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Security and disruptive technologies

Security Materials Technologies Roadmap

Synthesis Report prepared by the Security Materials Technologies Industry Steering Committee, National Research Council of Canada Security Materials Technologies Program, and Defence Research and Development Canada

National Research Council Canada
Conseil national de recherches Canada

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Executive Summary

Canada's armoured vehicle (AV) and personal protective equipment (PPE) industry is globally competitive. The industry is based upon conventional engineered materials such as aramid fabrics (e.g., Kevlar®), polymer matrix composite laminates, and monolithic ceramics, which are rapidly approaching their performance limits. While current materials are continuing to advance, the rate of development is relatively slow compared to the rapidly evolving demands for higher performance and lower-weight protection systems. New transformational technologies are required in order to improve armour mass-efficiency (protection for a given weight) and to address capability deficiencies identified by the user communities (military, law enforcement, and first responders).

The Security Materials Technologies (SMT) program, jointly lead by the National Research Council of Canada (NRC) and Defence Research and Development Canada (DRDC) and advised by an Industry Steering committee made up of Canadian Armour Industry peers, is working with industries across the value chain, from new and emerging materials to integrated armour systems, to demonstrate and transfer to Canadian industry transformational materials, structural concepts, and manufacturing technologies that will substantially improve the performance-to-weight ratio of AV and PPE protection systems. Collectively, NRC and DRDC have experience in developing high performance material solutions and multi-threat protection systems. The program can help develop improved and disruptive armour products, from concept to full-scale prototyping and evaluation, and can offer technical advice and consulting services to accelerate and substantially de-risk product development.

In November 2015, NRC, DRDC and the Canadian Association of Defence and Security Industries (CADSI) hosted the Canadian Security Material Technologies Roadmap (SMTRM) workshop. The SMTRM is an industry-led strategic planning process, designed to foster development of innovative products and systems to meet future market demands. Participants from across Canada and the United States had the opportunity to learn more about the current challenges and needs of the Department of National Defence of Canada and Canadian Armed Forces, and engaged in facilitated discussions about the future market demands.

The SMTRM report details the findings from the workshop. With input from the SMTRM Steering Committee, 11 technical challenges and nine advanced materials technologies solutions were identified. The workshop collected 44 project proposals, of which four overarching prioritized research areas will be explored. The selected projects support the objectives of the SMT program to better align government spending on R&D projects to the needs of industry and of future markets; and to develop highly focused partnerships, alliances, and opportunities to benefit all players.

Most beneficial to the SMTRM workshop participants was the opportunity to network and have open discussions with players in the defence and security, as well as materials technologies sectors. The information shared and obtained from the workshop will pave the way to develop state-of-the-art, built-in-Canada armour technology solutions.

Security Materials Technologies Roadmap Process

Background

Technology roadmapping is a proven and efficient approach for engaging stakeholders in a collaborative process that leads to the identification of science and technology (S&T) priorities and the definition of related research and development (R&D) projects. The roadmapping process relies on the active participation of Canadian companies and other stakeholders, which then become both the beneficiaries and the stakeholders of that process.

The technology roadmap process is not part of an acquisition process nor is it in direct support of any specific government procurement activity. It is meant to engage industry and other stakeholders to provide feedback, guidance, and recommendations on the strategic direction of the Security Materials Technologies (SMT) program and the security materials sector in general (see Figure 1).

The Security Materials Technologies Roadmap (SMTRM) framework is a free, voluntary, and non-binding collaboration process open to Canadian companies (companies with Canadian operations) and other stakeholders that are actively engaged in the defence and security sectors, with no need for membership in any given association. It is based on the mutual respect and understanding of the respective strengths, organizational structures, mandates, and capacities of the participants.

The SMTRM will help accelerate innovation, competitiveness, and productivity in Canada's security materials technology sector. Companies will gain a better understanding of market needs, which will help them shape their R&D and commercialization strategies more effectively. Working with the National Research Council (NRC), industry will have the opportunity to demonstrate their capabilities to potential users, identify new strategic business and research partners, and position themselves as global market leaders.

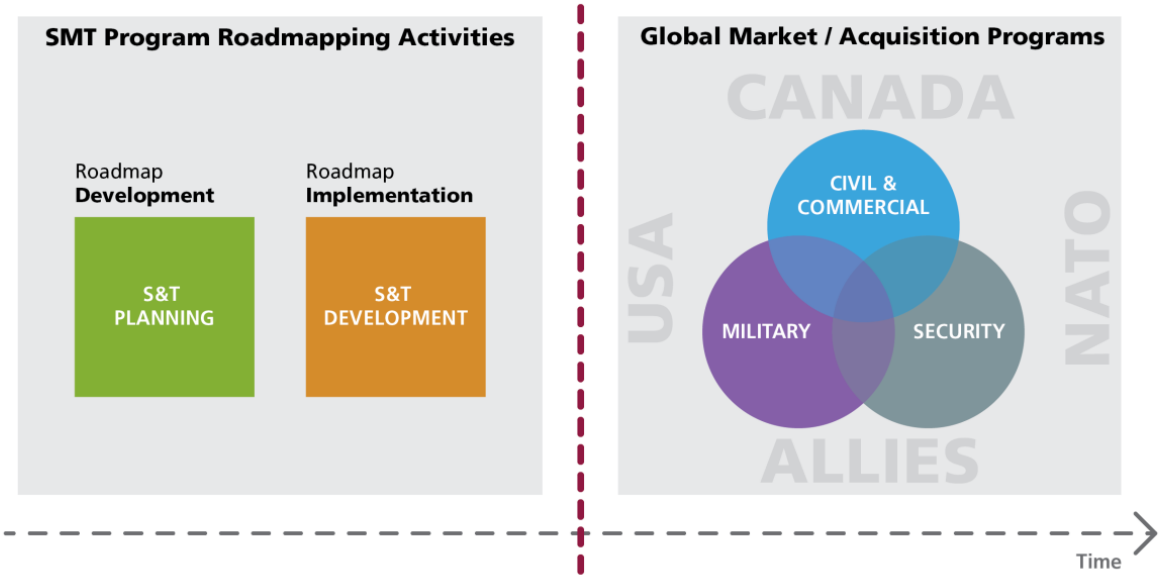


Figure 1: SMTRM versus Procurement

Governance

The Security Materials Technologies program is governed by the NRC-DRDC Joint Armour Board and supported by the NRC and Defence Research and Development Canada (DRDC) with guidance from the SMTRM Steering Committee, the Department of National Defence (DND), and the Canadian Armed Forces (CAF) (see Figure 2).

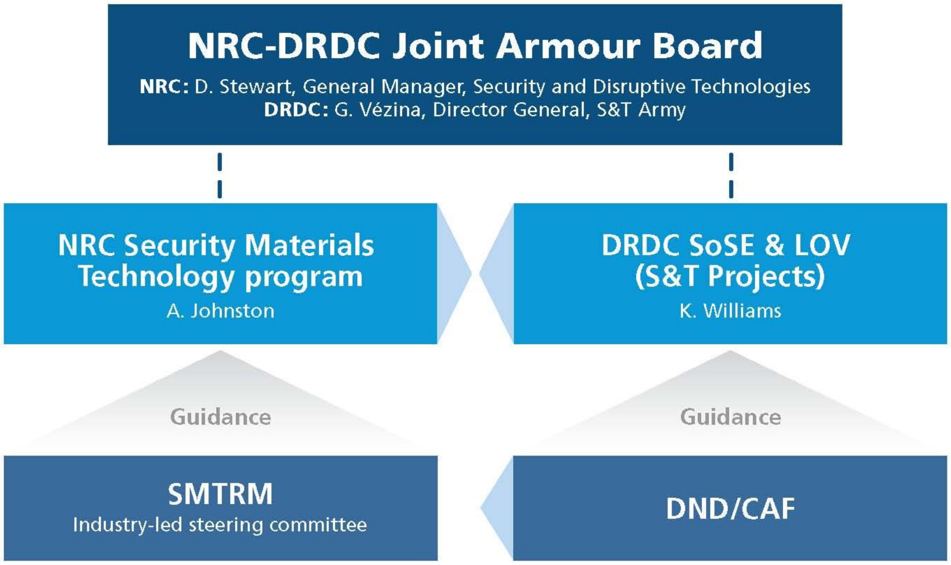


Figure 2: NRC-DRDC Joint Armour Board

The SMTRM Steering Committee (*see Appendix A: SMTRM Steering Committee Members*) consists of defence and security industry leaders, subject matter experts, and stakeholders who play a critical role in identifying activities focused on the security materials technologies sector. Members offer expertise in security materials research and technology development as applied to next-generation personal protective equipment (PPE) and vehicle armour (VA) products. Members were selected based on the merit of their applications, submitted in response to an open process that was advertised in 2014 and 2015 on BuyandSell.gc.ca.

The Steering Committee provides guidance to the overall SMTRM initiative, and provides industry leadership to the roadmap. The Steering Committee responsibilities include:

- Provide input into the direction and goals of the SMTRM;
- Vet the proposed work plan, objectives, and timeline;
- Actively participate in each stage of the roadmap development process and contribute to technical discussions;
- Strive for consensus in its recommendations, using the best available evidence, as well as best practices;
- Recommend appropriate implementation strategies, including leveraging from other initiatives or involvement from other stakeholders;
- Review and validate documentation produced throughout the process, such as workshop reports;
- Foster effective, open, transparent, and fair discussions;

- Encourage interchange of information between SMTRM participants;
- Act as a champion of the SMTRM among respective employing organizations and across the industry as a whole; and
- Report progress to the NRC-DRDC Joint Armour Board (see Figure 2).

Roadmap Process and Workshop

The SMTRM workshop, facilitated by NRC and DRDC in partnership with CADSI, was a collaborative exercise between Canadian industry, government, and academia. With 130 participants from Canadian and US companies, researchers, engineers, representatives of the user community, and government decision-makers, the two-day workshop provided networking opportunities, facilitated discussions between industry leaders, and ultimately paved the path for future collaboration.

The SMTRM helped identify the market need as it relates to PPE and vehicle armour, discussed technology challenges, and identified possible R&D projects of value for the Canadian security materials industry that would bridge the gap between what the market will require in 5 to 15 years (see Figure 3).

There is now a better understanding of future market needs and opportunities, and increased preparedness to develop technology options to fulfill future capability needs within the defence and security sector.

Figure 3: Illustration of the SMTRM workshop process

The SMTRM workshop was divided into four phases. The first three phases looked into a different element or lane of the roadmap:

1) future market needs (horizons: +5, +10, +15 years);

2) concepts, products, systems, and sub-systems; and

3) technologies.

The fourth phase aimed to integrate and connect the dots, and resulted in defined and prioritized R&D projects to which potential R&D programs and resources, including access to NRC research capabilities, will be aligned. (*See Appendix B: SMTRM Workshop Program*).

Open exchange of information enabled participating stakeholders to identify innovative technology options aligned with future security material market needs and competing demands, as illustrated in Figure 4. This process also facilitated the development of synergies between participants and other associated and interested entities.

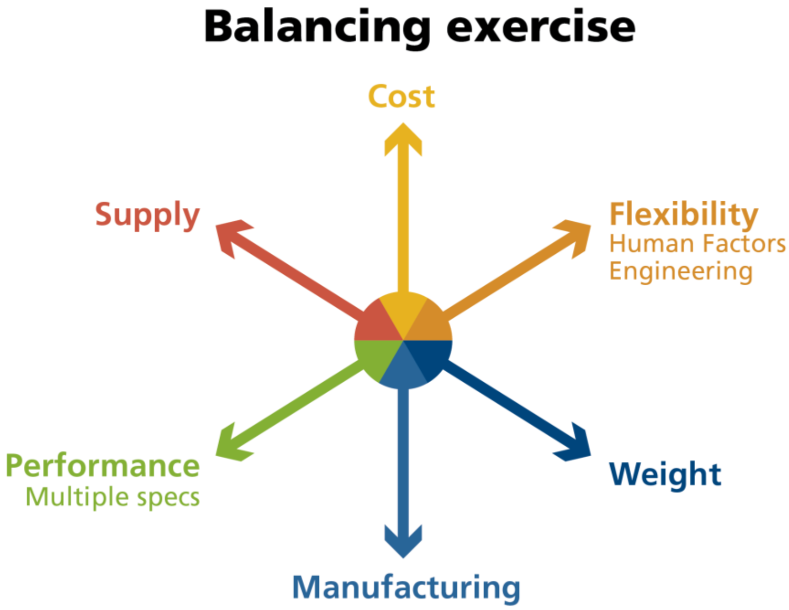


Figure 4: Various factors influencing the development of new technologies and solutions for the defence and security industry

Security Materials Technologies Roadmaps

The SMTRM is outlined in this section. The roadmap is divided into three time horizons (columns): the present to 2020, 2020 to 2025, and 2025 to 2040 and beyond. It is also divided into six tracks (rows): Market, Products/Systems Requirements, Technical Challenges, Technology Solutions, Research and Development Projects, and Resources.

There is one version of the map for vehicle armour (pages 8-10) and one for PPE (pages 12-13). Due to the format of this report, the roadmap has been divided into sections to fit on individual pages. However, it is available in its entirety on the Security Materials Technologies Roadmap website (www.nrc-cnrc.gc.ca/eng/solutions/collaborative/smtrm.html). The roadmap, as presented in this report, is primarily a framework for future dialogue and collaboration. The data included in this report has been informed by the SMTRM workshop and expert input, but should still be considered representative of the final data that will appear in the roadmap.

How the roadmap is developed

In each **time horizon,** there are forces and phenomena that shape the **market** for vehicle armour and PPE. These include the changing nature of conflicts and resulting threats, the development of new technologies for both weapons and armour, and the procurement trends and needs of allied and non-allied forces. A series of **products/systems requirements** for vehicle armour and PPE emerge in direct response to these market conditions. The requirement for increased modularity and interoperability in armour systems could result directly from an increase in joint operations with other countries (e.g., NATO missions) or the fiscal constraints of the buyers of these systems, for example.

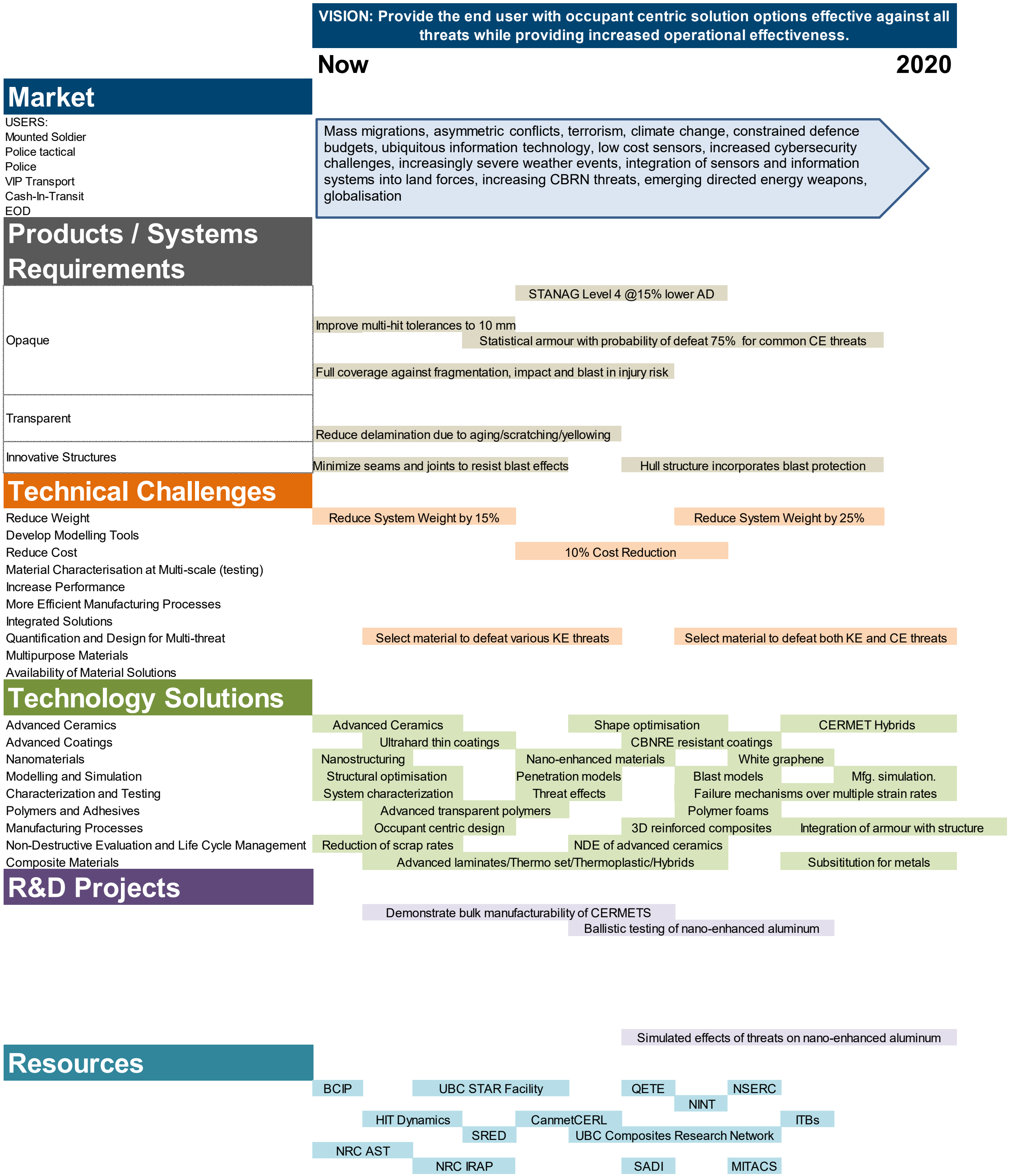
Achieving these product or system requirements typically results in **technical challenges** for industry, such as designing armour optimized for defeating a greater range of threats. There are a number of potential **technology solutions** that can be applied to address these technical challenges. Nine principle technology solutions were identified in the workshop. Whether individually or in tandem, these technology solutions offer pathways to addressing technical challenges that can be efficiently and effectively explored through the Security Materials Technologies program.

The exploration and ultimate selection of a technology solution is manifested in one or more **research and development projects**. These research and development projects draw on the expertise and facilities of research institutions, the know-how of industry partners, funding programs, and other assets that together form a pool of **resources** for innovation in the security materials sector in Canada. This systematic plotting of data onto a shared roadmap results in the rapid identification of requirements and the effective alignment and coordination of industry, research, and user resources to enable the Canadian security materials industry to better compete globally and provide the best armour systems to Canadian military and law enforcement.

Starting point of an evergreen initiative

The SMTRM will never be complete. Markets, technologies, and resources will continue to evolve, necessitating the addition, removal, or adjustment of data points or initiatives on the map over time. As this roadmap is just being launched, there are blank spaces or initiatives still to be defined. It will be up to industry, the user community, and the research community to continue to populate the map now that the framework has been established. Users seeking better vehicle armour and PPE, industry stakeholders that need to improve their systems and products to meet market opportunities and requirements, and organizations with expertise in materials and manufacturing in the nine technology domains prioritized for security materials are all encouraged to “get on the map” by visiting the SMTRM website.

Vehicle Armour


VISION: Provide the end user with occupant centric solution options effective against all threats while providing increased operational effectiveness.

