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REPORT NO. 17

COMFORT FACTORS IN LEATHER FOOTWEAR

CLOTHING & ORGANIC MATERIALS DIVISION

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U. S. ARMY NATICK LABORATORIES
Natick, Massachusetts

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Ludwig Seligsberger, Ph. D.
Rubber, Plastics and Leather Engineering Branch

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FOREWORD

A Footwear and Leather Series Report on comfort has long been overdue. In handbooks and scientific journals, the chemistry and technology of leather have received much more comprehensive treatment than its physical properties and wearing qualities, both of which have a bearing on comfort although they must be understood within the limitations imposed by the physiological requirements of the foot.

However, the question of comfort has not been neglected in the development of footwear at the Quartermaster Research and Engineering Center in Natick*. It has been the subject of many widely scattered and somewhat inaccessible reports that originally were confidential but were later declassified. This report attempts to bring together and evaluate this material, to summarize the thinking about footwear comfort that has taken place during the past twenty years, and to point out areas for further study. The material drawn upon helps to establish a broad and firm basis for the conclusion that there are many interrelated factors responsible for comfort in leather footwear.

Among earlier writings, special mention should be made of a series of articles by A. W. Stokes (British Ministry of Supply) in which he discusses the design and construction of military footwear. His articles were published during 1959 in the Journal of the British Boot and Shoe Institution. While his discussion on leather footwear comfort is rather brief and narrow in scope, the articles should prove useful in regard to certain problems connected with non-leather footwear.

Radical changes have been made in footwear over the last decade. Step by step, changes have been made in the combat boot. The leather-soled, flesh-out, Army Retan boot of old has been transformed into the grain-out combat boot with mildew-resistant chrome-tanned uppers, with developments like water resistance and molded-on cleated rubber soles about to be introduced.

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* Now called the U. S. Army Natick Laboratories.

This report testifies to the fact that during this period of constant change the question of comfort has not been neglected; in fact, it has played an increasingly important role. A summary of our knowledge at this juncture helps to point out the remaining gaps and the direction that future efforts should take.

S. J. KENNEDY
Director
Clothing and Organic Materials Division

APPROVED:

DALE H. SIELING, Ph. D.
Scientific Director

MERRILL L. TRIBE
Brigadier General, USA
Commanding

CONTENTS

ABSTRACT

Comfort in leather footwear is discussed as the result of physiological and environmental factors that influence its wearability, rather than as a matter of good fit, which is an obvious prerequisite. Physiological factors that are related to blood circulation and to the production of sweat in the foot area are discussed first. The report then turns to the properties of leather that are pertinent to its use in footwear. Instead of merely offering a record of various characteristics, the data are examined as to their practical significance.

Ranking low in importance for comfort are such properties as thermal expansion, color, air permeability, and the heat of wetting. Properties that depend largely on the tanning process used, such as stiffness and dimensional changes, deserve careful attention but do not usually create serious comfort problems. The most important combination of properties is one that copes both with foot perspiration and with the danger of "getting wet feet". In dealing with foot perspiration, the water vapor permeability and the capacity of leather to absorb liquid and vaporized water come into play. To avoid "wet feet", water resistant leathers have been developed. The report reviews methods of evaluating these properties in the leather that goes into footwear and in the shoes and boots themselves. It discusses comfort factors of uppers, insoles, and outsoles; the water balance around the foot; the distribution of body weight; and the weight of footwear.

The report also discusses the difficult topic of the subjective evaluation of footwear by means of wearer questionnaires and interviews. Two field trials, one Canadian and one American, are presented as the most interesting examples of this technique. A critical study of the findings will, it is hoped, aid in eliminating bias and in perfecting the art of gathering information on comfort during future tests. The principal points elicited by this report are summarized in the final section, and it is hoped that they will channel future research in those directions where it is likely to be most fruitful.

COMFORT FACTORS IN LEATHER FOOTWEAR

A. INTRODUCTION

Foot comfort depends not only on the fit of the shoe or boot but on the physical properties of the materials that go into the footwear. A comfortable fit is readily understood by the public but the physical properties of the materials are so difficult to assess that, even among experts, much confusion exists as to their relative significance. As a consequence, many claims have been made that are unsubstantiated. On the other hand, there have been many valuable investigations about foot comfort that have not been published in readily accessible magazines and therefore have not received the attention they deserve. Among these are a number of military studies undertaken in this country and abroad with a view toward finding the most suitable footwear for a given environment.

It is timely to examine critically all available information on comfort because the Armed Forces have recently adopted a new last and are contemplating a radical change in shoe construction (by adopting a boot with a direct-molded sole). While military considerations will prevail in this discussion, the conclusions should be helpful to the mass of the shoe and leather industry, which is geared to the demands of the civilian population. The only significant difference between military and civilian interests in foot comfort is that the former is centered on a high boot, the latter on a low quarter boot. The height (including the heel) of the combat boot (size 9) is 9 inches (recently reduced 1-1/2 inches). The height of a low quarter service shoe is 3-1/2 inches. It is obviously more difficult to maintain comfort in a boot than in a low quarter shoe; therefore, emphasis will be placed on boots, although where there are helpful studies on other types of footwear they will not be neglected.

The physiological factors that influence foot comfort will be discussed first. The foot, whether shod or unshod, has two means of regulating its temperature and maintaining it at a comfortable level: blood circulation and perspiration. Footwear supplements these "built-in" comfort devices and also protects the feet from external hazards (cuts, bites, etc.). When the climate turns inclement and the ground temperature is raised or lowered beyond human endurance, the wearing of shoes or boots becomes a necessity for physiological reasons, especially for the urbanized populations of the West whose feet are not as toughened by exposure to all types of weather as are the feet of people in other parts of the world. Therefore, the various leather and footwear properties believed to influence foot comfort will be examined next for their relative importance to normal foot functioning and consequent comfort. Finally, conclusions will be drawn to justify the policies that have been followed over the past few years in the development of military footwear.

B. PHYSIOLOGICAL MECHANISMS CONTRIBUTING TO COMFORT

1. The Circulation

The circulatory system promotes comfort by maintaining the body temperature at a uniform level; it helps the feet to cool off and "keeps the feet warm." Small blood vessels near the surface of the skin dilate to dissipate the body heat when the surrounding air is warm and constrict to conserve the body heat when the air is cool. Vasoconstriction occurs first in the feet, with the legs, hands, and arms following in that order. The feet are the most vulnerable part of the body, which is why cold feet, frostbitten feet, and "trench" feet are such serious problems under conditions that prevent the circulating blood from providing the extremities with sufficient warmth.

The regulatory effect of the circulation becomes apparent when skin temperatures of subjects with normal and abnormal metabolism are studied. The following surface temperatures, to the nearest degree (C), are based on clinical observations of resting nude subjects at room temperatures of 24° and 34° to 35°C (1a):

	Foot		Toes	
Metabolism	at 24°C	at 34°-35°C	at 24°C	at 34°-35°C
Normal	25	36	24	35
72% above normal	34	-	33	-

In a cold environment, the skin temperature inside insulating footwear will drop considerably without causing discomfort. When subjects, with their feet inside 6.5 mm of insulation, immersed them in water at 0.5°C, they did not begin to shiver until the skin temperature of the great toe (hallux) dropped to 11°C. Immersion in water was used in the experiment because it lowers skin temperature much faster than cold air (1b).

In the light of unpublished findings by the QM Environmental Protection Research Division, subjects at rest are unable to stop heat loss from the feet in a cold environment even though their feet are well insulated. In fact, the heat loss under these conditions and inside the same amount of insulation would be about the same as that from the hands, from which a heat loss of 9.9 kg cal/sq m/hr has been assumed during extreme vasoconstriction (1c). At about 0°C, there is increased danger of the extremities freezing from vasoconstriction and reduced blood flow (1b).

Whereas we get "cold feet" simply by exposure to a cold environment, the reason for having "warm feet" is more complex. In the first place, in a hot environment the temperature of peripheral points of the body, such as on the surface of the foot, will normally approach that of the rectum, i.e., it will advance from 37° to 39°C. Secondly, increased activity or energy expenditure will increase the blood flow to the foot and this will further raise its surface temperature. In a 6-hour experiment consisting of "light exercise", subjects wearing low quarter shoes have had measured heel temperatures of from 33° to 34°C and toe temperatures of from 23° to 30°C (2).

The British Shoe and Allied Trades Research Association (SATRA) has sought information about the skin temperatures of the foot (3-5). In one of their tests, the sole and upper surface of the foot of a test subject just returning from a brisk march had a temperature of 38°C (5a). This is not the highest temperature ever recorded for the surface of the skin of a shod foot; a Harvard Fatigue Laboratory study recorded a temperature of 43°C on a shod foot exercising on a treadmill (1d). In both studies, the increased activity and the environment were not the only factors contributing to the rise in foot temperature. A third factor, frictional heat (as from increased loads together with increased speed of marching), also played a part, especially on the surface of the sole and heel. Thus, in order to prevent an undue temperature rise, with the formation of blisters, frictional heat should be avoided.

Some individuals, one SATRA study suggests, can never be comfortable in conventional footwear because their circulatory system does not respond to the environment in a normal fashion (4). It relates the instance of a man who customarily wore open sandals because of a burning sensation on his feet during the early afternoon hours (about 3 p.m.) every day. It was found that the skin temperature of his toes and of his plantar and dorsal foot surfaces would increase from a low of from 22.8 to 26.1°C to an average of 34.3°C within a 15-minute period. About 1-1/2 hours later, the temperature would drop to between 29 and 30°C. The heat flow, which was measured by an instrument of Hatfield and Wilkins (6), more than doubled during the "hot flush" period, rising from 16.8 to 40.8 kg cal/sq m/hr. It is not known how widespread this type of phenomenon is.

In another study by SATRA (7), blood flow is related to the environmental temperature. Assuming a foot volume of 1000 ml, the blood flow was found to vary from 2 ml/min at 15°C to 165 ml/min at 44°C. The test subjects used were two young male adults resting on a couch.

2. Perspiration

The evaporation of perspiration is the body's second means of regulating its temperature. Perspiration that does not evaporate makes the foot uncomfortable and adversely affects the material that absorbs it. First, the composition of perspiration, especially those ingredients that are absorbed by leather, will be discussed. Next, the factors affecting its output will be considered, together with methods for its possible control.

a. Composition

The principal component of perspiration, other than water, is sodium chloride. Next in importance are lactic acid and potassium. These constituents have been used to measure the extent of sweating or the movement of sweat into layers of cloth or leather adjacent to the skin. Their average concentration, according to Kuno (8), is as follows:

Chloride (Cl)	3.2 gm/liter
Sodium (Na)	2.0 "
Lactic Acid	3.5 "
Potassium (K)	0.2 "

In addition, there are various nitrogenous constituents of perspiration, notably urea (0.32 gm/liter) and ammonia (0.06 gm/liter); appreciable quantities of amino acids; and, normally, very small amounts of uric acid, creatinine, and phenol, as well as many inorganic materials. Solids make up only from 0.3 to 0.8 percent of perspiration (8), but their amounts vary greatly, not only with the type of activity but also with the type of individual. A survey of 200 references on the chemical composition of sweat was published in 1954 (9).

In analyzing sweat, precautions are usually taken for it to be in as fresh a condition as possible. This is important because a number of the constituents are subject to rapid microbial attack that is promoted by the heat of the body. Urea is converted to ammonium carbonate or to ammonia, which is partially lost to the atmosphere (10, 11), and lactic acid is converted to acetic acid, which, **in contrast to lactic acid**, is volatile (12). A distinct increase in the lactate content of bacteriostatically treated hose, as compared with untreated hose, has recently been observed (13).

The sweat constituents extracted from worn shoes or boots do not necessarily match those originally present in foot perspiration. The constituents that react with the tanning complex (as, for instance, lactic acid, which can form complexes with the chrome (14, 15), and urea, which reacts with vegetable tanning (16)) gradually accumulate in the leather. Heavy deposits of lactic acid and urea have been reported in worn upper leather but they have not been related to the composition of the perspiration from the feet of the wearers or to the wearing period (15, 17). Other components that do not have an affinity for the tanning complex will accumulate in the leather only until equilibrium with the socks is reached. If the socks are frequently changed, this equilibrium is, of course, much lower than if the socks are worn for long periods without washing.

Evidence that the composition of the sweat deposited in socks and in shoe leather does not agree with the commonly accepted composition of body sweat (8) was provided in a recent SATRA study (13). A comparison based on the results of this investigation is shown in Table I.

