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RTO TECHNICAL REPORT **TR-HFM-089**

Test Methodologies for Personal Protective Equipment Against Anti-Personnel Mine Blast

(Méthodologies d'essais pour le matériel de protection personnel contre le souffle produit par les mines antipersonnel)

Final Report of the RTO Human Factors and Medicine Panel (HFM)
Task Group TG-024.

Published March 2004

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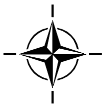

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The Research and Technology Organisation (RTO) of NATO

RTO is the single focus in NATO for Defence Research and Technology activities. Its mission is to conduct and promote co-operative research and information exchange. The objective is to support the development and effective use of national defence research and technology and to meet the military needs of the Alliance, to maintain a technological lead, and to provide advice to NATO and national decision makers. The RTO performs its mission with the support of an extensive network of national experts. It also ensures effective co-ordination with other NATO bodies involved in R&T activities.

RTO reports both to the Military Committee of NATO and to the Conference of National Armament Directors. It comprises a Research and Technology Board (RTB) as the highest level of national representation and the Research and Technology Agency (RTA), a dedicated staff with its headquarters in Neuilly, near Paris, France. In order to facilitate contacts with the military users and other NATO activities, a small part of the RTA staff is located in NATO Headquarters in Brussels. The Brussels staff also co-ordinates RTO's co-operation with nations in Middle and Eastern Europe, to which RTO attaches particular importance especially as working together in the field of research is one of the more promising areas of co-operation.

The total spectrum of R&T activities is covered by the following 7 bodies:

- AVT Applied Vehicle Technology Panel
- HFM Human Factors and Medicine Panel
- IST Information Systems Technology Panel
- NMSG NATO Modelling and Simulation Group
- SAS Studies, Analysis and Simulation Panel
- SCI Systems Concepts and Integration Panel
- SET Sensors and Electronics Technology Panel

These bodies are made up of national representatives as well as generally recognised 'world class' scientists. They also provide a communication link to military users and other NATO bodies. RTO's scientific and technological work is carried out by Technical Teams, created for specific activities and with a specific duration. Such Technical Teams can organise workshops, symposia, field trials, lecture series and training courses. An important function of these Technical Teams is to ensure the continuity of the expert networks.

RTO builds upon earlier co-operation in defence research and technology as set-up under the Advisory Group for Aerospace Research and Development (AGARD) and the Defence Research Group (DRG). AGARD and the DRG share common roots in that they were both established at the initiative of Dr Theodore von Kármán, a leading aerospace scientist, who early on recognised the importance of scientific support for the Allied Armed Forces. RTO is capitalising on these common roots in order to provide the Alliance and the NATO nations with a strong scientific and technological basis that will guarantee a solid base for the future.

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Test Methodologies for Personal Protective Equipment Against Anti-Personnel Mine Blast

(RTO-TR-HFM-089)

Executive Summary

In 2001, the NATO RTO established a new Task Group, HFM-089/TG-024, to review how various countries test Personal Protective Equipment (PPE) against Anti-Personnel (AP) mines, and to recommend a course of action for future testing. This was done in response to mounting evidence that anti-personnel mines pose a significant threat to soldiers, which has prompted the development of new PPE in several countries.

Hundreds of different AP mine types exist, but the majority fall into only two categories: *Fragmentation* and *Blast* mines. These category names reflect the primary injury mechanism associated with each. The accident data available to TG-024 demonstrated that the majority of fragmentation mine accidents result in ballistic wounds. Blast mines result in two patterns of wounds depending on whether a mine explodes under the lower extremity or in front of a soldier that is conducting mine clearance tasks. These three scenarios result in distinct patterns of injury, each scenario requiring that the PPE be subjected to a different test that is appropriate for the threat conditions.

TG-024 was interested in test methodologies that are tailored to the threat and that provide a realistic assessment of probable injuries. By consolidating the knowledge and experience of its participants, the TG could then make enlightened choices about test methods. Therefore, the mandate of TG-024 was structured around the following five objectives:

- Assemble a database of epidemiological data and existing/proposed test methods for PPE against AP mine blast from the participating nations;
- Develop and publish a consolidated description of the physics of AP mine blast, resulting human injuries, field medical procedures and generally available protective measures;
- Develop common injury assessment criteria (footwear and upper body);
- Develop common test procedures and equipment to test PPE (footwear and upper body); and
- Produce a comprehensive Technical Report.

One of the main products of TG-024 was to produce guidelines for testing footwear and upper body PPE against mines. This objective was central to the mandate and the members worked hard to reach decisions that account for the key injury mechanisms. The TG reviewed the various test methods that have been used within NATO and its Allies to assess the performance of PPE against mines. This review considered the strengths and limitations of each method, seeking to find what was essential for each type of test. The aim was to try, as much as possible, to define common test conditions that would be suitable for each test scenario, while remaining practical to implement. Agreement was reached on several points. In particular, it was agreed that a test methodology must be well structured (detailed protocol), that the test conditions must be realistic and well controlled, and that a suitable surrogate to the human body must be selected to assess the performance of the PPE. The main test conditions and surrogates that were agreed upon include:

Fragmentation Mine Tests:

- Anthropomorphic mannequin to obtain good fit of PPE;
- Fragmentation mine to be decided by the user;
- Main diagnostics consists of counting number of hits and penetrations.

Blast Mine Tests Against Footwear:

- Frangible or mechanical surrogate with suitable damage assessment method;
- Mine surrogate consisting of C4 or PE4 explosive packed in cylindrical containers with prescribed detonation point;
- Charge buried in dry medium sand;
- Test rig required for guiding the motion of the surrogate vertically;
- Defined total reaction mass of the surrogate and guidance system;
- Zero preload applied on the soil.

Blast Mine Test Against the Upper Body:

- Hybrid III anthropomorphic mannequin;
- Suitable instrumentation for head, neck and chest as a minimum;
- Charge and soil conditions as per blast tests against footwear;
- Location of the mannequin relative to the charge and blast cone is critical;
- Need for a test rig to position the mannequin.

Méthodologies d’essais pour le matériel de protection personnel contre le souffle produit par les mines antipersonnel

(RTO-TR-HFM-089)

Synthèse

En 2001, le RTO/OTAN a mis en place un nouveau groupe de travail, HFM-089/TG-024, pour inventorier les tests existants de PPE contre les mines AP, et préconiser une ligne de conduite pour les essais futurs. En effet, les mines antipersonnel sont devenues une menace de plus en plus réelle pour les soldats, ce qui a précipité le développement de nouveaux concepts de PPE dans plusieurs pays.

Il existe des centaines de modèles différents de mine, mais la majorité se résume en deux catégories : mines *à fragmentation* et mines *à effet de souffle*. Ces catégories reflètent le mécanisme primaire de blessures de chaque type de mine. Les cas répertoriés d’accidents, connus du TG-024, ont montré que la majorité des accidents avec une mine à fragmentation entraîne des blessures de type balistique. Les mines à effet de souffle provoquent deux types de blessure selon que la mine explose sous le pied ou devant le soldat chargé d’une opération de déminage. Ces trois scénarii conduisent à des types distincts de blessures, chaque scénario exigeant que le PPE soit soumis à un test différent, adapté à la menace.

Le TG-024 s’est intéressé aux méthodologies de test conçues en fonction de la menace et qui fournissent une évaluation réaliste des dommages probables. En combinant la connaissance et l’expérience de ses participants, le groupe de travail a pu faire des choix éclairés à propos des méthodes de test. La mission du TG-024 a été structurée autour des cinq objectifs suivants :

- Construire une base de données épidémiologiques et une base de méthodes existantes / proposées par les nations participantes pour tester les PPE contre les mines AP à effet de souffle ;
- Donner une description de la physique de la mine AP à effet de souffle, des effets lésionnels observés chez les victimes, des protocoles de prise en charge médicale sur le terrain et des mesures de protection généralement disponibles ;
- Etablir les critères communs d’évaluation de dommages (chaussures et haut du corps) ;
- Développer des protocoles communs d’évaluation des PPE (chaussures et haut du corps) et les équipements à mettre en œuvre ;
- Rédiger un rapport technique complet.

Un des principaux buts du TG-024 était de donner des lignes directrices pour le test de chaussures et PPE du haut du corps contre les mines. Les membres ont travaillé dur pour aboutir aux décisions qui prennent en compte les mécanismes essentiels de dommages. Le TG a recensé les diverses méthodes de test qui ont été employées par l’OTAN et ses alliés pour évaluer la performance de PPE contre les mines. Cet inventaire a mis l’accent sur les atouts et les limites de chaque méthode, cherchant à montrer ce qui était essentiel pour chaque type de test. Le but était d’essayer, autant que possible, de définir des conditions d’essai communes qui conviendraient à chaque scénario de test, tout en restant facile à instrumenter dans la pratique. Un accord a été conclu sur plusieurs points. En particulier, on a convenu qu’une méthodologie de test doit être bien structurée (protocole détaillé), que les conditions d’essai doivent être réalistes et bien maîtrisées, et qu’un substitut au corps humain doit être choisi de façon appropriée pour évaluer la performance du PPE. Les principales conditions d’essai et les substituts qui ont été approuvés incluent :

Tests de mine à fragmentation :

- Mannequin anthropomorphe pour obtenir le bon ajustement du PPE ;
- Mine à fragmentation au choix de l'utilisateur ;
- Le diagnostic principal consiste à compter le nombre d'impacts et de pénétrations.

Tests de mine à effet de souffle contre des chaussures :

- Substitut fragile ou mécanique avec la méthode appropriée d'évaluation des dommages ;
- Simulant de mine en C4 ou PE4 compacté dans des récipients cylindriques avec amorçage bien défini ;
- Charge enfouie dans un sable sec de granulométrie moyenne ;
- Dispositif d'essai requis pour guider le mouvement vertical du substitut ;
- Masse totale de réaction du substitut et du système de guidage définie ;
- Aucune charge initiale appliquée sur le sol.

Test de mine à effet de souffle contre le haut du corps :

- Mannequin anthropomorphe Hybride III ;
- Instrumentation appropriée pour, au minimum, la tête, le cou et le thorax ;
- Conditions de charge et de sol identiques aux tests des chaussures ;
- Aspect crucial de l'emplacement du mannequin par rapport à la charge et au cône de souffle ;
- Besoin d'un dispositif d'essai pour le positionnement du mannequin.

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HFM-089

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Test Methodology for Personal Protective Equipment against Anti-Personnel Mine Blast (Task Group)

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Acknowledgements

TG-024 did not happen by accident. It happened because there was a need to bring together the international community in order to address a specific problem: how to best test the effectiveness of Personal Protective Equipment against anti-personnel land mines. This was, and remains, a challenging problem that requires a mix of expertise to be properly addressed. The makeup of TG-024 reflected this, involving medical staff, scientists, engineers, manufacturers of protective equipment, people that test equipment for a living, and last but not least, users of the equipment. One can easily think that chairing such a diverse group can be difficult. This was not the case for TG-024 and I want to acknowledge the professionalism and dedication that the TG-024 members demonstrated throughout the 2 ½ years that we worked together. There existed a genuine spirit of cooperation amongst the participants with willingness to contribute and work towards the common goal. This made the Chairman’s job easy, and I would like to thank all the participants for their contributions.

Thanks are also due to the organisations that provided the time and financial support to individual members so that they could participate in the TG activities. The TG held five meetings over a two-year period. I am grateful to the organisations that hosted these meetings. The facilities and equipment put at our disposition made it possible to have productive meetings during working hours, starting discussions that often continued after hours. The five organisations that hosted meetings are:

- RTO Headquarters, Neuilly-sur-Seine, France;
- DRDC Suffield, Alberta, Canada;
- DSTL Porton Down, Salisbury, United Kingdom;
- US Army MRMC, during the ATACCC conference held in Florida, United States; and
- Central Institute of the GE Medical Corps, Koblenz, Germany.

There are a few individuals that I would like to recognize because of the special support they provided to the Chairman. First, Dr Prof Wulf von Restorff, as the HFM referee appointed to TG-024, provided guidance through the corridors of the NATO RTO process. Second, Major Matt Braid and Dr Kevin Williams spent a lot of time taking notes during meetings and drafting the minutes thereafter. Their assistance meant that I could focus on the discussions and exchanges taking place during the meetings. Gentlemen, thank you.

Finally, this report is the result from thousands of man-hours and experience gathered in no less than seven countries over a decade of testing. It is hoped that it will be seen, in due course, to have reached its main goal: guiding the international community towards a better way to test Personal Protective Equipment against the effects of land mines so that it will be easier to compare the results from one country to the next.

Denis Bergeron, Ph.D., P.Eng.
Chairman HFM-089/TG-024
September 2003

Chapter 1 – INTRODUCTION

The modern land mine appeared during World War I in response to the arrival of armoured vehicles on the battlefield. They have been an integral part of warfare ever since. During World War II, anti-tank (AT) mine fields deployed in North Africa and Europe played a major role in tank manoeuvre warfare. Their value was recognized through the deployment of anti-personnel (AP) mines to prevent lifting of the AT mines. Soon after, during the Korean War, AP mines were deployed on their own, as a weapon. They were used extensively in that conflict to counter the numerical superiority of North Korean forces. During the Vietnam War, and a decade later during the first Afghan War, the nature of land mine warfare shifted. These two conflicts saw large, well-armed armies fighting against numerically inferior opponents, which forced the latter to adopt guerrilla warfare tactics. All sides of these conflicts used land mines profusely, and that proved to be an equaliser that was particularly effective in this type of warfare. Land mines inflicted significant casualties to the better armed forces while containing the losses of the opposing forces. These weapons had, and still have, a strong psychological effect on the troops. More recently, the Gulf War conflict saw the Iraqi forces deploying an estimated 9 million mines around Kuwait City. These mines were of concern to Coalition forces, but the nature and terrain of this conflict allowed the extensive use of mechanized equipment and infantry vehicles, which minimised the impact of land mines.

The year 1989 was marked by the fall of the Berlin wall, which triggered a profound change in East-West relations along with a far-reaching transformation [1] of the international security arrangement. NATO and Partners for Peace countries started to work together to diffuse or contain regional conflicts. UN resolutions provided a common framework to decide where troops should be deployed. This was the case against the Former Republic of Yugoslavia. Starting in 1991, individual NATO nations contributed ground troops in Croatia and in the Republic of Bosnia and Herzegovina under the umbrella of UN resolutions. These troops had to contend with an estimated 3 to 6 million land mines deployed in the area. In late 1995, following the Dayton Peace Agreement between the Republic of Bosnia and Herzegovina, the Republic of Croatia and the Federal Republic of Yugoslavia, NATO was given the mandate to implement the military aspect of the Peace Agreement. It did so by deploying the Implementation Force (IFOR) in December 1995, which included 60,000 troops at its peak. As part of this mandate, military engineers were able to repair a significant portion of the road infrastructure. They were also involved in demining activities and the repair of railroads, airports, public utilities and the rebuilding of schools and hospitals. Land mines posed a constant threat to the troops during these operations. In December 1996, the Stabilisation Force (SFOR) replaced IFOR with the number of troops being reduced to 31,000. The initial mandate of SFOR was for 18 months. It was later renewed and the number of troops was reduced to 23,000.

In 1998, a new conflict arose in the region opposing Serbian and Kosovar Albanian forces. There were numerous reports of gross human rights violations and a massive exodus of an estimated 600,000 Albanian Kosovars. Once again, NATO provided support to UN resolutions to reinforce diplomatic efforts to bring an end to the violence and facilitate the return of refugees. A peace agreement was reached following an air campaign in mid-1999 and NATO deployed the Kosovo Force (KFOR) comprised of some 50,000 troops from 39 countries. The Serb forces laid a large number of land mines during this conflict, resulting in a large number of civilian casualties. NATO-led troops faced the same threat.

The above examples demonstrate the need for NATO countries to protect against land mines. It should also be noted that land mines continue to injure civilian populations long after the end of a conflict. The situation had reached such proportions by the early 1990's that several countries lobbied for, and obtained an international

Treaty to ban AP land mines. Many countries, including some from NATO, invested in Mine Action technologies to help clear land mines, an effort that included the development of Personal Protective Equipment (PPE). That research and development work saw the convergence of humanitarian and military demining needs to some extent and sparked a widespread requirement to test the performance of new equipment against the mine threat. Unfortunately, that testing was done largely in isolation without the benefit of coordination across NATO. The role of TG-024 is to address this issue through the definition of common test methods to evaluate PPE.

1.1 ADAPTING THE TEST METHODS TO THE INJURIES

It is important to realize that AP land mine protection differs considerably from protection against AT mines. This report is concerned only with AP land mines, thus any reference to the word *mine* henceforth refers to an AP land mine. Hundreds of different mine models have been manufactured, but the great majority of these mines fall in only two categories: *Fragmentation* and *Blast* mines. These category names reflect the primary injury mechanism associated with each.

Fragmentation mines [2] are area weapons that explosively disperse high velocity fragments that injure or kill personnel up to several tens of meters away. If initiated very close to the intended victim, the victim is also injured by blast, but if this is the case, the victim also has a very high probability of being killed by the fragments. Fragmentation mines can be activated through a variety of stimuli such as downward pressure or the pull from a trip wire. There also exist sophisticated fuse systems that detect ground vibrations, noise or infrared signatures, but these fuse types are not widely available and are seldom used in practice. With trip wires, it is difficult to predict the direction of a fragmentation mine attack. Thus, soldiers require all-round protection to defend against such a weapon.

The situation for AP blast mines is quite different. These devices come in a wide range of shapes, materials and colours. They often contain only a minimal amount of metal, which makes them difficult to detect with current mine detectors. Furthermore, they are designed for concealment in the ground, waiting for activation by the victim. They injure primarily by the direct effect of blast on human tissues. However, the mine case and the internal trigger mechanism break up and can become fragments that also injure the victim. The blast also propels soil, small pebbles, and other environmental debris that cause further fragmentation injuries and contaminate wounds.

Accidents involving buried blast mines [3] occur either when the victim steps on the mine or while the victim is trying to locate and remove a mine. Each type of accident yields a well-defined pattern of injury. When the victim steps on a blast mine, the body is usually in the standing position, which places the lower extremities closest to the blast while the sensitive organs of the upper body are further away. The near contact of the lower extremity with the blast results in traumatic amputation of the leg and severe contamination of adjacent soft tissues. When the accident occurs during mine clearance, the soldier is usually lying prone or in a kneeling position and, with the exception of the hands, most body parts are not in direct contact with the blast. However, the reduced distance from the blast greatly increases the probability of injury to the head and upper body organs.

To summarise there are three basic accident scenarios for mines as follows:

- A victim activates a fragmentation mine;
- A victim steps on a buried blast mine; or
- A victim triggers a blast mine while in a prone or kneeling position.

Each scenario generates a specific injury pattern. It is necessary to adopt different PPE approaches to protect a soldier for each case.

1.2 HARMONIZING TEST METHODS

The past decade has seen an increased awareness of the mine threat and a corresponding interest in PPE. Recent work in this area has improved our understanding of the injury mechanisms generated by mines. New PPE was developed on the basis of this understanding. It is equally important to highlight the important contributions [4] that were made by various national programs in support of humanitarian demining.

These development programs required evaluation of the performance of the new equipment. PPE designed to protect the upper body was assessed for both the fragmentation threat and for the scenario where a soldier performs mine clearance tasks in a prone or kneeling position. For the latter scenario, the mine threat to the upper body consists of a combination of fragments, air shock, jetting of detonation products that might or might not be burning, and impacts from soil particles. It is important that PPE components be in their intended location and proper orientation with respect to the mine because the mine blast and soil ejecta patterns can be very directional. In view of this and in order to provide the most realistic support possible for the PPE being tested, many test agencies adopted crash test dummies, such as the Hybrid III mannequin, to assess the performance of upper body PPE.

New anti-mine footwear has also seen much development over the past few years. Just as for upper body PPE, NATO countries that were interested in such footwear embarked on evaluation programs. However, there was a lack of a standard method to test footwear against this threat. As a result, a range of test apparatuses and protocols were invented and used for this purpose. Test models ranged from wooden pegs to human cadavers, encompassing a wide range of options in between. More importantly, these models were often used without suitable injury criteria to assess how well the footwear had performed. The proliferation of test models also meant that results were difficult to compare from one country to another.

During an exploratory team meeting held in Brussels in February 2000, it was decided to create a new RTO Task Group (TG), HFM-089/TG-024, to address the issues of test methods and human injury criteria for PPE evaluation. The TG participants were interested in using test methodologies that are tailored to the load mechanisms and that provide a realistic assessment of probable injuries. First, this required the consolidation of the available knowledge relating to loading mechanisms and injuries. Through this understanding, it was then possible to design test methods where:

- The threat is reproduced in a realistic manner;
- The response of the test models is well characterized; and
- Injury criteria are available to relate the response of the model to human injury.

1.3 THE MANDATE AND OBJECTIVES OF TG-024

The original mandate of TG-024, as expressed in its Terms of Reference (see Annex A), proposed to concentrate on the effects of blast mines. However, as work progressed, it became apparent that most participants had also performed tests to assess the more lethal threat from fragmentation mines; hence this report includes references to testing for both threats. Early in its mandate, TG-024 members agreed that because lower body injuries usually result from a person stepping on a buried blast mine, while upper body injuries result from prodding or excavating a buried blast mine or from fragmentation mines, different but complementary test methods were required for lower and upper body PPE. Each method must account for the appropriate injury mechanisms. The work of TG-024, which was conducted from June 2001 to October 2003, was structured around five objectives as follows:

- Assemble a database of epidemiological data and existing/proposed test methods for PPE against AP mine blast from the participating nations;
- Develop and publish a consolidated description of the physics of AP mine blast, resulting human injuries, field medical procedures and generally available protective measures;
- Develop common injury assessment criteria (footwear and upper body);
- Develop common test procedures and equipment to test PPE (footwear and upper body); and
- Produce a comprehensive Technical Report.

The first two objectives formed a solid basis to guide the group in selecting test methods that truly challenge the PPE being evaluated. Test methods should produce results that can be related to the probable medical outcome, however, it was found that this is not always realistic when one takes into account the practical issues related to testing. It is also difficult to interpret epidemiological data for real life mine victims because there is great uncertainty associated with this data given that most conditions prevailing at the time of accident (threat type, victim activity, location of the threat relative to the victim, etc.) are usually not known precisely. Another point to consider is that the bulk of the epidemiology is related to people that were not wearing protective equipment, while the focus of the TG-024 mandate was to evaluate PPE effectiveness.

More recently, tests were performed to evaluate the effectiveness of protective equipment against AP mine blast under controlled conditions. These tests involved a variety of human surrogates and cadavers, both of which have limitations in comparison with real accidents. Thus, the challenge for TG-024 was to extrapolate from test results and field accidents in order to develop appropriate injury assessment methods that take into consideration these limitations.

One of the main products of TG-024 was to produce guidelines for testing footwear and upper body PPE against mines. This objective was central to the mandate and the members worked hard to reach consensual draft guidelines that were founded on a database of tried test methods. The pros and cons of each method were examined to arrive at a consensus that accounts for the key injury mechanisms. The need for common test models and instrumentation was also examined in relation to the practicality of each method. The ethical and economical issues which will drive the adoption of one test model by a given nation or limit the use of a test surrogate by another, were recognized by the TG and rather than propose a single methodology, the TG has sought to highlight the strengths and weaknesses of each. TG-024 suggests techniques to control several of the test parameters while offering sufficient information about these existing models so that the reader can make an informed decision based on their own test objectives, practical limitations, and available resources.

1.4 ORGANISATION OF THIS REPORT

Starting with this introduction, this report is built around seven chapters. Chapter 2 provides background information about mine explosions and the injuries they inflict on their victims. The intent is to set a reference against which the reader can assess the discussion on test methodologies, the core subject of this report. The discussion about test methodologies is broken down in three sections, Chapters 3, 4, and 5. In Chapter 6, the reader can find the recommendations of the TG with respect to the proposed test methods for the assessment of PPE performance against AP blast and fragmentation mines. Finally, the conclusions are presented in Chapter 7 along with recommendations for future work.

Seven annexes supplement the main body of the report. These annexes contain information that relates to mines, the past experience of the participating nations, mine injuries, and other information that was too detailed for inclusion in the main text. For example, Annex C significantly expands on the physics of mine explosions while Annex D presents a detailed account of mine injuries and their medical treatment. Annexes F and G are particularly important as they present a tabulation of lower body and upper body tests that have been performed in the past decade. The Task Group believes that the information contained here is sufficient for readers to use as a starting point to design their own test programs.

Chapter 2 – MINE EXPLOSIONS AND THEIR INJURIES

Prior to discussing the merits of various test methodologies, it is first necessary to describe how the equipment is typically designed to defend against the mine threat, and what injuries might result. Data about mine injuries inflicted to soldiers during operations is not widely publicized, but fortunately, the United States sponsored a survey in 1998 to look at the distribution of mine injuries to deminers during humanitarian mine clearance operations. This study produced a public database [5] of 232 mine accidents that resulted in 295 victims. It should be noted that although this survey was conducted for humanitarian demining, it still applies to soldiers. Mines do not change their behaviour whether it is a civilian or a soldier that detonates them. Hence, the survey contains several elements that are applicable to what soldiers encounter in the field, particularly when it comes to the pattern of injuries as a function of mine type.

The deminer injury survey considered the full spectrum of threats, including Unexploded Ordnance and other threats. Figure 1 shows the distribution. Of all the accidents reported, the overwhelming majority, 79%, was the result of an AP mine. This threat accounted for 78% of all injured people and 81% of fatalities. The results from the survey clearly highlight the importance of the mine threat.

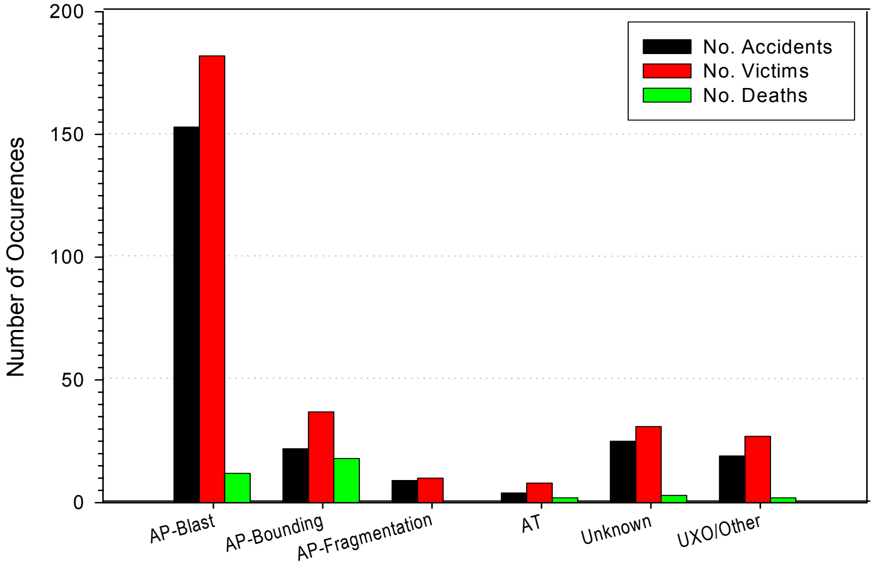


Figure 1: Distribution of Threats for Accidents that Caused Injury.

Another important piece of information relating to the threat distribution was the ratio of mine accidents involving blast versus fragmentation mines. Blast mines were involved in 83% of the accidents, but only 7% of the victims died from their wounds. On the other hand, 38% of the victims from fragmentation mines died, nearly six times more than for blast mines. This reflects the different nature of the threat. A blast mine is designed to maim its victims, thereby inflicting psychological as well as physical trauma to opposing forces and increasing the burden on the medical and supply chains of that force. On the other hand, a fragmentation mine is designed to kill its victims and maximize the damage to opposing forces. This fundamental difference in the two mine classes has a strong influence when selecting suitable PPE to defend against these threats as well as the test methodology needed to evaluate the PPE performance.

Another important fact regarding the deminer injury data was the very high incidence of the PMN blast mine, which was involved in 66 out of 153 (43%) of the blast mine accidents. This ratio is unusual and is likely an artefact of the large contribution from organizations in Afghanistan rather than a reflection of the prominence of this particular mine throughout the world. This is an indication of the kind of bias that can creep into a survey and which can very likely influence the distribution of injuries. The PMN is reputed to be the largest of all blast mines with 240 grams of TNT. It also has a thick hard-plastic casing that poses a significant fragmentation threat. Thus, the prevalence of the PMN landmine in the data most likely introduced a bias towards a greater level of injury in the survey.

The US deminer injury survey provided solid evidence of the distribution of mine injuries. Three basic accident scenarios prevail, one relating to fragmentation mines and two relating to blast mines. The scenarios are:

- A victim activates a fragmentation mine;
- A victim steps on a buried blast mine; or
- A victim triggers a blast mine while in a prone or kneeling position.

Each scenario results in a well-defined injury pattern. It is necessary to adopt different PPE approaches to protect a soldier for each case. This also means that different test methods are required to test the equipment. In order to ensure that these test methods are appropriate, it is useful to first describe the threat associated with each mine type, and to review the injury mechanisms for each scenario.

2.1 PHYSICS OF FRAGMENTATION MINES

Fragmentation mines use high explosive to propel fragments that might be pre-formed or that are produced from the natural break-up of a metal or polymer jacket. These mines are further classified according to their deployment characteristics and their fragment pattern. Hence, it is usual to refer to bounding mines and directional mines. Bounding mines, as shown in Figure 2, contain a mechanism that allows the mine to 'jump' up to a height of one to two metres above ground, where the detonation of the explosive disperses the fragments 360° in a horizontal plane. Directional mines consist of pre-formed fragments encased in a polymer matrix backed by a layer of high explosive. This design disperses the fragments along a limited arc, usually less than 90° in the horizontal plane.

Figure 2: Explosion of a Bounding Fragmentation Mine in front of a Mannequin Wearing PPE. (Pictures Courtesy of DRDC, Canada)

Fragmentation mines are area weapons that can injure personnel up to a several tens of meters away. They can be activated through a variety of stimuli such as downward pressure or the pull from a trip wire. There also exist sophisticated fuse systems that detect ground vibrations, noise or infrared signatures, but these fuse types are seldom used in practice. With trip wires, it is difficult to predict the direction of a fragmentation mine attack. Thus, soldiers require all-round protection to protect against such weapons.

The primary injury mechanism of fragmentation mines is, as their name implies, fragmentation. However, this class of weapons also inflicts thermal and blast injures when the victim is close enough to the point of detonation. From a biological point of view, each of the three components (thermal, blast and fragments) contributes to the wound, but it is difficult to determine which mechanism dominates. Nevertheless, each injury mechanism exhibits a definite dependence on distance from the explosion source, as illustrated in Figure 3. The importance of thermal and blast injuries decreases rapidly with distance, while fragment injuries act over a considerably greater distance.

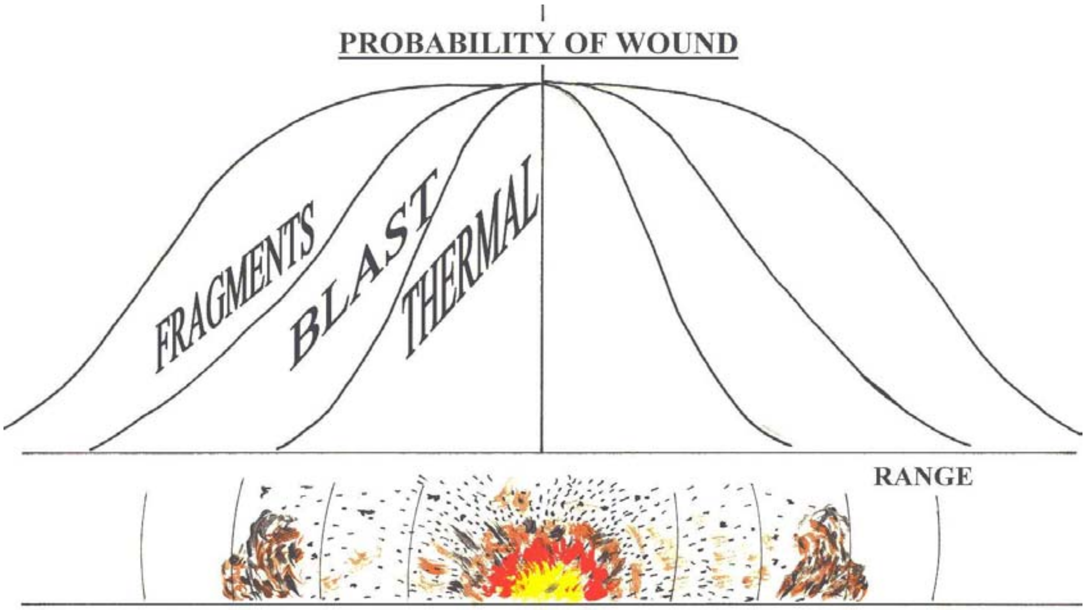


Figure 3: Mechanisms of Injury Depend on Range from the Explosion (Courtesy IB Anderson).

Thermal injury is common with any close range explosion, but it is often overwhelmed and hidden by other injury mechanisms. For a mine, thermal injury is usually restricted to the very near region to the blast and its severity depends on the time of exposure [6]. In the worst case, the duration of the after burn is of the order of 10-25ms, but the temperature can be of the order of 1000°C, which is sufficient to cause thermal injury. Blast injury is easier to notice. From a macroscopic point of view, the very high pressure near the explosion source overwhelms the strength of human tissues, causing their disintegration. Further away, the blast can cause more macroscopic injuries including damage to the ears, respiratory tract, and to the gastro-intestinal tract. Blast lung [7] can occur if the explosive mass is large enough or if the distance is small enough.

Fragmentation is the dominating injury mechanism. Mine fragments generally produce penetrating wounds. The lethality of fragments decreases rapidly with distance because they slow down due to air resistance, and because the fragments disperse, thereby decreasing the probability of hit. The traditional approach used to protect people from mine fragments is to cover them with layers of ballistic protection. To optimize performance, body armour must be judiciously distributed to provide enhanced protection to vital areas such as the head and chest, while lighter weight and more flexible materials are used to protect the extremities. Using this approach, it is feasible to design equipment that gives effective protection for distances greater than 1 to 2 metres from the mine explosion. However, protection at close range remains difficult due to the greater lethality of the fragments combined with the exponential increase of blast overpressure. In recent years, new equipment has been designed and deployed for mine clearance specialists. Annex B provides a generic description of this equipment.

2.2 PHYSICS OF BLAST MINES

Blast mines injure primarily by the direct effect of blast on human tissues, but the mine case and the internal trigger mechanism break up, becoming fragments that also injure the victim. The soil in the immediate vicinity, small pebbles and other environmental debris are propelled away from the blast, forming so-called secondary fragmentation. Accidents involving buried blast mines occur when the victim steps on the mine, as the weapons are designed to operate, or while the victim is trying to locate and remove the mine. Each type of accident yields a well-defined pattern of injury. These differences occur because the effects of blast depend very much on distance from the explosion and geometry. Thus it is important to understand the physics of the mine threat to properly quantify the injury mechanisms.

The explosives used in the majority of mines share the same basic characteristics. Upon initiation of the fuse, a detonation wave travels through the explosive at high speed (4–8 km/second) starting a chemical reaction that transforms the explosive into a mass of hot (3000–5000K), high-pressure (0.1–0.2 Mbar in the detonation front) gas called the *detonation products*. When the detonation wave reaches the physical boundaries of the explosive, it is partly transmitted to the surroundings. If the explosive device is in direct contact with an object, the stresses generated by the transmitted wave can easily exceed the strength of the receptor material and cause it to fail. This process, called *brisance*, refers to the ability of the explosive to shatter materials. It is believed that brisance is related to the extent of injury of a soldier that steps on a mine buried flush with the ground because this shattering high-pressure wave is transmitted directly into the lower limb. The effect of brisance diminishes rapidly as the *standoff* distance between the explosive and the target increases.

The expansion of the detonation products is believed to be a dominant injury mechanism to human tissue. Several studies [8,9,10] quantified the mine explosion process in physical terms such as pressure and velocity. It takes only 5μs for the detonation wave to transform the solid explosive into high-pressure gas. From that point onward, the soil confines the expansion of the detonation products. The hot gas pushes on its surroundings, deforming the soil directly above the mine into a hemispherical cap (see Figure 4). Hot gas then breaks through the soil surface at several points and jets out at supersonic speed, pushing the air ahead and creating an air shock. The push of the gas also creates soil ejecta, a stream of soil particles that flow along a thin conical zone surrounding the gas core. It is useful to define this conical zone in terms of the angle φ about a line perpendicular to the soil surface where the angle $\varphi = 0$ corresponds to the direction along this perpendicular. Note that depth of burial has a strong influence on the gas expansion process, as is demonstrated by the pictures in Figure 5.

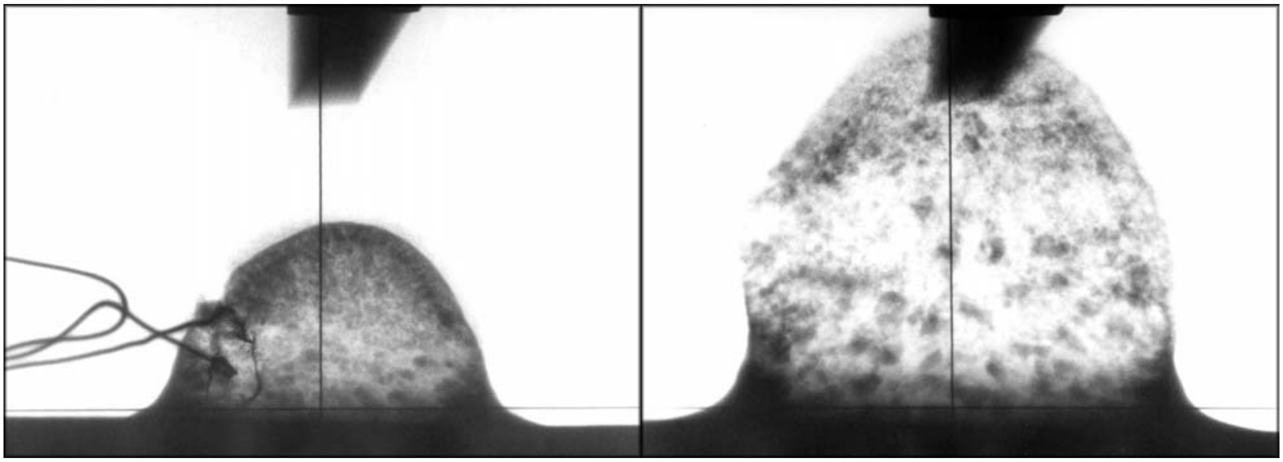


Figure 4: Flash X-Rays showing the Early Deformation of the Soil Cap above a 100-gram Charge Buried under 30mm of Sand. The reduced density indicates areas where the detonation products have penetrated through the soil cap (Pictures courtesy of DRDC, Canada).

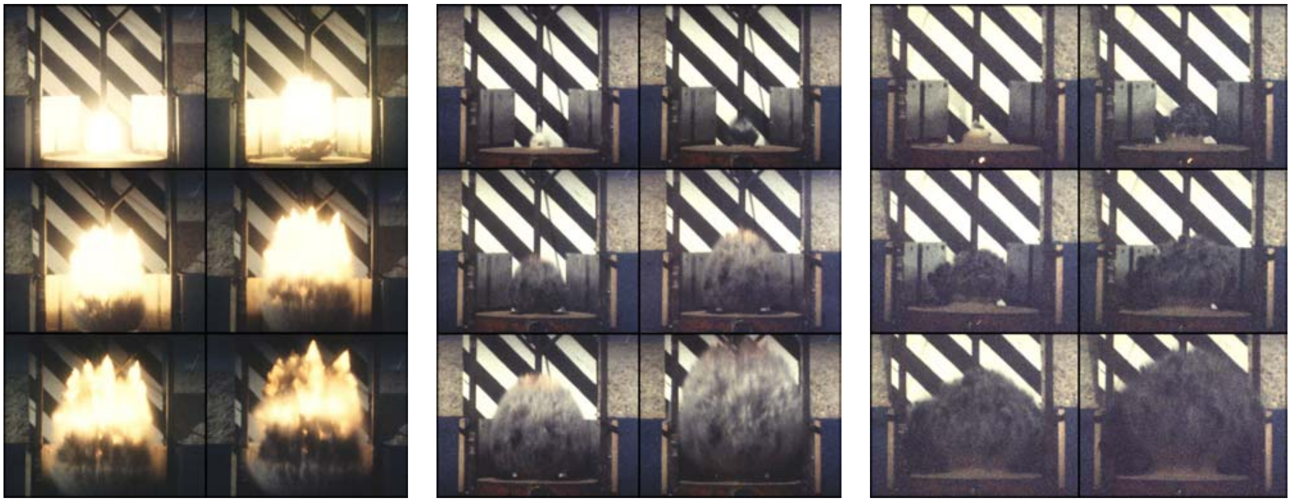


Figure 5: Selected Frames from High-Speed Films of the Detonation of 100-gram Charges in Sand. The charges were flush buried (left), below 30mm of sand (centre) and below 80mm of sand (right) (Pictures courtesy of DRDC, Canada).

The internal pressure of the detonation products is directly related to volume. Thus, the shape of the cloud of detonation products influences pressure. A sphere is a good approximation until the gas reaches the soil surface, but once the gas breaks through the soil surface, the expansion assumes more or less a hemispherical shape. Later on, the preferential development of the gas cloud in the vertical direction results in a more or less cylindrical shape. Figure 6 illustrates the dramatic drop in pressure of the detonation products with expansion. A simple spherical model for a 100-gram explosive charge indicates that the gas pressure drops to approximately 15% of its initial value while expanding from the charge volume to a sphere just touching the soil surface when the overburden is 30mm. When the charge is buried below 80mm of overburden, the gas pressure drops below 1% of its initial value by the time it reaches the surface.

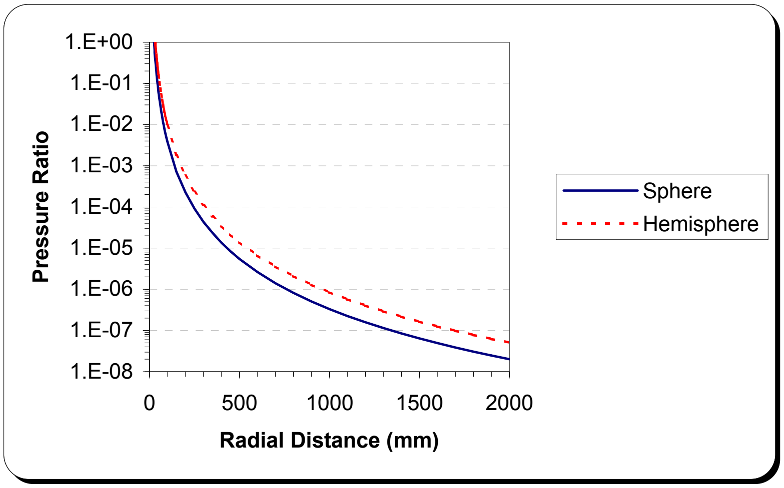


Figure 6: Approximate Decrease of the Detonation Products Pressure with Volume Expansion.

The gas bubble acts as a piston to accelerate nearby soil particles. Those particles that are closer get accelerated first, immediately transferring part of their momentum to neighbouring particles through collisions. If the soil cap is thin, the average particle speed is high, but as the overburden in increased, the energy is dispersed to a larger number of particles and the resulting velocity of the soil cap decreases rapidly.

An estimate of the initial velocity of the detonation products can be obtained from high-speed films such as those shown in Figure 5. The results are plotted in Figure 7. The initial velocity was determined from second order polynomial fits to each set of points. For a flush-buried charge, the initial vertical velocity is about 3000m/s and remains strong throughout the field of view of the camera. The event is very bright because burning of the hot combustion products continues long after the initial detonation due to the strong rate of expansion of the front, which makes it possible for the hot, unburned products to mix with fresh oxygen and sustain the combustion process. The jetting also indicates the presence of strong turbulent mixing at the interface between the detonation products and the air.

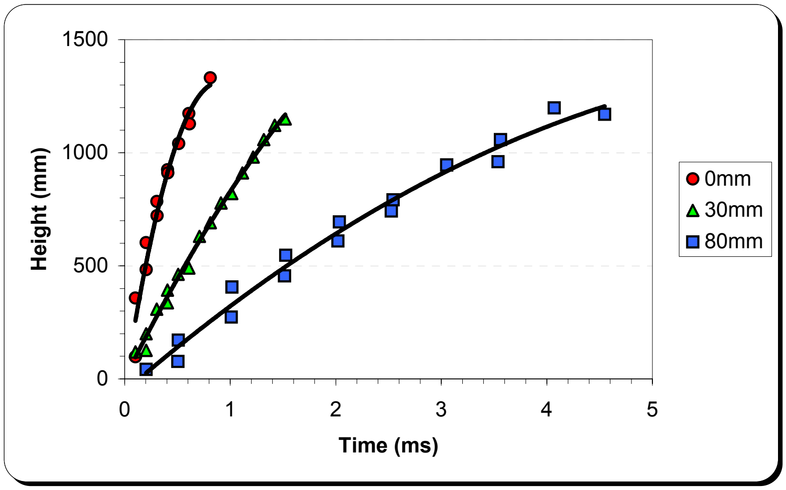


Figure 7: Vertical Expansion of the Detonation Products from High-Speed Films.

Having soil above the mine slows the growth rate of the cloud considerably. Maximum values of vertical speed were 940m/s and 400m/s for a 30mm and 80mm overburden, respectively, which influences the overpressure field above the mine. Peak overpressure increases with shock front velocity, thus the largest overpressure occurred with flush-buried charges and soil overburden decreased the peak overpressure. Peak overpressure also decays with distance from the blast source irrespective of overburden.

Other quantities that play an important role in the transfer of load to an object in the vicinity of the explosion are the kinetic energy of the detonation products and soil ejecta. For detonation products, the principles of fluid dynamics dictate that an object immersed in this transient flow is subject to a drag force. The magnitude of the drag force depends on density, flow direction and velocity, and the geometry of the object. As the flow is brought to rest, it creates a force that accelerates the object and propels it away from the centre of the explosion. The fundamental principles governing the impact of soil ejecta against that same object differ somewhat. Since soil ejecta consists of a multitude of small particles, each carrying its own momentum, the transfer of force to the object is governed by the law of mechanics for the conservation of momentum as individual particles impact the object in its path. Again, it can be seen that the geometry of the object plays an important role in this process.

Considering the factors discussed above, i.e., pressure, temperature, gas flow velocity and soil particle momentum, the reader can begin to appreciate the extreme environment generated by a mine explosion. The importance of standoff should be noted due to the rapid drop of pressure and temperature with distance.

2.3 BLAST MINE INJURIES TO THE LOWER BODY

When a victim steps on a blast mine, the body is usually in the standing position. The near contact of the lower extremity with the blast results in traumatic amputation and severe contamination of the adjacent soft tissues. Fomin [11], a Russian surgeon who was involved in the war in Afghanistan during the 1980's, treated a large number of soldiers that fell victim to mine blast. He also investigated mine blast trauma in further detail using amputated limbs and animal models. The Afghan war casualties provided a broad base of case studies from which the body response to mine blast trauma could be monitored. It was determined that the basic pattern of injury to the lower extremity includes a roughly hemispherical zone where there is complete destruction of tissues. The size of this zone is delimited by the distal location of bone damage. Figure 8 shows the dependence of this zone on the explosive content of the mine. Fomin also notes that the medical outcome is influenced by what part of the foot initiates the detonation; a heel detonation has a significantly different outcome than, say, a detonation under the big toe. Furthermore, the relatively fixed dependence of the size of this zone on explosive mass means that anthropometrics play a role in the outcome; people with a bigger stature are likely to suffer somewhat less damage.

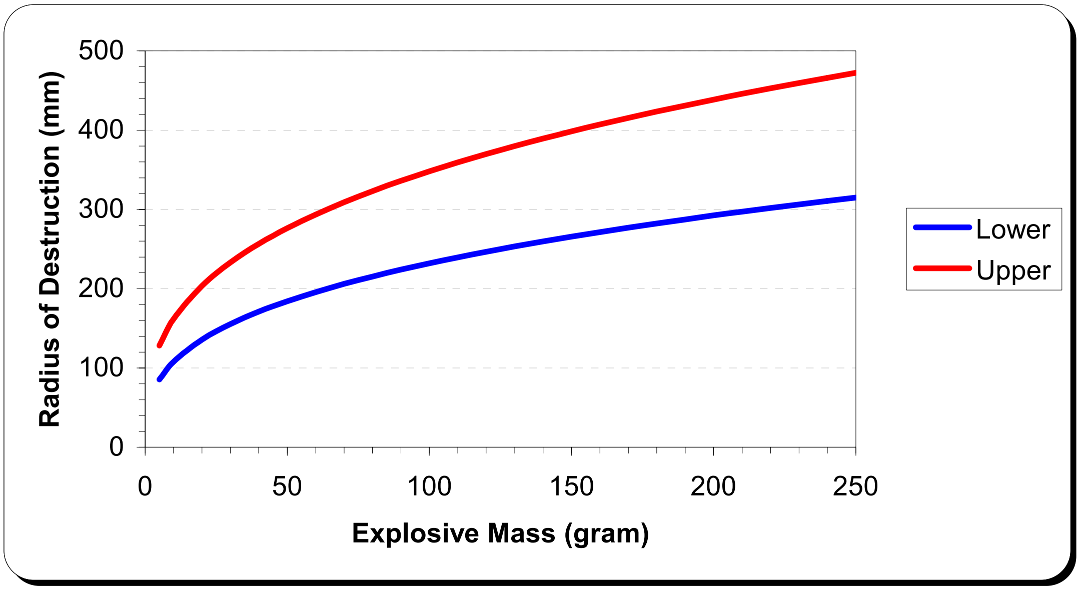


Figure 8: Approximate Radius of Destruction for AP Mines according to Pokrovsky, 1980.

