Fragment Characterisation & Threat Modelling - A Multinational Study to Re-Define & Represent the Fragment Threat

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Abstract. The Technical Co-operation Panel (TTCP) Land Group (LND) is a multinational defence science and technology collaboration between the governments of Australia, Canada, New Zealand, United Kingdom and United States. Under the auspices of this organisation, a study group was convened to focus on personnel protection and vulnerability. During recent conflicts in Iraq and Afghanistan, this group highlighted the need to gather relevant evidence of the nature of fragmenting threats injuring military personnel and document the relevant test methods. Use of evidence to define protection standards based upon the wrong threat risked providing the wrong level of protection performance: insufficient protection (underestimation of the 'threat') could result in injury but too much protection (overestimation of the 'threat') could result in burden. In the worst case, overestimation of the threat could result in no mitigation being developed if it were thought no practical solution achievable. Experience generated under TTCP LND Technical Panel 5 (TP-5) brought together a community that could challenge legacy beliefs of the fragment threat and protection requirements using updated evidence. Fragment collection and analysis methods were documented for each nation: fragment origin, preparation, examination, classification and attribution methods. A comparative analysis of the fragment collections from some of the nations was conducted. This provided a summary of the content of the fragment collections for use in setting equipment protection or mitigation standards. A record and assessment of fragment threat simulation methods and equipment was made. Some of the models used to assess and communicate the injurious potential of various threats were reported. The work of the panel led to improved understanding of the fragment threat and evidence gathering capabilities for characterising future fragment threats. This provides some commonality between TTCP nations in the analysis, testing and assessment of fragment threats, as well as ensuring that lessons learnt from recent operations are not lost.

1. INTRODUCTION

1.1 Data Content Caveat

In conducting this study, the team has accessed sensitive personal information. The study has complied with all TTCP and national policies in the handling and use of this information in order to preserve anonymity of personnel undergoing treatment or monitoring. In complying with national policies, some information has been removed from the paper in order to allow for its public release.

1.2 Overview

Under the auspices of The Technical Cooperation Program (TTCP) [1], a study assignment involving five cooperating nations was convened to collate evidence and test methods relevant to fragment injury. The project was undertaken to record the lessons identified, the procedures used, the information gathered and the state-of-the-art for fragment threat characterisation for TTCP nations who had been involved in combat operations in Iraq and Afghanistan.

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1.3 Requirement

The study team highlighted the need to gather relevant and up to date evidence of the nature of the fragmenting threats injuring military personnel. This was to ensure that protection strategies are based on current and appropriate assessment of the fragmenting threat, reducing the risk of over or under protecting personnel. The expertise within the panel made this possible and there was an ethical imperative to secure this knowledge for the future.

Whilst the study was conducted with the aim of providing a common understanding and some degree of commonality between the TTCP nations in the analysis, testing and assessment of fragment threats, the aim was not to produce a prescriptive standard. Many instances of national differences were reported.

2. FRAGMENT COLLECTION AND ANALYSIS METHODS

2.1 General

Methods used to collect and characterise fragments from various military operational threats were documented, allowing anyone in the future to reproduce the techniques if the national capabilities become dormant or lost.

2.2 Fragment Collection Methods

Opportunities for collecting fragments were identified as being:

- From the site of the incident (e.g. vehicle, surrounding environment) - by post incident investigators;
- Retained within Personal Protective Equipment (PPE) - extracted by trained PPE analysis teams, predominantly within home-nation laboratories;
- Retained within body tissues - commonly removed by medical personnel during treatment; or
- Removed during service police investigations – removed by the investigators.

Collected fragments were placed in a suitable container and labelled, to ensure each could be linked to the incident from which it was recovered.

There were a number of challenges associated with fragment collection, not least the medical, legal and ethical imperatives related to handling *sub-judice* information and preserving anonymity of personnel undergoing treatment or monitoring.