Now **2020**

Market

USERS:
Mounted Soldier
Police tactical
Police
VIP Transport
Cash-In-Transit
EOD

Mass migrations, asymmetric conflicts, terrorism, climate change, constrained defence budgets, ubiquitous information technology, low cost sensors, increased cybersecurity challenges, increasingly severe weather events, integration of sensors and information systems into land forces, increasing CBRN threats, emerging directed energy weapons, globalisation

Products / Systems Requirements

Opaque
STANAG Level 4 @15% lower AD
Improve multi-hit tolerances to 10 mm
Statistical armour with probability of defeat 75% for common CE threats
Full coverage against fragmentation, impact and blast in injury risk

Transparent
Reduce delamination due to aging/scratching/yellowing

Innovative Structures
Minimize seams and joints to resist blast effects
Hull structure incorporates blast protection

Technical Challenges

Reduce Weight
Develop Modelling Tools
Reduce Cost
Material Characterisation at Multi-scale (testing)
Increase Performance
More Efficient Manufacturing Processes
Integrated Solutions
Quantification and Design for Multi-threat
Multipurpose Materials
Availability of Material Solutions

Reduce System Weight by 15%
Reduce System Weight by 25%
10% Cost Reduction
Select material to defeat various KE threats
Select material to defeat both KE and CE threats

Technology Solutions

Advanced Ceramics
Advanced Coatings
Nanomaterials
Modelling and Simulation
Characterization and Testing
Polymers and Adhesives
Manufacturing Processes
Non-Destructive Evaluation and Life Cycle Management
Composite Materials

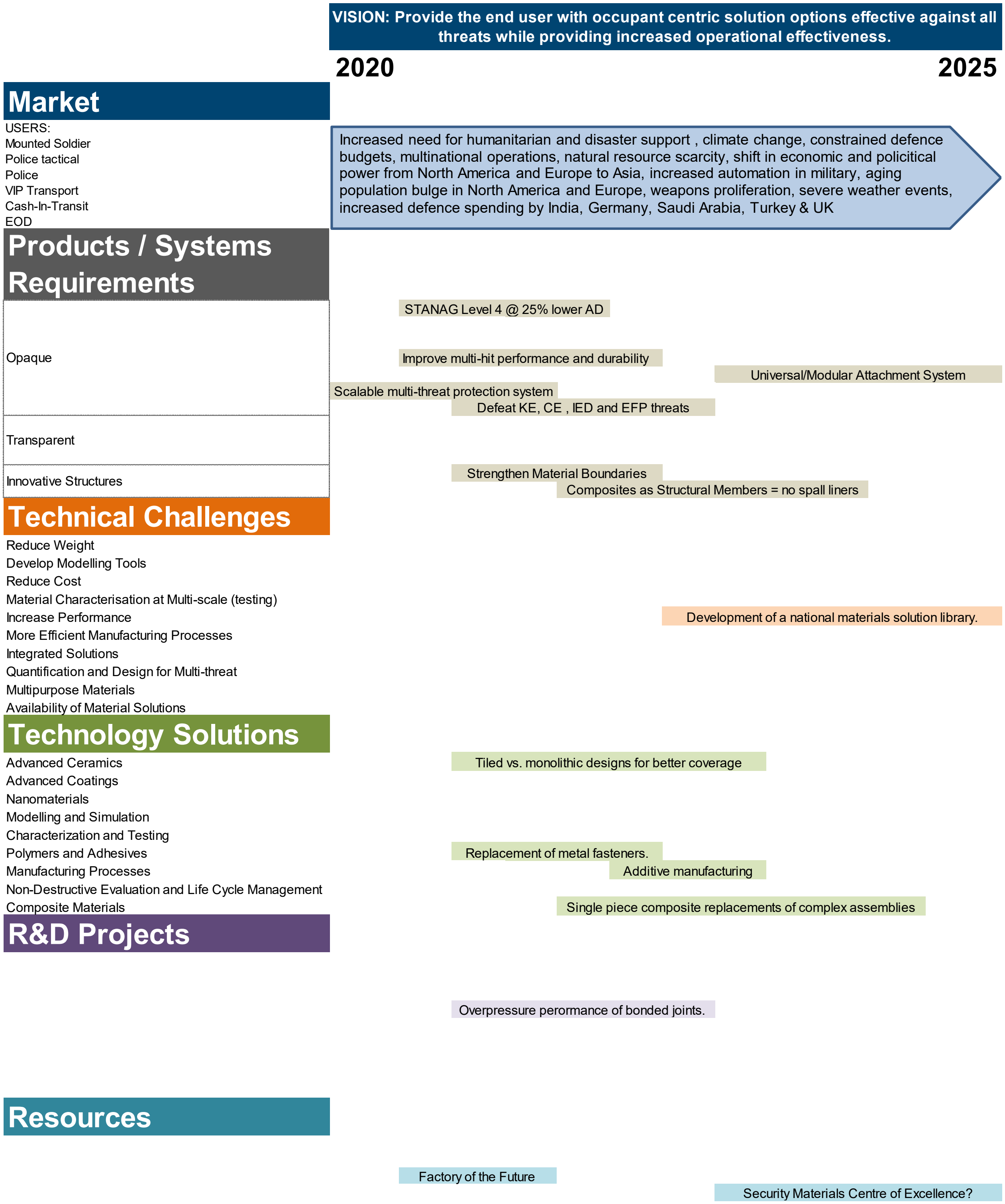
Advanced Ceramics
Shape optimisation
CERMET Hybrids
Ultrahard thin coatings
CBNRE resistant coatings
Nanostructuring
Nano-enhanced materials
White graphene
Structural optimisation
Penetration models
Blast models
Mfg. simulation.
System characterization
Threat effects
Failure mechanisms over multiple strain rates
Advanced transparent polymers
Polymer foams
Occupant centric design
3D reinforced composites
Integration of armour with structure
Reduction of scrap rates
NDE of advanced ceramics
Advanced laminates/Thermo set/Thermoplastic/Hybrids
Subsititution for metals

R&D Projects

Demonstrate bulk manufacturability of CERMETS
Ballistic testing of nano-enhanced aluminum
Simulated effects of threats on nano-enhanced aluminum

Resources

BCIP
UBC STAR Facility
QETE
NSERC
NINT
HIT Dynamics
CanmetCERL
ITBs
SRED
UBC Composites Research Network
NRC AST
NRC IRAP
SADI
MITACS



VISION: Provide the end user with occupant centric solution options effective against all threats while providing increased operational effectiveness.

2020 **2025**

Market

USERS:
Mounted Soldier
Police tactical
Police
VIP Transport
Cash-In-Transit
EOD

Increased need for humanitarian and disaster support , climate change, constrained defence budgets, multinational operations, natural resource scarcity, shift in economic and policitical power from North America and Europe to Asia, increased automation in military, aging population bulge in North America and Europe, weapons proliferation, severe weather events, increased defence spending by India, Germany, Saudi Arabia, Turkey & UK

Products / Systems Requirements

Opaque

- STANAG Level 4 @ 25% lower AD
- Improve multi-hit performance and durability
- Universal/Modular Attachment System
- Scalable multi-threat protection system
- Defeat KE, CE , IED and EFP threats

Transparent

Innovative Structures

- Strengthen Material Boundaries
- Composites as Structural Members = no spall liners

Technical Challenges

Reduce Weight
Develop Modelling Tools
Reduce Cost
Material Characterisation at Multi-scale (testing)
Increase Performance
More Efficient Manufacturing Processes
Integrated Solutions
Quantification and Design for Multi-threat
Multipurpose Materials
Availability of Material Solutions

- Development of a national materials solution library.

Technology Solutions

Advanced Ceramics
Advanced Coatings
Nanomaterials
Modelling and Simulation
Characterization and Testing
Polymers and Adhesives
Manufacturing Processes
Non-Destructive Evaluation and Life Cycle Management
Composite Materials

- Tiled vs. monolithic designs for better coverage
- Replacement of metal fasteners.
- Additive manufacturing
- Single piece composite replacements of complex assemblies

R&D Projects

- Overpressure peromance of bonded joints.

Resources

- Factory of the Future
- Security Materials Centre of Excellence?

VISION: Provide the end user with occupant centric solution options effective against all threats while providing increased operational effectiveness.

2025 **2040+**

Market

USERS:
Mounted Soldier
Police tactical
Police
VIP Transport
Cash-In-Transit
EOD

Predominently urbanised societies and rise of megacities, rise of human performance optimisation, increased state-state conflict, conflicts in multiple, dispersed locations, artificial intelligence in defence applications, increasing need for 'safe zones', mainstream use of automation and robotics, development of genetic weapons, blurred lines between policing and warfare

Products / Systems Requirements

Opaque

STANAG Level 5 and 6 as weight efficient add-ons to level 4

Adaptive Stealth

Transparent

Same level of protection as opaque armour+Transparent to the user

Innovative Structures

Technical Challenges

Reduce Weight
Develop Modelling Tools
Reduce Cost
Material Characterisation at Multi-scale (testing)
Increase Performance
More Efficient Manufacturing Processes
Integrated Solutions
Quantification and Design for Multi-threat
Multipurpose Materials
Availability of Material Solutions

Reduce System Weight by 50%

Technology Solutions

Advanced Ceramics
Advanced Coatings
Nanomaterials
Modelling and Simulation
Characterization and Testing
Polymers and Adhesives
Manufacturing Processes
Non-Destructive Evaluation and Life Cycle Management
Composite Materials

Materials design from the atomic level.

R&D Projects

Demontration of integral adaptive camouflage armour

Resources

Personal Protective Equipment

VISION: To provide, in a timely fashion, soldiers and first responders in Canada with human-centric armour in an integrated multi-functional protection system that maximizes chances of survival and mission success in a cost-effective manner.

NOW **2020**

Market

USERS:
Dismounted soldier
Mounted soldier
Police
EOD
First responders
Police tactical

Mass migrations, asymmetric conflicts, terrorism, climate change, constrained defence budgets, ubiquitous information technology, low cost sensors, increased cybersecurity challenges, increasingly severe weather events, integration of sensors and information systems into land forces, increasing CBRN threats, emerging directed energy weapons, globalisation

Products / Systems

HELMET	Heavy/EOD Combat Police	Modular, including nape/throat/jaws Double impact energy for the same injury risk
PLATES	Composite Ceramic	Minimize impact of protective systems on user ROM and mobility Ballistic + Blast Protection
TRANSPARENT	Heavy/EOD/Deminor Light/Goggles/BEW Riot	Increased protection + Maintain current field of view (horizontal and vertical) Light weight, high threat, 3D
THORACIC	Light (fragments) Medium (small arms) High (heavy/EOD)	
EXTREMITIES	Light weight/Targeted coverage Heavy/Full coverage (EOD)	Integrate basic ballistic protection and blunt impact
BODY ARMOUR	Textile	Improved comfort/fit Abrasion + fire resistance
SHIELDS	Riot Ballistic	Lighter for breaching ops.

Technical Challenges

Reduce Weight	Reduce System Weight by 15% Reduce System Weight by 25%
Develop Modelling Tools	
Reduce Cost	10% Cost Reduction
Material Characterisation at Multi-scale (testing)	Data for numerical models for ballistic + blast
Increase Performance	
More Efficient Manufacturing Processes	Form monolithic, transparent materials vs. EOD threats
Integrated Solutions	
Quantification and Design for Multi-threat	Select material to defeat various KE threats Select material to defeat both KE and CE threats
Availability of Material Solutions	
Improve Ergonomics	Exoskeleton tech. adaptable to various body sizes
Multipurpose Materials	

Technology Solutions

Advanced Ceramics	Advanced Ceramics Shape optimisation CERMET Hybrids
Advanced Coatings	Ultrahard thin coatings CBNRE resistant coatings
Nanomaterials	Nanostructuring Nano-enhanced materials White graphene
Modelling and Simulation	Structural optimisation Penetration models Blast models
Characterization and Testing	System characterization Threat effects
Polymers and Adhesives	Advanced transparent polymers Polymer foams
Manufacturing Processes	Occupant centric design 3D reinforced composites
Non-Destructive Evaluation and Life Cycle Management	Reduction of scrap rates NDE of advanced ceramics
Composite Materials	Advanced laminates/Thermo set/Thermoplastic/Hybrids Subsititution for metals

R&D Projects

NDE of existing armour materials to fully exploit service life
Application of anti-scratch coatings

Resources

BCIP
UBC STAR Facility
QETE
NSERC
NINT
HIT Dynamics
CanmetCERL
ITBs
SRED
UBC Composites Research Network
NRC AST
NRC IRAP
SADI
MITACS

VISION: To provide, in a timely fashion, soldiers and first responders in Canada with human-centric armour in an integrated multi-functional protection system that maximizes chances of survival and mission success in a cost-effective manner.

2020 **2025**

Market

USERS:
Dismounted soldier
Mounted soldier
Police
EOD
First responders
Police tactical

Increased need for humanitarian and disaster support , climate change, constrained defence budgets, multinational operations, natural resource scarcity, shift in economic and policitical power from North America and Europe to Asia, increased automation in military, aging population bulge in North America and Europe, weapons proliferation, severe weather events, increased defence spending by India, Germany, Saudi Arabia, Turkey & UK

Products / Systems Requirements

HELMET	Heavy/EOD	Scalable multi-threats protection system, including nape/throat/jaws
	Combat	Lightweight NIJ Level IV
	Police	
PLATES	Composite	Ballistic+blast+transparent to user
	Ceramic	Minimize impact of protective systems on user ROM and mobility
TRANSPARENT	Heavy/EOD/Deminor	
	Light/Goggles/BEW	Increased level of protection+No obstruction of the natural ambinocular field of horizontal and vertical view
	Riot	Lightweight, monolithic, 3D
THORACIC	Light (fragments)	
	Medium (small arms)	
	High (heavy/EOD)	
EXTREMITIES	Light weight/Targeted coverage	Ergonomic, ballistic resistant gloves
	Heavy/Full coverage (EOD)	
BODY ARMOUR	Textile	
SHIELDS	Riot	
	Ballistic	Ballistic + blast protection for EOD

Technical Challenges

Reduce Weight
Develop Modelling Tools
Reduce Cost
Material Characterisation at Multi-scale (testing)
Increase Performance
More Efficient Manufacturing Processes
Integrated Solutions
Quantification and Design for Multi-threat
Availability of Material Solutions
Improve Ergonomics
Multipurpose Materials

Enhanced textile ballistic performance for high dexterity gloves.

Establish materials solutions library

Technology Solutions

Advanced Ceramics
Advanced Coatings
Nanomaterials
Modelling and Simulation
Characterization and Testing
Polymers and Adhesives
Manufacturing Processes
Non-Destructive Evaluation and Life Cycle Management
Composite Materials

Tiled vs. monolithic designs for better coverage

Replacement of metal fasteners.

Additive manufacturing

Single piece composite replacements of complex assemblies

R&D Projects

Demonstration of self monitoring armour.

Resources

Factory of the Future

Security Materials Centre of Excellence?

VISION: To provide, in a timely fashion, soldiers and first responders in Canada with human-centric armour in an integrated multi-functional protection system that maximizes chances of survival and mission success in a cost-effective manner.

2025 **2040+**

Market

USERS:
Dismounted soldier
Mounted soldier
Police
EOD
First responders
Police tactical

Predominently urbanised societies and rise of megacities, rise of human performance optimisation, increased state-state conflict, conflicts in multiple, dispersed locations, artificial intelligence in defence applications, increasing need for 'safe zones', mainstream use of automation and robotics, development of genetic weapons, blurred lines between policing and warfare

Products / Systems Requirements

HELMET	Heavy/EOD Combat Police	Full coverage against fragmentation, impact and blast in injury risk
PLATES	Composite Ceramic	
TRANSPARENT	Heavy/EOD/Deminor Light/Goggles/BEW Riot	Same level of protection as opaque armour/Transparent to the user Monolithic, 3D with AD comparable to opaque
THORACIC	Light (fragments) Medium (small arms) High (heavy/EOD)	
EXTREMITIES	Light weight/Targeted coverage Heavy/Full coverage (EOD)	
BODY ARMOUR	Textile	360°coverage
SHIELDS	Riot Ballistic	

Technical Challenges

Reduce Weight
Develop Modelling Tools
Reduce Cost
Material Characterisation at Multi-scale (testing)
Increase Performance
More Efficient Manufacturing Processes
Integrated Solutions
Quantification and Design for Multi-threat
Availability of Material Solutions
Improve Ergonomics
Multipurpose Materials

Technology Solutions

Advanced Ceramics
Advanced Coatings
Nanomaterials
Modelling and Simulation
Characterization and Testing
Polymers and Adhesives
Manufacturing Processes
Non-Destructive Evaluation and Life Cycle Management
Composite Materials

Materials design from the atomic level.

R&D Projects

Integration of of structure and armour in exoskeletons

Resources

State of the Market and Sector

Future Security Environment

The future cannot be known with certainty. However, a number of trends and analyses point to the following overarching themes that will shape the future security environment.

- Global megatrends, such as climate change, urbanization, mass migrations, and resource scarcity destabilize society and will have a profound effect on security and the operational environment.
- As the world becomes multipolar, economic and political power will shift from North America and Europe to Asia.
- Future conflicts will be symmetric as well as asymmetric. Combatants will be both state and non-state actors. Certain countries (Russia, China, Iran, and North Korea) pose particular threats because of instability or nuclear/territorial ambitions. There will continue to be expeditionary campaigns.
- Terrorism will be an ongoing threat.
- Defence agencies will be required to operate in "austere" environments, often in smaller and dispersed teams.
- Armed forces will be called upon to perform multiple missions, including humanitarian assistance and disaster support.
- Multinational operations will be the order of the day, necessitating interoperability and standardization.
- Defence budgets will be constrained, leading to an emphasis on affordability and modularity.
- The speed of technological change will be an on-going challenge; procurement cycles and research programs will struggle to keep pace.
- Key technologies linked to these trends include:
  - Autonomous technologies;
  - Integrated electronics (e.g., sensors, communications and computing);
  - Net-centric systems (real-time, ubiquitous computing,, and communications);
  - Big data processing and predictive analytics;
  - Improved soldier systems (e.g., ballistics protection and design of protective gear for multiple functions and multiple environments, such as (advanced, lightweight but strong materials, flexible and tiered designs);
  - Technologies that enable operation in anti-access, area denied environments;
  - Additive manufacturing and other lean manufacturing techniques to reduce costs and enable flexible supply chains and remote production of parts;
  - Modelling and simulation (to shorten development time and reduce costs and risk);
  - Technologies for soldier enhancement (e.g., neurocognitive tools and exoskeletons); and
  - Space technologies (communications, surveillance).

It is with these themes in mind that the Department of National Defence in its Land Operations 2021 foresight document sets out the context for the future security environment. It establishes the concept of adaptive, dispersed operations, which envisages an operating environment "… characterized by complex, multidimensional conflict, a non-contiguous [geographically] dispersed operational framework and an approach to operating within that environment based on adaptive dispersed land forces conducting simultaneous full spectrum engagement."[1]

Network-enabled operations, pervasive information and communications technologies, and systems integration will be key underlying principles, going forward. Joint campaigns (e.g., with multinational partners) will be the norm, and will require higher than ever levels of interoperability. Modular forces and equipment designs will enable agility, as will improvements to logistics and supply chains.[2]

The Defence Market

Globally, military spending was about US$1.75 trillion dollars in 2014, 35% of which (i.e., about $610 billion) was by the United States (US).[3] The next five biggest spenders in 2014 were:

- China ($216 billion),
- Russia ($85 billion),
- Saudi Arabia ($81 billion),
- France ($62 billion), and
- United Kingdom (UK; $61 billion).[4]

The US experienced a notable drop in its percentage contribution to overall global military spending (from 40% in 2012 to 35% in 2014)—likely due to a reduction in operations in Afghanistan and Iraq. However, the US is still the dominant nation in this sector, and is expected to continue to be (by a significant margin) for some time.

"The vast majority [about three-quarters] of Canadian exports of defence and security equipment was sold to the United States…"[5] Canada also exported defence and security equipment to Europe (11%), the Middle East (4%), Asia-Pacific (3%), and other countries (6%).[6] This suggests that

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[1] Department of National Defence (Canada). Directorate of Land Concepts and Design. (2007).

Land Operations 2021: Adaptive Dispersed Operations: The Force Employment Concept for Canada's Army of Tomorrow. Kingston, ON: Directorate of Land Concepts and Design. Retrieved from: http://publications.gc.ca/collections/collection_2009/forces/D2-188-2007E.pdf

[2] Ibid.

[3] Deloitte Touche Tohmatsu Limited. (2015). *2015 Global aerospace and defense industry outlook.* Deloitte Touche Tohmatsu Limited. Retrieved from http://www2.deloitte.com/content/dam/Deloitte/global/Documents/Manufacturing/gx-mnfg-2015-global-a-and-d-outlook.pdf

[4] Ibid.

[5] National Research Council of Canada Knowledge Management. (2014). *Strategic Plan: Supporting Documentation [for NRC's Security and Disruptive Technologies]*. Henry Chou, Brenda Brady.

[6] Public Works and Government Services Canada. (2013). *Canada First: Leveraging Defence Procurement Through Key Industrial Capabilities.* Jenkins, T. Retrieved from http://www.tpsgc-pwgsc.gc.ca/app-acq/documents/eam-lmp-eng.pdf

regardless of what Canada does in defence and security exports, the US will remain the largest client by a significant margin.

At just above 84%, Canada's Department of National Defence (DND) is by far the largest domestic portion of the defence and security sector in terms of sales.[7] The following is a breakdown of the domestic segments (and in Figure 5):

- Department of National Defence: 84.3%
- Royal Canadian Mounted Police (RCMP): 4.5%
- Correctional Services Canada (CSC): 3.9%
- Canada Border Services Agency (CBSA): 0.8%
- Ontario Provincial Police (OPP): 0.8%
- Other municipal and provincial police services: 5.8%[8]

This shows that although the other sectors within Canada are important, relatively speaking they pale in comparison to the military sector domestically.

