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# A REVIEW OF FOOTWEAR FOR COLD/WET SCENARIOS PART I: THE BOOT (U)

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**DEFENCE RESEARCH ESTABLISHMENT OTTAWA**
TECHNICAL NOTE 92-30

Canada

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## ABSTRACT

This review summarizes a portion of the overall subject of footwear. Although sometimes straying, an attempt has been made to focus on the outermost layer of protection for the foot; the boot. A comprehensive list of requirements is presented, and some materials, designs, and construction techniques are discussed which may fulfill some of these requirements. An attempt is made to draw the reader's attention to the compromises which must be made in describing the boot design criteria. There is a massive amount of literature on the subject and so a selective bibliography has been used to give a complete enough picture to assist in establishing the objectives of a footwear research and development project.

## RÉSUMÉ

Ce résumé porte sur un aspect précis du vaste domaine des articles chaussants. Le cadre d'analyse initial est parfois dépassé, mais nous avons visé à axer notre examen sur les bottes, qui représentent la couche protectrice extérieure du pied. On présente une liste exhaustive des besoins en cause, et on traite de certains matériaux, designs et techniques de construction pouvant répondre à quelques besoins exprimés. On tente de sensibiliser le lecteur aux compromis nécessaires dans la description des critères de design des bottes. Comme la documentation relative à ce sujet est considérable, nous nous somme servis d'une bibliographie restreinte, qui permet de brosser un tableau suffisamment complet pour aider à établir les objectifs d'un projet de recherche-développement dans le domaine des articles chaussants.

## EXECUTIVE SUMMARY

Proper footwear for the military has been a subject of concern for a very long period of time. Although there have been many advances in the footwear industries in recent times with respect to new materials, new designs, and new manufacturing processes, it is suggested that the perfect boot for many scenarios is still not available. Research in the past few decades has yielded a better understanding of the science and engineering involved with respect to the reaction of the foot with its environment, but again it is suggested that not enough is known, such that a clear and undisputed way ahead to the next generation boot can be mapped. When considering most of the information published to date, the interaction and therefore the integration of many or all of these processes requires further study to allow for a better response to stated military requirements.

This review summarizes a portion of the overall subject of footwear. Although sometimes straying, an attempt has been made to focus on the outermost layer of protection for the foot; the boot. A comprehensive list of requirements is presented, and some materials, designs, and construction techniques are discussed which may fulfill some of these requirements. An attempt is made to draw the reader's attention to the compromises which must be made in describing the boot design criteria. There is a massive amount of literature on the subject and so the bibliography has been selected to give a complete enough picture to assist in establishing the objectives of a footwear research and development project.

## 1.0 INTRODUCTION

"It is even more important to recognize that the most perfect boot, fulfilling all the most stringent conditions of design and construction, is useless if given to the wrong man."

STOKES, 1960 (1)

"The 'poor bloody infantry' have had to trust their feet and thus their lives to their boots in every war, and have suffered in the Crimea, the two World Wars, the Korean War, and most recently the Falklands conflict. The Romans, using sandals, performed very poorly in cold climes, and Xenophon's Anabasis makes it clear that the Greeks suffered many casualties from the cold. Almost every military action since 1700, when doctors started to take a real interest in the health of troops, has highlighted the seriousness of foot disorders produced by the failure of boots to perform as required."

KILLIAN, 1981[1]

"A small number of men are broken by the pain in their feet... We attempt to give them the dryness and warmth that their damaged limbs need... Judging from the condition of some of the troops evacuated from the front line with trench foot, and hearing their stories, there are many others in the hills with the same problem ...this week's theme must be the possibility that we will run out of capable feet before the order is given to cross the start line."

JOLLY, 1983[2]

"It is clear from experience in the Falklands that many of the longstanding problems associated with military footwear design remain unsolved."

"It is a depressing fact that after over 200 years of research, there is still no military boot which enables the infantryman to escape or even postpone non-freezing cold injury."

OAKLEY, 1984 (2)

"Troops from the United Kingdom were engaged in a military conflict in the South Atlantic in May and June 1982.....The most common source of dissatisfaction with the troops related to the performance of boots and the state of their feet."

McCaig, 1986 (17)

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[1] COLD AND FROST INJURIES (BERLIN: SPRINGER-VERLAG)

[2] THE RED AND GREEN LIFE MACHINE (LONDON: CENTURY)

As evidenced by the previous quotations, proper footwear for the military has been a subject of concern for a very long period of time. Although there have been many advances in the footwear industries in recent times with respect to new materials, new designs, and new manufacturing processes, it is suggested that the perfect boot for many scenarios is still not available. Research in the past few decades has yielded a better understanding of the science and engineering involved with respect to the reaction of the foot with its environment, but again it is suggested that not enough is known, such that a clear and undisputed way ahead to the next generation boot can be mapped. Even when one considers only the information published to date, the interaction and therefore the integration of many or all of these processes requires further study to allow for a better response to stated military requirements.

It was decided that a review was required to establish where this field of study is now and where it could go from here, and thus possibly assist with establishing a new requirement. It was very quickly discovered through a cursory literature search that there was so much published information on this topic, that it would not be feasible to review all aspects of footwear research and development within a reasonable time frame. Thus, it is proposed to review footwear in several parts, this report comprising the first part under the general heading of "the boot ". For the purposes of this first part of the review, only the boot or outermost element of foot protection will be discussed with respect to designs developed in reaction to various previously proposed military requirements. It is currently thought that a second part of the review would include a review of the elements found between the boot and the foot i.e. liners, socks, removable insoles, etc.

A list of previously proposed military requirements will be presented, followed by a synopsis of several efforts to meet these requirements. The review will also focus on a cold (-10°C to +10°C) and wet scenario, which is currently perceived by many as those conditions against which protection should be improved in the near future. The discussion will then attempt to highlight areas where various requirements and their proposed solutions interact in such a way that compromises are required.

## 2.0 THE REQUIREMENT

Although the way of expressing the requirement for military footwear has changed over the years, the essence of the requirement has changed very little. The most appropriate statements of requirements for cold/wet scenarios have come from the US, the UK, and Canada. The following is a list of a collection of boot requirements from several sources (1-5).

