvable. The extent to which qualitative solutions indeed solve the problems is unknown, however, in many cases. As a good rule of thumb, the most optimal design principle therefore is that large problems require large measures. Too often, the requirements are being underestimated, for instance the thickness of clothing to obtain the required insulation, the oversize needed for freedom of movement and the amount of ventilation necessary to stay dry inside. One of the best examples of the underestimation of required ventilation is the well-known three little holes in the armpit of rainwear, where the magnitude of the measure is at least a factor of a hundred, out of proportion with the magnitude of the solution.

REFERENCES

1. Bruggen, E.J.G. van, and Wammes, L.J.A. (1984). Heat transmission through some insulative materials (in Dutch). Report TNO Institute for Perception, 1984-M25.

2. Crockford, G.W., Crowder, M., and Prestige, S.P. (1972). A trace gas technique for measuring clothing microclimate air exchange rates. Brit. J. Industr. Med. 29, 378-386.

3. Farnworth, B. (1979). Calculations of combined heat and vapour transport through clothing systems: Application to water vapour permeable rainwear. DREO tech. note 79-16.

4. Lotens, W.A. (1983). First semi-annual progress report on project no. TEX 23 NL, (N). Report TNO Institute for Perception 1983-16.

5. Lotens, W.A. (1985a). The effects of wind, motion and design of rainwear on air exchange. Report TNO Institute of Perception, (in press).*

6. Lotens, W.A. (1985b). Balancing vapour permeability of rainwear against ventilation: a theoretical study. Report TNO Institute for Perception, (in press).**

7. Shivers, J.L., Yeh, A., Fourt, L. and Spivak, S.M. (1977). The effect of design and degree of closure on microclimate air exchange in light weight cloth coats. In: Clothing Comfort, Hollies and Goldman (Eds.). Ann Arbor Science, Ann Arbor, ME.

8. Soule, R.G., and Goldman, R.F. (1969). Energy cost of loads carried on the head, hands, or feet. J. Appl. Physiol. 27, 687-690.

---

* contained in: Lotens, W.A., and G. Havenith (1988) Ventilation of rain-wear determined by a trace gas method. In: Environmental Ergonomics. Mekjavics, Bannister, Morrison Eds., Taylor and Francis, Philadelphia, pp 162-175.

** contained in: Lotens, W.A. (1993) Heat transfer from humans wearing clothing. Ph.D. Thesis, Delft University of Technology, February 1993, Delft.

APPENDIX CHAPTER

CONVERSION UNITS COMMON TO BIOMEDICAL RESEARCH ON MILITARY CLOTHING

R. R. Gonzalez

CONTENTS

SUMMARY

INTRODUCTION

CONVERSION FACTORS
- Length or Area
- Temperature
- Force
- Power
- Pressure
- Energy
- Torque or Moment
- Speed or Volume Flow Rate
- Volume or Concentration
- Mass
- Energy/(Area-Time)
- Heat Flux (q/A)
- Heat Transfer Coefficient (h)
- Thermal Conductivity
- Dynamic Viscosity
- Kinematic Viscosity
- Clothing Resistance
- Constants
- Gas Constants
- Specific heat of air
- Specific heat of water

REFERENCES

SUMMARY

Several conversion units familiar to personnel working in the general area of biophysical properties of clothing and thermal physics are arranged so that they can be easily transposed into metric units. Some of the basic units also found in the Système international d'unités (SI) have been defined and categorized to help the reader have a faster access towards metrication.

Key Words: SI units, metrication, clothing units

INTRODUCTION

This appendix chapter is set up slightly different from regular glossaries using SI in that conversion factors for familiar units and some obsolete terms (i.e. mm Hg) are also included. In SI, one and only one unit is acceptable for each physical quantity. It became apparent in the reading and preparation of this handbook that the chapters were filled with familiar units (such as $kcal \cdot min^{-1}$ or clo) which authors were reluctant to transpose to SI. It is hoped that this chapter clarifies for readers most of the conversions from common to SI units. The glossary does not include conversion units for the luminous flux (lumen, SI) or sound pressure level. More extensive guides are found in refs (1-4).

In the SI, approved units are as follows:

Angle. The correct unit for the plane angle is the radian. The degree (°) and its decimal fractions may be used but use of minute and second is discouraged.