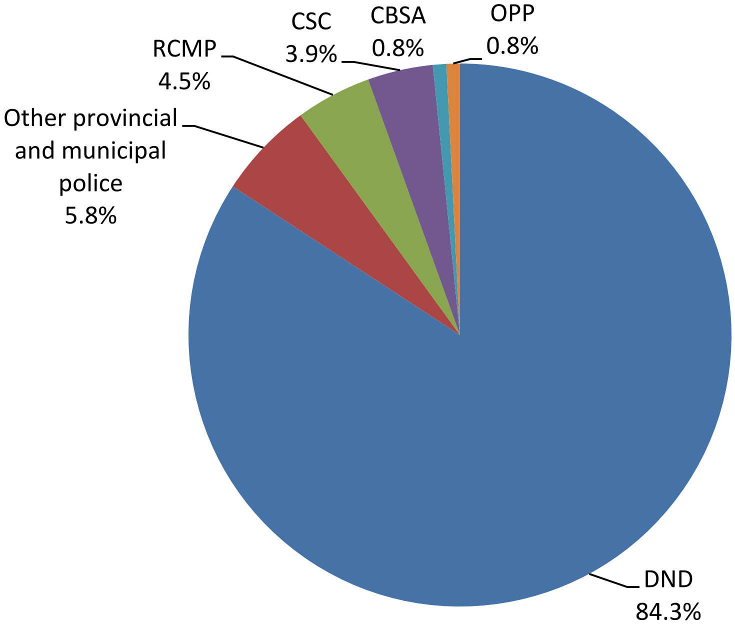

Figure 5: Defence and Security Expenditures by Selected Canadian Government Entities, 2011[9]

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[7] Op. cit. NRC Knowledge Management. (2014).

[8] KMPG. (2012). *Economic Impact of the Defence and Security Industry in Canada.*

[9] Ibid.

Force Protection Market

In 2013, Frost and Sullivan reported on the global market for force protection. Such protection covers fixed assets (such as military bases) as well as personnel (protective gear such as helmets, protective vests, goggles, etc.) and mobile assets (e.g., military vehicles). Frost and Sullivan (2013) noted the following key trends:

- Overall, there is a need to modernize, economize, and rationalize. Soldier modernization programs abound.
- A continuation of the trend to lighter equipment, both for personnel protection and vehicles. Such lightweight equipment must, however, be high-performing, adapted to the changing threat environment and strategic intent, and cost effective (in light of shrinking defence budgets).
- "There is a starker choice between quantity and quality of equipment. Where political and social acceptance of casualties is higher and manpower is less expensive, there is a lower requirement to provide advanced force protection. Light systems are cheaper than heavy ones and less advanced systems will prove adequate and affordable. Likewise, for the lower-tier end users, heavy or advanced force protection equipment is too costly."
- Post-Afghanistan, procurement systems are changing to reflect a new emphasis on proactive evasion and prevention (advanced threat detection), often based on electronic counter-measures, intruder detection, and biometrics. This may also signal a decline in acquisition of heavy armour systems, and a movement towards lighter, more high tech vehicles.
- In modern end-user countries (such as Canada and the US), the emphasis on technology and modernization is high, but political and social tolerance for casualties is low. Thus, the need for force protection will continue to be high, but solutions will need to be cost-effective.

Figure 6 shows the 2012 forecast of spending in the global force protection market out to 2019. Overall revenues for "Force Protection" are still showing as steady with annual global amounts expected to be somewhere just shy of US$7.5 billion.

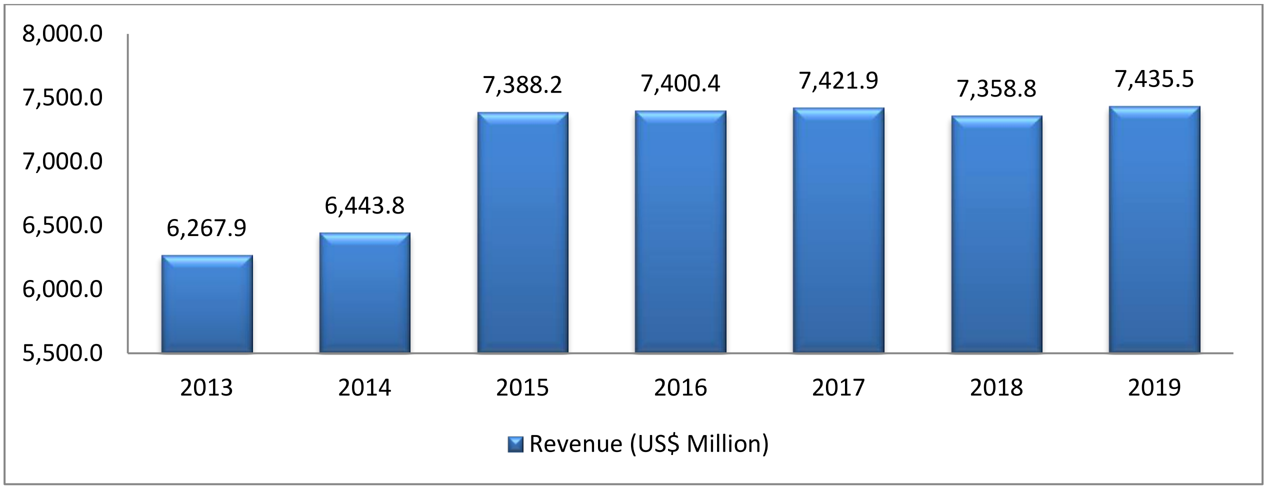

Figure 6: Global Force Protection Market (2013-2019); Revenue Forecast (US$)[10]

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[10] Frost and Sullivan. (2013). *Global Force Protection Market: Global Economics Will Dictate Force Protection Requirements for the Next 10 Years.* Mountain View, CA : Frost and Sullivan.

The Canadian Defence and Security Industry

According to the State of Canada's Defence Industries 2014, a survey conducted by Innovation, Science and Economic Development Canada and the Canadian Association of Defence and Security Industries (CADSI)[11], in 2014 the defence and security industry in Canada:

- Consisted of 640 firms, 90% of which have fewer than 250 employees;
- Contributed 63000 direct and indirect full-time equivalent jobs;
- Contributed 28,000 direct jobs in the defence industry alone, 30% of which were innovation-relevant such as engineers, scientists, researchers, technicians and technologists;
- Generated CAD$10 billion in sales with 60% derived from exports (defence sales export intensity is close to 20% higher than the Canadian manufacturing average); and
- Contributed CAD$6.7 billion to Canada's GDP[12].

Armoured Vehicles and Personal Protective Equipment

Figure 7 is a graphical representation of the distribution of total defence sales in 2014 by domain[13]. As Figure 8 illustrates within the Land and Cross-Domain activities in Canada combat vehicle (including armoured vehicles) goods and services dominate sales at CAD$2.8 billion[14]. Troop support, which includes personal protective equipment, is also an important economic contributor in this domain generating CAD$222 million in sales.

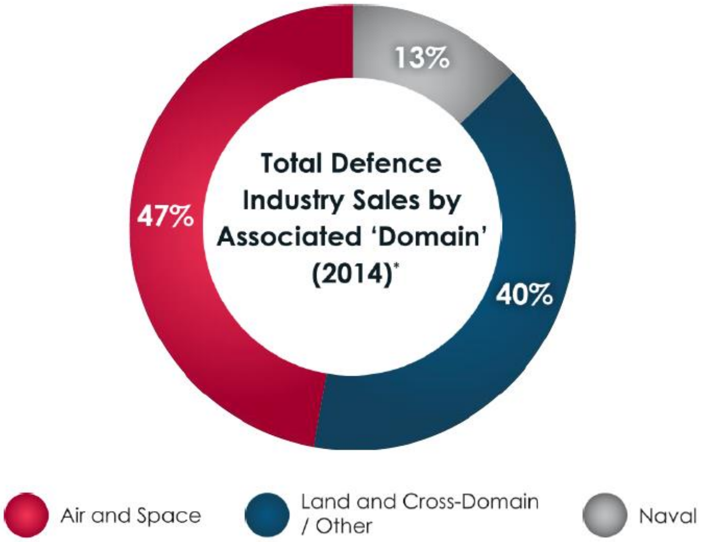

Figure 7: Percentage Direct and Indirect GDP Contributions per Sub-Sector of Canadian Defence and Security Industry[15]

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[11] Innovation, Science and Economic Development Canada and the Canadian Association of Defence and Security Industries. The State of Canada's Defence Industry, 2014.

[12] Ibid.

[13] Ibid.

[14] Ibid.

[15] Ibid.

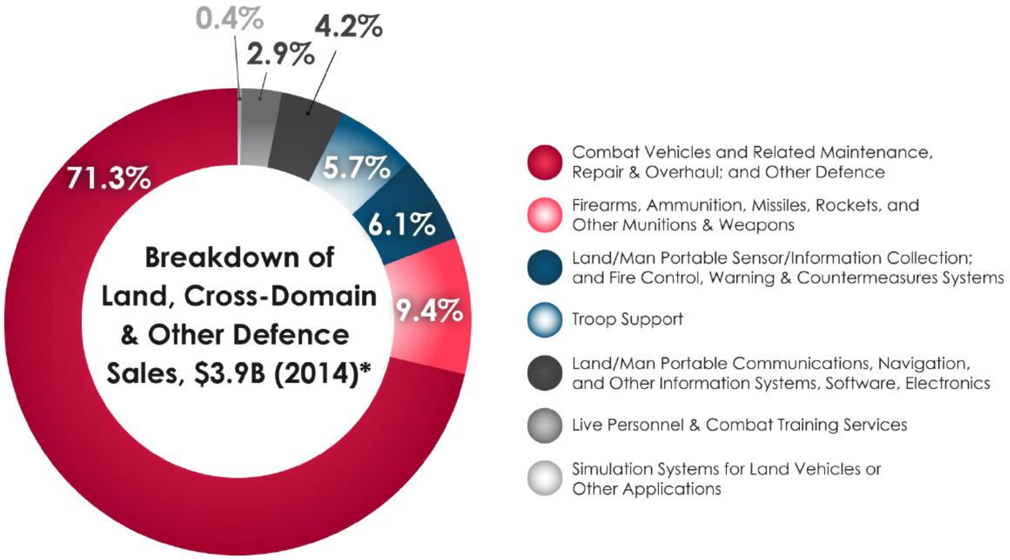

Figure 8: Distribution of sales within the Land and Cross-Domain field

Global Spending on Research and Development[16]

Figure 9 illustrates the relative spending on R&D by the top 40 countries that invest in R&D.

The US is by far the largest spender, but it is expected to be overtaken by China in 2026 if current trends continue. At more than US$60 billion (roughly half of total US R&D investments in 2016) the US Department of Defense (DOD) R&D budget is larger than the total R&D budgets of all but five countries—China, Japan, Germany, South Korea, and India. The DOD R&D budget is primarily dedicated to technology development (80%) with 17% dedicated to science and technology (S&T). This S&T budget is further divided into basic research (17%), applied research (38%), and advanced technology development (45%).

The Defense Advanced Research Projects Agency (DARPA) is considered a stand-alone account within the DOD with a budget of US$3 billion. According to an estimate from Statistics Canada, the total R&D in Canada in 2015 was CAD$35 billion. DRDC is the national leader in defence and security S&T and has an annual budget exceeding CAD$300 million.

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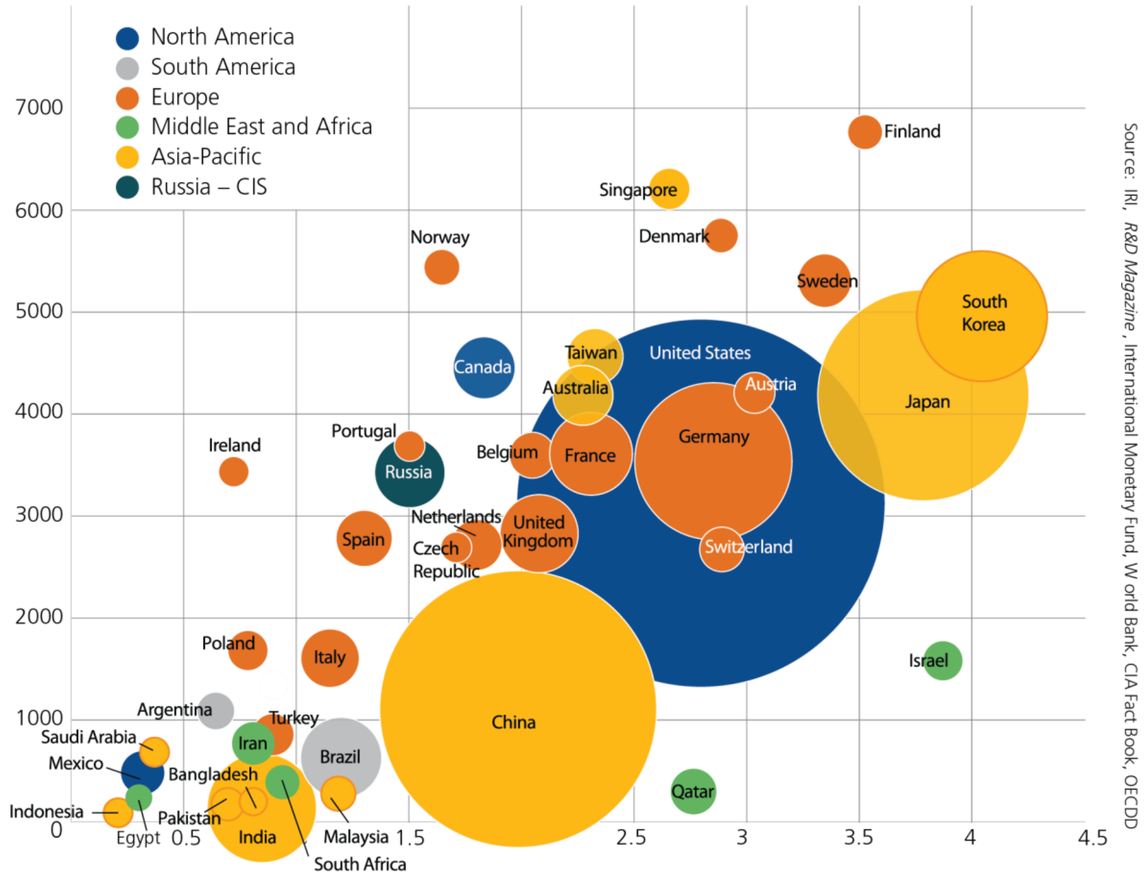
[16] Industrial Research Institute (2016). 2016 Global R&D Funding Forecast.



Source: IRI, *R&D Magazine* , International Monetary Fund, W orld Bank, CIA Fact Book, OECDD

Size of the circles reflects the relative amount of annual R&D spending by the indicated country.
Note the regional grouping of countries by the color of the balls.

Figure 9: Relative R&D spending by the top 40 spenders on R&D globally (x-axis indicates percentage of GDP and the y-axis indicates the number of scientists and engineers per million people)

Future Capability Needs for Vehicle Armour

During recent conflicts in Afghanistan and Iraq, the profile of protection and survivability was raised to such an extent that it became the predominant capability when considering the design of vehicles to be employed in the combat zone. In some cases, survivability enhancements were fielded as urgent operational requirements (UORs) to the detriment of other capabilities such as mobility. In fact, requirements for an enhanced level of survivability for some vehicle fleets led to a level of degradation in mobility such that the vehicles were required to remain on main routes, where they became easy targets for threats such as improvised explosive devices (IEDs).

> *The Army will have soldier-friendly, robust, adaptable, low-maintenance vehicles, weapons and equipment capable of rapid deployment and able to meet and defeat the threats encountered while conducting full spectrum, adaptive dispersed operations in the future operating environment.*
>
> *- LCol. Ron Bell*
> *Concepts 3, Canadian Army Land Warfare Centre*
> *(Quoted from the Canadian Army Hard Problems List)*

At the same time, the need for enhanced levels of survivability has increased for non-military vehicles, including police patrol vehicles, cash-in-transit vans, first responders, and VIP vehicles. In some countries, police forces are using vehicles that have evolved from a military design or have taken into use surplus military armoured fighting vehicles.

There is an urgent need to conduct R&D that will lead to the required level of vehicle crew survivability while striking a balance with other capabilities such as mobility.

Information provided by the Canadian Army Land Warfare Centre states that land combat vehicle design—based on purpose—must strike a balance between mobility, firepower, protection, digitization, and human factors. These design considerations must also contend with the needs of affordability, sustainability, future upgrades (increases in weight and capability), maintainability, deployability, commonality, standardization, tactical adaptability after deployment, training in all environments, autonomy, and resilience to network attacks. These requirements reflect the adaptive, dispersed operations that the Canadian army will increasingly find itself conducting in future operating environments.

In consideration of these realities as presented at the SMTRM workshop, the following market needs specifically related to vehicle armour were derived:

a. Systems with a level of performance that reflect the increasing nature of the threats. The penetration capabilities of evolving threats are increasing more rapidly than the capability of armoured vehicles to carry the weight of the passive armour systems needed to defeat those threats. The systems should also be more durable than current systems in terms of multi-hit, physical robustness to preclude damage from, for example, rocks and vegetation, and resistant to effects from environmental aging.
b. Holistic systems that are optimized for light-weighting of vehicles.

The U.S. Army's Tank and Automotive Research, Development and Engineering Center (TARDEC), in their 30-year value stream analysis, calls for the development, maturation, and integration of lightweight (10-20% lighter than present) base, add-on, electrified and adaptable armours. Such solutions must feature multiple defeat mechanisms, demonstrate improved performance against direct fire and fragmentation, and must also maintain performance and cost.

Influence of the Threat on Potential Solutions

As previously mentioned, and illustrated in Figure 10, the diversity and penetration capabilities of evolving threats are increasing more rapidly than the capability of armoured vehicles to carry the weight of the passive armour systems needed to defeat those threats.

Developments in passive armour materials have not provided significant mass improvements over the last 20 years. Recent conflicts have seen a proliferation of shaped-charge and explosively formed projectile (EFP) threats, as well as the now ubiquitous IED in all of its different forms. The very high energy levels impacting on a relatively small target area necessitate the use of armour solutions beyond purely passive materials.

Statistical armour systems have limited performance and were used as a stopgap to mitigate the protection issue on vehicles that could not afford the weight of passive armour required to defeat shaped charges (e.g., Chemical Energy (CE) threats). Reactive materials are an attractive solution to mitigate CE threats because of their relatively low weight (they can be up to 10 times lighter than the equivalent rolled homogenous armour (RHA) steel solution that is required). Even though reactive protection systems have been developed and mainly used to defeat CE threats, they can also be developed to defeat kinetic energy (KE) threats (e.g., electromagnetic system to defeat long rods).

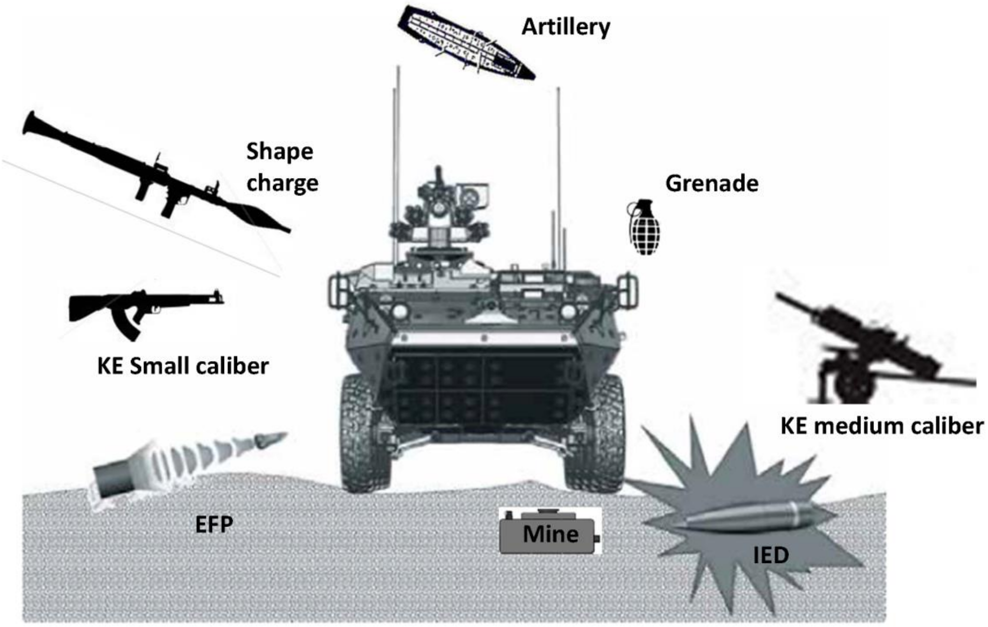


Figure 10: The diverse threat environment for armoured vehicles (source DRDC)

Existing KE threats can perforate up to 0.8 metres of RHA, while CE threats can defeat more than 1 metre of RHA. Existing vehicles with good passive technologies (e.g., tanks) can afford less than 0.5 metres of RHA equivalent armour capability. However, many vehicles, such as logistic and light armoured vehicles, are unable to carry more than 0.05 metres RHA equivalent. The best passive material can provide five times the performance of RHA, but only when projectiles are not armour-piercing. For armour-piercing projectiles and shaped-charge threats, passive armour with three to four times the performance of RHA is considered to be very good.