TABLE I. COMPARISON OF SWEAT COMPONENTS

(in mg/100cc based on a sodium concentration of 200 mg/100cc)

		Composition of Findings by SATRA			
	Normal Perspiration(8)	Chrome-Tanned Upper Leather*		Foot Washings**	Sock Washings**
Potassium (K)	20	230	286	267	157
Chloride (Cl)	320	205	276	386	289
Ammonia (NH_3)	60	-	24	98	69
Urea	320	-	149	225	105
Lactic Acid	350	460	695	862	476

NOTE: The above figures were calculated by subtracting the figures for hot and cold extracts from unaffected leather.

* The two columns represent figures taken from Tables VI and VIII, Reference 13.

** Mean values from four subjects, Table XI, Reference 13.

The most striking difference pointed out in Table I between normal perspiration and that found in leather is in the potassium concentration, which was about 12 times higher in the leather than would be expected according to Kuno (8) and exceeded that of sodium in three out of four determinations presented in Table I. This potassium apparently was attached to the lactic acid. In Kuno's figures of normal perspiration, most of the lactic acid was neutralized by ammonia. Although some of the NH_3 in the sweat solutes from the leather and from the washings was of course lost, it was more than replaced by ammonia derived from urea (see p. 4). The sweat solids that were singled out for this analysis were also much higher than would be expected, exceeding in the foot washings 2 percent of the total perspiration fluid.

The above findings may be explained by the "contamination" of the sweat solutes with cell debris that is constantly being rubbed from the horny layers of the epidermis. In the shod foot, the rubbing off of epidermal cells is accelerated by friction, especially where the relatively hard surfaces of nylon or leather rub against the skin. The perspiration fluid leaches out the soluble components of the debris, among which, as Table II shows, sodium, potassium, and lactic acid are present in proportions similar to those found in the foot and sock washings and in leather as reported in Table I.

TABLE II. CONCENTRATIONS OF EPIDERMAL COMPONENTS (in mg/100g)

	Horny Layer Only (18) (air dried)	Total Epidermis (19a) (with natural water content)
Sodium (Na)	950-1150	106-185
Potassium (K)	700- 900	210-320
Lactic Acid	1200-6000	- -

While no definite value can be given for the pH of perspiration, most observations support the view that both it and the skin surface are slightly acid. For the sole of the foot, pH values of from 5.25 to 5.47 have been reported (19b). In other locations, the body sweat is less acid, especially with Japanese subjects, who, under conditions causing profuse sweating, have shown a maximum pH of 7.8 (8).

b. Production

The physiologist distinguishes between sensible and insensible perspiration. Sensible perspiration is produced by the sweat glands when the individual is hot; insensible perspiration is given off through the skin constantly, regardless of the external temperature.

The flow of perspiration varies with the environment, the amount of exercise being performed, the emotional or nervous state of the individual, and the location on the body. Sensitive techniques have been developed for measuring the sweat output from relatively small areas of the skin. Results obtained on the foot by a number of workers are combined in Table III, in which, for the sake of comparison, all figures have been converted to grams per square inch per hour based on an estimate of 100 square inches for the total foot area covered by a low quarter shoe, with 40 square inches representing the sole and 60 square inches the dorsal surface (20, 21a). (A combat boot 8-1/2 inches high covers an additional 25 square inches of skin surface).

TABLE III. EXTREMES OF SWEAT PRODUCTION BY THE FOOT (in gm/sq in/hour)

Source	Sole Alone		Dorsal Area Alone		Whole Foot	
	(min)	(max)	(min)	(max)	(min)	(max)
Ref. 22	0.035	0.073	-	0.147	0.035	0.220
Ref. 23*	0.047	0.127	0.021	0.304	0.068	0.431
Ref. 24**	0.042	-	-	-	-	-

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* Computed from 3 successive collections taken from 50 sq mm of skin surface in 4 areas simultaneously during a 10-minute period with the temperatures at 20°C or 49°C and relative humidities at 74% or 53% respectively.

** Sweat production on the ball of the foot and under the great toe and heel after moderate exertion. (The figures of 0.048-0.065 gm/sq meter/hr, which were cited as the minimal sweat secretion in a Canadian field study (25), are so close as to appear to have been taken from the same source, although this is not stated.)

The figures given in Table III bear out an important fact: at minimum rates of perspiration the dorsal part of the foot perspires about half as much as the sole, but under maximum rates of perspiration the dorsal area perspires from two to almost three times as much as the sole. (The palmar and dorsal areas of the hand show the same behavior.) The dorsal area has fewer sweat glands than the sole but a single dorsal gland can secrete 6 times as much sweat as a sole gland (23). Furthermore, the sweat glands on the soles and palms have the special property of not reacting at all to a rise in the environmental temperature, whereas other areas will sweat profusely, especially the forehead and the back of the hand (1e). When the sole does sweat, the output is highest in those areas where standing or walking creates the greatest pressure (8).

The conditions for the extremes of sweat production cited in Table III are rarely found outside the laboratory and when they are found they cannot be sustained for long. Under normal conditions, the sweat production of the sole decreases during the first, second, and seventh hours at a ratio of 3.0 : 1.7 : 1.0, as has been shown by hourly weighings of removable insoles (26). It does not give a true picture, therefore, to compute an hourly rate of sweat production from figures obtained after a great number of hours, although this has been a common practice according to the literature on foot perspiration.

The accumulation of perspiration in footwear is influenced by its ability to escape in vapor form either by pumping action or through a permeable (leather or canvas) barrier. An impermeable barrier (rubber or plastic) placed next to the skin will reduce the sweat output by more than 60 percent, a value accepted 20 years ago on the basis of numerous arctic field studies and controlled laboratory experiments, and that has been corroborated by more recent investigations. Therefore the sweat accumulation within a vapor barrier cannot be taken as the norm for the sweat production of a foot not so surrounded.

Both the sole and the dorsal surface of the foot produce less sweat behind an impermeable "near" barrier, and both sensible and insensible perspiration are reduced equally by such a barrier (21b), although individual differences are very great, with decreases ranging from 20 to 77 percent among 25 test subjects (27a).

An impermeable barrier reduces the accumulation of sweat not only by the suppression of sweat output but probably also by causing reabsorption of sweat fluid. Folk and Peary, by pre-wetting socks worn under an impermeable barrier, found that it was reabsorption that reduced the sweat accumulation (27b). The reabsorption increased, during an 8- to 10-hour experiment, from 1cc of water per hour for seated subjects to from 2 to 3cc per hour for subjects walking part of the time. Chloride analysis proved that the sweat fluid had indeed been reabsorbed. The chloride concentration in the dry socks worn on one foot was similar to that in the water-soaked socks worn on the other foot; therefore, the amount of water in the sock, whether from external sources or from the foot, must have come to an equilibrium value because of reabsorption. Aside from this study, however, there has been little evidence for the reabsorption of sweat. Kuno (8), surprisingly, ignores the problem. Radioisotope tracer techniques might well be used here with good prospects of success.

An experiment with tritium water has shown that as much water can pass inwardly through the skin as passes outwardly as perspiration (28). It makes little if any difference whether, all other conditions being equal, the skin is immersed in the tritium water solution or is exposed to tritium vapor. It seems that there is a barrier under the skin that allows water to pass in the vapor state only (28). If this is correct, it would give support to former findings that skin is impermeable to electrolytes, such as sodium chloride (29), even though it invalidates the explanation that the skin carries a negative charge that makes it cation-permeable only, therefore allowing water but not salts to pass through it (30).

Several attempts have been made to estimate how much perspiration escapes as vapor from a low quarter shoe either by pumping action or through the leather, and how much remains in the shoe or sock. Results found in three such studies, expressed in percentages, are given in Table IV.

TABLE IV. DISTRIBUTION OF FOOT PERSPIRATION INSIDE LOW QUARTER SHOES

(in percentage of total production)

	Ref. 26	Ref. 31	Ref. 5b
Absorbed -			
by sock		8	3.0
by upper leather	25	40	36.0
by insole	25		13.5
Escaped as vapor -			
by pumping action	35-40	16	15.5
through upper leather	10-15	36*	28.5
through insole			3.5**

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* "probably less"

** 2% absorbed by bottom filler; 1.5% absorbed by leather outsole

The figures in the first column of Table IV were taken directly from the Swedish Leather Research Institute study (26); the figures in the next two columns were computed from the amounts in grams given by the Canadian (31) and SATRA (5b) studies. The number of grams given by the Canadians was based on their estimate of a total sweat output of 25 grams per a 7-1/2 hour day. The number of grams given by SATRA were amounts arrived at in a carefully designed test (except for the amount of sweat escaping by pumping action, which was calculated (5c)), in which the total sweat output per foot during a 7- to 8-hour day was found to average 46.3 grams.

The higher figure for total sweat output obtained by SATRA may have been due to the fact that their test subjects were chosen on the strength of their claim that their feet perspired very freely, and that a 15-mile walk was included in the test. In the Swedish and Canadian studies, office and laboratory personnel were used and it did not appear that vigorous exercise was required. It would seem that strenuous exercise might also affect the distribution of perspiration among the various components of the shoes.

The low figure given by SATRA for the amount of perspiration that escaped by pumping action was calculated as a definite possibility. The equally low figure given by the Canadians was arrived at by taking the difference between the total (100%) and the measured quantities. The figure given for the Swedish study was merely suggested. It should be noted that, had high boots been worn, the loss of sweat by pumping action would have been even lower than the lowest figures given here.

The low moisture absorption by the socks may seem surprising. In the SATRA study, lightweight wool socks were worn, which helps to explain why "it may not matter much for foot comfort whether lightweight hose are made of absorbent or non-absorbent materials" provided "the shoes are able to absorb the excess foot moisture" (5d).

As Table IV shows, the percentage of the total sweat production absorbed by the uppers is considerable. In actual grams per hour, the Swedish and SATRA figures are as follows:

	Swedish (26)	SATRA (5b)
Water vapor transmission	0.20*	2.00
Water absorption		
Mean	0.34	2.50
Range	0.18-0.89**	2.20-3.00
Number of shoes in test	28	11

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* Estimated from Ref. 26, Table II

** Half of total given in Ref. 26, Tables I and II (rest goes into insole)

Since the production of sweat is not at a uniform rate throughout the day (26), the highest figures obtained should probably be used, rather than the averages. This would give the following figures when related to the area of leather involved:

	Swedish (26)	SATRA (5b)
Water vapor transmission		
In g/sq in/7.5 hr*	0.045	0.250
In g/sq m/24 hr	223	1240
Water absorption		
In g/sq in/7.5 hr*	0.11	0.38

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* Total area=60 square inches

A special feature of the SATRA experiments was that the shoes were so constructed that they could be dismantled at once after the test. Each component could then be quickly weighed. The construction of these shoes is described in the appendix to the SATRA report (5e). The Swedish study applied itself to a question not answered by the others: whether or not both feet perspire at the same rate. One of their tests, using 14 subjects, showed that for all practical purposes they do. Weight increases between pairs varied an average of only 0.025 grams per hour (26). Both of the other studies tacitly assumed that both feet perspire at the same rate. In fact, in the SATRA test, an impermeable barrier was placed around the right foot in order to measure the weight changes in the shoe leather from atmospheric conditions alone as against the left foot, where perspiration was a factor.

c. Control

In clothing the foot, one is faced with two possible effects of sweat accumulation in footwear: damage from the chemical constituents of perspiration, and the loss of insulating ability when the material becomes wet. Water, irrespective of its source (from the outside or from the body) reduces thermal insulation and leads to "cold feet." The problem of the accumulation of perspiration can be met either by making footwear more resistant to water or by controlling the output of foot perspiration. The latter approach has been investigated by a US Army medical team in consultation with dermatologists (32).

The test subjects were treated with anhydrotic foot powders composed of from 3 to 10 percent aluminum chloride, from 10 to 20 percent potassium alum, and from 3 to 5 percent salicylic acid. These chemicals were mixed with from 70 to 85 percent talcum for ease of application. One foot of each test subject was treated with the powder for five consecutive days; the other foot remained untreated. The activities of the subjects were not supervised. Daily sweat production was measured by weighing the socks and boots. No harmful side effects were observed from the use of the powders.

The sweat flow was reduced by from 1.8 to 14.0 grams per day (from 4 to 24 percent of the total sweat production), with the individuals having the highest sweat rate experiencing the greatest reduction. Even after sixteen days, the sweat flow was still below normal, which suggests that the applications might be spaced a week or so apart instead of repeating them daily. The study was broken off before any conclusions were drawn as to the best way of using the powders. The possibility of furnishing foot powder to individual soldiers was apparently abandoned.