Area. The SI unit of area is the square meter (m^2). Large areas are expressed as hectares (ha) or square kilometres (km^2). The hectare is restricted to land or sea area and is equal to 10000 m^2.

Energy. The correct unit in SI is the joule (J). The kilowatt hour (3.6 megajoules) is widely used as a measure of electric energy. However, kilowatt hour will be replaced by megajoules or gigajoule so kWh is discouraged in new applications.

Force. The correct SI unit of force is the newton (N). Do not use the word weight or kilogram force. The newton is used also in combination units which also encompass units of force such as:

pressure or stress, $N \cdot m^{-2}$ = Pa (pascal)
work, $N \cdot m$ = J(joule)
power, $N \cdot m \cdot s^{-1}$ = W(watt)

Mass. The unit of mass in SI is the kilogram (kg). Among the base and derived units of SI, this unit is the only one with a prefix. Names of decimal multiples or sub multiples of the unit mass are formed by attaching prefixes to the word gram. The word weight should not be used as this could be confused with force.

Pressure. The correct unit of stress or pressure (which is force per unit area) is the newton per square metre. This unit has been given the special name pascal (Pa). No other units are acceptable in SI.

Temperature. The correct unit of temperature is kelvin (K, not deg K or °K). The thermodynamic temperature (called absolute temperature) is related to Celsius as follows (4):

$t = T - T_0$, where t = degrees Celsius (C)
T = the given thermodynamic temperature (K)
T_0 = 273.15 K by definition.

Time. In SI, the correct unit of time is second. Do not use minute or hour. In some cases of long cycles, day, week, month or year are used.

Exceptions: revolutions per min may be used but revolutions per second is the SI unit; beats per min may be used but frequency (cardiac) s^{-1} is the SI unit.

Volume. The correct SI unit for volume is the cubic metre (m^3). The cubic decimetre which has a special name – litre (ℓ) – is a regularly used submultiple of m^3. This is the correct SI unit to replace gallon or cubic foot. Litre per second thus replaces gpm or cfm. A smaller correct SI unit is the millilitre per second ($ml \cdot s^{-1}$). The litre is restricted for use only with liquids and gases and for volume of a vessel.

Finally, in SI, complex unit symbols are written with either parentheses or with exponents interchangeably.

Example: for oxygen consumption ($\dot{V}O_2$) the correct SI might be expressed as cubic metre per kilogram per second $m^3/(kg\text{-}s)$ or $m^3 \cdot kg^{-1} \cdot s^{-1}$. Both forms are equally acceptable.

D. CONVERSION FACTORS

TO CONVERT	MULTIPLY BY	TO OBTAIN
	LENGTH OR AREA	
acre (a)	0.405	hectare (ha)
foot (ft)	0.3048	metre (m) (exact conversion)
inch	25.4	mm
mile	1.61	kilometre (km)
mile, nautical	1.85	km
yd	0.9144	m
square (100 sq ft)	9.29	m^2
yd^2	0.836	m^2
yd^3	0.765	m^3
bolt (U.S. cloth)	36.58	m
bolt	120	ft
centimetre (cm)	$1 \cdot 10^{-5}$	km
centimetre (cm)	$1.09 \cdot 10^{-2}$	yd
centimetre (cm)	10000	micron
centimetre (cm)	$1.0 \cdot 10^{8}$	angstrom unit
hand	10.16	cm
	TEMPERATURE	
°C + 273.15	1.0	absolute (K)
°C	(°C * 1.8)+ 32	temperature (°F)
°F-32	5/9	°C
°F + 460	1.0	absolute (°R)
°F + 40	5/9	°C + 40
°C + 40	1.8	°F + 40

