THE MULTIFUNCTIONAL MATERIALS NEEDS OF THE FUTURE DISMOUNTED SOLDIER

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The Canadian soldier system vision is looking to three time frames: today, tomorrow and the future. The current efforts by the CF include the "Clothe the Soldier Plus" (CTS+), which involves incremental improvements to today's equipment (e.g., night vision goggles, non-lethal systems, etc.).

The dismounted soldier is now being considered as a system of systems where the new systems are designed to enhance the capability of the soldier. Some of these systems include the head-borne system, the battle management system, the ballistic protection system, the power system and the weapon system. This non-traditional view of the soldier is a direct result of Canada's Army of Tomorrow (AoT) and Adaptively Dispersed Operations (ADO) concepts.[1] Looking towards tomorrow and beyond, the future soldier will be required to carry more, utilize more technology and withstand more extreme environments.[2] Advances in materials and technologies will be required to alleviate the increased weight and related fatigue arising from these new demands.[2] *Multifunctional* materials may fulfill these needs. "Multifunctionality" is a cross-cutting idea that encompasses many classes of materials as well as their applications. Some of the applications of interest for the dismounted soldier include materials that are lightweight and enhance the stealth, ballistic protection, biological/chemical (BC) resistance, communications/energy storage properties, durability and comfort of soldiers' equipment and uniforms. The payoffs to developing these technologies include significant reductions in fatigue, casualties and detection, and improved individual environmental protection.

The focus on the soldier is not unique to the Canadian Forces (CF). The US has invested in the soldier as illustrated by the Massachusetts Institute of Technology's Institute for Soldier Nanotechnologies (ISN). Its mandate is to research advanced nanotechnologies to dramatically improve the survivability of the soldier of the future.[3] The ultimate goal for ISN is to create a 21st century battle-suit combining high-tech capabilities with both light weight and comfort.[3] The US Army Natick Soldier Center is also working on nanomaterials for protective materials, smart textiles and improved food packaging.[4] Other countries have programs to address the requirements of their own future soldiers. In the UK, the program is "Future Infantry Soldier Technology" (FIST), the Italian army has "Soldato Futuro," the German army has "IdZ" and the French army has "FÉLIN." The Netherlands have identified the wireless soldier in a smart uniform as the central element in the future combat system.[5]

The Integrated Soldier Systems Project (ISSP) will build upon CTS+ to significantly enhance individual and group lethality, mobility and C4I (command, control, communications, computers and intelligence); providing the framework to move the soldier of today towards the Army of Tomorrow.[6,7] The goal of ISSP is to provide soldiers with an integrated system of electronic devices, weapons accessories, operational clothing and individual equipment to allow them to operate in an evolving battle space.[6,7] The ISSP along with other CF initiatives will feed into Soldier System 2020, a vision of how the soldier will respond to the future battle space. As part of the Soldier System 2020 concept, a roadmap has been developed to encompass a wide range of research areas that may lead to enabling technologies. In the continuous process of trying to anticipate future needs and develop the capabilities to address them,[8] the CF army doctrine personnel have started the process of developing a vision for 2040.

Canada's ISSP has identified the need to explore novel technologies[1] for the soldier. Towards this end, Canada is involved in international collaborations to investigate appropriate technologies. These include the NATO research program on "Smart Textiles for the NATO Warfighter"[9] and a trilateral agreement with the Netherlands and Sweden on a "unigarment" for the future soldier. The ultimate goal is for the unigarment to utilize nanotechnology and multifunctional materials to integrate lightweight armour, thermal management, BC protection and power/electronics into a single system worn by the soldier. This article will review some potential functional requirements of the future soldier, and present examples of multifunctional materials that may address these needs.

Functions of Interest

The functions of interest include equipment/uniform weight, soldier fatigue, thermal management both for thermal stress (arising from wearing/carrying kit), heat/cold stress (environmental), BC contamination detection/protection and ballistic protection (both improved core protection with reduced thermal stress and weight, and improved extremity protection). Current BC protection is heavy and its lack of breathability contributes to soldier fatigue. Improved ballistic protection is needed for increasingly dangerous environments, but current products cause thermal stress and reduced mobility. To achieve these functions with minimal impact to the soldier, new materials or combinations of materials designed for multifunctionality are needed.

There is a dichotomy in the needs of the dismounted soldier. On one side there are the increasing requirements for improved protection and individual communications, etc. that tend towards increasing the weight a soldier must carry. On the other side, the ability of the soldier to perform a mission is improved if the weight he has to carry is reduced. With the future soldier having to carry more equipment, a reduction in the weight of individual components or overall systems is necessary. Reduction in weight of equipment and uniform contributes to the endurance of the soldier by reducing fatigue/exhaustion.[10] In the effort to reduce weight, lightweight materials must provide equivalent or improved functionality compared to the materials they are designed to replace.[11] In the US, the ISN has set as an ultimate goal, the reduction of the weight of a soldier's equipment/uniform from 45 kg to 7 kg (via an intermediate weight of 18 kg).[12] A reduction in weight can be achieved in one of two ways: utilising inherently lighter materials, or combining functionalities such that one item can do the job of two or more.