Immediately after an incident, the focus of personnel varied depending on their role. Those responsible for providing casualty treatment or recovering equipment were often not aware of the potential benefit of collecting and retaining any fragments. Additionally, those who survived a bullet or fragment impact were keen to keep the item as a souvenir. Therefore, one of the key elements to the success of the fragment gathering was the ongoing process of educating the stream of deployed people who may be involved in any element of the process, so that they understood the importance of data gathering in shaping future protection requirements.

2.3 Fragment Characterisation Methods

The key fragment characterisation methods were determination of mass, material composition, size, shape, velocity and estimation of source. The fidelity and complexity of measurement varied between nations, due to resources and capability.

Fragment mass was a key parameter due to the ease of measurement and ability to produce a profile of the fragments collected by mass (Figure 1). Mass was also related to existing Fragment Simulating Projectiles (FSPs) to enable determination of the relevance of surrogates. Due to variations in fragment materials, size and shape, mass was the only consistent parameter between the FSPs and collected fragments.

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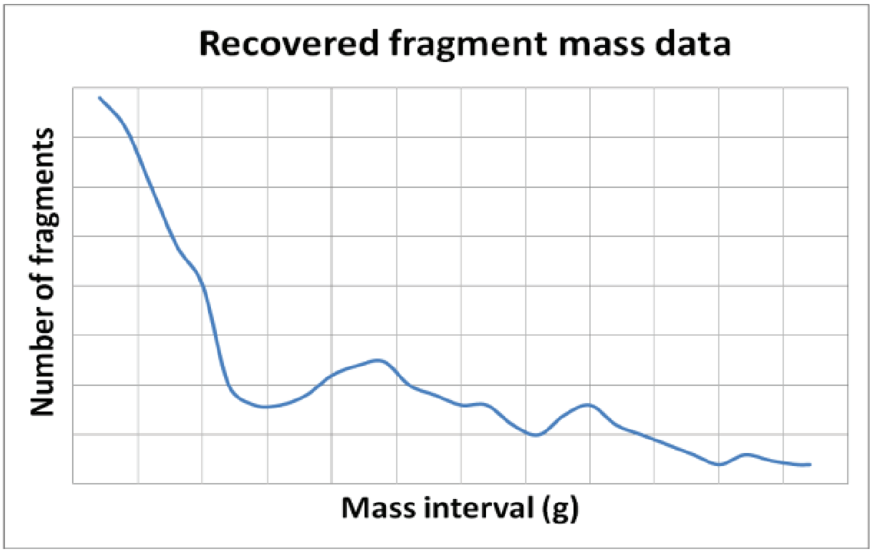

Figure 1. Example of a fragment mass profile based on fragment collections associated with a specific threat. Image © Crown Copyright Dstl

Simple determination of fragment material composition was achieved by visual investigation and by using a magnet. In some nations, qualitative elemental composition was determined using systems such as Scanning Electron Microscopy (SEM) with Energy Dispersive X-ray Spectroscopy (EDS). Detailed metallurgical analysis was achieved for some nations using inductively coupled plasma atomic emission spectrometry (ICP-AES).

The medical community was interested in fragment composition from the perspective of the long-term toxicological implications of any implanted material, which may remain in the tissues of the casualty. Material composition also supported identification of the origin of the fragment and understanding of the threat. Information was also used to determine whether existing FSPs accurately represented the operational threats.

The source of the fragment was determined by subject matter expertise; if the fragment was determined as a part of a component of the threat itself it was classified as a primary fragment. Secondary fragmentation was defined as those fragments that had been energised from the surrounding environment such as from soil, buildings, etc.. It was important to identify the source of the fragment to understand the nature of the threat and its employment. Size was documented for all fragments due to the ease of measurement. This was used in conjunction with weight to understand the distribution of fragments produced by specific threats or to correlate to a known threat type.

A basic level of shape assessment was obtained from size measurements and photographs; detailed investigation of fragment shapes was achieved using 3D scanning, particularly in Canada and the US. This preserved the geometry of a fragment when evidence needed to be returned back to the originating organisation; additionally, shape factor is useful for follow-on vulnerability analysis.