Beyond the zone of complete destruction, there is a zone characterized by the total destruction of soft tissues, while the more resilient bone tissues remain. Damage in this zone is mainly due to the expansion of the detonation products. Further away, the damage is attributed to the propagation of a shock wave through the tissues. Damage occurs at the cellular level between the major structures of the leg. The Russian team reported evidence of microscopic damage inside blood vessels and nerve structures that fit well with the wave propagation theory. It is very likely that these waves pre-condition the biological material prior to the strong push from expanding detonation products. There is also evidence of shock wave damage further up the leg causing microcirculation and dystrophic changes in the affected limb. Further up the body, the shock wave from larger blast mines is believed to cause contusion to internal organs. These effects can only be observed over time in patients that survive the primary accident.

A combination of shock wave and jetting of the detonation products is also believed to cause the stripping of tissues from the surface of the tibia and fibula above the level of traumatic amputation. Detachment of tissues along the facial planes of muscles opens the way for the penetration of foreign objects such as gas, disintegrated biological tissues, pieces of footwear, dirt, etc. The compartments of the leg provide preferential pathways for ingress of such contaminants. Thus, it appears that clinical observations made by different surgical teams operating in different parts of the world converge towards the same basic description of mine blast trauma to the lower extremity.

From a surgical perspective, a blast wound consists of tissue disruption due to overloading, thermal injury and fragments. Many types of tissues are affected, including skin, fat, muscles, bone and tendons. Beyond the zone of complete tissue disruption, high-pressure gas drives foreign materials and contamination up the leg through facial planes along paths that are easily self-dissected. All of these injury mechanisms result in unusual and severe injury patterns that pose an intimidating surgical challenge.

Because of the extreme pressure in close proximity to the explosive, most metal and composite materials that are used in the construction of protective equipment fail through plastic deformation. Figure 9 shows a series of flash x-rays that exemplify the difficulty in protecting the lower extremities from mine blast. In these tests, a frangible surrogate leg was ‘protected’ by a blast boot with a protective over-boot. The x-rays show that a metal blast deflector is used to reinforce the sole and prevent ingress of the detonation products. Other footwear manufacturers use ballistic materials such as Aramid to perform the same function. When the footwear was subjected to the detonation of a small blast mine, the over-boot failed but prevented breaching of the inner footwear. Post-test examination of the test model and the x-rays revealed that despite the inclusion of ballistic materials, the sole of the footwear deformed and was pushed into the foot with so much force that it destroyed the heel bone and/or the anklebone. When the same protective footwear combination was exposed to the blast of a medium size mine, it resulted in a traumatic amputation above the ankle level every time.

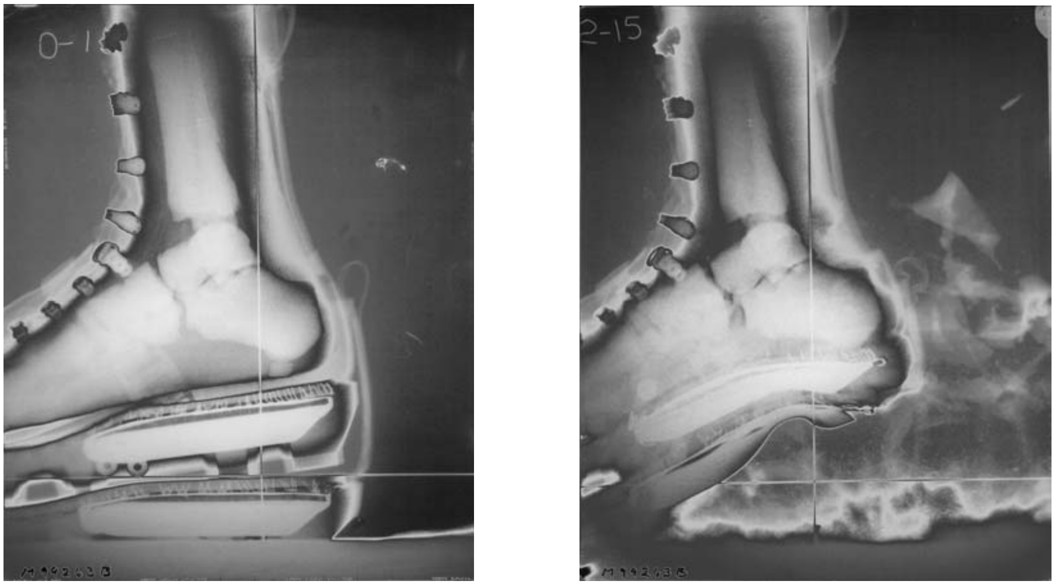


Figure 9: Flash X-Rays of a PMA-3 Mine Explosion under a Blast Boot with an Over-Boot. (Pictures Courtesy of DRDC, Canada)

2.4 BLAST MINE INJURIES TO THE UPPER BODY

Blast mine injuries to the upper body are often associated with soldiers that perform mine clearance tasks. Unlike injuries to the lower extremities, the upper body is normally not in near contact with the explosive. A typical situation is depicted in Figure 10. In that position, the upper body is vulnerable to the combined effect of *burns*, *blast* and *fragmentation*. From a medical point of view, it is difficult to identify and quantify the exact contribution of each of these three mechanisms and it is often preferable to describe a blast injury in terms of direct and indirect effects. Direct effects include those injuries that are clearly a result of exposure to blast such as injuries to the respiratory tract, ear injuries and gross disruption to tissues, particularly in the case of direct or near contact with the explosive. The arms and hands, usually being closest to the explosion, are particularly vulnerable to direct blast effects. Indirect effects include all other sources of injury such as the elastic deformation of the PPE due to the push of the air shock and detonation products, body translation, and fragmentation. Psychological trauma should also not be neglected from a medical perspective.

Figure 10: PMA-1 Mine Explosion showing the Loading Zone on a Mannequin Dressed with a Protective Ensemble. (Pictures Courtesy of DRDC, Canada)

Skin is vulnerable to superficial and deep burns if it is exposed to expanding detonation products that are still burning. This only occurs when the mine is buried flush or very near the surface. Furthermore, the duration of a flash burn lasts only a few tens of milliseconds. Therefore, the extent of flash burns can be limited simply by covering the skin with fire-resistant material, or in the case of the face, with a full-length visor. A series of tests carried out in the United States in late 2001 concluded that for a buried charge, the likelihood of flash burns was very low, even for a person that is unprotected. However, it should be added that for an unprotected soldier, there exists another source of burn injuries. The very high temperature of the detonation products ignites the plastic materials typically used to construct the mine case, which are then dispersed by the high-pressure blast front. The combustion of the case fragments takes a finite amount of time, as demonstrated in Figure 11. Thus, there is a high probability of burning fragments impacting the upper body.

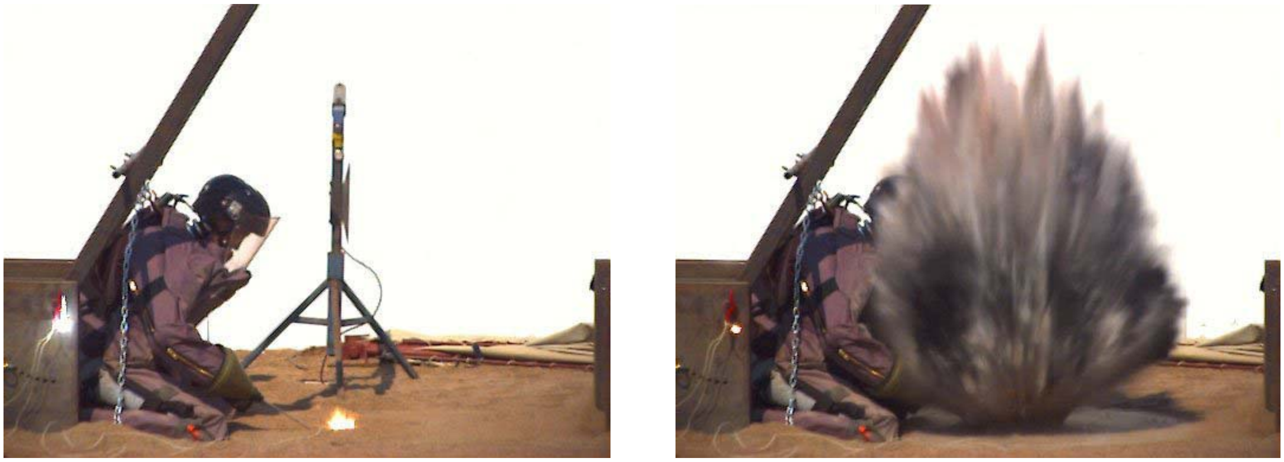


Figure 11: Explosion of a C4 Mine Surrogate Buried under 20mm of Sand showing the Loading Zone on a Mannequin Dressed with Protective Ensemble; timing between frames is 1msec; note the glow at upper edge of the detonation products indicating continued burning of case fragments. (Pictures courtesy of DRDC, Canada)

Blast injuries are related to the air shock and jetting of the detonation products. The physics of air shocks have been extensively documented for large blast weapons (tens to thousands of kg of explosive). The passage of a strong air shock results in a sudden change of local pressure, a change that the human body is ill equipped to cope with. Immediately after the passage of the shock, the air starts to flow outward from the source of the explosion. The flow from a large explosion can literally propel a person. However, a blast mine contains only a small amount of explosive and the strength of the air shock is insufficient to cause gross body translation. Yet, this air shock is still capable of injuring the human ear. Exposure to the high-speed flow of the detonation products is believed to be an important injury mechanism. The conical shape of the flow zone is such that the streaming gas often impinges on the upper body. The detonation products travel at great speed and can exert great force on objects in their path. When the flow stagnates on the body, it exerts a force capable of causing injury to the body. The magnitude of the force varies significantly within the blast cone, and the body position adopted by soldiers during mine clearance influences their likelihood of injury.

Fragmentation is usually not associated with the explosion of buried blast mines. However, the casing of some large blast mines, such as the PMN, is constructed from thick plastic that breaks up in a multitude of injurious fragments. The fragments from the top of the mine are particularly dangerous. Fragments from the sidewalls of the mine are also accelerated to great speed, however since their path is in the radial direction about the vertical axis of the mine, these fragments first hit the surrounding soil and get redirected upward before impacting the victim. This energy dissipation mechanism reduces the lethality of radial fragments. Another source of fragmentation is high-speed soil particles, small pebbles or rocks, and broken tool parts. Let us consider the soil particles first. Individual soil particles have a small mass, which limits their ability to penetrate the human body, but their large number has an abrasive effect that can injure exposed skin and sensitive organs such as the eyes. The distribution of particle mass and speed varies greatly within the conical danger zone. There are relatively few high-speed particles and these are concentrated within the central portion of the conical zone. Further away, particle speed drops rapidly, but there are more particles. Small pebbles and broken tool parts should be treated like primary case fragments due to their higher mass. They can usually pierce and penetrate the body. The wounding mechanisms and treatment for these large projectiles are fairly well understood by the medical community. From the perspective of protection, these fragments need to be stopped with armour, a process that is well developed for bullets and other high-speed projectiles.

Chapter 3 – ELEMENTS OF A MINE TEST METHODOLOGY

In the previous chapter, it was shown that fragmentation and blast mines generate a range of injuries to the lower extremities and to the upper body. The severity and extent of these injuries depend on the type and size of the mine, and its position relative to the victim. It was also shown that the injury data could be classified into three basic categories according to whether the victim activated a fragmentation mine, stepped on a blast mine, or was in a low-down position conducting a mine clearance task. It is known that PPE can protect soldiers against most types of potential mine injuries, but prior to deploying any PPE, the users want to know how well this equipment will work if it is ever needed. It is generally accepted that this is best achieved through testing, however it is unclear as to what testing should be done. Given that a soldier can be exposed to an almost limitless number of mine accident scenarios in the field, it is unlikely that a single test can produce results that cover all possibilities. Hence many tests might be required. But what should these tests be? In order to answer this question, it is useful to examine the basic characteristics and elements of a test.

Some basic characteristics of any PPE test include that the test conditions be *consistent* with the threat to be represented and the intended use of the equipment. A test method should also remain *practical*; otherwise, people might not perform the test at all. Some other important characteristics are:

- *Tractability* – the test conditions should be tractable so that anyone could reproduce that test. This includes elements such as the type of explosive charge, the type of soil, and the instrumentation used to measure some output.
- *Repeatability* – it should be possible to repeat the test over and over, within reasonable accuracy as defined by the physics of the phenomenon while remaining practical.
- *Sensitivity* – it should be possible to vary the input conditions and have this result in a detectable and meaningful change of the measured output, making it possible to rank the performance of the PPE.

The above characteristics should be intrinsic to any test. It is essential that the test conditions should be reproducible in any country willing to carry out testing. Furthermore, the test conditions should be sufficiently representative of the actual threats encountered by soldiers in the field. In order to achieve these requirements, a test methodology must be built around three elements as follows:

- A well-structured test protocol;
- Controlled, realistic test conditions; and
- An appropriate test surrogate.

3.1 WELL-STRUCTURED TEST PROTOCOL

Choosing a suitable test model and representative test conditions is important, but the procedures put in place to conduct the tests can be critical to the outcome. No test methodology would be complete without a detailed test protocol. A mine blast test usually involves a great number of steps during preparation of the surrogate, preparation of the test site, preparation of the test charges, etc. Immediately after the test, collecting the experimental evidence and properly identifying the test samples requires a lot of attention and care. This can be laborious and in the rush of ‘trying to get things done’, it is easy to miss something that could compromise the outcome of the test later on. Thus, it is important to put in place a system to minimize the probability that something important will be missed, and to document the process for analysis at a later date.

An objective review of any data would require careful documentation of all test variables and analysis techniques. Thus, the time and energy invested in a detailed test protocol is time well spent. It should be a consultative process that brings together all those who will have to implement the protocol, conduct the tests or analyse the results.

3.2 CONTROLLED, REALISTIC TEST CONDITIONS

It is important to subject any test device and protection to test conditions that are representative of real mine accident scenarios. There are two basic elements to such scenarios: the threat mine and the position of the victim relative to the mine. However, it is unclear what threat mines and what positions should be reproduced during the tests. The answer varies depending on the objectives of the test and the requirements of the users. Fortunately, only a few test conditions are required to cover a wide range of mine accident scenarios. It is useful to examine the basic elements required for a test methodology.

3.2.1 Reproduction of the Explosive Threat

There exist two mine threat classes: fragmentation mines and blast mines. PPE users often prefer that all tests be performed with ‘real’ mines, but access to real mines is limited because of the International Treaty that bans their production, transport and use. Moreover, there are so many variations of each mine type that it would be difficult to stipulate what mine or mines should be used. Finally, there is a degree of variability that is inherent in the physics of mine explosions, which further complicates the choice of the ‘most appropriate’ mine for a given test. From the standpoint of a test methodology, it is more important to reproduce the mine output within prescribed limits from test to test. Let us consider the simpler case first; fragmentation mines.

Fragmentation Mines

A quick survey of fragmentation mines reveals that the total mass of these devices ranges from 500g to 5000g and contains anywhere from 75g to 900g of explosive. In addition, the shape and construction of the fragmentation jacket varies considerably. Some fragmentation jackets are made of cast-iron, others from steel. The jacket shape might be smooth or there might be serrations, notches and/or grooves. Other jackets consist of pre-formed fragments embedded within a polymer or placed within inner and outer sleeves. Thus, the effective output of ‘real’ fragmentation mines can span a considerable range of fragment shape, mass and velocity. The exact fragment distribution cannot be predicted exactly as it is probabilistic by design. Finally, as the fragments disperse, fragment density decreases, and the probability of a fragment strike drops rapidly.

Given the characteristics of fragmentation mines listed above, it very difficult to obtain a pre-determined output. More important, there is no guarantee that a fragment will hit a particular portion of the PPE, and it is very difficult to determine the shape, mass and velocity of a particular fragment when it hits the target. This is undesirable for a test methodology and should be considered when testing PPE against fragmentation mines. When planning a fragmentation mine test, it is therefore important to carefully consider the aim to the test. Is it to verify the ballistic limits of the equipment? Or is it to find out areas that the equipment fails to protect? It might also be intended to subject the same equipment to the combined effects of blast and fragmentation by positioning the equipment in close proximity to the mine.

The investigation of the ballistic limits is better done under tightly controlled conditions. It is well known that the penetration of a fragment depends on several factors, including the shape, mass and velocity of the fragment. It also depends on the obliquity of the impact and the materials that the fragment and PPE are made from. A given PPE consists of several components that may be constructed differently, each with its own ballistic properties. Thus, proper testing of the ballistic limits of PPE involves testing each component separately under laboratory conditions using Fragment Simulating Projectiles (FSP) in accordance with NATO STANAG 2920. For a more realistic assessment, it is possible to test with different FSP shapes and sizes. The point of impact, the obliquity, and the velocity of the FSP can be controlled so that the results can be referenced to other tests. Tests against fragmentation mines should be reserved for final acceptance to provide confidence that testing with FSP is representative of mine fragments. Any PPE subjected to such testing needs to be exposed repeatedly to several mines in order to obtain a sufficient number of strikes. This will allow the use of limited statistics to quantify performance.

To summarize, when using a fragmentation mine, it is difficult to predict the shape, mass and velocity of each fragment, and the location of fragment strikes cannot be controlled precisely. This means that the same test must be repeated a multitude of times before the number of strikes becomes sufficient and the statistics meaningful.

Blast Mines

There exists a wide range of blast mines. From reference [2], it is seen that total mass varies from 75g up to 630g while the explosive content is between 28g and 300g. These mines come in a wide range of shapes with nominal diameters from 36mm up to 120mm. They are constructed from different plastics materials. Finally, the shape and composition of the explosive charge, as well as its location within the mine, vary from one mine type to the next. It is therefore expected that the effective output of blast mines will vary widely. The selection of a particular mine is difficult.

From the perspective of a test methodology, it is desirable to use a blast mine surrogate. This requires careful consideration of the loading mechanisms of blast mines, which might combine both blast and fragmentation. Epidemiology from blast mine accidents suggests that blast is the dominant injury mechanism for this class of weapon. However, the secondary fragmentation and environmental debris can prove highly injurious to the face, eyes, and other soft tissue. There is merit in having a mine substitute that reproduces the blast while keeping the fragmentation to a minimum. By using a widely available explosive and stipulating the geometric shape of the charges, it is possible to maintain some control over blast output. The use of a surrogate also avoids any issue relating to the International Treaty to ban AP land mines. However, there can be difficulties related to the selection of the type of explosive for testing. The explosive most commonly used in mines is TNT, but an explosive that is widely available across NATO is Composition C4 or PE4, which uses RDX as its main energetic material. The velocity of detonation of C4/PE4 is around 8200m/s, while the velocity of detonation for TNT is around 6900m/s. This means that the *brisance* (the ability to shatter a nearby object) of C4/PE4 is significantly greater than for TNT. Provided that this is taken into account, the use of an explosive such as C4/PE4 is acceptable.

It should be noted that even when using a well-characterized, widely available explosive, a mine explosion still exhibits an element of variability from one test to the next. There are several causes for this behaviour, mostly relating to the expansion of the detonation products. A simple observation of the early expansion of the detonation products shows that it is not perfectly uniform. The products jet out in some parts of the fireball. These jets produce localized regions of increased loading on nearby objects. This lack of uniformity implies that a given test, although conducted under seemingly the same test conditions, should be repeated several times to determine the level of variability. It also means that there is a minimum charge size increment under which the blast output may not be clearly distinct from one charge size to another. Generally, it is easy to select charge masses to mimic small, medium and large charges. Blast mines with less than 50g of explosive are generally considered small, while medium mines contain from 50g to 100g of explosive. Blast mines with more than 100g of explosive are considered to be large.

Blast mines are buried flush to, or just below, the surface of the ground. Research has shown that depth of burial and soil properties have a very strong influence on the overpressure and impulse distributions above the ground. Hence, soil type, grain size distribution, moisture content, and compaction, must be controlled so that variations of the mine blast output are minimized from test to test. From the perspective of a test methodology, it is also important that the soil conditions be easy to reproduce from one test site to the next. Finally, the preparation of the soil should be made easy so that it does not take so much time that it becomes the pacing item in a test methodology. Hence, the soil conditions should be selected so that they represent a compromise between realism, repeatability, control over the blast output, and practicality.

3.2.2 Positioning Issues

It was shown in Chapter 2 that during the explosion of a blast mine, the soil confines the expansion of the detonation products to create a conical danger zone above the ground, the so-called *blast cone*. The distribution of pressure and impulse within the blast cone is roughly symmetric about a vertical axis centred on the mine, but the blast loading on an object differs considerably depending on its location and orientation within the blast cone. Similarly, if a test is performed with a fragmentation mine, the number of hits, the range of fragment velocities, and the fragment distribution, all exhibit a strong dependence on distance from the point of detonation. PPE performance may often depend on its orientation relative to the source.

Whether a test involves a fragmentation or a blast mine, the position and orientation of the PPE is of paramount importance in a test methodology. Therefore, there is a need to position and hold a test surrogate in a particular location and orientation. Given the forces generally involved with a mine explosion, it might also be desirable to guide the motion of the surrogate or to allow specific motions to take place during the test. This might prevent unrealistic damage to the surrogate and better represent the injury mechanisms. In order to meet these requirements, various positioning rigs have been designed and used. These rigs also address the need for accurate positioning of the test model relative to the threat mine being tested. Several examples are given in the next two chapters.

Another issue that should be addressed with test surrogates and test rigs is *reaction mass*. Consider an object of a given shape and mass placed in the blast cone. Basic mechanics dictate that the effective forces acting on this object are greater when it is held fixed in place than when it moves with the flow. Mass also affects the time required for an object to accelerate to flow speed. For example, if a helmet is attached to a heavy object, it will be subjected to a greater force than if it is free to move. Similarly, within some range of impact velocity, fragment impacts might display more or less penetration power depending on how the object that it strikes is held in place. In some situations, depending on the protection level, reaction mass has a limited effect on outcome. For example, this is the case with a near-contact detonation under a leg where damage to the extremity occurs before any significant acceleration is imparted to the remainder of the leg.

3.3 TEST SURROGATES

The human body is composed of a very large number of cells that are organized into sub-systems. Each sub-system performs some function that is necessary for the proper functioning of other sub-systems, and so the proper functioning of the whole body depends on each part performing its function. Thus, the human body is highly complex and modelling its systemic response to injury is extremely challenging. One quickly realizes that a mechanical surrogate for the human body, no matter how complex, cannot come close to mimicking every reaction and deformation of the human body. One must make compromises and identify what responses dominate and drive the injuries being studied. A decision must be made as to the level of biofidelity required to achieve the objectives of a given series of tests.

A test surrogate could be anything, from a simple piece of metal, representing a small part of the body, to an intricate anthropomorphic model representing the whole body. The complexity of the model will be influenced by a wide range of factors such as the scope of the tests to be performed, whether the tests are developmental in nature, for manufacturing, or part of an acquisition program. And of course, there are always budgetary constraints. If the results from the model are to be used to assess the potential of injury to the human body, there is a need to validate or calibrate the model against results from a more biofidelic model or actual injury data (this is discussed in more detail in Annex E, Injury Models for Validation). The goal is to ensure that the injury risk assessment is as realistic as possible and includes the potential injury modes suitable for the scenario being considered. Irrespective of complexity, if a test model is to be successful in assessing the risk of injury, it must build upon three basic elements:

- *Surrogate* – this is the physical embodiment of the model. It could be physically very simple and may represent only a part of the human body. Furthermore, it could be robust for multiple uses, or frangible for single use. This surrogate must give a repeatable physical response that is consistent with known injuries as well as the aim of the test. Generally, a surrogate should be as simple as possible while still representing the relevant biomechanical response.
- *Engineering Measurement* – one or more physical parameters such as force or acceleration that may be used to quantify the physical response of the surrogate. The instrumentation must be selected in consideration of accepted or proposed injury criteria and the physical abuse it will be exposed to in the dynamic post-blast event. Data processing and filtering techniques must be suitable for what is being measured. Engineering measurements also include visible observations of physical damage.
- *Injury Risk Evaluation (IRE)* – a correlation between an engineering measurement and some injury model. For example, in frontal thoracic blunt impacts, an injury threshold of 60 times the force of gravity is used in the automobile industry. The IRE plays a very important role, linking the response of the surrogate to the probability of injury in real people. Annex E provides more details about the development of a suitable IRE for a given surrogate.

The elements listed above have been validated by the automobile industry where instrumented surrogates have been used for decades to evaluate the risk of injury from blunt trauma in automobile crashes. The success of this technique rests on the large body of work that was done to validate the model.

Chapters 4 and 5 present some of the surrogates used for PPE evaluation against AP blast and fragmentation mines. The advantages and limitations of the surrogates are discussed and guidelines on selecting appropriate surrogates for the different types of PPE evaluation are provided.

3.4 TRAUMA SCORING SYSTEMS AND INJURY RISK EVALUATIONS

The medical community uses Trauma Scoring Systems (TSS) for the purposes of triage and improving the quality of care. A TSS can be useful in a situation where the number of casualties to be treated exceeds the capacity of the trauma treatment centre. Therefore, there is an advantage in linking the IRE for a given surrogate to an existing TSS. This was achieved successfully for the Hybrid III when it is used for automotive crash tests. The same advantage might accrue when developing a new IRE for mine injuries. However, few TSS were developed for mine casualties and none applies to the full spectrum of mine injuries.

It is important to recognize that an IRE is developed for a specific surrogate, and that it is only valid when this same surrogate is subjected to specific loads within a range of physical inputs that has been validated against an appropriate injury model. Using an IRE outside this range, or for any other load mechanism, can lead to erroneous results. Given these facts, a new IRE must be developed for each surrogate and for each of the three basic mine accident scenarios discussed previously. Thus, it should be expected that a surrogate would have a different IRE if it is used against fragmentation mines than if this same surrogate is used to test upper body PPE against a buried blast mine. Since the surrogates used to test footwear against blast mines are different than surrogates used to test upper body PPE, there is a need to develop different IRE functions.

3.4.1 Fragmentation Mine Injuries

The International Committee of the Red Cross (ICRC) operates several hospitals in countries plagued with mines. The ICRC developed a TSS to assess gunshot wounds, and adapted it to assess the severity of mine accidents (see Table 1). Their scoring system deals primarily with missile wound injuries produced by fragmentation mines. It does not lend itself easily to scoring the traumatic amputations that are typically associated with blast mines. For example, the ICRC divides leg amputations into two rough categories, grade 3 type F for a below knee amputation, and grade 3 type VF for an above knee amputation.

Table 1: International Committee of the Red Cross Score

<table>
<tr><td colspan="4">DATA SECTION</td></tr>
<tr><td colspan="2">E = Entry wound diameter (cm)</td><td colspan="2">Estimate diameter of entry hole</td></tr>
<tr><td colspan="2">X = Exit wound diameter (cm)</td><td colspan="2">Estimate maximum diameter of exit hole
(X = 0 if no exit wound)</td></tr>
<tr><td colspan="2">C = Cavity? C = 0, 1</td><td colspan="2">Can the ‘cavity’ of the wound take two fingers before surgery?
No → C = 0; Yes → C = 1</td></tr>
<tr><td colspan="2">F = Fracture? F = 0, 1, 2</td><td colspan="2">No fracture → F = 0
Simple fracture, hole of insignificant comminution → F= 1
Clinically significant comminution → F = 2</td></tr>
<tr><td colspan="2">V = Vital Structures? V = 0,1</td><td colspan="2">Are brain, viscera (breach of dura, plura or peritoneum) injured?
No → V = 0; Yes → V = 1</td></tr>
<tr><td colspan="4">INJURY CATEGORIES</td></tr>
<tr><td></td><td>Grade 1</td><td>Grade 2</td><td>Grade 3</td></tr>
<tr><td>Type ST</td><td>Small simple wound</td><td>2 ST</td><td>3 ST</td></tr>
<tr><td>Type F</td><td>1 F</td><td>2 F</td><td>3 F</td></tr>
<tr><td>Type V</td><td>1 V</td><td>2 V</td><td>3 V</td></tr>
<tr><td>Type VF</td><td>1 VF</td><td>2 VF</td><td>Large wound(s) threatening life of limb</td></tr>
<tr><td colspan="4">Land mine blast injuries fall outside these classifications and are difficult to categorize:
Grade 3, type F, below knee amputation = 3 F BK
Grade 3, type F, above knee amputation = 3 F AK</td></tr>
</table>

The ICRC mine score was developed to treat real people with real injuries. It was never intended for use by agencies that develop or test PPE. If someone intends to develop a test surrogate and a corresponding IRE that can be related to the ICRC TSS, it will be necessary to proceed through a full validation process similar to that used in the automotive safety industry, as described in Annex E.

3.4.2 Upper Body Injuries Against Blast Mines

One of the better-known TSS is the Abbreviated Injury Score (AIS), which was first established in 1969 by a committee for the Advancement of Automotive Medicine. The AIS assigns severity scores to individual injuries and requires summary scores to classify multiples traumas. Injuries are ranked on a scale of 1 to 6, as listed in Table 2. The overall score provides a measure of ‘threat to life’.

Table 2: Abbreviated Injury Score

AIS Score	***Injury Level***
0	No Injury
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Not Survivable

Since its introduction, the AIS has proven to be extremely useful to rank blunt trauma injuries associated with automotive accidents. Thus, the automotive test community often makes an effort to relate their results, which are obtained with Hybrid III surrogates under laboratory conditions, to this TSS. Given that the same Hybrid III surrogate is often used to assess the performance of upper body PPE against blast mines, it is likely that this same TSS might be used.

3.4.3 Lower Body Injuries Against Blast Mines

In regard to lower extremity testing, there exist several medical scales that might be applicable. Surgically based medical assessment scales, such as the Mangled Extremity Scale (MES) (Gregory et al., 1985) are useful for field evaluation and treatment of injuries. However, the scientific comparison of various levels of protection often requires more detail in terms of damage to the leg (Harris et al., 1999). This was the motivation for the development of the Mine Trauma Score [12] (MTS), which is specific to blast mine injuries of the lower limb. This scale, shown in Table 3, is descriptive in terms of amputation level and is likely applicable to frangible and cadaver leg models, which can be evaluated by means of an autopsy. However, even here, there is debate about the coarseness of this scoring system and its use in differentiating between those less severe injuries likely to be seen with improved PPE for the lower limb.

Table 3: Mine Trauma Score for the Lower Extremity

Injury Assessment	*MTS*	*Contamination Level*
No major injury	0	Closed
Salvageable Limb	1	Closed
	1A	Open contained
	1B	Open contaminated
Below-Knee amputation	2	Closed
	2A	Open contained
	2B	Open contaminated
Below / Above-Knee amputation	3	Open contaminated
Above-Knee amputation	4	Open contaminated

Mechanical leg surrogates require alternate means of evaluation. Load cell, strain gauge, accelerometer, displacement transducer, and high-speed video data can be used to record the response of such legs for a relative comparison of the tested protection. Griffin et al. [13] have shown that some of these parameters can be correlated with bone fracture and trauma level.

Chapter 4 – SURROGATES AND INJURY MODELS FOR TESTS INVOLVING THE LOWER EXTREMITIES

The threat against the lower extremities comes predominantly from blast mines. Fragmentation mines are usually not considered for this type of test. Clinical experience [14,15] with typical blast mine victims indicates that the primary injuries occur in the foot, ankle and lower tibia. Thus, it is important that a lower extremity surrogate be able to assess the response in this region. Surrogates for the lower extremity might be classified into three categories: mechanical legs, frangible legs, and human cadavers. Given the high level of biofidelity of human cadavers, they are often used to validate simpler surrogates.

The selection of an appropriate test surrogate for the lower extremities requires trade-offs between cost, level of detail desired from the test, ethical issues, and ease of testing. However, irrespective of which category it falls in, a surrogate should be subjected to the same test conditions defined by the loading (surrogate mine, test soil) and the boundary conditions (test rig characteristics). Thus, a methodology for lower extremity tests must incorporate the elements depicted in Figure 12.

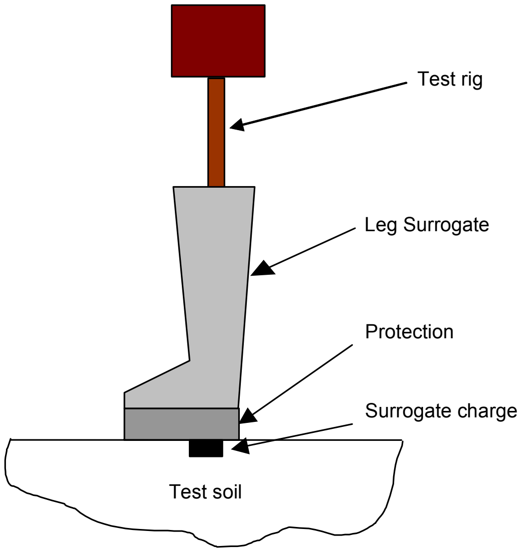


Figure 12: Schematic of a Typical Lower Extremity Test.

The level of detail and information required from a particular test determines the selection of a test surrogate. For example, it may be desirable to screen a variety of protective footwear and select one or more of them for further consideration. In this case, the first phase of testing might use a mechanical leg surrogate, which is cost-effective and simple, to provide a relative ranking of performance. The second phase of testing would be performed with frangible leg surrogates or cadaver legs to obtain more detailed information regarding performance and to better assess the level of trauma.

Assessing the likely medical outcome from a test is challenging. Here, medical outcome refers to the level of amputation, if any, and the long-term prognosis for a victim. This requires that a proper IRE be developed for each surrogate using a suitable injury model, e.g., a cadaver limb. The IRE relates some measurable quantities from the surrogate to the expected medical outcome or severity of injury. For example, the acceleration and impulse from a mechanical leg might be correlated to the level of trauma to a cadaver. It should be noted that, in all cases the true medical outcome must be inferred from the visible mechanical damage including tissue disruption, bone fracture, etc. The currently available injury models do not allow for physiological assessment, including certain aspects of nerve and arterial damage, as well as an assessment of the viability of some soft tissue.

In general, the assessment of trauma, or the performance of a protection system, must be evaluated using measurable and/or observable quantities related to the specific test device. The accuracy of the evaluation should increase from mechanical legs, to frangible legs, and finally to human cadaver legs. Examples of test devices for each category are now presented.

4.1 MECHANICAL (REUSABLE) TEST DEVICES

The category of reusable test devices includes a wide range of mechanical devices that are designed to reflect the mass and dimensions of the human leg while being rugged enough to survive multiple explosive tests. Since these devices are intended to be reusable, and blast testing can result in aggressive loading, these devices are commonly constructed out of rigid materials such as aluminium and steel. The motivation for this approach is that explosive experimental testing tends to be time consuming and expensive, making a reusable test device desirable both from a cost and efficiency perspective. Historically, mechanical legs were one of the first forms of surrogate for testing protection, with this type of leg being used by the Netherlands, United Kingdom, United States, and Canada.

4.1.1 Med-Eng Mechanical Leg

This rugged mechanical surrogate, shown in Figure 13, consists of a foot and the lower leg segment that are attached to a free resting counter mass. Two simple mechanical joints that allow motion about horizontal axes link the three components. The dimensions of the foot and the leg segment were selected to approximate the 50th percentile North American male.

**Figure 13: The Med-Eng Mechanical Leg.
(Pictures Courtesy of Med-Eng Systems, Canada)**

Performance Assessment

No attempt was made to develop an IRE for this test device. The output consisted of accelerometer data, which was used to gauge the amount of energy transferred to the model, and post-test examination of the level of damage to the footwear.

4.1.2 Netherlands Mechanical Leg

The mechanical leg designed in The Netherlands [16] evolved from several simpler versions. The first design of the leg surrogate consisted of separate metal tubes to represent the upper and lower leg, with the knee being modelled as a simple one degree of freedom mechanical joint. The volume between the metal foot and the protection was filled with gelatine to simulate the surrounding soft tissue of the foot and lower leg. The response of the leg was measured using high-speed imaging. To increase the biofidelity, efforts turned to an adaptation of the Hybrid III crash test dummy lower leg (Figure 14) and included accelerometers to monitor the response of the leg.

Figure 14: The Netherlands Mechanical Leg.
(Picture Courtesy of TNO PML, Netherlands)

Performance Assessment

No attempt was made to develop an IRE for this test device. The output consisted of load cell data and post-test examination of the level of damage to the footwear.

4.1.3 DRDC Mechanical Leg

The DRDC mechanical leg (ML) [17] is currently in use as a screening tool. This mechanical leg (Figure 15) is constructed of metallic and polymeric materials. The primary structural member is an aluminium tube with a urethane cast rubber calf and foot to allow a conventional boot to be fitted. Instrumentation includes accelerometers at the ankle and strain gauges on the aluminium shaft. The leg was mounted to a modified automotive shock absorber to obtain some measure of the momentum transfer to the leg.

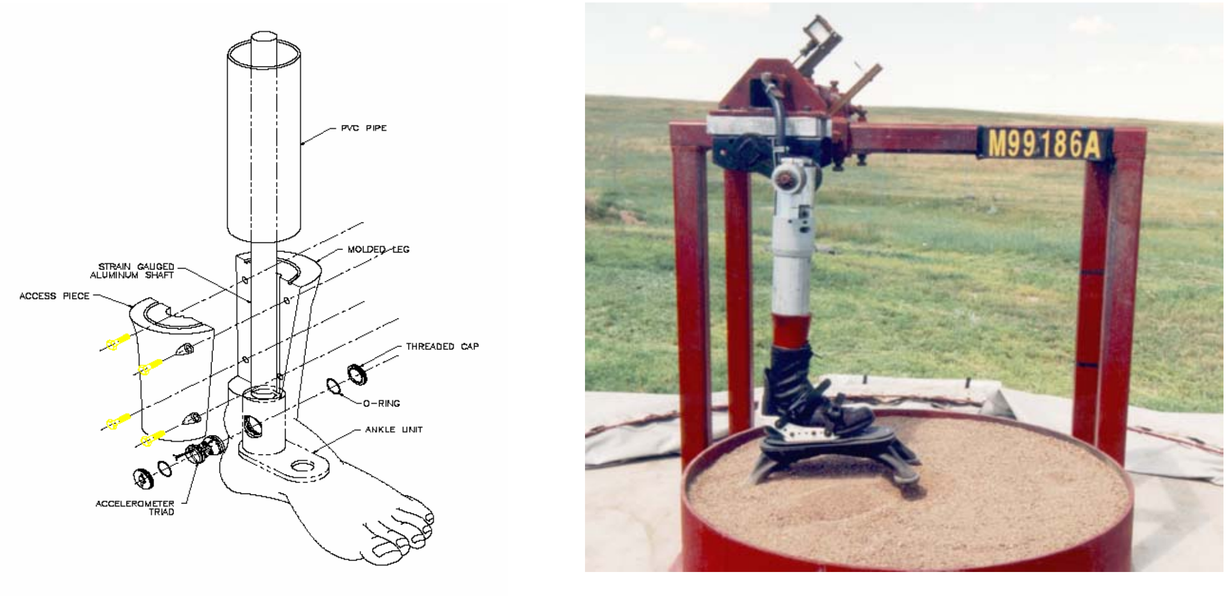


**Figure 15: The DRDC Mechanical Leg.
(Pictures Courtesy of DRDC, Canada)**

Performance Assessment

No attempt was made to develop an IRE for this test device. The outputs consist of strain gauge and accelerometer data. The strain gauge data was calibrated statically by subjecting the ML to known load inputs. Post-test examination included the level of damage to the footwear.

4.2 FRANGIBLE TEST DEVICES

The term frangible implies that the leg model is an approximate representation of the human leg, both in terms of geometry and material properties (elastic and fracture). In general, these models are expected to incur damage similar to the damage in a human leg under the same test conditions. As such, these models may be evaluated using autopsy-based procedures along with various measurements from accelerometers, load cells, strain gauges and high-speed imaging. Several leg models of this type are currently available, utilizing both biological and synthetic materials to represent those of the human leg.

4.2.1 Meppen Artificial Leg

Germany [18] developed a simple artificial leg using a hardwood rod, 20 mm in diameter, to represent the leg bones. The muscle tissue is represented with a light concrete material that has a density similar to that of soft tissue. Both components are attached to a steel pelvis simulator. The leg response is captured using high-speed imaging and acceleration measurements. A picture of the leg is shown below in Figure 16.

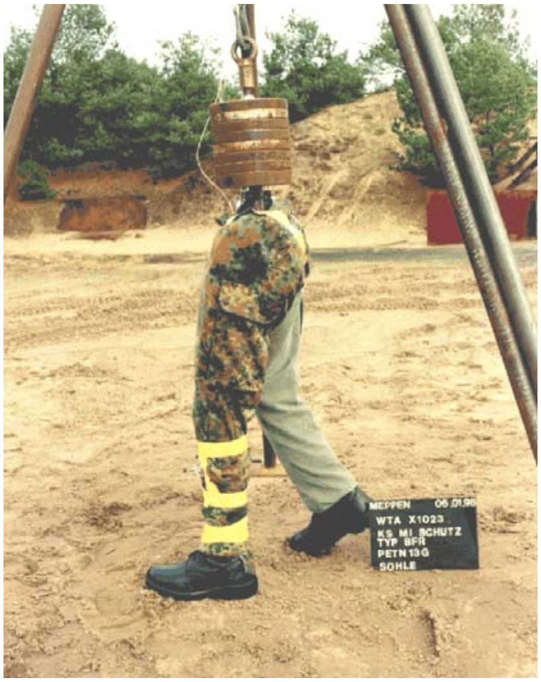


Figure 16: Artificial Leg.
(Picture Courtesy of WTD 91, Germany)

Performance Assessment

No attempt was made to develop an IRE for this test device. The outputs consist of acceleration data and post-test examination of the level of damage to the footwear. This device has the advantage that damage to the contra lateral leg can be assessed and it is relatively inexpensive to manufacture.

4.2.2 Red Deer Lower Limb Model

The UK developed a biological model of the human leg using the hind tibia of a Red Deer (Figure 17). The primary motivation for this approach was the similarity in dimensions between the Red Deer and human tibia. In addition, the mechanical properties of the bones, and in particular the fracture properties, were expected to be similar to those of human bone. The model incorporates the tibia, talus, calcaneus and metatarsal bones of the deer. Soft tissue is simulated with gelatine cast around the bones with dimensions representative of a human lower leg. Instrumentation includes accelerometers mounted on the tibial plateau. Evaluation of a given protection concept is accomplished by means of an autopsy to identify tissue disruption and bone fracture.

Performance Assessment

The main output is the level of damage to the bones. A limited study compared the level of damage to the red deer bones to that observed in the LEAP tests in the United States, but a formal IRE has never been developed.

Figure 17: Red Deer Lower Limb Model.
(Pictures © British Crown Copyright 20/DSTL/MOD)**

4.2.3 Frangible Surrogate Leg (FSL)

Australia [19,20] developed a frangible leg with human geometry. The geometry for the bones was created from a cadaver with dimensions corresponding to a 50th percentile Australian male. The FSL includes all of the major bones of the leg, which are cast using a synthetic material. The bones are assembled (Figure 18) with adhesive and simulated tendon materials. The resulting structure is then placed in a larger mould corresponding to the outer shape of the human leg, and gelatine is cast around the structure to simulate the soft tissues. A range of instrumentation has been tried with this surrogate, including strain gauges, load cells and accelerometers. The expected trauma to the leg may be evaluated using an autopsy-based approach to identify bone fracture and mechanical tissue damage.

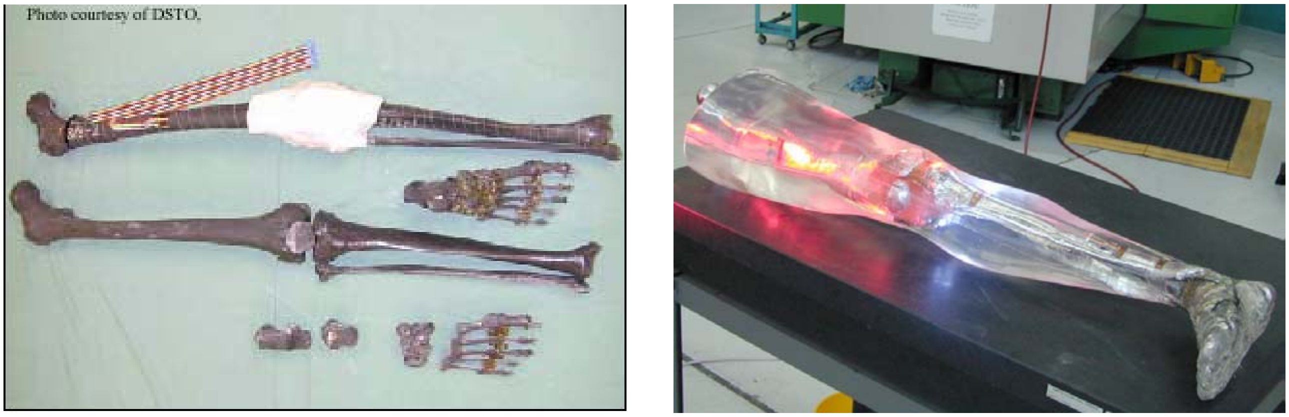


Figure 18: Frangible Surrogate Leg – Bone Structure (left) and Overall Cast Product (right).
(Pictures Courtesy of DSTO, Australia)

Performance Assessment

The level of damage to the soft tissue and bones of the FSL was obtained from post-test examination and compared [21] with the level of damage to cadavers observed during the LEAP program. This met with limited success because a one-to-one comparison using x-rays could not be done, but the FSL did display a similar level of damage. However, there has been no effort to develop a formal IRE for this model.

4.2.4 Simplified Lower Leg (SLL)

A simplified, frangible representation of the human lower leg [22] was developed for the purpose of evaluating landmine protection. This model consists of a central bone structure to represent the tibia/fibula, talus and calcaneus (Figure 19). A concentric volume of gelatine surrounds the bone structure to represent the soft tissues. Instrumentation includes strain gauges on the bone, as well as high-speed video and x-ray imaging to record the response of the leg. This leg has been used in both Canada and France for experimental testing of protection systems.

**Figure 19: Simplified Lower Leg.
(Pictures Courtesy of DRDC, Canada and DGA, France)**

Performance Assessment

A lot of consideration was given to matching the high-strain rate characteristics of the materials used in this model to those for human bones. The level of mechanical damage to the bones therefore corresponds well to those observed during tests against cadaver legs, this despite the simplified geometry. However, a formal IRE has not been developed for this model.

4.2.5 Complex Lower Leg Surrogate (CLL)

The design of the Canadian CLL [23] evolved from experience with the SLL (see Section 4.2.4). The design philosophy of the CLL was to create a synthetic surrogate leg, which could be evaluated using typical medical autopsy procedures to identify the extent and severity of injuries expected in a human leg. Key to the development of this leg was the selection of appropriate synthetic materials to represent the hard and soft tissues of the human lower leg. These polymeric materials were selected based on high-rate and quasi-static material properties including failure strengths. The geometry was designed based on the Visible Human Database (National Library of Medicine), corresponding to the lower leg of a human male. Care was taken to represent the load paths between the bones, while maintaining simplicity to reduce cost and increase consistency between legs. A finite element model of the leg also exists. Although instrumentation has been incorporated, the injury is primarily evaluated based on autopsies of the damaged CLL.

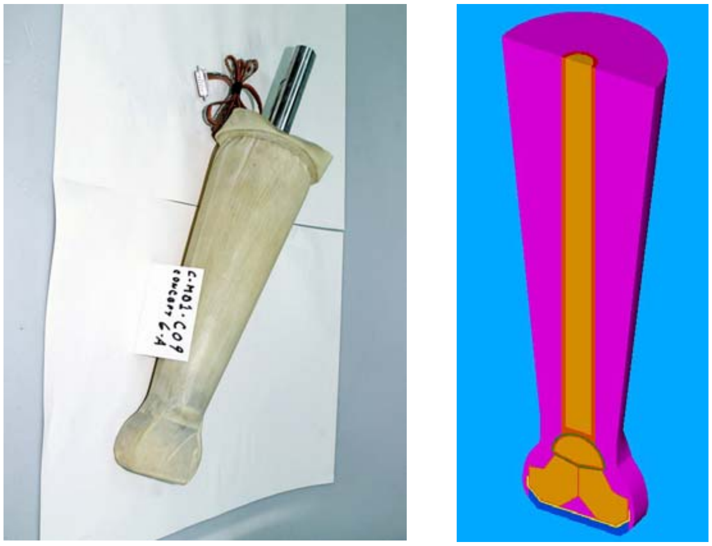


**Figure 20: Surrogate Complex Lower Leg.
(Pictures Courtesy of DRDC, Canada)**

Performance Assessment

A limited correlation of the soft and bone tissue damage predicted by the CLL was made with results from the LEAP program. The level of mechanical damage to the bones and the soft tissue stripping corresponds well to those observed during tests against cadaver legs. However, a formal IRE has not been developed for this model.

