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HEAT AND MOISTURE TRANSFER THROUGH FABRICS: BIOPHYSICS OF CLOTHING

by

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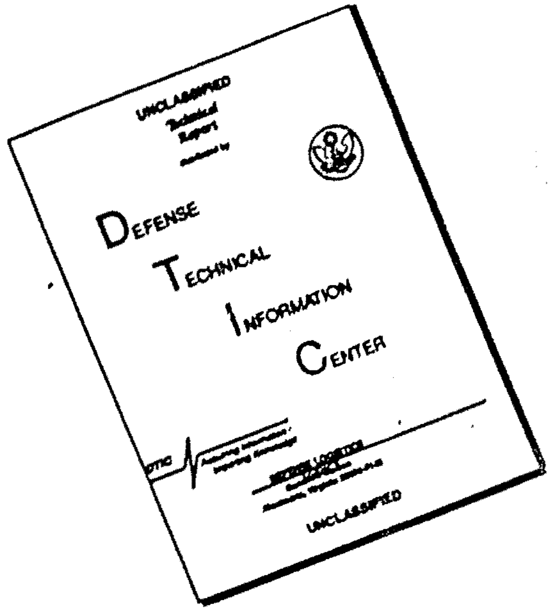

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FOREWORD

This is a continuing study covering the Evaluation of Experimental Fabrics as Alternates for Standard Wool Fabrics.

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This material is taken from contract Report No. 30 for the quarter ending November 18, 1958, the fourth quarter of the contract.

INVESTIGATION OF PROPERTIES OF SYNTHETIC FIBERS IN BLENDS WITH WOOL

Contract No. DA-19-129-QM-1073
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HARRIS RESEARCH LABORATORIES, INC.
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HEAT AND MOISTURE TRANSFER THROUGH FABRICS: BIO-PHYSICS OF CLOTHING

SUMMARY

There is need and growing opportunity to fill in the gap between physiological studies of human work efficiency or comfort in relation to the task and environment, on one hand, and physical studies of textiles and the environment on the other hand.

These cross-boundary studies between physiology, physics, and textile science, can be grouped in four main classes:

Contents:

I. Influence of clothing on the heat balance of the body,
II. Influence on the sense of touch and other senses.
III. Influence on mobility or support of the body,
IV. Other interventions between body and environment,

Going further, each of these classes is divided into more specific parts, with examples of problems on which information is currently needed, which can be usefully attacked by means which are available. Certain other problems which would require development of techniques are also indicated. A list of these precedes the general discussion.

LIST OF PROBLEMS DISCUSSED

I. HEAT BALANCE

Relation of tests on the whole man to physical tests.
Mathematical analysis and physical data.
Wicking, blotting, and the special features of wool.
Vapor barriers in clothing.
Microdistribution of water.
Combined flow of heat and moisture.
Heat effects of adsorption of moisture.
Heat of adsorption as an inertia effect.
Heat loss by radiation.

II. SENSE OF TOUCH AND OTHER SENSES

Fabric surfaces.
Fabrics as structures.
Forces across the thickness of the fabric.
Electrical effects.
Water holding capacity, skin contact and drag.

III. INFLUENCE ON MOBILITY OR SUPPORT OF THE BODY

Energy cost of loads or restraints.
Fatigue sparing effects.
Effects of continuous pressure or restraint.
Low pressure environments; anti-G suits, ventilated or heated clothing.
Clothing design in relation to wicking and ventilation.

IV. OTHER WAYS IN WHICH CLOTHING INTERVENES BETWEEN THE BODY AND THE ENVIRONMENT

Wind penetration.
Rain, mist, droplets, particles.
Biophysics of "bulletproof" vests.
Special problems of vision, hearing, face, and hands.
Sunlight and heat effects of nuclear weapons.
Industrial heat problems, fire fighting, and hot environments.
Absorptive, transmissive properties of fibers.