Rapidly delivering energy in a local area as part of reactive/active armour systems is one of the most promising avenues to achieve a true breakthrough in performance and allow significant improvements in protection for light to medium weight vehicle platforms. Reactive armour used on some light armour vehicles to defeat shaped charges showed that armour weight can be easily more than halved to defeat a threat when compared to the best passive armour solution.

To double the performance of passive material (which is possible with the use of reactive material) will require a significant investment of time and money, and a revolutionary breakthrough in materials technologies.

Future Capability Needs for Personal Protective Equipment

Personal protective equipment must continue to evolve to meet increasingly diverse and evolving threats to users as well as the increasingly varied operating environments where users will require them. A critical factor to the success of PPE is ease of use resulting from human factors engineering, including its impact on range of motion, heat retention, weight, and similar factors. Each of these factors were considered and discussed at the Security Materials Technologies Roadmap workshop. This section outlines the operational capability needs driving innovation in PPE.

Nature of the Threat

The users of PPE in the defence and security sector include the mounted and dismounted warfighter, police officers and other first responders, private security, protection details, armoured car staff, and those responsible for explosive ordnance disposal (EOD), both military and civilian.

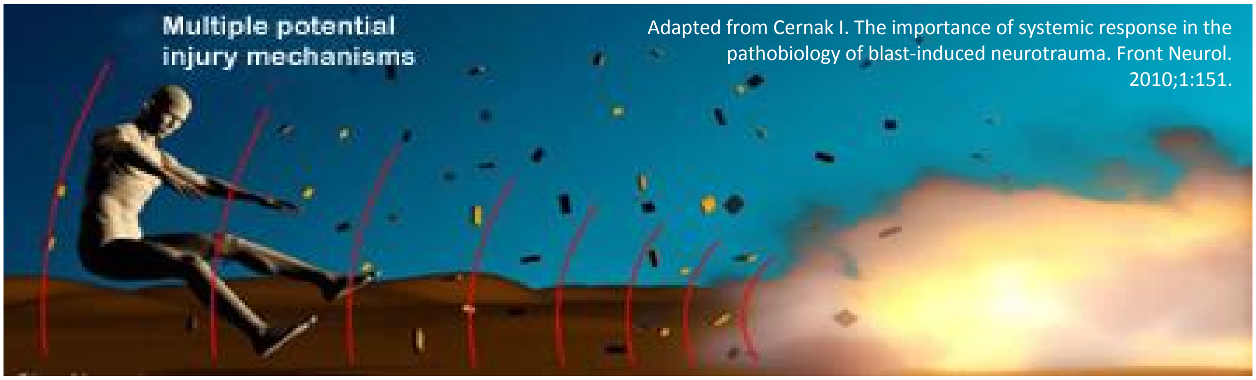
In the law enforcement environment, PPE is required to provide protection against low velocity ballistic threats (handguns), shotgun rounds, high velocity ballistic threats (e.g., hunting rifles), blunt force impact, stab/slash attacks, and flame. Aside from civil authority EOD operators, explosive threats are rarely a consideration in first responder armour systems. That may change in the future.

Warfighter PPE requirements are dominated by fragmentation threats and high velocity ballistic threats, including armour-piercing rifle projectiles, with handgun/submachine gun projectiles sometimes added. Flame resistance is also a common requirement for combat helmets and soft armour and plate carriers. Mitigation of stab and slash threats is currently not common in military PPE requirements, but that may change in the future, particularly if provision of a level of protection in combat clothing becomes feasible. The fragmentation vest already provides a level of protection even if the actual performance against stab and slash threats is rarely assessed.

Evolving requirements for high velocity ballistic threats are based on improvements in penetrator design and materials, accuracy of delivery, and a desire to increase coverage, usually through the addition of side plates (protecting the flanks of the torso) and/or by providing a level of rifle round protection in the combat helmet. The proliferation of IEDs and other blast threats has increased interest in providing a level of protection against primary blast injuries (i.e., physical trauma resulting from direct or indirect exposure to blast overpressure).

The complex loading environment generated by these threats (see Figure 11), can result in multiple potential injury mechanisms:

- Injuries from blast overpressure (ear, lung, bowels, central nervous system);
- Injuries from fragmentation (metallic/natural, lethal, or life changing); and
- Injuries from projection or blunt impact from large debris.



Adapted from Cernak I. The importance of systemic response in the pathobiology of blast-induced neurotrauma. Front Neurol. 2010;1:151.

Figure 11: Complexity of potential injury mechanisms associated with a blast event

This presents significant challenges for PPE designed to mitigate the effects of these threats. Traditionally, this was the domain of EOD systems, but PPE designed for mounted and dismounted warfighters brings with it significant human factors engineering requirements and the need to trade off coverage to ensure mobility and limit encumbrance. The proximity and angle of attack generated by many of these blast threats also create challenges for fragmentation protection--both the level of protection and coverage. These challenges, coupled with the success of fielded PPE in mitigating life threatening injuries, are driving a desire to provide increased coverage to mitigate life-changing injuries, again forcing S&T to explore the trade space of protection vs. human factors requirements. Emerging threats include directed energy weapons (e.g., lasers) that will add further complexity to PPE design and drive the need for integration of new material systems.

Operating Environment and Operational Requirements

PPE needs to remain effective and functional across a wide array of tactical requirements and operating environments— from arctic to desert temperatures, in high and low humidity, in urban, rural, forested, marine, or subterranean environments, and in almost every imaginable location. PPE users also have a variety of mission profiles, from high visibility patrol to assault and covert operations, with the nature of threats and the acceptable risk in each scenario being varied as well. These requirements, along with limited budgets and transport options, result in a strong demand for lightweight, low bulk, mission configurable (modular and scalable) PPE that provides protection against multiple threats.

Integration of Protection with other Functions

Users of PPE in defence and security have a variety of functions to fulfill while they carry out their missions and duties—each requiring specialized equipment. As Figure 12 illustrates, modern law enforcement officers and military personnel carry multiple pieces of equipment that increase capabilities but also increase bulk and complexity.[17,18] This drives the requirement for PPE that is seamlessly integrated with the rest of the warfighter/first responder's operational equipment. Opportunities in this area include multi-functional materials that reduce overall system weight and complexity through integration of functions, such as:

- Soft armour + data/power distribution;
- Soft armour + signature management + environmental protection;
- Rigid armour + sensors/antennae + data/power distribution; and
- Rigid armour + integrated energy storage.

Objectives for such integration include elimination of wires and reduction of power/data distribution and storage infrastructure, elimination of snagging hazards, reduction of weight, reduction of bulk, and the provision of additional capabilities, such as armour integrity monitoring.

BODY ARMOUR

Typically it is a composite material which weighs between 1.5kg and 2kg (up to 4.4lb) and is knife and bullet resistant. Those that provide the most protection weigh considerably more and contain ceramic plates ¾ of an inch thick.

TIE

Regulation clip-on design so that it will not cause harm if pulled during a struggle.

MOBILE PHONE

Attached to body armour by a velcro patch.

TWO RADIOS

The officer is wearing two radios that communicate via the encrypted Tetra network. One radio is for general use, and one specifically for communicating with other firearms officers in her team.

TASER GUN

The taser fires 2 short probes, on the ends of wires, into the suspect's clothing or skin. A 50,000 volt electric charge temporarily paralyses the target by disrupting their central nervous system. It has a range of about 10ft.

GLOCK PISTOL

Austrian-made and carried by most firearms officers, the £200 9mm handgun is rated for its reliability and accuracy. It has a 17-round magazine and incorporates a trigger safety mechanism.

BELT

Can have various attachments, including pouches for spare ammo, latex gloves, pen, notebook and a first-aid kit.

HANDCUFFS

Close to hand for quick use.

Figure 12: Both military and law enforcement personnel are expected to carry an increasing amount of equipment to perform their duties.

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[17] Evening Standard. (2008). The paramilitary face of a policewoman armed with handgun, taser, flak jacket and nine other pieces of equipment. Retrieved from http://www.standard.co.uk/news/the-paramilitary-face-of-a-policewoman-armed-with-handgun-taser-flak-jacket-and-nine-other-pieces-of-7267310.html; News.com.au. (2013, June 30). Soldier Systems Technology Roadmap.

[18] Photo credit: Cplc Robert Bottrill, Combat Camera, DND.

Human Factors

The design and function of PPE has intrinsic human factors engineering requirements that are critically important. Although not usually considered in the same way that explosive charges or rifle projectiles are, warfighter burden and other human factors requirements can have an impact on operational effectiveness and, potentially, survivability. Factors that affect the comfort or effectiveness of the user, such as thermal load and moisture management, weight, load distribution, and ease of movement, have a critical effect on the performance of the wearer. A poorly designed PPE system will increase the likelihood that the PPE will not be worn or used as intended (which would result in compromised protection), or not used at all. While obvious, it bears stating that the highest performance protection system that is not worn offers no protection at all.

While quantifiable assessment of performance is a field of study that is still maturing, qualitatively, the effects of bulk, stiffness, thermal resistance, and the weight of PPE systems are known to greatly affect the ability of warfighters and first responders to successfully complete their missions. Some examples of material challenges that are human factors driven include significant reductions in armour system weight for a given protection level, feasibility of providing flexible high velocity rifle projectile protection (”flexible hard armour”), and significant improvements needed in scratch and flog resistance for transparent armour. For some PPE, particularly those elements associated with increased coverage for the extremities, face, neck, and urogenital region, human factors requirements such as moisture transport, breathability, comfort, and flexibility dominate the armour design.

The requirements result in significant compromises to the protection level that can be provided to vulnerable areas of the body associated with poor outcomes when injured. Every PPE system is a study in compromise, but the human factor design, development, and fabrication of protective equipment are often based on subjective assessments of fit and usability. There is significant interest and need for investment in developing objective measures of human systems integration and performance for soldier system equipment design, including PPE, to support tradespace analysis of protection and mobility to properly assess overall mission effectiveness.

Products/Product Categories

Vehicle Armour

Armour for vehicles has been developed and fielded ever since vehicles found themselves in harm's way. There has always been a competition between the armour used on a vehicle and the threat it is countering. Today, vehicles must be resistant to a variety of threats including bullets, anti-tank rockets and missiles, IEDs, EFPs, and buried mines (blast/fragmentation/EFP).

Armour can be viewed as a generic term that encompasses a variety of products, techniques, and technologies to protect a vehicle and its crew. As outlined in Figure 13 and Figure 14, these products can consist of panels of opaque armour that are mounted when required, transparent armour ("bullet-proof glass") that is permanently mounted, "statistical" or "geometric" armour (bar, slat, net) that protects against specific threats fired from certain angles, and various systems that protect against blast, mainly from the side or underneath the vehicle. Blast threats have particularly affected the design of recently fielded vehicles for use in Afghanistan and Iraq, and will likely continue to do so.

There are also many internal products that can protect the crew, including spall liners, reinforced welds, and structural components that also protect against fragments.

A metric that is commonly (but not universally) applied to armour is the NATO Standardization Agreement 4569 – Protection Levels for Occupants of Armoured Vehicles. The document provides a hierarchical chart of threat levels and some specifics. For example, in the case of kinetic energy threats, it provides details on the caliber of the threat, the nature of the projectile, and the range from which it is fired. The associated Allied Engineering Publication 55 provides samples of threats and approved test procedures.

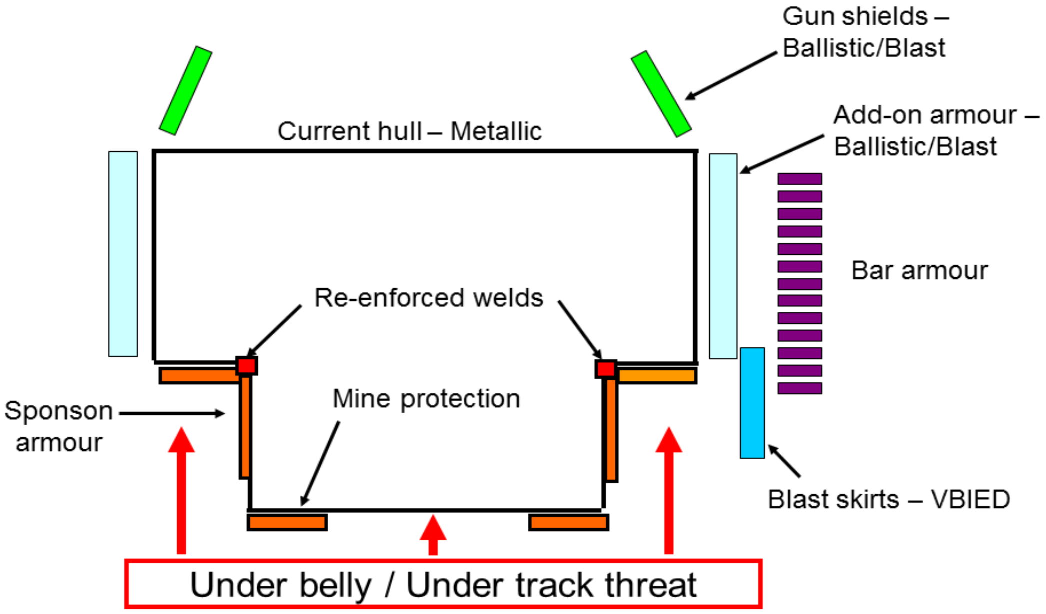

Figure 13: Illustration of survivability solutions for armoured vehicles.
Provided for Public Release by Director of Land Requirements 3.

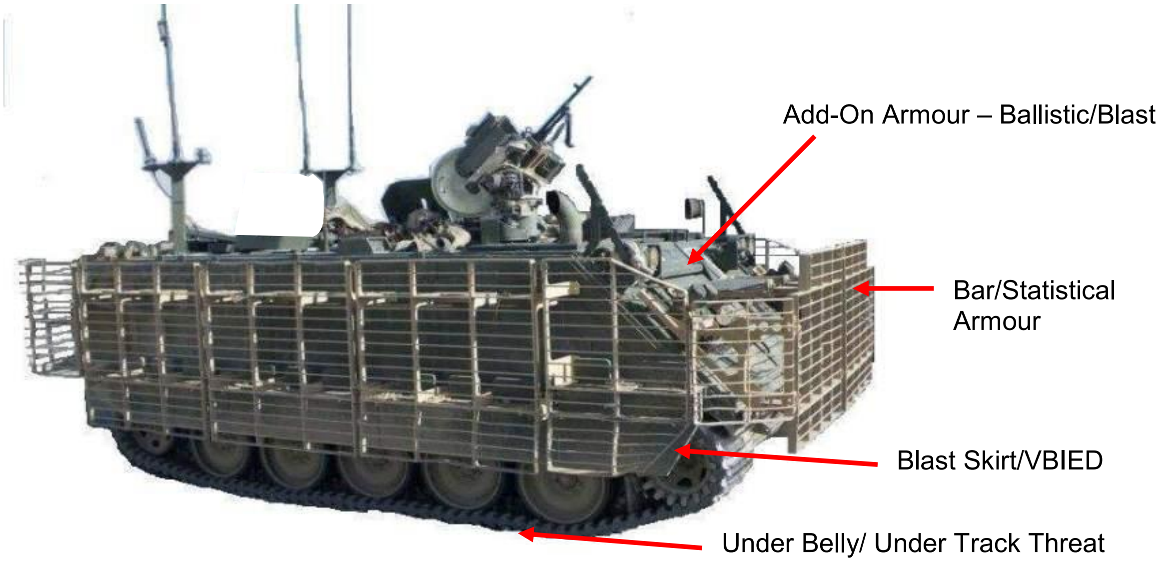

Figure 14: Survivability components in armoured vehicles – in field.
Provided for public release by Director of Land Requirements 3.

Personal Protective Equipment

PPE for military and law enforcement is employed to protect against a variety of threats and injuries ranging from knives and falls, to rifle projectiles, fragments, and overpressure. Table 1 and Figure 15 outline the various types and applications of PPE.

Table 1: Types of, and typical applications for, personal protective equipment

Area Protected	PPE Type	Mitigated Effects of
Head	Combat/first responder helmet	Blunt impact, fragments, handgun projectiles, rifle projectiles, blast overpressure/impulse, heat/flame
	EOD helmet	Blunt impact, fragments, blast overpressure/impulse, heat/flame
	Visors/goggles	Fragments, heat/flame, overpressure, blunt impact, environmental effects
Torso	Ballistic/fragment protective vest (soft armour)	Fragments, handgun projectiles, blunt impact, stab, spike
	Ballistic plates (hard armour)	High velocity rifle projectiles, high velocity/large mass fragments, blast overpressure/impulse
	Shields	Blunt impact, handgun projectiles, fragments, stab, spike, heat/flame
	EOD suit	Fragments, blast overpressure/impulse, impact, heat/flame
Limbs	Shoulder, arm, knee, and shin armour (soft armour)	Stab/slash blunt impact, fragments, heat/flame
	EOD suit	Fragments, impact, heat/flame, overpressure

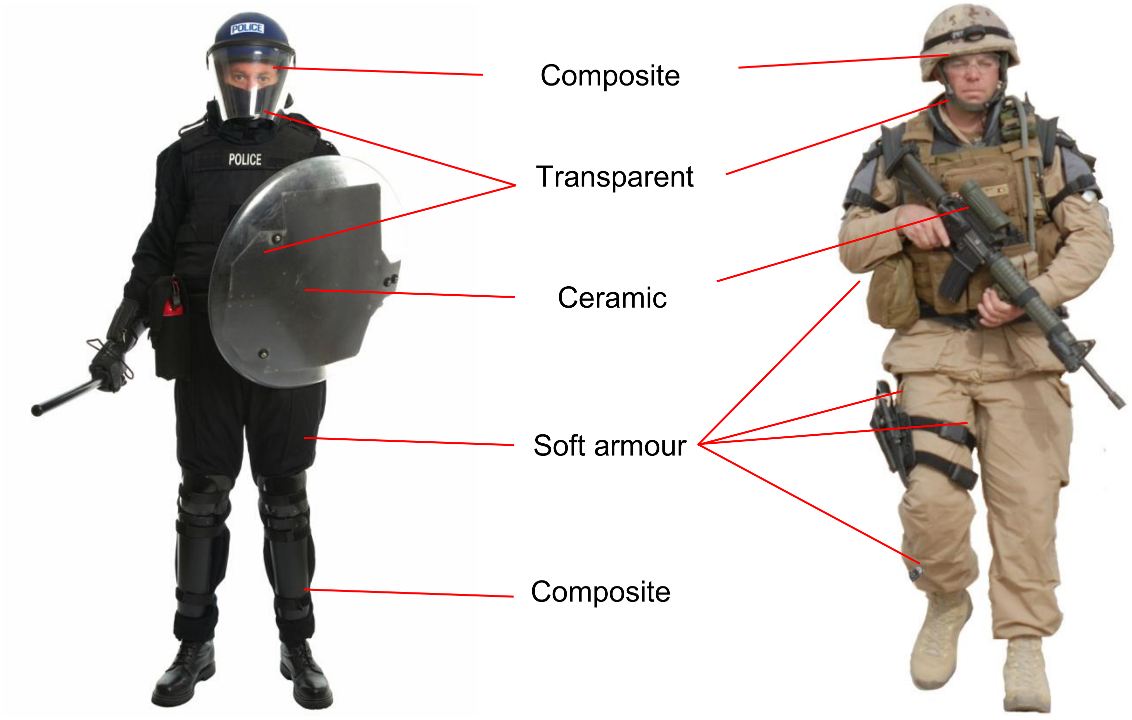

Figure 15: Personal protective equipment in military and law enforcement applications.
Photo credit (right): Cpl Simon Duschesne. Combat Camera DND.

Technical Challenges

To achieve the performance targets and requirements dictated by operational forces and market forces, a number of technical challenges must be overcome. This section outlines the 11 technical challenges that were identified as priorities for achieving the performance requirements of current and future armour systems.