1. Footwear must maintain and enhance mobility and thus:
   a. have good traction on a variety of surfaces (i.e. from loose sand to slippery rocks) over long distances;
   b. be light weight and not bulky;
   c. be flexible and yet have good support while carrying heavy loads over irregular surfaces;
   d. have a sole design to which foreign matter does not adhere;
   e. be properly sized;
   f. be balanced; and
   g. not present or intensify existing hazards (i.e. be non-toxic and not cause dermatitis or complications to wounds or burns or cause blisters).

2. In cold climates footwear must
   a. be insulated and protect insulation in case of puncture;
   b. be waterproof;
   c. be able to absorb and transmit sweat vapour (liquid sweat accumulation is to be avoided in cold weather);
   d. be water vapour permeable or adequately ventilated; and
   e. dry and/or drain rapidly.

3. Footwear must protect against
   a. ballistics;
   b. flame/heat;
   c. flora and fauna;
   d. terrain irregularities;
   e. falling objects;
   f. NBC (Nuclear, Biological, Chemical) threat e.g. protect against all CW (Chemical Warfare) agents for up to 24 hours, be easily and reliably decontaminated, resist adhesion of radioactive dust, and protect against thermal radiation levels up to 62.76 $J/m^2$ (15 $cal/cm^2$);
   g. antifreeze;
   h. POL (Petroleum, Oil, Lubricant);
   j. battery acid;
   k. spikes;
   l. wind;
   m. degradation by sea water, human sweat, or microbiological agents;
   n. blast; and
   o. in some cases, static electricity buildup.

4. Footwear must be well constructed and thus
   a. have reliable closures;
   b. be strong, i.e. will not come apart (strong seams and adhesives);
   c. be durable to resist abrasions and bruises from rocky outcroppings (wear resistant);
   d. be repairable;
   e. have a long shelf life without deterioration in any environment;

f. be undetectable either by visual (camouflage) or IR (Infrared) surveillance;
g. be shrink resistant;
h. form a safe seal between the boot and the trouser; and
j. be easy to don/doff even while wearing heavy gloves.

5. Footwear design must consider personal hygiene, i.e. the layer next to skin must be easy to remove and wash.

6. Footwear must be compatible with operation of land/sea/air vehicles and equipment.

7. Footwear must be compatible (integrate) with other combat clothing.

8. Footwear must be easily made (capable of mass production).

9. Footwear must be silent in use.

10. Footwear must be affordable.

Although the requirements are listed under group and subgroup headings, each component of each group and subgroup tends to evoke its own solutions. An attempt has been made to avoid duplication, but some authors may still argue that some of the requirements are actually subsets of others already listed. The author has also avoided subjective requirements such as "comfortable" or "stylish", as these are very difficult if not impossible to measure quantitatively.

## 3.0 MEETING THE REQUIREMENT

### 3.1 Introduction

With very few exceptions, all of the referred authors cite protection against the cold and wet as being the most important requirement for military footwear to keep personnel mobile. This is either stated directly, or simply the main topic of their studies. The reason for this becomes clear when one reviews a medical report or book (9) dealing with cold injuries and notes statistics (2,6,7,9) with respect to the number of cold injury casualties of soldiers, even in the twentieth century in such scenarios.

For example, during World War II, US military casualties as a result of foot cold injuries numbered in excess of 90,500. During an Allied campaign to capture the Aleutian Island of Attu, there were more losses from cold injury (1200) than from battle wounds (1148). In another example, Oakley (2) points out that there were a large number of men suffering from trench foot as recently as the Falklands War in 1982. L'Hollier suggests, "The actual cost of military effectiveness becomes apparent when one realizes an average of 83 days was lost from active duty per case. About 40% of the cases could not return to combat and about 20% were disqualified from further duty......It has been estimated that cold injuries in World War II cost the US forces the equivalent of 15 divisions of 15000 men each. The increased load on replacements and hospital facilities and medical costs must also be added."

Trench foot and frostbite make up the largest category of cold injury (2,6,7,9). Trench foot is a thermal injury resulting from prolonged exposure to cold/wet conditions (0°C to 10°C). This commonly occurs under combat conditions when immobility caused by enemy action or other circumstances make adequate foot care difficult. It is characterized by poor circulation (i.e. lack of oxygen) caused by continuous chilling, followed by local tissue inflammation and damage. The casualty usually feels no sharp pain as a warning to stimulate circulation or warm his feet.

Frostbite on the other hand involves actual freezing of the skin and subcutaneous tissue as the result of prolonged exposure to freezing and below freezing temperatures. Even a brief exposure to extremely low temperatures can cause frostbite. There is local pain or stinging when tissue freezing begins, acting as a warning to seek medical aid. This is followed by numbness and other more serious effects if not immediately treated.

Other types of cold injury identified by some authors (6,7,9) include immersion foot (clinically indistinguishable from trench foot), epidermophytosis (itchy skin), hyperhydrosis (excessive sweating), maceration (wrinkling or softening of skin), erythema (rash), and freezing of the deep tissue. The number of cases of deep tissue freezing, though, is estimated at only 6% of cold injuries (9), and the amount of medical attention required for epidermophytosis, hyperhydrosis, maceration, and erythema is minimal, compared to trench foot and frostbite.

### 3.2 Thermoregulation

Although this review is focused mainly on how the boot protects the foot against a number of external influences, a look at materials, construction techniques, and design of footwear cannot be complete without considering the thermoregulation of the foot itself. The foot is an active component of the overall system in that it produces its own heat and moisture and is constantly regulating itself or being regulated by the rest of the body. Thus the boot must protect the foot from the environment while at the same time must not obstruct the ongoing thermoregulation of the foot for prolonged periods of time.

A more in-depth look at thermoregulation of the foot is proposed for another part of this series of reviews, but a summary of some aspects of this topic is presented here.