I. HEAT BALANCE

Relation of tests on the whole man to physical tests:

The work of many physiologists, and especially that of Rubner, Du Bois, Winslow, and Herrington, has shown that the heat balance of the body can be completely accounted for in terms of measurable physical quantities. Much has been and much more needs to be accomplished by studies on the whole man involving environment, clothing, task, and rate of activity. However, the role of individual items of clothing or types of fabric tends to be diluted in whole man tests, because of the availability of alternate methods of heat balance through other areas, such as the face, the lungs, or the extremities. Hence whole man tests of clothing or equipment tend to be feasibility tests, and, while indispensable for assessing effects on body movement and task performance are poorly suited to comparing clothing structures as such. The task of finding the optimum balance of components of clothing in different areas can be guided by tests on the separate components, at great savings of time, money, and utilization of complex whole man test facilities.

A necessary condition in order that physical testing of separate parts shall correlate well with whole man testing is that the physical testing shall realistically combine the two chief modes of heat transfer, direct heat flow down a temperature difference, and heat loss by evaporation of sweat. These interact because the water which is secreted at the skin may either wick into the clothing, or evaporate at the skin and condense in the clothing. Once in the clothing, water changes not only the heat capacity and the thermal conductivity of the clothing, but also the vapor pressure differences and temperature differences which govern both heat and vapor loss.

Mathematical analysis and physical data:

There is need for advanced mathematical study based on the differential equations of the interacting flow of heat and water vapor or water, and for experimental study of the amounts of water present, the temperatures, and vapor pressures at different levels in the clothing under realistic and widely ranging conditions. Computer techniques are probably required for best application of the mathematical analysis, but much progress is needed in finding the physical limits justifying the simplifying assumptions required for even computer handling. However, a simplified approach using the principles of multiple plate distillation, as handled for chemical engineering purposes, could be instructive. Hottel and Chen's work at MIT on the propagation of pulses of heat in clothing can probably be modified to apply to normal changes of heat production in normal environments. Woodcock at the Quartermaster Laboratories at Natick has proposed electrical analog methods which should be tested more extensively, and fitted to physical data obtained either in whole man or physical tests. A beginning on the measurement of water contents in real clothing situations has been made by the Quartermaster, in such studies as the Mt. Washington field test of vapor barriers in clothing and in many others, as recently discussed by Vanderbie. Actual field tests, or tests in climatic chambers are essential to resolve the question of the amount of water really present during use of clothing, thus throwing light on the question of wicking or transport of liquid water.

Wicking, blotting, and the special features of wool:

Even under summer conditions, with clothing made of fibers (such as cotton) which wick readily, the extent of spread of sweat in the layers of fabric is relatively small. There is reason to believe that in winter clothing assemblies the amounts of water in individual layers seldom rise to the levels required for extensive spreading by wicking within a layer. The levels required for layer-to-layer transport of liquid water, which might be called blotting, as a special type of wicking, are even less often found in winter clothing. In fact, fabrics of the kinds used in Army winter clothing must be "wringing wet" and very firmly pressed together to transfer water by blotting, from one layer to the next. Nevertheless, this low level of wicking and blotting may be "accidental," in the sense that it is an "uncovenanted blessing" arising from the kinds of fibers used, the particular degree of wettability of these fibers, the degree to which they hold their springiness while wet or moist, and other factors, which are unlikely to come together for other choices of fibers and fabric manufacturing processes.

The fact that most Army fabrics for winter use contain a large proportion of wool is probably important, in securing a special combination of hairy fabric surface and randomness of fiber-to-fiber contact which are difficult to obtain with other fibers. The study of the special features which distinguish wool yarns and fabrics from those made from other fibers has been carried on extensively in several laboratories, and is of importance for better understanding and utilization of wool itself, as well as for its conservation in emergency, by best use of wool blends and other fibers. Parallel studies of the effects of other fibers and of the whole range of yarn and fabric structure are accumulating, and are proving useful to both fiber producers, and experimentally minded fabric manufacturers.

Vapor barriers in clothing:

A fascinating possibility, which is only imperfectly reduced to practice, is the use of vapor barriers in selected portions of clothing. The general idea is that the thermal insulating power of clothing can be kept higher if most of it is kept dry, while the water passage is either prevented, or localized in certain areas. One design is illustrated by small holes each perhaps half an inch in diameter, spaced at three inch intervals, as in polyethylene bags for vegetables; another is complete coverage of, say, the trunk, with no barriers on the limbs. The selection of areas, and the degree of impermeability required, as well as the practical means of doing it, remain to be worked out in many details. Possibly the new microporous plastic films, which permit some passage of water vapor but no passage of liquid water, may be useful here.