Weight Reduction

The Canadian infantry manual (volume 3) specifies that a soldier can carry 35% of his or her own body weight and still maintain a high percentage of agility, stamina and mobility.[13] When the load exceeds 45% of body weight, functional ability drops rapidly. For an average soldier (i.e. 80 kg) these limits correspond to 28 kg and 36 kg respectively. The British Army's APRE (Army Personnel Research Establishment) has conducted trials that concluded that the economical load for a fit soldier is approximately 30% of his or her body weight and that the maximum marching load is approximately 45%.[14,15] These correspond to 21 kg and 32 kg respectively. The US Army field manual on procedures for foot marches specifies that the fighting load should not exceed 48 lbs (22 kg) and the approach marching load should be less than 72 lbs (33 kg), based on an individual's ability.[16] A comparison of the weights carried by the Canadian, UK and US infantry is given in Table 1. These are idealized numbers: in reality, the weights being carried can often exceed what is listed.

A study of how weight affects performance has been carried out. A recent Defence Research and Development Canada study determined there is a 25% reduction in a soldier's performance due to weight and heat retention while wearing a fragmentation vest without ballistic plates.[17] With these results in mind, reducing the weight of any or all of the equipment carried is an important goal. Table 2 shows that the largest contributor to weight is a soldier's weapon and ammunition, followed by the fragmentation vest and ballistic plates and then the food and shelter. Areas that may benefit from weight reduction include new lightweight materials for pack frames (both small pack and rucksack), lightweight shell and

Image of the Canadian concept of the future soldier.

insulating materials for clothing, sleeping bags, bivy etc. and lightweight packaging and casing materials for rations and ammunition.

Thermal Management for Comfort and Signature

Temperature regulation is required for comfort as well as reducing infrared (IR) signatures. Thermal management covers both insulation in cold conditions and cooling in hot conditions. Both conditions are of concern as the CF can be called upon to deploy in environments that range from arctic to desert conditions.

Traditionally, trapped air has been used as the primary source of passive insulation in clothing. Well known examples include down feathers and ThinsulateTM. Insulation also works by reflecting back the body's radiant heat. The degree of insulation is determined by the material, the average distances between the insulation fibres, the fibre size and the thickness of the insulation layer. Finer fibres can be packed more densely, and in turn, can trap more air, thus improving the insulation.

Adaptive insulation is an active material that can expand/contract depending on the heat load. The goal is to create a network of fibres that are self-regulating and can transition between low-loft, low-insulation and a high-loft, high-insulation. The benefit to such a system would be a reduction in weight through the elimination of bulky layered clothing; meeting the ISSP's goal of thermal and environmental protection with minimum bulk and weight.

At the other extreme, excess heat is also an issue. In hot climates the need for cooling can be a pressing requirement (e.g., Afghanistan has a countrywide extreme summer high temperature of 48°C[18]). Heat stress is a serious concern because it can affect the health and safety of the individual as well as operational performance.[4] When the ambient temperature is above human body temperature (37°C), heat is transferred to the person. This heat added to the metabolic heat generated by the body itself results in the human body heating up. The fundamental issue for military personnel and emergency responders is the inability to reject heat (either metabolic or environmental) due to the insulating nature of the materials in their uniforms and/or personal protective clothing. As a result, core body temperature rises.

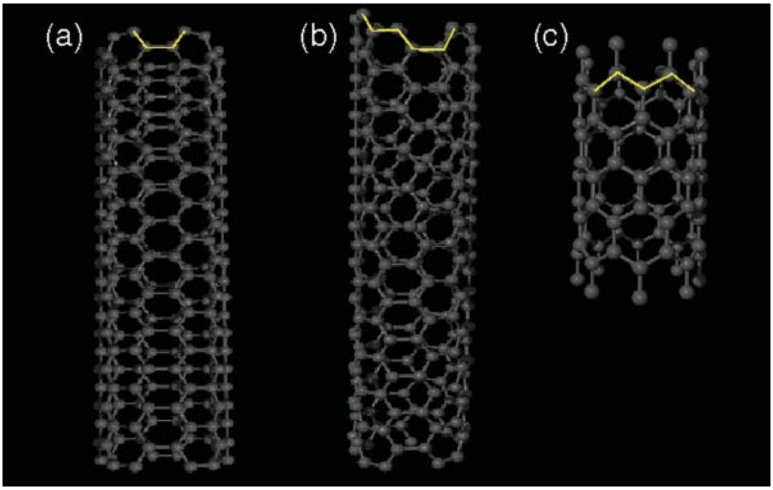
Passive or active cooling technologies can be considered to alleviate this problem. Passive technologies promote removal of perspiration from the skin. Such technologies include sweat-wicking textiles and other technologies that facilitate evaporation. Active cooling technologies include microclimate cooling (MCC). Microclimate cooling technologies remove excess body heat and reduce body core temperature by conduction and sometimes convection. The Natick Soldier Center reports that the use of MCC technologies "significantly increases a user's mission duration, improves mental acuity, reduces dehydration and enhances thermal comfort."[4] Microclimate cooling technologies work by altering the microclimate immediately surrounding the individual. Cooled air, liquid, ice or wax is circulated around a series of tubes incorporated into a cooling vest. Applying these systems to the dismounted soldier is challenging due to their weight and power requirements. Currently available personal cooling systems for the dismounted soldier operate on one of two principles:

- circulating air between the armour and the soldier's skin (convective cooling) or;
- body heat transfer (conductive cooling).

Both systems have draw backs. Circulating air requires fans, which need power, while heat transfer or phase change materials tend to lose their efficacy with time and require "recharging."[19] Cooling can also be achieved by applying thermal regulation elements into the body armour itself. Johns Hopkins University has filed a patent that describes the use of high thermal-conductivity channels embedded into body armour to conductively remove heat from the body.

Biological and Chemical Protection

With growing concerns over the possibility of terrorist attacks using biological and chemical (BC) threats, protection is of increasing importance. Chemical threats refer to nerve and blister agents, while biological threats include bacteria (e.g. Anthrax), rickettsia (e.g. Typhus), toxins (e.g. Botulinum Toxin) and viruses. The drawbacks to traditional personal protective clothing (PPC) are its bulk, weight and lack of breathability (i.e., contributes to heat stress). There are two parallel and complimentary research streams in this area; sensors and protective clothing. Both are a necessity. Sensors are important for early detection of contaminants, while light, comfortable and protective wear is essential for survival.



Courtesy of Author

Molecular depiction of the three types of carbon nanotube. a) boat configuration, b) chair configuration, c) zig-zag configuration.

There are many companies and research groups investigating sensors for BC agents. The important aspect from a soldier's point of view is to make these sensors compact, lightweight and inexpensive. In this way every soldier could carry them, either in the form of a wrist watch-type device or integrated into the fabric of the uniform.

The purpose of PPC is to shield individuals from BC hazards. Personal protective clothing to combat BC threats consists of a gas mask at the bare minimum, but includes a chemical suit, boots, mask and gloves when full protection is needed. Unfortunately, no single combination of PPC is capable of protecting against all hazards. A number of factors must be considered when designing BC protection. These include: thermal comfort, catalytic breakdown of contaminant and self-sensing/signalling. PPC can be classified by design and performance. There are three classes relevant to BC protection. In order of increasing contribution to heat stress they are: gas-tight, liquid-splash-protective and permeable-protective.[20] Gas-tight encapsulating suits provide a vapour-protective barrier. Liquid-splash-protective suits are not gas-tight, but are impermeable to liquid chemicals. Permeable-protective suits allow most molecules to permeate the surface, but chemically react with, or physically remove certain toxic materials before they can reach the skin.

Technologies for PPC include: permeable material treatments, permeable sorptive materials, engineered permeable materials and impermeable materials. Traditional textiles are permeable and do not offer protective properties against BC threats. Treatments and finishes can be used to enhance their protective capabilities. These treatments can impart high surface tension properties, and the ability to wick moisture. Permeable absorptive materials provide protection by trapping vapour-phase contaminants as they pass through the fabric. The two main materials for these technologies are active carbon and zeolites. The active carbon is selective for hydrocarbons, whereas zeolites can be tailored to absorb a range of contaminants.

Permeable materials can also be engineered to restrict the penetration of certain molecules while allowing others such as moisture or water vapour through. These materials are of particular importance because they allow for evaporative cooling and contribute to personal comfort. Engineered membranes include semi-permeable membranes, carbon-loaded semi-permeable membranes, nanofibre membranes and reactive material technologies.

Saratoga®, manufactured by Blücher is an example of an active-carbon-loaded filter fabric used in permeable-protective suits and is marketed by Tex-Shield Inc. as the Joint Service Lightweight Integrated Suit (JSLIST) for the US Armed Forces.[21] The corporate literature claims a minimum of 24 h reliable protection against neat and thickened chemical warfare agents, even after 45 days of wear and tear (including laundering) on the fabric.[21] The manufacturer also claims high air-permeability, leading to a reduced heat stress and sweat accumulation.[21] Impermeable materials prevent transmission of aerosols, liquids or vapours through their membranes. This includes the moisture produced by the user as well as exterior contaminants and can lead to increased heat stress for the wearer.