With respect to feet, there are three sources of heat input (2). One is metabolic heat production, which tends to be small (about 2 W at room temperature) and falls with tissue temperature (at T < 10°C this may be reduced to 0.2 W ). Another input is from the stored heat in the foot itself (at 35°C this is approximately 160 kJ of heat above an ambient temperature of 0°C, and even when the mean tissue temperature falls to 5°C, this is still 23 kJ). The third input is from the arterial blood supply, which is much more substantial ( > 30 W in warmth or during exercise), but is also reduced by cold (may fall below 3 W). This reduction is believed to be the result of blood cooling by a reduction in leg temperature, countercurrent heat exchange, and closing the arteriovenous anastomoses (AVA)(1,2,13). The AVAs can be described as valves, controlled by the thermoregulatory centre of the brain (hypothalamus), that determine the return path of blood from the extremities (superficial when open; deep when closed). When the body cools and heat to the vital organs via the circulatory system is reduced, heat to the extremities is reduced, i.e. the AVAs are closed, in an effort to conserve heat.

The heat in the foot is lost by conduction, evaporation, and radiation. Conduction is the main mode of heat loss from the foot to the outer surface of the boot. The other two routes of heat loss are from the evaporation of the sweat produced by the foot and the radiation of heat from the surface of the boot (brought there by conduction).

The surface area of each foot makes up approximately 5% of the total body surface area. The heat loss from each foot, though, ranges from 3.5% in cold scenarios to 7% in hot scenarios (4,11). This range can be explained by the typical vascular reaction to temperature, i.e. constriction when cold and dilation when hot. Within a 33°C room the foot temperature is approximately 36°C, the blood flow is approximately 44 cc/min, the total heat loss is approximately 75.4 $W/m^2$ (65 $Cal/m^2/hr$), and the evaporative heat loss is approximately 49.9 $W/m^2$ (43 $Cal/m^2/hr$); within a 20°C room the foot temperature is approximately 25.5°C, the blood flow is approximately 8 cc/min, the total heat loss is approximately 27.8 $W/m^2$ (24 $Cal/m^2/hr$), and the evaporative heat loss is approximately 9.3 $W/m^2$ (8 $Cal/m^2/hr$) (at a basic metabolism approximately equal in both cases). This type of information is useful in determining the amount of ventilation or heat conduction required to maintain the heat balance of the foot.

When considering footwear, Koeller (4) suggests that the tolerable range of foot temperatures is between 13°C and 38°C. The comfort zone lies between 20°C and 35°C, with the uncomfortable but tolerable range making up the rest of the range. Hardy et al (5) suggest that the comfort zone appears to be at a skin temperature of about 33°C with a relative humidity between 60% and 65%. At rest in the cold, however, toe temperatures drop rapidly to about 15°C, the relationship being approximately linear with time (1). The cooling rate then decreases until a temperature of about 7°C is reached (varies with individuals). This is typically followed by a phase of rewarming, then cooling, then rewarming etc. The frequency and effectiveness of this phenomenon is said to be dependant on the thermal state of the body as a whole. It is suggested (1) that if the body can periodically spare heat to warm its extremities, that "the feet will be maintained in thermal comfort for a longer period if the rest of the body is efficiently clothed".

There are apparently two types of sweating which occur in the foot (14,15), sometimes simultaneously. The soles of the feet sweat continuously at low levels, for the most part independent of temperature, whereas the rest of the foot sweats as the result of stress or to eliminate excess heat when in hot surroundings or during exercise. Estimates for the total amount of sweat produced by the foot of an inactive person range from 3 g/hr/foot to 5 g/hr/foot (4,14). Estimates for the total amount of sweat produced by the foot of an active person range from 25 g/hr/foot to 40 g/hr/foot.

When sweat occurs and accumulates in the material immediately surrounding the foot, volunteers in many footwear trials describe the feeling as unpleasant. Therefore, it would be advantageous to remove as much moisture as possible from the area immediately surrounding the feet. One method to reduce the amount of sweat produced by the foot is by the use of an anti-perspirant (4,10). It has also been found that the rate of sweat production can vary not only with the activity, but also with the placement of the vapour barrier in relation to the skin (4,12), i.e. when it was worn close to the skin, the perspiration rate was less compared to the rate with the vapour barrier some distance from the skin. Two possible explanations for this phenomenon are that the skin reabsorbs some of the moisture, or sweat production is inhibited by an increase in the partial pressure of water vapour.

### 3.3 Materials

One way to meet most of the above requirements is with an appropriate choice of materials. The most popular two materials used in boot construction are leather and rubber.

Leather is made from the hides and skins of animals such as cattle, sheep and goats. The hides are composed of three layers, the middle layer (corium) being the only one which forms leather. The corium is itself composed of layers of fibrous tissue composed of a protein called collagen. Collagen is readily swollen by acids and alkalis, and combines with various tanning materials to form leather. Tanning of the corium is required to prevent decay. The two main tanning processes are vegetable tanning for heavy leather soles and belting, and chrome tanning for uppers and other light leathers. The long fibrous structures in the raw hide remain after tanning but the presence of the tanning material reduces the adhesion between the strands when the tanned hide is dried, yielding a strong flexible leather.

Under the microscope, the bundles of collagen fibres can be seen running parallel to the surface, and embedded in a matrix which contains air spaces or voids. This structure is used to explain the permeability of leathers to water vapour and the ability to absorb quantities of liquid water, often a desirable feature of leather. Where water uptake is not desired, the leather is impregnated with fat or wax mixtures which fill the spaces. Although leather is fairly permeable to water vapour, leather does not 'breathe' in the sense of being freely permeable to air. Dense sole leather, usually vegetable tanned, is much less permeable than the chrome tanned leather used in the boot upper. "Patent" leather is completely impermeable to vapour.

Leather has a relatively high thermal conductivity ($K \times 10^4$ = 12.5-23.0 W $cm^{-1}$ $°C^{-1}$, depending on origin and treatment). This is a good quality for heat removal, but makes leather a poor insulator. Leather is readily wetted, becomes more permeable when flexed, absorbs large quantities of water, and is difficult to dry. The application of fats and waxes, and the absorption of water increase the thermal conductivity considerably.

The Inuit have used leather in their clothing, which is well suited to their environment (1). The conventional boot of the Inuit has a caribou skin upper, worn hair out, with a sole of bull caribou, worn hair in. For grip on ice, the skin of the bearded seal is used for the sole. In either case, the sole comes up 2.5 to 5.0 cm all round the foot, as in a moccasin. The skins are tanned by soaking in urine and made soft and pliable by repeated chewing. A layer of dry grass or moss is often worn in the bottom of the boot. Caribou hide is warmer than seal or walrus but less waterproof and not as strong. A significant virtue is said to be its high permeability to water vapour.