Reduce Weight

Current opaque and transparent armour systems pose a significant weight penalty to the user (vehicle or person) that is detrimental to performance, especially mobility. Transparent armour materials are the least mass efficient high performance protective materials currently fielded in PPE and VA applications.

Using novel materials and processes could allow a significant reduction in system weight while providing improved situational awareness to the vehicle crew or wearer of the PPE. Providing increased levels of protection will definitely require significant advancements in material technology.

Develop Modelling Tools

The development of new protection systems is complex, costly, and time consuming. The days when shooting at increasingly thicker layers of steel and observing the results was efficient are gone and are, arguably, now unnecessary. Modelling of new protection systems will become more important as a design iteration tool prior to prototyping and testing. This is because the cost and nature of new products and materials is putting a strain on the limited resources of most organizations. The use of modelling and simulation can reduce development time and production costs of new protection systems and materials allowing for better engineering before large-scale production. But today's digital tools need to be improved before industry can fully benefit from them. A synergistic project targeting the development and validation of modelling tools through comparison with results obtained from physical trials of low and high speed deformation of armour materials could offer interesting solutions to the challenges mentioned above. There is a need to improve modelling and simulation during material formulation, development, and manufacturing to decrease the time required to identify, engineer, and commercialize promising materials technologies, as well as to reduce manufacturing time and costs. A different approach would see the development of a synergetic project, focused on the development and validation of modelling tools through comparison with the analyzed mechanical and high strain-rate dynamics performance of armour materials and components of PPE and AV. It is expected that the modelling tools would incorporate validated technical data generated in the program.

Improve Human Factors Engineering

PPE that is designed without proper human factors engineering and system integration will have a negative impact on operational effectiveness and, potentially, survivability. PPE that is not worn, or not worn as intended, at worst offers no protection and at best offers compromised protection. Ergonomics, transfer characteristics, bulk, ease of mobility, and other design factors have a direct effect on user acceptance and operational performance of PPE. Human factors requirements cannot be an afterthought in the development and integration of advanced armour material technology. Human factors engineering is therefore an important area in the design and development of PPE.

Quantification and Design for Multiple Threats

Current protection systems are generally optimized to defeat a specific means of penetration. Protecting a vehicle against multiple threats has, up until now, required the use of a variety of systems. This increases weight, reduces mobility, and adds complexity to system integration. Ideally, one fully integrated system would incorporate materials that defeat a variety of threats, for example, both kinetic and chemical energy threats.

Developing integrated systems will require a detailed understanding of the penetration mechanics of a particular threat and the material properties needed to defeat the threat. It will also require modelling and other design tools to support trade-off and performance optimization analyses.

Availability of Materials Solutions

To capture market share, industry needs to be able to field solutions in a timely manner. This requires access to a variety of data, including performance requirements, threat effects, and the corresponding materials and material system response characterization. The materials selected must be available in the quantities necessary for scaled up production and must also be suitable for cost-effective production processes.

Industry also needs to be able to manufacture and test prototypes, sometimes using facilities and test munitions that are outside of their control. To meet this challenge, it is necessary to develop an S&T network that allows industry to access both data to develop their solutions and facilities to test them.

Reduce Cost

The challenge of reducing costs has three components: controlling the unit cost of a system through the development of more efficient manufacturing processes; reducing the cost of base materials through economy of scale or lower-cost material technologies; and producing a more robust, durable system that reduces life cycle costs.

Increase Performance

The continuous cycle of improvements to armour materials and weapon system efficiency drives the requirement for increased performance of protection systems while maintaining control over cost and weight. However, performance is more than the ability to defeat a larger projectile; it also includes fielding more robust, durable systems that are matched to operational requirements.

Develop Advanced Manufacturing Processes

While producing higher performance armour systems, industry must provide cost-effective solutions. One means of controlling cost is through the development of more efficient manufacturing processes, including new and re-usable tooling and optimized procedures. Advanced manufacturing processes can also unlock new armour capabilities and functionality that enhance operational effectiveness.

Improve/Enable Integration

Improvements can be made to the development and manufacturing of vehicle structures and armour systems. The main reason for this is that even the best plate armour is ultimately connected (and therefore transfers load) to the vehicle itself. The elimination of weld joints, which is an area susceptible to blast, is one example. In addition, the use of materials other than steel and aluminum, such as composites, could also provide enhanced crew survivability while reducing weight.

The integration of solutions during the vehicle design phase will provide the most effective and efficient end product. Industry will be able to realize the best use of materials to save weight and provide increased coverage for crew survivability. Early integration will also encourage the consideration of external features (e.g., stowage racks, sensors, optics) in the design.

There are a number of challenges for integration with respect to PPE. They include selecting and adapting materials for specific user and operational requirements; optimizing hybrid systems for protection, cost, weight, and human factors; providing the tools and objective measures to support tradespace analysis; developing concepts for mission-configurable armour systems; developing material systems for multi-threat protection; defining the threats against which protection is needed; and obtaining appropriate material properties.

Materials Characterization at Multi-scale

Materials characterization is used to quantify the features of a material's composition and structure (including its defects) that are significant for a particular application and are sufficient for its reproduction. Materials can be uniquely characterized based on their chemistry, microstructure, and processing defects.

In the same way that availability of materials solutions is a critical enabler, more efficient and accurate materials characterization is an important part of quickly and cost-effectively determining the suitability of a variety of materials for armour applications and supporting trade-off analyses and integration.

Multi-Purpose Materials

When selecting materials for design and manufacture, the intent should be to make selections that not only provide protection but also fill other functional or operational requirements in order to minimize weight and bulk. These products may evolve from multi-material solutions that can defeat a variety of threats (e.g., both CE and KE) or that can provide a means of energy storage, energy transformation, communication, self-diagnosis, and signature management.

Technology Solutions

Participants at the SMTRM workshop identified an initial set of nine immediate technology platforms that offer pathways for meeting the technical challenges to achieving the performance requirements of future armour systems. This section describes these technology solutions and includes an exploration of the state of the art, challenges, and potential applications in security materials.

Manufacturing Technologies – High Velocity Oxygen Fluid, Cold Spray, and Additive Manufacturing

High Velocity Oxygen Fluid (HVOF) is a thermal spray coating technology that deposits hard, dense coatings of pure metals, metal alloys, cermet, and certain ceramics and polymers on large surface substrates with high deposition efficiencies at normal temperature and pressure. The coating material, in powder form, is fed into the combustion chamber of a spray gun, where a fuel such as hydrogen, kerosene, or ethylene is burned with oxygen, and the heated and softened powders are expelled as a spray with the supersonic gases (see Figure 16). For example, the HVOF technique is the preferred thermal spray process for hard chrome plating replacement because it produces low porosity coatings (<1%) and highly adherent (bond strength >50 MPa) that generally have an oxide content less than 1% even for reactive metals. It also has beneficial health and safety attributes compared to hard chrome plating.

Figure 16: HVOF gun in operation (left) and thick HVOF cermet coating deposited on high-strength Al alloy (right).

CrC-NiCr and WC-CoCr cermet material systems applied using HVOF technology constitute two main carbide-based materials used to improve wear, erosion, and corrosion resistance (even in high temperature regimes) in the aerospace, automotive, and petrochemical industries. High density, high hardness, and modulus material coatings such as HVOF-deposited cermet may find applications for the defence sector that increase the effectiveness of armour components (i.e., either applied on the disruptor or absorber) or as an interlayer coating that can spread the stress wave propagation efficiently at the point of impact of a projectile. In this scenario, the HVOF cermet coating represents a potential solution for designing a multi-layered (ceramic strike face/cermet interlayer/metal absorber) composite armour with enhanced ballistic performance.

Cold-spray (CS) is a coating process in which heated and compressed propellant gas flows through a convergent/divergent nozzle into which powder particles are simultaneously fed. The propellant gas accelerates the powder particles to supersonic velocities towards a substrate of choice. Upon impact with the substrate, the particles undergo plastic deformation, adhere to the surface, and form a coating (solid-state process). The kinetic energy of the particles, supplied by the expansion of the gas, is converted to plastic deformation energy during bonding with the substrate. A wide range of metallic, cermet, and polymeric materials can be successfully deposited at high rates and efficiencies while offering significant flexibility in the choice of the substrates (e.g., metals or composites). CS coatings are very dense (approaching material bulk density) and the adhesion strength between the deposited material and substrate usually exceeds the strength values of the glues or adhesives used to prepare pull-tests specimens (e.g., 70 MPa).

As illustrated in Figure 17, the CS gun is attached to a robot (automated process) that can exercise a high degree of movement and therefore provides the ability to produce coatings on parts having complex shapes. The resolution of the deposits and rates of deposition can be tuned by adjusting spray parameters like the spray distance, angle, and traverse speed of the robotic (torch). For example, CS can be used to coat only selected locations of a metal-stamped profile or other complex geometries without the need for extensive masking or surface preparation. This makes it a powerful candidate technology for additive manufacturing.

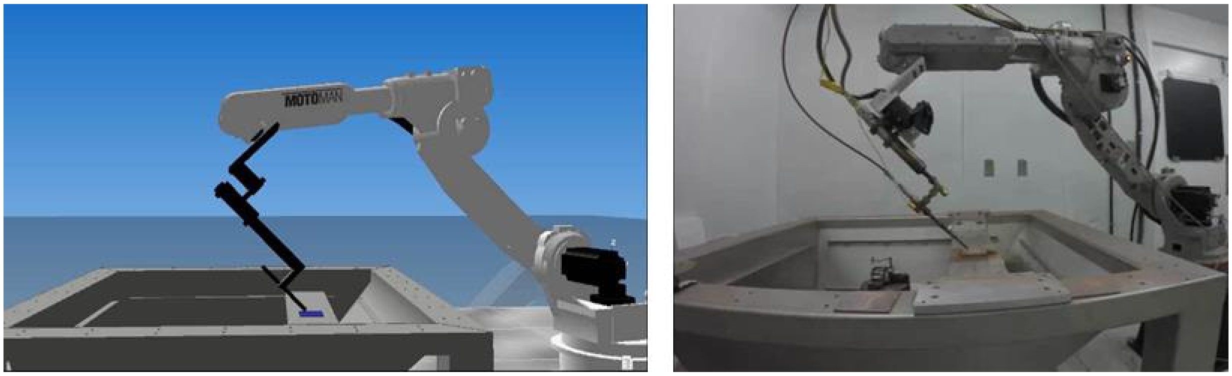

Figure 17: Cold-spray gun attached to a robot arm: (left) computer simulation of the sprat path and (right) gun in operation

Cold-spray solutions developed by NRC (Figure 18) address needs in various industry sectors, such as anti-wear steel-based coatings for aluminum parts used in automotive light weighting; coatings for high performance tooling, aircraft parts overhaul, and repair; metallic bond-coats for thermal barrier coatings used in land-based and aircraft engine gas turbines; and anti-wear coatings for engine components, among others.

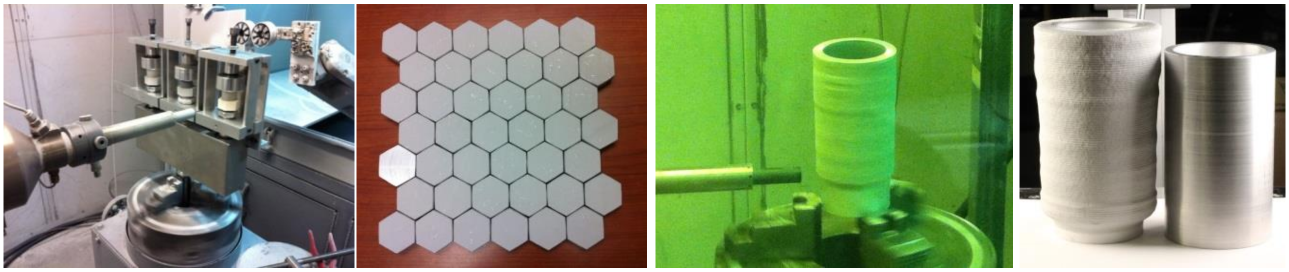

Figure 18: Cold-spray equipment, NRC in-house developed fixture for coating hexagonal ceramic tiles and metal encapsulated tiles (left); metal casings machined from cold-sprayed coatings(right).

More recently, cold-spraying was employed to produce coatings and parts for defence-related applications. One of these applications was confining ceramic tiles (e.g., Al_2O_3) in aluminum CS coatings for compressive stresses that can further render the strike face of a disruptor multi-hit. The cold-spray coating technique has minimal effect on the oxidation or phase transformation of the sprayed components (low temperature process) and thus prevents any deleterious effect that an armour component may experience with other techniques. It was demonstrated that CS can be used to integrate coated tiles into multi-component armour architecture (e.g., ceramic/backing plate). Another use of CS is to shape parts like structural energetic materials meant for explosive charge casings that can contribute additional energy to the air blast through its fragments, either reacting promptly after charge detonation or upon impact with the target.

Characterization and Testing

The capability of current computer models to predict shock physics for highly dynamic impact and ballistic studies used to select armour materials and design systems is dependent on the material models, equations of states, and properties that are used as inputs to the simulation. The properties required by these models and the equations they use are strain rate dependent. As a result, to conduct accurate numerical simulations, high performance servo hydraulic load frames and the Split Hopkinson Pressure Bar (SHPB) are two of several characterization methodologies that allow relevant and accurate material parameters to be determined.

Detailed knowledge of the deformation and fracture behaviour of candidate materials for armour applications is critical to selecting, optimizing, and integrating the materials into an efficient protection system that is designed to defeat a particular threat. The behaviour of materials under dynamic loading conditions typically found in shock and impact loading is dependent on the strain rate, strain hardening, and thermal softening effects. For many shock and ballistic impact events, the strain rate can be as high as 10^6 s^{-1}. Therefore, in order to fully characterize a material, depending on the type of material and the loading conditions, a combination of quasi-static, intermediate, and high strain rate tests must be performed. Using material properties that are not appropriate for the strain rates involved can lead to inefficient or, worse, ineffective armour systems.

Figure 19: DRDC Split Hopkinson Pressure Bar laboratory

Most characterization tests are performed in shear, torsion, tension, or compression, or using a combination of these loading modes and at various temperatures when thermal effects are non-negligible. One of the most widely used experimental configurations for high strain rate characterization of materials is the SHPB. An example of the SHPB is shown in Figure 19. This technique complements the more common and better known quasi-static material characterization using traditional mechanical load frames (<0.1 s^{-1}) as well as servo-hydraulic load frames, which allow the intermediate strain rate response to be measured (0.1 s^{-1} to 10^2 s^{-1}).

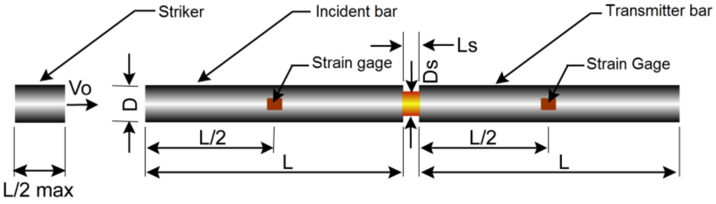

Figure 20: Example of striker, incident and transmitter bars

A typical Split Hopkinson compression bar system includes a striker bar, an incident (input) bar, and a transmitter (output) bar with the material sample sandwiched between the incident and transmitter bars, as shown in Figure 20. The bars are typically manufactured from high strength steel. The basic principle of the Hopkinson bars is the assumption of non-dispersive elastic waves traveling in the pressure bars and the assumption that, at least for high impedance, homogeneous materials such as most metals the specimen deforms uniformly. In a typical SHPB experiment, the striker impacts the incident bar and an elastic compressive wave is generated and travels through the incident bar. When this compressive wave reaches the specimen, the wave is partially transmitted to the transmitter bar and partially reflected back to the incident bar as a tension wave. Strain gages, fixed at the mid-point of the input and output bars, monitor the strains.

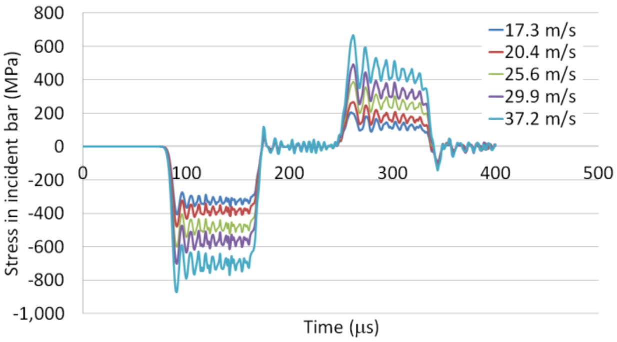

Figure 21: Numerical simulations of compressive

The stresses and strains in the specimen are then calculated using appropriate strain and shock wave relations. Figure 21 shows an example of the stress in the incident bar obtained from simulations of SHPB tests for Al 6061 T6 specimens impacted at five striker velocities. Figure 22 shows an example of the resulting stress-strain response, across a range of strain rates, obtained from SHPB tests for another material.

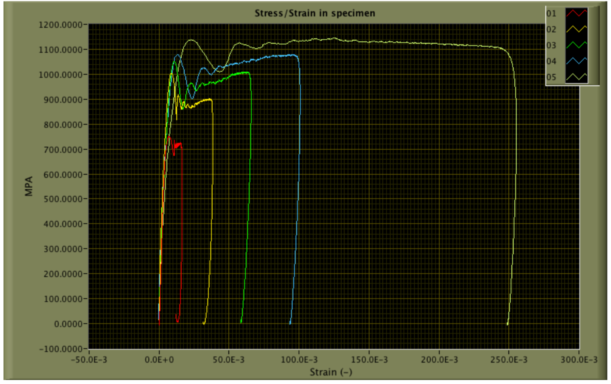

Figure 22: Numerical simulations of compressive Split Hopkinson Bar tests for AL 6061 T6.

The extraction of the stress-strain response of non-homogeneous and low impedance materials is more complex because the 1-D assumption used in a standard SHPB analysis is no more valid. However, in recent years through more complex analyses using advanced instrumentation, camera systems, and polymeric bars, it is now becoming feasible to characterize materials such as polymers and polymeric composites. This is an area that needs further S&T investment to improve the capabilities.

While SHPBs have been used to measure the dynamic properties of materials for the past 50 years, they are unsuitable for characterizing low to intermediate strain rate (<200 s^{-1}) response of materials. Indeed, the literature shows an evident gap in material characterization between quasi-static and high strain rate results. This is mainly due to the lack of appropriate facilities and reliable techniques that can bridge the gap between quasi-static and high strain rates. Mechanical load frames are not fast enough and control systems for hydraulic load frames are not up to the task at the upper end of the intermediate range. Recent developments in servo-hydraulic load frames (see Figure 23), suitable for generating intermediate strain rates, are opening the door to material characterization across the full range of dynamic response to which armour materials and armour systems are likely to be subjected.

Figure 23: NRC's High Speed Load Frame

Materials under shock and impact loading conditions are difficult to characterize and a variety of methods are used to investigate their applications. Ballistics tests and physics-based numerical simulations and analysis are required. This technology thrust is closely linked to the numerical simulations thrust. No single method—computations, ballistic testing, or dynamic material characterization—will by itself lead to a complete understanding of the mechanisms that govern the behaviour of materials and structures subjected to the impulsive loading conditions that are relevant to protection systems.

From a security materials development standpoint, a judicious use of all three of the foregoing methodologies together would lead to improved understanding of short time-response phenomena. This knowledge, in turn, will underpin revolutionary improvements in material technologies and armour system designs capable of mitigating the ever-evolving threats that warfighters and first responders face.

Modelling and Simulation

Modelling and simulation is widely used in engineering applications to reduce the number of experimental tests necessary to develop and optimize engineering systems. This also reduces the related costs involved in the development and manufacturing process. Modelling and simulation can be performed using analytical models or using finite element codes.