Fragmentation and Small Arms Ballistic Protection

Explosions from improvised explosive devices (IEDs) are designed to maximize injury to exposed as well as protected human targets. Medical facilities are seeing more devastating extremity injuries than ever before, and the wounded arrive with severe damage to bones, blood vessels and nerves. Although fragmentation vests (a.k.a. frag vests) protect the upper torso and reduce the number of fatal chest injuries, the number of arm and leg injuries is on the rise. American sources show injuries affecting the arms account for approximately 25%, while legs make up approximately 30% of all injuries.[22] The recent conflicts in Afghanistan and Iraq have resulted in numbers of limb amputations more than double those in previous conflicts.[22] This indicates that there is a need for new lightweight and flexible materials for both core and limb protection. Protection against projectiles is of ongoing importance because it is directly related to survivability.

Body armour is generally made from multiple layers of materials. When a projectile strikes the armour, it is caught in a mat of very strong fibres. The fibres absorb and disperse the impact energy. Each successive layer of material in the armour absorbs additional energy until the projectile is stopped. Frag vests with ballistic (armour) plates are the primary source of protection against shrapnel and small arms projectiles. Armour should defeat multiple hits of high level threats while maintaining the lowest possible weight, and provide the wearer with unrestricted movement. Historically, “combat assault” type frag vests were composed of soft fabric made of glass fibres. Modern vests are more advanced and are produced from synthetic fibres such as Kevlar® or Twaron®. These materials form the basic frag vest, which also allows ballistic plates to be added to pockets within. The ballistic plates can be steel, ceramic or high performance polyethylene (i.e., Spectra® or Dyneema®).[23] General frag vests provide front, back and side protection, but with increased threats new vests include neck, shoulder and groin protection.[23] The drawback to these new vests is the increase in weight and bulk that adversely affects a soldier's performance.

Advanced armour materials must enhance protection and increase survivability. A number of factors must be considered when engineering armour. These include penetration resistance, weight, bulk, deflection, multi-hit capability, flexibility, comfort and field durability.[11] There are a number of synthetic fibres suitable for use in armour applications. Kevlar® is a para-aramid (i.e., polyaromatic amide) material from DuPont™ with high strength, low weight, high chemical resistance, high cut resistance and flame resistance. Spectra® by Honeywell is an ultra high molecular weight polyethylene (UHMWPE). Honeywell claims that Spectra® is the highest strength-to-weight fibre in the world.[23] GoldFlex® is also manufactured by Honeywell using para-aramid fibres, in a process similar to Spectra®. Twaron® is another form of para-aramid manufactured by Twaron Products. It differs from other polyamides because it uses microfilaments that are finer and lighter than conventional fibres. Microfilament technology allows energy to be dispersed more quickly, while enhancing comfort and flexibility. Dyneema® (UHMWPE) has a high strength-to-weight ratio, can float on water and has high energy absorbing characteristics. Toyobo manufactures a polyphenylenebenzobisoxazole (PBO) fibre marketed as Zylon®. PBO has good thermal properties and almost twice the tensile strength of conventional para-aramid fibres. Toyobo claims Zylon will make excellent protective garments because its heat-and mechanical-resistant properties will yield light, flexible fabrics with increased mobility and comfort.

The new materials discussed have decreased the bulk and weight of body armour from traditional materials. Newer materials, yet to be developed, in conjunction with further advances in vest design and engineering will continue to improve comfort and performance for the future soldier. To be considered an improvement, new lightweight materials must provide equivalent functionality while having a 30% weight reduction over conventional rigid armour. Armour can be improved by incorporating other essential functionalities. For instance, the ISN is investigating Kevlar® vests that incorporate a layer to protect against biological agents.

Extremity armour is not a new concept. Gauntlets for the arms and greaves for the lower legs date back thousands of years. The key is to protect vulnerable areas with a minimal increase in weight and without adversely affecting the ability to perform tasks. The US has developed a product called QuadGard®. The QuadGard® design uses Dyneema® and has been transitioned to use. In the future, the ideal materials used for extremity protection will be as flexible as ordinary textiles and only stiffen to supply fragmentation/small ballistic protection when needed. DuPont™ has proposed fabrics that change properties on demand by using plastic fibres with parallel hollow channels that can be filled with a material whose properties can be altered (e.g., *ferrofluids*).[24] An extension of this reasoning could yield a makeshift splint, that with the "flick of a switch" could cause the fabric around an injured part to become stiff and supportive.[3,10]