To protect the feet in the Arctic, the Americans (1,19), British and Canadians use a mukluk, which somewhat resembles the fur Inuit boots. It consists of a heavy canvas shell with a rubber bottom. Inside this is a thick felt sock into which the foot, covered with one or two pairs of thick socks (wool or synthetic fibre), is placed. The mukluk is only suited for windy and dry cold environments, and should be siliconed if there is any possibility of coming in contact with melting snow.

The use of rubber in footwear is now more than a century old. A rubber sole, of natural or synthetic rubber, has the advantage of being completely impermeable to water, has three times the wear life of sole leather, and probably provides all the protection normally required for the plantar surface of the foot (1). Rubber compositions have a higher conductivity than leather ($K \times 10^4$ = 16.7-29.3 W $cm^{-1}$ $°C^{-1}$). In the late 1940s, the American army used a heavy all-rubber shoepac for cold wet scenarios (2,18), fitted to include a felt insole and 3 pairs of socks. A rubber sock worn next to the skin was also tested with this boot to prevent the insulation layer from becoming wet from sweating. In 1951, the double moisture barrier boot was adopted (2,19). This boot is described as a heavy double-walled rubber boot which enclosed an air layer in the upper to act as a thermal insulator, When considering the requirement for protection against chemicals, a boot made of leather laminated to sheet butyl rubber was proposed by the UK (29). Although such boots (23) give good thermal and chemical protection down to very low sub-zero temperatures, they may not be suitable for prolonged marching at near-zero temperatures since sweat will surround the feet for extended periods increasing the risk of cold injury.

The boots produced by SATRA for the final assault of Everest, also utilized the vapour barrier principle, the insulation being a light-weight kapok material (tropal) sealed between latex backed glace kid (type of leather) on the outside, and latex backed fabric on the inside. The prime requirement of these boots was that they should be light weight and provide maximum thermal insulation (1).

During the latter part of the discussion on thermoregulation, anti-perspirants were mentioned as a means of reducing the amount of sweat produced by the foot. Another method tried by the US to keep the foot dry (4) was to incorporate a replaceable desiccant liner in the boot to absorb the moisture. Desiccants tested included silica gel, lamisilite, vermiculite, and activated alumina. Silica gel was found to have the highest absorption capability at 39% dry weight, and a relatively high density compared with the other desiccants.

Before rubber or composition soles were introduced into army boots, a long series of laboratory and field experiments were carried out in the US and Canada. These showed that the essential role of leather was to absorb, rather than to transmit, moisture as either vapour or liquid. It was found that as long as the boot had a sufficiently absorptive leather insole, the nature of the outsole (fig. 1) was not of great importance. Moisture taken up during wear tended to be released when the boots were removed at night. Rubber, whether natural or synthetic, has a tendency to spread or creep under pressure, while leather tends to shrink with wetting and rapid drying. There is however the great virtue of water resistance and good wear with rubber materials. With exposure to rain, wet grass or free water, the main site for water penetration in a boot is not so much the material but the seams, most especially at the attachment of the soles. This has been overcome during the last thirty years or more by the Direct Moulded Sole (DMS) in which a rubber or composite sole is moulded to a leather upper (5) making a virtually water impermeable junction. This largely British innovation (35), is also used by Canada (21,22,24,25,34) for moderate sub-zero cold. Moulding the sole directly onto the upper allows the manufacture of a boot with a lighter sole, which is more flexible, is more water resistant, and has better wear characteristics than a heavier all leather boot. Rubber or composition material has also done away with the nails, screws, and metal reinforcements of earlier boots. As far as the military is concerned, a studded leather boot may remain traditional for parades, but because of its exposed metal is unlikely to be used in future for active service where silence is necessary.

Many other materials apart from leather and natural or synthetic rubber are used in footwear. The deficiencies of leather as an upper material can probably be best remedied by improvements in the leather itself and by more careful construction of the boot. The possible use of silicone dressings, Bavon (based on an alkyl derivative of succinic acid)(22), polyisobutylene (Vistanex), butyl titanate, thiokol, etc. as water repellant applications, or latex filled leather, may be worthy of consideration (1). None of the man made fibres available today possess all the virtues of leather, nevertheless, the economic situation with regard to leather in wartime, and its undesirable properties under certain conditions, justifies the investigation of possible alternatives. Artificial leather has been introduced which is essentially of a plastic nature. Corfam (21) consists of a polyurethane top coat over a substrate of non-woven polyester fibres, which may have a woven fabric inter-layer. Corfam has load/extension characteristics, water vapour permeability, and waterproofness more similar to natural leather than any known alternative upper material.

Prototype boots with uppers of nylon and Terylene duck and 'Vapotex' coated material, have been developed (1). These fabrics do not provide much thermal protection (although not greatly inferior to leather) and, as with the mukluk, the warmth is largely due to their wind resistance. Nylon also sheds snow better than cotton canvas and dries more rapidly, but unfortunately, it does not bond well with rubber. The boots are permeable to sweat vapour but their water repellency is not high even with a silicone treatment.

A Canadian study (24,25) used leather, corfam, Melovin, Lefatex, and Duralite in various combinations of uppers to assess the microclimate created in the boot by these materials. With respect to water vapour, the Melovin, Lefatex, and Duralite are all classified as non-absorbing and non-transmitting. It is thus not surprising that boots incorporating the latter three materials exhibited rubber-like conditions in the boot.

A US study (26,27) to develop a lightweight insulated boot with a weight of 426-511 g (15-18 oz) produced a boot made of polyurethane and/or polyethylene. A chemically expanded closed-cell polyurethane insulation was selected from which a prototype boot was constructed. This boot would be difficult to manufacture, however, because of the difficulty in cutting sheet expanded polyurethane. Thus a closed-cell polyethylene composition was also developed and another boot was easily constructed of this material into an extremely lightweight insulated boot.

Microcellular rubber gives a lightweight, good insulating sole of a slight bouncy nature and excellent traction (31). Ground cork has also been added to the rubber in soles to increase traction (34).