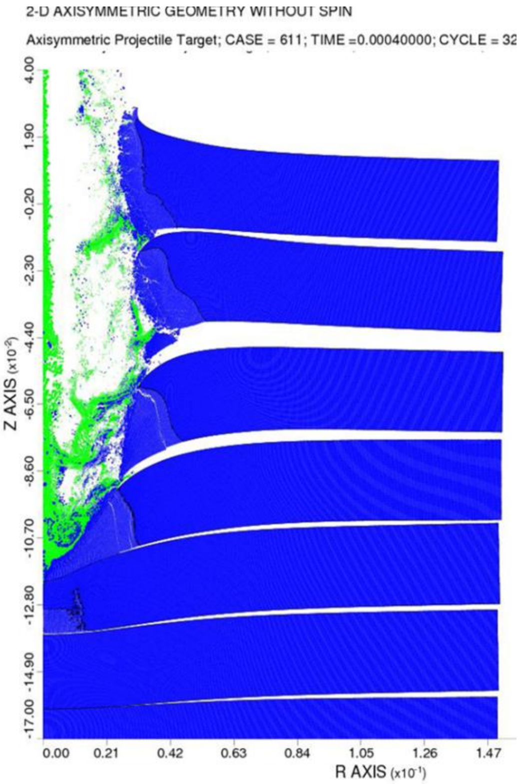

Figure 24: High velocity impact of a tungsten projectile on a steel target at 2.3 km/s

Analytical models, although restricted, are quite useful for examining dominant physical phenomena occurring in materials under ballistic or shock loading conditions. However, from a prediction standpoint, analytical models are limited within the scope of their empirical constants. Extreme care needs to be taken so as not to violate the simplifying assumptions involved in their derivation. If a complete solution to a highly dynamic event (e.g., defeat of a ballistic threat by an armour system) is necessary, physics-based numerical simulations must be used. Most often this involves simulations that use hydrodynamic shock physics computer codes or hydrocodes (also referred to as elasto-plastic hydrodynamic code).

A hydrocode may be defined as a physics-based code for solving large deformation, finite strain transient problems that occur on a short time scale, which exist in high velocity impact problems, or close blast or shock loading of structures. A typical high velocity impact problem, and the subsequent penetration of the target, is shown in Figure 24. In this case, the impact velocity of the tungsten projectile is 2.3 km/s and the target is made of RHA steel. Although the strength of the material may not necessarily be a major factor in the solution, it is usually included—a point that distinguishes hydrocodes from general fluid dynamics codes. In contrast to structural analysis codes, in hydrocodes the energy equations are integrated in time and pressure, and deviatoric stress terms are modelled separately. In a hydrocode simulation, the solution is advanced in increments of time. Therefore, the equations that govern the material response must be resolved accurately in both space and time. These codes (especially the recent finite element analysis codes) are called explicit codes because they use an explicit time integration scheme to handle the stress waves and shocks that are part of the solution. In general terms, there are three broad areas of concern for research and development:

(a) Numerical schemes that are required for modelling materials that contact each other in a physical way and represent physical phenomena that occur, such as the passage of a shock wave.

(b) Material constitutive models and equations of states to obtain the pressure and true stress state of the material as the problem progresses explicitly in time.

(c) Computational failure or damage models to accurately model material failure or damage.

It is obvious that (b) and (c) are quite closely linked, with (a) consisting the computational or mathematical schemes necessary to numerically implement (b) and (c).

As described above, the most serious limitation to the use of hydrocodes is not their cost or complexity, but the inadequacy of the constitutive models used to describe material response, damage, and failure under dynamic loading conditions. Material response, damage, and failure can occur by a variety of mechanisms that are dependent on the material constitution and the state of stress, temperature, rate of loading, and a number of other dependent variables. The methods and results of quasi-static material response and fracture are of little use in situations involving the high strain rate loading conditions that are found under ballistic impact or in shock loading environments.

Thus, the aim of the work of this thrust is to investigate the use of relevant constitutive models, equations of state, and failure models to simulate materials of interest under shock and ballistic loading conditions. This involves high strain rate characterization of materials for a wide range of strain rates up to 10^4 s^{-1} and to conduct experiments to validate the use of these parameters. Figure 25 shows an example of the strain rate effect on a material response. In this case, the Al 6061 T6 specimens were impacted at four striker velocities (m/s) using DRDC's SHPB. The basic idea was to capture the behaviour of a material (stress amplitude, strain, failure) under medium/high velocity impacts and to determine simulation parameters to conduct predictive studies of newer materials under high strain rate loading conditions.

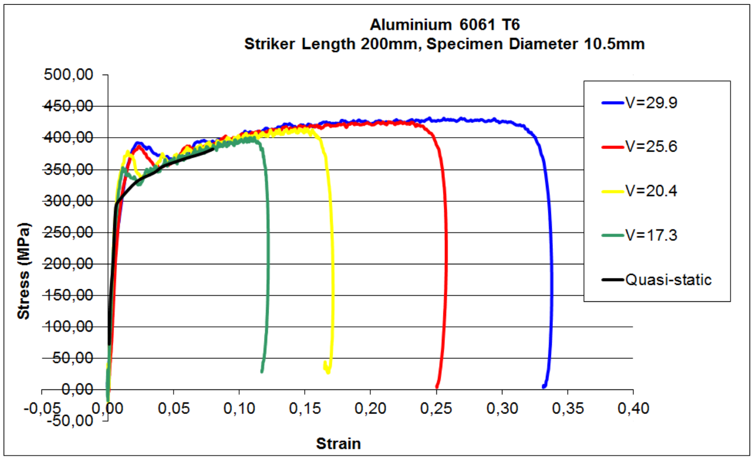

Figure 25: High Strain rate characterization of Al 6061 aluminium.

As with characterization and testing, no single method—computations, ballistic testing, or dynamic material characterization—will lead to a complete understanding of the mechanisms that govern the behaviour of materials and structures subjected to impulsive loading conditions. All three approaches will be required.

Polymers and Adhesives

Polymers in various forms (thermosets, thermoplastics, and elastomers) have a wide range of armour applications as bulk materials (e.g., transparent armour and foam materials), adhesives, and matrices in composites. Amorphous thermoplastic polymers such as poly (methyl methacrylate) (PMMA) and polycarbonate (PC) are widely used in applications in which transparency is critical (e.g., transparent armour for both PPE and VA).

While the application of multilayer transparent structures (e.g., PC/PMMA bilayer structures) has been successfully marketed, optimization of multilayer armour structures is still emerging (technology readiness level (TRL) ~ 5-8). This optimization includes the thickness of each layer and interfacial adhesion between layers (e.g., direct bonding or bonding using thermoplastic elastomers).

Nano-enhancement of transparent armour using optically transparent nanoparticles such as boron nitride nanotubes (BNNTs) is at an early stage of development (TRL ~ 1-3). BNNTs have the potential to address multifunctional properties of transparent armour and provide additional energy-absorption-enhancing mechanisms, increase outermost layer hardness, and enhance other functionality (e.g., thermal stability, scratch resistance, anti-fogging, sensing and self-repair). Figure 26 outlines the application of polymers and adhesives to the PPE and VA industry where NRC's knowledge and expertise can generate a competitive advantage.

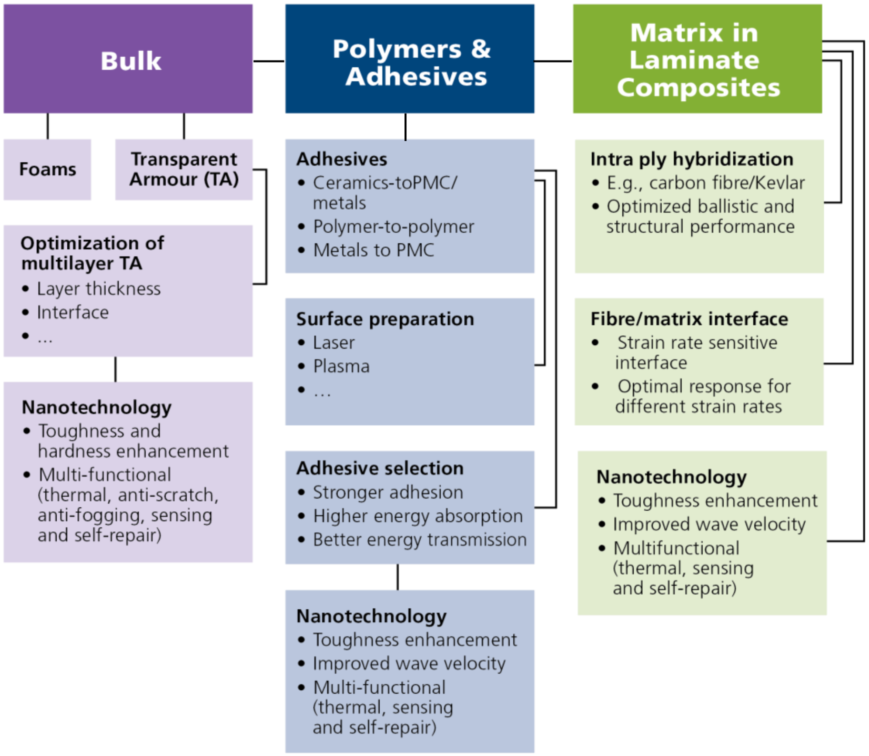

Figure 26: Armour applications of polymer and adhesive technologies

The main advantage of ceramic/polymer-matrix composite (PMC) armour systems over traditional metallic or metallic/PMC is a high resistance to penetration with a low density. However, a major disadvantage of this system is its reduced multi-hit capabilities. Studies have shown that this reduced ballistic performance is largely dependent on adhesive performance and was largely due to three different factors: poor adhesion between the ceramic plate and the backing material, limited energy transmission, and absorption by the adhesive.

The development of advanced surface preparation for bonding (e.g., laser and plasma surface preparation) and smart adhesive selection (e.g., nano-enhanced adhesives or adhesive with improved wave velocity that is more comparable to ceramic layer) over traditional adhesives (e.g., epoxy and polyurethane) can result in enhanced performance (e.g., at quasi-static, low-speed, and high-speed impact, ballistic regimes of personal protection equipment, and vehicle armour in a multi-layer armour assembly or “armour system”). While research in this area is still in the emerging stages (NRC currently has in-house expertise in this area), ultimately this can be transitioned to Canadian industry partners to make internationally competitive products in Canada.

In addition to surface treatments and the use of commercially available adhesives, new concepts using nanomaterial-enhanced adhesives can provide additional advantages. These include enhanced toughness, improved wave dissipation, and multi-functionality such as thermal enhancement, smart sensing and self-repair, although these are presently at the early stages of development (TRL ~ 2-4). Adhesive technology based on nanomaterials is being examined extensively by other industries including aerospace, sporting goods, and automotive. As a result, the PPE and VA technologies can benefit from the advancement achieved in these sectors.

Today, PMC armour systems with high energy absorption capabilities and low density are extensively used for both PPE and VA applications. PMC armour provides protection against more than just the fragmentation and ballistic threats that have dominated PPE development in the past. Increased requirements for blunt trauma protection are pushing laminate composites performance for protective equipment such as the combat helmet. New requirements for PPE, such as facial protection, are also being introduced, where laminate design for structural performance under impact is not compatible with the optimal design of a laminate for the ballistic requirements.

There are several routes to achieving structural and ballistic performance targets. They include functional grading of material properties to optimize energy absorption and areal density under ballistic loading (e.g., graded matrix content and inter ply hybridization), intra ply hybridization of carbon and aramid fibres to achieve mass efficient integrated ballistic and structural/impact resistance, and optimization of the fibres/matrix interface with thermoplastic polymers.

The TRL for developing hybrid carbon fibre/Kevlar® fibre is currently estimated to be medium to high (~ 5-8). A long-term solution for reducing armour weight and improving performance will involve the development and integration of advanced technology materials. Advancements in nanotechnology materials show a great potential to provide fibres and fabrics with drastically improved ballistic performance, largely based on carbon nanotubes (CNTs). While no Canadian-based company or research institute is currently involved with fibre technology, NRC is currently active in researching CNT-based and BNNT-based fabrics. The TRL for these technologies, however, is estimated to be low to medium (TRL ~ 1-5). The development of nano-enhanced composites, also known as hybrid or hierarchical composites, can provide superior structural performance to traditional PMC by modifying matrices (e.g., enhancing fracture toughness of resins or improving resin-matrix interface by providing an optimized ballistic/structural performance) or fabricating multifunctional composite structures (e.g., thermal enhancements, self-sensing and self-repair). These technologies are, however, estimated to be at early stages of development (TRL ~ 1-4).

Ceramics

The key objectives of the SMT program are increasing mass efficiency in armour products, transitioning armour technologies to industry, and developing effective research and technology development partnerships in Canada. There is a compelling need to produce tougher and lighter armour with improved ballistic protection for personnel and tactical vehicles. Advanced armour ceramics are superior to most materials in terms of hardness, density, and stability in harsh environments. Ceramic armour technologies are critical for weight reduction in current and future army systems and key to maintaining the global competitiveness of the Canadian security materials industry.

There is a need to optimize material properties to meet the requirements for armour applications such as threat defeat, providing multi-hit capability, successfully demonstrating reliability through long-term end-user field tests, and achieving cost-effective production technology to support market acceptance (see Table 2).

Table 2: Examples of R&D challenges to be addressed for ceramic armour improvement

Overview of identified ceramic armour development needs	
Development and manufacturing (TRL 6/7)	Powder technology: Hot Press, Pressure-less Sintering, Hot Isostatic Pressing
	CNT/BNNT mix
	ND testing/characterization
	Capability development
	Integrated ceramic armour
	Ceramic fibre and 3D materials
	Nanotube stability
	Toughening mechanisms
Screening/testing/verification (TRL 3/4)	Impact test: drop/charpy/impact tensile
	Indentation facture toughness
	Ring-on-ring
	Characterization and microscopy
Certification and field test (TRL 8/9)	Technology demonstrator
	High strain rate test (shoot)
	Depth of penetration
	V_{50}
	Areal density
Incorporation and integration (TRL 8/9)	Incorporation into existing PPE, vehicle armour, transparent ceramic armour
	Service release

Key ceramics research challenge areas include:

- improving fundamental mechanical properties relevant to armour performance;
- developing ceramic armour materials and manufacturing methods;
- characterizing mechanical properties under high strain rates and pressures;
- understanding penetration and failure mechanisms in ceramics; and
- identifying performance criteria and ballistic testing.

The four key performance parameters (themes) that need to be addressed in terms of improvements to armour ceramics are multiple hit capability, fracture toughness, weight reduction, and integration and improved adhesion of ceramics to other layers in the protection system (see Figure 27).

Comparable to the protection provided by opaque armour, transparent armour systems use layers consisting of different materials to disrupt and absorb the kinetic energy of incoming projectiles. However, careful attention to the construction and coupling of the various layers is essential. The front face, backing, and bonding layers should have a closely matching refractive index to allow substantial transparency. Transparent armour systems also experience excessive wear and surface damage, which leads to the loss of armour transparency when employed in sandy environments. Scratch resistance, fog resistance, and flexural strength are also identified as major required improvements.

Figure 27: Four key focus areas for improving armour ceramics.

The key barriers and challenges facing both the opaque and transparent armour industries involves lack of a sizable advanced ceramic manufacturing base in Canada, limited incentives for investment in fundamental research, as well as the politically based cyclical growth and contraction of the defence market.

Maximizing economic return from the investments that are needed in advanced ceramics research and infrastructure requires exploitation beyond the Canadian armour sector. Fortunately, recent NRC breakthroughs in mass manufacturing, and integration of CNTs and BNNTs into ceramics has led to an improvement in fracture toughness. This may maximize the economic return from investments in advanced ceramics research and infrastructure. There are also increasing demands for lightweight, hard, and high temperature engineering ceramic in the aerospace (engine), energy (land base turbines), and fuel cell industries that justify the capital investment in ceramic-matrix composites.

An increase in fracture toughness is required to improve multi-hit capabilities. However, this usually limits single-hit capabilities as other mechanical properties are affected (e.g., hardness/compressive strength). The challenge is to find the right balance between often opposing properties.

> *Fracture toughness will improve the multi-hit capability but usually, the single hit capability will be reduced since other mechanical properties will be affected (e.g., compressive strength). This might be a problem or not depending on the add-on armour. However, if the single hit capability reduces too much, the ceramic armour add-on might no longer be competitive with metallic composite armour which performs better in multi-hit mode. The challenge is therefore to increase fracture toughness without affecting other mechanical properties too much.*
>
> *- Yves Baillargeon*
> *Defence Scientist, DRDC*

Non-Destructive Evaluation and Life Cycle Management

In the armour industry, non-destructive evaluation (NDE) is used to test and inspect security materials. These two evaluation approaches are known as non-destructive testing (NDT) and non-destructive inspection (NDI). NDT is used for quality assurance or characterization of newly designed and manufactured components and assemblies to verify that they are produced at the expected standards and to verify that the manufacturing processes are properly optimized. For armour materials in service, NDI techniques are used to ensure that they are maintaining the same level of integrity and performance as initially sought. NDI is occasionally used as an advocate for repair and replacement of parts, components, or structures. NDE is concerned with in-service damage monitoring and quality of repaired structures.

Structural health monitoring (SHM) systems are proposed as a distributed sensing network that is permanently attached to or embedded in a structure and could be used as *in situ* NDE, at least for some applications. SHM techniques are aimed at both monitoring the performance of vehicle armour structures and assessing their health and degradation. However, the field implementation of SHM for armour structures is more problematic due to the fact that SHM systems could get damaged at the same time as the structure they are supposed to monitor.

The application of non-destructive characterization techniques depends on the armour material, structure geometry, and the type of defect sought. The most suitable NDE methods applicable to armour materials are ultrasonic waves, infrared thermography, terahertz imaging, magnetic flux, and radiography.

With the exception of the terahertz imaging method, all others methods indicated above are well-established in the industry and used for a variety of purposes. As is the case with the vast majority of NDE techniques, specific customized testing and inspection procedures need to be developed. In other industrial areas, prior knowledge is helping to reduce the procedure development time, but for armour materials and structures, the adaption and customization of NDE techniques is still in their initial phases.

In-service NDE, for both personnel and vehicle armour, requires capable, fast, wide-area, and single-side access techniques. Although radiographic and ultrasonic techniques are well-suited for depot/laboratory testing, they are not field-deployable. The terahertz imaging technique holds great promise for the evaluation of ceramic armours; however, the current cost of an inspection system is very high. Partnering with research groups that have or provide leasing/renting of such systems is a cost-efficient alternative at this time.

Current methodologies for determining the properties and behaviour of armour materials involve destructive, labour-intensive, and time-consuming mechanical testing. In the case of determining the post-ballistic performance of already impacted armour, X-ray radiography techniques are the methods of choice. However, these tests cannot be easily performed on the battlefield, while in laboratory they require stringent radiation protection, limitation of the specimen size, and expert personnel. DRDC's objective is to find field deployable methods, capable of fast and reliable inspections.

Below is a summary of the techniques discussed above and an indication of their TRL-levels:

Ultrasonic testing

For ultrasonic testing, high frequency waves, normally in the MHz range, are coupled with the material to be tested. The high frequency waves suffer reflection and attenuation along their propagation, due to interaction with non-homogeneities in the material, phenomena that could be monitored in-reflection (i.e., pulse echo), and through-transmission (i.e., pitch-catch) modes. The coupling of the ultrasonic wave-generated transducer with the part to be tested represents a critical component of the investigation, particularly as inspections are performed in water immersion. However, this does not represent an impediment for material characterization of ceramic armours, as the testing is done in the laboratory. To characterize the integrity of ceramic and metallic armours, the technique needs to be adapted to a field environment; therefore, more developmental work is required.

TRL: 6

Infrared thermography testing

Heat diffusion in a material can be captured via heat-sensitive solid-state sensors, working in the long-range of the electromagnetic spectrum (thousands of nm in wavelength). Infrared thermography is a non-contact, single-side access, wide-area technique. The outcome of this type of inspection is a two-dimensional temperature map of the surface of the inspected component. It is best-suited for the inspection of non-metallic parts of low-to-medium heat conductivity. The technique has the potential to determine the spacing between ceramic tiles arranged in two-dimensional arrays, and relating this to the armour's effectiveness. Although the method has a high level of maturity, it is not often applied for this purpose.

TRL: 5–6

Terahertz imaging

The terahertz imaging technique is an emerging non-destructive inspection method used for evaluating non-conducting (dielectric materials). It uses electromagnetic radiation at high GHz or THz frequencies. For ceramic materials, it can be used to evaluate non-visible (or hidden) cracking, as well as minute thickness variation. The technology is in its early stages. Although there are commercial manufacturers of the necessary instrumentation, at this stage terahertz imaging is prohibitively expensive. Partnering with owners and manufacturers of terahertz systems may be the appropriate step for the evaluation of terahertz technology for the inspection of ceramic armours.

TRL: 3–4

Radiographic techniques

Photons (such as X-rays and gamma-rays) and particles (such as neutrons) are used to inspect a test piece under evaluation. The interaction between the photons/particles and the structure of the material, in the form of absorption, attenuation, and scattering, produces images on sensitive media like films or imaging plates. These radiographic techniques are mature, but for the vast majority of cases are performed in laboratory environments.

TRL: 8–9, but not applicable in the battle theater.

NDE for armour technology goals includes:

- Non-destructively determining the mechanical properties of ceramic, composite, and metallic armour materials;
- Determining manufacturing defects in ceramic tiles before they are laminated in a final armour system;
- Analyzing drop and durability testing of ceramic armour; and
- Analyzing survivability of armour systems.