Microdistribution of water:

More emphasis than in the past should be placed on the distillation of vapor from layer to layer, and on the influence of the temperature as it changes through the thickness of the clothing on the condensation of moisture within the layers and each single layer. The water chemically adsorbed within the fibers is only part of the picture; consideration of this "non-liquid" water needs to be combined with a micropicture of the location of the "liquid" water. This micropicture depends as much on the number and type of fiber-to-fiber contacts, and the detailed surface structure of the fibers, as on the wettability or contact angles. Thus, Schwartz at Harris Research Laboratories has shown that the ridges and valleys on the surface of usual viscose rayon promote capillary flow along the surface of the individual fibers, while the smooth surfaces of other man-made fibers, together with the instability of a long cylindrical form for liquids causes liquids to stand in separate drops on such fibers, like the beads of dew on a spider web.

While a great deal of work has been done by and for the Quartermaster on capillary flow where the fabric dips into and can become saturated by water, much more is needed on the sub-flow range of water content since this corresponds to a wide range of clothing conditions. Hollies in work done for the Quartermaster at Harris Research Laboratories has shown that there are several possible types of distribution of liquid water in fabrics, depending on the chemical nature and type of fiber, and its physical micro-orientation with respect to other fibers and the fabric plane. The studies of fiber geometry in yarns at Fabric Research Laboratories and at MIT, and of elementary fiber capillarity by Schwartz at Harris Research Laboratory, together with studies on absorbency at DuPont, Personal Products Corporation, and elsewhere provide the jump-off point for a detailed study of water distribution in textiles at the micro-structure level.

Techniques are at hand to make a beginning. Water distribution can be seen with low power, deep field microscopes, or can be inferred from the locations of deposit of soluble dyes which are not absorbed by the fiber. Alternatively, particles of water soluble dyes can be applied to the fibers before spinning, to form a water-sensitive layer, like those used in dip and paint children's color books in which the color is brought out by using water alone on the brush. Application after fabric formation may be possible, but involves the hazard that the distribution will be governed by the drying of the medium used to suspend the particles of dye. This is particularly unfortunate, since typical wool fabric structures, a most important class, are only developed by wet processing. A possibility is that the water can be held in place in the fabric by freezing, followed by appropriate techniques to show where the water was located.

This rather laborious effort on the details of microdistribution of water in fabrics is important for rational understanding of the differences between different types of fabric structures, such as the relatively loose and random arrangement of fibers in woolen fabrics or the more regular arrangement of worsted or cotton-spun yarns; for the gradation of regularity with non-wool content, in worsted spun blends, and for comparisons of such diverse structures as frieze, pile or fur-like fabrics, cotton or synthetic fiber batts, needled felts, bonded non-wovens, or even assemblies of feathers and down, or foamed plastic sheets or microporous plastic films. Such understanding will aid in the production of wool, or blended or all-man-made fiber fabrics with specific properties of fuzziness or smoothness, loft or density, wicking or non-wicking, blotting or non-blotting, warmth or coolness, in terms of optimum fiber cross section and crimp, as well as chemistry, surface finish, and elastic properties.

Combined flow of heat and moisture:

In addition to the whole man tests such as the Mount Washington test, physical studies have been made in laboratory test systems, and further refinement in this area is possible and desirable.

Hollies, Bogaty, and Fourt at Harris Research Laboratories have developed testing equipment and methods which permit observation of the combined effects of heat and moisture in clothing assemblies under dynamic or changing conditions of moisture accumulation. In these tests, the water accumulates by evaporation from a saturated surface at body temperature, in fabric assemblies which correspond to clothing, and with temperatura gradients down to sub-freezing conditions or other temperatures as wished. This accumulation by distillation and condensation is regarded as important, in preference to arbitrarily wetting out the fabrics in a manner which would be different from the process when clothing is worn. In a recent development, the temperature gradient can be established in dry clothing, with measurement of dry heat transmission; then sweating can be started at a set time, without disturbing the arrangement of the fabrics. By automatic control the evaporating surface temperature can be held constant at the same skin temperature as the dry system, and the process of change of temperature gradient from inside to outside can be followed as water accumulates. After about thirty minutes a new steady state is obtained, in which the ratio of heat transmission to that in the dry condition can be determined, with separate but simultaneous measurements of direct heat loss and evaporative heat loss.