Boots with PVC uppers are used in many industries where protective footwear is required because they have good impact protection and abrasion resistance, but are virtually impermeable and have poor resistance to repeated flexing. They incorporate woven, knitted or non-woven fabrics, singly or in combination, and may have a cellular PVC (polyvinyl chloride) interlayer (28,31,32). Although these materials might be classified as having low absorption capacities, they exhibit rapid drying rates.

Quox is probably the best known British example of a synthetic upper material. It is a non-woven fabric containing a high proportion of nylon fibres, an acrylonitrile butadiene binder, and a coating apparently based on PVC. It is less water vapour permeable than leather but much cheaper. Absorptive vinyl is a US synthetic upper material (30) which will pass gases and absorb and transmit liquid water.

Kevlar and PBI (polybenzimidazole) have been used to protect the foot from heat or fire and Kevlar has also doubled for protection against blast, ballistics, and puncture in the sole and uppers (36).

One of the most recent new materials to enter the footwear market is a product known as Goretex (W.L. Gore & Associates Inc) (2,36,41). This material is a teflon based, microporous semipermeable membrane which is waterproof but water vapour permeable. It has many desirable features required by boot designers, except that it is expensive. More new materials similar to Goretex are being developed, some even cheaper.

Insulation to protect against the cold has thus far only been dealt with as an insulating layer (mostly air) between two impermeable vapour barriers. Removable insoles not only absorb sweat, but also act as an insulating layer between the foot and the sole, which is in contact with the cold ground. Socks are also referred to as the insulating layer, and it is proposed to discuss these topics in a separate review. Recently, however, boot manufacturers have begun to incorporate insulation in their products as a non-removable liner. More frequently these are made of Thinsulate (3M Company Limited), and less often of Polarguard (Celanese Canada Limited). Thinsulate is dense batting made from polyolefin microfibre, and polyester staple-fibre is added if a lower density batting is required. Because of its density, Thinsulate has the added property of compressing less and recovering more than other similar insulating materials. This property makes it an ideal insulation material for footwear, that typically fits tightly on the foot. Polarguard is made of a continuous-filament polyester batting.

Fibreboards which are cheaper and have superior resistance to heat damage during moulding are gradually replacing vegetable and semi-chrome tanned leather insoles. The boot trade has become more aware of the undesirability of fibreboards with a low capacity for moisture absorption. In the new Canadian DMS boot (21), use has been made of the only board which is regarded as suitable in this respect. It is composed of cellulose fibres and polychloroprene in the ratio of 2:1.

Metal strips have been used in boots (4) extending from the ankle on the inside of the boot where it is attached to a metallized cloth liner, over the top, and part way down on the outside of the boot. The purpose of the strips and metallized cloth is to obtain a low resistance heat flow path from the foot to the external environment.

Various materials have also been tried to provide boots with conductive bottoms to avoid electrostatic discharge. Conductive rubbers suitable for DMS construction are commercially available. Various other means of providing conductive pathways have been attempted after it was shown that a conductive rubber insole was intolerably uncomfortable. Metal inserts and conductive plugs were also discarded because of discomfort and unreliability, respectively. The problem was overcome by utilizing a carbon impregnated leatherboard (21,34) which contains sufficient carbon to provide conductivity without rendering the board unsuitable for shoemaking. This leatherboard is also absorptive and remains conductive when dry.

Steel is incorporated into the insole of some boots to offer protection against spikes and protect the sole of the foot from sensing rough terrain which can add considerably to foot fatigue and soreness (5,33). To protect against blast, a stainless steel wedge filled with aluminum honeycomb and covered with an aluminum plate (33) was moulded into the sole of another special boot, covering the heel and arch areas. It has a V-shaped cross section which deflects the blast upward and outward from the sole of the foot.

### 3.4 Design Concepts

Although an appropriate choice of materials can meet many of the requirements, how one assembles the materials can also meet certain requirements. A few design concepts relating to boots are described.

MacDonald et al (37) have put forward several design concepts relating to quick closures and better traction. The quick closure concepts include hook and loop material, slide fasteners, and multiple belts and buckles. The hook and loop designs include three ways of employing Velcro-like materials replacing laces. The slide fastener concept attaches a slide fastener to a boot using its laces, which are adjusted for fit. The boot is then donned and doffed quickly using the slide fastener. The belt and buckle concept consists of an array of four or five two-bar buckles and a one-inch-wide cloth strap across the opening of the upper, also replacing the laces.

Designs of traction devices which can be manufactured as an integral part of the sole, are discussed with respect to hard and soft terrain. On hard terrain such as ice or hard packed snow, walking is aided by the use of hard, wear resistant points which penetrate the terrain surface. One class of traction device is based on a flexible chain-meshed carrier to which metal hobs or points are attached. They are hinged at the front or the side of the boot such that they can be stored over the instep when not required. A similar device called a traction pad uses a reversible or removable pad as a means of attaching the hobs. A third class, edge grippers, consists of a saw-toothed metal frame (similar but smaller than a crampon) which is attached to the periphery of the sole by pins, locking cams, or straps. Individually retractable cleats and spikes have been developed primarily for walking over soft ice and hard-packed snow. These devices are normally hinged to the sole, either individually or in small groups, so they can be retracted when not required. The latter design is segmented to retain sole flexure.

Soft terrain surfaces such as mud and sand, inhibit an individual's forward progression by yielding under normal contact forces. Fatigue results from abnormal motion requiring large muscle groups to overcome cohesion and adhesion. The design considered to reduce these forces, increases the size of the footprint. One concept is a rigidized inflatable tube, larger than the sole, attached by cords to a shoe binding (like a snowshoe). To decrease the potential of material buildup on the upper surface of the device, a plastic bag can be worn over it. Another similar device is an inflatable overshoe. This concept has the appearance of a small sole-shaped inner tube which fits over the boot.

Pietraszek (38) has developed two concepts of a lightweight insulated polyurethane boot to accommodate skiwear worn by troops in the North. One concept was to add a shelf above the heel at the rear of the boot, and another was to incorporate a groove extending around the rear of the heel, to which a ski cable could be attached.

Combining leather and rubber (4) has been suggested as a possible modification to the US double moisture barrier cold-wet boot. A leather liner for improved moisture absorption is incorporated into the rubber vapour barrier boot. The inner rubber barrier has vertical channels so that moisture can escape from the leather liner and rise to an annular space at the top of the boot which is also made of leather, and escape to the environment.