Nanomaterials

While there is no single, internationally agreed definition, a nanomaterial can be broadly defined as a material that has at least one dimension less than 100 nanometres (Figure 28), contains constituents of such nanoscale dimensions, or was produced by nanotechnology. As a result of this nanoscale dimensions, the properties of nanomaterials can differ dramatically from other more conventional materials. They offer transformative potential to impact practically all technology sectors underpinned by advanced materials.

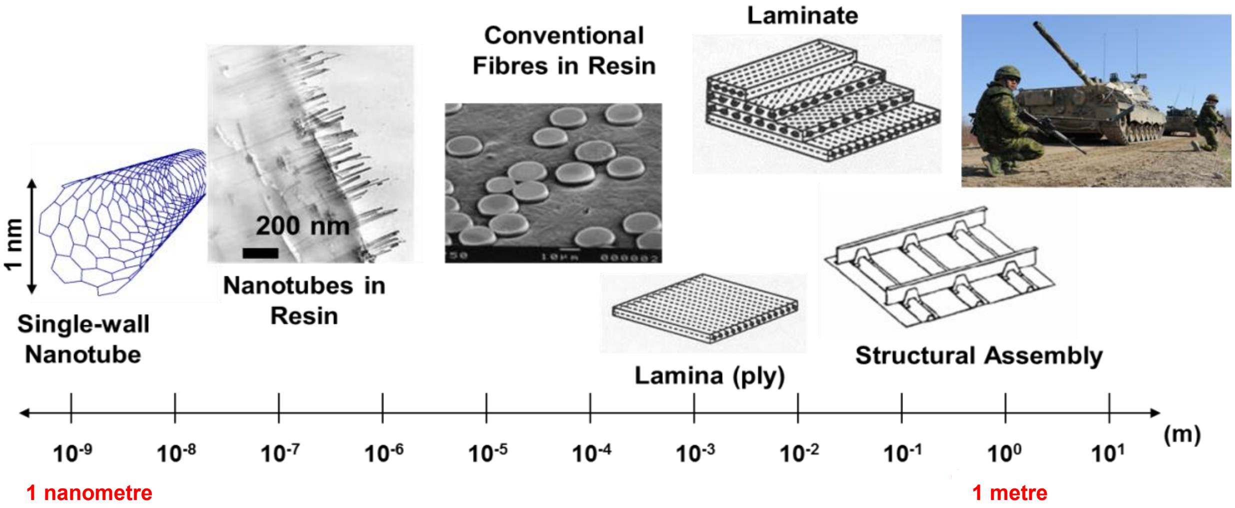

Figure 28: Length scales from nanometre to metre

Nanomaterials have a wide range of both present and envisioned applications, including structural nanocomposites used health care, energy harvesting and storage, electronics, smart/responsive materials (self-sensing, self-healing), textiles, catalysis, and others.

Engineered nanomaterials are produced by either top-down approaches in which the size of larger materials is decreased (e.g., powder technologies, electronics), or by bottom-up approaches where materials are built atom-by-atom or molecule by molecule (e.g., nanotubes). Engineered nanomaterials include fullerenes, graphene, carbon nanotubes (CNTs), high-temperature nanotubes (BN, SiC), nanofibers (ceramic, carbon and cellulose), metal nanoparticles and nanowires, nanosilica, nanoclay, semiconductor quantum dots, nanocrystalline materials (metals, semiconductors, oxides, ceramics and cellulose) and colloids. They also include polymer-, metal-, and ceramic-matrix composites or coatings possessing such nanoscale constituents.

The largest commercial applications of engineered nanomaterials are nano-structured coatings and nano-reinforced plastics, specifically conductive plastics wherein metal or carbon nanoparticles or CNTs impart sufficient conductivity for static dissipation or electromagnetic shielding. In the case of CNTs, there are a range of examples at TRL-9 (commercial products and materials used by in space), but the active research in this area covers the full TRL spectrum. In general, the commercialized applications for composites have mostly been based on the use of nanomaterials to impart multifunctional (electrical, thermal, optical) properties, although CNTs have also appeared in several sporting goods products (e.g., bicycle frames, hockey sticks).

Applications for high-performance structural composites, such as in aerospace and security materials, mostly range from basic research to technology development/demonstrations (TRL ~ 1‑6). However, there are a few commercial product examples, including lightweight vehicle armour based on a nanostructured ceramic (IBD Deisenroth, Germany) and lightweight PPE using composites based on CNT sheets (Nanocomp Technologies, USA).

According to a 2012 Frost & Sullivan report for Industry Canada, *Nanotechnology in Aerospace & Defence: Canadian Capabilities, Challenges, and Related Policy Insights*, Canadian nanotechnology activity is focused primarily on nanomaterials and nanocoatings. It is internationally competitive in the field but lacks the national-level coordination seen in other countries, including the United States and in Europe. Of particular note is applied nanomaterials research in Quebec, where there is more focused government support (CRIAQ, NanoQuebec, NRC) and industry concentration in the areas of aerospace composites and the industrial production of nanoparticles (CNTs, BNNTs, metal and oxide nanoparticles, and nanocrystalline cellulose). There are also clusters of nanomaterials research in Ontario, Alberta, and British Columbia around NRC locations and major universities. In 2014 and 2015, NRC also announced the planned establishment of a $3 million flexible research facility in Ottawa and a joint partnership with Xerox to build a “Canadian Campus for Advanced Materials Manufacturing” in Mississauga that will support pilot- or small-industrial-scale processing and production of nanocomposites.

The technical challenges and cost constraints associated with increased use and wide adoption of nanomaterials technologies for security materials and other structural composites primarily relate to (1) the availability of well-controlled nanomaterials and (2) both facilities and expertise for large-scale processing and composites integration involving nanomaterials. Worldwide annual production of multi-walled CNTs has surpassed the kilo-ton level. Industrial production of other structural nanomaterials including graphene, single-walled CNTs, BNNTs, and nanocrystalline cellulose is emerging; Canadian companies are significant players in the latter three cases.

Many successful approaches for processing and integrating nanomaterials in composites have been demonstrated at lab scales, but there are a range of challenges to the routine application of nanomaterials in industry. Some of these challenges apply across nanomaterials, including occupational safety and health considerations and developing regulations, as well as public and industry awareness and acceptance of nanotechnologies. Other challenges are specific to the type of nanomaterial or nanocomposite, due to the quite different methods, temperatures, and pressures required for fabrication of polymers, ceramics and metals.

Limited coordination of nanomaterials research, largely in the academic and government domain, with industry needs—along with researcher awareness of these needs—are other key barriers to development. Lack of a Canadian nanotechnology strategy was the most commonly cited challenge (ahead of funding, industry adoption, and technology challenges) in the 2012 Frost & Sullivan report on *Nanotechnology in Aerospace & Defence*. One goal of the SMTRM is to support such coordination and alignment of nanomaterials R&D with industry needs in the area of security materials.

Futuristic armour metals will feature nanoparticles (especially CNTs, nanocrystalline metals) in composites and coatings for greater ballistic performance. Shear thickening binders (e.g., a flexible matrix loaded with nanoparticles in which the materials stiffen/harden when impacted) are also under investigation. Biologically inspired and self-healing materials also feature in the research literature.

Composite Materials

In some PPE applications, such as combat helmets, the structural stiffness and strength performance of the composite, in addition to its ballistic protection performance, is of vital consideration. In this particular case, having a shell with appropriate mechanical properties is critical not only for in-service handling and durability, but also for protecting the head against external low-speed impact loads (blunt impacts). Furthermore, the structural stiffness and strength of helmet shells play an important role in behind-armour blunt trauma-type injuries, which directly relates to the structural response of the composite shell to a ballistic impact.

Recognizing that commercial success of defence products requires a cost-performance ratio adapted to each mission and application, the focus should be placed on the clever usage of materials and manufacturing technologies. As such, work has been conducted to improve both the ballistic and structural performance of aramid-based thermoplastic composites as illustrated in Figure 29. Technologies consisting of grading through-the-thickness properties of laminated composites, fibre hybridization, and optimization of polymer chemistry have been investigated.

Figure 29: Modular helmet system – NRC-DRDC collaboration (photo courtesy of DRDC Valcartier).

Grading the properties of laminated composites can be achieved by using fabrics woven with heavier yarns on the strike face. This approach leads to a decrease in cost as a result of the reduced total number of plies used and cheaper material cost (heavier fabrics are usually cheaper). Another approach consists of optimizing the matrix content with respect to the driving requirements of projectile penetration resistance, maximum dynamic backface deformation, and/or structural stiffness. This approach includes varying the matrix content through the thickness of the laminate. Although the ballistic resistance of such composites (on an areal density (AD) basis) is reduced, significant improvements in flexural and tensile properties can be obtained with such approaches.

Fibre hybridization is another technology under investigation. In essence, this concept consists of replacing (hybridizing) some of the aramid fibres (the ones able to mitigate the ballistic threat) by others that are more structural in nature (those that are able to provide more stiffness and strength), such as carbon fibres. The effect of two hybridization concepts (inter ply hybrids and intra ply hybrids) has been studied. In the first case, alternating plies of carbon fabrics and aramid fabrics are stacked (interleaved) and consolidated together, while in the second case, aramid and carbon yarns are co-woven together into the same fabric.

The ballistic and structural performance of composites results from the synergy developed between the fibres and the polymer matrix. Selecting the right polymer is of prime importance in designing composites for armour applications. A polymer that works particularly well with aramids has been identified. However, by characterizing the mechanical, thermal, and rheological properties of several unreinforced polymers and performing mechanical and ballistic tests on aramid-based composites manufactured from these polymers, the properties of the polymer where further improvements can be focused have since been revealed. Enhancing the properties of the polymer by using nanoparticles is another useful approach. A CNT nano-reinforced polymer can improve the mechanical properties without sacrificing the ballistic properties.

The technology readiness level for the different approaches described above, ranges from fairly mature and market ready in the case of aramid-based ballistic composites (Figure 29), to much lower TRL (~ 2–3) in the case of the nano-reinforced polymer matrix (see Figure 30).

Depending on the applications and requirements, these technologies could lead to very cost-competitive solutions as compared to the ultra-high molecular weight polyethylene (UHMWPE)–based composites that are expensive, pose manufacturing challenges, and show some drawbacks especially in stiffness and durability.

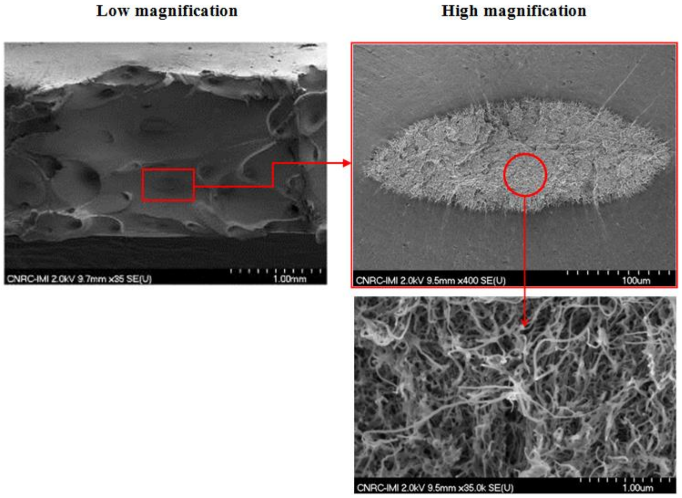

Figure 30: SEM micrographs of fractured surfaces of MWNT (5 wt%) nanocomposites tensile test specimens. Several large MWNT macro-aggregates are clearly visible on the fractured cross-section. They might have acted as failure initiation points in the nanocomp

An aramid-based solution is already marketable. Previous work has shown that it is possible to further improve the performance of this material system by using another polymer. It would be worthwhile to initiate a project aimed at testing the new assumptions, selecting a new, better polymer, and generating supporting data.

The use of CNTs seems to be an interesting route to develop nano-based hybrid composites with improved structural and ballistic performance. The use of nano-enhanced composites in armour applications is an emerging field and further systematic studies are necessary to confirm and improve the encouraging results obtained so far, possibly through optimization strategies with the characterization of the interface behaviour at different strain rates.

A barrier to the further development of those technologies is the availability of high strain rate testing and ballistic testing facilities.

Manufacturing Composites

Technologies are being developed to join together and integrate different materials into a system for improved PPE components. These technologies support stiffening strategies that are being explored to address issues related to the use of UHMWPE-based composites in PPE applications. They also more broadly support improvements in ballistic performance of PPE components.

Technologies were developed to join UHMWPE composites with carbon and aramid laminates; the challenge in this case being that the surface of the UHMWPE composite is non-reactive, inert, and hydrophobic, and thus very difficult to bond. Two approaches were explored to combat this problem. The first approach consists of joining all the different layers all at once while fabricating the armour panel (cofab approach). The second consists of joining (or assembling) the different layers in a secondary operation (postfab approach).

In the cofab approach, an ultra-violet (UV)-based surface modification technology was developed to “compatibilize” the surface of the UHMWPE composite. It consists of a relatively simple three-step process to modify the surface of UHMWPE sheets in order to create reactive polymer chains that are able to form covalent bonds with an epoxy layer during a one-step compression molding process. Contact angle measurements performed on treated specimens show a hydrophilic behaviour necessary to form strong bonds with an epoxy matrix. However, results obtained have shown lower than expected properties. Some polymer matrix degradation during treatment may explain those results. Further work would be necessary to determine the exact cause of the observed results. Adhesive films not requiring surface modification were also selected and used in the cofab approach. The work demonstrated that a significant increase in flexural strength is achieved by reinforcing the UHMWPE composite with carbon/epoxy laminates. Observation of the failure surfaces of specimens prepared with film adhesives show UHMWPE substrate (cohesive) failure. This indicates strong adhesion between the UHMWPE composite and the carbon/epoxy composite.

Proper adhesive selection and surface treatment are key in postfab approaches. Investigations have shown that proper epoxy adhesive selection with open-air plasma surface treatment leads to cohesive failure of the UHMWPE substrate rather than delamination at the interface between the reinforcing ply and the UHMWPE core of the ballistic laminate. This paves the way for stiffening strategies based on postfab approaches (see Figure 31).

Figure 31: Peel tests showing failure within UHMWPE

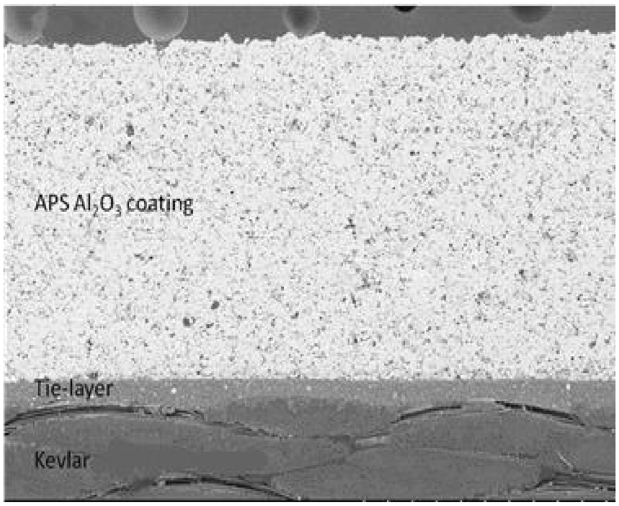

Figure 32: Cross-section showing the millimetre thick ceramic coating deposited onto a Kevlar®-based polymer composite

A strategy to improve the ballistic performance of composite armours is to use a layered approach, which puts a layer of a hard material on the strike face. The assumption is that the hard layer will disperse projectile impact energy and diminish penetration. A technology to spray Al_2O_3 coatings onto polymer composites was developed at NRC and using this concept for armour applications was tested on an aramid-based composite (see Figure 32). Structural characterization of the produced Al_2O_3 coatings showed a mixture of γ and α crystalline and amorphous phase. Depending on the spray conditions employed, densities of free-standing coatings were estimated at 2.8-3 g/cm^3, thus representing 72-77% of the density of a bulk alumina. Hardness of the as-sprayed coatings, evaluated via micro-hardness testing at 300 gf was also estimated to be around 47-57% of the hardness value reported for an armour-grade bulk Al_2O_3. For 17-grain fragment simulating projectiles, the ceramic coatings did not seem to bring an additional contribution to the penetration resistance. One way to improve this aspect would be to alternate ceramic and ductile (metallic) layers and thus the nature of their built-in residual stresses (tension and compression). This technology has a fairly low TRL (~ 2-3).

The joining/integration technologies described above have the potential to mitigate some of the drawbacks associated with the poor stiffness of UHMWPE composites. UV treatment did not lead to expected improvements in joint strength. Because of treatment duration and the poor results obtained, UV treatment does not seem to be a viable option from a manufacturing standpoint. However film adhesives and some epoxy-based adhesives with proper surface treatment (atmospheric plasma spray) have proven their efficacy for joining reinforcing layers (either aramid/epoxy or carbon/epoxy) to the UHMWPE substrate and they should be retained for future work on UHMWPE stiffening. Cofab approaches may make more sense from a manufacturing standpoint, although postfab approaches remain valid for certain geometries. With the joining technologies in hand, UHMWPE stiffening strategies should be further explored and development pushed towards PPE-relevant geometries. Of key importance would be the generation of performance data, both ballistic and mechanical (static, blunt impact, fatigue, aging effects).

Depositing hard coatings, such as alumina, onto polymer composites is an innovative way to improve the ballistic performance of PPE components and is an emerging R&D field. Early attempts have proven not to be as promising as expected, in part due to the crystalline nature of alumina generated with the thermal spray coating process and layer not being fully dense. As a result, work needs to be carried out to improve density and hardness. The layered hard surface concept generating favorable residual stresses may be worth exploring. However, with the density of the ceramic layer being approximately four times higher than the composite substrate, the improvement in performance would have to be significant to offset the added weight. Future work should focus at first on identifying the challenges ahead and on generating data to more thoroughly assess the potential of this technology. It should also focus on finding the best possible applications should it be used as a thermal barrier to provide heat resistance to armour systems instead of improving the ballistic performance.

Coatings

Thermoplastics such as polycarbonate are currently used as a component of transparent armour in both vehicles and PPE. There are three key conditions that must be considered. Thermoplastics can be easily scratched or abraded by simply wiping away dust or dirt. Moisture readily condenses onto the surface in low temperatures or humid environments and impedes visibility. Lastly, polycarbonate-based armour does not provide UV protection to personnel or to prevent material degradation. As a result, various thin film coatings are applied to improve abrasion resistance, hydrophilicity (to eliminate fogging), and ultra-violet protection.

Current state-of-the-art coating technologies, however, have limitations: they degrade too quickly, cracking and delaminating from the polycarbonate. BNNTs are an excellent candidate as a new additive as they have excellent mechanical properties, a high aspect ratio, and are optically transparent in the visible region. Multiple issues can be resolved simultaneously by developing an anti-fog hard coating using BNNTs. By improving the abrasion resistance of current commercial coatings used on thermoplastic equipment with BNNTs, increased equipment lifespan will be realized not just for transparent armour but also within the automotive and aerospace sectors. Enhancing and altering the hydrophobicity, and thereby the anti-fog properties of transparent armour such as windows and eye protection (i.e., goggles, masks and visors), will result in less employee fatigue and increased productivity—users will have a clear field of view for a longer period of time and will not need to stop work to clean or change equipment. BNNT anti-fog coatings technology will not only benefit PPE for security applications but also in sports apparel where, for example, required eye protection routinely fogs goggles during underwater activities.

NRC's expertise in manufacturing and processing nanotube materials, combined with its experience in incorporating nanomaterials into polymer matrices for various applications, uniquely positions the organization to develop BNNT coatings. Development of BNNT coating technologies is currently at the early stages (TRL~ 1-4) at NRC. The key development challenge with BNNTs is the way they assemble together to form large aggregates, commonly referred to as bundles, which scatter light and inhibit uniform distribution of BNNT within a polymer coating. Chemical functionalization of the BNNT surface is critical to de-bundle BNNTs in order to improve their ability to be processed and minimize light scattering.

There are two key methods by which BNNTs are functionalized: covalent or non-covalent. There has been a lack of focus towards the development of BNNT coatings pending further development of chemical functionalization methodologies and the establishment of a steady supply of consistent BNNT material. To date, covalent functionalized BNNTs produce white opaque solutions unless at very dilute concentrations due to the BNNT remaining partially bundled. Non-covalent functionalized BNNTs, on the other hand, typically produces coloured transparent solutions. The visible colour is a result of the conjugated molecules used to functionalize BNNTs and their interaction with the BNNT surface. Preliminary work incorporating BNNT into a polymer matrix has not been successful due to the aforementioned bundling and from the processed BNNT material separating within the coating matrix.