4.3 HUMAN CADAVERS

Biological specimens have been used successfully to test AP blast mine protective footwear. Tests have been performed with whole body cadavers as well as with isolated limbs. The obvious advantage of these models is the representative geometry of the leg, including the presence of muscles, fat, tendons, nerves, arteries and veins. This provides the ability to perform realistic autopsies to assess the mechanical damage to the leg. In general, the material properties of these biological models are excellent representations of the materials in a living human, with the possibility of reduced mechanical properties in the bone and tissue due to the average age typical of donors. When evaluating the results, consideration must be given to variability of the specimen size and bone strength.

It is generally accepted that this is the best human body model for validation of landmine protection, albeit with some potential constraints including ethical issues and availability. It is the most biofidelic model available for use in the development of an IRE. Thus, when performing tests with these specimens, the information should be catalogued for use in the development and calibration of frangible and mechanical leg surrogates.

4.3.1 Isolated Human Lower Limb Model

Researchers in the United Kingdom [14] investigated various protection concepts using amputated human lower limbs. The limbs were obtained from above and below-knee amputations due to peripheral vascular disease. The primary benefit of this approach was that the material properties of the bone and tissue had not degraded due to age. The limbs were mounted in a test fixture at or near the knee joint. Trauma was evaluated by means of post-test autopsies on the limbs.

4.3.2 Full Human Cadaver Body Model

A significant number of full body cadaver tests were done in the United States under the Lower Extremity Assessment Program [24]. Cadavers were typically received for testing in the 'fresh frozen' condition. They were thawed, instrumented, and tested within an appropriate time to maintain the mechanical properties of the various tissues. Instrumentation on many of the tests included strain gauges in the vicinity of the knee, as well as at the ankle, and a load cell located in the tibia (Figure 21). The benefit to this approach is the ability to assess mechanical injury to the leg through an autopsy. The use of full body cadavers also allows for the assessment of injury to the contra lateral limb.

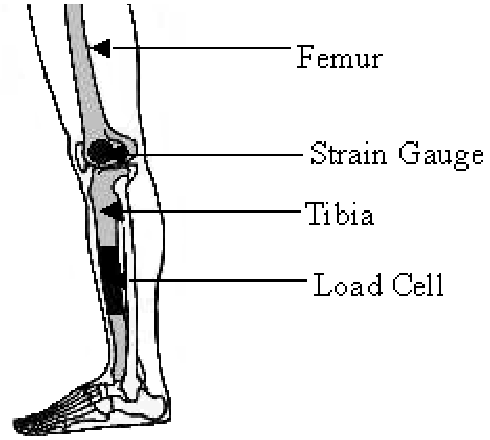


**Figure 21: Instrumentation for the Full Body Human Cadaver Model.
(Sketch Courtesy of CECOM, United States)**

4.4 SELECTING A SUITABLE LEG MODEL

From the above material, the reader can appreciate that a range of test surrogates exists and that selecting the best model for a given task can be difficult. In order to help a prospective user in that task, the TG-024 members compared the features that the models in each category have to offer. Several issues were considered, from the testing characteristics to the injuries. Table 4 presents the findings. In the first part of the table, the use of the qualifiers *low/medium/high* should be self-explanatory. For the remainder of the table, the qualifier *yes* means that a given model is definitely suitable to gauge the characteristic listed while the qualifier *no* means that the model is not suitable. The qualifier *maybe* was added because the characteristic listed might be evaluated through the response of existing instrumentation that has been calibrated, or by special modifications to the model.

Table 4: Applicability of Lower Body Surrogates

	Human Accidents	**Human Cadavers**		**Frangible Surrogates**		**Reusable Mechanical Surrogates**
		Full Body	**Lower Limbs**	**Organic Bones**	**Synthetic Bones**	
Testing Issues						
Availability	Low	Low	Medium	High	High	High
Repeatability	Low	Low	Low	Medium	High	High
Ethical issues	High	High	Medium	Low	Low	Low
Complexity (handling)	High	High	High	Medium	Medium	Low
Skeletal Injuries						
Bone disruption (forefoot/hind foot)	Yes	Yes	Yes	Maybe	Maybe	No
Tibial shaft or plafond fracture	Yes	Yes	Yes	Yes	Maybe	No
Knee joint fractures	Yes	Yes	Maybe	Maybe	Maybe	No
Femur fracture (not seen in practice)	Yes	Yes	No	Maybe	Maybe	No
Tarsal dislocation	Yes	Yes	Yes	No	Maybe	No
Ankle complex dislocation	Yes	Yes	Yes	No	Maybe	No
Soft Tissue Injuries						
Tissue stripping	Yes	Yes	Yes	Maybe	Maybe	No
Muscle contusion	Yes	No	No	No	No	No
Skin burn	Yes	No	No	No	No	No
Skin disruption	Yes	Yes	Yes	No	No	No
Internal/muscle burn	Yes	No	No	No	No	No
Neurovascular damage	Yes	No	No	No	No	No
Fragment damage (mine casing/soil)	Yes	Yes	Yes	Yes	Yes	Maybe
Contamination (soil/boot debris)	Yes	Yes	Yes	Yes	Yes	Maybe
Other						
Flailing	Yes	Yes	No	No	No	No
Contra lateral limb damage (fragment)	Yes	Yes	Yes	Yes	Yes	Maybe
Secondary Effects						
Swelling	Yes	No	No	No	No	No
Infection	Yes	No	No	No	No	No
Trauma cascade	Yes	No	No	No	No	No
Factors Affecting Injury						
Bone mass	Yes	Yes	Yes	Maybe	Maybe	No
Bone length	Yes	Yes	Yes	Yes	Yes	Maybe
Bone material properties	Yes	Yes	Yes	Maybe	Maybe	No

The primary goal of testing to evaluate protection against blast mines is to predict the resulting trauma to the human leg for a given combination of threat and protection. This includes mechanical as well as physiological damage. The various models allow for this assessment to varying degrees. What is important is that the model should be able to accurately assess the level of insult to the human leg, even for small changes in the threat. Thus, an increase in explosive charge size should result in increased injury for a given protection.

Human cadaver models are accepted as the best representation of the living human leg in terms of geometry, construction, and material properties. However, there are some limitations to this approach. One is that many countries do not actively participate in this type of testing due to ethical concerns. From a purely technical point of view, there are variations in geometry and material properties between cadavers. The cadaver age and medical history might also not be representative of the user population for PPE. Another important restriction is that cadavers must be treated as a Level 2 biohazard, which requires specialized facilities and personnel.

Despite their high level of biofidelity, cadavers still lack the very important physiological response necessary to truly evaluate the extent of trauma and long-term prognosis for the victim. Mechanical damage in the test model provides the primary correlation to real injuries but the evaluation of the long-term outcome based on the model results is open to interpretation.

Finally, cadavers require a physical examination necessitating the use of experienced personnel. While providing clear predictions of injury, the success of the evaluation relies on the relative experience of the staff performing the examination.

The philosophy behind frangible leg models is that by allowing the materials to fail in the same range as the human leg, a more accurate evaluation of the protection can be obtained. In addition, the control on material properties and geometry allows for high repeatability between tests. A frangible model can only be used once; hence each test requires a new surrogate. Depending on the number of tests and the cost of each model, this may or may not be cost effective. One of the issues with all current frangible models is the use of gelatine to simulate human soft tissues. For years, the ballistic community has used this material to study high-energy penetration of projectiles into human flesh. However, the uniformity of this material does not simulate the facia that divide the various muscle groups, nerve groups and vein/artery groups within the leg. These facia provide self-dissecting paths for the ingress of detonation products and environmental debris up the leg. Another difficulty is the short shelf life and need to refrigerate this material once cast, both of which complicate the testing procedures. Finally, frangible leg models, as with cadavers, require a physical examination that relies on the experience of the person performing the evaluation.

Mechanical leg models are designed for ruggedness, hence they might be cost effective if a large number of tests must be performed. This category of models usually requires less effort to prepare and set-up than frangible models. However, the ruggedness might affect how a given protection system deforms under load, thereby affecting the outcome of a test. This is the same effect that is seen in behind armour evaluations of ballistic vests where the backing material (i.e. the torso surrogate) affects the performance of the armour and potentially degrades or improves the performance over what would be expected on a human torso. This coupling between the PPE response and the leg is important when there is an overmatch between the threat and the protection.

Mechanical leg models rely on instrumentation such as accelerometers, strain gauges and load cells for injury evaluation. The IRE needs to be developed to correlate the instrumentation output with human injury. For this, cadaver and field results are required (Annex E explains the process and the need for a suitable injury model). One advantage of a mechanical leg model is that once an IRE exists and the level of protection is high, such models provide a quantitative method to rank performance for a given threat. This might make this type of model very useful and cost-effective within the context of quality assessment or a product improvement program.

4.5 TEST RIGS

Throughout Sections 4.1 to 4.3, it was often mentioned that the model was used in conjunction with a test rig. The reader should recognize the importance that a test rig has within the test methodology. A test rig serves several functions. First, it holds the model in a given location and orientation, thereby providing some control over the initial geometry and position relative to the explosive charge. Second, it provides a boundary condition with respect to how the model is attached (usually at its upper end). Third, it might guide the motion of the model after detonation. Finally, it might provide a specified preload prior to detonation and a reaction mass after detonation, the latter playing a role in the transfer of the explosive load within the model and the follow on global (late time) reaction.

Figure 22 shows an example of a test rig for lower extremity models. This particular design allows for the unconstrained vertical ‘jump’ of the leg while providing a reaction mass to the surrogate. The vertical motion of the cross head on which the leg is mounted, is tracked with a displacement gauge. Adjustable stops on the vertical rails hold the surrogate and protection systems in contact with the top of the soil/charge with a zero contact force. In the photograph the same stops are used to support the crosshead and leg during placement of the charge. All of these features are designed to provide the greatest possible repeatability of the boundary conditions between tests.

**Figure 22: Test Rig for Lower Limb Surrogate Testing and PPE Evaluation.
(Picture Courtesy of DRDC, Canada)**

The TG-024 members considered and discussed the issues related to boundary conditions for lower limb models during testing and decided that a test rig and appropriate reaction mass should be integral parts of a test methodology for footwear. Recommendations are made to that effect in Section 6.

Chapter 5 – SURROGATES AND INJURY MODELS FOR PPE EVALUATIONS ON THE UPPER BODY

It was seen in Chapter 2 that two scenarios prevail when it comes to mine injury to the upper body. The first scenario is that a soldier activates a fragmentation mine, in which case there is a high likelihood of being injured by fragments. If the soldier is very close to the fragmentation mine when it detonates, there is also a very high probability of thermal and blast injuries. The second scenario is that a soldier triggers a blast mine while in a low-down position, such as lying prone or kneeling. A PPE test methodology should try to reproduce the conditions for these two scenarios to ensure that the equipment performs satisfactorily. This also involves selecting a suitable upper body test model. Here, the definition of *upper body* needs to be examined more closely as it often differs for each scenario.

During a fragmentation mine test, the goal is usually to find out if the PPE leaves some areas of the body vulnerable. These tests are often performed with the test model in a standing position, albeit not necessarily facing the mine. During a blast mine test against a test model in the low-down position, the goal is usually to determine if the PPE stops fragments *and* whether the blast-induced forces transferred to the body reach injurious levels. In this case, given the position of the body and the nature of the blast mine threat, the definition of upper body refers to all body parts from the groin region up to the head, inclusive.

The selection of an upper body surrogate should also satisfy the basic elements of a mine test methodology, as was discussed in Chapter 3. Some of those key elements might include the anthropometrics, mass and inertia of the surrogate, instrumentation suited to the test conditions, and IRE functions that are applicable to the threat conditions. Relatively few test models have been used to perform upper body tests. Annex G provides an overview. Two tests were performed against larger explosive charges while the remainder relate to one of the two mine threat scenarios listed above. With the exception of one test series that was performed against head and arm components in isolation, all tests used a full-body Hybrid II or the Hybrid III anthropomorphic mannequin. These mannequins were developed for use in automotive safety tests, an application different than mine tests. This raises some questions regarding the suitability of these particular test models for mine tests. The mine type plays a key role in this determination.

5.1 FRAGMENTATION MINE TESTS

In the following discussion, fragment penetration is the primary injury mechanism that is being assessed by the model. Blast and thermal injuries will be considered in the following section on blast mine tests.

Assessing the performance of PPE against fragmentation often requires an anthropomorphic mannequin because it is important to fit the PPE properly over the body. For example, a visor might be mounted on a helmet such that it is held at a minimum distance from the face to provide space for back face deformation. It is important to properly fit the helmet over the head form to validate its performance. Mass plays a lesser role, but might still be important in some cases. Given that we are dealing with localized impacts, it is primarily the local characteristics of the PPE, and the fragment characteristics (mass, shape, velocity and obliquity), that determine whether there is penetration or not.

However, given that the tests are performed with high velocity fragments, what about the probability of damaging the mannequin? This is particularly relevant given the cost of a new anthropomorphic mannequin.

It turns out that there is an appreciable probability that penetrations will occur, which might damage the mannequin. Therefore, when formulating the test plan, it is important to determine what data needs to be collected. For most fragmentation tests, this consists of recording the number of hits and penetrations for each PPE component as a function of the test conditions. Given the probabilistic nature of fragmentation mines, there is also a need to perform a great number of tests to obtain a sufficiently high number of hits over any given part of the PPE. This can escalate quickly when one considers the distribution of fragment mass and velocity, orientation of the PPE relative to the mine, distance from the mine, etc. In practice, the same PPE is often exposed several times to the same test conditions until the cumulative number of hits is high enough to provide confidence in the results. It is then necessary to carefully monitor and record the location of hits, and preferably of penetrations, between each test. It is clear that the test model performs two and even three essential functions:

- It must fit the equipment properly;
- It might act as a reaction mass; and
- It otherwise acts like a witness panel.

Any test model that performs these three functions is well suited to this type of test. Expensive electronic instrumentation such as accelerometers and load cells are not required. Given the high likelihood of damaging the mannequin, it might be an expensive proposition to use a mannequin such as the Hybrid II or Hybrid III for such tests. Yet, the MCS4 tests [25] in Annex G used Hybrid II mannequins. However, these particular mannequins were no longer of use for automotive testing, which meant that they were acquired at a significant discount over the cost of new mannequins. Alternatively, there exist simpler anthropomorphic mannequins with mass characteristics approaching those of humans but that offer less biofidelity since they were not calibrated like the Hybrid family of mannequins. For example, FSTT fabricates and sells a low cost general-purpose anthropomorphic mannequin that is used in a wide range of roles such as training firefighters in evacuation drills.

As an alternative to full-body PPE testing, flat witness panels made of the actual material layers representative of a component of PPE may also be used for parametric testing. This controls costs where mines, distances and number of repetitions need to be varied.

5.2 BLAST MINE TESTS

Compared to a fragmentation mine test, a blast mine test is significantly more complex and demanding. In addition to the fragmentation hazard, there is a need to assess the effect that the blast force and soil ejecta stream might have on the body, including:

- Trauma to the head due to rapid acceleration or impact from the head gear;
- Trauma to the neck due to relative movement between the head and the torso;
- Trauma to the thorax due to acceleration of the chest wall or blast overpressure transmission;
- Trauma due to burns; and
- Trauma to the ears due to blast overpressure.

The first three of the above requirements mean that, in addition to having an anthropomorphic form, there is a need for the inertial response of the model (mass distribution and joint stiffness) to be representative of the response of the human body. In Annex G, it is noted that the Hybrid III mannequin is widely used.

This mannequin is available in several versions and a pedestrian kit makes it possible to position the mannequin in the prone, kneeling or standing poses that are typically adopted during mine clearance activities. Most of the mine blast tests listed in Annex G were performed against the 50th percentile male Hybrid III, while a lesser number of tests were performed against the 5th percentile female mannequin. The Hybrid III is believed to be one of the best options available for mine blast testing. However, it must be used with caution because it was designed for use in automobile safety. Automobile crashes and mine blasts are physically very different phenomena that occur on different time scales. Automobile crashes typically occur over a time scale of approximately 5 to 100 milliseconds while the time scale for mine blast injuries is of the order of 0.1 to 1 millisecond. Time scales have an effect on mannequin response, and mine blast injuries most likely fall outside the validated range of the injury criteria used for automobile accidents.

Experience with the Hybrid III mannequin has shown that it is rugged enough to be used in mine blast tests when wearing PPE, provided that some precautions are taken. The rubber skin and rubber components of the neck need to be protected, as these are very sensitive to damage from ejected sand and debris. The neck is also susceptible to becoming loose after several exposures to the vibration loads induced by blast. Thus, neck tension must be checked regularly (every three to five tests) during a test series. If these precautions are followed, the Hybrid III can be sufficiently rugged for the job. A range of instrumentation has been tested and it was found that the instrumentation used for automotive testing could safely be used. Table 5 provides an example of the instrument configuration used by Bass et al. [26] for their Hybrid III during mine blast tests performed in October/November 2000 (refer to Annex G for more details on the tests). The accelerometers, load cell and displacement transducers are standard for this mannequin. The remaining instrumentation, to monitor skin temperature and various pressures, was added specifically for evaluation in mine blast testing.

Table 5: Example of Hybrid III Instrumentation for Mine Blast Tests

Transducer	***Location***	***Evaluation***	***Sensor***
Accelerometer (Tri-axial)	Head Center of Gravity	Head Blunt Trauma	Endevco 7270A-6k
	Chest Center of Gravity	Thorax Blunt Trauma	Endevco 7270A-6k
Load Cell	Upper neck	Neck Blunt Trauma	Denton Upper Neck Load Cell
Accelerometer	Sternum	Thorax Blunt Trauma	Endevco 7270A-6k
Displacement Transducer	Sternum	Thorax Blunt Trauma	Servo 14CB1-2897
Pressure Transducer	Thorax: skin surface, between 3rd and 4th rib	Thorax Blast Lung	Kulite XCQ-093-500A Kulite LQ-125-500A
	Head, skin surface, mounted laterally at ear location	Ear Blast Damage	Kulite XCQ-093-500A
Thermocouple in Skin Simulant	1 each, thorax, head, hand	Thermal Blast Damage	Omega 0.5 mil and Omega 3 mil bare wire gages
Pressure Gauge	Free field at the same x y locations as ear and thorax	Free Field Pressure	PCB 102-A04

Given the higher loading rates associated with mine blast, the data acquisition rate must be increased relative to the rates used in automotive safety. The data must be sampled at 200 kHz or more to allow the use of a 40 kHz low-pass filter later on. Of course, some of the data, such as displacement and temperature can be sampled at much lower rates.

From 1999 to 2002, Canada and the United States developed a test methodology to assess the effectiveness of PPE against mine blast. This work included a detailed investigation to determine if the automotive injury criteria for the Hybrid III were applicable to mine blast. Some of the tests were performed with full-body cadavers as the injury model. The main findings from these investigations are summarized below.

5.2.1 Blunt Trauma to the Head

Injuries to the head are very common in actual mine accidents. These might be caused by environmental and casing fragmentation, direct blast impingement on the head, or blast forcing the protective headgear into the head. One injury criterion commonly used with the Hybrid III dummy head/neck complex is the Head Impact Criterion (HIC) for concussive head injury [27] based on the Wayne State Concussive Tolerance Curve [28]. HIC is defined as:

$$HIC = \left\{ (t_2 - t_1) \left[\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t)\,dt \right]^{2.5} \right\}_{\max}$$

where t_1 and t_2 are the initial and final times (in seconds) of the interval during which HIC attains a maximum value. Hence, HIC includes the effect of head acceleration and duration. When the acceleration is expressed in g's, a HIC value of 1000 is specified as the level for onset of severe head injury. The maximum time duration of HIC is limited to a specific value, usually 15ms. Physically, HIC predicts that large accelerations may be tolerated for short times and is evaluated using the head tri-axial accelerometers at the head centre of gravity. HIC is based on human cadaver and animal impact data with durations that are usually 5 milliseconds or greater, with extremely limited data less than 1 millisecond in duration. This raises serious questions about the applicability of the usual injury criteria to mine blast head trauma.

The standard HIC is computed from data that has been low-pass filtered at 1650Hz. However, a significant portion of the energy transmitted by a mine blast resides in frequencies higher than this cut-off. This was clearly demonstrated when HIC computations with data filtered at 10kHz produced much greater values of HIC. A subsequent series of validation tests was therefore performed with cadavers to obtain a definitive measure of mine blast trauma to the head. These tests demonstrated that applying the automotive version of HIC to mine blast is not valid as the automotive HIC criterion predicts head trauma well below the threshold of real mine blast injuries. However, these same tests determined that the concept of HIC might be applied provided that the acceleration is in the fore-aft direction and that a higher cut-off frequency is used with the filter. Thus, a new value of HIC is needed for mine blast trauma. Alternatively, Bass et al. [29] suggest that average acceleration might also be used.

5.2.2 Trauma to the Neck

Neck injuries from mine blast are possible when the rates of acceleration of the head and of the chest differ. Thus, the neck transmits the dynamic impulse due to the relative motion of the head and the chest. Physical trauma to the neck might then be evaluated using the neck force transducers designed for the Hybrid III. This transmission of force is relatively slow compared to the impact of the blast wave; hence neck injuries in blast are similar in rate to neck injuries that have been studied in automobile safety. There is a proposed Hybrid III neck injury criterion that is promulgated by the National Highway Traffic Safety Administration (NHTSA) termed the N_{ij} criterion [30]. It is a composite injury indicator based on a linear combination of neck forces and moments. The forces are the axial tension and compression, while the moments are flexion and extension. The postulated injury levels for these combined loads have been validated using human cadavers, volunteers, and animal subjects. N_{ij} is defined as:

$$N_{ij} = \frac{F_Z}{F_{INT}} + \frac{M_Z}{M_{INT}}$$

where F_z is the tension/compression force and M_z is the flexion/extension moment. The values F_{INT} and M_{INT} are the normalization values for the mode of axial force or bending as shown in Table 6. The hexagonal perimeter in Figure 23 represents the Injury Reference Value (IRV) of N_{ij} = 1.0 that corresponds to a 30% risk of severe neck injury. The shaded portion is considered acceptable neck loading by this criterion.

Table 6: Normalized Forces and Moments for N_{ij} Criteria

Intercept Value	*Hybrid III 50th % Male*	*Hybrid III 5th % Female*
F_{INT} – Tension (N)	4170	2620
F_{INT} – Compression (N)	4000	2520
M_{INT} – Flexion (N-m)	310	155
M_{INT} – Extension (N-m)	135	67
Peak Tension (N)	6806	4287
Peak Compression (N)	6160	3880

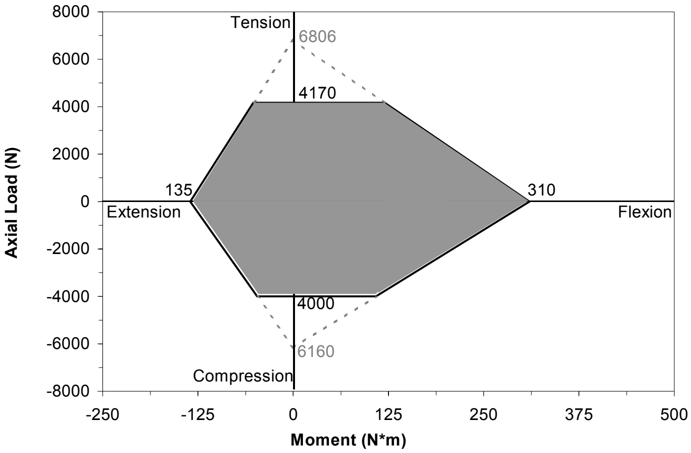


Figure 23: N_{ij} Criterion for the 50th Percentile Male Dummy.

During the above tests, it was found that the neck load cell performed well and that blast loads were within the range of application of the sensor. The data was repeatable and showed good sensitivity to the mine threat with the N_{ij} levels generally increasing with charge size. For the positions that were tested, the highest

N_{ij} value reported was 0.5, which is well below the IRV threshold (1.0). Other positions of the mannequin might generate values above the IRV as standoff distance is reduced, or the mannequin is placed further within the blast cone.

5.2.3 Blunt Trauma to the Thorax

Two injury criteria for thoracic trauma were examined for applicability to mine blast. The first criterion is direct displacement of the chest wall, similar to the thorax hitting the steering wheel during an automobile crash. A larger displacement corresponds to a greater impact force, and thus a greater risk of injury. The injury reference value (IRV) for chest displacement in a Hybrid III 50th % male dummy is 63mm [30]. The second criterion is the viscous criterion (VC), developed by Viano et al [31]. VC is the product of the velocity of chest wall displacement and the deformation of the chest relative to the initial thickness of the thorax. This quantity has been linked with the rate of energy storage in the thorax. A value greater than 1.0m/s is considered injurious.

In practice, it was found that there was no substantial motion of the chest wall. During a series of test performed by Chichester et al. [32], the chest displacement remained below 1mm, which is significantly below the 63mm reference value. Given this fact, the VC values were computed. Given the mode of loading, it might be possible that the displacement remains small while the velocity is significant. The velocity was obtained by integrating the Hybrid III chest wall acceleration measured with an accelerometer. The VC values were small, with the maximum value being around 0.35m/s. It was concluded that the risk of thoracic injury due to mine blast was low for the body positions that were used during that test series. The study questioned whether this measurement should be done in future tests.

5.2.4 Burns

Injury statistics suggest that there is only a small probability of burns from blast mines. Yet, there is a potential for burns close to mine blast through rapid radiant and convective heat transfer into the skin. The time scales for this injury, flash burn, are so short that heat transfer from the skin into the body is limited. This was investigated experimentally using a skin simulant for thermal insults [33]. The technique uses a plastic resin 0.5mm thick with an embedded thermocouple. The temperature output of the thermocouple was correlated with human injury 120µm below a living skin surface. These skin simulants were attached to the Hybrid III skin at the chin and on the left hand, and then exposed to the blast.

The burn sensors proved very delicate for this blast application, and only limited data could be recorded. The maximum temperature rise registered, less than 20°C, is due to the very short duration of the event and the mine depth of burial selected. This indicates that there is only a small risk of serious burns, with the caveat that this appears to apply for buried mine blast scenarios. More incendiary explosives (e.g. delayed or inefficient combustion) might increase the risk of serious burn injuries. Indeed, the depth of burial plays an important role in the amount of afterburn [8].

The above study recommended not using burn sensors in future tests, unless the test conditions generate a large amount of afterburn and radiant heat.

5.2.5 Blast Lung and Eardrum Rupture

The pressure transducers mounted to the head and chest of the Hybrid III were used to measure the likelihood of eardrum rupture and blast lung. The latter could result from coupling of the shock wave with poorly designed torso armour, as reported from British operations in Northern Ireland [34]. However, it was found that the loads generated by an AP mine, for the body positions considered, were well below the threshold required for blast lung injury. These findings do not exclude the possibility of such blast injuries for more severe conditions than those tested, due to the high sensitivity of blast strength to standoff distance.

Ear pressure was found to often exceed the acceptable threshold for eardrum rupture. It was found, in particular, that current helmet designs can increase the overpressure at the ear level. This is due to complex wave interaction within the cavity of the helmet when a blast mine explodes below. If the helmet is within the blast cone, there is also stagnation of the flow, which increased both the intensity and duration of the pressure pulse at the ear. The presence of a visor was found to lessen these effects significantly.

5.2.6 Traumatic Amputation and Soft Tissue Avulsion to the Hands

During full body cadaver tests performed in the United States in 2002 [29], the position of the hands and forearms relative to the explosion was deduced post-test using pre-test photographs. It was found that the risk of injury to this body part is a strong function of position relative to the blast cone. Figure 24 shows the position of the hands relative to the blast cone, which is indicated by the sloping lines. The injured hands are all within the blast cone at 10ms in the event. The uninjured hands are either close to or outside the blast cone. This emphasizes the important role of the blast cone in injuries from mine blasts. It is important to note that all of the tissue injuries seen in the hands and forearms would likely have been prevented by minimal protection of the upper extremity.

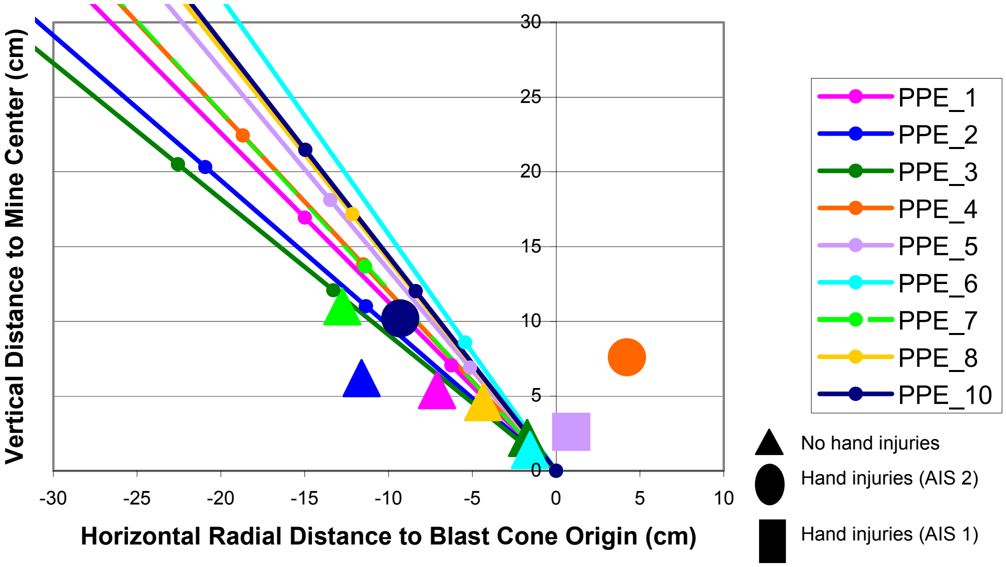


Figure 24: Hand Injuries using the Position of the Knuckles at 10ms after the Blast. (Results Courtesy from US Army CECOM)

5.3 COMPONENT TESTING

There are times when only certain components of the PPE need to be tested. It might then be cost effective to test these components in isolation, thereby avoiding using a full mannequin and a full PPE. Component testing might also be advantageous by reducing the setup time required to get results. This was demonstrated successfully in the United Kingdom (see Annex G) when there was an urgent need to test a variety of helmets and visors, and protective gloves. In preparing these tests, close attention was given to mounting the helmets on just the head of a mannequin, which was then rigidly attached to another structure so that the headgear would be at its proper location and orientation relative to the blast cone. Similarly, arm and hand surrogates were fitted with gloves and located appropriately relative to the mine. These tests were prepared and performed in a short time period.

The above example shows that component testing can be an efficient way to test specific PPE items. However, it is important that the threat be modelled realistically, that the PPE be mounted as it would on a person, and that the whole test apparatus (surrogate and protection) be located and oriented appropriately relative to the blast cone. The method of fixing the items is important as it might influence the outcome and there is a risk that the quantitative measurements taken might not be fully representative, particularly if the components are held rigidly in place against the blast.

5.4 TEST RIGS

Experience has shown that accurate positioning of the mannequin and PPE is crucial to ensure repeatability from test to test. Furthermore, the strong dependence between blast loading, position and geometry has been demonstrated repeatedly. Early during the development of an upper body test methodology, mannequins were positioned over a prepared soil bed using ropes attached to an overhead support frame. This demanded an inordinate amount of labour. More importantly, the mannequins could not be located in an accurate and repeatable manner nor could they be held immobile in a given position. The need for repeated and precise positioning of the mannequin in three dimensions required a more robust apparatus. A solution to this problem, which was adopted by two countries [26] to replicate a range of demining postures, is shown in Figure 25. It uses two support columns that can be tilted at various angles. Each column has a series of holes that can receive support brackets. A steel tube rests freely on these support brackets and the mannequin is fastened to the steel tube using chains and special brackets that are attached to hard points on the mannequin itself, as seen in Figure 26. The chain links permit discrete positioning while the support brackets allow backward motion of the mannequin away from the blast. The tube is free to fall from the support brackets if the blast is sufficient strong.

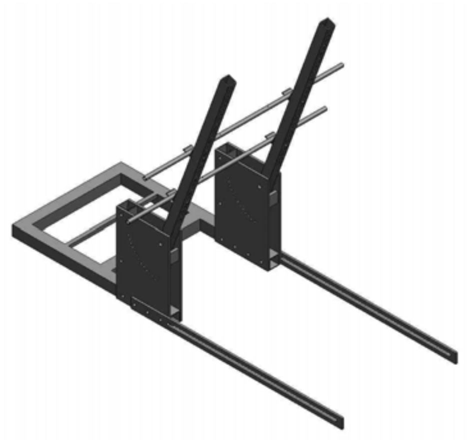


Figure 25: Basic Positioning Rig Concept Developed in Canada and used in Canada and the United States. (Sketch Courtesy of Med-Eng Systems, Canada)

Figure 26: Details of a Special Bracket made to Support the Hybrid III Mannequin. (Picture Courtesy of DRDC, Canada)

The support columns are mounted on a metal platform that provides a firm surface for the mannequin. Without this firm surface, it was found that small changes in the position of the knees (e.g. when they sank into the soil) made it difficult to locate the remainder of the body. With the firm surface, sand that may be blown under the mannequin during a test is easily removed and the knees can be repositioned accurately at positions marked on the surface of the platform. The platform also allows for the attachment of peripheral equipment such as reference gauges.

Prior to each test, a method was needed to confirm that the position of the mannequin had indeed been achieved. Measuring reference points on the chest and nose of the mannequin verified this. The measurement fixture consists of a vertical column with a ruler and two sliders that can be moved along the vertical axis. Each slider holds another ruler that moves along the horizontal axis. The measurements are simply read from the three rulers once all horizontal rulers are touching the points of interest on the mannequin. The measurement fixture was bolted on the rigid surface, thereby providing self-alignment. It also included a charge locator. As a result, the fixture allows a quick and accurate verification of the mannequin position and creates the charge hole at GZ at the same time. Combined with the quick repositioning of the knees on the platform, it is possible to reposition the mannequin to within ±5mm in a matter of minutes. Figure 27 shows the measurement fixture in place.

Figure 27: Rigid Test Platform with Positioning Rig and Measurement System. (Picture Courtesy of DRDC, Canada)

The same test rig can be used to support the mannequins in a standing position during fragmentation tests. A simpler alternative is to build a pair of ‘crutches’ with short horizontal supports that can be moved vertically until they fit below the arm pits of the mannequin, as shown in Figure 28.

Figure 28: Crutches Type Support Rig for Fragmentation Tests.
(Picture Courtesy of DRDC, Canada)

Chapter 6 – RECOMMENDED GUIDELINES FOR MINE TESTS

The mandate of TG-024 stopped short of a Standardisation Agreement (STANAG). However, the members of TG-024 recognised that the lack of standardised test parameters makes it difficult for NATO nations to compare test results, which potentially slows down the rate of development and acceptance of PPE. Consequently, following a review of test methodologies used by various NATO nations, the members of TG-024 agreed to produce guidelines as a first step towards common methodologies to test PPE performance against the effects of mines. This section details the committee recommendations in this regard.

The guiding principle of a test methodology is to define test conditions that are easily reproducible from one country to the next while being reasonably representative of actual threats encountered by soldiers in the field. Soldiers can be exposed to an almost limitless number of tactical scenarios in the field, and each case can be different. As has been noted earlier in this report, despite the diversity of scenarios, injury data suggests that the majority of situations can be related to only three scenarios:

- Activating a fragmentation mine;
- Stepping on a buried blast mine; and
- Triggering a blast mine while in a low-down position.

The material that follows is organized accordingly. Each scenario has its own test requirements, but many elements can be carried from one scenario to the next. Basically, a test methodology must build upon three key elements:

- A detailed protocol;
- Controlled, realistic test conditions; and
- A test surrogate suitable for the task.

The purpose of a detailed test protocol is foremost to document the process and ensure that steps are not missed. Proper planning, execution and later analysis of a test is mostly a matter of common sense. Time and effort spent upfront to better prepare will yield dividends later on.

Selecting the same controlled test conditions along with appropriate test surrogates is crucial if different test agencies plan to compare their results with each other. Therefore, each section that follows explains the committee recommendations in regard to explosive threat, soil conditions, choice of surrogate, positioning requirements, and instrumentation/measurement requirements.

6.1 FRAGMENTATION MINE TESTS

This type of test exposes a full body PPE or PPE components to fragmentation mines in order to investigate the extent of coverage provided by the PPE. The primary injury mechanism for these tests is fragmentation. However, resistance to blast effects might also be investigated if the PPE is located close to the source.

6.1.1 Explosive Threat

A wide range of fragmentation mines has been deployed. The threat type will likely be specified by the agency requesting the tests, or will be dictated by what is available.

6.1.2 Surrogate

A full body anthropomorphic mannequin is recommended in order to obtain a proper fit of the PPE. A range of commercially available mannequins exists that can be acquired for a reasonable cost. Alternatively, discarded automotive type mannequins might be used. There is a significant probability that the PPE will be penetrated and that the mannequin might be damaged.

6.1.3 Positioning

The standing position has typically been used for this type of test, although some tests have also been performed closer to the mine in the kneeling and prone positions (including component tests). The test plan usually specifies the test distances and the orientation of the PPE relative to the threat. For example, distance might vary from 1 to 5 metres and orientation might include having the PPE facing the threat, facing away from the threat, or being sideways to the threat.

Anthropomorphic mannequins require some form of frame for support. A crutches type support is sufficient for the standing position, but a more elaborate support frame (see Chapter 5) might be required for the kneeling position. Mannequins are relatively easy to place in the prone position, but the neck often needs modifications to assume the proper angle, as shown in Figure 29.

Figure 29: Discarded Hybrid II Mannequin with Modified Neck. (Picture Courtesy of DRDC, Canada)

6.1.4 Diagnostics

For fragmentation mine tests, the primary diagnostic is to count the number of fragments hits on the PPE and the corresponding number of penetrations. This is done by physical inspection. Refer to the section on blast mines versus the upper body, below, for diagnostics when the mannequin is in close proximity to the blast.

6.2 BLAST MINE TESTS VERSUS THE LOWER EXTREMITIES

The purpose of this type of test is to determine the level of protection that a given footwear design provides to the foot and leg. The TG-024 committee reviewed the test methods used across NATO nations for this type of test and agreed on test conditions that should make it easier to compare footwear performance between countries.

6.2.1 Explosive Threat

Table 7 lists the recommended parameters to standardize the blast mine surrogates for footwear tests. These do not preclude the use of actual blast mines to conduct the tests. However, it is increasingly difficult to obtain blast mines in the quantities required and at a reasonable cost. Furthermore, a test protocol should aim at standardising the threat used for testing. Most NATO nations have access to RDX-based explosive such as C4 and PE4. Since this is a ‘plastic’ explosive, it is easily moulded into the shape required for the tests. The smallest threat should contain 25 grams of this explosive, not including the explosive within the detonator and a booster, if required. It should be noted that C4 and PE4 have a velocity of detonation greater than TNT, which increases brisance. The specific energy of RDX is also greater than TNT. The committee limited the largest ‘required’ size to 100 gram for conventional footwear.

Table 7: Recommended Parameters for a Standardized Blast Mine Surrogate

Parameter	*Value(s)*	*Comment(s)*
Explosive Mass	25, 50, 75 and/or 100 grams	150 and 200 grams for platform footwear
Explosive Type	C4 or PE4	RDX based, 1.55 g/cm^3
Charge Geometry	Short Cylinder, 35% height to diameter ratio	
Detonation Point	Bottom centre of charge	Use as small a detonator as feasible
Container Characteristics	Plastic with 2 mm maximum case thickness	
Placement of Charge	Diameter dimension parallel to soil surface	±5° accuracy should be maintained
Depth of Burial	20 mm overburden	Top of container to soil surface

The geometric shape of the container for this explosive was obtained from a rough average of dimensions from actual AP land mines. An effort was made to use only the dimensions pertaining to the explosive portion of the mines, although this information is not always available. It was agreed that a 35% height to diameter ratio was representative of a wide range of AP mines. Once this ratio had been agreed to, it was simply scaled geometrically to each charge mass.

The location of the detonation point followed from two facts. First, the detonator is located on the underside of most mines to make it easier to separate this sensitive component from the explosive charge during transport of the munitions. The upper portion of the mine is usually reserved for the fuse mechanism, which is predominantly a mechanical system such as a pressure plate abutting to a Belleville spring or a plunger mechanism. The second reason for using bottom initiation of the detonation is that tests have shown that this produces a greater mine output in the vertical direction, primarily due to the direction of travel of the detonation wave impinging more directly onto the footwear. Having said that, it is also recognised that this mechanism is more important when there is direct contact between the explosive charge and the footwear. In most cases, it is the expansion of the detonation products, the hot gas bubble left after the passage of the detonation wave through the explosive, that is the main contributor to the blast loading. Tests have also shown that initiating the detonation at the centre of the explosive produces a blast overpressure similar to the bottom centre location.

The choice of detonator depends on the procedures in effect at each test site and specific instrumentation requirements for given tests. In most cases, there is a need to record electronic information and the accuracy required depends on the type of information sought. If the timing requirements are not stringent, a low voltage detonator can be used, however these detonators can take up to 100 to 200μs to initiate. When higher accuracy is required, then using a break wire around the detonator or a piezo pin in contact with the detonator to measure time zero can circumvent timing problems in the data acquisition during a test. High voltage detonators have initiation times usually less than 5μs, but they can cause voltage spikes in some sensors, corrupting some of the data acquired during the test. Detonators contain various amounts of explosive, from tens to hundreds of milligrams. Smaller detonators often require a booster to reliably initiate RDX based explosives. The mass of explosive within the detonator and booster should be recorded.

The burial method parameters were selected on the basis that the vast majority of mines are deployed parallel to the ground surface because of the fuse design. The 20mm overburden is realistic as most land mines are buried at shallow depth for concealment. Burying the mine too deep is generally not desirable because the surface force required to depress the pressure plate becomes significantly greater. The 20mm overburden also simulates the upper portion of the mine containing the mechanical components of the fuse, which do not contribute to the blast.

6.2.2 Soil Conditions

Table 8 lists the recommended parameters to standardize the soil type for footwear tests. The properties were selected for practical reasons including the need for the test method to be easily reproducible from one geographical location to the next. One major consideration is soil moisture, which is known to have a strong effect on the effective blast output transmitted to an aboveground target [35]. In general, blast output increases with soil moisture and a significant portion of this increase is attributed to soil ejecta momentum. However, for a near contact situation such as with footwear, soil moisture plays a lesser role and it is the close coupling with the gas bubble that dominates the event. Therefore, a dry soil is a suitable medium for the task. Dry soil also presents the advantages of being easily available and low cost.

Table 8: Recommended Parameters for a Standardized Test Soil

Parameter	***Value(s)***	***Comment(s)***
Soil Container Dimensions	600 mm × 450 mm x 300 mm (L × W × D)	Minimum dimensions, 12 mm steel
Soil Type	Medium sand, 300-700 micron particles	
Humidity Limit	< 1% relative humidity	
Compaction	1,3 to 1,7 g/cm^3 bulk density	Obtained from loose pour in container
Soil Replacement	Completely replace after each test	For larger containers, might change only upper soil portion that is contaminated

The main reason for the choice of minimum dimensions of the soil container is that they are the same as those used in the LEAP trials in 1998/99 [36]. LEAP is special because it used human cadavers for the tests, which resulted in a high fidelity dataset that can be referenced. Tests using this or larger sized containers should provide data sets that can be validated against the LEAP trials. Note that using a larger container means that more sand will be required. The reader should also be aware that a small container might be susceptible to wall effects, i.e., the initial pressure pulse may be reflected towards the test model. Such wall effects are believed to be minimal because footwear testing occurs in the near-contact regime where the expansion of the gas bubble is the dominant damage mechanism. However, there is still the risk that wall effects may modify the loading applied to the footwear and lower limb, and those influences could bias the results.

6.2.3 Surrogate

After careful consideration of various test models, the TG-024 committee agreed that there exists a range of surrogates that are acceptable for footwear testing. Consequently, it is left to the user to determine what surrogate best fits the requirements and expectations of their own test program. In support of that determination, the reader should refer to the material in Chapter 4 and Annex F for further information.

6.2.4 Positioning and Reaction Mass

Table 9 lists the recommended parameters to standardize the position of lower extremity surrogates and guide their motion after detonation. It is desirable to maintain a relatively constant orientation to generate test results that can be compared to other tests. For this reason, the committee recommends that the long axis of the model, defined as the orientation of the tibia or a measuring column, be kept vertical. For models containing a knee joint, the ‘leg’ should be fully extended. Motion of the surrogate should be constrained to the vertical direction using a test rig, as depicted in Figure 22. The use of this test rig provides good control over the position of the surrogate. Also, the vertical ‘jump’ is a useful physical output that can be measured, but this requires that the total mass of the surrogate and moving portion of the test rig be controlled.

Table 9: Recommended Parameters for Standardized Positioning of the Surrogate

Parameter	*Value(s)*	*Comment(s)*
Orientation of Leg	Vertical	±5° accuracy should be maintained
Degree of Knee Flexion	Fully extended	
Reaction Mass	25 ± 0.5 kg	Does not include footwear mass
Pre-Load on the Charge	0 kg	Lower stop on test rig prevents sinking
Location of Charge	Under centre of heel	Selected to produce worst outcome under conventional footwear

The TG discussed the issue of applying the weight of the surrogate on the soil surface. The load carrying capacity of loose poured dry sand is very low; hence the model will sink into the sand, reducing the standoff distance from the explosive. In the interest of controlling the explosive input into the footwear and lower limb, it is desirable to maintain a consistent standoff. This requires the use of a lower end stop on the test rig, effectively resulting in a zero pre-load on the charge.

The charge should be located under the centre of the heel, or centred under the vertical axis of the surrogate. The heel location was chosen because it usually results in the worst clinical outcome for the victim, i.e., traumatic amputation of the foot. Other locations can be used if called for by the test requirements.

6.2.5 Diagnostics

The choice of instrumentation will depend on the type of leg surrogate selected and the goal of the tests. Frangible surrogates might be instrumented with strain gauges that can be calibrated to measure peak forces and moments. Displacement and acceleration of the test rig crosshead might be monitored to estimate the total momentum transfer to the surrogate. However, the greatest value from frangible surrogate comes from a post-test inspection of the physical damage. The details of the surrogate preparation, the initial set-up, the conditions of the surrogate immediately after the test, and the post-test inspection should all be recorded photographically.

Flash x-rays have been found useful to capture the process of deformation of the footwear and surrogate during the blast event, leading to a better understanding of the event. High-speed film and video might provide useful information if the framing rate is high, in excess of 5,000 frames per second. Otherwise, their usefulness is limited as the detonation products quickly obscure the view.

Mechanical leg surrogates must be instrumented to provide useful information. Typical instrumentation has included strain gauges that might be calibrated to measure force, moments and torsion. Accelerometers might also be useful, but care must be exercised in mounting them so that they are isolated from the higher frequency vibrations associated with the metals typically used in the construction of a mechanical leg surrogate.

6.3 BLAST MINE TESTS VERSUS THE UPPER BODY

The purpose of this type of tests is to determine the level of protection that PPE provides to the upper body, defined as all body parts from the groin region up to, and including, the head. The TG-024 committee reviewed the test methods used across NATO nations for this type of test and agreed on test conditions that should make it easier to compare PPE performance between countries.

6.3.1 Explosive Threat

The explosive threat should be the same as that defined in Table 7, with the caveat that due to the increased standoff between the charge and the PPE, only the larger charges (100 to 200 grams) might generate injurious outputs. Of course, this will depend on the distance between the surrogate and the charge as well as the position of the surrogate relative to the blast cone. It is very easy to create conditions with a 25-gram charge that would challenge the PPE.

The recommended depth of burial is 20 mm, which was selected as a good compromise that is representative of the average conditions in the field. However, the user should be aware that this might be a very powerful parameter to vary. Depth of burial can be used to vary the balance between blast overpressure and the amount of momentum stored in soil particles. For example, burying the charge flush with the soil surface will maximize blast overpressure and generate a very hot event, i.e., with an intense fireball, but there will be minimal soil ejecta. By burying the charge deeper, say below 120 mm of soil, there will be very little blast overpressure, but a large amount of soil particles will be accelerated upward, which will have a strong abrasive effect on the PPE.

6.3.2 Soil Conditions

For ease of handling and to minimize preparation time, a dry, medium sand, as stipulated in Table 8, should be used for upper body tests. However, given the importance of the blast cone, the container walls should not be less than 600mm apart because they affect the direction of the ejecta flow later in the event.