Power/Data/Conductive Applications

The dismounted soldier of the future will be carrying increasing amounts of high-tech equipment. With more technology, comes the need for energy to power it. Increased energy demand translates to more weight unless overall power requirements are reduced or improved storage materials are implemented. Along with need for new power systems and storage, novel ways to transfer data are needed. Examples of applications include antennas that are integrated and/or embedded within clothing or other pieces of equipment, flexible displays, equipment that is powered either through wired or wireless systems, novel interconnects for equipment and power harvesting and energy storage for technology life extension. In some cases, integrating these applications into intelligent textiles may be desirable.[25]

Network-centric Warfare

Information technology (IT) is playing an increasingly important role in the battlefield. Future soldiers will have an array of wearable IT to assist in their tasks. A head-up display (HUD) is a transparent display that supplies data without obscuring the user's view. The goal of an HUD is to increase situational awareness and operational effectiveness. Head-up displays have been used in fighter planes to centralize critical flight data within the pilot's field of vision, but they also have applications for the dismounted soldier. When supplied to the soldier via a visor or glasses, the technology is referred to as "head-mount" display (HMD). Head-mount display design is inherently a multidisciplinary endeavour encompassing engineering, materials and human factors. An HMD needs to be flicker-free for near-eye applications (i.e., less than a millisecond refresh rate), provide high-resolution information, have low power consumption and operate across a wide temperature range. Ideally, the HMD would be viewable under varying light conditions (e.g., daytime, dusk/dawn, night time, indoor and outdoor).

Night-vision technologies use image intensifiers to amplify the available light to achieve better vision. The most common methods for intensifying an image use low-light imaging, thermal imaging or near-infrared (IR) illumination.[26] Low-light imaging focuses the available photons onto a photocathode. The photocathode amplifies the image by generating more electrons than the incoming photons. The electrons hit a phosphor screen, providing the enhanced image. Typically a green phosphor is used because the human eye can differentiate more shades of green than any other colour.[26] Thermal imaging does not require any ambient light at all. All objects emit IR energy as a function of their temperature; the hotter an object, the more IR radiation it emits. Thermal imagers collect the IR radiation and use it to create an image. Because thermal imagers are based on IR radiation, they are able to penetrate smoke, fog and haze. Near-IR illumination combines a detector that will detect both low-light images and near-IR, with a near-IR illuminator. Near IR illuminators (e.g., 730 nm, 830 nm and 920 nm) provide supplemental IR illumination. The added illumination eliminates the variability of available ambient light, eliminating shadows and enhancing image contrast. It allows the observer to illuminate specific areas of interest. The supplemental near-IR lighting improves the quality of the image. The only drawback is that the device emits an IR signal which can be detected by others with the appropriate equipment.

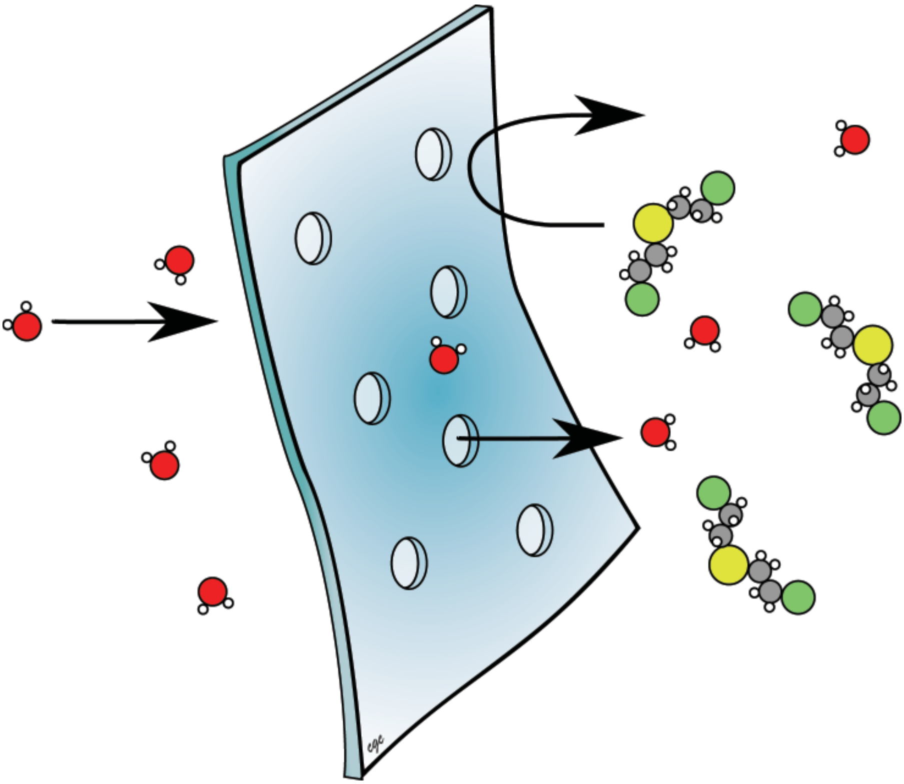
In 1997, the CADPAT (Canadian Disruptive Pattern) was adopted by the CF to replace the traditional camouflage pattern. The CADPAT is a computer-designed pixelated pattern, which not only protects against visible detection, but is designed for near-IR protection as well, thus hiding a soldier from image intensification devices (i.e., night-vision technologies). Since implementation of the CADPAT design, armies in other nations have also started using a digitized disruptive pattern. The disruptive pattern can reduce detection by up to 40% when within 200 m of the subject. The requirements for improved camouflage include development of a pattern that is more universally applicable and that can transition between different environments, thus, eliminating the need for separate woodland, arid and arctic uniforms. Also, at distances greater than 200 m, the disruptive pattern begins to lose its effectiveness. A pattern that improves camouflage at greater distances may be of interest. Such a pattern might incorporate mathematical expressions such as fractals.