C. CONTRIBUTION OF LEATHER PROPERTIES TO FOOTWEAR COMFORT

In considering the various comfort factors in footwear, the qualities related to the insulating and water-resistant effectiveness of leather will be considered. A certain tendency to associate with comfort some factors that have no real bearing on it will also be discussed.

1. Thermal Conductivity

The thermal conductivity of leather, like that of all fibrous materials, is directly related to the amount of air trapped on its surface, in other words to its apparent or bulk density (33) and thickness. Chamois has the lowest density of all leathers (approximately 0.3), hence is low in heat conductivity and a good insulator. Sole leather has a higher density than upper leathers (1.1 or more) and is therefore high in heat conductivity and a poor insulator. Most leathers fall between these two and are from five to eight times more heat conductive than air (34) unless they are wet (water is 25 times more conductive than air). A water-soaked leather sole conducts more than twice as much heat as a dry sole, and soles made from bends conduct 20 percent more heat than soles made from bellies or shoulders. The sole, cork gum filler, and insole combined conduct about 20 percent less heat than the sole alone (35). Composition soles are as high in heat conductivity as wet leather soles. Crepe rubber soles, on the other hand, are almost as low in heat conductivity as dry leather soles and few people are able to distinguish between them in "warmth"; therefore, crepe rubber is a more serious competitor of leather than composition soles (33).

The thermal conductivity of various types of leather and soling materials has been reported in the literature (33, 35) in units consisting of the number of gram calories of heat passing through one cubic centimeter of material per second when the opposing surfaces of the material differ in temperature by one degree (C).

From these conductivities and those for the cushion sole sock and for air, the heat loss through the combat boots of a man standing in the open at -20°C (-4°F) can be calculated.

The following formula is used to compute the heat loss (H) in cal/sec/°C:

$$H = a_1 \left(\frac{1}{\frac{d_1}{k_1} + \frac{d_2}{k_2}} \right) + a_2 \left(\frac{1}{\frac{d_3}{k_3} + \frac{d_4}{k_4}} \right) + \frac{a_3}{\frac{d_5}{k_5}}$$

In this formula, a_1 is the area in sq cm of the bottom and a_2 the area in sq cm of the upper part of the boots, while a_3 is the area in sq cm of the layer of still air inside and outside the boot which contributes to the insulation provided by footwear of any type. The heat conductivities for the soles, the bottom of the cushion sock, the upper part of the boots and socks, and finally of the still air are k_1 to k_5, while the corresponding thicknesses in cm are d_1 to d_5. Inserting into the formula the correct figures for each item, one obtains:

$$H = \left[500 \left(\frac{1}{\frac{1.5}{3.5} + \frac{0.1^{*}}{1.35}} \right) + 1100 \left(\frac{1}{\frac{0.2}{2.0} \quad \frac{0.08^{*}}{0.6}} \right) + \frac{1100}{\frac{0.4^{**}}{0.54}} \right] 10^{-4}$$

$$= \left(\frac{500}{0.50} + \frac{1100}{0.233} + \frac{1100}{.0.74} \right) \cdot 10^{-4} = 0.296 \text{ cal/sec/}^{\circ}\text{C}$$

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* by QM measurements on standard sock

** 0.3 cm air next to surface of boot uppers and 0.1 cm air inside boot (= approximately 100 ml air enclosed by boot)

Heat loss in one hour (at -20°C, and a temperature gradient of about 55°C) would be 0.296 x 3600 x 55/1000, or 58.6 kg cal. While this amount of heat loss is small in terms of the work done by an active individual, it is far too large to be counteracted by the flow of blood into the feet (normally about 15 kg cal/sq meter/hour (7), or about 2 kg cal/hour for both feet). In other words, the feet of a resting individual in combat boots are bound to get cold and freeze in cold weather.

Many observers believe that the insulating value of different footwear materials can be compared simply by measuring the foot temperatures of the subjects wearing shoes or boots made from these materials. Tests have already been mentioned in which foot temperatures were measured while one type of footwear was worn (p. 3). Unfortunately, similar measurements taken while different types of footwear were worn have been unrewarding, with combat boots with either leather or vulcanized rubber soles producing sole temperatures of only 36.7°C (98°F) when worn on day-long marches across desert sands at temperatures of 50°to 55°C (122°to 131°F) (36). The temperature increased by 2.2°C (4°F) across the sock, but with a Saran insole, it increased by 4.2°C (7.7°F). The test subjects did not notice this small temperature difference, an unexpected result that discourages the use of an insulating slip-on sole under such conditions.

Unusually low initial skin temperatures were reported in a British study (36) in which four different types of footwear were worn. The changes after moderately heavy exercise in a Hot Chamber (26°C) and after 1-1/2 hours in a Cold Chamber (-10°C) were surprisingly small except at the ankle and could not be related to the subjects' reactions (see Table V). There were differences, however, that are clearly significant at the 95 percent level:

In warm surroundings, the spun nylon boot kept the feet from 1.4 to 1.8°C cooler than the Army Retan, and the ankles remained cooler than the rest of the foot in all of the boots.

In cold surroundings, the Army Retan boot kept the feet 3°C warmer on the sole than the spun nylon, and 1.4°C warmer than the impermeable polyvinylchloride. Irrespective of the type of shoe, the temperature of the ankles remained about the same, and that of the great toe area also.

TABLE V.

EXERCISE-INDUCED CHANGES IN SKIN TEMPERATURES OF THE SHOD FOOT

	Hot Chamber (26°C)			Cold Chamber (-10°C)		
	Great Toe	Sole	Ankle	Great Toe	Sole	Ankle
Initial temperature, °C	19.3	20.7	23.2	19.3	20.7	23.2
Change in temperature, °C						
-Composition-soled cotton drill boot	+11.7	+10.3	+5.1	-16.5	-10.8	-10.3
-Composition-soled spun nylon tropical boot*	+10.3	+ 9.6	+4.7	-17.8	-11.4	-10.3
-Leather-soled Army Retan combat boot	+11.8	+11.0	+6.5	-17.6	-8.4	-10.0
-Leather-soled polyvinylchloride impermeable boot	+12.5	+11.5	+6.3	-17.6	-9.8	-10.4

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* With leather toe-cap, counter, cuff, and ankle

Thermal conductivity is affected by color. Dark colors and dull finishes absorb heat whereas light colors and glossy finishes reflect heat. One SATRA study (37) reports temperature differences of between 4° and 10°C due to the color of the footwear. This author knows of no other such study. The SATRA measurements were taken during a "static" test in which the shoes were not in motion. They did not resolve the question as to whether the results would be applicable to an actual wear situation. The present combat boot has a dull black finish because a high gloss reflects light even from a weak source and thus might endanger the wearer. A greenish color is under study for the tropical boot; the color is similar to that of combat clothing and is the mandatory color in France.

Contrary to popular belief, the type of floor covering has little significance in regard to foot warmth. "Warm" cork tile floors are less than 1.5 degree (C) warmer than "cold" cement floors (38), a difference small enough to be compensated for by raising the temperature of the room a mere 0.4 degree (C) (39). In an experiment in which test subjects sat in a room with the air temperature varying between 14° and 30°C, the mean difference between foot temperatures on cement and cork floors was 0.66 degree (C). Three out of the four subjects were not conscious of any temperature difference. The fourth admitted that his prejudice against cement floors colored his judgment (38, 39). Comfortable foot temperatures ranged from 20° to 27°C and no discomfort was felt until the temperature changed by at least 2 or 3 degrees (C) (40).

2. Air Permeability

Most textile fabrics have a high air porosity, but that of leather is so low that a vacuum or pressure must be applied to one surface to drive the air through. On the opposite side, this air is collected and measured (41a-45).

A few figures from the literature illustrate the order of magnitude of the air permeability under 25 inches water gage pressure (50 mm mercury).

	Air Permeability (ml/min/sq cm)	Source from Which Computed
Calf, chrome-tanned		
In equilibrium with 64% RH	53	Ref. 43
In equilibrium with 98% RH	89	Ref. 43
Side leather, chrome-tanned		
From grain side	89	Ref. 44
From flesh side	91	Ref. 44
Cow grain, vegetable-tanned	595	Ref. 42
Sheep, vegetable-tanned	218*	Ref. 42

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* Under 5 cm water gage pressure

The relatively low pressure differential of 25 inches of water causes the leather to assume a domed appearance that influences the results (43). Finishes sharply reduce the air permeability of leather, and patent leather and impregnated leathers are impermeable to air even when under considerable pressure or with one side facing a high vacuum.

The pressure applied in obtaining the results noted above, even though low, appears exceedingly high when related to wind velocity. Water pressures compare with wind velocities as follows:

Water Pressure (in)	Wind Velocity (mi/hr)	Wind Velocity (ft/sec)
0.5	32	47
5.0	92	135
10.0	142	208
140.0	500	734

A storm creates air movements of from 64 to 72 miles per hour and assumes hurricane proportions at over 73 miles per hour. Even at 32 miles per hour, winds are considerable. At this level of air turbulence, the QM Leather Laboratory found that no air passed through unfinished or finished upper leather. At wind velocities approaching 100 miles per hour (5 inches water pressure), about 10 ml/min/sq cm will pass through. Glove leather is more permeable; at 0.5 inches of water pressure, from 3 to 6 ml/min/sq cm of air will pass through, at 5 inches of pressure, from 25 to 50 ml/min/sq cm of air will pass through. Air porosity is apparently negligible in footwear, not only in normal weather but even when winds reach gale force.

In this connection, it is appropriate to point up a fallacy prevalent among technologists who prepare leather replacement materials. Frequently they provide such material with innumerable fine perforations in order, as they say, to make it "breathe" like leather. Actually, leather is not at all porous in this sense and does not have air passages such as a perforated material of comparable thickness would have.

3. Water Resistance

Leather for functional footwear is expected to "keep the feet dry" by resisting moisture from the outside and by absorbing moisture (perspiration) from the inside and allowing it to evaporate. For the greatest number of wearers to be assured of the greatest degree of comfort, a compromise between these two somewhat conflicting requirements must be found.

Makers of civilian footwear often disregard these problems. Uppers made from patent leather, cordovan, or even vinyl or other types of plastic do not allow water vapor to pass. At the other extreme, perforated, open-toed, straw, and canvas shoes circumvent the problem by providing direct access of air to large areas of the foot surface. But military footwear must enclose the whole foot, have a box toe for added protection, and must "stand up" under conditions where perspiration or a wet ground surface are encountered.

Normally, leather is in equilibrium with its environment and carries about 10 or 12 percent of its weight in moisture. It will absorb additional water and transmit it to the surrounding air as water vapor unless special treatments are applied to make it water resistant.

The present combat boot offers little protection against water penetration from the outside. Only the rubber-composition outsole, which one might call the first line of defense, is water impermeable. Water can enter the upper parts of the boot rather freely, either along the seams or through the leather, which is a fatliquored, sparsely re-tanned, black chrome side leather about 5 ounces (2 mm) thick and worn grain side out. The future combat boot will have a Paracril-ozo rubber sole to which the upper leather will be molded directly, hence leakage through the welt seam will be eliminated. Also, the upper leather will be factory-treated to make it moderately water resistant. The tropical boot is already using this kind of leather. The treatment not only keeps the water out but it also keeps the leather supple, for leather which is frequently waterlogged becomes stiff and tends to crack.

Many methods have been developed for measuring the water resistance of leather. They include static and dynamic tests.

"Static" tests consist of immersing the leather for a given time and observing the weight or volume increase (46a, 47). Originally this test was designed for sole leather but it can be used for other leathers also, particularly if the vessel with the water and specimens is agitated. A refinement of this test consists of placing a leather specimen in the aluminum cup ordinarily used to determine water vapor permeability, but filling it with water instead of a desiccant (48). This assembly is agitated in a tumbler for a specified time. Differences in pickup between untreated leather and leather treated with a water-repellent or with a water-resistant material on the surface facing the water in the cup are readily detected. When unimpaired, absorption should run between 40 and 100 percent by weight of the leather. On treated leather, it may vary from 10 to 30 percent. Repeated testing causes the water absorption to decline (49). It is not known whether this decline, which is very pronounced under laboratory test conditions, occurs also in footwear while it is worn.