In some cases and nations, fragment velocity was estimated by reverse engineering the outcome: either by using experimental data combined into a look up table to correlate fragment masses, impact velocities and Depths Of Penetration (DOP), or by using numerical injury models, e.g. the Operational Requirement-based Casualty Assessment (ORCA) model developed and maintained by the US Army Research Laboratory. Estimation of fragment velocity provided a further insight into the fragmentation produced by a specific threat and was used to inform Personal Protective Equipment (PPE) testing and protection requirements. In this case, numerous simulations were run, recording depth of penetration for different fragment masses at different velocities, in order to predict the velocity required to achieve a given injury or DOP. An example of this is the prediction of the fragment velocity needed to penetrate different depths into a forearm, shown in Figure 2.

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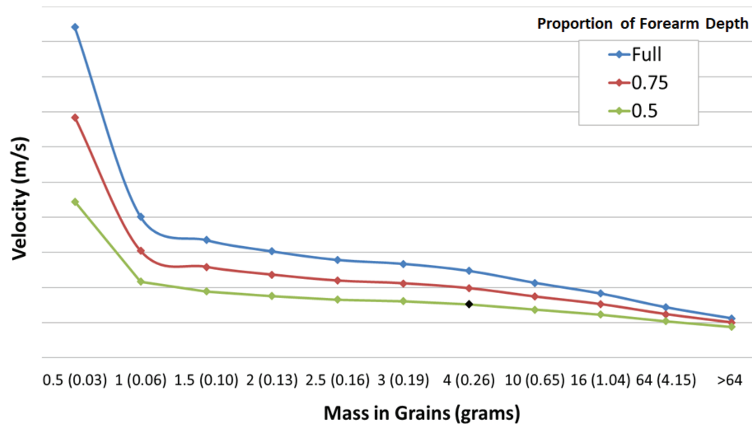

Figure 2. Velocity estimates for fragments recovered from the upper extremity. Outputs from the ORCA model relating to the velocities estimated for different fragment masses to cause different levels of penetration of the forearm
Image © Army Research Laboratory

2.4 Summary

Fragment analysis methods undertaken by TTCP nations varied, due to national capabilities and resources. Fragment threat, mass, size and PPE or tissue location are the four fields of information collected across all of the nations. These are the four easiest measurements to conduct and require minimal resources. The key aspect to success of these methods is documentation of the collection of the fragment, including linkages to the incident to aid determination of the threat.

3. NATIONAL FRAGMENT COLLECTION RESULTS

3.1 Analysis Results

The analysis included the following:

- Number of fragments recovered by each country for each year of conflict;
- Evidence distribution between event types (mounted, dismounted) and threat origins, .e.g. Small Arms Fire (SAF), Improvised Explosive Device (IED), mortar, Rocket-Propelled Grenade (RPG), artillery, grenade and rocket;
- Composition of non-metallic evidence for mounted and dismounted events;
- Primary composition of metallic evidence;
- Mass distribution of metallic evidence – plotted as a cumulative sum of the log fragment mass, to enable the reader to easily extract mass percentiles – also by recovery location & composition;
- Comparison of recovery locations (on the body) of metallic evidence.

3.2 Conclusions and recommendations

Differences in the practices for collection of combat evidence between countries were a limiting factor in some aspects of the analysis, in-particular, that of mass and recovery location.

Recommendations were made as to data fields that should be included in any future analysis.

Mandatory fields included:

- Date (dd/mm/yyyy);
- Unique identifier,
- Mass (g);
- Metallic (Y/N);
- Principal material;
- Other materials;
- Recovery location (body/armour/clothing/vehicle/helmet/other);
- Threat class;

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- Status (mounted/dismounted);
- Abbreviated Injury Scale (AIS) body region (1/2/3/4/5/6/7/8).

Optional fields included:

- Source (device/Behind Armour Debris/environment/soldier's equipment),
- Whether armour was worn (yes–missed armour/yes–armour defeated/yes–fragment stopped/no);
- Size/shape of fragment;
- Threat direction (from above / below / front / back / side).