The results indicate that a gradient of heat flow and vapor pressure is set up such that both heat flow and vapor flow are at constant rate, although water continues to condense in the fabrics. A second order effect of this increasing water content on the heat flow is to be expected, but further refinement in measurement or longer periods of testing will be required to demonstrate it.

Since this steady state of heat and moisture flow is independent of accumulated water content, it is also largely independent of fiber type. Two important features of the clothing do depend on fiber type, however. One is the amount of water held back, which depends in part on the chemical adsorption of water in the fibers, as well as on the microstructure of the layers. In addition, the transition between dry steady state and moist steady state is strongly dependent on fiber type, and shows a distinct rise of fabric temperatures when sweating begins. This sudden rise of temperature comes from the adsorption of moisture, and has been called the heat of adsorption or heat of regain.

Heat effects of adsorption of water:

Cassie and Baxter, and Welbach and Harrington, with others, have demonstrated the large temperature rises and quantities of heat involved in the adsorption or removal of moisture from clothing fibers. Measurements of the relative saving in heat loss available to the body have been reported to the Quartermaster by Hollies and Fourt, but these measurements involved going from relatively dry fabric to moist conditions, and the energy was measured in a device which involved some rather arbitrary features of heat production. With a proposed system very similar to that which is now available for beginning sweating under clothing in an established "natural" thermal gradient, the energy saving effect, if any, of heat or adsorption can be determined more realistically. This can be determined either for really dry clothing, such as one might have put on inside a heated cabin before going out into the wet cold, or for clothing already in balance with the wet cold, under such conditions as an increase in work activity and consequent sweating.

Heat of adsorption as an inertia effect:

It is by no means certain that high water adsorption and correspondingly large heats of adsorption, for which viscose and wool are conspicuous, are correlated with maximum effectiveness in maintaining heat balance or comfort. Indeed, the production of heat in the fabric layer is in opposition to the effect desired by the physiological control mechanism, when an area of skin begins to sweat. It will be of interest, therefore, to examine the range of changes in moisture content, especially since it is certain that the natural ranges are smaller and further toward the high moisture side, than those used by either Cassie and Baxter, or by Hollies and Fourt.

These tests may have more significance for choice of fiber for hot environments than for cold. Furthermore, the effects of water content on other properties, such as effect on the sense of touch, clinging and friction, electrostatic fields or electrical conductivity, fiber stiffness, and swelling, with its further effect on yarn diameters, are probably also involved in assessment of suitability for clothing use.

Heat loss by radiation:

The main emphasis in heat flow studies of clothing has been on the interacting flow of direct heat and of water vapor but it is possible to divide the direct heat flow into two parts, one of which is heat flow in the sense of energy flowing through material particles, such as fibers or air or the skin, while the other is radiation. This radiation is the infra red waves which are given off by every surface, to an extent which depends on two factors, one of which is the temperature of the surface, the other, its emissivity or tendency to give off radiation. Clean, bright, metals have low emissivity; most other materials have high emissivity. We usually recognize the property of emissivity by its opposite, reflectivity. A bright, clean metal surface has high reflectivity corresponding to its low emissivity. Both characteristics can be grouped under the term "radiation barrier" since the metal surface opposes both the exit and entrance of radiant heat.

If the radiating surface is hot enough, we can see the red radiation, as from a red hot stove, as well as feel the infra red waves which are absorbed by the skin and recognized as heat. The wave lengths given off by surfaces at body or clothing temperatures are longer than those used in infra red photography but can be made visible or detected by newer techniques, such as the evaporation techniques of Baird Associates, and new photosensitive cells and thermopiles. These may be useful in demonstrating heat leaks especially in tests with men wearing complete assemblies of clothing and equipment.

The possibilities of improvement of normal clothing in natural environments by alteration of radiation relations by such means as aluminum coatings are rather limited, since savings in radiation effects are connected with increased temperature differences, and increase the tendency to heat loss by convection. Indeed, a definition of the insulating requirement of clothing for the cold might be that it reduces the surface temperature to levels where both wind loss and radiation loss are acceptable.