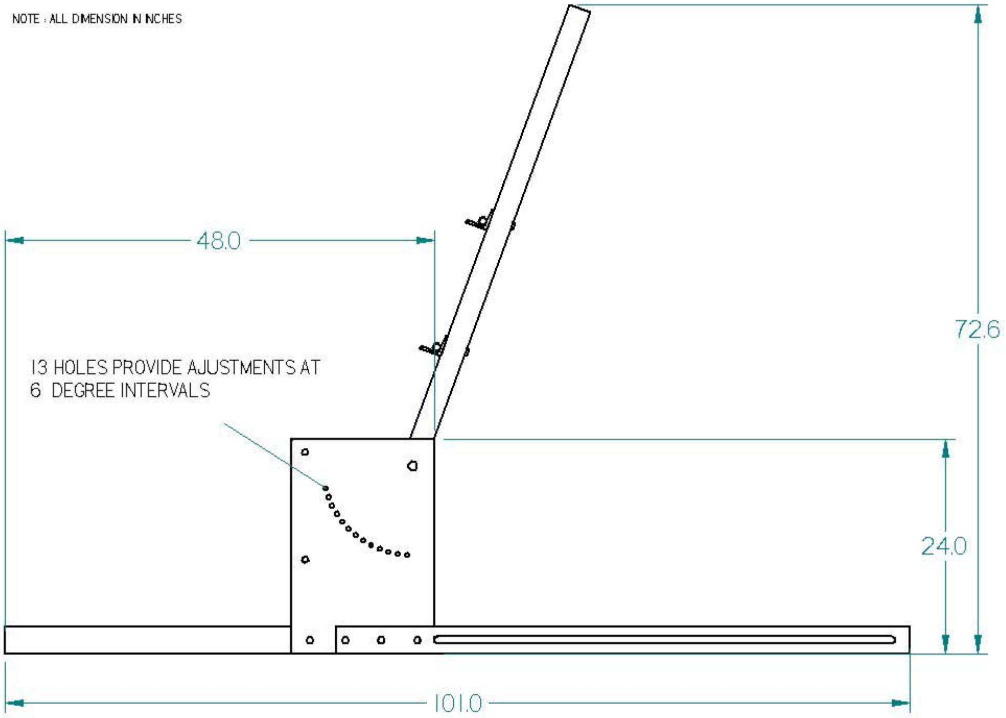
6.3.3 Surrogate

Due to the large body of data that has already been accumulated while using the Hybrid III anthropomorphic mannequin, the TG-024 committee agreed that, by default, this mannequin is the most appropriate surrogate for this application. The Hybrid III is therefore recommended for testing upper body PPE against the effects of blast mines. Provided that care is exercised with the mannequin, as explained in Chapter 5, it should provide reliable results that can be compared with the growing database of upper body PPE performance.

It should be noted that component testing remains a viable avenue for upper body tests, provided that the PPE is fitted properly to suitable surrogate components.

6.3.4 Positioning

Positioning of the mannequin relative to the blast cone is crucial. In order to minimize handling difficulties with the Hybrid III mannequin, it is recommended that the test rig depicted in Figure 25 be used. This will also require the manufacture of specialized brackets that attach to the mannequin, as shown in Figure 26. Figure 30 provides the basic dimensions of the rig.



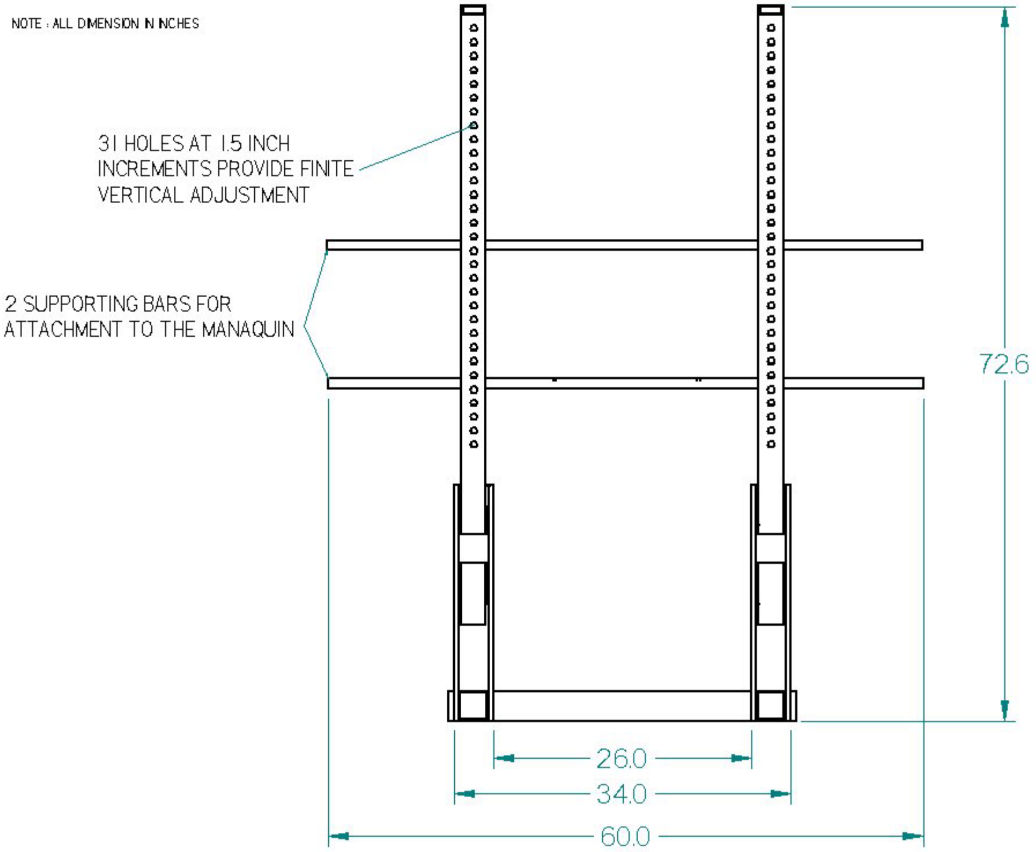


Figure 30: Dimensions of the Test Rig used to Position the Hybrid III Mannequins. (Sketches Courtesy of Med-Eng Systems, Canada)

6.3.5 Diagnostics

Table 5 provided a list of instrumentation for the Hybrid III. From this list, it is recommended that the minimum instrumentation should include head acceleration, neck forces and moments, and acceleration of the chest centre of gravity. The remaining instrumentation is optional, depending on the purpose of the tests. However, it is recommended that free-field side-on overpressure be measured in order to monitor the repeatability and quality of the explosive charges.

In regard to the data acquisition system, the sampling rate should be 200 kHz or more so that the data can be filtered with a 40kHz low-pass filter during post-processing. Experience has shown that the duration of the sampling should be of the order of 100 milliseconds or more.

Data interpretation for neck loads can be done using the N_{ij} injury criteria developed for automotive safety. For estimating head injuries, the automotive HIC has been used to interpret experimental results. However, experience has shown that the HIC cannot be applied to mine blast data directly and that a modified version of the HIC must be used. At the time of writing this report, work was till ongoing to develop a modified HIC for blast load applications.

Chapter 7 – CONCLUSIONS

TG-024 was established in response to mounting evidence that anti-personnel mines had become a significant threat to soldiers. This had prompted the development of new PPE in several countries. However, there had been no effort, until TG-024, to coordinate how PPE should be tested against AP mines.

The accident data available to TG-024 demonstrated that the majority of mine accidents belong to one of three types. A soldier is either the victim of a fragmentation mine or a blast mine. The majority of fragmentation mine accidents result in ballistic wounds, but blast mines result in two patterns of wounds. A blast mine may explode under the lower extremity, or in front of a soldier conducting mine clearance tasks. Since these three scenarios result in distinct patterns of injury, each scenario requires that the PPE be subjected to a different test that is appropriate for the threat conditions.

The work of the TG then focussed on reviewing the various test methods that have been used within NATO and its Allies to assess the performance of PPE against mines. This review looked at the strengths and weaknesses of each method, seeking to find what was essential for each type of test. The aim was to try, as much as possible, to define common test conditions that would be suitable for each test scenario, while remaining practical to implement. Agreement could be reached on several points. In particular, it was agreed that a test methodology must be well structured (detailed protocol), that the test conditions must be realistic and well controlled, and that a suitable human body surrogate must be selected to assess the performance of the PPE. The main test conditions and surrogates that were agreed upon include:

Fragmentation Mine Tests:

- Anthropomorphic mannequin to obtain good fit of PPE
- Fragmentation mine to be decided by the user
- Main diagnostics consists of counting number of hits and penetrations

Blast Mine Tests Against Footwear:

- Frangible or mechanical surrogate with suitable damage assessment method
- Mine surrogate consisting of C4 or PE4 explosive packed in cylindrical containers with prescribed detonation point
- Charge buried in dry medium sand
- Test rig required for guiding the motion of the surrogate vertically
- Defined total reaction mass of the surrogate and guidance system
- Zero preload applied on the soil

Blast Mine Test Against the Upper Body:

- Hybrid III anthropomorphic mannequin
- Suitable instrumentation for head, neck and chest as a minimum
- Charge and soil conditions as per blast tests against footwear

- Location of the mannequin relative to the charge and blast cone is critical
- Need for a test rig to position the mannequin

7.1 WHAT COMES AFTER TG-024?

TG-024 was assembled in response to a need for improved PPE for soldiers, and the corresponding need for improved test methodologies to evaluate PPE performance. This brought together an excellent team of professionals from several branches of science, engineering and medicine. It included PPE manufacturers, people that test PPE for a living as well as soldiers with field experience in countermine activities. This team of experts considered the problem at hand with the best information available during the mandate of the TG. As such, TG-024 captured a snapshot of the state-of-the-art at the present time. The situation will change in the future, so what next?

A great deal of the TG-024 work was based on field reports of accidents that happened before the introduction of new PPE. There is therefore a need to monitor the situation in coming years to see how new PPE performs. It is possible that in 5, 10 or maybe 25 years, the need will rise again to assemble a team to carry the mandate of TG-024 further. In the mean time, the recommendations of the TG-024 are considered to be state-of-the-art, as they are based on all available knowledge in this area, and represent an evolution of this knowledge towards common test methodologies. This report represents an honest and best effort from the participants, and is the first consistent and detailed approach for testing PPE over a wide range of conditions.

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Annex A: TG-024 TERMS OF REFERENCE

TASK GROUP HFM-089/TG-024

TEST METHODOLOGIES FOR PERSONAL PROTECTIVE EQUIPMENT AGAINST ANTI-PERSONNEL MINE BLAST

ORIGIN

A. Background: The protection of dismounted soldiers against anti-personnel (AP) land mines has been a major objective of Military Forces since WW II. Much effort has been directed towards the development of personal protective equipment (PPE) over the past 5 decades with varying degrees of success. The past five years has seen a renewed interest to address this problem and has lead to the emergence of new PPE, ranging from footwear to full body protection.

B. Justification (Relevance to NATO): Individual nations or consortia of nations have conducted most of the recent PPE development work. It was recognised that there is a lack of common international procedures to evaluate and assess the performance of this equipment. A team of subject experts confirmed this during the HFM ET-007 meeting held in Brussels, 22-24 February 2000. The meeting also identified that advantages would accrue from pooling knowledge and experience from the participating nations; developing a common and quantitative understanding of the physics of AP mine blast and the resulting injury mechanisms to the human would benefit all participants. It should guide the development of more effective strategies to mitigate the effects of mine blast and lead to future PPE improvements.

OBJECTIVES

A. General Goals:

- Assemble a database of epidemiological data and tried/proposed test methods for PPE against AP mine blast
- Develop and publish a consolidated description of the physics of AP mine blast, resulting human injuries, field medical procedures and generally available protective measures
- Develop common injury assessment criteria (footwear and upper body)
- Develop common test procedures and equipment to test PPE (footwear and upper body)
- Produce a comprehensive Technical Report

B. Expected Deliverables:

- Annual progress reports
- Technical Report on the physics of AP mine blast, resulting human injuries, field medical procedures and protective measures
- Guidelines of procedures, equipment and injury assessment criteria for testing PPE
- Final administrative report of the activities and results of the TG

The duration of the TG will be 2 ¾ years.

2001				2002				2003			
Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
	1st meeting (RTA HQ)		2nd meeting (CA)		3rd meeting (UK)		4th meeting (US)		5th meeting (GE)		Publish final reports

RESOURCES

A. Membership:

Team Chairman: Dr. D.M. Bergeron (CA)

Vice Chairman/Secretary: Mr. S. Waclawik (US)

Participating nations: CA, FR, GE, NL, UK and US

The TG members require expertise in at least one of the following areas:

- Medical aspects of mine injuries and their treatment
- Explosive effects related to AP mines
- Material performance against mine blast
- Protective measures and equipment for soldiers
- Test methods and instrumentation

B. National and/or NATO Resources Needed:

Most participating nations already have a national program to develop and tests PPE. The TG members need to obtain permission for the release of national test data and experience to the TG. Each nation is responsible for its own travel. Invitation of the TG members to relevant national PPE tests should be considered.

SECURITY LEVEL

NATO Unclassified or NATO Restricted.

PARTICIPATION BY PARTNER NATIONS

Partners are welcome. Australia is also invited to contribute.

LIAISON

- Coordination/collaboration will be established with the proposed TG on protection of vehicle occupants from AT mine blast. The two TG share some aspects of mine blast protection and close coordination will allow TG members to gain a broader perspective on the subject.
- The US volunteered to act as a central collation and distribution point for TG information/data.
- In addition to the initial meeting at the RTA in Paris, four additional meetings will take place during the duration of the TG, two meetings will take place in North America and two in Europe.

Annex B: CURRENT MINE PROTECTION EQUIPMENT

There exists a range of protective equipment for soldiers. At the upper range of the threat, countries have developed PPE for specialists such as Explosive Ordnance Disposal (EOD) technicians. The resulting equipment, often called a bomb disposal suit, is heavy and bulky, which increases the body's metabolic rate and quickly leads to an excessive heat load that results in physical and mental impairment. The ergonomics of this equipment interferes with human senses such as hearing, vision and tactility. Mobility and flexibility are also hindered, which limits the person's capacity to carry out their tasks. This equipment is therefore limited to special functions, and it is impractical for mainstream soldiers.

Figure B1: Components of a Generic Mine Clearance, Search or Lightweight EOD Suit. (Photo ® British Crown Copyright 20/Dstl/MOD)**

PPE FOR MINE CLEARANCE

In recent years, lightweight bomb suits have been developed for specialists clearing AP mines. The main difference is a suit-wide reduction in the protection against primary fragmentation, while retaining sufficient protection over vital areas such as the head, torso, abdomen and pelvis. There is also a lesser need for blast protection to the torso. Figure B1 (above) illustrates the generic protection available and why it has been designed the way that it has. For ease of presentation, each part of the body is taken in turn from the head downwards. It must be noted that not all of these components of protection are used all the time and by all users. The minimum for locating mines should be eye protection with polycarbonate glasses and a visor. Consideration should be given to adding a helmet, then body armour, then a complete demining suit, and then, possibly, move to a full EOD suit.

Head

Some type of composite helmet should protect the head. The helmet might be of a common fragmentation protective material, and probably similar to a combat helmet. The helmet should be designed to defeat both secondary and primary fragmentation.

Face and Eyes

As a minimum, the face and eyes need to be protected with a visor, with some type of goggles (see Figure B2), or even both. The visor and goggles are usually manufactured from a transparent impact resistant material such as polycarbonate or polycarbonate with acrylic. This should provide a high level of protection against secondary fragmentation, dirt and debris, and a limited level of protection against primary fragments from the mine body. One concern with transparent protection is that it is usually susceptible to damage and degradation that obscure vision. The visor or goggles need to be replaced when this occurs. In particular, polycarbonate scratches easily. It should also be noted that a visor should be fixed in the down position, when operating. If it is in a partially raised position, particularly when in a prone position, the blast from a mine explosion gets under the visor, causing lift and could lead to serious neck injury. It has also been shown that a visor in this position will focus any secondary fragmentation from an AP mine blast into the face, to a greater extent even than with the visor in the fully up position.

Figure B2: Protective Goggles.
(® British Crown Copyright 20/Dstl/MOD)**

Neck

Neck protection usually consists of a flexible collar that is constructed from a common protective textile material. Examples of this type of material could include the para-Aramids (Kevlar® or Twaron®), the ultra high molecular weight polyethylenes (Dyneema® or Spectra®) or PBO (Zylon®). The collar could be stand-alone, or part of the body armour below it. The rear (nape) of the neck may have additional protection provided by a protective textile nape protector. This fills any gaps between a helmet and a collar, and might take the form of an attachment to the helmet.

Torso

The torso should be protected with a garment akin to a combat body armour or fragmentation vest. It should be designed to protect against primary and secondary fragmentation, and manufactured from common fragmentation protective materials. In some cases, it may actually be in-service body armour against fragmentation. If the protection ensemble is that of the EOD (bomb disposal) suit type, then it may also incorporate some level of blast protection for the lungs and the gastrointestinal tract.

Arms

Some type of sleeve should protect the arms. This should be designed to give protection against primary and secondary fragmentation. It will also give some level of protection against traumatic amputation of the forearm. Again it should be manufactured from common protective textile materials for maximum flexibility.

Hands

It is quite rare for any operator involved in demining to accept any protection for the hands. A significant threat to the hands is that of soft tissue (flesh) stripping. It is possible to reduce this potential for injury significantly by using thin, lightweight, gloves made from knitted ballistic protective materials such as a para-Aramid (Kevlar® or Twaron®). Such items in a fingerless design (as seen in Figure B3) have recently entered service in some countries.

Figure B3: Thin Gloves.
(® British Crown Copyright 20/Dstl/MOD)**

Pelvis / Abdomen

This area should be protected with a component that is a downward extension of the thorax body armour, for example a groin protector. It may, however, be completely separate from the body armour. This component should be designed to defeat primary and secondary fragmentation and is usually manufactured from common protective textile materials. The fragmentation performance of such a component should be similar to that of the body armour above it.

Legs

In cases where there is a potential for a fragmentation mine attack from the front, rear or side of the legs, some type of leggings that are designed to defeat primary fragmentation should protect the legs. These leggings might also give limited protection against traumatic amputation of the lower leg. Again these leggings should be manufactured from a common protective textile material. Underfoot initiated mines are discussed under the section relating to the feet.

Feet

Protection for the feet can be of two different types depending on the type of mine. Protection against a fragmentation mine is simpler. It is provided only for the top of the foot using a spat or gaiter that is manufactured from a common protective textile, or from a rigid composite of the same material.

The more complex issue is protection against the effects of standing on, and detonating, a blast mine. This type of protection is summarized under the heading of anti-mine footwear, which has taken a variety of shapes since WW II. The primary purpose of anti-mine footwear is to prevent a breach of the footwear under the extreme pressure of the blast. Constructing a portion of the sole with Aramid materials such as Kevlar® often does this. A blast deflector constructed from metallic materials is sometimes added under the rear portion of the sole. Materials might also be used to attenuate the shock transmission to the foot. Another approach to anti-mine footwear is to use a platform to elevate the foot away from the blast. Three basic approaches have been used, each worn in addition to the primary footwear:

- Use of an overshoe that is essentially an additional sole strapped over the primary footwear;
- Use of a large cushion to spread the load over a large surface area with the intention of preventing the actuation of the mine in the first place;
- Use of a platform to elevate the primary footwear. In some cases, the platform is supported on legs that extend outside the platform to displace the detonation point away from the underside of the foot.

POSTURE OF THE OPERATOR

The effectiveness of these different components of protection depends upon the posture and the standard operating procedures (SOPs) of the operator. It is not intended to discuss SOPs in this section, as these vary greatly between different countries and even between users within the same country. However, mine clearance involves search and disposal that can be carried out in the standing, kneeling and prone positions. As the operator moves closer to the ground, and hence closer to the mine, the need for protection of the upper body become more significant, while there is a reduced need for protection of the lower body. There are cases where the user community will specify protection for parts of the body that may not seem to correspond with the SOPs. For example an operator who is clearing mines in the prone position may require protection to the rear of the body for fear of activating a bounding fragmentation mine that could then impact the back from above.

PROTECTION / USABILITY TRADE-OFF

When any component of personal armour is worn, it has disadvantages for the user. These might include reduced flexibility, added weight and bulk, increased heat build up, etc. As the area of coverage is increased, so will these disadvantages. The trade-off between protection and usability differs for operators in different scenarios.

A mine clearance suit is often too cumbersome for mainstream soldiers; hence this equipment is usually reserved for the specialists. For mainstream soldiers, it has been the norm to treat mine fragments as simply another ballistic threat that can be defeated by regular PPE such as bullet-proof vests and helmets. Soldiers are often taught that the best countermeasure against AP fragmentation mines is through careful procedures and early detection. Metal detectors work well against fragmentation mines due to the large amount of metal contained in the fragmentation jacket, however they are less effective at detecting blast mines.

Protection might also be sought for use in humanitarian demining. The above discussion regarding protection concepts and ergonomics applies equally well to this context. However, cost is a factor that might limit the availability of PPE for this application. There are also several other considerations. Military mine clearance and Humanitarian demining operations are very different in regards to their environment. Most of the mines are older generation, simple mines fitted with mechanical fuses. Many of the mines have been in the ground for a prolonged period of time. Thus, corrosion and other aging processes may make the mine more unpredictable and more hazardous.

Humanitarian demining has some advantages over military clearance operations. Deminers are normally not being fired upon. Safety and reliable clearance of virtually all mines are paramount. Speed of clearance, although desirable, is not essential. Deminers can pick the time of day and wait for favourable weather conditions for clearance. There is some scope for preparing or conditioning the ground, if that will make the demining task easier or more effective.

Annex C: PHYSICS OF MINE EXPLOSIONS

This annex provides a more detailed treatment of Anti-Personnel (AP) land mines than Chapter 2. Modern day land mines evolved over several centuries from a concept of victim-actuated weapons [C1]. They are sometimes likened to silent sentries that wait for the enemy without ever resting. Several characteristics have contributed to their popularity. They are simple, cost-effective, and difficult to detect once in place and armed. They can remain active for many years, which might be desirable while a battle is being fought but quickly becomes a liability once a war is over. Because AP mines are so difficult to locate, their usage over the past five or six decades has left a pollution legacy that is staggering. It is estimated that more than 90 countries [C2] have a mine and/or unexploded ordnance pollution problem, as depicted in Figure C1. The number of mines currently in place has been estimated between 60 to 70 million, with the highest concentrations in Afghanistan, Angola, Cambodia, Iraq, and Laos [C3]. These numbers include both anti-tank and AP mines.

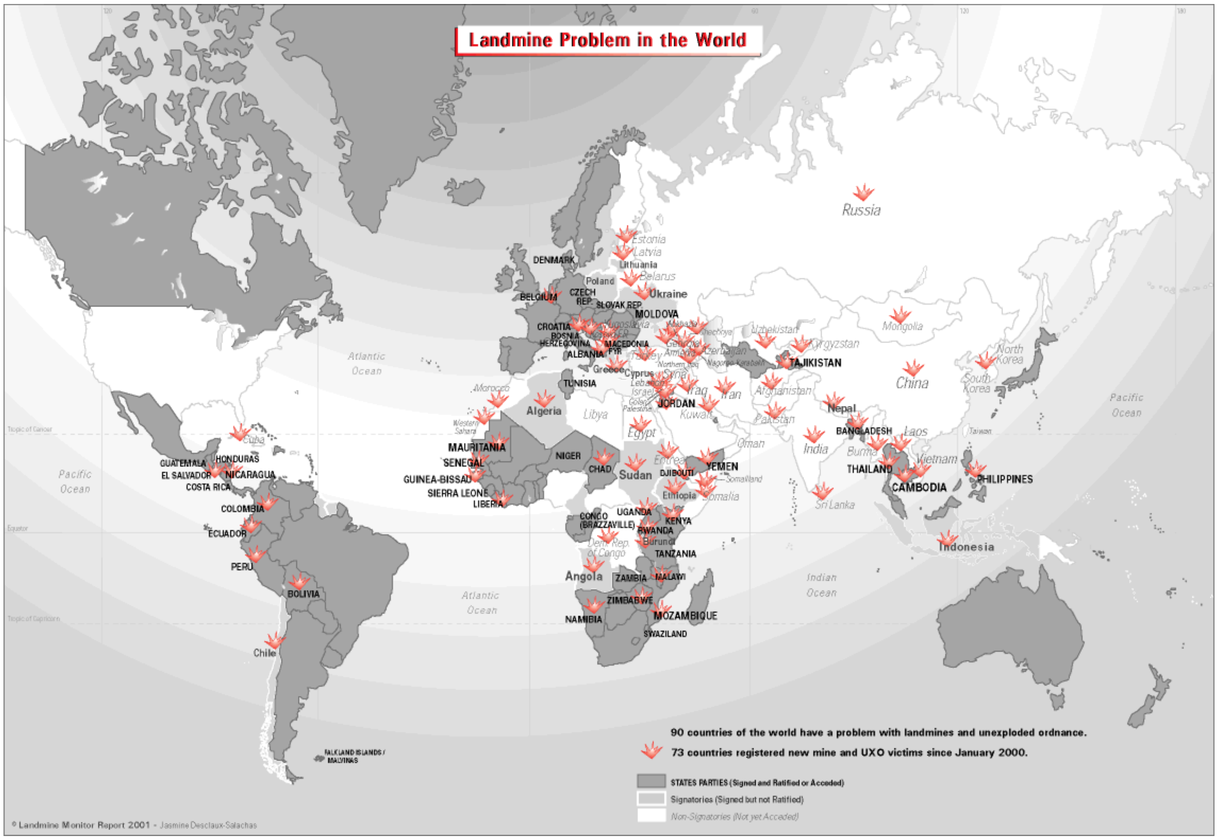


Figure C1: Distribution of Countries that have a Mine Pollution Problem as per Reference [C2].

AP mines fall into two main categories: *fragmentation* and *blast* mines. These category names reflect the primary mechanism used to injure victims. Fragmentation mines disperse high velocity fragments that can injure personnel up to tens of metres. They come in three basic packages: grenade, bounding and directional mines, which refer to some of their characteristics. A grenade type mine is pre-emplaced and disperses it fragments in all directions when exploding. A bounding mine is a two-stage weapon that is usually buried in the ground. Upon activation, the mine body bounds up to a height of one to two metres, and then disperses its fragments in all directions when exploding. Directional mines, as their name implies, disperse their fragments only within a limited arc. While bounding mines are usually buried in the ground, grenade-type and directional mines are placed above ground and hidden behind camouflage. Fragmentation mines may be actuated using the downward pressure of a foot. More commonly, they are actuated when tension is applied to – or relieved from – a trip wire.

AP blast mines rely primarily on blast overpressure to injure their victim. Additional injuries may also incur from environmental debris and soil. They are typically designed to injure the target, however, mines with larger explosive charges can be lethal. A typical blast mine consists of an explosive charge, a detonator, and a mechanical device to trigger the detonator. Blast mines contain few metallic parts, making them very hard to detect using conventional metal detectors. They are surface or subsurface buried and the great majority are pressure activated. Buried blast mines often remain operational for decades after a conflict [C4].

The physics of AP mine explosions may be examined from a science point of view or from a functional point of view. These two perspectives are complementary. The scientific approach aims at describing the details of the fundamental processes that come into play when an AP mine is actuated. This might involve chemistry, physics, metallurgy, etc. The functional approach aims more at the end state, trying to describe the terminal effects of the mine against people and equipment. Each approach has its merits. Hence, it was decided to write this annex to describe both approaches such that a non-scientist can gain an appreciation of the science without getting too much in the details. The following material is divided in three main sections. The first section presents some fundamental concepts of physics used by scientists to model an explosion and the subsequent transfer of this explosion energy to the surroundings. The next two sections describe the explosion of fragmentation and blast mines, respectively, from a more functional point of view.

C1.0 FUNDAMENTAL CONCEPTS ASSOCIATED WITH MINE EXPLOSIONS

All mine explosions share the same fundamental elements: a chemical reaction transforms an explosive material into a hot, high-pressure gas. This gas then performs work, in a thermodynamics sense, on its surroundings. This could be fragmenting the casing of the mine, pushing soil or water, or driving a shock in neighbouring air. It could also be damaging an object or injuring a person nearby. Chemistry and physics provide mathematical equations to describe and quantify these processes.

Waves are one of the fundamental quantities in nature. They appear in almost every branch of physics [C5], being associated with light, heat, electromagnetism, etc. Our interest here is with the transmission of *mechanical waves* through a deformable or elastic medium. Reference [C5] states that such waves

> "originate in the displacement of some portion of an elastic medium from its normal position, causing it to oscillate about an equilibrium position. Because of the elastic properties of the medium, the disturbance is transmitted from one layer to the next. This disturbance, or wave, consequently progresses through the medium. […] Energy can be transmitted over considerable distances by wave motion."

Thus, waves might be construed as being one of nature's mechanisms to transmit and propagate information to materials. Therein lies their importance in describing the physics of mine explosions. This includes the propagation of a detonation wave through the explosive and the subsequent behaviour of the explosive by-products with their surroundings.

C1.1 Propagation of Mechanical Waves through Elastic and Deformable Media

Mechanical waves, or stress waves, propagate through a medium at a specific velocity. There are several kinds of elastic waves: longitudinal, shear, surface, interfacial, and bending. It can be shown that Equation C1 describes the longitudinal elastic wave propagation velocity, $V_{Longitudinal}$, in an infinite medium.

$$V_{Longitudinal} = \sqrt{\frac{(1-\nu)E}{(1+\nu)(1-2\nu)\rho}} \qquad \text{(Equation C1)}$$

where E is the Young's modulus of elasticity, ρ is the density of the medium, and ν is the Poisson's ratio that relates the lateral and longitudinal deformation for a given medium. For a thin bar, the Poisson's ratio can be neglected and the equation reduces to the sound velocity for the medium, as shown in Equation C2.

$$V_{Longitudinal(thin\ bar)} = \sqrt{\frac{E}{\rho}} \qquad \text{(Equation C2)}$$

Elastic waves propagate at the speed of sound in a medium as long as the stress level remains below the dynamic yield strength of the material. If the stress level exceeds the yield strength, a portion of the wave becomes plastic and propagates at a slower velocity due to the decreasing slope of the stress-strain curve for most materials of engineering interest, i.e., metals and hard polymers. Substituting the slope of the stress-strain curve for the modulus in equation (C2) gives

$$V_{Longitudinal(thin\ bar)} = \sqrt{\frac{1}{\rho}\left(\frac{\mathrm{d}\sigma}{\mathrm{d}\varepsilon}\right)} \qquad \text{(Equation C3)}$$

This is shown schematically in Figure C2(A). As the slope of the stress-strain curve decreases, the wave speed decreases leading to dispersion of the wave, as depicted in Figure C2(B). The typical stress-strain curve, as shown in Figure C2(A) is concave downwards. In contrast, the stress-strain curve for many viscoelastic materials, such as human soft tissue and other tissue simulants, is concave upwards. As a result, the wave velocity will increase with increasing stress for the latter materials. However, at very high values of stress, the hydrostatic material response dominates the wave velocity as described below.

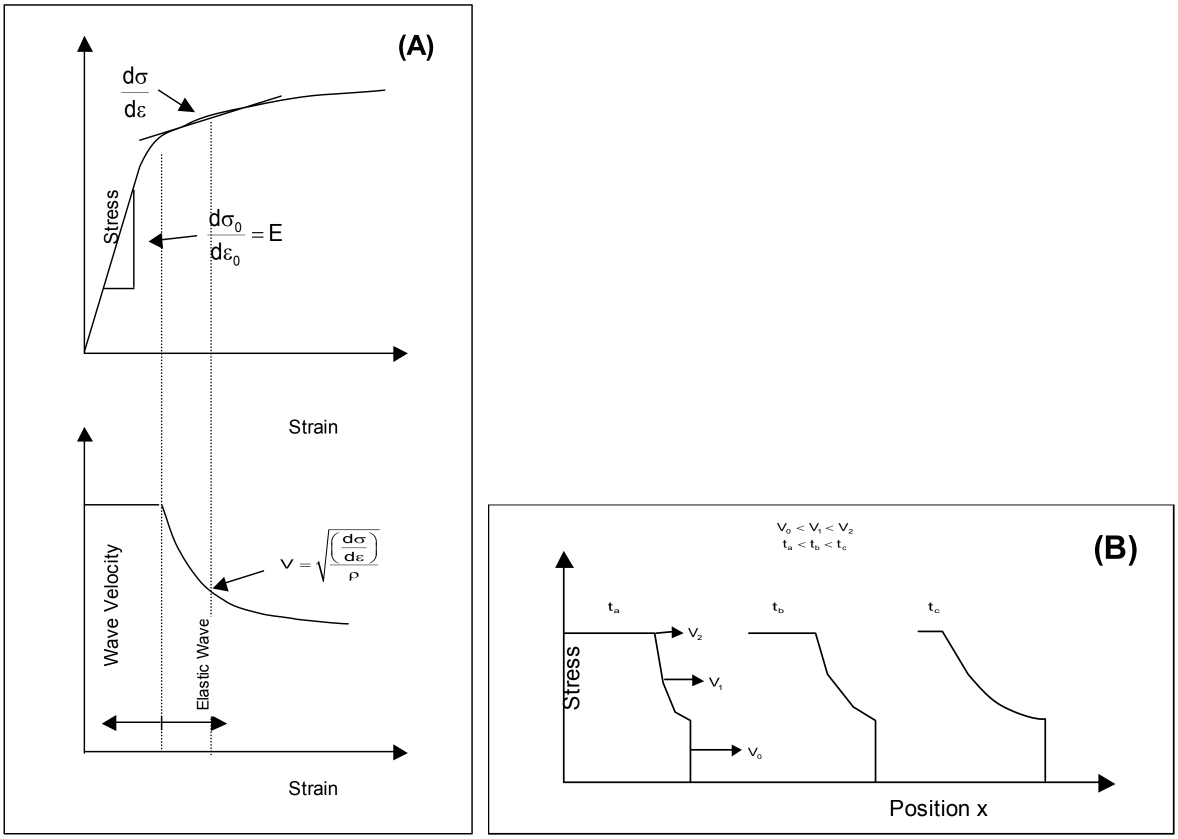


Figure C2: (A) Relationship between the Slope of the Stress-Strain Curve of a Material and the Wave Propagation Velocity within this Material; (B) Dispersion of a Plastic Wave as it Propagates through the Medium.

As the amplitude of an applied stress wave increases beyond the strength of a material, the shear stress in the material becomes small in comparison to the hydrostatic stress, leading to the creation of a shock wave. Thus, the compressibility of the material (pressure-volume relationship) at high pressure dominates the material response. In general, the compressibility of a material decreases with increasing pressure due to the increasing repulsive forces between atoms as they are forced together. Figure C3 shows a schematic of a pressure-volume relationship and the requirement for the formation of a shock wave. The magnitude of the rate of change of hydrostatic stress with respect to volume must be concave upwards for a shock wave to form. Physically, this means that the bulk modulus of the material must increase with increasing stress. Analogous to Equation C2, the shock wave velocity increases with increasing bulk modulus so that, as the shock wave forms, the latter portions of the wave have a higher velocity than the wave front since the material was previously compressed by the wave front. This leads to a ‘pile up’ of waves creating a steep gradient traveling at some velocity greater than the elastic wave velocity of the material. Note that, in reality, the wave front is not a discontinuity, but has a finite slope that is related to the deviatoric behaviour of the material.

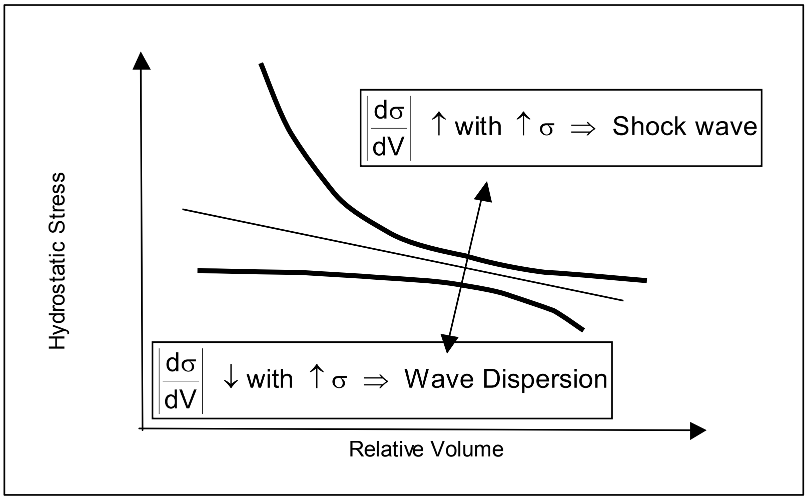


Figure C3: For a Given Material, Pressure and Volume are Related; when the wave velocity increases as the material is compressed, follow-on waves catch up to the leading wave to create a shock wave.

Thus, there are two requirements for the formation of a shock wave:

- The hydrostatic stress amplitude must significantly exceed the dynamic flow strength of the material at the current strain rate.
- The wave velocity in the material must increase with increasing pressure.

Theoretically, a shock wave is assumed to be a discontinuity in density, pressure, and temperature where the material is in a state of uniaxial compression (required to develop the high hydrostatic stresses). Rankine and Hugoniot are credited for developing a one-dimensional shock wave analysis [C6] by applying the equations of conservation for mass, momentum and energy. There are five basic assumptions in this analysis:

- The shock front is a discontinuity (i.e. no thickness).
- The material response is dominated by the hydrostatic stresses.
- The process is adiabatic.
- The material does not exhibit elastic-plastic behaviour.
- There are no phase transformations.

Equations C4a-c show the conservation equations as applied to a shock front where the '0' subscript refers to the unshocked material. U_S is the shock velocity and U_P is the particle velocity of the shocked material. It has been assumed that the particle velocity of the unshocked material is zero.

Conservation of Mass $$\rho_0 U_S = \rho\left(U_S - U_P\right) \qquad \text{(Equation C4a)}$$

Conservation of Momentum $$\left(P - P_0\right) = \rho_0 U_S U_P \qquad \text{(Equation C4b)}$$

Conservation of Energy $$E_n - E_{n0} = \tfrac{1}{2}\left(P + P_0\right)\left(V_0 - V\right) \qquad \text{(Equation C4c)}$$

The shock wave behaviour depends on the pressure-volume relationship, also known as the Hugoniot curve. This material relationship is determined experimentally by measuring particle velocities. The shock velocity and particle velocity can be empirically related since

$$U_S = C_0 + S_1 U_P \qquad \text{(Equation C5)}$$

Where C_0 is approximately equal to the speed of sound in the medium and S_1 is a slope determined experimentally. Thus, Equations C4a-c allow this empirical relationship as a function of pressure and volume. A generic Hugoniot curve is shown in Figure C4 with two states: the initial state (0) and the shocked state (1). It should be noted that the material actually reaches a particular shock state along the Rayleigh line, and not along the Hugoniot. The Hugoniot only represents the locus of possible shocked states for the material and is known as the equation of state (EOS) for a material.

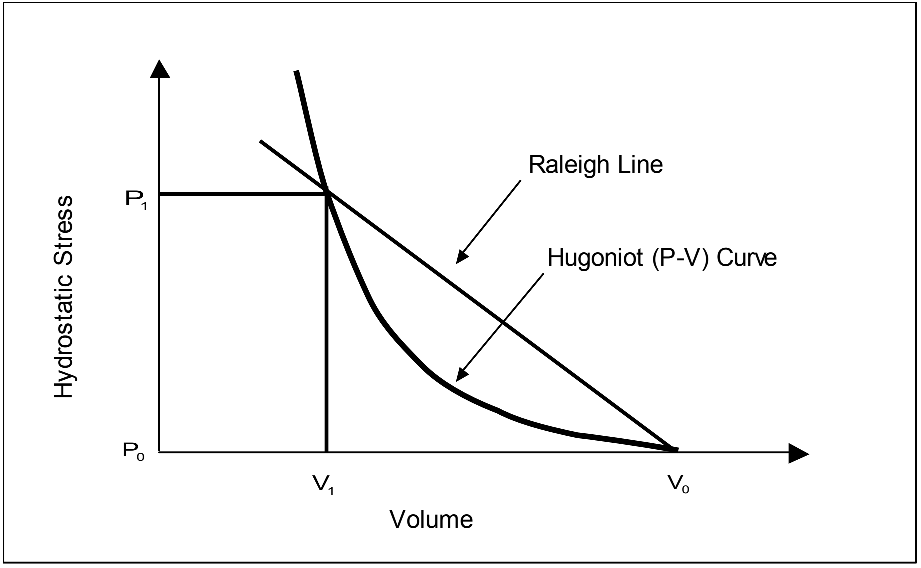


Figure C4: Pressure-Volume (Hugoniot) Curve and Rayleigh Line.

As elastic, plastic, and shock waves propagate through a solid, the waves may undergo changes in shape due to loss of energy and material behaviour. The attenuation of a wave refers to a decrease in the amplitude of the stress wave, while dispersion refers to the change in shape of a wave. The deformation resulting from an elastic wave is reversible. However, these waves damp out eventually due to frictional effects within the medium. Plastic waves, by definition, perform irreversible work on the material, a process that attenuates the wave. The dispersion (spreading out) of a plastic wave was depicted in Figure C2(B) due to varying velocity through the wave. The passage of a shock wave through a material is assumed adiabatic, resulting in a temperature increase in the shocked material. However, the release is isentropic and, as a result, the final temperature of the shocked material is higher than that of the original material so that the shock wave loses energy. The attenuation and dispersion of a shock wave is shown schematically in Figure C5. A shock wave will eventually decay into plastic and elastic waves, and finally into elastic waves as shown in Figure C6.

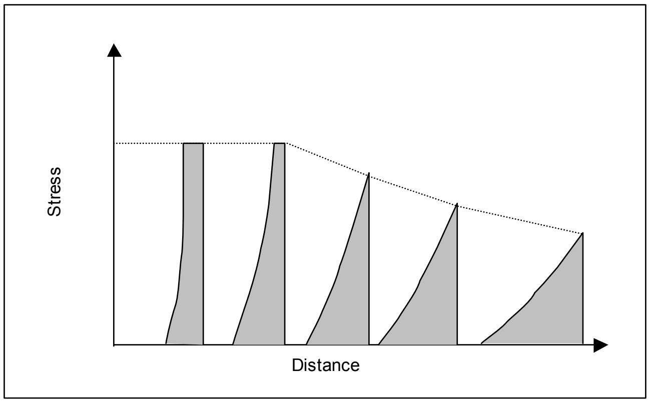


Figure C5: Attenuation and Dispersion of a Shock Wave.

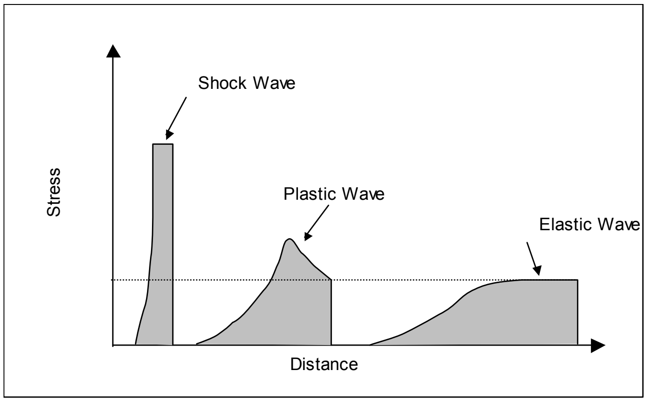


Figure C6: Attenuation of a Shock Wave to an Elastic Wave.

C1.2 Modelling the High-Pressure Gas from an Explosion

Explosive materials are converted into gas through a chemical reaction, usually referred to as burning. There exist two modes of combustion depending of the propagation velocity of the burning front into the material. When the propagation velocity is below the speed of sound of the medium, it is called a *deflagration*. If the propagation velocity is greater than the speed of sound, it is called a *detonation*. The propagation velocity is directly related to the violence of the event, as expressed by the rise in pressure. A faster propagation yields a greater pressure rise. Thus, a deflagration is a reaction between fuel and atmospheric air [C7] that produces heat and generates a relatively small increase of pressure. This burning process can transition to a detonation if the burning occurs within a confined space.

A detonation results from the propagation of a shock wave, or *shock front*, into the explosive material. The explosives used in mines require a significant amount of energy to detonate. They are known as high explosives (HE). The velocity of the shock front through most HE is of the order of 6 to 9 km/sec. The exact value depends on the chemical composition and density of the explosive. For a given chemical composition, the velocity increases with density.

As the shock front moves through the HE, it raises the temperature of the material. After a short period of time (typically 1 to 2 μs), the HE starts to burn. The resulting chemical reaction transforms the solid (or liquid) explosive into hot, high-pressure gas called the *detonation products*. The temperature of the products is of the order to several 1000's of degrees Kelvin while the pressure can reach values up to 100,000 to 200,000 bars immediately behind the shock front. This release of energy occurs within a zone of finite and constant thickness known as the *reaction zone*. The thickness of the reaction zone is of the order of 1 mm, making it possible to feed energy upstream to the shock front in order to sustain its propagation. The detonation process is stable and continues until the shock front encounters the physical boundary of the explosive.

Working independently, Zeldovich (1942), von Neumann (1942) and Doering (1943) derived a simple model [C8] (thereby named the ZND model) that describes the process within the *reaction zone*. The ZND model relates the physical state variables of the reacting material as a function of time and space behind the shock front. These variables include density, pressure, temperature, and particle velocity. The highest pressure achieved within the explosive is known as the von Neumann spike (P_{VN}). It occurs at the leading edge of the reaction zone. The trailing edge of the reaction zone, where the chemical reaction is complete, is known as the

Chapman-Jouguet point and the associated pressure is known as the Chapman-Jouguet pressure (P_{CJ}). It should be noted that P_{VN} and P_{CJ} are related by the pressure-volume relationships of the products and unreacted explosive [C9].

The release of energy during a detonation occurs so quickly that it can be considered to be adiabatic, i.e., there is little transfer of heat to the surroundings during the short duration of the explosion. Thereafter, the pressurized gas performs work through expansion [C10] according to Equation C6.

$$\text{Work} = \int_1^2 P dV \qquad \text{(Equation C6)}$$

The detonation wave traveling through a high explosive can be described with the conservation equations (Equations C4a-c) for mass, momentum and energy. But the energy equation must account for the release of chemical energy (Q) from the explosive [C6] as per Equation C7

$$E_n - E_{n0} - Q = \tfrac{1}{2}\left(P + P_0\right)\left(V_0 - V\right) \qquad \text{(Equation C7)}$$

The behaviour of the detonation products is governed by an equation of state that relates pressure and volume. Generally, the internal pressure of a volume of gas drops as the volume expands. The most common representation for explosive products is the Jones-Wilkins-Lee (JWL) equation of state as shown in equation C8.

$$P = A\left[1 - \frac{\omega}{R_1 V}\right]\mathrm{e}^{-R_1 V} + B\left[1 - \frac{\omega}{R_2 V}\right]\mathrm{e}^{-R_2 V} + \frac{\omega Q}{V} \qquad \text{(Equation C8)}$$

The pressure of the detonation products just after detonation is P_{CJ}, which is determined by the intersection of the Chapman-Jouguet Rayleigh line and the Hugoniot for the explosive products. The energy of the explosive (Q) is equal to the total energy released during the reaction minus the activation energy [C11].

The high explosives that are most frequently used in mines are TNT ($C_7H_5N_3O_6$) and RDX ($C_3H_6N_6O_6$), or a combination thereof (Composition B). RDX is the more powerful of these explosives. A mixture of 91% RDX with 9% plasticizer yields the explosive known as C4, which has been suggested for surrogate mines to test protective systems. The relevant material properties for C4 [C12] are listed in Table C1. It should be noted that the material density could vary from from 1.5 g/cm^3 to 1.8 g/cm^3 depending on packing. This has a significant effect on the detonation velocity as shown in Equation C9, where ρ is the density in g/cm^3.

$$V_{Detonation} = 2660 + 3400\,\rho \qquad \text{(Equation C9)}$$

Table C1: Material Properties for C4 Explosive

Composition (weight %):	91% RDX, 9% Plasticizer
Density	1601 kg/m^3
Chapman-Jouguet Pressure	2.80E+10 Pa
Detonation Velocity	8190 m/s
JWL EOS (equation 2.10) parameters	
A	6.10E+11
B	1.30E+10
R1	4.00
R2	1.40
ω	0.25
E0	9.00E+09

For a C4 density of 1.767 g/cm^3, the detonation pressure is 33.79 Gpa, and the detonation velocity is 8639 m/s. The shock Hugoniot of the explosive material is given in Equation C10 as

$$U_S = 2.78 + 1.9U_P \qquad \left[\rho = 1.799\, g/cm^3\right] \qquad \text{(Equation C10)}$$

The heat of formation for the reaction is 139 kJ/kg and the calculated heat of detonation [C12] is 6.65 MJ/kg.

C2.0 FUNCTIONAL DESCRIPTION OF FRAGMENTATION MINE EXPLOSIONS

Table C2 presents a compilation of 35 fragmentation mines from Reference [C1]. It is seen that the total mass of these devices ranges from 500 to 5000 grams with the explosive component accounting anywhere from 65 to 900 grams. The large variation is even more apparent from the mass ratio of the inert components to the explosive content, which varies from 0.25 to 39! Combining the above numbers with the different explosive types used, it is clear that the construction of fragmentation mines varies widely.