"Dynamic" tests flex the leather under water. Grain-out and flesh-out military leather has been so tested, but the latter type, vegetable-retanned and stuffed with fats and oils, is now obsolete, its weakness having been revealed by this type of test. The first dynamic test method, and one that is still widely used, was designed by M. Maeser of the United Shoe Machinery Company (46b, 50). Other methods based on the same principle differ in the size of the leather specimens, in that the water is either outside or inside the cupped leather, and in the speed or angle of flexing (and this latter difference is the most important). Leaks are observed visually or by closing an electric circuit either in an ohmmeter with leads by which an operator continuously probes the sample or in the leather cup which contains either lead shot or a roller chain and machinists' waste (51-56). In the Maeser tester, initial water penetration occurs faster when the leather is inverted and the water is inside instead of outside the cup formed by the specimen (49). Sharp declines in water resistance have been observed after repeated testing of the same specimen. Some of these phenomena probably depend on the type of treatment.

The first dynamic tests were conducted with stuffed leathers that did not allow water to penetrate until after a few hundred flexes—an improvement over standard leather that usually leaks after 40 to 100 flexes. However, with the introduction of chemical treatments of leather, the dynamic test methods produced no penetration at all even after more than 10,000 or even 100,000 flexes (49, 51). For specification purposes, it is necessary to limit the time consumed by a test. According to results obtained by the National Bureau of Standards, screening of leather for resistance to water penetration on the two most popular testers, the Maeser and Dow Corning, need not exceed 10,000 and 3,000 flexes respectively (51). Treatments that permit no leaks under these conditions may be considered successful. Directions for the proper use of the treatment materials as given by their manufacturers are quite explicit and must be closely followed for optimal effect: applications in the aqueous phase are carried out in the coloring drums; after the leather is dry, applications are by one-side surface treatment (49, 56) or by full immersion (57). Some treatments impart additional properties to the leather, for instance gasoline and oil resistance (49). The treatment that offers the greatest protection for leather is impregnation with urethane prepolymers. This treatment, which has been worked out during the last two years by the QM Leather Laboratory, combines resistance to water, gasoline, oil, and corrosive chemicals, scuff resistance, and a high degree of resistance to CW agents, especially mustard*.

4. Water Absorption, Water Vapor Absorption, and Water Vapor Permeability

Leather disposes of the moisture produced by perspiration by absorbing it and allowing it to evaporate when the shoes are not worn or by allowing it to pass through in vapor form and to thus mingle with the atmosphere while the shoes are being worn. Laboratory methods for measuring the water absorption and water resistance of leather have been described above. Water absorption has also been measured by wear trials in which socks and shoes or boots worn by test subjects are weighed before and after walking, marching, or light or heavy exercise, but these results are inaccurate unless corrected for changes in the relative humidity of the atmosphere that occur during the experiment. Frequently this precaution has not been taken. For correct results, one shoe and sock are

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*Mustard resistance is being evaluated in conjunction with the Army Chemical Center.

worn as usual while the other shoe and sock are worn outside an impermeable barrier so that their weight changes depend only on atmospheric conditions. This technique recommends itself since the left and right foot of one subject sweat at about the same rate (26). Curves showing the equilibrium moisture content of chrome leather at 20-degree (F) intervals between 80° and 140°F have been published (58a). Surprisingly, at higher temperatures where a given volume of air carries more water vapor than at room temperature, the equilibrium moisture content of the leather is lower. The QM Leather Laboratory confirmed these findings by measuring initial weight gains of leather transferred, at various temperatures, from an atmosphere of 50 percent relative humidity to one saturated with water vapor.

Readings on the curves mentioned above show that, at about 50 percent relative humidity, increases or decreases of 10 percent in relative humidity would change the weight of 280 grams of upper leather (approximately the weight of leather needed for one size-10 boot) by about 7 grams. However, it would probably take at least a week for the boot to be in equilibrium with the new atmosphere. In a wear trial extending over 8 hours, the change would be a mere fraction of the total. No such changes take place in the rubber outsole, of course, but they do occur in the leather insole and midsole (if present) but at a slower rate.

Water vapor permeability is determined in the laboratory by measuring the weight increase of an assembly surrounding a leather diaphragm with one surface exposed to air held at a controlled amount of relative humidity and the other surface close to but not in contact with either a desiccant (preferably calcium chloride) or a water surface. The surface of the leather that would face the sock, i.e., the flesh side, except in boots using flesh-out or suede leather, is exposed to the more humid atmospheric conditions. For instance, Method E32 of the American Leather Chemists Association, which was taken over by the Federal Specification (46c), requires that this side be exposed to 50 percent relative humidity at 23°C. The British method requires 70 percent relative humidity at 21°C (70°F) and the Canadian method 90 percent relative humidity at 35°C (95°F), the latter representing an obvious attempt to simulate conditions inside a boot or shoe as closely as possible. Objections can be raised against two of these methods on the ground that they do not reflect actual service conditions, the Canadian method being an exception. The atmosphere next to the foot is more humid that 50 percent and values of from 73 to 85 percent were found in the more confined parts of oxford-type shoes (26, 31a). Also, the temperature next to the foot is near body temperature and not as low as specified by most methods. The reason for the discrepancy probably is that the conditions were adopted from textile methods and with textiles the need for measurements near body temperature generally does not exist. Finally, the use of desiccants on the "dry" side of the leather is unrealistic because very few climates have a very low relative humidity; in fact, most comfort problems arise in rather humid zones where 50 percent relative humidity is on the low side.

Important in this connection are findings of the QM Leather Laboratory that half as much water vapor passes through leather from an atmosphere with 50 percent relative humidity toward absolutely dry air as from an atmosphere saturated with water toward an atmosphere with 50 percent relative humidity. Steep gradients are ideal for the transmission of water vapor but normally the gradient is small. In hot, humid climates, the gradient is negligible; therefore, all the moisture condenses, and this gives rise to comfort problems. Most of the United States studies of water vapor transmission have been made by methods using a desiccant and not water and they therefore arrived at lower values. Leather technologists have employed many refinements, like controlling the air circulation, stirring the desiccant, using moist cotton, etc. (59-62).

The only method seriously competing with the standard method of the Federal Specification for leather is the "control dish" method, so called because it uses controls to measure the resistance to water vapor transmission of the air layer in the experimental apparatus. Thus, it distinguishes the resistance of the material to be tested from that of the air layers adjacent to it. Originally, this method had been designed for textiles (63), but more recently it has been suggested for leather also (64). Test results indicate how many centimeters of still air have the same resistance to the diffusion of water vapor permeability. This method is being investigated at present by the British Leather Manufacturers' Research Association and by the QM Leather Laboratory. It requires extreme care in handling the assembled apparatus, especially when the air layer between the water and the diaphragm is only 4 mm wide. Maeser, who used a modified version in a comparison test (62), was very outspoken in his criticism of using this method with leather, which has a much lower water vapor permeability than most textile materials. While many of the data published on water vapor permeability (59, 64-67) are expressed in grams/25 sq cm/100 min, for the sake of uniformity this unit has been converted into grams/sq m/day (a more widely accepted unit today) by applying the factor 5760 (59).

Results obtained with leather samples by three different methods of testing (all using a desiccant facing the grain) are compared in Figure 1, adapted from a Canadian study (31b). For the leathers tested, with transmissions ranging from 200 to 1100 grams/sq m/day by the American Leather Chemists' Association method, the average rate of vapor transfer in the Canadian method was about 4.2 times the rate observed in the American Leather Chemists' Association method. The linear relationship between them shown in Figure 1 probably does not hold for low water vapor transmission. Most of the Canadian leathers, even those two which had been treated for water resistance, were remarkably vapor permeable. Such is not the case with most leathers examined at the QM Leather Laboratories, as Table VI shows. In this table, the different leathers are identified as closely as possible and are divided into three groups,

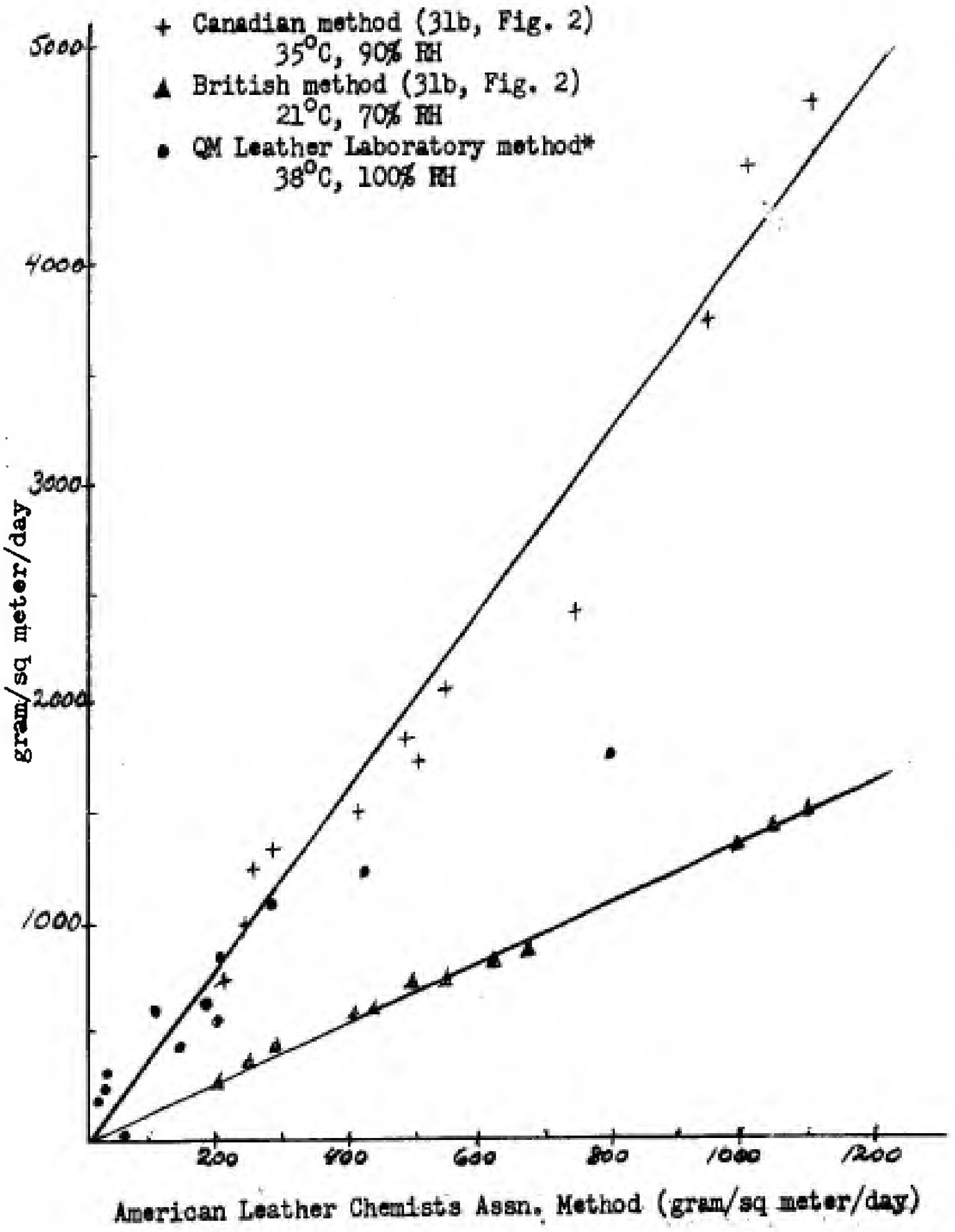

Figure 1. Water Vapor Transmission by Different Types of Leather

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* From Table VI (p. 22) except for data on patent leather

NOTE: American Leather Chemists Assn. method is at 23°C, 50% RH according to tannage, with the magnitude of the increase in water vapor transmission at the higher temperature and relative humidity level determining the place of each leather in the first two groups.

TABLE VI. WATER VAPOR PERMEABILITY OF LEATHER

(QM Leather Laboratory results in gram/sq m/day
Method 8011 of Federal Specification KK-L-311)

	23°C and 50% RH	38°C and 95% RH	Times Increase
Chrome side leather			
Patent leather			
Semi-lustrous	9	170	19
High gloss	5	80	16
Standard Army upper			
Polysulfide-treated	50	320	6.4
Urethane -impregnated	50	290	5.8
Special (TITEKOTE) finish	110	630	5.7
Regular finish	200	830	4.2
Urethane-impregnated and urethane-finished	45	190	4.2
Silicone treated	190	630	3.3
Regular finish, Navy fleet shoe (treated for water resistance)	205	525	2.6
Regular finish, dress oxford	790	1700	2.2
Chrome Retan side leather (stuffed)			
Flesh out (former Marine boot)	270	1100	4.1
Grain out (former Army boot)	150	430	2.9
Vegetable-chrome lining leather			
Lining for dress oxford	480	1200	2.5

The results of Table VI are also recorded in Figure 1 (except those for patent leather), but no curve or straight line could be drawn, reflecting the general trend as with the Canadian results. Apparently some leathers with a negligible water vapor transmission at 23°C and 50 percent relative humidity are able to pass considerable quantities of water vapor in a hot, humid environment. In other words, they are actually more comfortable than would be expected from laboratory tests at standard conditions. From the military point of view, this is very important. Some of the lowest water vapor permeability values in Table VI are associated with a urethane treatment, yet these leathers, when used in combat boots, did not cause discomfort because of excessive perspiration. Instead, the main criticism was their greater stiffness, which is a frequent side effect of impregnations or surface treatments.