However, relations to heat radiation from the sun are quite different for different dyes and pigments, and the Quartermaster has information available for adjustments here. Radiation to the night sky is a problem in some climates, which might be reduced by low emissivity surfaces, especially metallic surfaces. In general, however, except where low emissivity, high reflectivity surfaces can be used to confront large temperature differences across relatively large open spaces, or on the exposed outer surface of clothing, there is little advantage in radiation barriers. Clothing for fire fighting is a conspicuous good example of a good application; there are also some possibilities in hand coverings.

Radiation relations are also important in protection against heat pulses from nuclear weapons, which are considered separately in section IV.

II. SENSE OF TOUCH AND OTHER SENSES

Fabric surfaces:

Hollies and Bogaty have made advances in the description of fabric surfaces in terms of warm or cool feel and harsh or soft "hand" as well as by analysis of compressibility. The study of fabric surfaces and of response to touch and handling needs further development, to specify the finishing and structure of fabrics made from new fibers. The textile art has given us a wide variety of textures in the natural fibers, with some degree of rational understanding of the effects of fiber diameter, crimp, fulling, napping, shearing, and singeing. The new combinations of fiber elasticity, fiber strength and size, fiber electrification and response to relative humidity, all give new means for improving our control of fabric texture and mechanics. New methods of yarn production such as differential shrinkage (high bulk), bonded twistless yarns from short (staple) fibers, bulked or textured yarns, and high stretch yarns add further dimensions.

Fabrics as structures:

Joel Lindberg in Sweden has made the first large step since the work of F. T. Peirce in the experimental analysis of fabric hand, that is, the feel of fabrics to the hand, by developing means of measuring forces and displacements in the plane of the fabric. Backer at MIT has developed the analytical geometry of yarn and fiber structures, enabling one to express the stresses and stains in mathematical terms and Hamburger, Platt, Coplan, and others at Fabric Research

Laboratories have applied and extended this geometry, both theoretically and by measurements on real yarns. This work is in competent hands and should continue, with the use of these tools of understanding, as well as techniques of measurement, spreading to other groups.

Forces across the thickness of the fabrics:

Another dimension of study of fabrics as structures is in terms of forces across or between the two surfaces of the fabric. This particularly involves the motions parallel to the fabric surface, and the "prickle" sensations perceived by the skin. A method of measuring displacement between the two sides of a fabric, as a function of both sidewise or shear force, and the pressure, has been envisioned at Harris Research Laboratories, but would require new and sensitive instrumentation (of available but expensive types) to reduce to practice. It would, however, give a new approach to the assessment of fabric hand, and to the problems of clinging and restraint by clothing.

Electrical effects:

There is need for correlation of the electrical effects of fabrics with the sensations experienced in handling or wearing them. This includes the obvious effects of electrostatic charge, and its dissipation, as influenced by rate and energy of rubbing, relative humidity, and finish or contamination. A biophysical assessment of the contact potential between fabric and near-by skin would be an exploratory venture of much interest. This contact potential is different from the potential built up as an electrostatic charge; it is a potential which exists at any exposed surface, independent of friction. Macheels in Germany has alluded to possibilities of effects related to this, but so far there seems to be little if any definitive work in this area.

The influence, if any, of different fabrics on the potential of the skin surface with respect to ground or to the body interior also deserves exploration. The potential at the skin surface is probably more directly connected with sensation than is the contact potential of the fabric.

These explorations are suggested both for their own interest and for the possibility that they may throw light on the baffling problem that people recognize differences between certain man-made fabrics and rayon or natural fibers, as "hot" or "uncomfortable", in spite of demonstrable lack of difference in heat or moisture transfer.

Water holding capacity; skin contact, and drag:

Another possible difference between fabrics composed of low moisture content man-made fibers, in contrast to high moisture content or natural fibers, may be in liquid water holding capacity. This is especially important in comparing thin, smooth fabrics made of continuous filament yarns with thicker, hairier fabrics made of short fibers twisted together in spinning. It is important that critical comparisons between different fibers should always be made in one form of yarn or the other, since the contact sensations are so different for filament and continuous yarns spun from short fibers. Recent work by Werden, Fahnestock, and Galbraith at the University of Illinois, comparing different fibers, in its continuation will, it is hoped, give more attention to this point, and to equalizing or using a range of fabric weights and thicknesses.