Table C2: Characteristics of a Selection of AP Fragmentation Mines

Mine Designation	***Total Mass (grams)***	***Explosive Mass (grams)***	***Approximate Case: Explosive Ratio***	***Explosive Type***	***Country of Manufacture***
NO-MZ 2B	660	65	9.15	TNT	Vietnam
MBV-78A1	1770	75	22.60	TNT	Vietnam
PMR-1	2000	75	25.67	TNT	Yugoslavia
PMR-2	2200	75	28.33	TNT	Yugoslavia
Type 58	2300	75	29.67	TNT	China
POMZ-2	2300	75	29.67	TNT	Russia
OZM-3	3000	75	39.00	TNT	Russia
NR-413	640	100	5.40	TNT/RDX	Belgium
PMR-2A	1700	100	16.00	TNT	Yugoslavia
Type 69	1350	105	11.86	TNT	China
P-40	617	120	4.14	TNT	Vietnam
PPMP-2	1200	150	7.00	Unknown	Yugoslavia
PRB M966	2950	154	18.16	TNT	Belgium
M26	1000	170	4.88	Comp B	USA
PSM-1	2450	170	13.41	RDX	Bulgaria
OZM-4	5000	170	28.41	TNT	Russia
S-Mine 35	4100	182	21.53	TNT	Germany
PMR-4	2000	200	9.00	TNT	Yugoslavia
Model 123	1500	250	5.00	RDX	Thailand
PP Mi-Sr	3200	360	7.89	TNT	Czech
M/966-B	500	400	0.25	TNT	Portugal
PMR-3	2000	410	3.88	TNT	Yugoslavia
M3	4360	410	9.63	TNT	USA
V-69	3200	420	6.62	TNT/RDX	Italy
PROM-1	3000	425	6.06	TNT/RDX	Yugoslavia
P-40	1500	480	2.13	TNT	Italy
Mk2	4500	500	8.00	Amatol	United Kingdom
OZM-72	5000	500	9.00	TNT	Russia
DM-31	4000	540	6.41	TNT	Germany
M16A1	3750	575	5.52	TNT	USA
M16A2	2830	600	3.72	TNT	USA
M18A1	1580	682	1.32	RDX	USA
Claymore	1600	700	1.29	TNT/RDX	Egypt
MON-50	2000	700	1.86	RDX	Russia
MRUD	1500	900	0.67	RDX/PETN	Yugoslavia
Minimum ->	**500**	**65**	**0.25**		
Maximum ->	**5000**	**900**	**39**		
Average ->	**2379**	**314**	**12**		

Despite significant variations in geometry, mass and materials, all fragmentation mines share the same basic elements and the same working principle, as illustrated in Figure C7. There are four main elements to a fragmentation mine: a main explosive charge, a fragmentation case, a detonator, and some actuation (fuse) system. Triggering the fuse usually releases a spring-loaded striker that hits the detonator. The latter is simply a small receptacle that contains a highly sensitive explosive that can be ignited by a simple mechanical hit. This first explosion ramps up to ignite the high explosive that makes up the main charge of the mine. It should be noted that a high explosive is usually much less sensitive than the explosive used in the detonator. This makes it safer to handle and transport the munitions. Detonators are much more sensitive, requiring special packaging and careful handling.

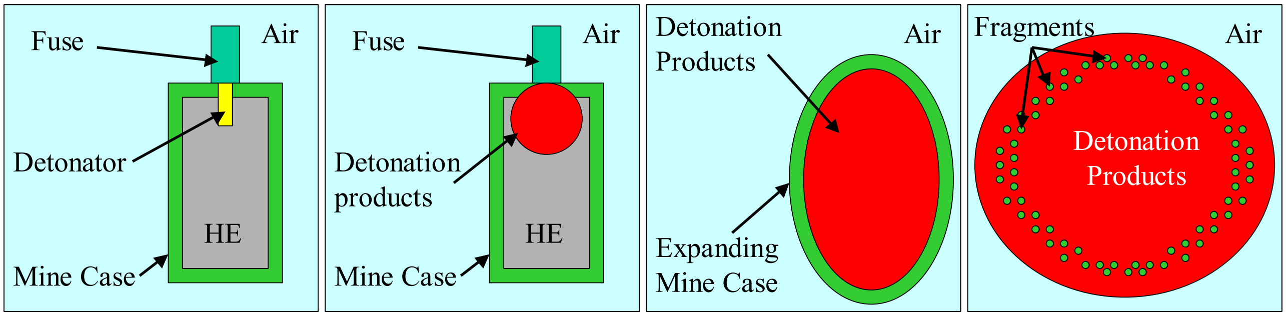


Figure C7: Illustration of the Working Principle of a Fragmentation Mine.

The explosion of the detonator, as its name implies, causes the main charge to detonate. As the shock front propagates through the high explosive, it transforms the solid (or liquid) explosive into detonation products. Given that the maximum physical dimension of the main charge for the average fragmentation mine is of the order of 100 to 200 mm, and assuming an average shock front velocity of 7 km/sec, it takes approximately 15 to 30 µs to transform the solid explosive into detonation products. In the thermodynamics sense, this mass of hot, high-pressure gas then performs work on its surroundings. For a fragmentation mine, this means breaking up the metallic case into a large number of small fragments and propelling these fragments at high velocity away from the centre of the explosion.

C2.1 Estimating the Number and Velocity of Fragments

It is feasible to pre-condition the mine case to exert some control over the size and distribution of fragments. This includes techniques such as the inclusion of grooves inside and outside the case, or simply constructing the case from preformed fragments that are arranged in a pre-determined pattern. Alternatively, the casing can be a simple cylinder of uniform thickness. Bangash [C13] provides formulae to estimate the initial velocity of the fragments for various configurations of case and explosive. For a simple cylinder filled with explosive, the initial velocity (m/s) is given by:

$$v_0 = 0.3045\sqrt{2E'}\sqrt{\frac{2\xi}{2+\xi}} \qquad \text{(Equation C11)}$$

where $\sqrt{2E'}$ is the Gurney constant, given as 6940 for TNT, and ξ is the ratio of explosive mass to the mass of the cylindrical portion of the casing. The significance of the above equation is better illustrated by a simple example. Consider a right cylinder, 100 mm in diameter and 100 mm in length, composed of a steel case and filled with TNT explosive. The thickness of the steel case can be varied from 1 mm up to 45 mm. For this example, the value of ξ varies over three orders of magnitude from $\xi = 0.0019$ for the thick case to $\xi = 4.63$ for the thin case. Figure C8 shows a plot of the value of initial velocity as a function of case thickness.

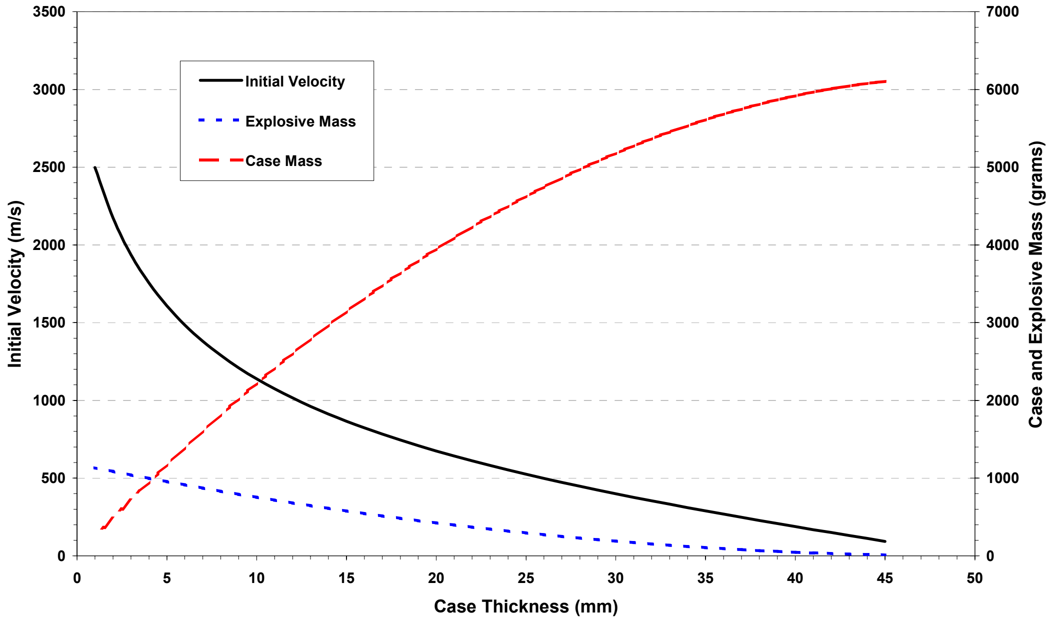


Figure C8: Distribution of Fragment Velocity for a Steel Cylinder filled with TNT as a Function of the Case Thickness.

There is no guarantee that the above formula would work for very thick cases. One should expect that the containment couldn't be increased indefinitely. A limit would be reached where the explosion would be contained. However, the results demonstrate the basic physics of fragmentation mines, i.e., that the case thickness can be adjusted to tune the initial velocity of the fragments. In the above example, the mass of the thin case (1 mm) is 244 grams and the explosive content is 1131 grams, which yields an initial velocity of nearly 2500 m/s. At the other extreme, a very thick case (45 mm) has a mass of 6104 grams and the 10 mm diameter central charge is reduced to 11.8 grams of explosive, which leaves little energy to propel the fragments once fracturing has taken place. The latter case results in a fragment velocity of 93 m/s only.

The reader familiar with ballistics will have recognised that knowing the initial velocity of the fragments is only part of the information required. The mass of these fragments is another key variable that is required. Bangash presents a formula to estimate the number of primary fragments produced from the explosion of a case of uniform thickness as follows:

$$\ln(N_f) = \ln\left(\frac{8W_c}{*M_A^2}\right) - \frac{\sqrt{W_f}}{*M_A} \qquad \text{(Equation C12)}$$

where W_f is the weight of the primary fragments, N_f is the number of fragments with weight greater than W_f, W_c is the total weight of the cylindrical portion of the mine, $*M_A$ is a fragment distribution parameter defined as:

$$*\,M_A = B t_c^{5/6} d_i^{1/3} \left[1 + \left(t_{av}/d_i\right)\right] \qquad \text{(Equation C13)}$$

where B is a constant between 0.24 and 0.35, which depends on the explosive and casing, t_c is the thickness of the casing, d_i is the internal diameter of the casing, and t_{av} is an average time. Reference [5] does not provide guidance about selecting the most appropriate values of B and t_{av}. The reader should use the values for B listed here and experiment with values of t_{av}.to find upper and lower bounds on fragment distribution.

Using the above formula, the number of fragments for the previous example was computed for three case thicknesses of 5, 10 and 20 mm. The results are plotted in Figure C9. It is seen that the equation indicates that the number of smaller fragments increases as the case thickness is reduced. In addition, it is seen from the intercept of the curve with the value of $N_f = 1$ that as the casing gets thicker, the larger fragments become progressively larger and more massive. This is intuitively the behaviour that should be expected.

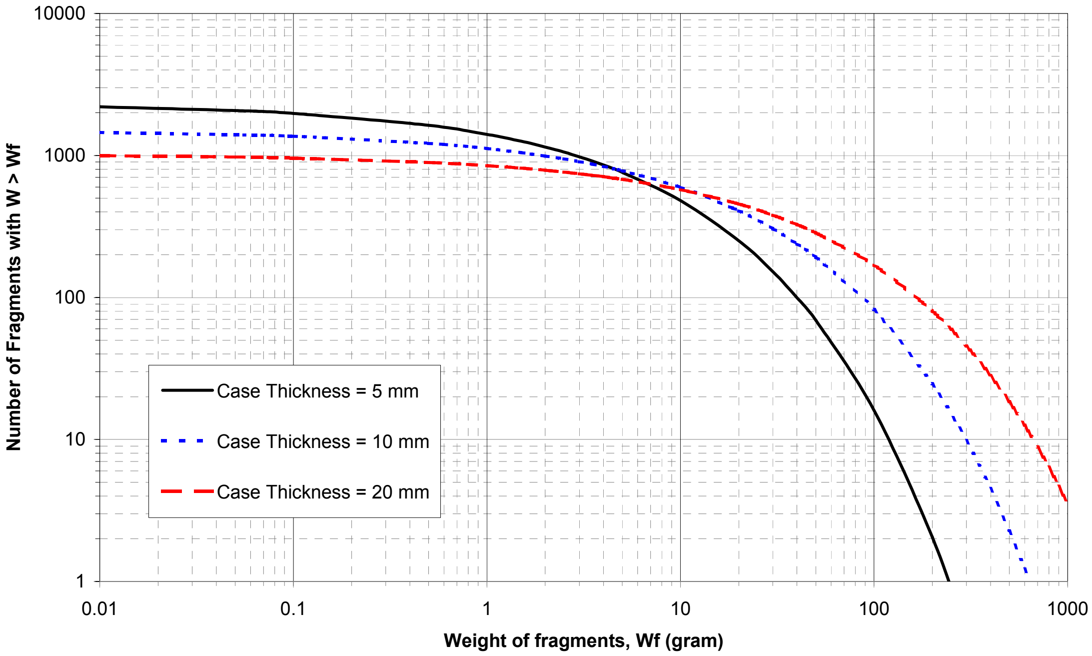


Figure C9: Number of Fragments of Mass Greater than W_f for Case Thicknesses of 5, 10 and 20 mm.

C3.0 FUNCTIONAL DESCRIPTION OF BLAST MINE EXPLOSIONS

Table C3 presents a list of blast mines currently deployed in the world, including total mass, explosive mass, and explosive type. The average blast mine contains about 110 grams of explosive. The maximum reported charge mass is 300 grams and the minimum is 28 grams. Blast mines are typically classified in terms of small (less than 50 grams explosive), medium (50 to 100 grams of explosive) and large (greater than 100 grams of explosive). The most common explosive used in blast mines is TNT, with Composition B, RDX, and other explosives being less common. Most blast mines are concealed in ground.

Table C3: Characteristics of a Selection of AP Blast Mines

Mine Designation	*Total Mass (grams)*	*Explosive Mass (grams)*	*Approximate Case: Explosive Ratio*	*Explosive Type*	*Country of Manufacture*
MD-82B	100	28	2.57	TNT	Vietnam
M14	100	29	2.45	Tetryl	USA
MN-79	100	29	2.45	TNT	Vietnam
P4 Mk1	140	30	3.67	Tetryl	Pakistan
VS-MK-2	135	33	3.09	RDX	Italy
SB-33	140	35	3.00	RDX/HMX	Italy
PMA 3	180	35	4.14	Tetryl	Yugoslavia
PFM-1/1S	75	37	1.03	Liquid	Russia
VAR-40	100	40	1.50	Comp B	Italy
VS-50	185	42	3.40	RDX	Italy
TS-50	186	50	2.72	RDX	Italy
Type 72 A	140	51	1.75	TNT	China
Type 72B	150	51	1.94	TNT	China
R2M2	128	58	1.21	RDX	South Africa
MI AP DV 59	130	70	0.86	TNT	France
PRB M409	183	80	1.29	TNT/RDX	Belgium
PMA 2	135	100	0.35	TNT	Yugoslavia
PRB M35	158	100	0.58	TNT	Belgium
P-4-A/B	171	100	0.71	TNT/PETN	Spain
PMN-2	420	100	3.20	TNT/RDX	Russia
PPM-2	375	110	2.41	TNT	Germany
AUPS	300	115	1.61	Comp B	Italy
MAI-75	300	120	1.50	TNT	Romania
DM 11	231	122	0.89	TNT	Germany
FMK-1	253	152	0.66	TNT/RDX	Argentina
PP Mi-Ba	340	152	1.24	TNT	Czech
No 4	348	188	0.85	TNT	Israel
PN-1	350	200	0.75	TNT	Cuba
PP-MI-D	350	200	0.75	TNT	Czech
PMA 1A	400	200	1.00	TNT	Yugoslavia
PMD-6/7	400	200	1.00	TNT	Russia
PMN	550	240	1.29	TNT	Russia
Type 58	550	240	1.29	TNT	China
APP-M57	450	250	0.80	RDX	North Korea
GYATA-64	520	300	0.73	TNT	Hungary
Minimum ->	**75**	**28**	**0.35**		
Maximum ->	**550**	**300**	**4.14**		
Average ->	**251**	**111**	**1.68**		

The vast majority of blast mines are pressure-actuated. Two scenarios prevail against this class of mines. In the first scenario, the victim steps on the mine and detonates it as per the intent of the design. In the second scenario, the victim is conducting a mine clearance drill and is in a low-down position when the mine goes off. The main difference between these scenarios is the *standoff* distance between the mine and the victim.

Figure C10 depicts the basic components of a blast mine and the early stages of the explosion after a buried mine is triggered. A blast mine is a simple device that usually consists of a plastic container filled with the main explosive charge, a detonator and a mechanical actuation (fuse) system. Most detonators rely on stab initiation or a friction sensitive compound to start the combustion process, which quickly transitions to a detonation. When a downward force of sufficient magnitude (often less than 10 kg) is applied to the fuse, the mine detonates. It takes between 5 and 10 µs to transform the explosive charge into detonation products. As the detonation wave reaches the mine case, the shock is transmitted to the case, then to the soil, and finally to the sole of footwear or to air.

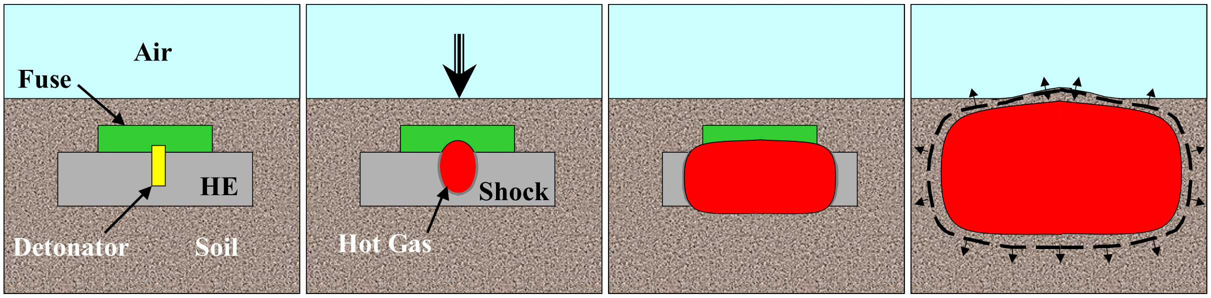
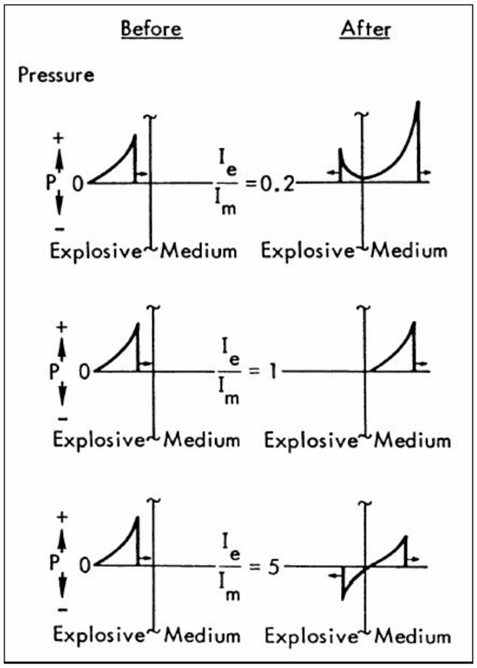


Figure C10: Illustration of the Working Principle of a Buried Blast Mine.

Similar to fragmentation mines, the case breaks up due to the combined effect of the transmitted stress wave and the extreme pressure from the detonation products. However, since the ignition temperature of plastics is much lower than for metals, the case materials also start to combust and continue to do so as they are ejected by the expanding gas. The reader can surmise that a blast mine relies on three main mechanisms to impart energy to an object nearby. First, it transmits a high amplitude stress wave into the soil, footwear and air. Second, the detonation products expand and perform work on the immediate environment. Third, part of the explosive energy imparts motion to the soil, which is then ejected at relatively low velocity and strikes the victim. It is now useful to consider each of these mechanisms in isolation in order to better understand and quantify the violent environment generated by the explosion of a buried mine.

C3.1 Shock Transmission to the Neighbouring Medium

When the detonation wave reaches the boundary of the explosive medium, part of this energy is transmitted as a stress wave in the neighbouring medium. The efficiency of this wave energy transfer depends on the ratio of acoustic impedance of the two media, where acoustic impedance is defined as the product of the bulk density of the medium with its bulk speed of sound. Figure C11 shows how the ratio of impedance, I_e / I_m, influences the interaction of a detonation wave with the surrounding medium. The subscripts denote the ‘explosive’ and the surrounding ‘medium’, respectively. The table next to Figure C11 lists the acoustic impedance value for selected media.



Material	*Wave speed*	*Specific density*	*Acoustic impedance*
	(m/sec)	*(g/cm^3)*	*(-)*
TNT (cast)	6900	1.59	10971
Composition B	7800	1.65	12870
Steel	4997	7.85	39226
Alluvium	1000	1.54	1540
Clay Shale	2000	2.06	4120
Water	1460	1.00	1460
Air	340	0.00121	0.4114

Figure C11: Diagram Illustrating the Effect of Acoustic Impedance on Wave Transmission between Two Media.

Figure C11 tells us that if the acoustic impedance of the two media can be matched, the wave transmits perfectly from one medium to the next. This rarely occurs in reality and in most instances, the acoustic impedances will be mismatched. Consider the case of the transmission from the detonation wave to the steel jacket of a fragmentation mine. In this case, the acoustic impedance of steel is greater than that for the explosive, making the ratio I_e / I_m less than 1. In this case, part of the detonation wave is transmitted to the steel and a compression wave is sent back into the detonation products, effectively telling the products that they are encountering resistance and to increase pressure. The wave transmitted into the steel is a stress wave, which increases the local stress (pressure) of the material. Eventually, the stress wave encounters the outer edge of the metal case where it is transmitted once again, but to air this time. In this case, the ratio of impedance I_{Steel} / I_{Air} is much greater than 1. Thus, a portion of the wave is transmitted to the air, but a strong rarefaction wave is sent back into the steel to tell it that it can expand outward.

For explosions in soil, the acoustic impedance of the explosive is higher than that of soil, hence a compression wave is transmitted to the soil to tell it to compress and start moving outward. The wave reflected back into the detonation products is an expansion wave telling the products that the medium encountered will 'move out of the way' in order to allow the products to expand.

C3.2 Soil Ejecta from the Detonation of a Buried Explosive

As explained above, the detonation of a high explosive buried in soil transmits a shock wave into the soil, crushing the nearby material and absorbing some of the explosive energy. Note that the term soil is used in the general sense to refer to materials ranging from loose sand, clay, limestone, and granite. Reference [C13] lists typical material properties for these different soils and describes their response under explosive loading. In general, the passage of the shock wave creates three zones in the soil: the crushed zone, the rupture zone, and the elastic zone. Adjacent to the explosive, in the crushed zone, there is total disruption of the soil due to extreme pressure. With harder materials, this zone typically extends from 2 to 3 times the charge radius for a spherical charge. The rupture zone, in which fissures are created due to wave rarefactions, extends to approximately 5 or 6 times the radius of the charge.

For a deeply buried explosive, a spherical charge creates a spherical cavity, known as a *camouflet*, with the cavity radius depending on the mass of the charge. In reality, AP mines are buried at or near the surface of the ground and this has a significant effect on the behaviour of the explosion. Bergeron et al. [C14] conducted experiments with surrogate mines that showed that soil type and explosive confinement significantly affect the impulse from a blast mine on a target. The charges consisted of 100 grams of C4 explosive buried at three depths of burial (DOB), 0, 30, and 80 mm, where the DOB is measured from the soil surface to the top of the charge. Supplementary research by Braid [C15] expanded on this work by repeating the same experiments with charges of 50 and 200 grams of C4 and an additional soil type that consisted of a mixture of sand and clay. During the mine blast, the soil deformation can be described in three phases:

- Phase I – The soil adjacent to the mine is crushed as the shock wave passes through the material.
- Phase II – Deformation (swelling) of the soil surface begins due to the expansion of the detonation products and reflection of the compressive stress wave at the soil and air interface. For mines with a DOB greater than zero, a small volume soil cap is ejected at high velocity.
- Phase III – A large volume of soil is ejected due to the continued expansion of the detonation products. This soil is ejected upwards in a conical annulus shape, with the included angle of the cone increasing with decreasing DOB and decreasing soil density.

This process is illustrated in Figure C12. It should be noted that the effect of increasing DOB is not monotonic. That is, the DOB can be adjusted to optimize the volume of soil ejected from the crater, which is useful for explosive excavation. The maximum volume of soil ejecta is a function of DOB and depends on the soil type and charge size. This is shown in Figures C13a and C13b, which were computed from Reference [C13], where the resulting crater diameter is plotted as a function of the DOB for 100-gram and 50-gram charges with varying soil types. For dry sand, the maximum crater diameters for the 100-gram and 50-gram charges are achieved for a DOB of 0.92 m and 0.74 m, respectively. Clearly, this is deeper than the burial depths normally used with mines. Most mines are buried much closer to the surface for two reasons. First, as a mine is buried deeper, it requires a larger force on the surface to actuate the fuse because the soil spreads the surface load with depth. Hence, if a mine is buried very deep, it will not be triggered. Second, most AP mines are buried by hand. Burying a mine deeper requires a lot more work and time, which might be in short supply to the combatants.

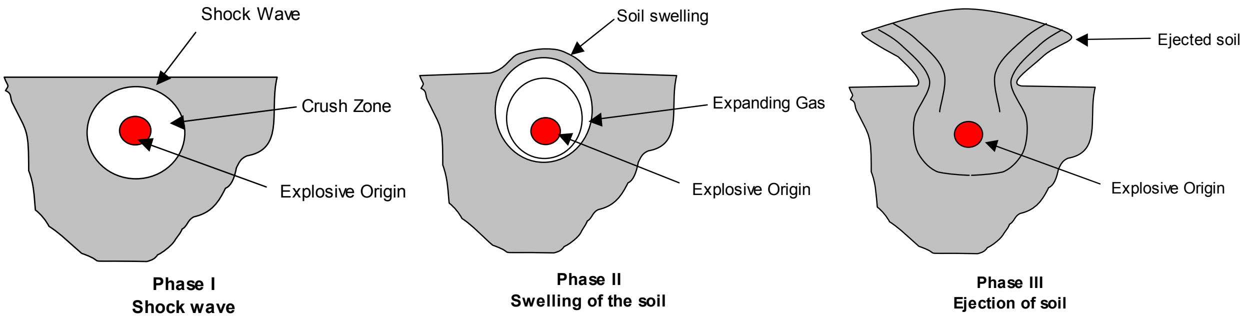


Figure C12: Diagram Illustrating the Formation of a Crater by the Explosion of a Buried Explosive.

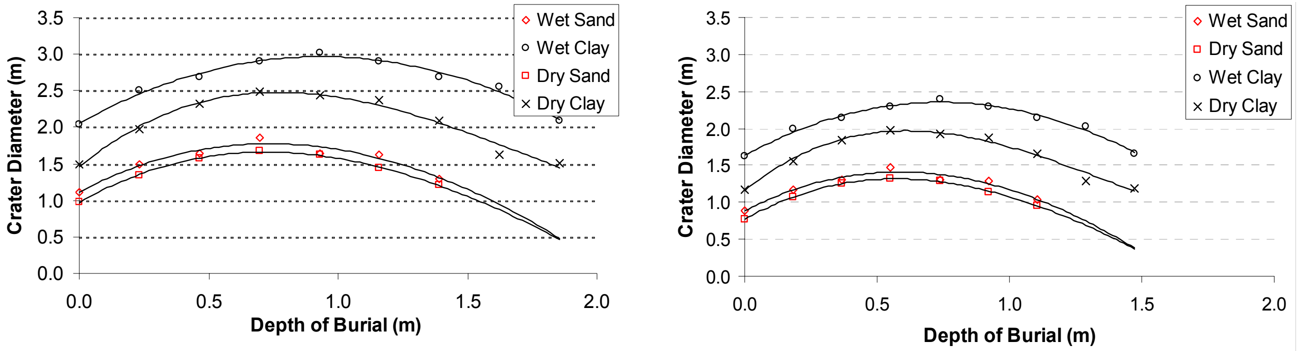


Figure C13: Formation of a Crater by the Explosion of a Buried Explosive for Two Explosive Masses: 100 grams on the left and 50 grams on the right.

Another important quantity to consider is the velocity of the ejected soil. Reference [C14] measured the early deformation of the soil cap above shallow buried charges using flash x-ray photography, as shown in Figure C14. Measuring the displacement from the x-rays as a function of time, the early velocity of the soil cap was estimated to be approximately 1000 m/s for the 30 mm DOB, but less than 200 m/s for the 80 mm DOB. To explain these numbers, it is necessary to consider the driving force behind soil movement. It takes only 5µs for the detonation wave to transform the solid explosive into high-pressure gas. From that point onward, motion of the soil cap depends on the reaction of the soil and the expansion of the detonation products. For the experiments of Reference [C14], loosely poured sand was used, which resulted in a very porous soil medium. The expanding gas could flow into the voids and also pushed hard on adjacent soil particles, creating a radial flow about the centre of the explosion. As individual soil particles hit each other, they transfer a portion of their momentum to neighbouring particles, quickly spreading this momentum. The result is that DOB has a strong effect on the ejection velocity of the soil cap.

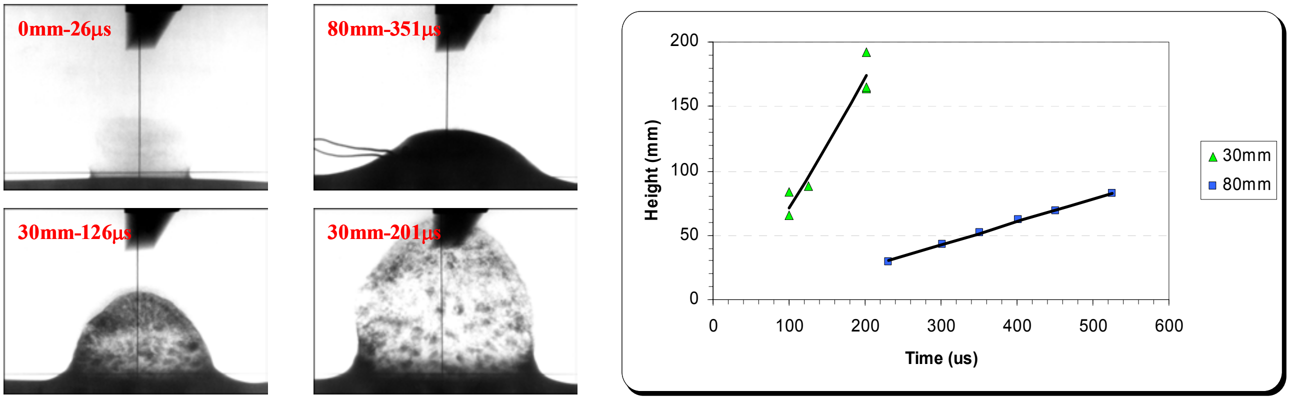


Figure C14: Measurement of Soil Cap Displacement using Flash X-Ray Photography showing the Strong Influence of DOB on Ejecta Velocity – from Reference [C14].

Soil ejecta velocity depends on the explosive charge mass and soil properties. Bangash [C13] provides data for particle velocity as a function of distance from the charge, which is plotted for different soils in Figure C15. In general, a shallower DOB results in a smaller amount of soil being ejected, but with a higher velocity. The denser the soil, the more energy is directed upwards to the target.

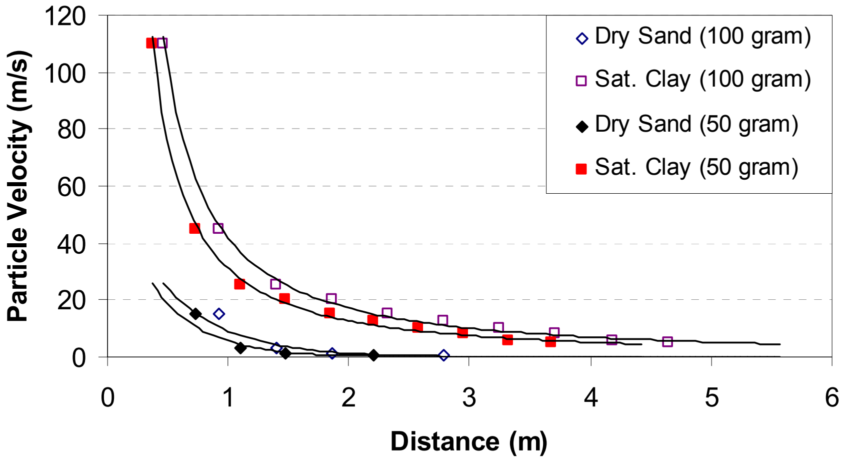


Figure C15: Distribution of Soil Ejecta Velocity as a Function of Radial Distance from the Charge – from Reference [C13].

C3.3 Expansion of the Detonation Products

Immediately after detonation of the explosive, the high-pressure products start to expand. In the process, the products cool down, pressure drops, and the rate of expansion decreases. The laws of physics determine the relationship between temperature, pressure and density as expressed by an equation of state, e.g., Equation C8. The expansion of the gas happens very quickly, which limits the time for heat transfer. The gas expansion can therefore be described roughly as an adiabatic process, expressed as

$$(p/p_o)=(V_o/V)^{\gamma} \qquad \text{(Equation C14)}$$

where p and V are the pressure and volume of the expanded gas, while p_o and V_o refer to the condition immediately after detonation. As an example, p_o is set to 100,000 atm and V_o is set to 66 cm^3, the latter volume corresponding to 100 grams of C4 explosive in its pre-detonation state. The ratio of specific heats, γ, is assumed to be 1.35. Figure C16 shows the drop of pressure as a function of the radius of the expanding gas, assuming that the shape of the gas bubble is a sphere or a hemisphere. The plot on the left uses a linear scale to demonstrate the very rapid drop of pressure with increasing volume, while the plot on the right shows the same data on a semi-logarithmic scale.

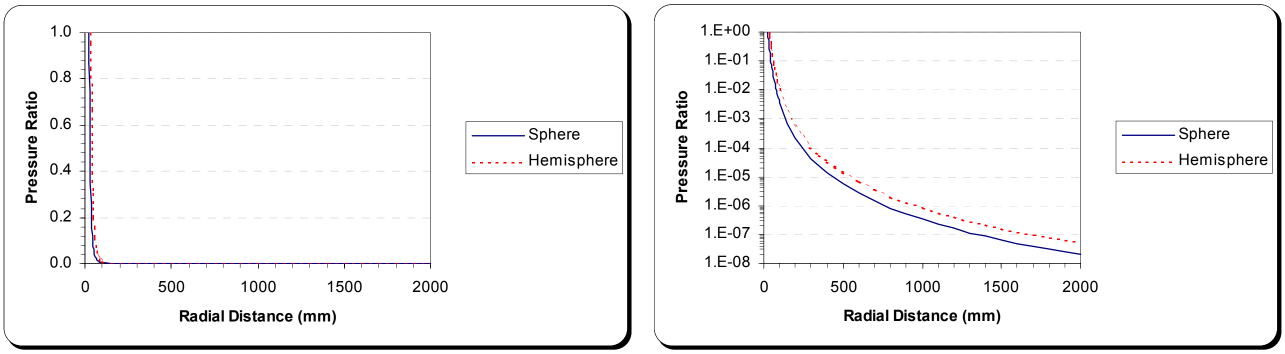


Figure C16: Drop of Pressure with Volume Expansion using an Adiabatic Expansion as per Equation C14.

The spherical model is a good approximation until the gas reaches the soil surface. Applying this model to the cases of section C3.2 above indicates that gas pressure drops to approximately 15% of its initial value in expanding from the initial charge volume to a sphere just touching the soil surface when the overburden is 30 mm. When the charge is buried below 80 mm of overburden, the gas pressure drops below 1% of its initial value by the time it reaches the surface. These dramatic changes in pressure illustrate how quickly the detonation products expend their energy with expansion. Yet the initial energy is high and the gas bubble acts as a piston to accelerate nearby soil particles when the charge is buried. The products eventually break through the surface and continue to expand in air, still acting as a piston to generate an air shock.

The process of expansion can also be viewed from a more global perspective. Figure C17 shows three frame sequences extracted from high-speed films of the detonation of 100 grams of explosive buried in sand. The sequence on the left is for a charge buried flush with the sand surface, while the sequences in the middle and on the right are for charges buried 30 mm and 80 mm below the surface, respectively. It is apparent that depth of burial has a strong influence on the expansion process.

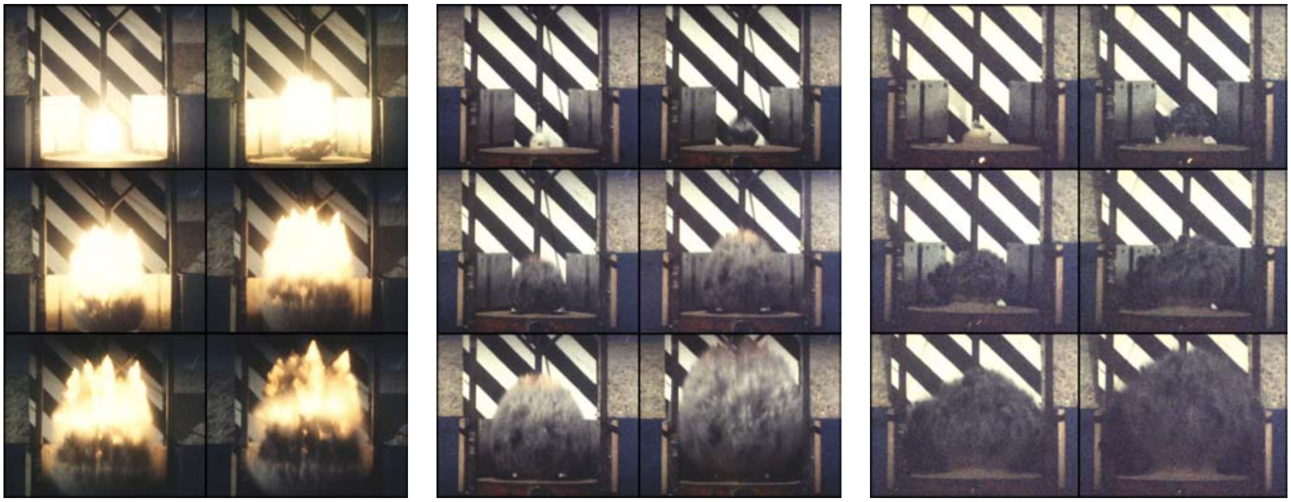


Figure C17: Selected Frames from High-Speed Films of the Detonation of 100-gram Charges in Sand; The charges were flush buried (left), below 30 mm of sand (centre) and below 80 mm of sand (right).

The growth of the detonation products was measured from the high-speed films for the three depths of burial. The results are plotted in Figure C18. The initial velocity was determined from second order polynomial fits to each set of points. For a flush-buried charge, the initial vertical velocity is about 3000 m/s and remains strong throughout the field of view of the camera. The event is very bright because burning of the hot combustion products continues long after the initial detonation due to the strong rate of expansion of the front, which makes it possible for the hot, unburned products to mix with fresh oxygen and sustain the combustion process. The jetting also indicates the presence of strong turbulent mixing at the interface between the detonation products and the air.

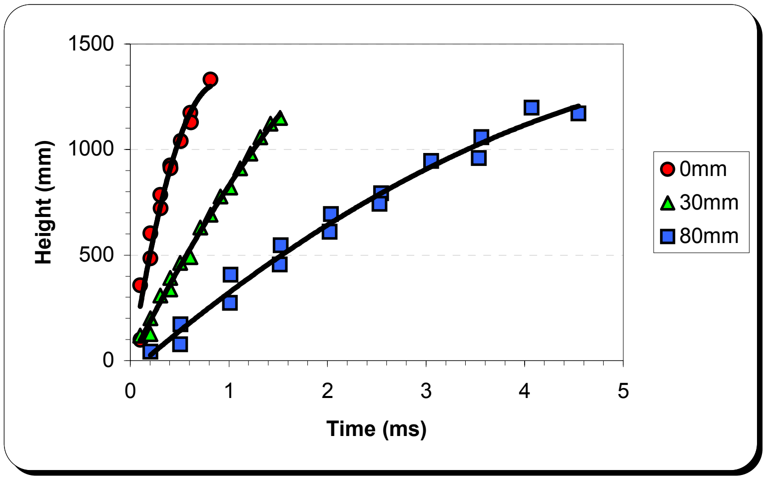


Figure C18: Vertical Expansion of the Detonation Products from High-Speed Films.

Having soil above the mine slows the growth rate of the cloud considerably. Maximum values of vertical speed were 940 m/s and 400 m/s for the 30 mm and 80 mm overburdens, respectively. The data clearly indicates that the velocity of the detonation front decreases rapidly, with the greatest deceleration being experienced by the flush-buried charge. Within the first 1000 mm, the front velocity for the flush-buried charges decreased by about 50%.

The rate of expansion influences the side-on pressure field above the mine. Recall that the expansion of the detonation products acts like a piston, pushing the air and creating a closely coupled air shock. Peak overpressure increases with shock front velocity. Passage of the material interface associated with the detonation products also influences the overpressure. Figure C19 shows clearly that the largest overpressure occurred with flush-buried charges. Soil overburden decreased the peak overpressure. Peak overpressure also decays with distance from the blast source in all cases irrespective of overburden. Magnan and Rondot [C16] found similar results in subsequent experiments and expanded the work by measuring off the vertical axis.

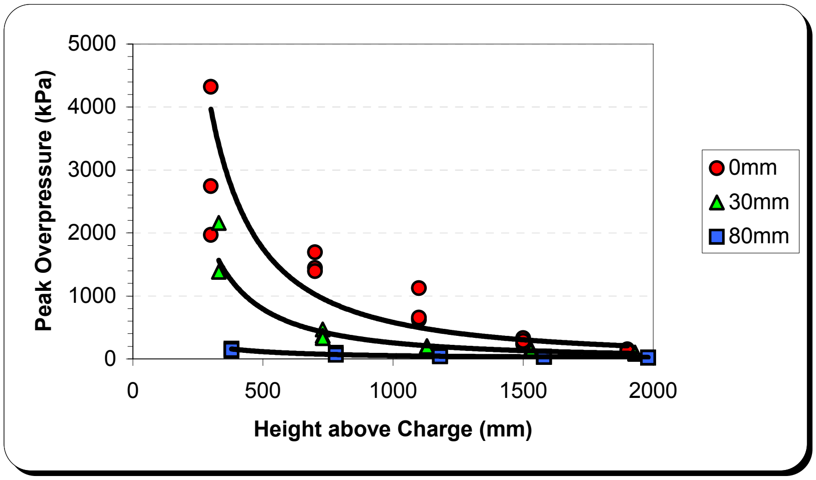


Figure C19: Decrease of Side-On Overpressure Vertically above the Mine as a Function of DOB.

Static overpressure is only one characteristic of the flow. It is also important to consider the dynamic pressure associated with the strong, transient and highly directional flow. Figure C20 presents three curves to illustrate the impact that the flow might have on nearby objects and personnel. The curves represent static overpressure, p_s, dynamic pressure, q_s, and reflected pressure, p_r, in accordance with the theoretical derivation made by Rankine and Hugoniot [C17] in 1870 to describe normal shocks in an ideal gas. It is seen that dynamic pressure becomes greater numerically than static overpressure at a shock speed of 775 m/s. For some burial depths, the shock speed exceeds this value. Reflected pressure is related to geometry and can reach very high values. If the body of a soldier is located in such a way that it stops the flow, it can be subjected to injurious pressure levels. This is certainly the case when stepping on a mine, given that the foot attempts to stop the flow in addition to being in the region of greatest static overpressure.

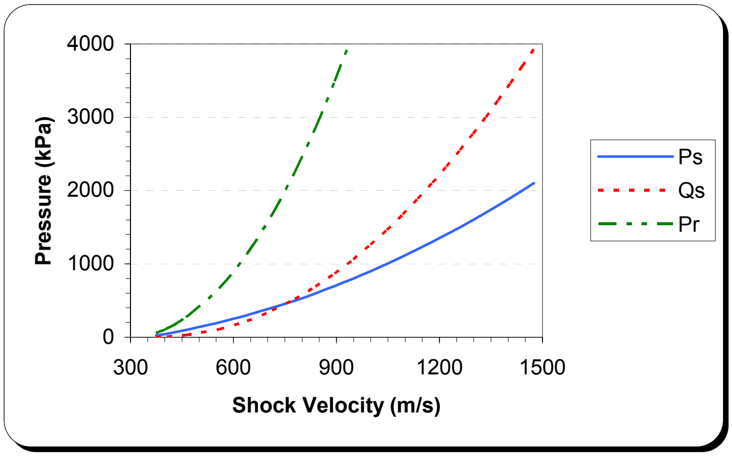


Figure C20: Static, Dynamic and Reflected Pressure behind an Ideal Normal Air Shock.

C3.4 Effective Impulse Delivered to Objects Above the Mine

The previous measurements of free field blast above 100-gram charges provided only partial information about the overall loading. There is often a need to determine the effective load, or impulse, that a mine blast delivers to a physical object placed above the mine. Total impulse is the result from the combined loads from the transient flow of detonation products past the object, and momentum transfer from the impact of individual soil particles. The net effect of total impulse can be determined by measuring the momentum transferred to a target of defined mass and geometry placed above the mine. Such measurements [C18,C19] were performed in the past against targets of practical interest such as flat plates. Some of these authors claimed that soil ejecta loading is an order of magnitude more severe than any loads from explosively driven shock in air.

Westine et al [C20] used a rigid plate with plug inserts to measure the distribution of total impulse resulting from the explosion of sub-scale charges buried in soil. The plate was mounted parallel to the ground plane and plug motion was captured on high-speed film. Combustion products obstructed viewing the early plug motion, but initial velocity was deduced from the analysis of late time motion. The resulting impulses were fitted to a non-dimensional model, Equation C15, which expresses the spatial distribution of total specific impulse as a function of explosive energy, W, soil density, ρ, and geometry. The lateral distance from the centre, x, the standoff from the bottom of the target plate to the centre of the explosive, s, and the depth of burial (defined to the centre of the explosive), d, defines the geometry. These geometric variables are depicted in Figure C21.

$$Y = \frac{0.1352\ \tanh^{3.25}\left(0.9589\,Z\right)}{Z^{3.25}} \qquad \text{(Equation C15)}$$

where Y is scaled impulse and Z is scaled distance expressed as:

$$Y = \frac{I_V\sqrt{s}}{\sqrt{\rho W}\left(1+\frac{7d}{9s}\right)} \qquad \text{(Equation C16a)}$$

$$Z = \frac{xd}{s^{5/4}A^{3/8}\tanh\left(2.2\frac{d}{s}\right)^{3/2}} \qquad \text{(Equation C16b)}$$

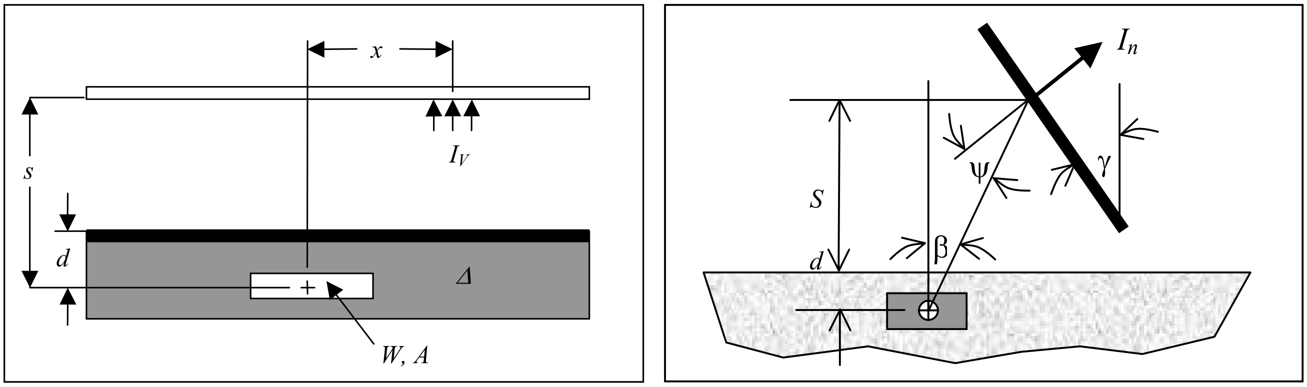


Figure C21: Left: Mine-Target Geometry as Defined in the Total Impulse Model from Reference [C20]; Right: Extension of the Model from Reference [C21].

The Westine model does not provide the finer details about how the mine blast event unfolds with time, i.e., the partition of momentum transfer between the detonation products and soil ejecta impact. On the other hand, the model is simple and relatively easy to apply. It provides practical answers to a relatively complex problem. The reader should note that the total impulse relates only to the geometry depicted in Figure C21. Morris [C21] expanded the application of the Westine model to flat plates that are inclined. He found that the specific impulse for such plates is obtained by multiplying the impulse obtained from Equation C15 by the cosine of the angle about the normal to the plate and the direct line from the centre of the charge to the point of interest on the plate, and dividing by the projected area, as depicted in Figure C21 (right side). The resulting expression is given in Equation C17.

$$I_N = I_V\frac{\cos(\psi)}{\cos(\beta)} \qquad \text{(Equation C17)}$$

C3.5 Effect of Soil Moisture on Total Impulse

Equation C16a lumps the soil properties into a single quantity, the bulk density. Yet, it is known that soil type and moisture content can have a strong effect on the total impulse transferred to an object above a mine.

Bergeron and Tremblay [C22] investigated the effect that these parameters have on mine output using a horizontal pendulum, as shown in Figure C22. This structure was designed for use with 1 kg charges that were shaped as short cylinders with a 35% height to diameter ratio. The pendulum was subjected to a comprehensive series of tests where depth of burial and moisture content of the soil was varied. The main output from the pendulum is the maximum angle reached following the explosion, which can be related directly [C23] to total impulse using conservation of momentum and energy principles. One characteristic of a horizontal pendulum is that a minimum energy threshold is required to move the arm. To demonstrate this, define the maximum impulse, I_{max}, as the impulse just sufficient to bring the arm to the vertical position. Then, delivering 50% of I_{max} to the pendulum face results in a maximum deflection angle of only 15°.