It is believed (4) that foot operated air pumps cannot generate enough air volume to completely eliminate evaporative moisture. It is however suggested that air pumps used for cooling by convection should not be dismissed. A concept was developed (4,39) which used a number of small volume pumps at various pressure points of the boot-foot interface to assist in distribution of air more uniformly around the foot.

Utilizing the cooling effect from the expansion of a compressed gas such as $CO_2$, a concept for boot cooling has been developed. Release of the gas could be either thermostatically or manually controlled. Strategically placed air pumps take in ambient air through the heat exchanger and circulate it through the boot. After being partially warmed, expanded gas will also be circulated within the boot.

A concept of a boot with variable insulation (4) features a corrugated construction, with interconnected spaces. The boot is fitted with an air valve to vary the amount of air within the structure. By evacuating the air, insulation can be increased e.g. if pressure is reduced to 34.5 kPa (5 psi), insulation will be tripled.

A double moisture barrier boot with different insulation inserts (two or three inserts to protect against mild to very cold temperatures) (4) was another design concept considered by the US. The insulation would be inserted and secured between the inner (rubber) vapour barrier and the outer boot cover, would extend the length of the sole up to the heel, and would cover the entire forward portion of the foot.

Designing the uppers to fit over the ankle up to mid-calf would protect feet from snagging on rocks and scrub, and affords better defence against insect bites and entry of parasites (1,5,35). Making a toe cap (fig. 1) of hard material provides protection from possible injury due to stubbing of the toes against objects and from falling weights. The specific shape of the toe cap also determines to what extent the boot can be used as a weapon of last resort.

The conventional form of boot closure (frontal lacing with ankle tie) can be criticised because of its impairment of the normal mechanics of walking (1). Localized pressure by the laces on the upper part of the foot can also cause discomfort particularly with high boots, where a full bellows tongue increases the bulk under the laces. Securing the instep to the heel grip is required and this is possibly best effected by suitably placed straps (1,5) or gussets (21). Rear lacing has also been tried as an alternative (5,35) which also appeared to give good test results re water proofing, since a clear seam-free vamp results.

Pratt et al (40) have calculated that approximately 5 watts of heat would be required to maintain both feet at a temperature of 10°C within an ambient temperature of -40°C, wearing a standard insulated boot. A pair of electrically heated socks powered by batteries was designed and tested. The results suggested that battery powered electric heat was feasible, and could double the exposure time of an inactive foot soldier at -40°C before the danger of frostbite.

When the ankle is flexed while wearing a boot of mid-calf height, the facings (fig. 1) are displaced causing unsightly gaping. This effect can be lessened by redesigning the side panels of the boot so as to reduce the width of the panel (5). This keeps the sides off the forepart of the leg, reduces the flexed height difference of the panel from front to back, and considerably reduces gaping of the facings. This also allows for the inclusion of the quick closure slide fastener concept described above.

Using several of the ideas described thus far in part and in whole, several designs of new boot systems have emerged. One such system is the US MCBS (Multi-Component Boot System) (42) which is made up of four components i.e. Army black leather boot, the tan/ski mountain sock, the Goretex sock, and the Goretex gaiter. Another system of note is the Canadian Overboot, CW, Standard, considered by the US as a multi-use overboot (MULE) (44). The upper portion of this boot is made of an olive green and black butyl rubber coated with neoprene. The combined outsole and heel are made from a black neoprene soling compound.

### 3.5 Construction

"...the boot itself should not form a potential cause of injury due to its construction. Seams, rivets, nails etc. obviously should not protrude. Abrasions from creasing of the upper, stiffeners, and from restriction at the ankle, should be avoided by correct last measurements and sound construction. The high toe spring and hard toe cap of the Army boot reduces the creasing of the vamp (fig. 1) which can be agonizing but there does not appear to be any apparent reason for the high back stiffener at the heel. The continual flexing of this stiffener in wear, produces deep creasing with punishing effects to the wearer's heel,..."(1).

Even with modern adhesive developments, it is doubtful that they alone can be used to hold a boot together. When the sole is not moulded directly onto the upper, stitching is generally preferred to using screws and nails, because it provides strength along the outer edge of the boot, where a strong attachment is needed most. Furthermore, using screws and nails will increase the thermal conductivity of the sole. The application of the direct moulded sole process to the production of heavy footwear solved the problem of attachment of the rubber outsole to the leather throughsole. Also, the absence of any screws and nails or stitching would fundamentally provide for a more waterproof boot. Together with the elimination of two sole layers (insole and throughsole) a more flexible boot was another result. The sole also had greater elasticity, tending to return to its original shape after flexing.

Canada has been successful after many years of research in developing specific solvent types of rubber/resin adhesives which are employed in the manufacture of Goodyear welt and DMS types of service footwear (34). When applied and cured in the prescribed manner, these adhesives have an exceptionally good shelf life because of their excellent affinity to the soling and upper materials. They provide high and continuous bond strengths and possess outstanding oil-resistant properties. The two main types of adhesives developed are neoprene and nitrile. The neoprene adhesives are for bonding sole and heel components to the bottoms of Goodyear welted types of footwear, prior to stitching or other permanent means of attachment. Two nitrile adhesives with different viscosities have been developed to achieve a high strength and permanent bond between the sole and the upper of the DMS combat boot.

If boots are constructed with a material such as leather, then waterproofness is increased with better designed seams (5,21,22). By designing the upper without a separate toe cap and counter (fig. 1), the total length of seams is reduced by one third. Also, water penetration occurs more readily where seams intersect and where sharp changes in direction occur (22). Stitching passing from the outside to the inside of the boot should be avoided i.e. seaming of the outer leather and the lining should be done separately except where joined at the edges. Seams coated on the unexposed side with a rubber base sealant are recommended. Stronger thread should be used where the number of rows of stitching has been decreased e.g. cotton-wrapped polyester core threads are suggested over cotton or linen thread. The incised edge is a new seam being tested in the UK (5) which splits the edge of the outer material to facilitate stitching of the lower flap to the inner material, after which the upper flap is cemented over the stitching.

Besides improvements in seaming, another trend in boot closing is in seam welding (29), as more synthetic leathers come on the market. Ultrasonic energy is being used to combine PVC, nylon and polyester materials.