Studies on the water vapor permeability of leather have, of course, not been limited to leathers for footwear. Figures obtained on gloves that caused profuse sweating after working in them for 10 minutes led to the postulation of a threshold value of 400 grams/sq m/day (65) for water vapor transmission. The chances of arriving at a similar value for military footwear, based solely on the water vapor permeability of the upper leather, are slim for two reasons: first, footwear leather is of two different kinds, the upper and the insole; and, secondly, the leather in footwear is twice as heavy as that in handwear (5 to 6 ounces as against 2-1/2 ounces) and hence it can absorb and hold more water, unless treated to repel or resist water. In fact, it has been shown that the water vapor permeability depends at least in part on the ability of the leather to draw moist air into the drier center layers and to deliver water from there to the outer surface, from whence it is lost to the air (62). Most of the water vapor moves through the capillaries of the leather. Diffusion through the solid fibers is insignificant except perhaps at very high humidities (68).

In demonstrating the water vapor permeability of leather, observations on its air permeability are not useful because at normal atmospheric pressure shoe leather is practically impermeable to air (p. 15).

A very important aspect to be considered in assessing the role of water vapor permeability is that often in summer or winter the humidity is very high and the air cannot carry any additional water vapor transmitted through shoe uppers. Under these circumstances liquid water accumulates inside the capillaries of the leather, surrounding the fibers with multiple layers of water molecules. Only when the relative humidity of the air drops again can this moisture in the leather gradually escape.

It is not known what role the volume of air surrounding the shod foot plays in the speed of water vapor transfer from the foot to the leather and from the leather to the outside. One would think, however, that the daily changes in this air volume would be of importance. A comfortably fitting shoe encloses about 100 ml air, but the volume of the foot increases about 4-7 percent, as was found by SATRA in a modest two-subject test (69), leaving only an air volume of 45 to 65 ml in the late afternoon. At any one time 100 ml of air at 32°C, saturated with water vapor, holds only 3.4 mg water. At 73 to 85 percent relative humidity, which prevails in shoes (p. 19), it is considerably less. During wear, the quantity of water vapor transmitted, by comparison, is 25 grams in 7-1/2 hours (Canadian estimate, p. 19) or about 1 mg/sec. At this rate, the air in the shoe or boot evidently can pass on water vapor without becoming saturated. During exertion, this figure might double or triple; the air becomes saturated with water vapor and some liquid perspiration may actually trickle from the foot into the shoe leather.

5. Resistance to Perspiration

In considering the action of perspiration on leather, the effect of the sweat solutes must be studied apart from the effect of the water. The water produced by sweating acts no differently than water from other sources with which leather comes in contact, resulting successively in wetting and drying of the leather. The action of the water soluble matter in sweat, on the other hand, is cumulative, i.e., the concentration of the components is built up in the leather. High levels of sweat components, therefore, are generally used in artificial perspiration solutions, but often without regard to the relative proportions which characterize their occurence in natural sweat. Moreover, in nearly every study of the action of sweat solids, the artificial sweat solution has a different composition (58b). Some of the solutions have become national standards in a number of countries.

We have already seen how leather can more or less successfully cope with the physical action of sweat, thanks to its capacity to absorb water in liquid or vapor form and to transmit water vapor. Leather ordinarily is also resistant to the chemical action of sweat, otherwise it would not be the material universally used for footwear, but this resistance has certain limits unless measures are taken to improve it. After observing frequent failures of the vegetable insole, for instance, the Armed Services now require the use of a certain amount of chrome in insoles (70). The chrome is preferably used as a retannage and not as a pretannage (71, 72). Alum as a retanning agent improves durability when combined with vegetable blends (73) and with lignosulfonates (74). A formaldehyde alum retannage (75), or the deposition of a urea formaldehyde resin (72) or of cationic tanning agents (76) has also been recommended. In recent wear trials, a combination of chrome with an unspecified syntan was rated as better than a chrome retannage (13). At the present state of our knowledge, chrome retannage seems to be the most practical treatment available. Economics stand in the way of any others, with the possible exception of aluminum but, unfortunately, there is a lack of basic information as to how to fix this in vegetable leather properly.

Several testing devices and testing methods have been published which are supposed to predict the durability of insole leather (58c, 77). The results obtained on some of them could not be reconciled with field test results; others were never compared with wear trials. In the QM Leather Laboratory, a simple test consisting of heating insole leather to 150°C (302°F) for two hours and bending it immediately afterwards over various mandrel sizes (1-1/2, 1, 1/2, and 1/4 inches in diameter) showed a better agreement with wear trials than any other test method (77).

The symptoms of insole deterioration are darkening, cracking, dimensional changes, and brittleness. The insole may break up into pieces and force the wearer to discard the shoe or boot prematurely, or it may develop an objectionable odor. The darkening of the color is caused by a slow increase in the pH of the leather due to the neutralizing effect of the ammonia in the perspiration. Surprisingly, no great accumulation of sweat solids, especially of salt, takes place in the insoles because the socks leach out the water soluble matter and each time they are changed they remove some of it (13, 58c). These findings support the view of the QM Leather Laboratory that the laborious testing of leather with artificial sweat solutions is inconclusive and dubious unless followed by a wear test to point up the validity of the test method.

Whereas attempts to attach the blame for insole damage on the sweat solids only, particularly on urea (16, 17), are unconvincing, upper leather damage is without doubt often caused by a single constituent of perspiration: lactic acid, which has been identified in large quantities in badly damaged chrome uppers. The detanning action of lactate on the chrome collagen complex has been amply demonstrated (58d). While here the culprit is known, no cure for the damage has as yet been suggested. What is obviously needed is a tannage with an extremely stable cationic chrome complex. It has been hinted, but without experimental evidence, that sulfophthalates might be useful for this purpose (15).

On perspiration-damaged uppers, cracks appear first in the vamp area, especially near the fifth toe. White shoes, which are low in chrome, seem to be more susceptible to perspiration damage than footwear made with fully chrome-tanned upper leather. Unserviceable shoes are often returned to the manufacturer with the assumption that the damage is the fault of the leather, but SATRA's experience is that the blame rests primarily on the wearer (15).

The leather industry has yet to be persuaded to make a highly sweat-resistant upper leather, for the majority of shoes wear out before perspiration damage appears. As a rule, military footwear, too, wears out so fast that perspiration damage to uppers is rarely seen.

6. Dimensional Changes

Customarily, dimensional changes are thought of as being important only to those who buy and sell leather. Occasionally, differences in footage in a shipment of leather may be caused by expansion or contraction because of atmospheric conditions. Extremes in humidity may cause chrome leather to gain or lose as much as 10 percent in area. Vegetable leather rarely expands more than 3 percent (41b). These changes are gradual and require several days until the new equilibrium is reached (78). Data on dimensional changes in many different kinds of leather were collected 30 days after their exposure to a new relative humidity level (41b), but there is no way of knowing how many days before this the leathers had reached equilibrium.

Nevertheless, dimensional changes in chrome upper leather have a bearing on comfort. In the course of a day, while absorbing up to 50 percent of its weight in perspiration, chrome leather expands sufficiently to compensate for the increase in foot volume mentioned above (p. 24). Theoretically, increased humidity may add one whole size to shoes across the vamp (79). In the sole area, this is not serious because of the greater area stability of vegetable leather.

High temperatures also will cause leather to expand, but to a much smaller degree. The coefficient of linear expansion due to temperature is only about 3.10^{-5} per 1°C and varies little with the type of tannage or with the moisture content of the leather. This amount of expansion is too small to affect comfort appreciably. Even a temperature rise of 50°C causes only 0.15 percent of linear expansion, or about 1/40 inch per shoe (80).

7. Resistance to Stiffening

The consumer constantly stresses mellowness and "temper" as important leather qualities. Experienced sorters grade upper leather by subjective criteria but the Tanners' Council laboratories have shown that instruments also can distinguish between leathers with respect to these qualities (81). Military upper leather until recently had no requirements for mellowness and still has none for temper. Sylmer-treated upper leather for the tropical boot, however, must be tested for stiffness using the Tinius-Olsen Stiffness Tester and Method 4211 of Federal Specification KK-L-311.

Polysulfides and polyurethanes, some of the most effective of the leather impregnation materials, have a distinct stiffening effect. In a wear test conducted by the QM Field Evaluation Agency (82), boots with polyurethane-treated uppers were found to be too stiff to be comfortable, although the boots could be worn for the entire wear trial period. Nevertheless, this grievance will have to be seriously considered in future tests of treated upper leathers.

The stiffening of leather at low temperatures is due to a hardening of the oils and greases used for its lubrication. These oils and greases comprise about one-third of the weight of the Army Retan boot of World War II but constitute only one-tenth, and often less, of the weight of the chrome side leather now used. There is no record of any discomfort during cold weather with the old type of boots. Neither are there any laboratory data showing differences in stiffness or firmness between the two types of leather, old and new.

8. Heat of Wetting

Heat of wetting is another reaction of leather to water that has been linked to foot comfort, but perhaps with too much emphasis. It is true that the temperature of leather and of any comparable material goes up when it takes up water suddenly or when there is a sudden rise in the relative humidity. The integral heat of wetting is about 22 calories per gram for vegetable leather and about 40 calories per gram for chrome leather (83-86). This amount of heat develops when absolutely dry ground leather is wet with water at 25°C, both leather and water being present in equal quantities. However, the leather receives only two-thirds while the water receives one-third of the total heat of wetting, e.g., chrome leather would receive only 27 of the total 40 calories. Temperature increases actually observed on a variety of leathers varied from 12° to 20°C (86).

Theoretically, the temperature should rise more when water vapor instead of liquid water moistens finely ground dry leather because the heat of condensation of the vapor (1 cal/gram water) is added to the heat of wetting. Thus, 100 grams of leather at 4 percent moisture would, by taking up 10 percent more water from the vapor phase, produce 6100 calories or get 130°C warmer (86)! In a small experiment, a temperature rise of 5.7°C has been observed after hydration of chrome leather with liquid water as against a rise of 27°C after hydration with water vapor (86). In another laboratory (87), in which moist air was passed over chrome shavings, the temperature of the leather rose only 14°C and then it began to fall. Under less controlled conditions, and especially when the leather has not been finely ground, the increase would be even less. For instance, the temperature of chrome retan leather rose a mere 2.6°C in changing from 32 to 75 percent relative humidity and only 9.3°C in changing from 0 to

96 percent relative humidity (88), but these situations are difficult to imagine in actual use.

Another point to remember is that, if one steps into a puddle, the shoe leather does not become wet so suddenly that the heat of wetting would be felt by the wearer. In fact, at least 15 minutes must pass before a shoe or boot that is fully immersed in water has picked up from 15 to 20 percent of its weight, and this is ample time for any heat of wetting to dissipate into the water. Also, if the water is cold and penetrates the boot quickly, a sensation of cold is much more likely to be felt than any heat of wetting.

D. COMFORT PROPERTIES OF FOOTWEAR

Leather is procured by the Armed Forces on the basis of specific tests, such as those we have mentioned. These tests are designed for a particular end use. After footwear items are made up, subsequent examination is limited to establishing compliance with specifications that govern their construction; thus, many studies about footwear have dealt with the system as a whole and not with the individual components. An attempt has been made here to integrate this type of information with that which has emerged about the physical mechanism of the foot and the properties of leather.

1. Perspiration Absorption

The quantity of sweat remaining in shoe uppers after a 7- to 8-hour day varies considerably. In a recent study (5b), it was as high as 22.5 gm. Assuming a 60 sq in inner surface of the leather (p. 6) and a weight of 1 gm/sq in, the 22.5 gm would increase the moisture content from 12 percent, which is normal for 50 percent relative humidity, to about 50 percent. This increase should not cause discomfort since leather can hold its own weight in water, as has been stated before. In fact, even when leather is heavily impregnated from the grain inward and has become non-absorptive to a depth of one-third of its thickness, the remainder can be expected to gain up to about 100 percent of its weight from absorbed perspiration.