TO CONVERT	MULTIPLY BY	TO OBTAIN
	PRESSURE	
bar	100	kPa (exact conversion)
in Hg	3386.4	$N \cdot m^{-2}$
in H_2O	248.8	$N \cdot m^{-2}$
mmHg, (20 °C)	133.3	$N \cdot m^{-2}$
mmHg, (20 °C)	0.13332	kPa
mm H20 (20 °0	9.80	Pa
millibar	0.100	kPa
m H_2O	9.80	kPa
atmospheres	76	cm Hg (at 0 °C)
atmospheres	29.92	in Hg (0 °C)
atmospheres	1.058	$ton \cdot ft^{-2}$
atmospheres	14.7	$lb \cdot in^{-2}$
atmospheres	1.0333	$kg \cdot cm^{-2}$
bar	0.9869	atmospheres
bar	$1 \cdot 10^{6}$	$dynes \cdot cm^{-2}$
bar	$1.02 \cdot 10^{-4}$	$kg \cdot m^{-2}$
bar	14.5	$lb \cdot in^{-2}$
bar	$1 \cdot 10^{5}$	$N \cdot m^{-2}$
dyne-centimetre	$1.02 \cdot 10^{-3}$	cm-g
dyne-centimetre	$7.376 \cdot 10^{-8}$	ft-lb
cm Hg	$1.316 \cdot 10^{-2}$	atmosphere
psi	6.89	kPa
Torr (1 mmHg at 0 °C)	133.322	Pa
Torr (1 mmHg at 0 °C)	$1.33 \cdot 10^{-3}$	bar
$dyne \cdot cm^{-2}$	0.100	Pa
Pa	$7.5 \cdot 10^{-3}$	Torr (name of unit is torr)
kPa	7.5	Torr

TO CONVERT	MULTIPLY BY	TO OBTAIN
	FORCE	
kilogram force (kgf)	9.807	newton (N)
kilopond force (kpf)	9.807	N
pound force (lbf)	4.45	N

TO CONVERT	MULTIPLY BY	TO OBTAIN
	POWER	
Btu per min ($Btu \cdot min^{-1}$)	17.58	watt (W)
calorie per second ($cal \cdot s^{-1}$)	4.187	W
horsepower (550 ft·lb/s)	0.746	kW
kilocalorie per h ($kcal \cdot h^{-1}$)	1.163	W
kilopond metre per min ($kpm \cdot min^{-1}$)	0.1634	W
$Btu \cdot h^{-1}$	0.2931	W
$Btu \cdot h^{-1}$	0.07	$cal \cdot s^{-1}$
$Btu \cdot h^{-1}$	0.2162	$ft \cdot lb \cdot s^{1}$
ft·lbf/min	0.0226	W
horsepower	10.69	$kcal \cdot min^{-1}$
horsepower	0.7457	kW
horsepower	745.7	W

TO CONVERT	MULTIPLY BY	TO OBTAIN
	ENERGY	
British thermal unit (Btu)	1055.1	joule (J)
calorie (cal)	4.187	joule (J)
foot-pound (ft-lb)	1.3558	J
kilocalorie	4.187	kJ
Btu	$1.055 \cdot 10^{10}$	ergs
Btu	$7.7816 \cdot 10^{2}$	foot-pound
Btu	252	cal
calorie	$3.9683 \cdot 10^{-3}$	Btu
ft·lbf/lb (specific energy)	2.99	$J \cdot kg^{-1}$
therm (U.S.)	105.5	MJ
therm (U.S.)	$1 \cdot 10^{-5}$	BTU
calorie	$1.163 \cdot 10^{-3}$	W·h
ft·lb (work)	1.36	J
W·s	1	J
W·h	3600	J
joule(J)	$2.778 \cdot 10^{-4}$	W·h

TO CONVERT	MULTIPLY BY	TO OBTAIN
	TORQUE OR MOMENT	
ft·lbf (torque)	1.36	N·m

TO CONVERT	MULTIPLY BY	TO OBTAIN
	SPEED OR VOLUME FLOW RATE	
foot per min, fpm	0.00508	$m \cdot s^{-1}$
foot per sec, fps	0.3048	$m \cdot s^{-1}$
kilometre per hour, $km \cdot h^{-1}$	0.2778	$m \cdot s^{-1}$
mile per hour, mph	0.447	$m \cdot s^{-1}$
mph	0.8689	knots
ft^3/h, (cfh)	7.87	$m\ell \cdot s^{-1}$
ft^3/min (cfm)	0.472	$\ell \cdot s^{-1}$
gal per h (gph) U.S.	1.05	$ml \cdot s^{-1}$
gal per min (gpm) U.S.	0.0631	$\ell \cdot s^{-1}$
knots	1.852	$km \cdot h^{-1}$
knots	51.44	$cm \cdot s^{-1}$