4. FRAGMENT TEST/REPLICATION METHODS

4.1 Overview

A record was made of the various methods that have been used to simulate fragment projection. A selection of key apparatus and methods are described here and their pros and cons summarised. Categories covered are:

- Buried charge assessments;
- Propelled fragments (metallic and non-metallic FSPs);
- Sand Cannon usage (multiple non-metallic fragments).

4.2 Buried Charge Assessments

Three of the TTCP nations have conducted buried charge assessments in the context of PPE testing:

- Starting in 2014, Canada developed a suite of operationally-relevant test methodologies for specific personnel protective equipment. Explosive trials were carried out to characterise the severity of buried charge threats and evaluating the performance of PPE and fabrics;
- The UK conducted a trial to assess dismounted survivability and protective material / PPE performance against Afghanistan type buried IEDs;
- US performed controlled blast trials with conventional explosives and Home-Made Explosives (HMEs) to understand the threat to dismounted personnel from victim operated IEDs.

Trials typically examined the influence of explosive composition, charge mass, standoff, setup, soil test pad dimensions, soil type, granulometry, moisture content, density and burial depths. They also investigated a range of models for assessing fragment injury (see section 5).

A typical trial arena setup is shown in the schematic within Figure 3 below.

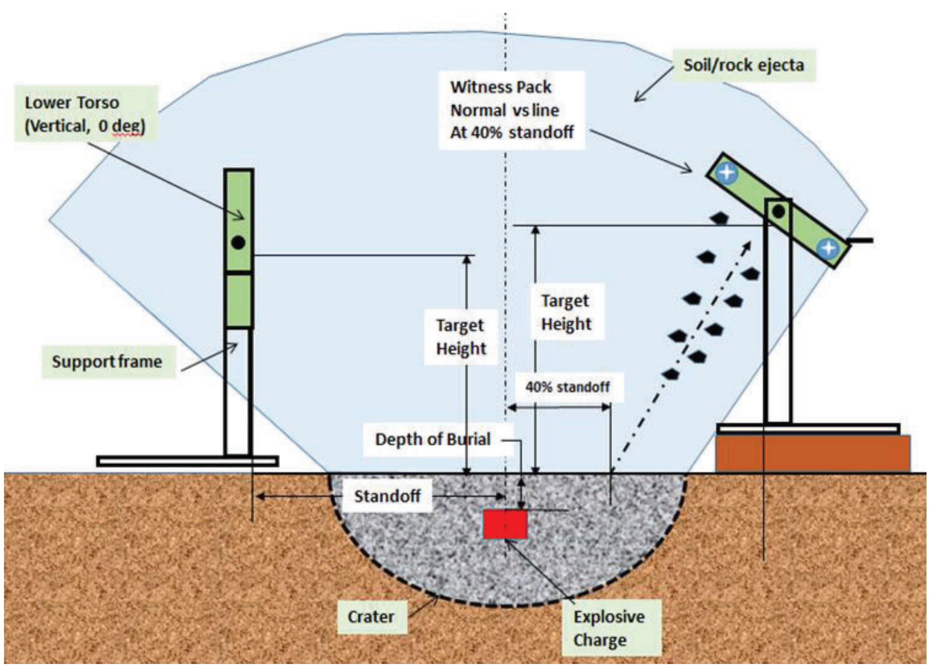

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Figure 3. Schematic of a test set-up prior to detonation.
Image © Defence Research and Development Canada

These trials improved TTCP nations' understanding of the key factors to control to achieve repeatable testing, and how to tailor testing to the type of PPE being assessed. For example, soil conditions must be well characterised and controlled in terms of composition, saturation and compaction. Severity of the insult should be repeatable within a test (i.e. it should be radially symmetrical) as well as between tests in the same soil pads. Some specific outcomes were the ability to rank different blast conditions (moisture, burial depth, charge mass, charge composition); knowledge that blast conditions in such tests may be more severe than those survived in theatre and an understanding of which fragment collection models should be applied for which purposes.