Commercial treatments have not always preserved the ability of leather to pick up moisture from the foot even though the vapor absorption and transmission rate of the leather remained high and thus would be considered adequate for comfort. It has been assumed that vapor transmission automatically rises when absorption is low but all existing evidence is to the contrary; in fact, preserving the absorptive capacity of leather on the flesh side is one of the basic tenets that must be upheld in promoting comfort in footwear.

It is very important to give shoes an opportunity, during out-of-service hours, to release the moisture they contain and to allow them to resume equilibrium with the atmosphere. The rate at which moisture is released by a combat boot under various levels of humidity is not known, but it is apparent that the rate is much slower than that from leather specimens because the moisture accumulation is inside where the air circulation is poorest.

Another important point to be remembered is that, just as in leather, the transmission rate from uppers is affected by the humidity gradient between the interior of the shoe and the atmosphere. If the humidity within and without the shoe is similar, no water vapor will diffuse out of the leather but rather it will condense in the leather. It is apparent, therefore, that it is necessary for shoe uppers to be capable of absorbing water.

A seldom discussed complication in footwear is the drastic reduction in water vapor transmission that occurs when two layers of leather are present, as in a leather-lined shoe or in a shoe with two toe caps of the same type of leather, one above the other. (The hindquarter of the military dress shoe is leather lined, but double toe caps are no longer a combat boot feature.)

The combined water vapor permeability of any two layers of leather can be calculated with the help of the equation:

$$\frac{1}{D} = \frac{1}{D_1} + \frac{1}{D_2}$$

where D_1 and D_2 are the individual water vapor transmissions of each layer (24). For instance, if a leather has a water vapor transmission of 200 gm/sq m/day, two layers would have:

$$\frac{1}{D} = \frac{1}{200} + \frac{1}{200} = \frac{1}{100}, \text{ or } D = 100$$

If this leather is lined with a leather that has a water vapor transmission of 600 gm/sq m/day, the combined water vapor transmission would be 150 gm/sq m/day, or 25 percent less than the unlined despite the fact that the lining is three times as vapor permeable as the leather. Cotton linings offer negligible resistance to water vapor diffusion and do not affect that of the leather except where they are glued on. However, when cement or latex is spread over the entire vamp lining before it is brought into contact with the leather vamp, a practice not uncommon in the shoe industry, not only does the water vapor permeability of the vamp become negligible but its absorptive capacity is limited to the fabric and thus it is probably no longer able to cope with the sweat production during exercise.

In the absence of stress, the insole receives from 0.5 to 0.8 grams per hour of perspiration fluid (26). Distribution is uneven, with more entering the ball and heel areas, where the sweat glands are concentrated and where the greatest pressure is exerted during standing or walking. Assuming, as earlier (p. 6), that the area of the sole is 40 square inches, and anticipating that one-quarter of the insole receives two-thirds of all the perspiration, or 0.8 gram per hour (the highest of the above-quoted figures), the pickup is $\frac{0.8 \cdot 2}{10 \cdot 3} = 0.053$ or, in round figures, 0.05 gm/sq in/hour, or 0.5 gm/sq in/10 hours.

A leather sole that is 9 irons* thick weighs about 120 grams, or 3 gm/sq in. The insole would ordinarily gain a little more than 0.5 percent in weight per hour but certain areas could gain as much as 1.7 percent per hour, or over 15 percent per day. Not all of this moisture would stay at the surface, of course, but its distribution within the leather is open to speculation since freshly worn insoles have never been analyzed layerwise for their moisture content**. It has been stated that some of the moisture diffuses through the insole and condenses in the cavities underneath it, since the bottom filler and the composition outsole would not allow moisture to dissipate further and a leather outsole would allow only a very limited amount of moisture to escape (5f).

For popular consumption, the role of a leather outsole has often been exaggerated, and here, too, "breathing" has become a standard term by which its alleged function is described. Actually, the water vapor transmission through a 10-iron outsole wetted with cotton wool on the flesh side is only 16 percent of that of the chrome- or vegetable-tanned upper leather (35, 42). After impregnation with a rubber resin mixture, which is required today for the dress shoe sole, this figure would be even smaller. Water vapor transfusion through the soles of military footwear, therefore, does not appreciably affect the water balance.

A theoretical calculation made in connection with a Canadian field test (25) in which leather-soled boots were worn supports this conclusion. The water vapor permeability of the sole was found to be, in gm/sq cm/hr, equal to $\frac{8(A-B)}{R}$, where A and B are the water vapor pressures near the foot and in the atmosphere respectively, while R is the resistance of the sole construction to water vapor penetration in centimeters of still air of equal resistance. At 30°C, A was 31.5 mm; at 2°C and 50 percent relative humidity (the test took place in the late fall), B was 2.6 mm. The result, 8.3 gm/sq m/hr, or 0.0053 gm/sq in/hr, represents only 10 percent of the perspiration pickup by the more exposed parts of an insole. At higher temperatures and humidities, B becomes larger and the water vapor transmission, therefore, becomes even smaller.

The absorptive capabilities of a footwear item under conditions of stress can be determined by a simple non-destructive test designed at the QM Leather Laboratory. A shoe or boot of known weight is mounted on a platform that can be gently rocked by a horizontal movement, and 750 ml of water at 25°C (77°F) are poured into it. (The platform of a "clinical

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* 1 iron equals 0.021 inches.

** An instrument of potential usefulness for this purpose, made by the Kaydel Corp., 122 Liberty St., New York 6, has been described (89).

oscillator" will accommodate up to four shoes or boots.) After 15 minutes, the water is poured out and the shoe reweighed. The difference in weight represents the quantity of water absorbed. If scales are not available, the volume of water poured in and out may be measured in a graduated cylinder and compared. The few milliliters of water that collect in the footwear after the bulk of the water has been poured out should be added to the rest. It will require from two to four days for the shoe or boot to dry out. This period may be shortened without harm to the leather by heating the items in a draft oven at 38°C (100°F).

An untreated combat boot (size 10) absorbs 30 ml of water in 15 minutes. Any treatment applied from the grain side does not affect this value. However, a treatment applied by total immersion or from the flesh side reduces the water absorption. Rubber cement applied indiscriminately to the seams on the inside (a common practice for hunting boots) has the same effect and can seriously offset the other comfort features of an expensive footwear item. The absorption ability that remains is essentially that of the insole which, in military footwear at least, is degrained and without any finish and is therefore highly absorptive. Boots with uppers that have been immersed in a silicone solution for water resistance will absorb only between 10 and 12 ml of water in 15 minutes. While it is true that perspiration is rarely, if ever, excreted in this amount in so short a time, the figure is "too low for comfort", since it indicates that any liquid sweat absorption that occurred would be restricted to specific parts of the shoe or boot—in most instances to the insole.

Box toes and counters would reduce absorption but the effect would be relatively small since water vapors emanating from perspiration have a tendency to migrate inside the shoe and would either enter the vamp leather behind the box toe or rise up around the counter.

Water vapor absorption of a whole combat boot was also measured at the QM Leather Laboratory. A boot upper and insole suspended at 38°C in a water-saturated atmosphere absorbed 4 grams of water vapor during the first hour and 1.5 grams during the next hour, i.e., the most rapid absorption of water vapor exceeded 1 mg/sec, but decreased sharply with time. The figure of 1 mg/sec has already been calculated from the hourly rate of sweat (p. 9). As was pointed out at that time, this rate was relatively low and the boot experiment again indicates that, at peak rates, perspiration in liquid form passes into the shoe leather.

Many investigators have studied the absorption of perspiration by footwear. Gran (26) recorded hourly increases in the weight of shoes. An isolated finding was a 3-gram pickup of perspiration by a leather sole over a 7-hour period, although he also has reported drastic decreases in pickup over longer periods. Other investigators measured sweat absorption using different types of sole and upper material and sometimes strenuous exercise to increase the sweat flow. Results of six of these, stated only as gains in weight of the shoe and sock without (except for the oft-quoted SATRA study (5)) considering the distribution of sweat pickup between the uppers and sole, are summarized in Table VII. Two studies (85, 86) allowed a direct comparison between different types of footgear by testing them under the same set of conditions; two followed essentially a single set of conditions (2, 31d); and one varied the conditions and the footgear simultaneously (92).

Table VII shows 1) a distinct difference between the sweat pickup from quiescent (Nos. 2, 5, 16) and from mobile (Nos. 4-7, 12-14, 17) subjects and the very low sweat content of the socks; 2) except for Nos. 7 and 11, a markedly higher sweat content of footwear with leather uppers (Nos. 6, 10, 14) than of that with non-leather uppers* (Nos. 4, 5, 8, 9, 12, 13); and 3) the highest sweat pickup by leather boots (Nos. 6, 17) in tests that included a brisk march. In regard to the last point, it is unfortunate that the rise in sweat output at the start of the marches and the gradual decrease during the later stages was not recorded. It is safe to assume, however, that about 10 grams of sweat was absorbed during the first hour.

2. Weight

Footwear should be as light in weight as is compatible with the requirement for it to give sufficiently durable protection. Treadmill experiments at the Harvard Fatigue Laboratory have shown that the addition of one pound to the weight of a man's footgear raises his metabolism as much as the addition of four pounds to his pack (1d).

The new vulcanized combat boot is lighter than the standard combat boot but the new vulcanized tropical boot differs very little from the standard tropical boot. Both are much heavier than the low quarter oxford, as will be seen below.

Footwear Type	Description	Weight/Pair (gm)	Weight/Pair (lb)
Combat, standard	Composite sole	1950	4.3
Combat, vulcanized	Paracril-ozo sole	1700**	3.75**
Tropical, standard	Composite sole	1600	3.5
Tropical, vulcanized	Paracril-ozo sole	1550	3.4
Low quarter oxford	Impregnated leather sole	1140	2.5

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* With the exception of polyvinylchloride uppers in Nos. 7 and 11.

** Uppers: 740 gm (1.6 lb), including 140 gm (5 oz) for the insoles
Sole: 900 gm (2.0 lb)
Steel shanks 60 gm (2.1 oz)

TABLE VII. ABSORPTION OF SWEAT BY FOOTWEAR

Test No.	Temp. (°F)	Humid. (% RH)	Hours Worn/Test (no)	Boots Tested (no)	Type of Footwear Material: Uppers	Type of Footwear Material: Sole	Sweat Absorbed (gm/foot): Sock	Sweat Absorbed (gm/foot): Shoe	Remarks and Source
1	79*	92*	8	10	Leather	Leather	19**		Various occupations; oxfords (92)
2	72*	41*	8-9	12	Leather	Rubber	22**		Office workers; oxfords (92)
3	72*	43*	2	38	Canvas		25**		Tennis Shoes (92)
4	69**	65**	2.5	8	Cotton drill	Composition	4	9	A 6-mile march included (90)
5				8	Spun Nylon	Composition	7	10	
6				8	Army Retan	Leather	12	22	
7				8	PVC	Leather	16	25	
8	79	50	4.5	16	Cotton drill	Composition	10	17	A hot chamber test (90)
9				16	Spun nylon	Composition	9	16	
10				16	Army Retan	Leather	15	20	
11				16	PVC	Leather	15	20	
12	50**	55**		10	Canvas	Rubber	5	10	A 2½-hour road march preceded by a 50-mile march in 61°F climate chamber (91)
13				10	Terylene	Composition	5	8	
14				10	Army Retan	Composition	5	14	
15			7.5		Leather***		2	10	Sedentary occupations (31d)
16			7	17	Leather	Leather	0.5	9	Office workers (2)
17	43**	85**	7-8	11	Leather	Leather or rubber	1.5	25	A 15-mile march included (5)

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* Maximum

** Averaged from individual figures in the original

*** Fatliquored chrome tannage

Note: Spun nylon was treated with silicone
Army Retan = stuffed chrome vegetable tannage
PVC = polyvinylchloride
Terylene = British polyester

A glance at these figures reveals that: 1) the vulcanized combat boot is lighter than the standard, 2) the vulcanized tropical boot is almost as heavy as the standard and not very much lighter than the vulcanized combat boot (the difference is 150 gm, or about 1/3 lb), and 3) boots are approximately between one and two pounds heavier per pair than low quarter shoes.