TO CONVERT	MULTIPLY BY	TO OBTAIN
	MASS	
gram	0.03527	ounce (avdp)
gram	0.03215	oz (troy)
gram	$2.205 \cdot 10^{-3}$	pound
ounce (mass, avoir)	28.3	g
lb	453.6	g
stone	14.0	Lb

TO CONVERT	MULTIPLY BY	TO OBTAIN
	VOLUME OR CONCENTRATION	
m^3	$2.642 \cdot 10^2$	gal
m^3	1000	ℓ
ft^3	28.32	ℓ (liter)
ft^3	0.0283	m^3
gal	$3.785 \cdot 10^{-3}$	m^3
gal	3.785	ℓ
gal H_2O (U.S.)	8.337	pounds H_2O
gal (British)	1.20095	gal (U.S.)
ℓ	0.2642	gal(U.S)
ℓ	1.057	quart (U.S.)
$mg \cdot ℓ^{-1}$	1.0	ppm
$mg \cdot kg^{-1}$	1.0	ppm
tablespoon	15	ml
teaspoon	5	ml
pint (liquid)	473	ml
in^3 (volume)	16.4	ml
quart (liquid)	0.946	ℓ
oz	29.6	mℓ
m^3/s	$6.0 \cdot 10^4$	$ℓ \cdot min^{-1}$ ($\dot{V}_{O_2}$)

TO CONVERT	MULTIPLY BY	TO OBTAIN
	ENERGY / (AREA•TIME)	
Btu per sq foot and hr ($Bt/(ft^2 \cdot h)$)	3.1546	$W \cdot m^{-2}$
$kcal/(m^2 \cdot h)$	1.163	$W \cdot m^{-2}$
$Btu/(ft^2 \cdot min)$	$1.22 \cdot 10^{-1}$	$W \cdot in^{-2}$

TO CONVERT	MULTIPLY BY	TO OBTAIN
	HEAT FLUX (q/A)	
$Btu \cdot ft^{-2} \cdot h^{-1}$	$3.154 \cdot 10^{-4}$	$W \cdot cm^{-2}$
$kcal \cdot h^{-1} \cdot m^{-2}$	$1.163 \cdot 10^{-4}$	$W \cdot cm^{-2}$
$cal \cdot s^{-1} \cdot cm^{-2}$	4.1868	$W \cdot cm^{-2}$
$W \cdot cm^{-2}$	8598	$kcal \cdot h^{-1} \cdot m^{-2}$
$W \cdot cm^{-2}$	3170.75	$Btu \cdot ft^{-2} \cdot h^{-1}$
$W \cdot cm^{-2}$	0.2389	$cal \cdot s^{-1} \cdot cm^{-2}$
$Btu \cdot ft^{-2} \cdot h^{-1}$	3.155	$W \cdot cm^{-2}$

TO CONVERT	MULTIPLY BY	TO OBTAIN
	HEAT TRANSFER COEFFICIENT (h)	
$Btu \cdot ft^{-2} \cdot h^{-1} \cdot °F^{-1}$	$5.6785 \cdot 10^{-4}$	$W \cdot cm^{-2} \cdot K^{-1}$
$kcal \cdot h^{-1} \cdot m^{-2} \cdot °C^{-1}$	$1.163 \cdot 10^{-4}$	$W \cdot cm^{-2} \cdot K^{-1}$
$cal \cdot s^{-1} \cdot cm^{-2} \cdot °C^{-1}$	4.186	$W \cdot cm^{-2} \cdot K^{-1}$
$Btu \cdot ft^{-2} \cdot h^{-1} \cdot °F^{-1}$	4.8826	$kcal \cdot h^{-1} \cdot m^{-2} \cdot °C^{-1}$
$W \cdot cm^{-2} \cdot K^{-1}$	8600	$kcal \cdot h^{-1} \cdot m^{-2} \cdot °C^{-1}$
$Btu \cdot ft^{-2} \cdot h^{-1} \cdot °F^{-1}$	5.68	$W \cdot m^{-2} \cdot K^{-1}$

TO CONVERT	MULTIPLY BY	TO OBTAIN

THERMAL CONDUCTIVITY (k)