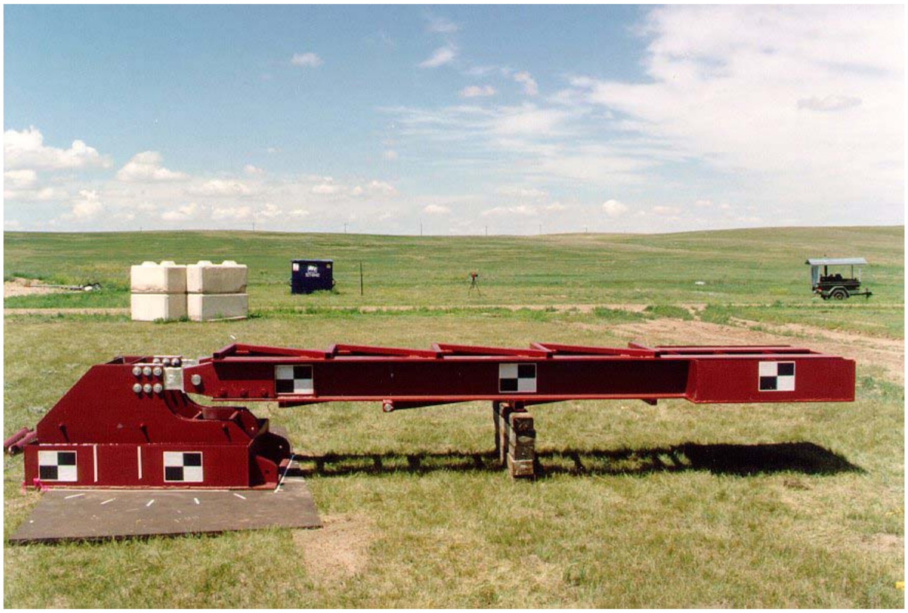


Figure C22: Horizontal Pendulum used in Reference [C22] to Quantify Mine Blast Output.

Equation C18 defines how the maximum deflection is linked to the total impulse delivered. This assumes that most of the loading takes place before any significant motion of the pendulum arm has occurred, which is a reasonable assumption given that the loading phase duration is of the order of 1-2 ms while several hundreds of milliseconds are required for the pendulum arm to reach apogee. The formula depends on the mass and inertia properties of the pendulum to compute the total impulse I_P.

$$I_P = \sqrt{\frac{2mgrI_0 \sin\theta_{\max}}{R^2}} \qquad \text{(Equation C18)}$$

where m is the mass of the pendulum arm, g is the gravitational constant, r is the distance from pivot point to the centre of gravity of the arm, I_0 is the mass inertia of the pendulum arm about the pivot point, $\theta_{\max}$ is the maximum angle reached by the pendulum arm, and R is the distance from the pivot point to the point where the impulse is applied.

Figure C23 shows impulse as a function of soil moisture for three soil types: prairie soil which contains a high level of silt and clay; uniform silica 3050 sand; and a steel plate buried flush with ground level. All the data of this graph, with the exception of the steel plate test, is for a 400 mm standoff from the ground to the target and for 50 mm of overburden over the charge. All charges were made from C4 explosive. A quadratic curve fit though the prairie soil data provides a visual reference to evaluate the results. It is seen that the charge resting on top of the steel plate produces the smallest impulse delivery on target. Given that the distance from the top of the charge to the target was 350 mm for this case and 450 mm for all other cases, this result supports the statement that lateral confinement plays an important role in focussing the mine blast energy on target. Figure C23 also displays clear evidence that mine blast output increases with soil moisture content. For saturated soil, impulse on target increases nearly three times relative to a surface laid charge. It is also interesting to note that the test results suggest that soil type and compaction play only a minor role in mine blast output.

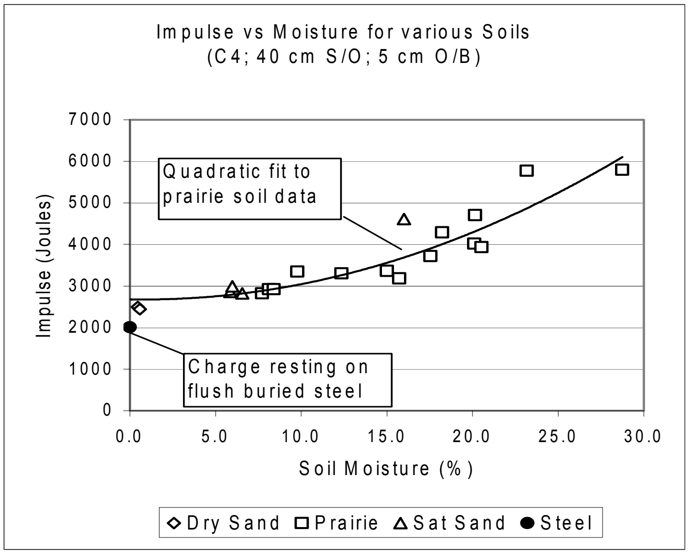


Figure C23: Mine Blast Output for Various Soils as Measured with a Horizontal Pendulum.

Figure C24 shows the impulse as a function of soil moisture for various overburdens from 100 mm to surface laid. The data is for C4 charges in or on prairie soil with a 400 mm target standoff. Curve fits through the data for each overburden provide a visual reference for interpretation of the results. The surface laid charges produced the smallest impulse transfer to the target and a relatively weak dependence on soil moisture, as would be expected intuitively since there is no lateral confinement of the explosion for this case. Flush burying the charge significantly increases the impulse on target, and the impulse now shows a much stronger dependence on soil moisture. The impulse is further increased as the target is buried deeper. However, it is also seen that the results for the 50 mm and 100 mm cases are similar. This supports previous cratering work [C24] that showed that a crater size can be maximized for an optimum depth of burial combined with a specific soil and charge size. A similar analogy can be developed thereby mine blast output can be optimized as a function of overburden.

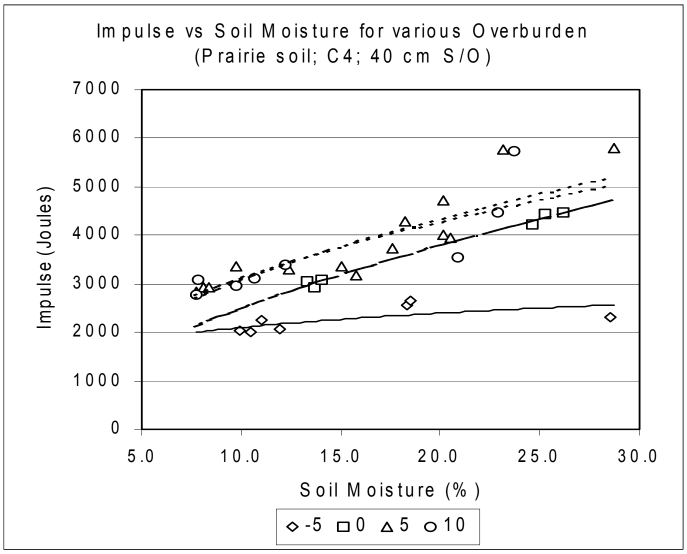


Figure C24: Mine Blast Output for Various Values of Depth of Burial as Measured with a Horizontal Pendulum.

Finally, Bergeron et al. investigated the effect of explosive type. Figure C25 shows a plot of impulse delivery as a function of soil moisture and a quadratic fit through the C4 data to provide a visual reference for interpretation of the results. The explosive was varied only for low moisture. It is seen that Comp B and C4 deliver comparable impulses to the target. TNT produced significantly lower output. Comparing the average impulse from the TNT tests to that from the C4 tests for equivalent moisture yields a factor of 2 as the TNT equivalence for mine blast output. This indicates that the use of equivalency to describe the output of a given explosive relative to another must be done with great care, as it is dependent on the application.

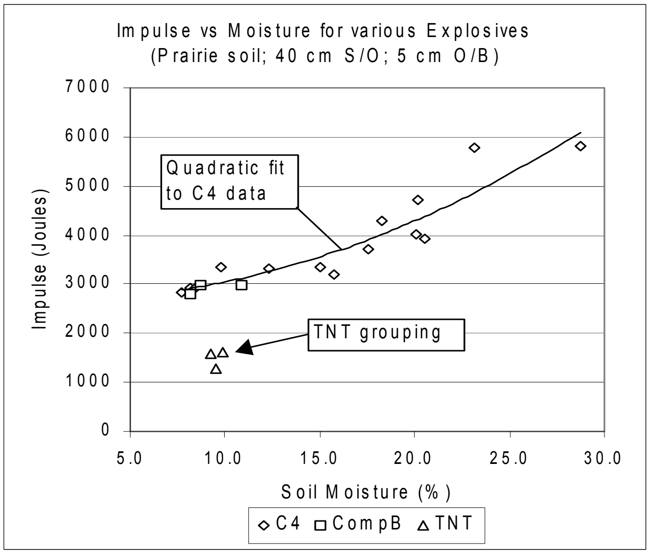


Figure C25: Effect of Explosive Type on Mine Blast Output as Measured with a Horizontal Pendulum.

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Annex D: MEDICAL PERSPECTIVE OF MINE INJURIES

PART ONE: THE CULTURE OF MINE INJURIES

The past twenty years has seen a proliferation of wars, internal disorders, terrorism, and conflicts with a profound impact on the civilian populations and military forces involved. Weapons may be highly technical or fairly cheap and improvised – the only thing constant is the ability to kill and disable anyone coming into contact with them. Anti-Personnel (AP) mines are cheap, easy to produce, portable, and can be distributed many ways on the battlefield. They have been used by military forces to deny areas to the enemy, slow them down, channel the enemy into pre-selected areas and to defend "dead ground" with a minimum of troops. Unfortunately they also affect civilian populations in a most sinister manner. Mines do not distinguish between friend or foe, military fighter or civilian, soldier or child.

Injuries caused by blast mines are at the same time impersonal and extremely personal. They are impersonal since the person who laid the mine in the ground rarely if ever sees the victim. The people responsible for setting the weapon in the ground are almost always at a considerable distance in geographical terms and time from the intended or accidental victim. By their very nature, AP mines are designed to deny land from a user be that an opposing military force, civilians using the land to move from one area to another, or a farmer displaced off his land and sent off to be a refugee. [D1,D2].

Figure D1: Mines will prevent rebuilding this power grid.

Figure D2: Unknown mines in this heavily fought over farming area will prevent its use for a long time.

Blast mines are intensely personal – they explode in very close proximity to the victim. With no other weapon system is there such a potential for complicated injuries from several mechanisms that are applied, in most cases, directly to the casualty's body. This results in unusual and severe injury patterns and an intimidating surgical problem if the victim survives long enough to make it to hospital.

AP mines lend themselves well to use as a terrorist weapon and irregular warfare. Besides exacting a severe toll of killed and wounded, many more people and families are affected by loss of employment, displacement from their homes and land, the elimination of skilled labour, and the destruction or denial of infrastructure. All of these destabilize societies and threaten the countries forced to support the refugees fleeing the conflict.

AP mines are deployed in areas where the indigenous population and military personnel have little or no access to equipment that can protect them from these weapons. Either the equipment is totally lacking or they do not have specialized knowledge to use it so as to minimise the risk of injury. Education about the risk of these devices and how to eliminate them is extremely important.

The struggle to control and eliminate AP mines is complex and requires concurrent action at many different levels. No matter how well constructed protective suites are, there will always be casualties. These need to be evacuated by an efficient ambulance service, resuscitated and then undergo surgery to prevent death or worsening of the injury. Finally, rehabilitation is necessary to bring dignity and gainful employment back to the victims. Paradoxically, the nature of the injury may change and become more challenging as levels of protection improve.

Figure D3: Somali Victim of Mine Injury.

Many of these countries lack a sophisticated health care system and such as existed prior to the conflict has been seriously impaired by a lack of trained professionals, support personnel and money. What this means is that for years to come, decades perhaps, there will be tremendous opportunities to help countries develop educational programs to prevent injuries, acquire the technology to protect their citizens, and introduce the medical infrastructure and programs to improve care to the victims of land mines.

PART TWO: PATHOLOGY OF MINE BLAST TRAUMA

Before describing the pathology of mine blast trauma, it is useful to consider the larger picture of blast injuries. Here, the term *blast* refers to the explosion of military munitions, which generate injuries due to the effect of heat, overpressure, and fragment impacts on the body. Mine blast trauma is simply a subset of this larger class of blast injuries. Thus, injuries from explosives are the result of widely different mechanisms that depend on the size of the explosive charge and the range between the casualty and the explosion. This is depicted in Figure D4 where thermal injuries are usually confined to the zone closest to the source of the explosion (the so called fireball). Within this zone, overpressure and fragments also injure the victim.

The effects of overpressure extend farther than thermal effects and finally, fragments can injure over a very large zone. Blast injury is divided in four categories as follows:

a) *Primary Blast Injury* relates to the actual physical interaction between the body of the victim and the detonation products, defined by the physical boundaries of the fireball, and/or the blast wave generated by the explosion.

b) *Secondary Blast Injury* results from the impact of primary and secondary fragments with the body of the victim. Primary fragments are those originating from the casing of the weapon; they are usually very energetic and lethal. Secondary fragments originate from nearby objects or soil surrounding the explosion; the force of the explosion accelerates them.

c) *Tertiary Blast Injury* results from either the whole body of the casualty being flung violently or from part of the casualty's body being violently accelerated relative to the remainder of the body.

d) *Quaternary Blast Injury* are caused by the collapse of buildings and other structures, or by fires started by the explosion.

Tertiary and quaternary blast injuries are usually the most significant cause of casualties in large explosive accidents or terrorist bombings. However, the injury mechanisms for these types of injury mimic other types of blunt trauma closely and will not be discussed further. In addition to the above injuries, the inhalation of toxic compounds created by the explosion can lead to injury. Some examples include phosphorous contamination of wounds, hydrocarbons, and the unburned compounds from air fuel explosive devices.

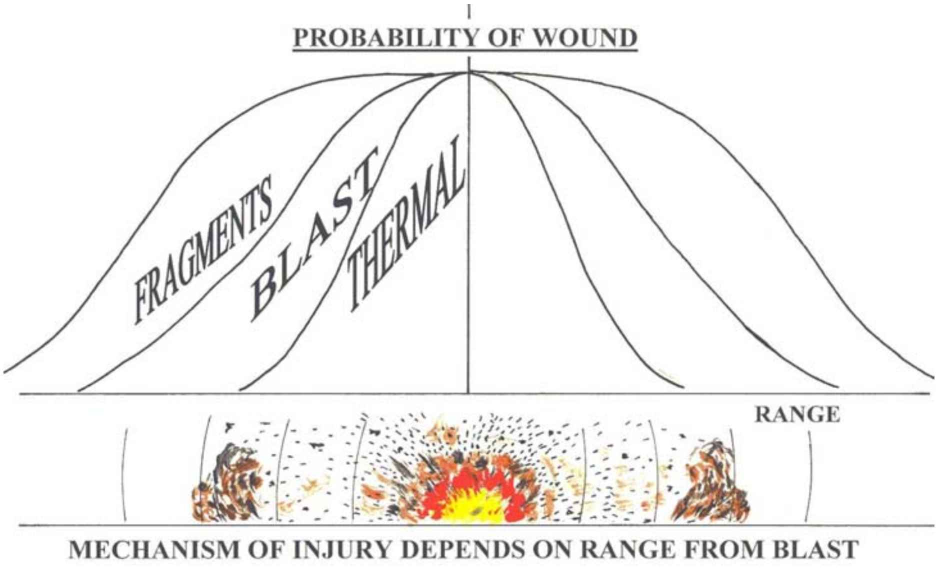

Figure D4: Mechanisms of Injury Depend on Range from Blast.

Primary Blast Injury

The biological effects and types of injuries from primary blast are extremely complex. There still exist many debates about the exact mechanisms that come into play. This is due to the extremely short time over which blast injury occurs, which makes it very difficult to observe the intricate details of how blast interacts with biological tissues. What is known is that primary blast injury has a number of direct and indirect results on several tissues including:

a) Organs with an air water interface
b) Solid abdominal organs
c) Other tissues such as muscle and bone
d) Peripheral nerves
e) Central Nervous System
f) Blood filled arteries and veins

The pathophysiology of primary blast injury is complex. Some of the mechanisms depend upon:

a) Direct coupling and shattering of tissue
b) “Irreversible work”
c) Spalling at the microscopic level of tissue
d) Compression and re-expansion of tissue
e) Air embolism
f) Neurologic reflexes
g) Body wall and solid organ displacement

The damage associated with a blast wave appear to depend on:

a) Actual change in pressure of the blast front (ΔP)
b) Duration of the pressure wave
c) The rapidity of onset of the pressure (upward slope on the pressure wave)

Most casualties in close range to the explosive device, including being in near contact with an AP mine, will suffer primary blast injury. The injury mechanism consists of thermal injury and overpressure injury. At that distance from the explosion, the victim also suffers secondary blast injury due to fragments. Each of these will be discussed separately but it must be understood that the casualty might suffer wounds from all mechanisms.

Thermal Injury

Thermal injury is common in any close range explosion, but it is usually overwhelmed by other mechanisms. Flash burns depend on the temperature, time of exposure, thickness of skin, conductance of skin, and protective clothing. The relationship to time of exposure and temperature is a log scale (see Figure D5) and it might take only a few milliseconds of exposure to cause a burn. [D5] High explosives can create temperatures in the thousands of degrees and burning can be considered to be virtually instantaneous. Much of the burned skin will be exposed to blast wave injury and so disrupted that it is difficult to distinguish thermal from blast injury. The net result is the same: the need to surgically remove this tissue to avoid toxic and infectious complications. Another serious cause of thermal injury is the inflammatory effects on clothing. Many soldiers wear uniforms based on nylon and other polymers. These burn and smoulder causing serious full thickness burns that make a serious injury that much worse. Grass and building fires started by the explosion are the main causes of burns to casualties. This is not typical of AP mine injuries.

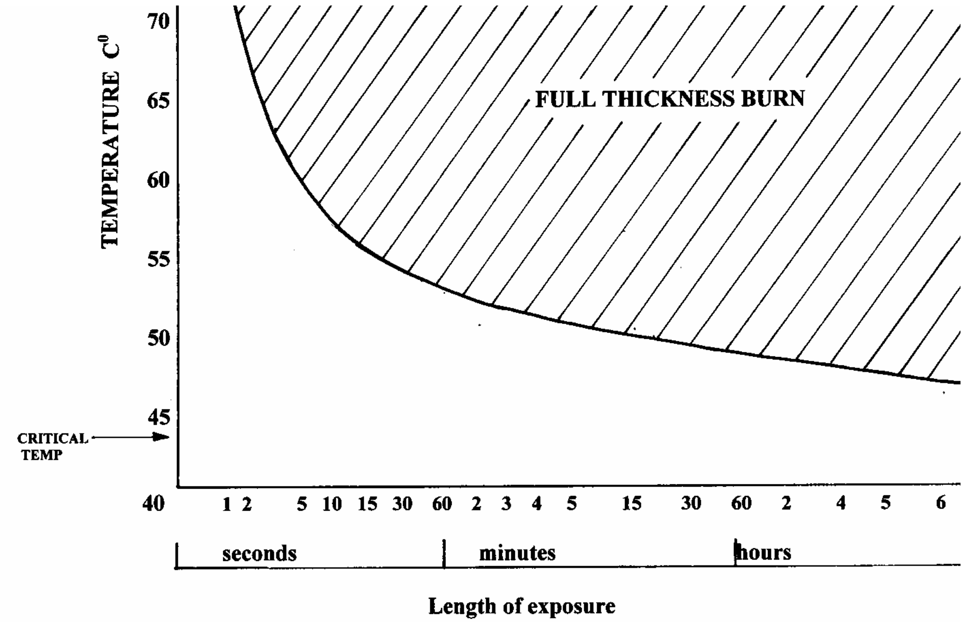

Figure D5: Relationship of Burn to Time of Exposure.

Blast Injury to Gas Containing Organs

Primary blast injury has very typical pathology in organ systems. Organs containing air-fluid interfaces are most sensitive to primary blast wave. These consist of the ear, the lung and the gastrointestinal (G.I.) tract in decreasing order of sensitivity. The exact mechanisms of primary blast injury are still subject to controversy because of the very small time scales (micro to milliseconds) over which these injuries occur, which makes it nearly impossible to observe (seeing is believing). As a blast wave passes through a tissue filled with liquid, it creates high velocity microscopic droplets that damage the tissue. In some cases, it is surmised that gas-filled tissue suddenly implodes and forcefully re-expands. At the microscopic level, the shear stress between different tissue planes causes tears that create bleeding and inflammation. Blast waves travel at different velocities in different densities. The density of tissues that contain water is high relative to tissues that contain air. These differences in density affect the shear stresses and lead to injury.

Ear: This is the most easily injured organ with children being most susceptible. The threshold can be as low as 2 psi with reliable injury at half an atmosphere of overpressure. Children’s ears are more susceptible to damage than adult ears. This is associated with:

a) Perforated eardrums.

b) Dislocated ossicles of the middle ear.

c) Overpressure of the inner ear with degeneration and later inflammation of the fine nerve endings.

d) Disruption of the semicircular canals, fistulae etc… These result in long-term hearing loss and balance problems that can be very disabling.

It should be noted that ear damage acts as a marker for more serious primary blast injury in other organs. This depends on complex issues including protective equipment, direction of blast waves, and orientation of the body relative to the blast wave.

Lung: Blast damage to this main organ system can incapacitate or kill a casualty. Damage is usually found in the lung closest to the blast wave and is similar to a pulmonary contusion found in other blunt trauma situations. The injury can be more serious if the casualty is within an enclosed space. The contusion is seen as small areas of bruising (ecchymosed) on the surface of the lung, which can include the space between alveolar membranes. As the contusion becomes larger, the alveolar space becomes filled with blood and as the process continues, inflammatory products such as macrophages, neutrophils and fibrin appear. Depending upon the size of the contusion, this can interfere with gas exchange (particularly oxygen) and result in a physiologic condition known as *shunt*. Not only is this a potentially serious problem in and of itself, but it will greatly increase the risk of surgical procedures to treat other blast or fragment related injuries.

This acute lung injury makes the lung susceptible to a number of problems that increase mortality, lengthen hospital stay, and can make any surgical procedure much more dangerous. Pneumonia is an ever-present hazard and may include unusual organisms due to the soil blasted into the air and aspirated. This acute lung injury can go onto a more severe and long lasting Acute Respiratory Distress Syndrome (ARDS) because of the general release of inflammatory mediators. [D7]

Blast lung was found in a significant number of survivors of terrorist bombings, especially if the victims were within an enclosed space. This even includes buses where it is relatively easy to displace the windows; the space remains closed long enough for the full impact of reflected waves to increase the level of injury. This was clearly seen in survivors of Israeli bus bombings, 38% to 47% of which had blast lung. If they survived other injuries, blast lung survivors had a good prognosis [D8] and recovered normal lung functions and gas exchange. This might have been due to the relatively young age of those injured in these incidents. Other problems are common with primary lung blast injury:

a) Injury to medium sized vessels can result in bleeding into the air sacs and passageways, which results in hemoptysis (coughing up of blood).

b) Trapped gases in the alveoli or air pockets can cause a pneumothorax or collapsed lung. As the blast wave passes through the lung, it can compress the air, which, if it re-expands against a blocked airway, will stretch the tissue beyond its elastic limits with the escape of air into the mediastinum or pleural cavity. If untreated, this can be very serious.

c) Finally, simple displacement can cause broken ribs making recovery more difficult later.

Sudden gas trapping within the lung and vascular injury can cause an air embolism. Injury to the low-pressure venous side of the circulation and high pressure within the gas trapped lung results in gas being transferred to the pulmonary vein where it will rapidly move to the systemic circulation. The immediate and most catastrophic result of this will be cardiac ischemia from obstruction of the coronary arteries and stroke from embolization of the carotid artery. Massive air embolism can result in an uncoordinated pumping action of the heart and sudden collapse and death from cardiac arrest. The heart cannot pump blood effectively with valves functioning normally when it is full of air.

Gastrointestinal Tract: Air in the G.I. tract can cause haemorrhage into the intestinal wall, which may or may not continue into tissue death and perforation. Air trapped in the confined spaces can cause localized perforation. This has been seen several times in Northern Ireland and Israel. It creates a problem about how to recognise casualties that may need urgent surgery or may become critically ill two or three days later when the contused bowel perforates. The traditional means of diagnosing blunt trauma by ultrasound, Computerized Tomographic Scanning (CT), or Diagnostic Peritoneal Lavage (DPL) may not demonstrate any abnormality. Small areas of contused intestine may gradually degenerate with contamination of the abdominal cavity and sepsis. [D9,D10]

Blast waves are additive and can be reflected off of solid objects making their biological effects difficult to predict under realistic field conditions. This is seen within biologic models as well. For example, lung contusions are frequently found adjacent to the diaphragm possibly due to reflection of the blast wave off the dense diaphragm muscle and into lung adding to the effect of the blast wave already present in the tissue.

Traumatic Amputations of the Extremities

Extremities have a large surface area relative to the remainder of the body. In traditional conflicts, 30-40% of wounds were of an extremity. [D3] With the systematic deployment of mines, this can reach 60-90% of casualties. [D3,D4] In traditional conflicts with gunshot or fragment wounds, casualties were able to recover quickly, or at least could resume some form of duty within days to weeks of the accident. However, blast injury to an extremity may render a soldier unfit for duty for weeks to months. He or she may never return to duty in the military sense, and this despite having access to modern medical care!

When the explosion occurs in contact or near contact with an extremity, the immense overpressure causes direct tissue destruction. In the case of an explosion under a foot, the expanding shock wave can shatter the boot and foot. This has been observed on high-speed photography and cine x-rays. As the foot disintegrates, the remainder of the limb is sheared off with pieces of soft tissue and bone flying in all directions.

As the shock wave enters tissue, it interacts with many types of tissue including skin, fat, muscle, bone, and tendon. All of these differ in density, elasticity, content of collagen, tensile strength and many other factors. The shock wave is subject to interference, reflection, refraction and can act at borders between tissue to compress, stretch, shear, impact and otherwise disrupt the tissue. Overall, the tissue disintegrates due to overloading. [D4] All this occurs in the first milliseconds of the explosion (see Figure D6). As the explosion proceeds and the high-pressure gaseous by-products expand, they act on local tissues to drive them apart and inject dirt, other foreign material, and gas up the leg, dissecting through fascia planes along paths that are easily “self dissected”. This is seen from the stripping of soft tissue and periosteum of the leg bones. Gas has also been seen on x-rays high up the leg of mine victims, even though the direct blast effects were restricted to much lower levels. This concept is also called “irreversible work” and occurs when the shear stress exceeds the tensile strength of the tissue.

Based on their experience in Afghanistan, Russian researchers have developed a model of mine trauma based on biophysical causes of injury. (Figure D7) The lower part of the leg in direct contact with the mine undergoes a “brisant” effect with the upper part undergoing contusion and other effects of the shock wave. They describe the process as the casualty being cut down as his foot dissolves rather than having it torn off by a blast of high-pressure wind. The amputation may be higher up because of fracturing of leg bones and then having the flailing limb torn away. The severity of wound and the amount of tissue that is avulsed or amputated depend on the size of charge. The individual strength of tissues, density of bone and amount of muscle can influence the severity of injury and relative size of these zones.

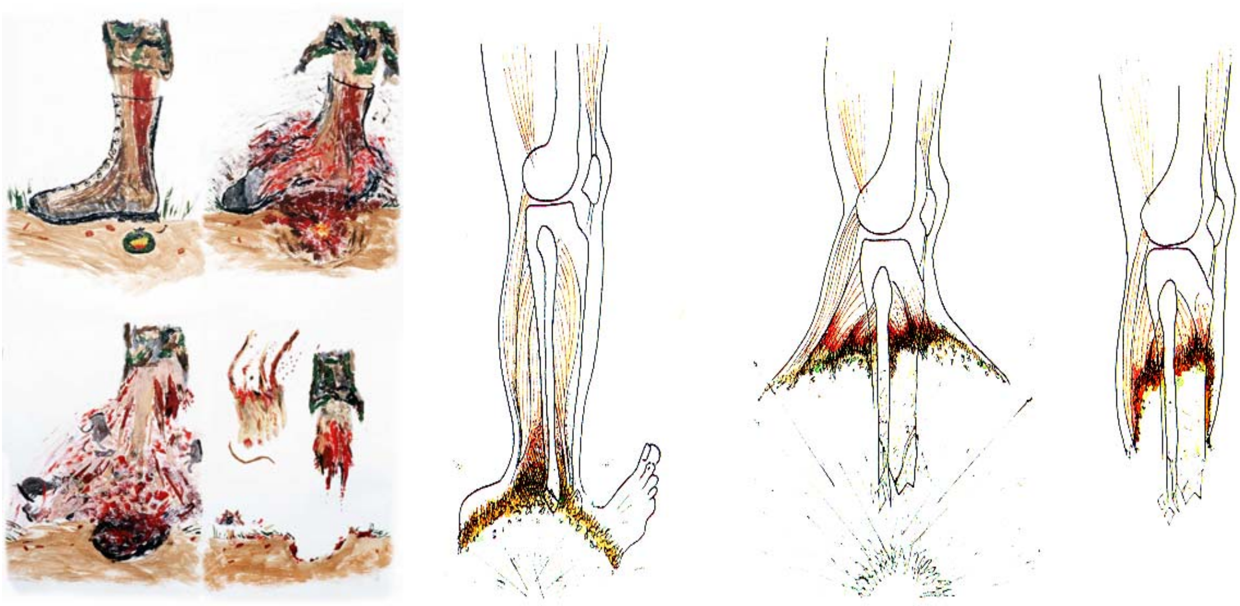

Figure D6: Left Side: Artist Conception of Blast Mine Injury Depicting Disintegration of the Foot under the Extreme Pressure Generated by the Mine Explosion; Right side: Depiction of the Mine Injury Process by Coupland.

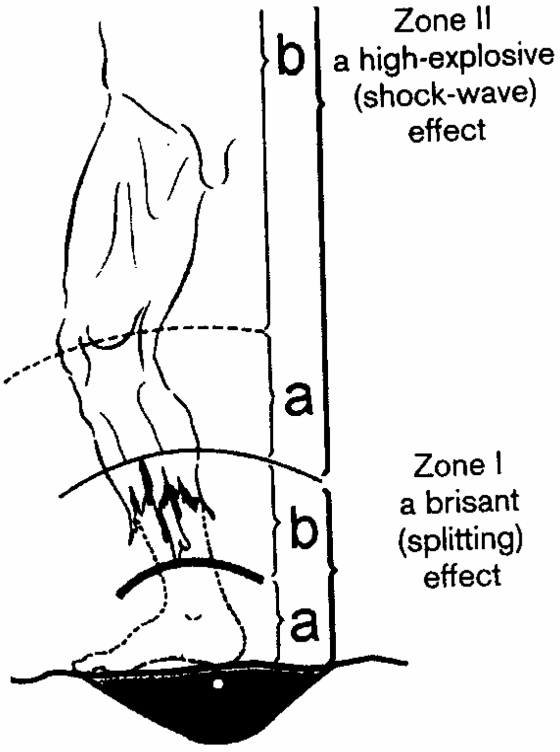

Figure D7: Russian Model of Mine Injury Zones [D4].

Traumatic amputation of the extremities has also been observed with large explosions. A review of bomb victims from Northern Ireland demonstrated that amputation rarely occurs around joints. The blast wave creates stress waves that result in fractures and the resulting flailing results in further tearing of tissue and amputation through the fracture site rather than the joint. [D6] This process occurs over a time period that is much longer than the time required by the blast wave to generate its peak stresses, which is of the order of 0.2 millisecond. Modelling of the flailing has demonstrated that these stresses last as long as 200 milliseconds. Other causes of amputation include fragments, although it would take a large fragment to remove a leg (this is seen most often with large artillery rounds or aerial bombs).

Secondary Blast Injury due to Fragments

In addition to the effects of blast waves on the lower extremities, the possibility of fragment injury is significant even for bystanders that are not directly affected by the mine. Fragments consist of pieces of mine case, fuse, rocks, dirt, shoe and foot bones that are driven upwards into the proximal leg, perineum, and abdominal cavity. Fragments from a high explosive device can have an extremely high velocity (up to 1500 meters per second). Since mine fragments are not aerodynamic, their velocity decreases rapidly.

Fragments considerably complicate the treatment of blast wounds. Complicated lower extremity wounds are a challenge and may require repeated debridement under anaesthesia, but having to extend incisions further up the leg will make a surgical procedure longer. These casualties may be poorly prepared for surgery with shock, anemia, and sepsis. As fragments affect more proximal areas of the lower leg and perineum, casualties will have to undergo abdominal lapartomy and creation of colostomies to divert the flow of feces from this area. Failure to do this puts the patient at risk of catastrophic sepsis. The presence of abdominal fragment wounds will mandate laparotomy and management of intra-abdominal pathology using general principles of trauma surgery. Hospital units of the third world are usually poorly supplied with colostomy dressings and supplies. The presence of a colostomy may have even more adverse effects on the relationship of the casualty to his or her family and society due to cultural influences.

Medical Complications from Primary Blast Injury

The majority of AP mine injuries suffer amputations and fragment injuries. The level of trauma in most victims is related to the relatively small explosive charge, as well as to the distance between the detonation and the torso. Several medical complications might arise from the detonation of a mine near the human body. These include not only the penetration of fragments in the body, but also the effect that the concussion of the explosive shock has when it travels through the body. The following are some examples.

Injury and Shock

Shock is a medical term that describes the loss of blood pressure, flow of blood and delivery of oxygen to the various tissues of the body. As the body adjusts to this state, the aerobic metabolism slows down and the anaerobic metabolism (production of energy without oxygen, which is much less efficient than aerobic metabolism) takes over. This will result in an oxygen debt but also accounts for the flat affect of casualties, altered pain perception, and generalized weakness. Shock is caused by the initial loss of blood as the traumatic amputation occurs. The limb has a certain amount of blood in it that will be lost, but more importantly is the fact that very large high-pressure arteries and low-pressure veins will be severed and continue to bleed. It is true that blood vessels will go into spasm and can completely shut themselves off to stop the loss of blood. There is a limit to this as these can be very large vessels. The extremities have a rich supply of collateral vessels around joints, which result in continued supply of blood to the injured tissues. This, together with the large raw surface of the amputated limb and open fractures, means that the risk of bleeding is significant. Major fractures also result in significant blood loss even if they are distant to the primary blast wound. A femur fracture can result in the loss of a litre of blood (more if the fracture is open). Fragment injuries increase the problem of blood loss.

There is a point of no return in shock from which it is difficult or impossible to resuscitate the casualty. No amount of fluids or blood administered intravenously, or drugs to stimulate cardiac contraction, will save the patient.

Solid Organ Displacement

While solid organs do not seem to be susceptible to compression, blast waves that enter the body can displace intra abdominal organs such as the liver, spleen, and kidney on their attachments. These organs are relatively mobile except where they are attached to major blood vessels and peritoneal reflections and are easily torn. These can be injured by direct displacement of the abdominal wall either by contact with a blast wave or by being thrown onto an object (this is a tertiary blast injury). The result is the same: intra-abdominal injury with bleeding and shock. [D11]

Vascular Injuries

Injuries to blood vessels can be extremely important in trauma. No matter how expert the overall care of the casualty and management of the extremity fracture, failure to treat vascular injuries will threaten the life of the casualty. Arterial injuries can result in unexpected bleeding and shock or render a limb ischemic and in need of amputation. Venous injury can likewise threaten a limb with gangrene. It is not surprising that vascular injuries are common. Large vessels extend quite distant in the limbs, they are pressurized, and, due to the nature of their fluid containing tubes, can act as hydraulic conduits of pressure for some distance. Multiple radial fissures and ruptures of the tunica intima and media can be seen in casualties and animal experiments for 8-10 cm proximal to the area of avulsion of the artery. [D4]

Neurologic Reflexes

Several neurologic syndromes are reported after large-scale exposure to blast injury. Blast waves directed toward the chest can cause hypotension, bradycardia and apnea resulting in a shock state that may be mediated by vagal stimulation. Several animal models have demonstrated periods of apnea lasting 30 seconds. Mean arterial pressure fell from 124.8 mm Hg to 34.8 mm Hg and an interval between beats increasing from 133 ms to 489 ms (in rats). Research found that division of the vagus nerve in the neck abolished the bradycardia and apnea while atropine reduced the bradycardia. [D12] Similar research found significant electrocardiographic abnormalities in rats exposed to blast waves against the chest (as opposed to the abdomen) including ventricular extrasystoles and ventricular fibrillation. Some of these arrythmias were fatal. [D13] Blast has been observed to decrease exercise performance significantly in animals but this returns to normal within 24 hours. [D14]

In a pig model, no cardiovascular suppression was seen after blast exposure. In this experiment the authors reported abdominal injury at autopsy but no lung injury. There were periods of apnea and electroencephalographic slowing which rapidly recovered raising the issue of possible brain stem changes to account for some of the physiologic influences of blast injury. [D15] Peripheral nerves can conduct blast waves further up the limb. Nerves consist of hundreds or thousands of fibres with fatty myelin sheaths that can transmit pressure wave proximally. The significance of this is unknown, however the nerves appear analogous to bundles of fibre optic cable.

Blast injury can have direct effects on the brain. Several studies have shown cognitive dysfunction in animal experiments [D14,D16] and in some research, this was found to improve within 24 hours. [D14] There is biochemical evidence that this may be due to the accumulation of reactive inflammatory compounds and products. [D16] The cause of this is not well understood. There are biochemical changes that can be seen under electron microscopy. [D17] The effect of this on mine injuries is especially relevant in engineers who kneel or work in the prone position with their head closer to the site of potential detonation.

Risk of Infection

Mine injuries are at particular risk of infection. Since most are buried in soil, large numbers of microorganisms are forcefully pumped into the extremities that are disrupted. As gas is pumped up into the facial planes, bacteria will also be carried up and mixed into tissue. Bacteria will find fertile areas for reproduction, infection, and sepsis with fat (which has less blood supply) and with blood, and devascularized tissue placing these wounds at extremely high risk of gangrene and mixed infections, which can be extremely challenging to treat. Another infection typical of soil borne organisms is tetanus – rarely seen in modern medical systems.

In wartime, and third world situations, delays in evacuations are not uncommon due to distance, lack of means of transport, and lack of security. This increases the risk of sepsis and the experience in the past with International Committee of the Red Cross hospitals is that casualties arrive with advance stages of infection and gangrene. Unfortunately, uninformed or misdirected attempts at emergency treatment can contribute to infection. Tourniquets placed above the wound will render the tissue distal to the tourniquet anoxic and may precipitate the conditions for gas gangrene.

What Kills People

This may seem like a superficial question. People stop breathing and have a cardiac arrest when they die but what causes this? It is well known that some blast injury casualties die immediately or soon after the explosion – sometimes with very few marks on the body. It is probable that some blast waves induce arrhythmias on the heart and if these are “non-perfusing” – so called lethal arrhythmias such as ventricular fibrillation, then the casualty will die if cardiopulmonary resuscitation is not started immediately. Fatal air embolism may be another cause of death. Victims of quaternary blast injury (from collapsing buildings – will suffocate because of the inability to expand their lungs due to rubbles compressing their chest.

The overwhelming majority of AP mine victims die of shock from the initial and delayed loss of blood. The ongoing loss of blood and anaerobic metabolism reaches a point where regulatory mechanisms cease to function (with the loss of tone in the muscles of blood vessels compounding the shock and continued blood loss), failure of respiratory muscles and resulting respiratory failure; and worsening hypoxia, cardiac ischemia, and cerebral ischemia (with less respiratory drive). This results in a vicious cycle of hypoxia, respiratory failure, cardiac ischemia and cerebral ischemia that finally causes the heart to stop beating. This ultimately kills the patient.

PART THREE: IMMEDIATE CARE OF MINE VICTIMS

Surgical Problem

Patients presenting with mine injuries may be some of the most challenging problems seen. They are characterized by multiple system injury, respiratory failure, and shock. This may depend upon the availability and extent of local emergency services. In the third world, emergency services outside of hospitals may be unavailable.

The Problem of Evacuation

The problem of any trauma is to find the casualty, apply first aid, triage the injuries to decide how to evacuate the casualty, and finally deliver the casualty to the appropriate facility. In western military medical care, there is a well-structured organization of medical care based on echelons. The increasing use of air evacuation has changed this somewhat in that casualties frequently pass over some echelons and end up directly in hospitals within a short period of time – a hospital designed to receive trauma casualties and, once stable, pass them back through a complex evacuation chain to well supplied general and rehabilitation hospitals.

Civilian facilities, in particular third world hospitals, frequently lack organised evacuation. Casualties must make their own way to these facilities, lack the advantages of qualified first aid or have care that compromises their condition (such as inappropriate use of a tourniquet). This increases the challenge of care of mine casualties. Local medical teams and facilities need support and advice to provide well organised and prepared hospitals. This ultimately includes the ability to give aid and assistance to casualties who are at a distance from the facility. Distance and delays in evacuation places the casualty at risk for his or her life. Distance and time unfortunately also act as a triage tool. Those at extremis will die before arriving at hospitals.

Collateral Injury

It is important to keep in mind the fact that others may be injured in the same mine blast, either from the effects of the blast wave (if close to the detonation), or most frequently from fragments. These casualties and other bystanders may well trigger other mines hidden in the ground as they try to escape or attempt to recover the first casualty to a place of safety.

Multiple Casualties

The number of casualties as a result of a mine blast depends of many things including the number of people in close contact with the victim, type of mine (pure blast or fragmentation), and intent of the mine layer. Facilities must be prepared to receive several casualties at the same time especially since transportation may be improvised with the aim of getting everyone to the hospital as fast as possible. It is imperative that triage be carried out immediately to identify the most severely injured and those who will need surgery. In high-risk areas, the facilities should be ready at all times and personnel should be readily at hand or able to be recalled. Preplanning will pay enormous dividends but nothing beats experience for the calm orderly flow of casualties when there is the pressure of numbers.

Security is extremely important not only to keep minor casualties from flooding the facility (and diverting care from more severely injured), but to keep relatives and friends of the injured from interfering with the evaluation of all the casualties. Third world hospitals frequently must deal with family and friends of casualties that swells the number of patients by 500%-800% of planned numbers.

Some consideration should be made to prevent injuries and train people that work in mine environments in the principles of First Aid. Security of the site is important as there are probably many more mines in the area and these must be found and cleared to prevent injury to the rescuers (this applies to blast and fragmentation AP mines with trip wires). Bleeding should be controlled with pressure, pressure bandages, elevation of the limb, and resting the patients. Pain relief in the form of morphine should be given intravenously. Intramuscular injections will not be absorbed due to the shock state until later resuscitation and may then result in sudden unpredictable overdosing.

International Committee of the Red Cross Wound Classification

Three distinct clinical patterns of injury caused by the detonation of AP land mines were documented by Coupland and Korver in the British Medical Journal in 1991. [D18] This study was a retrospective observational analysis of 757 patients injured by AP mines treated in hospitals of the International Committee of the Red Cross.

The three commonest observable injury patterns are:

a) *Pattern 1*: Injury caused by the person treading on the pressure plate of a buried AP blast mine. The detonating explosive causes a traumatic amputation of part of the foot / leg and a variable degree of 'collateral' damage to the contra lateral limb. In some cases, injury to the groin can also occur.

b) *Pattern 2*: Injury caused by fragments of the mine case or energized secondary fragments. The precise injury depends on which part of the body is hit by the fragments.

c) *Pattern 3*: Injury caused by detonation of an AP mine in close proximity to the face or hand.

Figure D8: A Typical Pattern 1 AP Land Mine Injury.

Casualties may have combinations of injuries – there may be a challenge finding all of the injuries. If one is focused on the massive injury to the foot, one may miss important fragment wounds to the perineum or back.

The extent of the particular injury depends on a number of factors:

a) The size of the explosive charge in the mine

b) The spatial relationship between the explosive and the body at the time of detonation

c) The body mass / size of the person detonating the mine [D19]

d) The depth of burial of the mine [D20]
e) The type of footwear worn (in the case of pattern 1 injuries) [D21]
f) The use of a visor (in the case of pattern 3 injuries) [D22]
g) The order of detonation of the explosive in the mine
h) The type of soil that the mine is buried in [D23]

Figure D9: Pattern 3 Type Injury, with Extensive Soft Tissue Damage to the Face. The right arm also suffered a below elbow traumatic amputation.

PART FOUR: EMERGENCY AND SURGICAL TREATMENT

The medical treatment of AP land mine injury can be subdivided into general resuscitation of the patient and specific matters relating to the surgical management of the injury.

Initial Resuscitation

Irrespective of first aid, casualties will need to be stabilized before they can be operated on. [D24,D25] If they are in shock, they will need intravenous lines started and fluids including blood given to bring their blood pressure back to normal. In addition to rapid resuscitation, casualties must be thoroughly examined to determine the extent of their injuries. It is not the intent to review the details of well-established protocols. However, medical facilities that expect mine blast casualties can markedly improve the management of patients if the following measures are taken:

a) Sufficient room close to hospital emergency entrances should be set aside for these casualties.
b) Adequate stocks of intravenous, fluids, blood, dressings need to be immediately available.
c) Sufficient personnel should be immediately available to manage the casualties.
d) Diagnostic tests such as x-ray machines should work efficiently to avoid delays in fully evaluating the casualty.

Ultimately, the goal is to fully resuscitate and evaluate the casualty within one hour of arrival in the facility. Time should be invested in training personnel in special techniques in resuscitation especially in rural third world areas so that the facility will not be dependent on western support and not be capable of assuming responsibility for management of all of their casualties. Even military field units may lack practical experience in these types of injuries.

Timing of Surgical Procedures

Ideally, surgical procedures should take place as soon as possible and preferably within six hours of wounding. Even in ideal circumstances, this is achieved less often than desired usually because of the pressure of numbers and lack of facilities and personnel. Some casualties, delayed by hours or days in their trek to hospital will arrive in extremis and will die no matter what is done. Many will need to be resuscitated. Nevertheless, a well-run facility will be able to carry out this initial resuscitation and stabilization in the matter of one or two hours or the casualty may not be able to be stabilized. Well-conducted first aid with early administration of intravenous fluids, antibiotics, and tetanus prophylaxis may make it permissible to delay surgery but only if there is a requirement to operate on more severely injured casualties.

Principles of Surgery

The principles of surgery for these patients in hypovolemic shock are the same as for any other surgical problem. Upon arrival at the surgical facility, the initial medical assessment should proceed along the Guidelines of the Advanced Trauma Life Support Course [D26], starting with an initial survey of airway, breathing, circulation, neurological status, and exposing the entire body. This is extremely important, as it is easy to overlook small but deadly fragment penetrating injuries in the back or perineum. At this time, oxygen intubation (if necessary) and intravenous lines are placed. The key is to detect any limb threatening injuries at this time and initiate a treatment plan. One then proceeds to a secondary survey of all potential injuries.

X-rays of the limbs are needed to look for fractures, metallic fragments, foreign material and gas. If there is concern for a blast injury, a chest x-ray is warranted. Unfortunately many of these casualties appear in third world medical centres that lack many of the sophisticated diagnostic equipment of modern trauma centres. Penetrating injuries do not need these diagnostic aids in most cases. The presence of a perforation needs to be explained and may need exploration. These open wounds are classified according to a system originally described by Gustilo (see Table D1 [D27,D28]).

Table D1: Wound Classification System According to Gustilo

Gustilo 1	Open fracture with open skin wound less than one cm long and clean.
Gustilo 2	Open fracture with laceration longer than 1 cm without extensive soft tissue damage, flaps, or avulsions.
Gustilo 3	Either an open segmental fracture, open fractures with extensive soft tissue damage or a traumatic amputation; these are further classified as:
Gustilo 3a	Adequate soft tissue coverage of a fractured bone despite extensive soft tissue laceration, or flaps, or high energy trauma irrespective of the size of the wound.
Gustilo 3b	Extensive soft tissue injury loss with periosteal stripping and bone exposure usually associated with massive contamination.
Gustilo 3c	Open fracture associated with arterial injury requiring repair.

Antibiotics specific to the wound and suspected microorganisms are given as soon as possible. With grossly contaminated wounds, antibiotics should aim at gram-positive bacteria, gram-negative bacteria, and soil borne bacteria (this includes high dose penicillin). Active and/or passive immunization against tetanus is obligatory. The risk of infection is reflected in the obvious escalating degree of injury and one can easily see that AP mine injuries are some of the most serious fractures related injuries seen in trauma. The risk of infection increases with delayed surgery, failure to use antibiotics or the correct antibiotics, the development of resistant bacteria, extensive soft tissue damage, positive cultures at the end of surgical procedures, and wound closure in the presence of *clostridium perfringes* bacteria in the wound, all put the patient at risk.

Patients are operated on as soon as they are stable or they are resuscitated as much as possible. Badly mangled and devascularized limbs must be amputated. The surgeon will ultimately tailor the operation to his or her training, the activity of the casualty, and the resources of the facility.

A pattern 1 AP mine injury invariably causes significant blood loss. [D29] Bleeding may cease spontaneously as clotting occurs on the injured soft tissue and severed blood vessels go into spasm. Occasionally active bleeding may continue despite application of direct pressure on the wound. In such circumstances 'on scene' management may include judicious application of an arterial tourniquet especially if a prolonged evacuation time is likely.