Technologies of Interest

The previous paragraphs outlined the developments and requirements for reduced weight, thermal management, BC protection, ballistic protection, power systems, and improved situational awareness. These requirements can be achieved through new materials, combinations of materials and careful design to impart multifunctionality. As soldiers are equipped with new technologies that enhance their capabilities and safety, it is essential that the weight of the equipment they are required to carry not be increased. In addition, it is essential that enhanced environmental, ballistic and BC protection not increase thermal stresses or limits on mobility to the point where the soldier becomes ineffective in the field. The application of new materials, multifunctional materials and technologies have the potential to address these requirements. Some promising research areas are discussed below.

Nanomaterials

A nanometre (nm) is one-billionth of a metre; a human hair is approximately 80,000 nanometres thick. Another way to think about "nano-scale" is that one nanometre is to a metre what a pea would be to the distance between New York and Miami. A new class of materials, "nanomaterials," have at least one dimension that is on the nanometre scale. Nanomaterials take advantage of the fact that when a material is of a size comparable to only a few atoms (i.e., 1-100 nm), size effects result that lead to unique properties.



Courtesy of Author

Illustration of a membrane with nanopores; selective to allow water vapour through while restricting larger molecules such as chemical warfare agents.

Carbon nanotube (CNT) chemistry is a rapidly growing field. Carbon nanotubes can be thought of as sheets of carbon rolled into tubes. They are very strong, thermally conductive, either electrically conducting or semiconducting, and behave as field emitters. Some possible applications include: ultra-strong lightweight fabrics, field-emission based flat-panel displays, hydrogen storage devices, novel semiconductors, chemical/biological sensors, and electromechanical sensors.[27] When added to a polymer matrix to make a composite material, CNTs impart a mechanical reinforcement at low loading levels, thus reducing the overall weight of the composite required for a particular application.

Carbon fibre composites have been used for two decades to make strong, light materials. Specific examples of carbon fibre composite applications include automotive applications and sporting goods. The weakest part of a carbon fibre composite is the resin between the fibres. Technologies that use a combination of conventional carbon fibre composites with CNT additions are now being investigated. Because the CNTs are orders of magnitude smaller than the carbon reinforcing fibres, they improve the properties of the resin by improving strength and toughness. This technology is already being used commercially by Easton to make lighter, stronger composite baseball bats. The Easton CNT composite has also been used to make racing bikes that weigh less than a pound (0.456 kg) and are strong enough to withstand the rigors of the Tour de France. This technology has a lot of potential for many areas where lightweight, strong materials are needed (e.g., backpack frames, tent frames, etc.). Carbon nanotubes also have excellent energy absorption capacities. As such, they have potential applications in antiballistic materials. In a proof of concept demonstration Mylvaganam and Zhang have shown through modeling that nanotubes with large radii withstand higher velocity impacts. The ballistic resistance is greatest when the CNTs are tethered at both ends and the impact is in the middle of the CNT.[28] Okoli from Florida State University has developed a composite manufacturing process to create lightweight body armour (for legs, arms and head) that utilizes carbon nanotubes.[29]

The term “nanofibre” refers to any fibre that has a diameter between 1-100 nm. Spider silk, collagen and cotton are examples of naturally occurring (protein) nanofibres. Polymer nanofibres are produced through “electrospinning” a polymer feedstock.[30] Bacause polymer nanofibre composites may be used to dissipate energy, they have applications in soft armour technologies. Soft armour is desirable to protect the extremities because it does not restrict movement. Teijin produces a woven textile with a large number of densely packed, very fine-denier Twaron® fibres—referred to as “microyarns”—that offer an improved protection level compared to thicker, coarser textiles made of the same composite materials.[31] The microyarns are woven to minimize the crossover of warp and fill. Teijin then uses laminated fabric technology (LFT) to sandwich the woven textile between thin thermoplastic films, yielding the lightweight armour end product.[31] Liu et al. have shown that when electrospun polycarbonate nanofibres are added to polycarbonate/poly(methyl methacrylate) matrices they improve the ballistic impact resistance of the composite while maintaining the material’s transparency.[32] These materials show promise for eye protection and other transparent armour technologies.[33,34]