Coplan of Fabric Research Laboratories and Steele at Rohm and Haas have shown that the chemical composition of the fabric blend, or chemical modification of the fiber can affect the water holding and drainage characteristics of fabrics, as well as the rate of drying in the final phase. Further correlation with subjective impressions of comfort or well being, which are more important in this connection than heat balance measurements, are desirable. Heat balance measurements on the whole body are very blunt tools to use on this problem, since heat balance can be obtained by such a variety of mechanisms. Nevertheless, we are quite sensitive to changes in heat flow, locally and over all, and can recognize differences in the means used to obtain heat balance.

Hock, Sookne, and Harris showed that the contact between a flat surface and a wet fabric depended on the structure, the kind of fiber, and the water content. This sort of study can be combined with measurements of drag or friction over the skin, and with whole man studies of the physiological cost of varying degrees of contact or drag. The development of new fibers, and new textured yarn structures has widened the field of possible types of contact between fabric and skin.

It is also worth noting that studies of the final phase of drying are closely related to, and may supplement and extend the studies of microdistribution of water discussed already.

III. INFLUENCE ON MOBILITY OR SUPPORT OF THE BODY

Aside from the readily apparent interest of the bathing suit and foundation garment industries, there are many functional problems of mobility and support. One has been discussed, under the influence of water content on skin contact and drag, which might also be classified as a problem in mobility.

Energy cost of loads or restraints:

The general problem of the energy cost of load carrying and weight distribution in different alternatives is important to the military, to industry, sport, and even as a matter of general comfort. Sid Robinson's finding that the energy cost of carrying one pound of weight as shoes on the feet is equal to that of carrying eight pounds on the back, is applicable in every day life as well. The energy or performance cost of the restraints imposed by clothing has seldom been measured, but is easily appreciated. A characteristic motion of the batter in every baseball game is to free the fabric of his shirt from his shoulder and upper arm, as he takes his stance. There are many instances where clothing design could be guided, for functionality, by physiological tests and by physical measurement of contact and drag as a function of water content. Similarly, the effort involved in bending, or in the sliding of one layer over another in the actions required for various tasks, or in walking or running, can be attacked both on the man and by physical tests. An example is the advantages of a textured yarn liner for sleeping bags, with less friction or drag on the occupant than that given by smooth fabric.

Fatigue sparing effects:

The fatigue sparing effects of resilient flooring or floor covering, of rubber heels, and of thick or wool socks versus thin ones, are facts of common experience which could be developed systematically, especially with regard to footwear.

Effects of continuous pressure or restraint:

Aside from the energy costs in load carrying or friction, certain forms or portions of clothing exert long duration restraints or pressures on portions of the body. Collars, cuffs, belts, garters, leggings, shoes are familiar examples. It is probably not necessary to measure the value of good fit and design in these matters, unless sometime there is need to show the folly and physiological cost of some style or fashion feature. Even in sedentary work there are advantages in good heat balance without restraint or mal-distribution of load: an example is Balzac's choice of a monk's robe (but made of fine material) for wear while he was writing.

However, constraints less open to individual adjustment than on collars or belts can arise, in such forms as the elastic restraint of knit underwear, and especially of components, such as socks, made from "high stretch" yarns. Definite harm to the circulation and increased foot fatigue can develop from using stretch socks which have too much tension. This is aggravated by the fact that many forms of stretch socks show a progressive shrinkage with laundering, not unlike non-shrink resistant wool. Better standards of fit and performance are needed in the stretch sock industry, in spite of the popularity of "one size fits all" with merchants or logistics officers.

Low pressure environments; anti-G suits; ventilated or heated clothing:

Flyers have some special problems of low pressure environments and of preventing the centrifuging of blood away from the brain, which require special supporting and restraining structures (Anti-G suits). These combine with problems of mobility for special tasks, and of heating or cooling. Suits cooled by forced ventilation, as well as heated by electricity, have been reduced to practice and much basic work has gone into optimal design and distribution of heating and cooling. Some of these designs may be applicable to tank crewman, vehicle drivers or cyclists, fuel handlers and missile workers, de-contamination crews, or Artic or desert distant early warning or observation crews, that is, to men operating at fixed stations or with powered vehicles. The principles may also be applicable to motor or air borne soldiers, to maintain optimum combat readiness while being transported. The combat soldier on his feet, however, has to have clothing which matches with his own activity to an optimum degree, without dependence on any other source of power for heating or cooling than the capacities of the soldier's own body.