There are several ways that the weight of footwear might be reduced. First, the density of the heel plug (approximately 0.7) could be decreased. The heel plug, in the center of the heel, replaces about 22 cc of rubber (density 1.24-1.28) in each boot, hence saves only 25 grams per pair, or approximately 1.5 percent of the total weight. Secondly, a hollow space in place of a heel plug would save about 30 grams per pair, and this would be approximately the equivalent of a 4-ounce lighter pack load. The volume of this space cannot be increased without its extending into the roughened area of the leather "overlap" to which the rubber sole is molded. If the density of the rubber, which appears to be the greatest hindrance to lowering the weight of the boot, were decreased to 1.0, 225 grams (8 oz) per pair could be saved, enough to offset an additional pack weight of 2 pounds! However, low-density rubber has a low abrasion resistance, and it would not be feasible to solve the weight problem by sacrificing durability.

It is usual to treat upper leather with silicone, but this adds about 8 to 12 percent to the weight of the upper leather and increases the weight of a pair of boots by about 45 to 70 grams (1.65 to 2.5 oz). Impregnation with urethanes, with prospects of protecting against CW agents, adds about 30 percent to the weight of the uppers and increases the weight of a pair of boots by 175 grams (6 oz). This treatment would make the weight of a pair of vulcanized boots be about 4.11 pounds, i.e., 0.2 pounds less than the old standard boot and approximately the same as the silicone-treated boot. This added weight insures not only water resistance but a very high scuff resistance and excellent resistance to gasoline, oil, and corrosive chemicals and (for at least 6 hours) to penetration by mustard. The only way to balance this increase, if this is a must, would be by using less rubber for sole and heel. The use of 10 percent less rubber would reduce the weight by 90 grams (3.2 oz) per pair and make up for almost 60 percent of the weight increase due to the use of urethanes instead of silicones.

3. Distribution of Body Weight

Footwear comfort requires not only lightness but balance and sufficient elasticity to permit conformity to the shape of the foot and to its normal "pressure points". Foot pressure generally decreases after footwear has been "broken in". An American study (88) recorded pressures in six locations before and after a 3- to 4-week wear test. Pressures ranged from 16.4 to 32.3 pounds per square inch before the test and from 7.8 to 26.5 pounds per square inch after the test. Only at the base of the third metatarsal bone did the pressure rise (by 14 percent). There may also have been small pressure increases in areas not included. Pressures are more evenly distributed in a shod foot than in an unshod one, and it is the shift to an even distribution that is an important contribution to footwear comfort.

A Japanese study (94) recorded pressures as high as 36 pounds per square inch--using 20 to 35 mm heels. (The American study did not give the height of the heels used.) Obviously the higher the heel, the higher the metatarsal and great toe pressures. It is also obvious that pressure increases with loads to be carried. Men on the march carrying heavy loads may show areas of foot pressure that exceed 50 pounds per square inch but the pressure is exerted for only 40 percent of the time and for very short periods (0.2 sec per step if 2 steps per sec are taken). Any dynamic study of the interplay between the foot and insole should take this alternate pressure and relaxation into account.

Wear establishes permanent individual pressure peaks in a shoe. Feet with abnormal prominences require longer periods for this shaping since, except on the sole, only light pressures are exerted by the foot. Maeser showed (95) how this breaking-in can be demonstrated by repeatedly and rhythmically distorting a piece of upper leather in the Instron tester. Initially a load of 30 pounds was necessary for the distortion, but after 5000 cycles only 7 pounds were required. After the leather is set in a new shape, a substantially higher load is required to cause additional distortion. It is important that the shape of most shoes, and especially of military footwear, should not change too much under repeated light pressures, lest the shoe or boot "get out of shape" in a short time.

Much of the breaking-in of footwear has to do with shaping its soles to the foot. Here the hardness and elasticity of the outsole and the ease of flow of the bottom filler determine the length of the breaking-in period.

4. Water Resistance

In 1945, during the period of manpower shortage for lengthy wear tests, the idea of building a "walking machine" to test the water resistance of boots seemed very attractive (50). The upper leather available at that time was the Army Retan. This leather was so highly absorptive to water, however, that this test could serve no purpose, hence it fell into disuse for a time.

With the introduction of silicone impregnation to increase water resistance, interest in the walking machine was revived. One model, constructed by the Dow Corning Company (96), was investigated by the QM Leather Laboratory, but proved to be impractical (97); among the reasons were primarily the unrealistic angle of flex and the use of lead shot to make an electrical conducting path between an electrode in the trough (of salt water) into which the boot dips and an electrode in the shoe. In normal walking, the angle of flex is approximately 55 degrees; the machine used a 35- to 40-degree angle of flex. If the angle in the machine were increased by 10 degrees across the vamp area (by inserting a spacer beneath the portion of the clamping arm), the lead shot would interfere. Furthermore, the coating of the lead shot is readily oxidized and in this condition is up to 100 times more resistant to an electric current. It had been claimed that 30,000 flexes on this particular model would be the equivalent of the flexes during three 8-hour marches (96). Actually, about 2000 flexes are made per mile; therefore, one day alone, at 20 miles per day, would require 40,000 flexes (at the rate of 88 steps per minute and 2.5 feet per step).

Another model, from Finland, uses steel wool as a filling. This is inexpensive and can be discarded after each test (98). In the Finnish model, the resistance was fixed at 200,000 ohms, whereas in the first machine described, resistance was found to be between 12,000 and 18,000 ohms before the cut-off mechanism went into effect and by then the inside of the boots had large moist stains!

Because of the lack of a useful walking machine, the QM Leather Laboratory turned to a simple wading test for evaluating the water resistance of boots. The test boots were worn under plastic overshoes into which was poured 200 ml (7 fl oz) of tap water while the wearer performed indoor work duties. A fairly large leak would usually be felt by the wearer, but a very gradual wetting of the sock would be detected better by an ohmmeter*. After a certain period (2 to 4 hours), the increase in weight of both boot and sock was calculated. A successful water-resistant treatment of uppers and seams should keep the inside of the boot dry for several hours. In SATRA tests, the maximum period for keeping the inside dry was more than two and one-half hours (99); in QM Leather Laboratory tests, it was more than four hours. SATRA found that some silicone-treated leathers were quite water resistant in wear when the boots had sealed seams, although they leaked in the machine after a few hundred flexes (99). No explanation for these findings can be offered at this time. At the QM Leather Laboratory no such observations were made since leather treated for water resistance but performing poorly in the flexing test was considered unsuitable for further testing.

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* A multi-tester instrument with an ohm scale up to 250,000 ohm is used. One of the leads is dipped into the water inside the overshoe; the other is pressed against the bare skin of the leg above the boot. The instrument needle indicates any decrease of resistance due to a leak.

The QM wading test proved that upper leather is wettable from the outside even when successfully treated for water resistance. In a two-hour wading test, a boot made with such leather gained from 50 to 100 grams, with the socks picking up no more than 2 to 4 grams of this. Evidently, the determining factor is the water absorption by the sock; the absorptive capacity of the boot is irrelevant. This conclusion was also reached after analyzing published figures obtained by the QM Field Evaluation Agency, using a leak detector that audibly signals leaks to the wearer of a foot harness while he is traversing a shallow trough of water (100, 101). An average of two traversals and the absorption of from 3 to 14 grams of water (avg. 7.4 grams) by the socks were needed to produce the signal. In a parallel test, the test subjects were able to feel water penetrating into the foot area after an average of three and one-half traversals and the absorption by the socks of from 2 to 15 grams of water (avg. 7.8 grams). Altogether, five individuals participated in this test and all wore the new (unpolished) standard combat boots, untreated. The same boots with silicone-treated uppers did not leak until after from five to forty-six traversals. This difference does not seem great enough to justify the treatment unless the test is much more rigorous than it seems to be on the surface. No comparison was made between the number of traversals and distances walked in the rain across marshlands or over wet grass.

Strictly speaking, the above tests (QM wading test and Field Evaluation Agency leak detector) for measuring the water resistance of boots depend, at least partly, on subjective findings, namely on the ability of a few individuals to discern wetness inside their boots. Apparently the difference among individuals in ability to sense wetness has not been investigated. There is no doubt that there is such a difference and that it is "masked", in a test run in which everyone's feet will eventually get wet, by an eagerness to be among the first to score. The statement of an individual who claims he feels water reaching his feet when only 2 or 3 grams have been taken up by his socks can hardly be taken at face value. Much more extensive tests are obviously necessary. A true threshold must be established for the feeling of wetness. Unless this is done, it will not be possible to state with assurance whether an electric signalling system for detecting leaks in footwear is more reliable than subjective statements.

Other comparison tests which should be of interest to users of water resistant leathers may resolve the questions: 1) whether the use of upper leather treated for water resistance in the tannery is superior to leather treated with a water-resistant solution by the wearer, and 2) whether the water resistance of boots with treated or untreated uppers changes during wear and especially by frequent polishing.

E. SUBJECTIVE EVALUATION OF FOOTWEAR COMFORT

A lack of basic information is evident in many studies of foot comfort that have been carried out on soldiers in the field or on private individuals. Reliable information, in a scientific sense, as to the reaction of wearers to various types of footwear has never been gathered, or if it has it has not been published. Also, for the results to be conclusive, tests should be run on a reasonably large scale (36, 85) and interpretation should not favor any existing prejudice.

In the opinion of this author, two investigations merit detailed discussion, not only because of their insight into the psychology of the participants but also because they point out inherent difficulties in the subjective appraisal of comfort factors in footwear.

1. Canadian Study

In 1945, the Canadian Army conducted a test (25) of boots with regular leather soles, oil-treated leather soles, and synthetic soles, and with taps (also called "clamps") of the same three kinds. Participants, randomly selected from two widely separated camps representing a warm-dry climate and a cold-wet climate, were carefully fitted to boots of each sole type. Questionnaires were distributed weekly to each man over a 6-week period. Altogether, 1500 questionnaires were filled out.

The purpose of properly fitting each man was to insure a high proportion of "just right" and "easy" replies to the two preliminary questions about comfort: "How well do the boots fit you--just right, poor, too large, too small?" and "Were the boots hard or easy to break in?". Actually, 87 percent of the replies registered no complaint as to fit. It was only when these questions could be answered favorably that the replies to the following four subsequent questions could be evaluated with any degree of confidence:

Were the boots comfortable or uncomfortable?
Were the boots hard or easy on your feet while marching?
Did your feet sweat--much, little, none?
Did the boots burn or draw your feet--much, little, none?

Table VIII breaks down the results from the untapped shoes into those from the warm-dry and cold-wet locations. Results from the tapped shoes were substantially the same. Also included are two cross-comparisons, not broken down by location, and the water-vapor-resistance determinations for each type of sole.

TABLE VIII. COMFORT ASPECTS OF DIFFERENT TYPES OF OUTSOLES

	Resistance to Water Vapor*	Un-comf.**	Hard on Feet***	Much Sweat-ing**	Much Burn-ing**	Burning by Men Who Sweat Much**	Sweating by Men Who Burn Much**
Leather							
Regular							
Warm-dry	28	6	14	34	6		
Cold-wet		13	30	18	8		
Oil-Treated							
Warm-dry	40	9	17	34	6	32	91
Cold-wet		10	34	23	14		
Synthetic							
Warm-dry	172	20	27	45	9	52	78
Cold-wet		26	49	31	17		

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* In percentage of still air of equal resistance as complete sole (App. 4, p. 3, Ref. 25)

** Percentages or means of percentages given in original tables (Tables 8, 12, 18, and 19, respectively, Ref. 25)

*** Percentages calculated from the grand totals in Tables 20, 16, and 17, respectively, Ref. 25

The following conclusions may be drawn from the data in Table VIII:

1. Synthetic soles are less comfortable than leather soles in both warm-dry and cold-wet weather.

2. Oil-treated leather soles are more comfortable in cold-wet weather than untreated soles.

3. All soles are hard on the feet while marching in cold-wet weather.

4. As would be expected, more men sweat in warm-dry weather than in cold-wet, but the synthetic soles caused more complaints than the leather soles.

5. More men complained about sweating than about burning or drawing of the feet.

6. Cold-wet weather and synthetic soles caused more burning and drawing than warm-dry weather and leather soles.

7. It is more common for men whose feet burn much to complain about their feet sweating than it is for men whose feet sweat much to complain about their feet burning.

8. The questionnaire results placing the synthetic sole the lowest in comfort are consistent with the water vapor permeability of the soles. (Of course the possibility that prejudice might have colored the responses in favor of leather cannot be ruled out, although it was not mentioned anywhere in the report. Also unmentioned was the fact that even when the distance of synthetic soles from the foot was increased by using them as taps, this did not influence materially the scoring; thus it was seemingly a psychological reaction.)