While there are challenges in developing the necessary BNNT chemistry, cost should not be a limiting factor with this technology. A BNNT coating should be readily interchanged with the current commercial systems.

A 2012 report produced by the U.S. National Research Council on opportunities in protection materials science and technology for future army operations stressed the long-term importance of lightweight materials. It discussed the role of simulation, modelling, and ballistic evaluation coupled with materials research. Characterizations, microstructures, behaviours and deformation/penetration mechanisms were topics of particular research interest. Computational materials engineering (e.g., of ceramic plates or advanced polymers, bringing them to an improved state of performance and speeding the time to market) was also stressed. Basic and applied research was recommended in areas such as:

- *Creation of a database of high strain-rate materials;*
- *Opaque and transparent ceramics and ceramic powders;*
- *Polymeric, carbon, glass and ceramic fibres;*
- *Polymers as matrices (improved performance and measurement for deformation mechanisms);*
- *Magnesium alloys (low density, high strength);*
- *Other composite armour improvements based on metal alloys and nanomaterials (the latter usually based on carbon fibres);*
- *Adhesives and active brazing/soldering materials;*
- *Improved test methods and material characterization;*
- *Cost reductions and improved small-lot manufacturing capability; and*
- *Intelligent manufacturing (i.e., with improved sensing, controls, and analytics, and systems-engineered.*

Prioritized Research Areas

Given the technical challenges identified at the workshop, the following areas of research are currently being explored:

Reduced Weight and Increased Performance

- Replacement of metal components with cermet materials, composites or polymers
- Improved materials through use of nano-structuring and nanomaterials
- Biomimetic design
- Very thin anti-fog, anti-scratch coatings for transparent armour
- Ultra-hard, thin coatings for polymers and composites
- Structural optimization including shape optimization of strike face and elimination of welds and joints through single piece composites
- Materials integration – reduced design space for multilayers

Reduce Cost

- Non-destructive evaluation to utilize full performance of new and existing materials and armour systems
- Improved modelling and simulation tools for armour performance
- Improved modelling and simulation of manufacturing processes
- Substitute high cost, high performance materials with nano-enhanced lower cost materials
- Improve use of automation and robotics in manufacturing processes

Improved/Enabled Integration

- Leverage modelling and characterization to enable assessment of opportunities for multilayer structures allowing for multilayers in an integrated structure
- Leverage ability of polymers to be formed into complex shapes to replace multiple components

Quantification and Design for Multi-threat

- Leverage materials characterization in the development of a materials database

Resources

The following resources have been identified in the development of this report and at the SMTRM workshop hosted in November 2015. The list is not exhaustive and will be amended over time with the input of stakeholders from the user, industry, and research communities.

Build in Canada Innovation Program

Created to bolster innovation in Canada's business sector, the Build in Canada Innovation Program helps companies to bridge the pre-commercialization gap by procuring and testing late stage innovative goods and services within the federal government before taking them to market by:

- Awarding contracts to entrepreneurs with pre-commercial innovations through an open, transparent, competitive and fair procurement process.
- Testing and providing feedback to these entrepreneurs on the performance of their goods or services.
- Providing innovators with the opportunity to enter the marketplace with a successful application of their new goods and services.
- Providing information on how to do business with the Government of Canada.

Natural Sciences and Engineering Research Council

Natural Sciences and Engineering Research Council (NSERC) makes investments in people, discovery, and innovation to increase Canada's scientific and technological capabilities for the benefit of all Canadians. NSERC invests in people by supporting postsecondary students and postdoctoral fellows in their advanced studies. NSERC promotes discovery by funding research conducted by postsecondary professors and foster innovation by encouraging Canadian companies to participate and invest in postsecondary research and training.

CanmetCERL

CanmetCERL (Canadian Explosives Research Laboratory), within the Explosives Safety and Security Branch of the Minerals and Metals Sector at Natural Resources Canada is the only Canadian government laboratory dealing with commercial explosives, and one of the few in the world.

Our work at CanmetCERL is diverse, with many different applications, from testing whether a product is fit for use to reducing the effects of accidental or terrorist blasts. CanmetCERL offers client services in two broad areas: Explosives Analysis, and Explosives Safety and Security Technology.

NRC Automotive and Surface Transportation

Building on Canada's excellent reputation for turning research into innovative solutions, NRC Automotive and Surface Transportation can help industry take ideas from concept to commercialization. With a proven track record, unmatched research, development and demonstration capabilities and access to innovation support. NRC is a valued contributor to the automotive and surface transportation sector including: passenger vehicles, heavy-haul and light rail, heavy-duty trucking fleets, specialized military vehicles, and first response vehicles.

Scientific Research and Experimental Development Program

The Scientific Research and Experimental Development (SR&ED) Program is a federal tax incentive program designed to encourage Canadian businesses of all sizes and in all sectors to conduct research and development (R&D) in Canada. The program is administered by the Canada Revenue Agency (CRA), which delivers SR&ED tax incentives in a timely, consistent and predictable manner, while encouraging businesses to prepare their claims in compliance with Canada's tax laws and the CRA's policies and procedures.

UBC Composites Research Network

The University of British Columbia's (UBC) Composites Research Network (CRN) is a collaboration of academia and industry partners supporting the composites industry in Western Canada and beyond. It was launched in January 2012 with a $9.8 million investment from Western Economic Diversification Canada. CRN's mission is to create knowledge in practice documents that enable effective and low-risk knowledge-based composites manufacturing and design. CRN has its hub at UBC in Vancouver and other nodes located across Western Canada.

NRC Industrial Research Assistance Program

For over 70 years, the National Research Council of Canada Industrial Research Assistance Program (NRC-IRAP) has been stimulating wealth creation for Canada through technological innovation. This is largely accomplished by providing technology assistance to small and medium-sized enterprises at all stages of the innovation process, to build their innovation capacity. NRC-IRAP helps small and medium-sized enterprises understand the technology issues and opportunities and provides linkages to the best expertise in Canada.

Strategic Aerospace and Defence Initiative

The Strategic Aerospace and Defence Initiative (SADI) was launched in 2007. It provides repayable contributions to support research and development (R&D) projects in the aerospace, space, defence and security (A&D) sectors. SADI is available to firms of all sizes to support product, service or process innovation.

SADI has three objectives:

- to encourage strategic R&D that will result in innovation and excellence in new or improved products, services and processes;
- to enhance the competitiveness of Canadian A&D companies; and
- to foster collaboration between research institutes, universities, colleges and the private sector.

MITACS

MITACS is a national, not-for-profit organization that has designed and delivered research and training programs in Canada for 15 years. Working with 60 universities, thousands of companies, and both federal and provincial governments, we build partnerships that support industrial and social innovation in Canada.

Recommendations

The SMTRM has been instrumental in re-positioning the scientific arm of the Government of Canada and industry in a way that will allow Canada to be more competitive in global markets by collaborating across sectors. The success of the initial phase of the process has resulted in a roadmap that will guide both the private and public sectors in the development and application of security materials.

With this framework established, success in the next phase of the roadmapping process will depend on the shared spirit of collaboration, innovation, and competitiveness across all affected stakeholders in Canada. The focus going forward must therefore be on implementing projects that encourage this outcome.

Appendix A: Steering Committee Members

Main role: provide guidance to the SMT Roadmap initiative to ensure it is aligned well to industry needs

Members:

- **Co-chair**: CADSI, NRC SMT program lead
- **Core member:** Representatives from Canadian industry
- **Associate member:** Government representatives
- **Observer:** Other government departments and academia reps
- **Support member:** SMTRM program management office staff

Name	Title	Organization	Role
Andrew Johnston	Program Leader, Security Materials Technologies program	National Research Council	Co-chair
Janet Thorsteinson (repl.) Nicolas Todd	VP, Government Relations Associate VP, Policy, Communications and Government Relations	CADSI	Co-chair
Jean-Philippe Dionne	Director, Research Engineering	Med-Eng	Core member
James Kempston	Business Development Director – North America and Asia Pacific	Morgan Advanced Materials Composites and Defence Systems	Core member
Steve Carkner	Research/Development/ Engineering Integrated Systems Business Unit	Revision Military Inc.	Core member
Maj. General David Fraser	David Fraser: Board Director	INKAS	Core member
Alain Bujold	President	Mawashi Protective Clothing Inc.	Core member
Fabio DeWitt	Senior Director, Armour	DEW Engineering and Development ULC	Core member
Jérôme Pollak	Director, Business Development	Tekna	Core member
Scott McClennan (repl.) Dustin Pearson	Senior Research Engineer Structural Specialist, Applied Technology Group	Lloyd's Register Martec	Core member
Alberto Da Rocha	Research & Development Survivability Engineer	Armatec Survivability Corp	Core member
John Spray	President	HIT Dynamics Ltd	Core member
Bradley Field	President	PRE Labs Inc.	Core member
Kevin Williams	Defence Scientist, Weapons Effects and Protection Section	Defence Research and Development Canada	Associate member
Andrew Plater	Program Leader, Land Combat	Defence Research and	Associate member

	Systems Program	Development Canada	
Perry Mangione	Portfolio Business Advisor	National Research Council	Associate member
John Preston-Thomas	Thrust Leader, SMT program	National Research Council	Associate member
Sylvain Labonté	Thrust Leader, SMT program	National Research Council	Associate member
Benoit Simard	Thrust Leader, SMT program	National Research Council	Observer
Christopher Kingston	Thrust Leader, SMT program	National Research Council	Observer
Hugo Lalonde	Manager, Wheeled Light Armoured Vehicle Projects and Support	Public Works and Government Services Canada	Observer
Mathieu Poirier	Supply Specialist, Defence and Major Projects Sector	Public Works and Government Services Canada	Observer
Marc McArthur	Innovations Networks Advisor	National Research Council	Support member
Alan Bolster	Client Relationship Leader	National Research Council	Support member

Back row: Nicolas Todd, James Kempston, Alain Bujold, Andrew Johnston, Kevin Williams, Alan Bolster, Dustin Pearson, Christopher Kingston

Front row: Brad Field, Jean-Philippe Dionne, Jérôme Pollak, Marc McArthur

Photo credit: National Research Council Canada

Appendix B: SMTRM Workshop Program

Workshop **Agenda**

Day one: Monday, November 23

Location: Auditorium

OPENING REMARKS 11:00 – 11:10

Duncan Stewart, General Manager, Security and Disruptive Technologies, National Research Council Canada (NRC)
Janet Thorsteinson, Vice President, Government Relations, Canadian Association of Defence and Security Industries (CADSI)

Presentation of workshop program: goals and process 11:10 – 11:25

Master of Ceremonies

Future land operating environment and Canadian Army hard problem list 11:25 – 11:45

LCol R. Bell, Concepts 3, Canadian Army Land Warfare Centre

Emerging Weapon Capabilities and Proliferation 11:45 – 12:05

Maj Brian Corbett, Directorate Scientific and Technical Intelligence, Canadian Forces Intelligence Command

LUNCH 12:05 – 13:00

PHASE I: Setting the stage 13:00 – 14:20

Cafeteria

PERSONAL PROTECTIVE EQUIPMENT

Department of National Defence (DND) and Canadian Armed Forces (CAF) future soldier protection requirements 13:00 – 13:30

Maj. Edward Jun, Director Land Requirements 5 – Soldiers Sytems, Department of National Defence

Law enforcement future personal ballistic protection requirements 13:30– 13:55

Sgt. Dave Radu, National Emergency Response Team Coordinator, Royal Canadian Mounted Police

Protective material system science and technology (S&T) challenges posed by Army soldier system requirements 13:55 – 14:20

Kevin Williams, Defence Scientist, Defence Research and Development Canada

Library

VEHICLE ARMOUR

Department of National Defence (DND) and Canadian Armed Forces (CAF) future vehicle armour requirements 13:00 – 13:25

Maj. Mark McNeil, Director Land Requirements 3, Department of National Defence

Mobility, Protection, and Firepower and the Future of Mounted Warfare 13:25– 13:40

Ted Maciuba, Deputy Director, Mounted Requirements, US Army Maneuver Center of Excellence

Law enforcement future vehicle protection requirements 13:40 – 14:00

Jean-Philippe Ethier, Royal Canadian Mounted Police

Protective material system science and technology (S&T) challenges posed by Army vehicle requirements 14:00 – 14:20

Alexandra Sirois, Defence Scientist, Defence Research and Development Canada

HEALTH BREAK 14:20 – 14:50

PHASE II: Identifying the science and technology challenges related to security materials 14:50 – 17:00

Location: Cafeteria PERSONAL PROTECTIVE EQUIPMENT	Location: Library VEHICLE ARMOUR
Facilitated discussions – Develop/validate vision statement, goals and drivers 14:50 – 15:25 Round tables, Led by facilitator	**Facilitated discussions – Develop/validate vision statement, goals and drivers** 14:50 – 15:25 Round tables, Led by facilitator
Facilitated discussions – Identify science and technology challenges 15:25 – 16:25 Round tables, Led by facilitator	**Facilitated discussions – Identify science and technology challenges** 15:25 – 16:25 Round tables, Led by facilitator
Recap from day 1 and set the stage for day 2 16:25 – 17:00 Facilitator	**Recap from day 1 and set the stage for day 2** 16:25 – 17:00 Facilitator

Day two: Tuesday, November 24

PHASE III: Identifying technology solutions and barriers 8:15 – 12:00

Cafeteria PERSONAL PROTECTIVE EQUIPMENT	Library VEHICLE ARMOUR
Welcoming and Recap from Day 1 8:15 – 8:30 Facilitator	**Welcoming and Recap from Day 1** 8:15 – 8:30 Facilitator
Security materials: PPE integration issues 8:30 – 8:50 **Jean-Philippe Dionne,** Director, Research Engineering, MED-ENG	**Security materials: Vehicle Armour integration issues** 8:30 – 8:50 **Karl Pfister,** President and CEO, Armatec Survivability
Challenges on structural sides of laminates 8:50 – 9:10 **David Boucher-Trudel,** Research Officer, Advanced Polymer Composites, NRC	**State-of-the-art review of technologies for transparent armour** 8:50 – 9:10 **Alexandra Sirois,** Defence Scientist, Defence Research and Development Canada
Critical review of the role that ceramics play as armour material 9:10 – 9:30 **Vladimir Krstic,** President, Functional Materials Manufacturing, Inc.	**Hybrid Composite Armor Materials R & D at Natural Resources Canada** 9:10 – 9:30 **Jason Lo,** Program Manager and Principal Scientist, Defence and Emerging Materials Program (CanmetMATERIALS), Natural Resources Canada
State-of-the-art review of technologies for composite materials and soft armour 9:30 – 9:50 **Chris Fitzgerald,** Sales Manager, DSM Dyneema	**Steels and metallic composite** 9:30 – 9:50 **Eddie Terrenzi,** Regional Manager, North America, SSAB Americas
State-of-the-art review of technologies for hard armour products 9:50 – 10:10 **Arnold Wong,** Business Manager, Advanced Material Division, 3-M Ceradyne **Annie Villeneuve,** Project Leader, Ceramic systems, 3-M Ceradyne	**Applications of nanotechnology in security materials** 9:50 – 10:10 **Michael Jakubinek,** Research Officer, Nanocomposites Group, NRC

Day two: Tuesday, November 24 (continued)

HEALTH BREAK 10:10 – 10:25

Location: Cafeteria

PERSONAL PROTECTIVE EQUIPMENT

State-of-the-art review of technologies for transparent armour (visor) 10:25 – 10:45

Vlad Lucuta, Director, Armor Technology, Revision Military, Ltd.

Applications of nanotechnology in security materials 10:45 – 11:05

Christopher Kingston, Research Officer, Nanocomposites Group, NRC

Facilitated discussions - Connect potential technology solutions with Phases I & II – Identify and prioritize R&D areas 11:05 – 12:00

Led by facilitator

Location: Library

VEHICLE ARMOUR

Challenges and opportunities for ballistic composite laminates 10:25 – 10:45

David Boucher-Trudel, Research Officer, Advanced Polymer Composites, NRC

Critical review of the role that ceramics play as armour material 10:45 – 11:05

Vladimir Krstic, President, Functional Materials Manufacturing, Inc.

Facilitated discussions - Connect potential technology solutions with Phases I & II – Identify and prioritize R&D areas 11:05 – 12:00

Led by facilitator

LUNCH 12:00 – 13:00

Auditorium

PHASE IV: Defining the action plan 13:00 – 16:45

Leveraging The Canadian Security Materials Innovation Eco-System 13:00 – 13:30

Andrew Johnston, Program Leader, Security Materials Technologies, NRC

Proposed SMT R&D projects funding models & key funding opportunities for Canadian industry/academia 13:30 – 14:15

Pierre Vallée, Innovation Advisor, Concierge Service, NRC

HEALTH BREAK 14:15 – 14:30

Cafeteria

PERSONAL PROTECTIVE EQUIPMENT

Facilitated discussions – Define actual R&D projects (quad-charts) 14:30 – 15:45

Led by facilitator

Library

VEHICLE ARMOUR

Facilitated discussions – Define actual R&D projects (quad-charts) 14:30 – 15:45

Led by facilitator

Auditorium

United States Army International Technology Center – Canada 101 15:45 – 16:10

Robert C. Murray, LTC, LG, US Army International Technology Center Canada

Joint R&D team in a competitive environment 16:10 – 16:20

Karl Pfister, President and CEO, Armatec Survivability

Summary of outcomes from the workshops and next steps 16:20 – 16:45

Master of Ceremonies

Closing remarks 16:45 – 17:00

Duncan Stewart, General Manager, Security and Disruptive Technologies, NRC

NETWORKING 17:00 – 18:00

Appendix C: Access to presentations on ICEE

To access presentations from the Security Materials Technologies Roadmap workshop, please follow the instructions below.

1. Go to Industry Canada registration page to sign up for a username: https://www.ic.gc.ca/cgi-bin/allsites/registration-inscription/update.cgi?screen=3

2. Once you have registered for a username, log in to the ICEE platform. https://www.ic.gc.ca/app/scr/pssb/sstrm-crtss/icee-eeci.pub?lang=eng

3. Create an ICEE user profile. This will take 10 to 15 minutes.
   You will be asked some questions and to provide the name of a reference to confirm your identity. Please advise your reference that he or she will receive an email asking for confirmation of your identity.

4. Once your ICEE user profile is created, (it usually takes about 24 hours) you can start to take advantage of the ICEE platform.

Reminder: Bookmark the Login page and record your username and password.

Note: Not all presentations could be made available outside of the workshop setting.

Appendix D: Glossary of Terms

A&D	Aerospace, space, defence and security
AV	Armoured Vehicle
BNNT	Boron Nitride Nanotube
CADSI	Canadian Association of Defence and Security Industries
CAF	Canadian Armed Forces
CanmetCERL	Canadian Explosives Research Laboratory
CE	Chemical Energy
CNT	Carbon Nanotube
CRA	Canada Revenue Agency
CRIAQ	Consortium for Research and Innovation in Aerospace in Québec
CRN	Composites Research Network
CS	Cold-Spray
DARPA	Defense Advanced Research Projects Agency
DND	Department of National Defence
DOD	US Department of Defense
DRDC	Defence Research and Development Canada
EFP	Explosively Formed Projectile
EOD	Explosive Ordnance Disposal
HVOF	High Velocity Oxygen Fluid
IED	Improvised Explosive Device
KE	Kinetic Energy
NATO	North Atlantic Treaty Organization
NDE	Non-destructive Evaluation
NDI	Non-destructive Inspection
NDT	Non-destructive Testing
NRC	National Research Council of Canada
NRC-IRAP	National Research Council of Canada Industrial Research Assistance Program

NSERC	Natural Sciences and Engineering Research Council
PC	Polycarbonate
PMC	Polymer-Matrix Composite
PMMA	Poly (methyl methacrylate)
PPE	Personal Protective Equipment
R&D	Research and Development
RHA	Rolled Homogenous Armour
S&T	Science and Technology
SADI	Strategic Aerospace and Defence Initiative
SHM	Structural Health Monitoring
SHPB	Split Hopkinson Pressure Bar
SMT	Security Materials Technologies
SMTRM	Security Materials Technologies Roadmap
SR&ED	Scientific Research and Experimental Development
TRL	Technology Readiness Level
UBC	University of British Columbia
UHMWPE	Ultra-high-molecular-weight-polyethylene
UOR	Urgent Operational Requirement
UV	Ultra-violet
VA	Vehicle Armour
VBIED	Vehicle-borne Improvised Explosive Device
VIP	Very Important Person

Appendix E: References

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