### 3.6 Fit

The fit of boots determines mobility. Shearing forces within improperly fitted boots have been determined to be a major cause of blister formation (8). There are many factors to be considered when attempting to determine a proper shoe fit. A previous foot measurement survey (45) has shown that no two feet of a pair are exact mirror images. If the two shoes of a pair are exact mirror images, then the result must be some degree of shoe misfit for one foot. Another obstacle preventing a correct fit is that the boot is required to fit when the foot is at rest, when the foot is weight bearing, when the foot is walking, and when the foot is exposed to conditions (thermal) that alter its size and shape. Every boot also requires some degree of breaking in (42), though this should never be with any pain or discomfort. It is obvious a compromise must be reached with the initial fit.

The last or boot shape is the single most important element in boot fit. It determines the boot size, shape, style, fit, comfort, wear performance, and boot dynamics. In the past, lasts were made of wood, but today most are made of plastic. The advantage of plastic is that it will not shrink or swell with temperature changes. There is no straight line on a last, which means a wide variety of contour measurements must be made. This requirement has led to large anthropometric studies (47,48). These types of studies are expensive, but are required frequently because size distributions within populations change. They are also necessary in establishing size distributions, such that a range of sizes, and an approximation of the numbers required of each size, can be determined which will fit the population. For military purposes, an attempt should be made to keep the number of sizes to a minimum to ease the load of resupply (2).

One of the current reasons for a shift in military size distributions is the increase in the number of women in the armed forces, although some studies (46) have shown that 95% of military women who require safety footwear, can be accommodated.

The axis of the foot is an imaginary line drawn from the rear centre of the heel, through the centre of the midfoot and ball, to the space between the second and third toe. Virtually all feet are straight-axis feet. An unfortunate consequence of using large databases of foot measurements to determine last contours, results in a crooked last. It is necessary to gradually redesign lasts to convert the long-reigning crooked lasts to straight lasts to conform to the straight-axis principle found in most feet.

Many errors are made in determining the proper boot size for a particular pair of feet. In the military, too often, there is no fitting service i.e. fitting done by personnel trained and experienced in fitting boots. Some errors in fitting (42) are that only one foot is measured (instead of both to determine which is larger), the measuring is done seated instead of standing, and test for fit is done in only two or three places (an experienced fitter will check as many as 14 different test sites). It is essential to train personnel to provide a high standard of boot fitting service to customers (48).

## 4.0 DISCUSSION

Many of the requirements, when addressed alone, can be met with a proper choice of materials, and/or design, and/or construction. Problems usually arise when more than one requirement must be met at the same time. If the primary requirement to be met is that of protection, and the result is a boot which is so heavy, rigid, and bulky that it would make walking difficult, then the design is a failure. Likewise, if the primary requirements to be met are that of light weight and water vapour permeability, and the result is a boot which cannot protect against the cold, this is also a failure. The key to solving this entire dilemma is compromise. The essential requirements of footwear must be specified, and then a compromised solution must be sought which will meet the essentials as much as possible, and secondly to meet as many of the desirable requirements (ranked in order of importance) as is practical.

During the discussion of materials, design, and construction, it has been difficult to avoid discussing some of their pros and cons in relation to one another, and how they affect other requirements. A few more comparisons between them, and between their advantages and disadvantages, follow.

With respect to the US double vapour barrier boot designed to protect the foot against the cold, and the insulation from getting wet, Stokes (1), Court (18), and Schwartz (19) point out that the heat lost by the foot during exercise or warm weather (0°C or above) can not be sufficiently dissipated. The foot becomes overheated and the sweat is not removed. Therefore the boot's upper temperature limit of use is low. The boots are also heavy and clumsy and lack support. Blaber (42) also suggests that when the boots get soaked with sweat, they will take several days to dry, increasing the risk of cold weather injury.

Stokes (1) has also suggested that in boots using better developed rubber soles for better traction, there is a greater relative movement between the foot and the inner-sole. The resulting friction, possibly combined with accumulated sweat, may be the cause of the drawing or burning of the feet some people complain of when walking on rubber soles. On the other hand, as Blaber (42) points out, if a steel insert is incorporated into the sole for protection against spikes, the sole becomes too rigid for marching long distances. The steel also acts as a good conductor of heat which is not desirable in the cold. PVC soles are attractive because they allow a wider choice of uppers than do rubber soles, because rubber soles require high vulcanizing temperatures. PVC soles, though, exhibit poor traction characteristics at low temperatures (21).

In the 1960s a new soling process appeared which had many good properties including good traction, light weight, and flexibility. Direct vulcanized microcellular soled footwear unfortunately proved to be difficult to manufacture as many inconsistencies in the cell formation were found.

To balance the need for a boot which is both waterproof and water vapour permeable, leather uppers are still used because of their water and water vapour permeability (outward). The boots are then treated with a water repellant finish. Silicone and Bavon improve the mechanical properties of the leather but unfortunately reduce the water vapour permeability. Bavon increases absorption of water and water vapour. This property might be advantageous in a hot and dry climate, but could be quite a disadvantage in a cold and wet climate.

One of the reasons why many people prefer a leather boot, is because of its ability to permanently deform to the contour of the foot. This is sometimes called the "give" or the result of "breaking in", and is frequently anticipated during the initial fitting. However, because the world demand for leather is increasing faster than the supply, synthetic leather is growing quickly in popularity. Corfam, an example of a synthetic leather, exhibits many of the properties of leather but has the added advantage of stable pricing, less weight, and greater possibility of automated construction. On the other hand, the elastic nature of Corfam does not give or break in. Thus a boot which does not fit quite right will cause pressure sores every time it is worn.

Insulation implies bulk (13), because insulation usually implies materials which efficiently trap air. Bulk is normally associated with impaired function. Unfortunately, this particular problem of warmth without bulk, cannot be fully overcome by good design.

MacDonald (37) discusses quick closure advantages and disadvantages. Desirable features of the hook and loop concept are that they are easily adjustable, and can be donned and doffed very rapidly. Undesirable features include strap replacement is a depot maintenance function, long term field behaviour is unknown, and they are not silent when used. The slide fastener is the most rapid donning and doffing concept tested, but its water resistance is poor. With respect to the buckle-up concept, a wide range of fit control can be exercised and the system remains functional even with some missing elements. The one big disadvantage of the buckle design is that the large number of elements may increase the cost.