Electrospun polyurethane nanofibres have been proposed for breathable, water-proof textiles.[35] These may have applications for sweat-wicking applications. Lee and Obendorf have shown that electrospun polypropylene webs provide excellent barrier performance against a high surface tension challenge liquid (specifically pesticides).[36] The goal of their research was to examine novel materials for protective clothing for agricultural workers, although the work could be extended to first responders and military personnel requiring BC protection. They identified a need for textiles that had both high protection and increased comfort in hot environments. Comfort was assessed by examining air permeability and water permeability (i.e., increased permeability meant increased comfort). Shreuder-Gibson et al. from the US Army Natick Soldier Center have been investigating electrospun polymers for protection against BC threats in aerosol form.[36,37] Due to their high surface area, nanofibres could possibly be used for decontamination via adsorption and/or catalytic breakdown of toxins[36].

The thermal insulating efficiency of fibre-based insulation increases as the diameter of the fibre decreases.[38] This suggests that nonwoven textiles made from nanofibres should exhibit good insulating properties. The thermal properties of nanofibres and their potential for protection against cold environments are relatively unknown, but it has been postulated that they offer potential as insulating materials due to low mass, high strength and high surface/volume ratio.[38] The resulting decrease in weight and bulk over current thermal protective clothing could result in an increased mobility for the soldier.[38] Unfortunately,

Table 1: Summary of recommended weights carried by Canadian, American and British Infantry.

	Fighting Order	Battle Order	Marching Order
CAN	10-15 kg	15-20 kg	30-35 kg
UK	21 kg	24 kg	32 kg
US	22 kg	n/a	33 kg

Table 2: Examples of equipment carried by Canadian Infantry and their weights.

Item	Approx. Weight
weapon (excl. ammo)	4.7-7.6 kg
ammo	5-6.2 kg
helmet	1.6 kg
night vision goggles	0.5 kg
fragmentation vest	2.8 kg
ballistic plates (2) – for frag. vest	2.6 kg ea.
NBCD mask & case	2.3 kg
tactical vest (alone)	1.1 kg
camel back (3 L)	3.3 kg
small pack (alone)	1.5 kg
rations (24 h)	2.1 kg
rain gear	1 kg
rucksack (alone)	3 kg
rations (48 h)	4.2 kg
sleeping bag, bivy *etc*.	4.5 kg
ground sheet	1.4 kg
clothing	1.5 kg
combat jacket	1.3 kg
NBC suit, boots & gloves	4 kg

Table 3: Comparison of the strengths of various armour materials.

Tradename	Material	Yield Strength (GPa)	Density (g/cm^3)	strength/weight ratio
-	low carbon steel	0.5	7.8	0.1
-	high strength steel	0.7	7.8	0.1
Spectra®	UHMWPE	3.0	0.97	3.0
Dyneema®	UHMWPE	2.4	0.97	2.5
Kevlar®	para-aramid	3.0	1.4	2.1
Twaron®	para-aramid	3.6	1.4	2.5
Zylon®	PBO	5.8	1.6	3.7

Gibson's preliminary work in this area suggests that nanofibres are not useful for high-loft thermal insulation and that below 1 micron diameter and at low fibre volume fractions, they are not thermally efficient.[38] However, nanofibres may be incorporated into hybrid battings where a proportion of the fibres are larger to provide durability and compression recovery[38].

Smart Materials

Conventional textiles serve two purposes:

- to function as a protective layer for the skin and
- to perform technical functions.[39]

When a textile performs additional functions, it is know as a smart textile. Desirable textile properties for military use include durability, “launderability,” flexibility and non-toxicity, with additional functionalities including light weight (low mass), improved camouflage, and BC protection. When considering the addition of new functionalities, the textile should retain the usual tactile, flexible and comfort properties of the cloth. As well, new textiles should not exceed the current bulk or increase the heat stress on a soldier. The ultimate goal for smart textiles is to be able to mimic skin, which can sense pressure and temperature, and reacts to these stimuli. Skin can change colour, is permeable, can shed and regenerate itself.