All nations noted the resource-intensive nature of this type of trial; they are cumbersome to run and generate large quantities of data, which slows down the reporting of results. This led to Canada developing a more automated analysis method using Computed Tomography (CT) scanning technique to replace manual dissection of targets, post-test [3].

4.3 Propelled Single Fragments (metallic and non-metallic FSPs)

All TTCP nations have some capability to conduct testing with single propelled fragment surrogates in a laboratory environment using pressure housings driven by compress gas or pyrotechnic propellent.

Typical fragments used for testing by TTCP nations are the 0.16 g and 1.1 g Chisel Nosed (CN) cylinder FSPs from Allied Engineering Publication (AEP) Standardisation Agreement (STANAG) 2920 [2] and 1 to 20 mm diameter spheres of steel, ceramic and glass. Less frequently used are the other FSP masses in AEP 2920, cubes of 2 to 10 mm side length (aluminium, steel and tungsten carbide) and spheres of other materials (aluminium and tungsten carbide). The test capability has evolved over the course of recent conflicts, in response to the type of analysis described in previous sections, to include a greater range of velocities and material types. Other 'non-standard' projectiles include stones, soil and irregular fragments (recovered fragments and glass shards).

Methods for launching fragments have evolved too, with a move from pyrotechnically driven weapons, through use of compressed gas cartridges towards custom-designed systems using laboratory gases. This has enabled a greater range of fragment calibres and velocities to be accommodated simply by being able to substitute barrels and adjust pressure; it has also enabled a reduction in associated legislation (no ammunition) and infrastructure (housed in small enclosures, as opposed to ballistic ranges), which has led to faster turnaround times for testing.

Examples of such systems are the Defence Research and Development Canada (DRDC) single-stage gas gun system, which uses nitrogen and helium gas at pressures up to 414 bar and the UK Sabre ballistics gas gun, pictured (Figure 4). These systems have been used to consistently launch projectiles with masses between 0.004-54 grams at velocities from 0-1600 m/s (not across all fragments). DRDC has also developed a set of custom muzzle extension rods to guide the projectile when exiting the barrel in order to ensure stable flight with minimal yaw up to the target.

Figure 4. An example of a modern gas-gun: the UK Sabre gas gun weapon system fitted with an 800 mm barrel
Image © Crown Copyright Dstl

An innovation to bridge the gap between laboratory consistency and blast arena trials is the new gas gun device currently being commissioned by DRDC. This will be capable of simultaneously

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launching up to seven 0.22 calibre FSPs with shot dispersion depending on the barrel length selected (see Figure 5).

Figure 5. DRDC Simultaneous gas gun.
Image © Defence Research and Development Canada

4.4 Sand Cannon Usage

The purpose of a 'sand cannon' is to allow a laboratory based test to bridge the gap between the simple, repeatable, inexpensive but potentially unrealistic single fragment V_{50} test and the complex, expensive, more realistic buried charge assessment.

Some of the TTCP nations have developed methods for firing multiple fragments in a controlled laboratory environment. An example is the UK sand cannon [4]. It is a 20 mm smooth bore barrel fitted with a reduced diameter aperture just after the muzzle. A Low Density Polythene (LDPE) one-piece sabot (20 mm depth and ~1 mm wall thickness) is used to contain multiple fragments. When fired, the sabot walls hit the reduced diameter aperture and the contents continue on at their original velocity.

The UK sand cannon with the 20 mm LDPE sabots can be used to fire approximately seven grams of soil or soil surrogate, which was seen to replicate local aspects of the damage seen from actual buried charges and that from buried charge assessments [4]. The maximum velocity achieved to date is 700 m/s with seven grams of sabot contents, although in excess of 1000 m/s should be achievable using 7.62x51 mm blanks for this mass of projectiles.