Although Woodcock (39) suggested that air pumps in boots might ventilate the foot better and thus make it more comfortable, he further suggests that it is not possible to maintain dry socks with a ventilation volume equal to the air space within the boot. Also, the use of a foot pump would considerably increase the expenditure of energy in walking and would tend to reduce stability and make walking insecure and unsafe.

While it has been indicated that small quantities of local heat in the form of electrically heated socks, will delay the onset of frostbite (40), the practicality of a soldier carrying an electric source of heat is dependant on other factors such as weight and the availability of batteries.

An axiom suggested by Oakley (2) is that the heavier a boot, the more durable it is. This would imply another compromise. All the above materials and designs described which meet at least one of the proposed requirements and add weight to the boot, should be considered carefully. Adding weight to boots greatly affects mobility. Each kilogram of footwear is equivalent, in energy cost, to 5 kilograms carried on the torso (49).

Even with regard to fit, compromises must be made. If every soldier is fitted with the best fit possible, there would be a very large number of different sizes and shapes of boots, which is impractical. The best compromise would therefore be a careful selection of sizes which will provide the best fit for the greatest number in the population. Companies already exist which can convert anthropometric databases into such an optimum range of sizes.

## 5.0 CONCLUSION

As was mentioned earlier, this review summarizes only a portion of the overall subject of footwear. Although sometimes straying, an attempt has been made to focus on the outermost layer of protection for the foot; the boot. A comprehensive list of requirements is presented, and some materials, designs, and construction techniques are discussed which may fulfill some of these requirements. An attempt is made to draw the reader's attention to the compromises which must be made in describing the boot design criteria. The bibliography would be larger given more time, but it is hoped that a complete enough picture is drawn to assist in establishing the objectives of a footwear research and development project.

## 6.0 RECOMMENDATIONS

It is recommended that the Canadian Forces requirements and/or deficiencies for army footwear for cold/wet scenarios be reviewed, and a new set of requirements be written which would list a realistic set of essential and desirable guidelines for the development of such footwear. It is hoped that the desirable features of such footwear can be further grouped and ranked in decreasing order of importance. This document would then form the basis of the objective of a research and/or development project which would address these concerns.

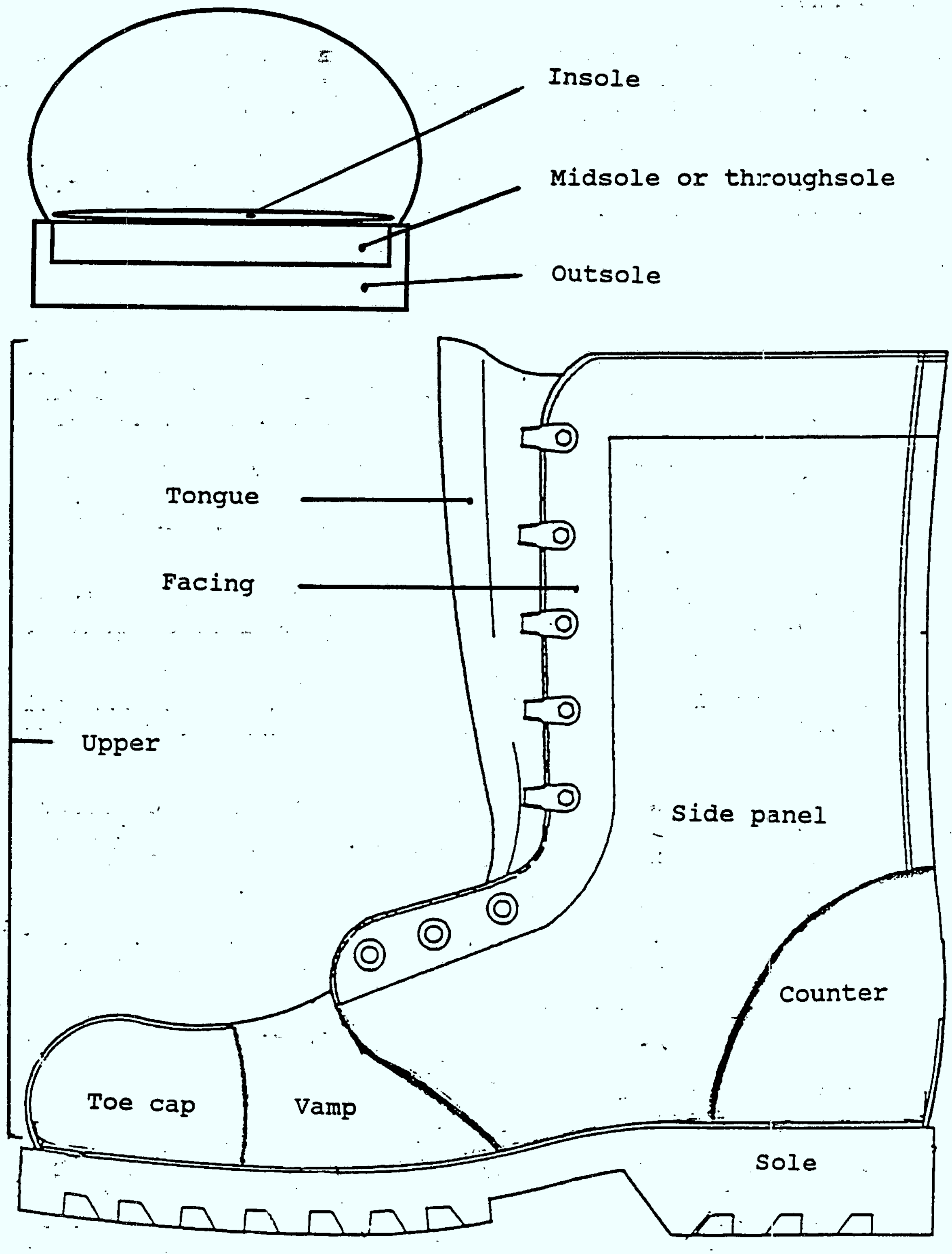


Figure 1. Some of the components which make up a boot.

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