The use of tourniquets is very controversial, as misuse of these devices will usually cause unnecessary further injury to the limb, resulting in an amputation above the level of the tourniquet. [D30] The tourniquet should be broad (at least 4cm), such as an Esmarch bandage or blood pressure cuff, rather than a thin band. It must be applied in the lower third of the thigh, to compress the superficial femoral artery against the femur, rather than below the knee, where the anatomical position of the anterior and posterior tibial and peroneal arteries make it impossible to compress them against the bones. The tourniquet should also be suitably padded to avoid any damage to the skin, and a careful note made of the time of application, so that it can be let down intermittently to allow adequate perfusion of viable soft tissue. The appropriate use of a tourniquet by suitably experienced surgeons is a safe and effective intervention. Tourniquets applied in the field should be as distal as necessary to stop the bleeding – even over the raw tissue of the blasted muscle. These should not be let down but rather should force urgent evacuation.

Control of ongoing haemorrhage is extremely important – there is no point resuscitating the casualty with intravenous fluids and blood if haemorrhage is not controlled. If it is impossible to control, the patient should be taken directly to the operating room. If the patient continues in a state of shock in spite of what seems to be adequate resuscitation and control of bleeding, hidden sources of bleeding should be considered such as abdominal and back injuries. Without adequate control of bleeding, excessive volumes of fluid resuscitation may be harmful [D31] through dilution of clotting factors and hypothermia.

Intravenous antibiotics and anti-tetanus prophylaxis are both mandatory treatments for all AP land mine injuries as the wounds are heavily contaminated by both soil and dead soft tissue. Benzyl penicillin is the antibiotic of choice on the grounds that it is both cheap and effective against Group B Streptococci and Clostridia species. Early administration may reduce the incidence of post-operative infective complications. [D32]

On arrival at the place of definitive treatment, once cardiovascular stability has been achieved, the patient should be anaesthetised for definitive surgical treatment, which will usually involve a major amputation and debridement of other associated wounds. Either regional or general anaesthesia may be suitable.

Once adequate anaesthesia is achieved, a thorough wash with warm soapy water is advisable to remove gross surface contamination of the skin and exposed soft tissue, which may otherwise interfere with the effectiveness of antiseptic skin preparation. [D33,D34]

The technique for amputation following a pattern 1 AP land mine injury features some important differences from that used in civilian practice in North America and Europe, where the indication for amputation is for complications of peripheral vascular disease.

Firstly, the use of a pneumatic tourniquet during the operation is highly advisable, as the majority of patients suffering a pattern 1 mine injury will already have lost considerable blood volume and have an essentially normal peripheral vascular tree, leading to massive preoperative bleeding if a tourniquet is not used. The tourniquet should be applied above the knee to compress the superficial femoral artery against the femur as previously mentioned.

The aim of amputation is to excise all dead and contaminated tissue from the wound while leaving sufficient soft tissue to cover a stump that will heal and permit mobilization of the patient on a prosthetic limb. A secondary consideration is the preservation of the knee joint if possible. Amputation following an AP land mine injury is a two-stage procedure. The first operation involves the excision of dead and contaminated tissue and sectioning of the bone at an appropriate level. The second operation, some five days later, aims to close the stump if the wound looks clean and healthy. [D33]

Skin flaps should be left as long as possible at initial operation to allow for the inevitable swelling of the muscle that occurs in the immediate post-operative period. Any devitalised skin can be trimmed back at the second operation.

Figure D10: Preservation of the Medial Gastrocnemius Muscle to use as a Myoplasty in a Below Knee Amputation. The skin flaps have been reflected proximally in this picture.

The extent of injury to the muscles is often more proximal than is initially appreciated by external examination. [D35] In addition, there is often contamination with dirt, which is propelled up the fascial planes of the leg by the gases generated by the explosion. This contamination must be excised prior to closure of the stump, even if this means excising muscle proximal to the level of bone section. [D36,D37] These dissected tissue planes and tissue should be vigorously irrigated with sterile water or saline to further remove foreign material. The fascia defining major muscle groups should be incised (so called fasciotomy) to permit the unrestricted swelling of viable tissue and prevent secondary tissue loss. If possible, a flap of muscle is preserved to act as a myoplasty to cover the end of the bone. Below the knee, the medial head of gastrocnemius is usually suitable for this purpose. Above the knee, the vastus medialis is suitable. [D38] In addition to covering the bone end, the use of a myoplastic flap allows the placement of a split skin graft over the end of the stump if there is insufficient skin cover.

Once the amputation has been completed, the tourniquet must be deflated before applying the dressing to check that haemostasis is adequate. After irrigation of the wound with saline to wash off surface blood clots, a bulky dressing consisting of fluffed gauze and wool bandage covered with a firm crepe bandage is applied. The dressing fabric soaks up the tissue exudates from the open wound and provides a protective cushion that reduces post-operative pain. [D39]

The post-operative care should include five days of antibiotic treatment (can be given orally after the first 48 hrs), adequate analgesia and blood transfusion to maintain a haemoglobin of 8 g/dl. [D35] The dressing should not normally de disturbed at this time. If the operation has been successful and the limb is free of infection, the patient will appear improved, regain his or her appetite, have a normal pulse and temperature, and have gradual improvement in the amount of pain. If this does not occur, and if the dressing is fouled with constant discharge and odour, the patient must be taken back to the operating room. Further debridement and possible re-amputation at a higher level may be necessary. In spite of the ICRC doctrine of “Get it right the first time”, these are very severe complex injuries. One should always be on the lookout for missed injuries.

Wounds should be inspected and if possible closed by delayed primary closure at 4 to 5 days after the initial operation. [D40] If there is doubt about the suitability of the wound for closure (usually because of the presence of infected tissue), a further debridement can be performed and the wound redressed for a further few days. Although delayed closure at the time of the second operation is the ideal, attempts to preserve the knee joint may result in two or more debridements before becoming clean enough to close without undue tension. [D41] Areas of soft tissue that cannot be closed by skin at the second operation can be covered with split skin grafts.

Contaminated wounds to the soft tissue of the contralateral limb also require thorough excision and cleaning to remove all debris and devitalised tissue and muscle [D33,D42,D43] in order to prevent infective complications. These wounds can often be quite large and adequate debridement can be a time consuming procedure [D45] involving substantial blood loss if a tourniquet is not used.

The in-hospital mortality rate from Pattern 1 injuries varies from 1 to 5 percent depending on the series reported. [D18,D21] It is widely believed that many patients injured in this way die before reaching medical attention due to inadequate resources for rapid evacuation and lack of pre-hospital care. In series where a high standard of medical care was available close to the point of wounding, the mortality rate from isolated pattern 1 AP mine injury is low. [D21,D22]

Important Technical tips for the Surgery of AP mine wounds:

DO:

- Use a tourniquet for amputations and wound excision if possible
- Preserve as much skin as possible

- Excise all dead and devitalised tissue at the earliest opportunity
- Explore thoroughly the extent of contamination along fascial planes between muscle compartments
- Perform fasciotomy to anticipate swelling of contused but viable tissue
- Use a myoplasty for stump coverage
- Preserve the knee joint if possible

DO NOT:

- Perform a guillotine amputation
- Close wounds at the first operation (primary closure)
- Close wounds under tension
- Close contaminated wounds

Pattern 2 Injuries

Pattern 2 injuries are essentially random wounds caused by fragments of mine case or energized secondary fragments. The treatment of such wounds affecting bone or soft tissue should proceed along established guidelines of war surgery [D45,D46] with treatment of specifically injured major structures such as blood vessels, intra-abdominal organs or the brain being dictated by the precise anatomical area of injury.

Pattern 3 Injuries

Pattern 3 injuries are particularly common amongst clearers of AP mines [D22] and are the type of injury most likely to be fatal. Brain contusion from blast and direct injury to the face and neck can create a threat to the airway, occasionally requiring a surgical airway.

In a retrospective analysis of mine clearers on the Afghan border, 61% of wounded personnel sustained ocular injuries of which 78% affected both eyes. [D25] Small, multiple foreign bodies are found in the majority of injured eyes. Use of simple face visors has been shown to reduce the incidence of injury to the eyes in a retrospective review of injuries sustained during land mine clearance operations. [D22]

Simple corneal foreign bodies can be removed using topical anaesthesia and a needle. A good light source and a magnifying glass will help in this procedure. Topical antibiotics and a short acting mydriatic should be given prior to application of an eye pad.

Penetrating ocular trauma usually requires specialist treatment, consequently casualties should be evacuated if possible. There are, however, steps that can be taken by the non-specialist to minimise further injury. Placing a rigid eye shield over the affected eye will prevent further injury. It is not uncommon for patients to rub their own eyes following ocular injury [D47] thereby worsening the initial insult. Intravenous antibiotics have been advocated in reducing the risk of development of endopthalmitis. [D48]

There are some features in injuries of the face that differ from extremity injuries. Tissue on the face has a rich blood supply and is more resistant to infection. It is important to close the mucosa of the mouth to avoid salivary fistulas but in most cases only obviously dead tissue should be removed. Skin can and should be primarily closed – this can be difficult in some stellate wounds. There may be several flaps of tissue, but careful repositioning will permit the surgeon to see how the complex facial laceration can be reconstructed. Complex injuries with fractures may need expert maxillofacial surgery but even careful primary closure of these wounds can simplify the surgical management of the tissue until the casualty can be evacuated to a specialty facility.

Figure D11: Pattern 3 Injury after Initial Surgical Care. There is a tracheostomy in place. Extensive debridement of the soft tissues of the face has been carried out, including the removal of both eyes. There is also a compound fracture of the frontal bone.

Ethics in Resuscitation

Whenever trauma patients are treated, one must be aware of the local cultural and religious views on resuscitating critically injured casualties. Amputation carries severe stigmata in many societies and many patients would rather risk death in preventing a high amputation or no amputation rather than undergo a simpler operation.

In treating several casualties with critical injuries, judicious triage of patients may be required. Some casualties might have such severe injuries that they are unlikely to survive. One must be aware of the limited resources available and know when not to exhaust them in treating one casualty that threatens the security of the rest of the facility’s patients.

Finally, one should recognize the futility of care of some injuries. For example, a patient might be deeply unconscious with significant brain injury. Casualties with significant blunt trunk trauma or massive limb blast injury presenting in cardiac arrest should not be resuscitated.

PART FIVE: POST SURGICAL TREATMENT

Rehabilitation

Nothing stresses the fact that these casualties are treated within the framework of a team more than rehabilitation. Mine blast injuries are devastating. They affect many body systems and may require months of rehabilitation and repeated surgeries before the patient is able to return to his or her family and work. Hastily performed amputations done under the pressure of mass casualties, and those with painful stumps, may need to be revised.

Figure D12: Several Non Governmental Organizations manufacture simple robust artificial limbs and instruct local technicians to provide prosthesis to locals.

Rehabilitation starts with the initial surgery by planning a procedure aimed at using a comfortable prosthesis and as distal an amputation as possible (if an amputation is necessary). Early mobilization is necessary, not only to get the casualty ambulating, but also to avoid many of the pulmonary complications of major surgery. Nutrition is extremely important in promoting tissue healing, fighting infection, and mobilizing the casualty.

Finally, the casualty must be fitted with prosthesis if he or she has undergone amputation. This requires a well-padded myofascial stump, excellent wound healing, and skilled prosthesis technicians. Much work has gone on in making simple, sturdy and comfortable prosthesis. In fact, this has become quite an industry in some mine-plagued regions. The resources of the West have produced some very advanced prosthesis using new materials, but there may be some time before these are available in the third world. Once fitted, the casualty is faced with a daunting task of increasing muscle strength, regaining balance and learning to walk. Physiotherapy is of the highest importance in any team working with mine victims.

Casualties of mines are not successfully treated until they have been fully rehabilitated, can return home, and are fully reintroduced into society, family, and employment.

The Paradox of Protection Against Mines

Equipment to reduce injuries has the potential to save lives and limbs when injuries in the past may have killed the victim outright or subjected him or her to mutilating surgery. With the use of mine injury attenuating equipment, the patient may be saved amputation but require complicated reconstructive surgery. This may include additional surgery to debride the wound, vascular reconstruction, bone grafting, and nerve grafts. Will this highly specialized care be available in third world medical facilities? These require not only surgeons highly trained and experienced in such procedures but a large technically sophisticated facility, sophisticated diagnostic equipment capable of selecting patients for limb saving surgery, nursing staff experienced in the post operative care of these patients, and very specialized rehabilitation resources. Medical facilities will need stocks of medical devices including vascular grafts, orthopaedic graft material, instruments, and operating microscopes. On the other hand, skill in amputation is fairly common and the construction of prosthetic legs can be relatively low tech.

The importance of critically evaluating this problem cannot be over emphasised. The ultimate aim for these casualties (most of whom work with their feet in these rural based societies) is a sensate limb with adequate blood supply, free of pain, capable of being worked on for a full day.

Ultimately, attenuation of the injury will pay dividends with less severely injured casualties, fewer systems of injuries, less shock, and casualties more fit to withstand emergency surgery. Medical facilities in developing countries will develop with the help from more developed countries.

Continued Development of Mine Protective Equipment and Mines as Weapons

There have been significant developments in recent years to eliminate AP land mines from the dangers faced by civilians in and adjacent to conflicts. Legal and international initiatives have decreased stockpiles of weapons and largely halted their use in many parts of the world. Many nations have banned their use or severely restricted their use.

Research is ongoing into equipment (both personal protective equipment and other detection and vehicular equipment) to decrease the threat of injury or death. Yet, the simplest way to defeat personal equipment is to increase the explosive charge. Thus, a strong continuous effort is necessary to ensure that rogue countries and terrorist organizations do not acquire and deploy these weapons. Efforts are also needed to find the manufacturers of these weapons.

SUMMARY

AP mines can inflict some of the most challenging injuries seen in trauma. Frequently, mine casualties are innocents in the conflict and isolated from sophisticated medical care. Blast mine injuries are somewhat limited because of the limited size of explosive charge. Yet these devices can still inflict lethal and disabling injuries over many body systems from direct and indirect blast effects as well as fragment wounds. Well-organized and well-equipped medical facilities are necessary in the management of these casualties. Rehabilitation is extremely important to return mine casualties to useful employment.

The protection against mine injury is complex and may change the injury pattern. This may help avoid amputation as the only surgical option but may create a problem for medical facilities in impoverished countries in providing advanced surgical procedures and rehabilitation. Nevertheless, research and technical developments will pay dividends to these countries with fewer disabled and destitute victims of mines.

Political and international efforts must continue to strive for the eradication of mines while supporting countries in eliminating the dangers resting in their territory.

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Annex E: INJURY MODELS FOR VALIDATION

An injury model is a correlation between the injury risk evaluation and a physical model of injury. Without successful validation, the credibility of an injury risk evaluation is seriously compromised. The development of a relationship between a surrogate and a validated injury model is therefore very important in the success of a model. This requires serious consideration of injury biomechanics. Viano et al. [E1] outlined some essential elements of injury biomechanics as follows:

- Identify and define the mechanisms of impact injury.
- Quantify the responses of the human body tissues and systems to a range of impact conditions.
- Determine the level of response at which tissues or systems will fail to recover.
- Develop test devices and computer models that respond in a human like manner so that protective systems can be accurately evaluated.

To perform the first three of these elements, an injury model must be developed. Use and validation of this injury model is essential to the development of a test methodology to assess human injury. The validation should be some correlation between the injury risk evaluation and a physical surrogate as shown in Figure E1. Three basic techniques may be used to develop an injury model suitable for the development of a test methodology. These are:

- Use of a human cadaver injury model,
- An animal injury model, and
- Epidemiology or physical reconstruction of an actual injury event.

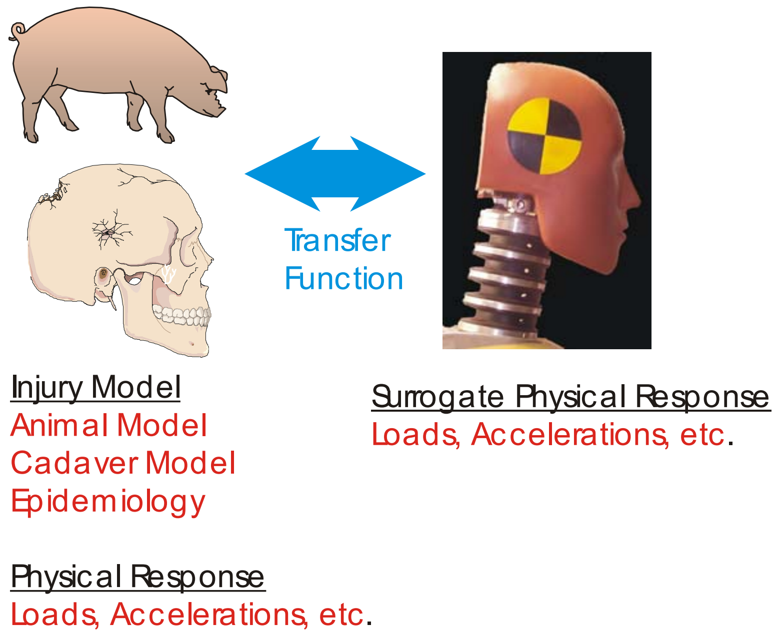


Figure E1: Development of Surrogate Injury Model.

With human volunteers, human anatomy and human physiology may be obtained together. However, human volunteers may be used only to get non-injurious response data. Human test subjects may not be used as injury models as it is unethical to intentionally produce injuries in human test subjects [Nuremburg–1947]. Each injury modeling technique has advantages and disadvantages. These are:

- *Human Cadaver Injury Model*. The strength of human cadaver injury models is appropriate human anatomy, particularly skeletal anatomy. The use of anatomical damage and tissue response with objective test methodologies is well developed [c.f. Bass-1997]. The biofidelity of such models may be limited by post-mortem changes in anatomy. This is a larger issue for soft tissues and organs than for the skeletal system. Further, the available cadaver population is often elderly and has pre-existing pathologies. Appropriate selection procedures must be adopted to ensure the use of an appropriate subject population in cadaver models. The weakness of cadaver models is the lack of a living physiology. Injuries that require physiology are difficult to assess using human cadaver models.
- *Animal Injury Model***.** The strength of animal injury models is the presence of physiology. Many human injuries require life processes to form or progress. Examples of such injuries are systemic hemorrhagic shock, commotio cordis and diffuse axonal injury. The weakness in animal models is the significant difference in anatomy between the model and humans, especially for the livestock and rodent models commonly used for human injury. In addition, there may be significant ethical considerations with the use of animal models.
- *Epidemiological Injury Model*. The strength of epidemiology is that the injuries seen are often directly applicable to injuries modeled. In addition, the model involves appropriate human anatomy and physiology. The weakness is that the conditions are uncontrolled and are always retrospective. In addition, epidemiological information is also often sensitive, especially in the military environment.

The goal of injury biomechanics is to use as many of the possible injury models as appropriate. Careful selection of the model is necessary for a given situation to ensure that the risk of injury assessed is as realistic as possible and includes the potential injury modes suitable for the injury situation under consideration. The outcome of using an appropriate model is an injury assessment that is as *realistic as possible*. If not, there is a potential for *increasing* the injury risk.

To assess blunt skeletal trauma, especially for lower extremity, head and thorax, animal testing is difficult. Anatomical variations between available animal surrogates, typically livestock models, and humans raise issues of appropriate injury response that may only be addressed using either cadaver or epidemiological information. For example, quadrupeds such as sheep and pigs do not load their heel bone (calcaneus) in normal gait. This implies non-quantified differences between heel response of such a model and the human that would potentially compromise lower extremity tests with blast loading below the foot.

So, for evaluation of skeletal response using engineering measurements and skeletal injury, human cadaver models are essential. The United States National Academy of Sciences Committee on Injury Prevention and Control echoed the value of such models through its 1999 recommendation:

> “The committee recommends the continued development of physical, mathematical, cellular, and biofidelic models of injury, particularly in high risk populations (such as children and small women) while continuing to use animals and cadavers to validate biomechanical models of injury.”

This recommendation emphasizes the continued need to test with cadavers in appropriate situations. Indeed, investigations using thousands of human cadaver subjects have been reported in the open literature from 1959 to 1990. Most of these experiments focus on the use of cadavers for injury risk assessment and injury tolerance in automobile environments.

For development of injury risk models from mine blasts, the use of cadaver subjects is invaluable. Such models have been used for lower extremity injury assessment [E2], lower extremity test methodology, head, and thorax injury validation [E3]. The success of a cadaver model depends on the injury mode to be investigated.

The cadaver model is most effective in the evaluation of skeletal injury. This is especially effective for lower extremity, thoracic skeleton, face and skull. The bones retain lifelike (biofidelic) behaviour longer post mortem than does soft tissue. Bulk disruption of soft tissue may be evaluated using a cadaver model. However, it is more difficult to evaluate vascular injuries, and it is very difficult to assess the level of nerve damage using a cadaver model. Injury modes that involve development by physiology, such as functional brain injuries or development of acute respiratory distress syndrome (ARDS) are generally inaccessible. Evaluation of severe burns is possible using cadavers, however, the development of later consequences is not possible.

To correlate subject response among subjects of different sizes, subject response scaling may be necessary. This is certainly needed for animal experiments, and is likely needed for cadaver experiments to scale body mass. Eppinger et al. [E4] give a typical technique that allows the scaling of velocity, time, force, acceleration or any mechanical parameter to that of a 50th percentile male body or any other typical anthropometrics.

In the United States, the ethical considerations regarding use of cadavers are not as well developed or as restricted as the use of human subjects in research. However, several organizations have developed recommendations for ethical treatment of cadavers, these include, the Association of Anatomical Chairman (1978), the National Highway Traffic Safety Administration (1979), and the National Academy of Sciences (1978). Further, cadaver experiments are generally regulated as human biohazards, specifically Biosafety Level 2 as defined by the Centers for Disease Control in the United States and by the World Health Organization. To protect the researchers, cadaver testing should conform to these research protocols.

REFERENCES

[1] D.C. Viano and I.V. Lau, A Viscous Tolerance Criterion for Soft Tissue Injury Assessment, *Journal of Biomechanics*, Vol. 21, p. 387, 1988.

[2] Lower Extremity Assessment Program (LEAP 99-2), TECOM Project No. 8-EI-495-BPF-001, Report No. ATC-8199 (Volume II), USAIR, August 2000.

[3] C.R. Bass, B. Boggess, M. Davis, C. Chichester, D.M. Bergeron, E. Sanderson and G. Di Marco, *A Methodology for Evaluating Personal Protective Equipment for AP Landmines*, Proceedings of the 2001 UXO Conference, New Orleans, USA, April 2001.

[4] R. Eppinger, E. Sun, S. Kuppa and R. Saul, Supplement: Development of Improved Injury Criteria for the Assessment of Advanced Automotive Restraint Systems – II, National Highway Traffic Safety Administration, March 2000.

Annex F: COMPENDIUM OF TEST SET-UPS
LOWER BODY PROTECTION SYSTEMS

TITLE: FSL TRIALS – SEPTEMBER 1999 – DRDC SUFFIELD, CANADA

TEST OBJECTIVE(S)

(i) Obtain a relative performance comparison of selected mine protected boots;

(ii) Build a database to compare with the results of LEAP to calibrate the FSL.

THREAT CONDITIONS

Charge mass: PMA3, PMA2, VS50, 50-gram C4

Charge geometry: Actual mine geometries, 35% h:d ratio for C4

Placement of charge: Always in geometric centre of container

Depth of burial: Flush buried, except PMA2 that was buried with standoff equivalent to fuse height

Initiation point: Fuse location; bottom for C4

Charge type: Tetryl, TNT, TNT/RDX and C4 (RDX)

Notes:

SOIL CONDITIONS

Soil type: Medium sand, dry

Soil container dimensions: Box 450 x 600 x 450 mm (W x L x D)

Soil replacement: Complete, each time

Compaction: Loose pour

Notes: Container constructed from 12 mm thick mild steel to reproduce that used in LEAP

SURROGATE

Description: Frangible Surrogate Leg (FSL) that consists of geometrically accurate synthetic bones, ballistic gelatine for soft tissues, nylon skin

Landmine pre-load: Full weight of FSL (~13 kg)

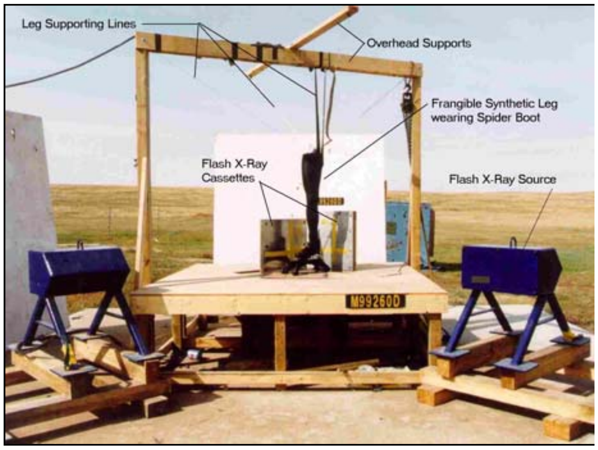
Reaction mass: Weight of FSL (~13 kg)

Orientation of leg: Standing vertically

Location of charge: Below the axis of the tibia

Degree of flexion in knee: None, 0 degree

Notes: The FSL was still under development, hence there did not exist a calibration to relate the injuries observed to actual mine blast injuries at the time of these tests.



INSTRUMENTATION

Pressure gauge: Not used

Regular video: Frontal and lateral views

High-speed video/film: Frontal view at 1000 fps

Flash x-ray: Lateral and frontal views

Accelerometer: Not used

Strain gauge: Compression at bottom and top of tibia, triple rosette at 1/3 distal tibia, triple rosette on femur

Load cell (uni-axial/multi-axial): 5 or 6 axis at ½ tibia on selected shots

Displacement: Not recorded directly, can be obtained from flash x-rays

Temperature: Recorded ambient conditions (weather)

Signal conditioning: For strain gauges only

Data acquisition: 1 MHz digital data

Notes:

FOOTWEAR

Test items: Standard Canadian Forces combat boot; Wellco blast boot; Wellco overshoe; Spider boot

Control: Canadian Forces combat boot

Notes: Overshoe was used with CF combat boot and with Wellco blast boot

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REFERENCE(S)

Bergeron, D.M.; Anderson, I.B.; Coley, G.G.; Rountree, M.S.; Fall, R.W.; Harris, R.M., ‘Assessment of Lower Leg Injury from Land Mine Blast – Phase 1 – Test Results using a Frangible Surrogate Leg with Associated Protective Footwear and Comparison with Cadaver Test Data’, Defence R&D Canada – Suffield, Technical Report to be published in 2004.

TITLE: LOWER EXTREMITY ASSESSMENT PROGRAM (LEAP) – SPRING 99 – TEXAS, US

TEST OBJECTIVE(S)

1. Provide data for the initial assessment of the effectiveness of mine protective footwear.
2. Acquire strain and axial force measurements on a cadaver lower limb during antipersonnel mine detonations.
3. Document the blast event.
4. Provide empirical data for development of injury criteria.

THREAT CONDITIONS

Charge mass: 28g Tetryl, 100g TNT, 240g TNT

Charge geometry: M-14, PMA-2, PMN

Placement of charge: Centered under the heel of the boot, or the boot leg-pod for the spider boot.

Depth of burial: Top of mine flush with surface.

Initiation point: Blasting cap (M-7 and RP-80 were used) in detonator well of mine.

Charge type: See above.

Notes:

SOIL CONDITIONS

Soil type: Dry sand.

Soil container dimensions: 18” x 24” x 18” deep, steel box.

Soil replacement: Contaminated sand was replaced each test.

Compaction: None.

Notes:

SURROGATE

Description: Fresh, whole-body, human cadavers in a single leg stance with the contralateral limb protected in all but two tests.

Landmine pre-load: Mine was loaded to actuation then primed for command detonation.

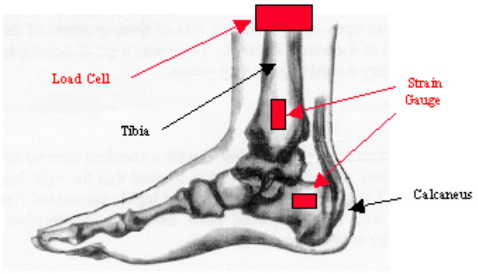
Reaction mass: Dependant on body weight. Approximately 70 kg.

Orientation of leg: Single leg stance in axial alignment.

Location of charge: Centered under the boot heel.

Degree of flexion in knee: Zero degrees. Knee immobiliser used to maintain stabilization, pretest.

Notes:



INSTRUMENTATION

Pressure gauge: NA

Regular video: Sony SSC DC-50, standard video

High-speed video/film: Kodak HG-2000, 2000 FPS Color and Kodak 4540, 13,000 FPS B&W

Flash x-ray: Cinerad, Hadland 468 camera with an HP 450KV x-ray. 8 individual channels of pulsed x-ray with a duration of 25 nanoseconds and typically a 250 microsecond interval. Images were rendered from an FSL-1 intensifier screen illuminated for 10 microseconds before delay.

Accelerometer: N/A

Strain gauge: 350-ohm.

Load cell (uni-axial/multi-axial): Denton uni-axial and six-axis load cells were used.

Displacement: N/A.

Temperature: Specimens were stabilized at 65 degrees Fahrenheit before testing. Ambient temperature was recorded.

Signal conditioning: Analog low-pass filter of 10kHz for the load cell. Strain gauges were sampled at 50,000 and 100,000 samples per second with a wide-band frequency setting.

Data acquisition: Pacific model No. 5700 transcient data recorder, 16 channel programmable, 1,000,000 samples per second.

FOOTWEAR

Test items: Spider Boot (Med-Eng), Blast Overboot (Wellco), Blast boot (Wellco), BFR V-40, (BFR), improvised sandal (BF Goodrich)

Control: Standard US combat boot (Rosearch)

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: MINE PROTECTED BOOT TRIALS – SPRING 1998 – WTD 91, MEPPEN, GERMANY

TEST OBJECTIVE(S)

Obtain a relative performance comparison of selected mine protected boots.

THREAT CONDITIONS

Charge mass: 14 g PETN, 35 g PETN, DM 11, PPM 2

Charge geometry: Spherical, slightly flattened (PETN), actual mine geometry

Placement of charge: -

Depth of burial: Above ground on soil

Initiation point: Lateral ignition, fuse

Charge type: PETN, cast TNT (DM 11), moulded, ring-geometric TNT (PPM 2)

Notes: -

SOIL CONDITIONS

Soil type: Medium sand, medium wet

Soil container dimensions: -

Soil replacement: -

Compaction: Medium compressed

Notes: Trials were not conducted in a special container. Mines placement was shifted each trial. Soil was always medium compressed.

SURROGATE

Description: Artificial leg filled with light concrete ($1 g/cm^3$) and a hardwood stick of 20 mm diameter. Leg was mounted to a steel pelvis simulator in order to ensure upward movement of leg and a total mass of approx. 90 kg of test setup.

Landmine pre-load: 50 - 100 N

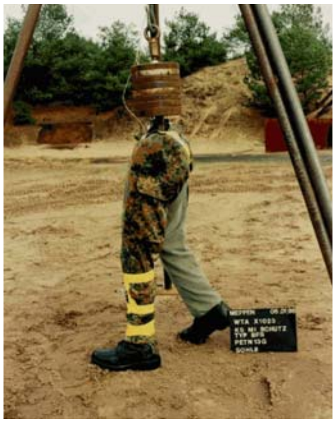
Reaction mass: approx. 30 - 45 kg

Orientation of leg: upright in realistic walking posture

Location of charge: tiptoe, middle of sole, heel

Degree of flexion in knee: 0° -10°

Notes:



INSTRUMENTATION

Pressure gauge: -

Regular video:

High-speed video/film: 250 frames/sec

Flash x-ray: -

Accelerometer: 3 axis at 28 cm above foot sole

Strain gauge: -

Load cell (uni-axial/multi-axial): Can be obtained from accelerometers

Displacement: Can be obtained from accelerometers

Temperature: Roughly between 5 and 15 deg C

Signal conditioning: -

Data acquisition: 1 kHz digital

Notes:

FOOTWEAR

Test items: BFR blast and fragment protection boot, Wellco blast protection boot, Wellco blast protected overshoe, standard German Forces combat boot.

Control: German Forces combat boot

Notes: Overshoes was used in combination with all boot types. Additional tests were conducted with 10 cm styrofoam blocks underneath GF combat shoes.

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REFERENCE(S)

Schaad, Gerhard: “Ansprengversuche unter den Sohlen marktgängiger Minenschutzschuhe zur Bewertung der Schutzwirkung”; WTD 91-400/59/1998; Wehrtechnische Dienststelle für Waffen und Munition; Meppen (Germany); 1998.

TITLE: SLL TRIALS – 2000/2001 – DRDC VALCARTIER, CANADA

TEST OBJECTIVE(S)

(i) Validate Simplified Lower Limb (SLL) model;

(ii) Gather data for the validation of numerical models of the SLL and protection concepts.

THREAT CONDITIONS

Charge mass: 25-grams, 50-gram and 100-gram C4, M-14

Charge geometry: Cylindrical mine surrogates, 35% h:d ratio

Placement of charge: Geometric centre of container

Depth of burial: Flush buried

Initiation point: Fuse location; bottom dead centre

Charge type: C4 (RDX)

Notes:

SOIL CONDITIONS

Soil type: Medium sand, dry

Soil container dimensions: Cylinder 73.7 cm dia. 69.9 deep

Soil replacement: Remove top 30-40 cm each test with complete replacement every 2 tests

Compaction: Loose pour

Notes:

SURROGATE

Description: Simplified Lower Limb (SLL) that consists of a tapered ballistic gelatine cylinder simulating soft tissue with concentric FRP bone (representative tibia, talus, and calcaneous).

Landmine pre-load: Weight of SLL (~ 13 kg)

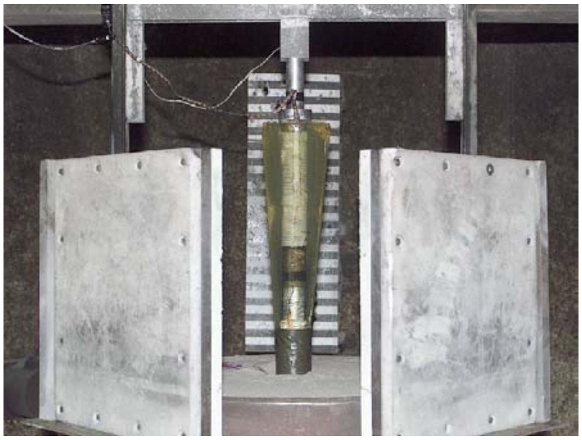
Reaction mass: Weight of SLL (~ 13 kg)

Orientation of leg: Vertical

Location of charge: Concentric with SLL

Degree of flexion in knee:

Notes: The test series started with a very simple cylindrical leg concept and covered the development of the final SLL design with separate bones, RTV cartilage, and a tapered tissue simulant. The series concluded with the use of the SLL to screen protection concepts.



INSTRUMENTATION

Pressure gauge: Lollipop gauge just outside the soil container for blast level comparison

Regular video: No

High-speed video/film: Frontal view, 1000 fps video

Flash x-ray: 2 screens (90º) per test

Accelerometer: Not used

Strain gauge: 5 uniaxial gauges: 4 placed 90 degree apart at mid-tibia height + 1 placed 10 cm underneath

Stress gauge: 1 carbon gauge or 1 PVDF gauge placed 1 cm above the leg bottom

Load cell (uni-axial/multi-axial): No

Displacement: Displacement gauges for global leg jump

Temperature: Ballistic gelatine and ambient temperature before the firings

Signal conditioning: For strain gauge only

Data acquisition: 1 Mhz sampling, 100 KHz filtering

Notes:

FOOTWEAR

Test items: Cylindrical rubber pads; Wellco blast boot/overshoe combination; standard US Army and Canadian Forces combat boots; and cylindrical protection concepts for material evaluation

Control: US Army and Canadian Forces combat boot

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: FIRST SERIES OF DUTCH TRIALS – 1998 – TNO PML

TEST OBJECTIVE(S)

Exploratory trials to evaluate the test fixture and its suitability for AP mine protection boot testing – Phase 1.

THREAT CONDITIONS

Charge mass: 22C1 AP Mine

Charge geometry: Actual mine geometry

Placement of charge: Parallel to soil surface

Depth of burial: Surface buried

Initiation point: Bottom dead centre

Charge type: 57 g trotyl (charge) and 17g tetryl (booster)

Notes:

SOIL CONDITIONS

Soil type: Not specified (regular sand)

Soil container dimensions: Box 91 x 30 x 10 cm (L x W x H)

Soil replacement: Not replaced, refilled

Compaction: Equalized and stamped after each explosion

Notes:

SURROGATE

Description:

Landmine pre-load:

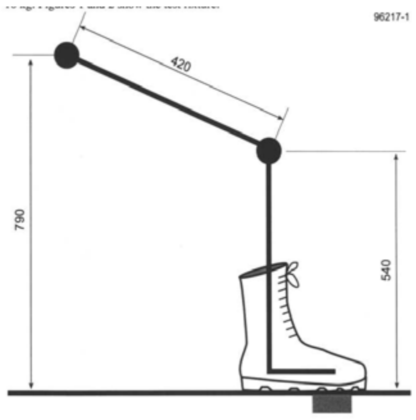
Reaction mass: 16 kg

Orientation of leg:

Location of charge: Under forefoot

Degree of flexion in knee:

Notes:



INSTRUMENTATION

Pressure gauge:

Regular video:

High-speed video/film: High speed camera (2000 fps)

Flash x-ray:

Accelerometer:

Strain gauge:

Load cell (uni-axial/multi-axial):

Displacement: Small iron wire enabled acceleration measurement

Temperature:

Signal conditioning:

Data acquisition:

Notes:

FOOTWEAR

Test items: Dutch combat boot, BFR boot, Wellco boot, and Dutch combat boot with Wellco overboot

Control:

Notes:

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REFERENCE(S)

TNO Report PML1998-A89.

TITLE: SECOND SERIES OF DUTCH TRIALS – 1998 – TNO PML

TEST OBJECTIVE(S)

Exploratory trials to evaluate the test fixture and its suitability for AP mine protection boot testing – Phase 2.

THREAT CONDITIONS

Charge mass: 33, 38, 44, and 58 g

Charge geometry: 1 to 2 h:d ratio

Placement of charge: Parallel to soil surface

Depth of burial: Surface buried

Initiation point: Bottom dead centre

Charge type: TNT

Notes:

SOIL CONDITIONS

Soil type: HOM sand (Dutch demining program)

Soil container dimensions: Box 70 x 60 x 31 cm (L x W x H)

Soil replacement: Not replaced, refilled

Compaction: Equalized and stamped after each explosion

Notes:

SURROGATE

Description:

Landmine pre-load:

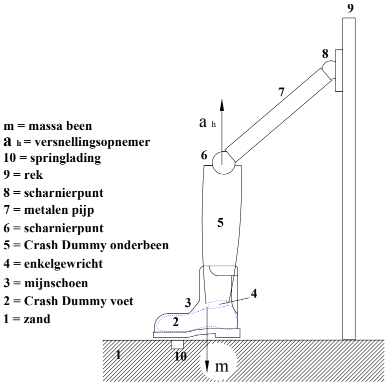
Reaction mass: 17 kg

Orientation of leg:

Location of charge: Under forefoot

Degree of flexion in knee:

Notes:



INSTRUMENTATION

Pressure gauge:

Regular video:

High-speed video/film: High Cam (3313 fps)

Flash x-ray:

Accelerometer: ENDEVCO 7270 mounted on knee

Strain gauge:

Load cell (uni-axial/multi-axial):

Displacement:

Temperature:

Signal conditioning: BSI Digistar III

Data acquisition:

Notes:

FOOTWEAR

Test items: BFR boot

Control:

Notes:

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REFERENCE(S)

TNO Report PML1998-A89.

TITLE: THIRD SERIES OF DUTCH TRIALS – TNO PML

TEST OBJECTIVE(S)

Exploratory trials to evaluate the test fixture and its suitability for AP mine protection boot testing – Phase 3.

THREAT CONDITIONS

Charge mass: 77 g (22C1), 60, 75, 100, and 150 g (TNT)

Charge geometry: Actual mine geometry, 1 to 2 h:d for TNT

Placement of charge: Parallel to soil surface

Depth of burial: Surface buried

Initiation point: Bottom dead centre

Charge type: 22C1: 57 g trotyl (charge) and 17g tetryl (booster); TNT (surrogate)

Notes:

SOIL CONDITIONS

Soil type: HOM2000 sand (Dutch demining program)

Soil container dimensions: Box 70 x 60 x 31 cm (L x W x H)

Soil replacement: Not replaced, refilled

Compaction: Equalized and stamped after each explosion

Notes:

SURROGATE

Description:

Landmine pre-load:

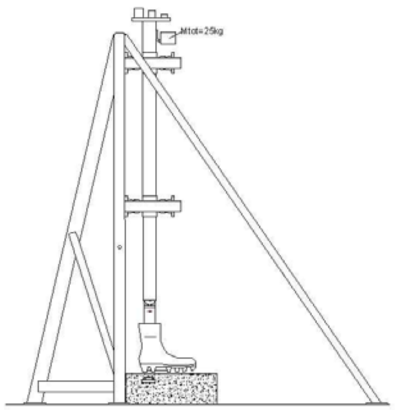
Reaction mass: 25 kg

Orientation of leg: Vertical

Location of charge: Under forefoot

Degree of flexion in knee:

Notes:



INSTRUMENTATION

Pressure gauge:

Regular video:

High-speed video/film: High speed camera (2000 fps)

Flash x-ray:

Accelerometer: ENDEVCO 7270 and PCB 350B04

Strain gauge:

Load cell (uni-axial/multi-axial):

Displacement: Chalk, grease, electronic, Tekel TK45

Temperature:

Signal conditioning: BSI Digistar III

Data acquisition:

Notes:

FOOTWEAR

Test items: Anonymate, Wellco boot + Wellco overboot, Aigis PPE100, Med-Eng Spider boot, Dutch combat boot

Control:

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: UK PRE-FUNDING TRIALS – AIGIS LTD

TEST OBJECTIVE(S)

To show potential viability for UK Government funding.

THREAT CONDITIONS

Charge mass: 25 g

Charge geometry: Cube

Placement of charge: Parallel to soil surface

Depth of burial: Surface buried

Initiation point: Rear centre

Charge type: PE4

Notes:

SOIL CONDITIONS

Soil type: Sand (dry – not controlled)

Soil container dimensions: Box 600 x 800 x 400 mm (L x W x H)

Soil replacement: Sand replaced

Compaction: Local had compaction

Notes:

SURROGATE

Description: Steel box section leg with shaped wooden feet.

Landmine pre-load: 67 kg

Reaction mass: 67 kg

Orientation of leg: Vertical

Location of charge: Centre heel

Degree of flexion in knee: Fully extended

Notes:

INSTRUMENTATION

Pressure gauge:

Regular video: Yes

High-speed video/film:

Flash x-ray:

Accelerometer:

Strain gauge:

Load cell (uni-axial/multi-axial):

Displacement: Visual against graded backdrop.

Temperature: Yes

Signal conditioning:

Data acquisition:

Notes:

FOOTWEAR

Test items: Prototype AIGIS PPE100

Control: British combat boot

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: UK METAL LIMBS – JUNE 98 – AIGIS LTD, UK

TEST OBJECTIVE(S)

To optimize material thicknesses and combinations.
To investigate performance of instrumentation prior to human limb trials.

THREAT CONDITIONS

Charge mass: 25, 50 g

Charge geometry: Flat cylinder – light fitting ceiling rose

Placement of charge: Parallel to soil surface

Depth of burial: 30 mm

Initiation point: Bottom dead centre

Charge type: PE4

Notes:

SOIL CONDITIONS

Soil type: Top soil (damp)

Soil container dimensions: 600 x 400 x 250 mm (LxWxH) washing basket flush buried

Soil replacement: Soil replaced

Compaction: Loaded and stamped down by same person each time

Notes:

SURROGATE

Description: Box section steel tube. Flat rectangular plate used for material tests. Shaped steel foot plate used for prototype boot tests.

Landmine pre-load: 67 kg

Reaction mass: 67 kg

Orientation of leg: Vertical

Location of charge: Centre heel

Degree of flexion in knee: Fully extended

Notes:

INSTRUMENTATION

Pressure gauge: Kistler 603B

Regular video: Yes

High-speed video/film: 400 fps digital

Flash x-ray:

Accelerometer: Kistler tri-ax 8790A500

Strain gauge: Uni-axial

Load cell (uni-axial/multi-axial):

Displacement: LVDT

Temperature: Yes

Signal conditioning:

Data acquisition:

Notes:

FOOTWEAR

Test items: Blast/fragmentation protection material combinations. Prototype PPE100 Boots

Control: British combat boot

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: ISOLATED HUMAN LIMB TRIALS –SEPTEMBER 99 – AIGIS LTD, UK

TEST OBJECTIVE(S)

Gather clinical evidence on the performance of the PPE100 boots, an overboot concept and a Serbian design of boot.

THREAT CONDITIONS

Charge mass: 25, 50, and 75 g

Charge geometry: Flat cylinder – light fitting ceiling rose

Placement of charge: Parallel to soil surface

Depth of burial: Surface buried

Initiation point: Bottom dead centre

Charge type: PE4

Notes:

SOIL CONDITIONS

Soil type: Top soil (damp)

Soil container dimensions: Box 600 x 400 x 250 (LxWxH) washing basket flush buried

Soil replacement: Soil replaced

Compaction: Loaded and stamped down by same person each time

Notes:

SURROGATE

Description: Below Knee and Through Knee amputated human limbs. Male and female subjects.

Landmine pre-load: 67 kg

Reaction mass: 67 kg

Orientation of leg: Vertical

Location of charge: Centre heel with one forefoot

Degree of flexion in knee: Fully extended

Notes: Below knee limbs used for confirmation of data gathering capability.

INSTRUMENTATION

Pressure gauge:

Regular video: Yes

High-speed video/film: 400-1000 fps digital

Flash x-ray:

Accelerometer: Kistler tri-ax 8790A500

Strain gauge: Uni-axial

Load cell (uni-axial/multi-axial): Kistler uni-axial

Displacement: LVDT

Temperature: Yes

Signal conditioning:

Data acquisition:

Notes: Post test EOD portable X Ray, photographs, mass, length, plain X Ray, CT scans

FOOTWEAR

Test items: AIGIS PPE100 boots, AIGIS concept overboot, Serbian ‘protective’ boot.

Control: British Combat Boot

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: FSLL TRIALS – MARCH 2001 – DRDC SUFFIELD, CANADA

TEST OBJECTIVE(S)

(i) Build database to compare with the results of LEAP to calibrate the FSL;

(ii) Assess fidelity of improved bones.

THREAT CONDITIONS

Charge mass: M14 (28 grams) & PMA2 (100 grams)

Charge geometry: Actual mine geometries – stub cylinders

Placement of charge: Always in geometric centre of container

Depth of burial: Flush buried, except PMA2 that was buried with standoff equivalent to fuse height

Initiation point: Fuse location; bottom for C4

Charge type: Tetryl (M14) and TNT (PMA2)

Notes: Threat conditions were identical to those used in LEAP

SOIL CONDITIONS

Soil type: Medium sand, dry

Soil container dimensions: Box 450 x 600 x 450 mm (W x L x D)

Soil replacement: Complete, each time

Compaction: Loose pour

Notes: Container constructed from 12 mm thick mild steel to reproduce that used in LEAP

SURROGATE

Description: Frangible Surrogate Lower Leg (FSLL) that consists of geometrically accurate synthetic bones, ballistic gelatine for soft tissues, nylon skin; upper leg replaced by counterweight.

Landmine pre-load: Full weight of FSLL (~10 kg)

Reaction mass: Weight of FSLL (~10 kg)

Orientation of leg: Standing vertically

Location of charge: Below the axis of the tibia

Degree of flexion in knee: None, 0 degree

Notes: The FSLL contained improved bones that had their strength tuned to that of their human counterparts; the FSLL is a development from the FSL.

INSTRUMENTATION

Pressure gauge: For reference far field pressure only

Regular video: Frontal and lateral views

High-speed video/film: Side view at 1000 fps

Flash x-ray: Two 92% frontal views

Accelerometer: Not used

Strain gauge: Compression at bottom and top of tibia, triple rosette at 1/3 distal tibia

Load cell (uni-axial/multi-axial): 5 or 6 axis at ½ tibia on selected shots

Displacement: Not recorded directly, can be obtained from flash x-rays

Temperature: Recorded ambient conditions (weather)

Signal conditioning: For strain gauges only

Data acquisition: 1 MHz digital data

Notes:

FOOTWEAR

Test items: Standard US Army combat boot; Wellco blast boot with Wellco overshoe

Control: US Army combat boot

Notes: Overshoe was used with Wellco blast boot only; US Army combat boot was used on its own

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REFERENCE(S)

Bergeron, D.M.; Anderson, I.B.; Coley G.G.; Fall, R.W., 'Assessment of Lower Leg Injury from Land Mine Blast – Phase 2 – Test Results using an Improved Frangible Surrogate Lower Leg and Comparison with Cadaver Test Data', Defence R&D Canada – Suffield, Technical Report to be published in 2004.

TITLE: MECHANICAL SURROGATE LEG – JANUARY/JULY 1999 – DRDC SUFFIELD, CANADA

TEST OBJECTIVE(S)

To determine the influence of charge size and location on load transfer to the leg when using a platform protective concept.

THREAT CONDITIONS

Charge mass: 25, 50, 100, 150 & 200 gram C4

Charge geometry: Cylindrical, 35% H:D ratio

Placement of charge: Always in geometrical centre of container

Depth of burial: 0, 10, 30 & 50 mm overburden

Initiation point: Bottom centre

Charge type: C4 (RDX)

Notes: Tests were also done against a conventional boot for reference purposes.