The main benefit of this design compared to conventional fragment propulsion equipment is that the muzzle to target distance can be very short, as space for sabot separation is not required as normal for a 2 or 3 piece separating sabot. Muzzle to target distances of 0.5 m to 2.0 m are typical and varying this distance controls the dispersion of the fragments at the target.

Although fully operational, there has been minimal appetite from UK Ministry of Defence (MOD) customers to move away from requesting test fragments other than those in AEP 2920 [2]. There remain some challenges to resolve with the design, should it be adopted for use by test houses, for example, design changes to improve ease of use, separation of sabot and contents and minimise wear on weapon system components.

5. FRAGMENT INJURY MODELS

5.1 Introduction

A variety of methods have been used by TTCP nations during recent conflicts to assess the severity of injury likely to be sustained by personnel for a given threat environment. These methods include legacy models such as the TTCP spaced metal fragment witness pack [5] and strawboard packs [6]. In addition to these, the TP-5 community has generated new methods for their own use (such as witness packs for assessing the effects of non-metallic fragments) and adapted others (such as the use of gelatin in arena trials and mannequins for coverage assessments).

5.2 TTCP Metal Witness Packs

A spaced metal witness pack has previously been developed by a TTCP team for use within physical trials to enable an assessment of the injury to people inside armoured vehicles from a threat that overmatches the vehicle protection. It is often referred to as a Behind Armour Debris (BAD) pack or the 'TTCP metal witness pack'. It is comprised of thin metal sheets, interlaid with 25 mm of expanded

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polystyrene. A review of this witness pack was conducted in 2016, which identified new materials to replace those that had become obsolete in the UK. The anti-personnel lethality criterion was also updated.

5.3 Strawboard

Strawboard fragment packs may be deployed in order to characterise both the distribution and typical velocity of sources of metallic fragments. The distribution of fragments is given by the X-Y coordinates of each fragment in the strawboard layer where it comes to rest. The velocity of each fragment is estimated, based on the depth of penetration into the pack. This may then be used to predict a probability of incapacitation using a shot line model.

5.4 Witness Packs for Non-Metallic Fragments

5.4.1 General

Ideally, a witness pack will be able to capture the full range of size and velocity of fragments from a device and store these at a range of depths, without itself being destroyed during the event. Strawboard packs have been shown to be unsuitable for use in buried charge assessments, where many of the fragments are 'secondary' and non-metallic – originating from the soil under which the charge is buried.

TP-5 participants have collaborated to develop models applicable to the characterisation of non-metallic fragment threats, for which other witness packs are not suitable. These models are for use within TTCP nations' national laboratories. Key stages in this process are described below.

5.4.2 UK Multiple Discrete Fragment Physical Injury Model (MDFPIM)

The development of this model was initiated in 2011 following attempts to use other materials and existing models to investigate the injury risk from the penetration of soil and stones projected during testing of buried explosive devices were unsuccessful. The model has been through several design iterations since its initial development and can be applied to scenarios other than just buried charge assessments. The current/most recent documented version is MDFPIM V2.0 (and V2.1).

The MDFPIM V2.0 is based on layers of neoprene foam interleaved with a polythene sheet. The MDFPIM V2.0 allows assessment of:

- The potential for corneal abrasions (a low severity eye injury) by any particles that adhere to the sticky front surface of model;
- The risk of penetrating eye injury, by any perforations to layer 1 of the model;
- The risk of skin perforation, by any perforations to layer 2 of the model;
- The 'severity' of injuries from penetrations deeper into the model, based on estimated impact velocity of the projectile(s);
- Overmatch compared to unprotected cases.

The pack has been deployed extensively within UK and has been very successful in allowing the assessment of potentially injurious projectiles that would not penetrate 'legacy' models. It is calibrated to provide velocity estimates for wide range of projectiles (geometries, diameters, masses and densities) and multiple packs can be tiled to cover large areas or complex shapes.