$Btu \cdot h^{-1} \cdot ft^{-1} \cdot °F^{-1}$	0.0173	$W \cdot cm^{-1} \cdot K^{-1}$
$Btu \cdot in \cdot h^{-1} \cdot ft^{-2} \cdot °F^{-1}$	$1.442 \cdot 10^{-3}$	$W \cdot cm^{-1} \cdot K^{-1}$
$kcal \cdot h^{-1} \cdot m^{-1} \cdot °C^{-1}$	0.01163	$W \cdot cm^{-1} \cdot K^{-1}$
$cal \cdot s^{-1} \cdot cm^{-1} \cdot °C^{-1}$	4.186	$W \cdot cm^{-1} \cdot K^{-1}$

TO CONVERT	MULTIPLY BY	TO OBTAIN

DYNAMIC VISCOSITY (u)

$lb \cdot ft^{-1} \cdot h^{-1}$	0.413	$mPa \cdot s$
$lbf \cdot s \cdot ft^{-2}$	47900	$mPa \cdot s$
centipoise	2.42	$lb \cdot ft^{-1} \cdot h^{-1}$
centipoise	3.6	$kg \cdot m^{-1} \cdot h^{-1}$
centipoise	1.00	$mPa \cdot s$

TO CONVERT	MULTIPLY BY	TO OBTAIN

KINEMATIC VISCOSITY (υ)

$ft^2 \cdot s^{-1}$	92900	$mm^2 \cdot s^{-1}$
$ft^2 \cdot h^{-1}$	0.092903	$m^2 \cdot h^{-1}$
stokes	0.3600	$m^2 \cdot h^{-1}$

TO CONVERT	MULTIPLY BY	TO OBTAIN
	CLOTHING RESISTANCE	
tog	0.645	clo
clo	1.55	tog
clo	0.155	$m^2 \cdot K/ W$
tog	0.1	$m^2 \cdot K/ W$
clo	200	$s \cdot m^{-1}$
clo	2	$s \cdot cm^{-1}$

TO CONVERT	MULTIPLY BY	TO OBTAIN
	OTHER	
radians	57.296	degrees
radians	$3.438 \cdot 10^3$	minutes
radians/s	57.296	$deg \cdot s^{-1}$
radians/s	9.549	$rev \cdot min^{-1}$
steradians	$3.283 \cdot 10^3$	square·degree

GAS CONSTANTS

R = 8.314·kJ/(kg-mol·K) = 0.0821 (atm)(ℓ)/(g-mol·K)

air (R_a) = 0.287 $kJ \cdot kg^{-1} \cdot K^{-1}$

water vapor (R_w) = 0.462 $kJ \cdot kg^{-1} \cdot K^{-1}$

SPECIFIC HEAT OF AIR

dry air

constant pressure c_p = 1.006 $kJ \cdot kg^{-1} \cdot K^{-1}$

constant volume c_v = 0.717 $kJ \cdot kg^{-1} \cdot K^{-1}$

moist air = 1.024 $kJ \cdot kg^{-1} \cdot K^{-1}$ (for 10 g moisture per kg dry air)

WATER

heat of vaporization at 101.325 kPa (760 Torr) and 30 °C

2426 kJ/kg

0.674 W·h/g

1. 16.7 g/min is normal human limit (1 g sweat ≈ 1 ml H_2O)
   a. 16.7·60 = 1002 mℓ h^{-1} or 1 canteen/h
   b. 20·60 = 1200 mℓ·h^{-1} or 1.2 canteen/h

2. In 1-a, 1 ℓ·h^{-1} is about 674 watts per person; in 1-b, 1.2 ℓ·h^{-1} is about 816 watts per person based on latent heat constant of 0.674 W·h/g.

General Antoine eq: Saturated vapor pressure (P,t)

P,t = exp (16.6536 - 4030.183/t + 235), kPa
= exp (18.6686 - 4030.183/t + 235), Torr.

heat of fusion at 0 °C

335 kJ/kg

REFERENCES

1. Lowe, D.A. A guide to international recommendations on names and symbols for quantities and on units of measurement. WHO (ISO) Geneva, 1975 314 pp..

z. Bligh, J and K.G. Johnson. Glossary of terms for thermal physiology. J. Appl. Physiol. 35: 941, 1973.

3. American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) Metric Guide, 1978.

4. CRC Handbook of Chemistry and Physics, 67th Edition. (R.C. Weast, ed-in-chief). CRC Press, Inc. Boca Raton, FL, 1987.