An example of design for increased effectiveness without external power is the wettable decontamination suit, which permits evaporative cooling without exposure of the skin. Finding the optimum in this kind of equipment involves the other heat balance studies already discussed. The use of vapor barriers in cold climate clothing presents similar problems of finding best balance of many factors.

Clothing design in relation to wicking and ventilation:

In hot environments, the wearing of sufficient clothing for protection from the sun, or from fire or the heat effects of nuclear weapons, is a severe problem. For heat effect protection, the protective clothing needs to be worn constantly. Everything which can be done to promote evaporative cooling within the clothing, by wicking and by providing open channels for ventilation, is needed.

Work done for the Quartermaster at Harris Research Laboratories has shown that the restricting effect of the walls of channels rapidly increases as one goes below one inch clear gap, but that little is to be gained above two inches. There is a considerable chimney effect of increased draft with increased height, but with decreasing cooling effect per unit length, which makes the channel length, in the scale available in clothing, less critical than the free clearance in the channel. However, there are large ranges of actual climatic conditions in which the movement of air in a chimney or channel, when the movement depends on differences in air density between the general environment and the body surface, is less than is needed.

Clothing design to utilize air scoops, and to make use of bellows effects in motions, and the expansion-contraction effects of breathing, to move air in the clothing, are desirable.

A very desirable development would be "tuned" clothing, elastically supported away from the body with such spring constants and masses that the clothing movements would be near resonance with some normal rates of body motion. This tuning should not be sharp, but should not be as heavily damped as most clothing movement is. This is a challenging but feasible problem in dynamic analysis and in reduction to practice with suitable elastic supporting and spacing materials.

Whether or not valves of some kind will be needed, or can be used to direct air flow in such a system is an interesting question.

IV. OTHER WAYS IN WHICH CLOTHING INTERVENES BETWEEN THE BODY AND THE ENVIRONMENT

Wind, rain, and sun are the classical antagonists against which clothing provides a shield. Military or industrial needs add to this list chemical, biological, and radioactive aerosols or fine particles, in addition to fragmentation missiles and other weapons. Hazards of insects, leeches, other animal enemies, and brambles can be opposed by clothing. The effects of fire, and the heat effect of nuclear weapons can also be mitigated to some extent by even conventional clothing, and to a greater extent by special means.

Wind penetration:

The work of Fonseca and Woodcock at the Quartermaster Laboratory at Natick, and of Niven at the National Research Council, Ottawa, have shown that a much more sophisticated approach to wind penetration is needed than has been usual theretofore. Results obtained by Fourt and Harris on the effect of air permeability of fabric on evaporation from underlying surfaces also show that the relation of air permeability (as usually measured) to cooling effect is no simple one-to-one correspondence. Work at the University of California (Berkeley) Institute of Engineering Research, by Dunkle, Geir, Bevans, and Edwards has special interest in being an interpretation in terms of aerodynamic concepts of heat and mass transfer. Considerable further work is needed in this general area to obtain an agreed upon and systematic body of knowledge and technique of testing.

Sensitive infra red radiation detecting devices to measure local surface temperatures can aid greatly. If all this can be combined with the geometric fabric analysis of Backer and others, with properly understood similitude conditions to go from physical tests to man-environment situations, it will make the physical tests much more valuable in predicting field test results and in screening fabrics, perhaps even more discriminatingly than field tests can.

Rain, mist, droplets, particles:

The filtering, wetting, and wicking effects of fabrics and clothing structures are involved in resistance to these droplet or fine particle agents. For liquids particularly the capillary effects of individual fibers (as fluted rayon versus smooth fiber) and of the surface fuzz and interior fabric microstructure are very important. Work of Schwartz at Harris Research Laboratories has established some optimum conditions with regard to wicking of droplets, but there are special points considered desirable in fabric structure for this purpose which require balance with questions of loft, warmth, and strength.

Biophysics of "bulletproof" vests:

The physical problems of fiber and fabric assembly involved in ballistic protection mostly lie outside the biophysics of clothing, and are purely physical problems, except in the incorporation of these structures in general design of clothing and equipment, with respect to burden in terms of pounds load, mobility, and heat balance.