In view of the great care exercised in the fitting of the boots, the high percentage of complaints that the boots were hard on the feet and caused sweating and burning may come as a surprise. However, the most important finding in this connection is that the feet of only one out of ten men wearing leather soles (9 percent) and only two out of ten men wearing synthetic soles (22 percent) burnt much without sweating much. The authors therefore believe that "sweating is rather a consequence of burning than its cause", and thus they consider it a sound practice to discount the responses of those subjects who reported burning without sweating.

The key to these baffling conclusions seems to be found in the fact that sweating on the sole of the foot, as anywhere else on the body, varies widely from subject to subject and men who perspire little suffer from burning without the soothing effect of sweat. Furthermore, synthetic (composition) soles are known to conduct heat to the insole better than leather (see p. 12). Also, subjects with small feet carrying the same load as those with large feet will experience higher pressures and will tend to develop more frictional heat. Data as to boot sizes and data coordinating boot sizes with burning sensations are not supplied but it is reasonable to assume that it is a combination of causes that explains the existence of a group of men more prone to foot burning than to perspiring feet. At any rate, despite the adverse responses to the synthetic soles, they have been worn by millions of soldiers not only in Canada but in the United States as well during and since World War II without leading to any widespread complaints or to serious discomfort such as sore feet and burning.

2. American Study

More recently, an American field test (102) attempted on a much larger scale an evaluation by Army and Marine troops of the standard Army Combat Boot and the standard Marine Boot, each made over the old Munson last or the new geometrically-graded Fort Knox V last. The Army and Marine boots differed principally in the type of upper leather used. The Army uppers were made of straight chrome side leather, fatliquored and sparsely retanned, worn grain out. The Marine uppers were made of vegetable-retanned stuffed-chrome side leather worn flesh out.

A controversy over which side should be exposed has been raging since World War II. When the Army changed to grain-out leather, the Marines refused to go along, although the Army had not abandoned the flesh-out boot without ample evidence that grain-out leather has many advantages, the most obvious of which was that the boot is easier to shine and is more water resistant. As early as 1946, in a test consisting of wading in from 3 to 5 inches of mud with a grain-out stuffed Army Retan boot on one foot and a flesh-out boot of the same leather on the other (102), the socks gained 9 and 16 grams respectively by moisture uptake.

There were other minor differences between the flesh-out and grain-out boots, for instance in the closure system and in the heel, but these do not concern us in this discussion.

Several precautions were taken to eliminate personal bias. The boots were fitted with extreme care. Each test subject's feet were inspected prior to the issuance of the boots and any "hyperreactors" found (subjects with clinical symptoms) were equally distributed among the groups. Size stampings in the boots were made illegible. Finally, all boots were of the same color, i.e., the buff-colored Marine boots were dyed to the black of the Army boots and fitted with black laces.

Two wear trials of different duration were conducted. The first comprised four 4-week wear periods one week apart and included both lasts. The second test comprised two 4-week periods four weeks apart and included only the Fort Knox V last. During the tests, the boots were "subjected to all of the hazards and uses normally associated with garrison field wear". After each wear trial, the men were given a questionnaire with 24 statements, each relating to a particular characteristic of the boots to be rated on a 6-point scale from "0" (not important) to "5" (extremely important). Only about one-third of the troops replied under all 6 categories and 9 percent of the men used only three.

After each 4-week wear period, the men were directly questioned as to the comfort provided by the boots and their suitability for field use. The results are summarized in Table IX. Supplementary investigations, including a durability test, were also conducted but none of these falls within the scope of this report.

TABLE IX. JOINT ARMY-MARINE FIELD TEST*

Boots and Lasts Worn	Number of Troops Fitted			Percentage Reported as:			
				Comfortable**		Satisfactory for Field Use**	
	Army	Marines	Total	Army	Marines	Army	Marines
First Trial							
Army Boot							
Munson Last	491	443	934	81	83	87	80
Fort Knox V Last	484	436	920	87	87	90	81
Marine Boot							
Munson Last	490	430	920	73	79	85	94
Fort Knox V Last	485	444	929	83	85	92	94
Second Trial							
Army Boot							
Fort Knox V Last	213	182	395	92	99.5	95	96
Marine Boot							
Fort Knox V Last	237	173	410	94	95	94	95
Total	2400	2108	4508				

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* From Reference 102, Tables VIa, VIb, and XIX
** Excluding responses of "undecided"

While the responses from the two services are closely parallel, scrutiny of the results reveals a few highly subjective attitudes, as follows:

1. In the first trial, the Army found its own boot more comfortable* than the Marine boot; the Marines found both boots equally comfortable.

2. In the second trial, both groups scored both boots much higher in comfort. Too few were at variance with the majority in this judgment; therefore, no valid conclusions can be drawn as to differences between the boots or between the services.

3. In the first trial, the Army found both boots equally satisfactory for field use*; the Marines preferred their own boot.

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* Difference significant at the 99 percent level by the chi square test

4. In the second trial, both groups scored the field use of both boots higher and again there was too little bias to permit conclusions.

5. In the first trial, both services judged the Fort Knox V last to be the more comfortable*, but only the Army expressed as strong a preference for this last for field use.

6. In the second trial, both lasts scored high for field use and it was impossible to detect any bias in favor of one over the other.

In reporting this test (102), no attempt was made to analyze the interview replies or to probe into the reasons for the difference between the first and second trial results. Possibly the longer recovery period between the wear tests might have been one reason for the difference. At any rate, the preference for the Fort Knox V last was considered sufficiently strong for its adoption by all the services.

The replies to the questionnaire about specific footwear features showed a similar unanimity of opinion. The four properties that were scored the highest in importance by both services and in both trials are "good fit at feet", "good arch support", "ability to protect the feet", and "water repellency". Properties that received slightly lower scores are "durability", "traction on wet surfaces", "ease of breaking in", "weight", and "comfort in hot weather". Among the properties that were considered the least important are "ease of cleaning", "neatness of appearance", and "ability to take a high polish". It is not surprising that the practical features took precedence over the esthetic considerations. Had the troops been asked about the dress shoe, the responses most certainly would have been different.

In order to determine whether the properties that were considered important were actually found in the boots, we must compare the replies concerning the likes and dislikes after each period of wear (Ref. 102, Appendix H), using three of the four top-scoring properties (an opinion on the ability to protect the feet was not asked).

	Fit		Arch Support		Water Repellency	
	Trial 1	Trial 2	Trial 1	Trial 2	Trial 1	Trial 2
Army Boot (Fort Knox last)						
Liked (percent)	3.6	6.1	2.4	5.6	5.9	5.6
Disliked (percent)	1.7	1.3	1.6	0.8	12.3	2.8
Marine Boot (Fort Knox last)						
Liked (percent)	4.0	8.8	3.9	2.0	18.8	7.7
Disliked (percent)	1.1	0.7	1.0	1.0	2.6	1.7

---

* Difference significant at the 99 percent level by the chi square test

Men who had no comment or no likes and dislikes were in the majority. Therefore replies like those listed above are not very informative, with the exception of those on water repellency. Here the Marine boot emerges as the clear favorite. This was to be expected because the uppers of this boot were stuffed with greases. The contemplated change to a vulcanized boot with silicone-treated uppers would change that situation. Strangely enough, the dislike for the Army boot because of its lack of water repellency dropped sharply in the second trial. The responses to the questions about fit and arch support were favorable to both the Army and the Marine boot, but fewer men commented on them than on the question about water repellency.

In regard to two other important and controversial issues, hotness and ease of shining, the Marine boot was considered too hot by about 25 percent of the men in the first trial; less than 5 percent of the men complained in this respect about the Army boot. There were no differences between the two services on this question. In the second trial, the percentages were much lower, i.e., 3.4 against the Marine boot and 0.5 against the Army boot (about the same ratio as in the first trial, but pointing up a much less critical attitude by the men participating in the second trial). Also, the Army boot, with its grain-out upper leather, was found to be softer and easier to shine than the Marine boot (flesh-out)*. As a result, the grain-out upper leather was adopted for the Marine boot.

	Soft Leather		Easy to Shine	
	Trial 1	Trial 2	Trial 1	Trial 2
Army Boot Liked (percent)	9.0	11.4	22.0	31.1
Marine Boot Liked (percent)	3.7	3.2	1.2	0.7

It is probable that the asking of so many questions could well have bewildered many of the enlisted men who might never have worn boots in civilian life and were probably unfamiliar with many of the features they were expected to judge. It would seem that the emphasis should have been more on the essentials, on avoiding such overlapping questions as

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* Actually, the Marine boot was not supposed to be shined. Yet many individual and group efforts were made to shine these flesh-out boots, especially by the Marines, who are accustomed to producing a shine on their flesh-out boots. The Army did not require their flesh-out boots to be shined.

"overall comfort" and "comfort in hot weather", and on eliminating what one might call gray areas, where the opinions are of no real consequence, as whether or not the boot is "acceptable". Future tests should consider using fewer questions and fewer choices, as in the Canadian, and should take into account any psychological factors that could color the results.

F. SUMMARY

An effort has been made to examine critically the relationship between leather and footwear properties and foot comfort. The physiological requirements and behavior of the foot and the singular properties of leather as the material best suited for fulfilling the needs of the foot were discussed first. This was followed by a discussion of the comfort properties of footwear itself and subjective responses to its use in the field. The material used has been gathered from a wide variety of sources many of which are inaccessible to the general public.

The report is primarily concerned with the high military boot and, more specifically, with the material this boot is made of rather than with construction problems. Because of this, studies about this boot by the Armed Services have provided particularly useful source material. Footwear principally made of rubber, canvas, or other materials was not considered. In dealing with this subject, it has been necessary to draw attention to studies that have linked comfort to leather properties that actually have no bearing on comfort and to point out duplications of effort that have failed to shed any new light on the subject.

The significant points that we have attempted to make may be summed up as follows:

1) Leather footwear insulates sufficiently in hot surroundings, but can provide only limited insulation in a dry-cold or a wet-cold environment.

2) In a cold environment, measurements of foot temperature and blood flow into the foot properly reflect the failure of footwear to keep the feet warm; however, in wear tests, foot temperatures have been taken too often under "normal" conditions which contribute little or nothing to the problem at hand.

3) The damaging action of perspiration on shoe leather is twofold: it wets the leather, which afterwards has to dry again, and it deposits solid matter in the leather.

4) The reproduction of sweat damage by the use of artificial perspiration solutions has not been successful. In preparing these solutions, it has been overlooked that the perspiration fluid permeating shoe leather near the foot differs from ordinary body sweat because of the presence of epidermal debris.

5) Many leather properties (air porosity, color, heat of wetting, thermal expansion) have little or no bearing on comfort.

6) Other factors that are connected with comfort, such as thermal conductivity, dimensional changes, water vapor permeability, water absorption, and water vapor absorption, cannot be considered in isolation from each other. Instead of a single threshold value for one or the other of them, their combined function in the boot or shoe during wear must be taken into account.

7) Similarly, increases in the weight of boots or in their stiffness because of chemical treatments must be balanced against the benefits derived, i.e., greater perspiration and scuff resistance, resistance to penetration by water, gasoline, oil, or chemical warfare agents, and durability.

8) Interesting data can be collected by questionnaires and interviews but in the past these techniques have been used in a rather haphazard way. As a source of information, they are of questionable value unless bias is excluded and they are closely correlated to the physical characteristics of the footwear.

The report clearly shows that the Armed Services are fully aware of the necessity of providing comfort in military footwear, not only to avoid injuries and casualties but to satisfy the expectations of the average wearer. At the present time, the services are about to introduce a new type of boot that has a vulcanized rubber sole but no midsole. It is particularly appropriate at this juncture, therefore, to take stock of what we know about comfort so that it may be given the consideration it deserves. As a morale builder, comfort in footwear has been and will surely continue to be very important. It is hoped that a second report will be issued a few years hence to sum up reactions to the new boot when it is introduced to the troops.

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Ranking low in importance for comfort are such properties as thermal expansion, color, air permeability, and the heat of wetting. Properties that depend largely on the tanning process used, such as stiffness and dimensional changes, deserve careful attention but do not usually create serious comfort problems. The most important combination of properties is one that copes both with foot perspiration and with the danger of getting "wet feet." In dealing with foot perspiration, the water vapor permeability and the capacity of leather to absorb liquid and vaporized water come into play.

To avoid "wet feet," water-resistant leathers have been developed. Methods are reviewed of evaluating these properties in the leather that goes into footwear. Discussed are comfort factors of uppers, insoles and outsoles; the water balance around the foot; the distribution of body weight; and the weight of footwear.

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2. Leather
3. Perspiration
4. Blood circulation
5. Body weight
6. Thermal conductivity
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8. Physiology
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