5.4.3 The 'TP-5 Pack'

Due to material sourcing issues, in 2016, Canada initiated the development of an alternative to the UK MDFPIM in support of a TP-5 study assignment on backing materials for personnel protection. The proposed backing system, provisionally named the 'TP-5 pack', is currently under review by the other TTCP nations and has already been deployed in several trials/studies in Canada. The pack has multiple capabilities and is designed in three versions: the standard version for testing soft armour, the overmatch version for conducting V_s-V_r testing and the witness pack version. The witness pack version (Figure 6) comprises a skin layer (neoprene rubber), several layers of foam and a plywood backing.

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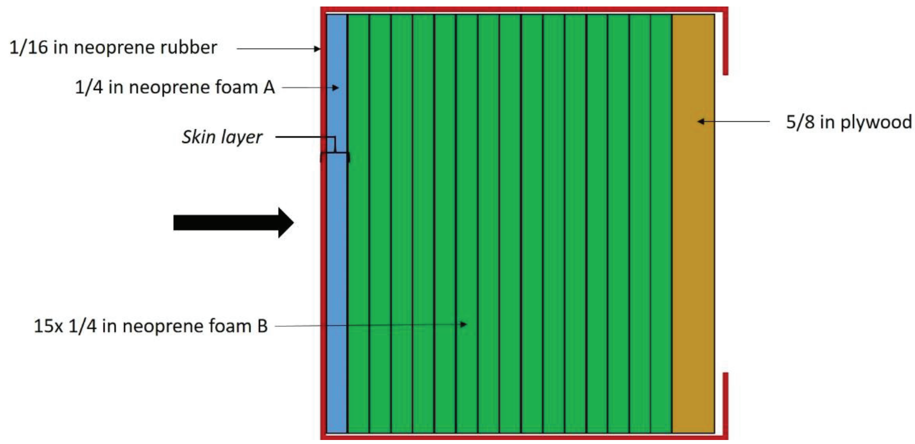

Figure 6. TP-5 Pack in witness pack configuration.
Image © Defence Research and Development Canada

Based on laboratory characterisation data, estimates of the mass, size and velocity distributions of the ejecta cloud can be obtained. The pack has also successfully been shaped in the form of a lower body (pelvis and upper legs) to test pelvic protection systems.

5.5 Other models

TTCP nations have variously experimented with deploying other models, such as tissue simulants and collection media in arena trials using buried explosive charges. Models have included gelatin, clear ballistic gel, mannequins and plywood witness packs [6,7].

5.6 Analysis methods

In order to predict or display injury outcome, a number of analysis methods may be applied to data generated from fragment packs. Two examples of these are the UK-generated Interactive Mapping Analysis Platform (IMAP) and the US Visual Anatomical Injury Descriptor (VAID) tool.

The VAID tool can be used to visualise severity and location of injuries for single or multiple cases, to give a representation of impact frequency distribution for different body regions.

IMAP contains a fixed body model, based on an anthropometrically accurate 50th percentile male and can be used to graphically represent surface impact locations. The tool also enables the geometries of any type of PPE to be imported and overlaid onto the body. This has enabled the effect of PPE coverage to be illustrated. Examples of these are shown in Figure 7.

Figure 7. Left: mapped model in IMAP with no PPE. Right mapped model in IMAP with PPE (helmet, soft armour collar, soft armour). Blue dots represent fragment impact locations. Light blue lines indicate a continuously damaged area
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6. CONCLUSIONS

The study demonstrates methods for assessing the fragment threat by examining evidence from conflicts. It documents methods for replicating the threat in the laboratory using surrogates, in order that personal protective equipment can be tested against a representative fragment threat. It also documents tools that may be used to assess the effect of the fragmenting threat on personnel, in order for effective protective strategies to be developed.

This work has led to an improved collective understanding among TTCP nations of the fragment threat in recent conflicts. It has also provided methods for assessing fragment threat in any future conflict, ensuring that lessons of the past are not forgotten.

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- E Mazuchowski (Lt Col US Air Force), Chief Forensic Services at the Joint Trauma System (JTS) and Medical Examiner for the Armed Forces Medical Examiner System (AFMES)

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