Smart textiles can be either passive, meaning they only sense the environmental conditions, or active, meaning they can both sense the environment and respond to it (e.g., thermoregulating garments that maintain the wearer’s body temperature). Smart textiles could be used to augment the sensory system of the skin by sensing external stimuli such as proximity, touch, pressure, temperature and chemical/biological substances. Antibacterial properties can be added by incorporating nano-sized silver, titanium dioxide and zinc oxides.

Smart textiles will play a major role in future camouflage technologies. Metallic pigments are used for near-IR camouflage; a new generation of fibres using nanofibres of nickel, copper or silver may lead to fibres that could change colour.[25] Adaptive (or switchable) camouflage in the visible region may be possible with thermochromic inks or electroluminescent materials.[25]

The comfort aspect of clothing is very important. A new technology that could be used to address comfort and possibly BC protection is “changeable pores.” It may be possible to change the size of the pores in a polymer film using micro-polymer actuators. By changing pore size, the permeability is changed[39]. Smaller pores have better BC protection and reduce the breathability of the membrane, making it more effective at insulating. DRDC Valcartier has developed a knitted shape-memory polymer textile for infrared camouflage of structures.[40] Other adaptive thermal insulations include VARILOFT[41] and “aerogel” insulators such as Nanogel®.[42] VARILOFT is also based on thermally responsive shape-memory polymer fibres. A thermally induced strain is created within the fibre as the temperature changes. Through engineering the fibre mats, the strain allows the resulting textile to transition from a flat, two-dimensional configuration to a larger volume three-dimension structure. The result is a self-regulating batting that transitions from low-loft, low-R to high-loft, high-R insulation. Nanogel® is Cabot Aerogel’s tradename for the aerogel it markets as “the world’s lightest and best insulating solid material.”[42] Nanogel® is a silica-based aerogel lattice of 5% glass strands and 95% air which allows for high insulating properties while still transmitting light.

Smart materials are materials that can sense and react to environmental conditions or stimuli (e.g., mechanical, thermal, chemical, electrical or magnetic). Their functionality responds when required or dictated by the environment. Types of smart materials include: piezoelectric materials, shape-memory materials (e.g., alloys or polymers), pH-sensitive polymers, chromic materials (e.g., halochromic, electrochromic, thermochromic, or photochromic), and viscosity sensitive materials (e.g., magneto-rheostatic or electro-rheostatic).

Nanoscale manipulation results in new functionalities for intelligent textiles, including self-cleaning, sensing, actuating and communicating capabilities. Additionally, advances in processing techniques will result in improved yarns, films and textiles. A multi-component extruder can produce novel fibre structures, for instance, combining a sheath material over a core material to produce a unique core-shell fibre. The resulting fibre may combine properties of different polymers and additives including resistance to microbes, improved ability to retard fire, thermal protection, and electrical conductivity. This may be the engineering answer to achieving some multi-functionality that cannot be accomplished through chemical formulation.

Super-rheological Fluids

Also known as shear-thickening fluids (STF), the viscosity of super-rheological fluids change as a function of shear rate or applied stress. Typically, a carrier fluid is loaded to a high volume fraction (50-60%) with sub-micron sized oxide particles. These particles have been referred to as “nanobinders.” The particles are stabilized against flocculation by either surface charge or surface treatments. Joint research between the US Army Research Laboratories and the University of Delaware has developed a method to apply STFs to fabrics.[43,44] Fabrics with STF show potential in the production of extremity armour. Materials with STF have demonstrated reduction in “back face deformation,” suggesting an ability to reduce the blunt trauma effect resulting of high energy ballistic impacts.

Conclusions

The predictions made during the Cold War that future warfare would be fought more by machine than man have proven to be wrong. Recent conflicts have shown the continuing importance of the dismounted soldier. As conflicts change and more importance is placed on the asymmetric threat, technology must be leveraged to gain full strategic and tactical advantage in Adaptive Dispersed Operations.

The systems soldiers use must enhance their capabilities to provide improved situational awareness, comfort (heat and weight reduction), and protection (ballistic, BC, camouflage). However, as new systems are added, the weight that soldiers must carry is increasing. This puts increased strain on soldiers, limiting mobility and effectiveness. New materials and engineering of materials offer an approach to enhancing the capabilities of these systems without increasing weight. Along with weight, added equipment may increase power requirements. New technologies to meet changing energy demands are needed.

To take full advantage of new and improved technologies, an understanding of the materials used to make them is required. A fundamental understanding of multifunctional materials is essential before they can be implemented effectively for defence applications. With understanding, these materials can be evaluated and transitioned into new products.

Developments in the areas of nanomaterials, smart materials, super-rheological fluids and numerous other technologies not discussed here show great promise for use in multifunctional materials. Applications of these materials and technologies should lead to soldier systems incorporating some or all of: reduced weight, increased comfort, reduced signature, improved chemical and biological protection, improved ballistic protection and improved situational awareness.

About the Author...

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