Special problems of vision, hearing, face and hands:

The protection of the face and ears against cold or high thermal energy presents special difficulties and is almost a field in itself. Likewise, the protection of the hands, preserving dexterity and sensory perception, is a unsatisfied problem. There is something to be said for extra long sleeves as a simple measure, to provide constant protection against high thermal energy, and a "Chinese Muff" effect against cold, but comparisons involving men, equipment, and tasks are required to settle such questions. Low emissivity surfaces on anti-contact gloves, or on outer glove surfaces, may be especially valuable, in reducing radiation effects.

Sunlight and heat effects of nuclear weapons:

These environmental agencies are more similar than might be thought at first, with a wave length distribution of energy which is relatively similar. The Quartermaster is fortunate in having a large scale solar furnace to investigate the effects of high concentrations of this distribution of energy on comparatively large areas, so that edge effects can be minimized. Both sunlight at the earth's surface and the radiation from a nuclear fireball at distances compatible with survival have been filtered of a great deal of the shortest wave length energy originally present, so that the spectral distribution has its peak near the border between ultraviolet and visible light, with the bulk of the energy in visible and infra red wavelengths.

This energy distribution has lead to suggestions by Dr. Robert Hoffmann that reflection by white surfaces, such as fibers heavily loaded with titanium dioxide or other whitening agent, may be more practical than attempts to utilize metallic reflection. While metals are more effective than other pigments in the infra red range, they are lower than good pigment whites in the visible. It is worth noting that a white due to pigment is more opaque than the "white" of white cotton which arises from multiple reflection from rather transparent surfaces.

This problem has had and continues to have extensive study at the Quartermaster laboratory and elsewhere. It is related to the problem of fire proofing or preventing heat transfer by tars and distillates. The effectiveness of reflectors is also increased and indeed is dependant upon the spacing between layers, and the exposure of the reflector. The whole problem of heat attenuation plus durability (survival of the protective system for use against the next blast) is complex, but deserves thorough physical analysis. The mathematical analysis of fabric system and skin response carried out by Chen, Hottel and Williams of MIT is basic to these questions and should be extended, fitted with additional experimental data, and applied.

Industrial heat problems, fire fighting, and hot environments:

A more moderate range of radiation problems arises in connection with furnaces and fires. Here, external aluminum coatings perform very well. The practical problems are chiefly of durability and flexibility. Reflection can be effective where there is a local or directional source of heat, and sufficient heat capacity or short duration of exposure to permit the clothing system to ward off or slow the advance of heat for the required time.

For continuous exposure in a completely hot surrounding, such as a tank [illegible] insulation barriers can reduce the rate [illegible] energy transfer to the only heat sink, which is the evaporating surface of the body. This must be shielded from radiation, and protected by conventional, thickness dependent insulation from the hot air, permitting enough access to air, however, to keep evaporation going. Protection of the eyes and respiratory system can become critical points.

Absorptive, transmissive properties of fibers:

In the past it has usually been sufficient to regard clothing systems as non-selective or "black" bodies, with regard to thermal radiation, but in problems of high energy levels in the ultra violet, visible, and infra red spectra, selective absorption or transmission has special importance. Physical data on absorption and transmission are accumulating; information at high temperatures would be desirable. Some of the polyolefin fibers are comparatively transparent to infra red wavelengths. The basic properties of the fibers can of course be modified by dyes, pigments, or finishes, which also require compilation over a wider range of wavelengths and temperatures.

Finally, it may be noted that while the composite, over-all thermal transmission of fabric systems, and very rough estimates of fiber heat capacity are sufficient for the slow time scale dynamics of normal activity and environment, the analysis of the effects of nuclear weapon thermal pulses requires accurate knowledge of heat capacity and thermal conductivity all the way up to high temperatures.

CONCLUSION

In this consideration of the biophysics of clothing, an effort has been made to present a broad picture, citing at least a small part of the work of other laboratories as well as that of the Quartermaster and Harris Research Laboratories, with which the writer is more familiar. Significant work on general and special problems has been done by the Armored Forces Laboratory at Fort Knox, by Aeromedical Labs, and Navy agencies, as well as by industrial laboratories of fiber producing companies and many university departments. It is hoped that enough has been presented here to show that detailed and practical work on many important problems in the biophysics of clothing could come from many research groups.