SOIL CONDITIONS

Soil type: Coarse sand - manufactured

Soil container dimensions: 1220 mm diameter x 710 mm high

Soil replacement: Top 1/3rd after each test shot

Compaction: Loose

Notes:

SURROGATE

Description: Mechanical surrogate leg consisting of vertical shaft, ankle bulb and moulded rubber foot

Landmine pre-load: Nil

Reaction mass: Shock absorber system

Orientation of leg: Vertical

Location of charge: Various location under pods and platform; two locations under heel of control boots

Degree of flexion in knee: 0 deg (straight column)

Notes:

INSTRUMENTATION

Pressure gauge: Nil

Regular video: Yes, x2 views

High-speed video/film: Yes, side-on and frontal views

Flash x-ray: No

Accelerometer: Tri-axial located in ankle location

Strain gauge: Fore/aft and Port/Starboard at two heights + compression and torsion at centre of column

Load cell (uni-axial/multi-axial): Nil

Displacement: Angular deflection of shock absorber

Temperature: Ambient from local weather report only

Signal conditioning: Standard conditioning for strain gauges

Data acquisition: 500 kHz digital data acquisition system

Notes: Shock absorber system showed variable spring stiffness as a function of outside ambient temperature due to internal rubber components that were temperature sensitive.

FOOTWEAR

Test items: Majority of tests conducted with various versions of the Spider Boot™

Control: Wellco blast resistant boot with and without overshoe

Notes:

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REFERENCE(S)

Coffey, C.G.; Torrance, K.; Lonson, D.; Markov, A.B., "Design, Construction and Commissioning of a Surrogate Human Leg Test Facility", Amtech report TR9775.2701, Rev. 1, November 1999.

TITLE: PRESSURE MAP IN AIR AROUND AP BLAST MINE SURROGATES – MAY 2001 – FRENCH-GERMAN RESEARCH INSTITUTE OF SAINT-LOUIS, FRANCE

TEST OBJECTIVE(S)

Provide basis to characterise better the initial phenomenon and use them as a reference for current and future SLL trials.

THREAT CONDITIONS

Charge mass: 25, 50, 100 and 200 grams C4

Charge geometry: Cylindrical surrogates (0.35 h/d ratio)

Manufacturer: AMTECH (Canada)

Placement of charge: Parallel to soil surface, in geometric centre of container

Depth of burial: Flush buried and buried at –3 cm

(ref.: top surface of the casing)

Initiation point: From underneath, to the centre of charges without any booster

Charge type: C4 (RDX)

Notes: Used detonators: Bickford SA 4003 B03

SOIL CONDITIONS

Soil type: Dry silica sand, type silice S28 (SIKA France)

Grain size: 200-500µ; moisture: 0.03

Soil container dimensions: Cylindrical steel container with rounded bottom (in. diameter x height x thickness) = 880 x 850 x 13 mm

Soil replacement: ½ container

Compaction: Loose pour

Notes:

SURROGATE

Description:

Landmine pre-load:

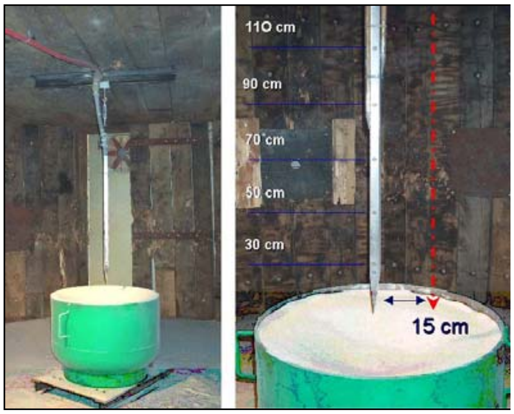
Reaction mass:

Orientation of leg:

Location of charge:

Degree of flexion in knee:

Notes:



INSTRUMENTATION

Pressure gauge: 5 piezoelectric transducers

Regular video:

High-speed video/film:

Flash x-ray:

Accelerometer:

Strain gauge:

Load cell (uni-axial/multi-axial):

Displacement:

Temperature: Ambient spring conditions

Signal conditioning: To each transducer

Data acquisition: 1 MHz digital data

Notes: Transducers are placed at 30/50/70/90/110 cm from soil surface in a sharpened probe hanging on ceiling in axial and shifted (15 cm) positions.

FOOTWEAR

Test items: Not used

Control: Not used

Notes:

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REFERENCE(S)

Magnan P., Parmentier G., De Mezzo S., Rondot F. Vassout P., “Protection des membres inférieurs du combattant contre les mines AP à effet de souffle: cartographie du champ de pression,” ISL- S-CR/RV 409/2002 (in french), 2002.

TITLE: RED DEER LLM – MAY AND SEPTEMBER 2001 – DSTL PORTON DOWN TRIALS

TEST OBJECTIVE(S)

Study the effects of M14 surrogate in contact and compare with LEAP data. Study effects of increasing standoff.

THREAT CONDITIONS

Charge mass: M14 Surrogate (50 g generic)

Charge geometry: Cylindrical surrogates (0.35 h/d ratio)

Placement of charge: Parallel to soil surface, in geometric centre of box

Depth of burial: Surface buried

Initiation point: Bottom centre, RP85

Charge type: PE4 (RDX 88%, binder 12%))

Notes:

SOIL CONDITIONS

Soil type: Sand (sharp) dry, uncontrolled

Soil container dimensions: 600 x 450 x 450 mm box (W x L x D)

Soil replacement: Contaminated sand replaced

Compaction: None

Notes:

SURROGATE

Description: Red deer LLM

Landmine pre-load: Weight of LLM (5kg)

Reaction mass: Weight of LLM

Orientation of leg: Vertical

Location of charge: Centre of heel

Degree of flexion in knee: N/A

Notes: Radiographics of bone model pre and post firing.

INSTRUMENTATION

Pressure gauge: B12 incident

Regular video: Yes

High-speed video/film: No

Flash x-ray: No

Accelerometer: Piezotronics 305A02 (50 000 g)

Strain gauge: No

Load cell (uni-axial/multi-axial): No

Displacement: No

Temperature: Ambient 10-20 C

Signal conditioning: Pressure: AWE PB2, ACC: PCB Signal Conditioner

Data acquisition: Nicolet Multipro 1MHz capture rate

Notes:

FOOTWEAR

Test items: British Army combat boot, insole, and sock

Control:

Notes:

M14: in contact.

50g: Contact, 25mm, 50mm, 75mm, and 100mm stand off

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REFERENCE(S)

None available at time of printing.

TITLE: CLL TRIALS – 2001/2002 – DRDC VALCARTIER, CANADA

TEST OBJECTIVE(S)

(i) Validate Complex Lower Limb (CLL) model;
(ii) Validation of numerical models of the CLL and development of protection concepts.

THREAT CONDITIONS

Charge mass: 50-gram, 75-gram, and 100-gram C4, PMA-2, M-14

Charge geometry: Cylindrical mine surrogates, 35% h:d ratio

Placement of charge: Geometric centre of container

Depth of burial: Flush buried

Initiation point: Fuse location; bottom dead centre

Charge type: C4 (RDX) except for real mines

Notes:

SOIL CONDITIONS

Soil type: Medium sand, dry

Soil container dimensions: Cylinder 73.7 cm dia. 69.9 deep

Soil replacement: Remove top 30-40 cm each test with complete replacement once per week

Compaction: Loose pour

Notes:

SURROGATE

Description: Complex Lower Limb (SLL) that consists of plastic and polymer foam cored bones representing a simplified tibia, calcaneous, and talus arranged to capture the critical load paths and geometric arrangement of the actual human foot.

Landmine pre-load: None

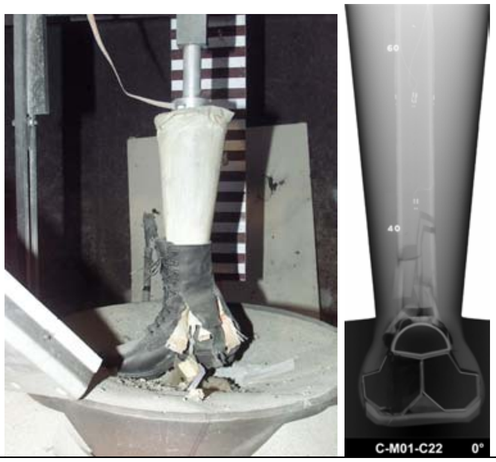
Reaction mass: Weight of CLL + cross head

Orientation of leg: Vertical

Location of charge: Concentric with CLL and centred on rear surface of CLL calcaneous

Degree of flexion in knee:

Notes:



INSTRUMENTATION

Pressure gauge: Lollipop gauge just outside the soil container for blast level comparison

Regular video: No

High-speed video/film: Frontal view, 1000 fps video used in some tests

Flash x-ray: 2 screens (90º) per test

Accelerometer: Not used

Strain gauge: 5 uniaxial gauges: 4 placed 90 degree apart at mid-tibia height + 1 placed 10 cm underneath

Stress gauge: 1 carbon gauge or 1 PVDF gauge placed on the lower surface of the tibia in contact with the talus (only used on a few tests)

Load cell (uni-axial/multi-axial): No

Displacement: Displacement gauges for global leg jump

Temperature: Ballistic gelatine and ambient temperature before the firings

Signal conditioning: For strain gauge only

Data acquisition: 1 Mhz sampling, 100 KHz filtering

Notes:

FOOTWEAR

Test items: Wellco blast boot/ overshoe combination; standard US Army and Canadian Forces combat boots; and protection concepts for material evaluation.

Control: US Army and Canadian Forces combat boot

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: LEAP 2003 AP MINE BLAST PROTECTIVE FOOTWEAR AND CADAVERIC SPECIMEN TESTING – JANUARY AND FEBRUARY, 2003 – ABERDEEN TEST CENTER, ABERDEEN PROVING GROUNDS, MARYLAND, USA

TEST OBJECTIVE(S)

(1) To evaluate commercial off-the-shelf AP mine blast protective footwear.

(2) To establish risk of injury criteria and objective test methodology for AP mine blast protective footwear.

THREAT CONDITIONS

Charge mass: 25, 50, 75, 100, 200 grams

Charge geometry: Cylindrical surrogates (0.35 ratio of height to diameter). From Suffield specs.

Placement of charge: Parallel to soil surface

Depth of burial: 2 cm

Initiation point: Bottom dead center

Charge type: C-4, DETA sheet, RP-80 detonator

Notes:

SOIL CONDITIONS

Soil type: Sand 13% 150, 29% 210, 37% 300 & 15% 420 micron size. 6% other.

Soil container dimensions: 2’ x 2’ x 2’ (60 cm x 60 cm x 60 cm)

Soil replacement: Replaced only needed amount.

Compaction: Loose pour, screeded

Notes: Soil hygrometry performed, 0% humidity in all cases

SURROGATE

Description: LEAP 2003 fixture (22 tests), cadaveric legs (20 tests)

Landmine pre-load: 0 N ± 10 N

Reaction mass: 25 kg.

Orientation of leg: Vertical

Location of charge: Worst case detonation location (generally center of heel under calcaneus)

Degree of flexion in knee: Zero to minimal, fully extended.

Notes: Modified DRDC Valcartier cross head and frame, modified DRDC Suffield mechanical leg and Canadian rig mounted on ATC test fixture.

INSTRUMENTATION

Pressure gauge: Free field: face on, side on

Regular video: Observing bio-hazard test area

High-speed video/film: 1,000, 13,000 fps

Flash x-ray: no

Accelerometer: cross head

Strain gauge: calcaneous and tibia for cadaver, none for LEAP 2003 rigs

Load cell (uni-axial/multi-axial): Above femur uniaxial load cell (all tests), 6 axis tibial load cell (LEAP 2003 rigs), 5 axis tibial load cell (10 cadaver tests)

Displacement: Strain potentiometer on cross head

Acoustic Sensor: Upper tibia for cadaver

Temperature: 24C (75F) in test area

Signal conditioning: 40kHz filter

Data acquisition: 200 kHz

Notes: Pre and post radiographs, necropsy, MTS scores, AIS scores

FOOTWEAR

Test items: 5 boot candidates

Control: LEAP series

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: ASSESSMENT OF PROTECTION LEVEL OF ANTI-MINE BOOTS AGAINST SURROGATE AP BLAST MINES – 2002 – ETBS/ISL, BOURGES AND SAINT-LOUIS, FRANCE

TEST OBJECTIVE(S)

Assessment of the protection level of current anti-mines boots

THREAT CONDITIONS

Charge mass: 25 and 50 grams

Charge geometry: h/D ratio 0.35 (plastic containers)

Placement of charge: flush buried with soil surface

Depth of burial: -/-

Initiation point: bottom dead center (ETBS) geometric center (ISL)

Charge type: C4

Notes: 2 different types of detonators are used. Explaining why the initiation point is different.

SOIL CONDITIONS

Soil type: dry silica sand 200-500 microns

Soil container dimensions: D=88 cm H=90 cm

Soil replacement: 1/3rd of container

Compaction: loose poured

Notes: moisture are kept constant (<3%)

SURROGATE

Description: Simplified Lower Limb (SLL) that consists of plastic and polymer foam cored bones representing a simplified tibia, calcaneus, and talus.

Landmine pre-load: None

Reaction mass: Weight of SLL + connection steel piece

Orientation of leg: Vertical

Location of charge: Concentric with SLL and centred on rear surface of SLL calcaneus

Degree of flexion in knee:

Notes:

INSTRUMENTATION

Pressure gauge: 2 probes with conical tips at 60 cm to the mine

Regular video: yes

High-speed video/film: not used

Flash x-ray: 2 shots 500 and 1000 microsec.

Accelerometer:

Strain gauge: pre instrumented strain gauges SLL (x5)

Load cell (uni-axial/multi-axial): pre instrumented pressure gauge SLL

Displacement: velocity by wires (4 cm distance)

Temperature: -/-

Signal conditioning: Vischay

Data acquisition: Gould Nicolet ODYSSEY OD200
with data viewer software

Notes:

FOOTWEAR

Test items: Anonymate, Aigis, Wellco/ overshoe combination, and Med-Eng spider blast boot with standard FR Army

Control: FR combat boot

Notes:

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REFERENCE(S)

None available at time of printing.

TITLE: SPIDER BOOT DEVELOPMENT – JANUARY 97 TO MAY 98 – MED-ENG SYSTEM INC. AT MREL, CANADA

TEST OBJECTIVE(S)

Provide a semi-quantitative method for screening materials and concepts in attenuating blast AP mines, leading to the development of Spider Boot.

THREAT CONDITIONS

Charge mass: For most tests, ranging from 75g C4 to 150g C4. A few tests also carried out at 25g C4.

Charge geometry: Rectangular (75g charges: 2” x 1.5” x 1” thick); unmodified extruded block of C4 for consistency; minimal shaping of charge after initial tests

Placement of charge: Parallel to ground (mostly bare)

Depth of burial: Flush buried

Initiation point: Electronic blasting cap at centre (12 grain)

Charge type: C4 with 2 g pressed RDX DetaPrime Booster

Notes: Charges were initially shaped without a container but this added scatter in results

SOIL CONDITIONS

Soil type: construction grade sand mixed with loose soil

Soil container dimensions: no container

Soil replacement: replaced crater with fresh sand/soil

Compaction: loose

Notes: humidity of soil/sand was not controlled

SURROGATE

Description: Articulated steel leg designed by Biokinetics and Associates, dimensioned to represent the 50th male percentile.

Landmine pre-load: Weights were added so that the total mass of the system was 77.7kg

Reaction mass: 77.7 kg, inclusive of surrogate leg

Orientation of leg: Standing vertically

Location of charge: Below the axis of the tibia, below the toe, or under a pod of the Spider Boot prototypes

Degree of flexion in knee: Surrogate leg is articulated at the knee and ankle, allowing it to move naturally.

Notes: Some tests with biological specimens were also carried out (porcine legs butchered for human consumption).

INSTRUMENTATION

Pressure gauge: PVDF pressure gauge was used initially but discarded due to unreliable data interpretation

Regular video: Used to determine maximum vertical displacement and range of debris scatter.

High-speed video/film: Not used

Flash x-ray: Not used

Accelerometer: Two tri-axial clusters of accelerometers, one located at the center of gravity of the foot, one located at the center of gravity of the tibia (PCB Model 305A for initial tests; replaced by PCB Model 350A to avoid signal saturation, signal conditioner PCB model 482A20 power supply).

Strain gauge: Not used

Load cell (uni-axial/multi-axial):

Displacement: Determined by regular video

Temperature: Not controlled: tests carried out between April-December in non-freezing conditions

Signal conditioning: FFT 10,000 Hz

Data acquisition: 125 kHz digital

Notes:

The integral under the acceleration curves were considered.

FOOTWEAR

Test items: Stacking of various thicknesses of energy absorbing materials, metallic wedges with various angles, as well as early prototypes of the Med-Eng Spider Boot.

Control: Wellco boot and overboot, BfR boot, fresh porcine leg

Notes: Tall blocks of foam layers used initially, leading to the Spider Boot elevated concept with deflector under plate

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REFERENCE(S)

None available at time of printing.

Annex G: COMPENDIUM OF TEST SET-UPS UPPER BODY PROTECTION SYSTEMS

TITLE: DEVELOPMENT OF UPPER BODY PPE TEST METHOD AGAINST AP BLAST MINES – APRIL TO OCTOBER 99 – MREL AND DRDC SUFFIELD, CANADA

TEST OBJECTIVE(S)

Develop a test methodology to evaluate the effectiveness of PPE in protecting the upper body against the effects of an AP mine blast.

THREAT CONDITIONS

Charge mass: 50 g to 200 g

Charge geometry: Short cylinder, 35% height:diameter

Placement of charge: Cylinder axis of symmetry is vertical

Depth of burial: 2 cm overburden

Initiation point: Bottom dead centre, using a RP-2 detonator.

Charge type: Packed C4 explosive

Notes: Reliable detonation of the C4 with the RP-2 requires a small 1 g booster made from two small discs of Datasheet™

SOIL CONDITIONS

Soil type: Dry medium sand (moisture < 0.5%)

Soil container dimensions: Cube made from 25mm thick steel, 60cm x 60cm x 60cm dimensions

Soil replacement: Scoop out approximately 1/3rd of the upper volume where contamination from detonation products and debris occurs, and refill

Compaction: Loose pour

Notes: Previous tests showed that loose pouring the sand results in a consistent 94% to 95% compaction

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: Compared head acceleration to 300 g limit

X-ray: Not used

CT scan: Not used

Dissection: n/a

Anthropometry: Defined by Hybrid III standard; not measured otherwise

Filters/Electronic Post processing: Butterworth and median filters used as appropriate

Notes:

INSTRUMENTATION

Pressure gauge: Kulite transducers mounted flush to surface at side of head with hole drilled in Hybrid II head box. Pressure transducer also used to measure pressure at the chest location

Regular video: 8mm standard video, 2 viewing angles

High-speed video/film: Kodak HG2000 at 1000 fps, side view only

Flash x-ray: not used

Accelerometer: Endevco 2264 in the head of the Hybrid II

Strain gauge: not used

Load cell (uni-axial/multi-axial): not used

Displacement: not used

Temperature: not monitored

Signal conditioning: Vishay system

Data acquisition: Pacific System used at 500 kHz

Notes:

SURROGATE

Description: Hybrid II anthropomorphic mannequin

Posture: Kneeling (single and both knees on the ground) and prone; the squatting position was considered, but it was difficult to achieve consistency with the mannequin

Range: Position of the mannequin was varied so that specified distances to the centre of the chest and to the nose, as measured from the centre of the mine, could be maintained

Orientation: All tests were performed with the mannequin facing the explosion, simulating a mine prodding or mine excavation procedure

Positioning/Measurement System: The mannequins were supported by ropes through an overhead frame, which proved unreliable and difficult to work with. The ropes were cut loose with detonator at time zero; the September 99 tests were the first time that the Med-Eng positioning rig was used; distance from mine to nose and mine to chest were recorded.

Surrogate Calibration: Stiffness of joints and neck was adjusted at beginning of test program and not monitored until completion of the test series.

Anthropometry:

Notes: The Hybrid II used were discarded from automotive testing; they were acquired for cost reason to assess if such surrogate could be used for this type of testing.

UPPER BODY PROTECTION SYSTEM

Detailed Description: Used as required to achieve the principal aim of the project, i.e., to develop the test procedures themselves. The mannequin was dressed with sweats for unprotected shots and with the Med-End Humanitarian Demining Ensemble for protected shots.

Mass: Approximately 8 kg

Fitting: The equipment was fitted tightly to the mannequin body.

Projected Area: not measured.

Control: n/a

Notes:

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable with the Hybrid II mannequin, which is a mechanical system.

Control:

DIAGRAM SHOWING SURROGATE POSITION

Not available

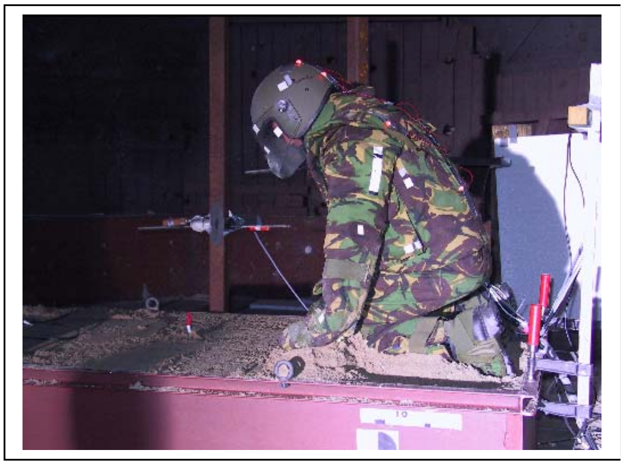
REFERENCE(S)

None available at time of printing.

TITLE: EVALUATION OF PROTECTION LEVEL OF COMMERCIAL PPE – TNO, NETHERLANDS

TEST OBJECTIVE(S)

The main objective of this study is to get more information of the protection level of the PPE, which was manufactured by RBR, Inc.



THREAT CONDITIONS

Charge mass: 50 g and 100 g

Charge geometry: Short cylinder, 2:1 height:diameter

Placement of charge: 0.45 m and 0.70 m and 0.9 m from the mine to the nose of the dummy

Depth of burial: 11.5mm overburden

Initiation point: Bottom and in the centre of the mine, using a DM42 detonator.

Charge type: Number 8 explosive

Notes: The charge masses used of number 8 explosives are equivalent to the charge mass 50g and 100g of C-4 explosives

SOIL CONDITIONS

Soil type: Dry sand

Soil container dimensions:

Soil replacement:

Compaction:

Notes: HOM sand

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria:

X-ray: not used

CT scan: not used

Dissection: n/a

Anthropometry:

Filters/Electronic Post processing: Instrumentation for impact test, part 1, electronic instrumentation, SAE J211/1, March 1995

Notes:

INSTRUMENTATION

Pressure gauge: Two pressure gauges were located at 0.45m and 0.70m to measure the pressure near the mannequin. First two tests blastpencils were used of Kulite, type XCQ093. For the other experiments Endevco type 8530 pressure gauges were used.

Regular video:

High-speed video/film:

Flash x-ray: not used

Accelerometer: Endevco 7267A were used for the acceleration of the head, thorax and pelvis of the Hybrid III

Strain gauge: Not used

Load cell (uni-axial/multi-axial): Denton model 1716, 6 channel upper neck load cell measuring three axis forces and three axis moments. The Denton model 1842 was used for two axis forces and one axis moment.

Displacement: Standard Hybrid III potentiometer used to measure chest displacement, Servo, 14cb1.

Temperature:

Signal conditioning:

Data acquisition:

Notes:

SURROGATE

Description: Hybrid III anthropomorphic mannequin

Posture: Kneeling (both knees on the ground) and prone; in prone position the dummy was placed with the knees on the ground outside the container with sand. This was done due to the fact that the dummy is not able to stretch its legs completely.

Range:

Orientation: All tests were performed with the mannequin facing the explosion, simulating a demining procedure.

Positioning/Measurement System: From the mine the distance to the nose was measured. To assure the same position of the dummy markers were placed on the mannequin and the distances were measured from a reference point.

Surrogate Calibration: Stiffness of joints and neck was monitored throughout the test program. Instrumentation calibrations were performed prior to the test series. Instrumentation health was monitored throughout the test series.

Anthropometry:

Notes: The Hybrid III and the injury criteria are standard for automotive safety. Therefore the use of the dummy and criteria in mine blast testing is still being investigated.

UPPER BODY PROTECTION SYSTEM

Detailed Description: The protective equipment has been manufactured by RBR, Inc. under the name Bomb Search Suit.

Mass: 16.6 kg (inclusive helmet with visor)

Fitting: The equipment fitted good to the mannequin body.

Projected Area: Not measured.

Control: n/a

Notes:

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable with the Hybrid III mannequin, which is a mechanical system.

Control:

DIAGRAM SHOWING SURROGATE POSITION

Not available

REFERENCE(S)

None available at time of printing.

TITLE: COMPARING UPPER BODY PROTECTION FROM 5 PPE AGAINST AP BLAST MINES – OCTOBER/NOVEMBER 00 – ABERDEEN TEST CENTER, USA

TEST OBJECTIVE(S)

Compare the protective performance of five PPE using the US/CA test procedure to measure the effect of AP mine blast against the upper body.

THREAT CONDITIONS

Charge mass: 50g, 100g and 200g; Some tests done with PMN mines

Charge geometry: Short cylinder, 35% height to diameter

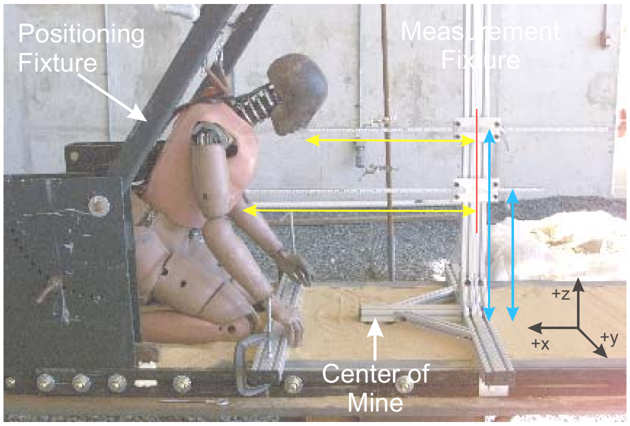
Placement of charge: Cylinder axis of symmetry is vertical

Depth of burial: 2 cm overburden

Initiation point: Bottom dead centre, using a RP-87 detonator.

Charge type: Packed C4 explosive

Notes: Reliable detonation of the C4 with the RP-87 requires a small 1g booster made from two small discs of datasheet™



SOIL CONDITIONS

Soil type: dry medium sand (moisture < 0.5%)

Soil container dimensions: cube made from 25mm thick steel, 60cm x 60cm x 60cm dimensions

Soil replacement: scoop out approximately 1/3rd of the upper volume where contamination from detonation products and debris occurs, and refill

Compaction: loose pour

Notes: previous tests showed that loose pouring the sand results in a consistent 94% to 95% compaction

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: from SAE J211 and Nij

X-ray: n/a

CT scan: n/a

Dissection: n/a

Anthropometry: defined by Hybrid III standard; measured using 3D technique throughout tests

Filters/Electronic Post processing: Butterworth and median filters used as appropriate

Notes:

INSTRUMENTATION

Pressure gauge: Kulite XCQ-093-500A flat pack transducers mounted flush on the head of the mannequin at (roughly) the ear location; Kulite XCQ-093-500A and LQ-125-500A on thorax skin surface, between 3rd and 4th ribs; PCB 102-A04 side on pressure at ear level for reference

Regular video: 8mm standard video

High-speed video/film: Kodak HG2000 at 1000fps, side view and Kodak 4540 at (up to) 13,000fps, side view

Flash x-ray: not used

Accelerometer: Endevco 7270A-6k, tri-axis configurations in the head and chest cavities; single axis in the sternum

Strain gauge: not used

Load cell (uni-axial/multi-axial): Denton model 1716A, 6 channel upper neck load cell measuring three axis forces and 3 axis moments

Displacement: Servo 14CB1-2897 in sternum

Temperature: Thermocouples in skin simulants on thorax, head and hand, Omega 0.5mil and Omega 0.3mil bare wires

Signal conditioning: 40kHz antialiasing hardware filter

Data acquisition: Data sampling at 200kHz

Notes:

SURROGATE

Description: Hybrid III anthropomorphic mannequins, 50th percentile male. Limited tests were also done using the 5th percentile female mannequin

Posture: Kneeling (both knees on the ground) and prone

Range: Nominal kneeling position had nose of mannequin 65cm from mine (x = 29.2cm, y = 63.4cm) while prone position had nose 45cm from mine (x = 30.5cm, y = 33.2cm). Variations from this position were also tested to measure the influence

Orientation: All tests were performed with the mannequin facing the explosion, simulating a mine prodding or mine excavation procedure

Positioning/Measurement System: 3D positioning information was gathered during test series to determine variation from test to test. The results were in a x-y-z coordinate system and a second test rig was used in x-y to locate the mannequin

Surrogate Calibration: Stiffness of joints was monitored throughout the test program; although neck tension was not and became loose during the test series. Instrumentation calibrations were performed prior to and after the test series and health checks were done throughout the test series

Anthropometry: 3D measurements along centreline of mannequin around the head and down the thorax was performed for both positions

Notes: The Hybrid III is the standard for automotive safety testing and the injury criteria for the device are for the type of blunt impact due to inertial acceleration of the body form. The use of a Hybrid III in mine blast testing is still being investigated since the load mechanisms might differ significantly, particularly when testing in an unprotected configuration

UPPER BODY PROTECTION SYSTEM

Detailed Description: The 5 PPE ensembles were obtained from commercial sources, representing a range of protective equipment available to the demining community. All ensembles provided some form of protection to the face and thorax, although there were significant differences in the implementation of these protective measures, e.g., extent of the facial coverage of the visor. Three ensembles also offered protection to the groin area and three used a helmet to further protect the head.

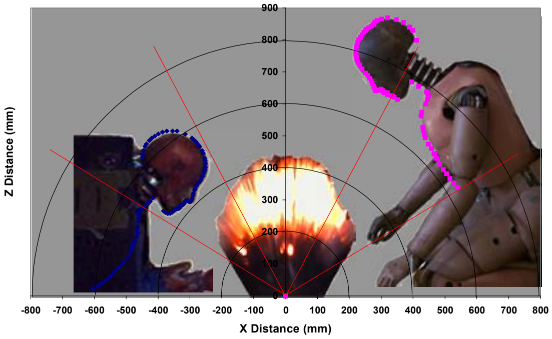
Mass: Total ensemble mass varied from 3.6kg to 9.0kg; Helmet/visor mass from 0.77kg to 2.6kg; body ensembles from 2.6kg to 4.5kg and trousers from none to 3.6kg.

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable with the Hybrid III mannequin, which is a mechanical system

Control:

DIAGRAM SHOWING SURROGATE POSITION



REFERENCE(S)

Tests were performed at Aberdeen Test Center, in October and November 2000.

C. Chichester, C.R. Bass, B. Boggess, M. Davis, D.M. Bergeron, E. Sanderson and G. Di Marco, “*Effectiveness of Personal Protective Equipment for Use in Demining AP Landmines*”, Proceedings of the 2001 UXO conference, New Orleans, USA, April 2001.

TITLE: EFFECT OF BODY POSITION ON TRANSMISSION OF AP BLAST MINES LOAD TO THE UPPER BODY – SEPTEMBER 01 TO JANUARY 03 – DRDC SUFFIELD, CANADA

TEST OBJECTIVE(S)

Mapping of the relation between effective force transfer to the head and chest as a function of body position, body size and AP mine mass

THREAT CONDITIONS

Charge mass: 50g, 100g and 200g

Charge geometry: Short cylinder, 35% height to diameter

Placement of charge: Cylinder axis of symmetry is vertical

Depth of burial: 2cm overburden

Initiation point: Bottom dead centre, using a RP-87 detonator.

Charge type: Packed C4 explosive

Notes: Reliable detonation of the C4 with the RP-87 requires a small 1g booster made from two small discs of datasheet™

SOIL CONDITIONS

Soil type: Dry medium sand (moisture < 0.5%)

Soil container dimensions: Cube made from 25mm thick steel, 60cm x 60cm x 60cm dimensions

Soil replacement: Scoop out approximately 1/3rd of the upper volume where contamination from detonation products and debris occurs, and refill

Compaction: Loose pour

Notes: Previous tests showed that loose pouring the sand results in a consistent 94% to 95% compaction

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: From SAE J211 and Nij

X-ray: n/a

CT scan: n/a

Dissection: n/a

Anthropometry: Defined by Hybrid III standard; measured using 3D laser imaging

Filters/Electronic Post processing: Butterworth and median filters used as appropriate

Notes: Post-processing done through MatLab® programming software

INSTRUMENTATION

Pressure gauge: Kulite LE-125-500SG flat pack transducers mounted flush on the head of the mannequin at (roughly) the ear location on both sides of the head; pressure transducers were also used to measure reference free-field side-on pressure at ear and head-on pressure at chest levels

Regular video: 8mm standard video, 2 viewing angles

High-speed video/film: Kodak HG2000 at 1000 fps, side view

Flash x-ray: not used

Accelerometer: Endevco 2264 and 7264B, tri-axis configurations in the head and chest cavities of the Hybrid III

Strain gauge: not used

Load cell (uni-axial/multi-axial): Denton model 1716A, 6 channel upper neck load cell measuring three axis forces and 3 axis moments

Displacement: not used

Temperature: Taken statically prior to test using external thermocouple gauge

Signal conditioning: Integral to Data acquisition system

Data acquisition: Pacific System used at 1 MHz

Notes:

SURROGATE

Description: Hybrid III anthropomorphic mannequins, 50th percentile male and 5th percentile female (modified to remove the breast to obtain a chest profile similar to that of the larger mannequin).

Posture: Kneeling (both knees on the ground) and prone

Range: Position of the mannequin was varied so that specified distances to the centre of the chest and to the nose, as measured from the centre of the mine, could be maintained

Orientation: All tests were performed with the mannequin facing the explosion, simulating a mine prodding or mine excavation procedure

Positioning/Measurement System: 3D positioning information was gathered prior to the test series and specific measurements were used to check that the same position was obtained during tests using an x-y coordinate system.

Surrogate Calibration: Stiffness of joints and neck was monitored throughout the test program. Instrumentation calibrations were performed prior to and after the test series. Instrumentation health was monitored throughout the test series.

Anthropometry:

Notes: The Hybrid III is the standard for automotive safety testing and the injury criteria for the device are for the type of blunt impact due to inertial acceleration of the body form. The use of a Hybrid III in mine blast testing is still being investigated since the load mechanisms might differ significantly, particularly when testing in an unprotected configuration.

UPPER BODY PROTECTION SYSTEM

Detailed Description: A special lightweight, throwaway protective system was designed to add minimal weight to the mannequins and to maintain the basic profile so that the shots would be representative of an unprotected human shape.

Mass: 929 gram for the 50th percentile mannequin and 668 gram for the 5th percentile mannequin.

Fitting: The equipment was fitted tightly to the mannequin body.

Projected Area: Made minimal difference to the standard area of the base mannequin.

Control: n/a

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable with the Hybrid III mannequin, which is a mechanical system.

Control:

DIAGRAM SHOWING SURROGATE POSITION

Not available

REFERENCE(S)

Tests performed by DRDC Suffield on behalf of CCMAT. Reports are currently in preparation and will be available at a later date.

TITLE: DEVELOPMENT OF TEST METHOD FOR UPPER BODY PPE AGAINST AP BLAST MINES – MARCH 99 TO AUGUST 00 – DRDC SUFFIELD AND FORT BELVOIR/NVL

TEST OBJECTIVE(S)

Develop a test methodology to evaluate the effectiveness of PPE in protecting the upper body against the effects of an AP mine blast.

THREAT CONDITIONS

Charge mass: 50g to 200g

Charge geometry: Short cylinder, 35% height:diameter

Placement of charge: Cylinder axis of symmetry is vertical

Depth of burial: 2cm overburden

Initiation point: Bottom dead centre, using a RP-87 detonator.

Charge type: Packed C4 explosive

Notes: Reliable detonation of the C4 with the RP-87 requires a small 1g booster made from two small discs of datasheet™; The detonator changed as a function of what test site was used.

SOIL CONDITIONS

Soil type: Dry medium sand (moisture < 0.5%)

Soil container dimensions: Cube made from 25mm thick steel, 60cm x 60cm x 60cm dimensions

Soil replacement: Scoop out approximately 1/3rd of the upper volume where contamination from detonation products and debris occurs, and refill

Compaction: Loose pour

Notes: Previous tests showed that loose pouring the sand results in a consistent 94% to 95% compaction

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: From SAE J211

X-ray: not used

CT scan: not used

Dissection: n/a

Anthropometry: Defined by Hybrid III standard; not measured otherwise

Filters/Electronic Post processing: Butterworth and median filters used as appropriate

Notes:

INSTRUMENTATION

Pressure gauge: Kulite LE-125-500SG flat pack transducers mounted flush on the head of the mannequin at (roughly) the ear location; this transducer was also used to measure pressure at the chest location; pressure transducers were also used to measure reference free-field side-on pressure at ear and chest levels

Regular video: 8mm standard video, 2 viewing angles

High-speed video/film: Kodak HG2000 at 1000 fps, 2 viewing angles

Flash x-ray: not used

Accelerometer: Endevco 2264 and7264B, tri-axis configurations in the head and chest cavities of the Hybrid III

Strain gauge: not used

Load cell (uni-axial/multi-axial): Denton model 1716A, 6 channel upper neck load cell measuring three axis forces and 3 axis moments

Displacement: Standard Hybrid III potentiometer used to measure chest displacement

Temperature: Taken statically prior to test using external thermocouple gauge

Signal conditioning: Vishay system

Data acquisition: Pacific System used at 500 kHz; another system used at Fort AP Hill

Notes: The instrumentation configuration given here was that used during tests at DRDC Suffield; the development of this test methodology involved tests at 3 locations, but instrumentation remained basically the same from one location to the next except for brands and sometime range of transducers.

SURROGATE

Description: Hybrid III anthropomorphic mannequin

Posture: Kneeling (both knees on the ground) and prone; the squatting position was considered, but it was difficult to achieve consistency with the mannequin

Range: Position of the mannequin was varied so that specified distances to the centre of the chest and to the nose, as measured from the centre of the mine, could be maintained

Orientation: All tests were performed with the mannequin facing the explosion, simulating a mine prodding or mine excavation procedure

Positioning/Measurement System: A special wooden rig was constructed to help in the positioning process; the hips and knees were positioned and the angle of the upper body was then adjusted using the positioning rig. The final position was measured using an x-y coordinate system

Surrogate Calibration: Stiffness of joints and neck was monitored throughout the test program. Instrumentation calibrations were performed prior to and after the test series. Instrumentation health was monitored throughout the test series

Anthropometry:

Notes: The Hybrid III is the standard for automotive safety testing and the injury criteria for the device are for the type of blunt impact due to inertial acceleration of the body form. The use of a Hybrid III in mine blast testing is still being investigated since the load mechanisms might differ significantly, particularly when testing in an unprotected configuration

Early tests during this development used Hybrid II mannequins, 50th percentile male. All later tests used the Hybrid III equivalent

UPPER BODY PROTECTION SYSTEM

Detailed Description: Used as required to achieve the principal aim of the project, i.e., to develop the test procedures themselves. The mannequin was dressed with sweats for unprotected shots and with the Med-End Humanitarian Demining Ensemble for protected shots

Mass: Approximately 8kg

Fitting: The equipment was fitted tightly to the mannequin body

Projected Area: not measured

Control: n/a

Notes:

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable with the Hybrid III mannequin, which is a mechanical system

Control:

DIAGRAM SHOWING SURROGATE POSITION

Not available

REFERENCE(S)

This work involved 3 test series at 3 locations: DRDC Suffield in Canada (2 test series) and 1 test series in Fort AP Hill, US.

C. Chichester, C.R. Bass, B. Boggess, M. Davis, E. Sanderson and G. Di Marco, “A Test Methodology for Assessing Demining Personal Protective Equipment (PPE)”, CECOM Report, May 2001.

C.R. Bass, B. Boggess, M. Davis, C. Chichester, D.M. Bergeron, E. Sanderson and G. Di Marco, “A Methodology for Evaluating Personal Protective Equipment for AP Landmines”, Proceedings of the 2001 UXO Conference, New Orleans, USA, April 2001.

TITLE: ASSESSMENT OF PROTECTION LEVEL OF PPE AGAINST BLAST EFFECTS – 1998 – WTD 91, MEPPEN, GERMANY

TEST OBJECTIVE(S)

Assessment of the protection level of an EOD 7B-suit against blast effects.

THREAT CONDITIONS

Charge mass: 5 kg

Charge geometry: spherical

Placement of charge: placed 1 m above the ground

Depth of burial: -/-

Initiation point: Bottom dead centre

Charge type: Seismogelit 2

Notes:

SOIL CONDITIONS

Soil type: -/-

Soil container dimensions: -/-

Soil replacement: -/-

Compaction: -/

Notes: Charges were placed 1 m above the ground.

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: Bowen et al (pressure); HIC (acceleration head)

X-ray: not used

CT scan: not used

Dissection: n/a

Anthropometry: -/-

Filters/Electronic Post processing: Defined by Hybrid III standard

Notes: -/-

INSTRUMENTATION

Pressure gauge: Kulite HKS-375-M70 transducer were used. Two of them were located directly at the chest of the ATD, which means inside the EOD-suit. Two additional gauges were adopted outside the suit on chest level.

Regular video: yes

High-speed video/film: 250 frames/sec

Flash x-ray: -/-

Accelerometer: 3 axis in the head and pelvis cavities of the Hybrid III

Strain gauge: -/-

Load cell (uni-axial/multi-axial): -/-

Displacement: Obtained from the accelerometers

Temperature: -/-

Signal conditioning: -/-

Data acquisition: -/-

Notes:

SURROGATE

Description: Hybrid III 50th percentile male

Posture: Standing upright

Range: 1 m / 3 m / 5 m from charge

Orientation: All tests were performed with the manikin facing the explosion.

Positioning/Measurement System: Wooden supports were used in the positioning process and to maintain the manikin in its final position.

Surrogate Calibration: defined by Hybrid III standard

Anthropometry: -/-

Notes: -/-

UPPER BODY PROTECTION SYSTEM

Detailed Description: Med-Eng Systems EOD 7B-suit, consisting of jacket, trousers, groin protector, boots, hand protection, helmet and accessories

Mass: Approximately 30 kg

Fitting: The equipment was fitted tightly to the body.

Projected Area: not measured.

Control: n/a

Notes: -/-

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable

Control: -/-

DIAGRAM SHOWING SURROGATE POSITION

REFERENCE(S)

None available at time of printing.

TITLE: ASSESSMENT OF PROTECTION LEVEL OF PPE AGAINST BLAST EFFECTS – 2002 – WTD 91, MEPPEN, GERMANY

TEST OBJECTIVE(S)

Assessment of the protection level of an EOD 8-suit and a SAFECO 2000E-suit against blast effects.

THREAT CONDITIONS

Charge mass: 5 kg

Charge geometry: Spherical

Placement of charge: 1 m above the ground

Depth of burial: -/-

Initiation point: Unknown

Charge type: Seismogelit 2

Notes: -/-

SOIL CONDITIONS

Soil type: -/-

Soil container dimensions: -/-

Soil replacement: -/-

Compaction: -/

Notes: Charge was placed 1 m above the ground.

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: Bowen et al (pressure); HIC (acceleration head), con3ms (acceleration chest)

X-ray: not used

CT scan: not used

Dissection: n/a

Anthropometry: Defined by Hybrid III standard

Filters/Electronic Post processing: Defined by Hybrid III standard

Notes: -/-

INSTRUMENTATION

Pressure gauge: Kulite HKS-375-M70 transducer were used. Two of them were located directly at the chest of the ATD, which means inside the EOD-suit. Two additional gauges were adopted outside the suit on chest level.

Regular video: -/-

High-speed video/film: -/-

Flash x-ray: -/-

Accelerometer: 3 axis in the head and chest cavities of the Hybrid III

Strain gauge: -/-

Load cell (uni-axial/multi-axial): -/-

Displacement: -/-

Temperature: -/-

Signal conditioning: Peekel Signalog 4000

Data acquisition: Gould Nicolet 2580P, 12 bit, with ProVIEW recording software

Notes:

SURROGATE

Description: Hybrid III anthropomorphic test device, 50. percentile, male, pedestrian

Posture: Standing upright

Range: 3 m / 5 m from ATD to charge

Orientation: All tests were performed with the ATD facing the explosion.

Positioning/Measurement System: Wooden supports were used in the positioning process and to maintain the ATD in its final position.

Surrogate Calibration: The ATD was calibrated before the test series. The measurement equipment was also calibrated before the tests, according to ISO 9001

Anthropometry: -/-

Notes: -/-

UPPER BODY PROTECTION SYSTEM

Detailed Description: Med-Eng Systems EOD 8-suit, and Nero SAFECO 2000E-suit, both consisting of jacket, trousers, groin protector, boots, hand protection, helmet and accessories

Mass: Approximately 25 - 30 kg

Fitting: The equipment was fitted tightly to the ATD body.

Projected Area: not measured.

Control: n/a

Notes: -/-

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable with the Hybrid III, which is a mechanical system.

Control:

DIAGRAM SHOWING SURROGATE POSITION

Not available

REFERENCE(S)

Mörker, Dieter: “EOD-Schutzanzüge - Bewertung der Ansprengversuche im Mai/Juni 2002”; WTD 91 – 400 / 128 / 2002; Wehrtechnische Dienststelle für Waffen und Munition; Meppen (Germany); 2002.

TITLE: DETERMINATION OF THE RISKS TO PERSONNEL OPERATING IN A DE-MINING CAPACITY, WORKING IN A PRONE POSITION, TO AP MINE THREATS – SEPTEMBER 99 – DSTL PORTON DOWN

TEST OBJECTIVE(S)

Establish the threats to personnel 'prodding' for mines and testing of concept protection systems.

THREAT CONDITIONS

Charge mass: 75 g to 100 g

Charge geometry: Short cylinder, PMA2 type geometry

Placement of charge: Cylinder axis of symmetry vertical

Depth of burial: Surface and 10 cm overburden

Initiation point: Top centre, using a RP-80 detonator.

Charge types: PE4 and TNT explosive

Notes: Detonation of the TNT with the RP-80 and a 1g booster was not reliable so PE4 was used instead.

SOIL CONDITIONS

Soil type: Damp medium sand (moisture ~ 6%)
Undisturbed in-situ chalk (moisture ~22.5%)

Soil container dimensions: Sand – 3.6mx3.6mx1.2m
Chalk – In situ sub soil

Soil replacement: Scoop out where contamination from detonation products and debris occurred, and refill

Compaction: Loose pour then light compaction of the surface

POST PROCESSING AND ANALYSIS

Blast lung Injury Assessment : Thoracic rig with in house analysis software

Radiography: Limb models radiographed post test

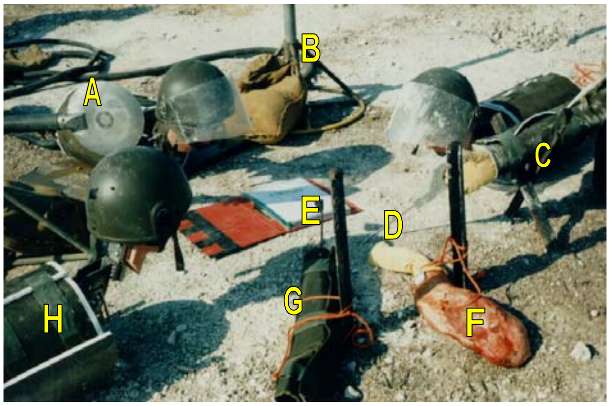
CT scan: not used

Anthropometry: Visual examination and clinical assessment of tissue and gelatine stripping and bone fracture (visual and radiographic assessment).

Filters/Electronic Post processing: Cumulative Sum Criteria software to determine injury/lethality from blast lung injury

Eye simulant : Analysis of particles embedded

Ear Damage: Pressure converted to sound levels and assessed relative to noise level legislation.



A, low level B12 pressure gauge. **B**, stand for high level B12. **C**, tissue-stripping model at handle position. **D**, model prodder. **E**, mine location marker used for measurement datum. **F**, pig forelimb with protection on trotter. **G**, traumatic amputation model. **H**, thoracic rig with concept decoupler.

INSTRUMENTATION

Pressure gauge: B12 pressure transducers at ear height in prone position and at standing height. To assess consistency of mine output, pressure characteristics at visor level and assessment of ear injury/hearing loss.

Thoracic rig: Wall acceleration and blast lung damage assessment.

Regular video: No

High-speed video/film: No

Flash x-ray: No

Accelerometer: Piezotronics PCB 305A02/305A03

Pressure Transducers: AWE B12, 3.3Mpa max pressure.

Strain gauge: No

Signal conditioning: PCB (Acc) & AWE PB2 (Pressure)

Data acquisition: Nicolet Multipro with Metrum Tape back-up.

Notes:

SURROGATE

Description:

Thoracic rig with RTV rubber moulded head model with underlying steel support structure allowing rotation of the head relative to the thorax. Used to assess effectiveness of visors and other eye protections.

Hand tissue stripping models a) a skeletal structure with gelatine moulded around to give a geometrical form of forearm and b) Pig forelimb.

Traumatic amputation model. Sheep long limb bone moulded in gelatine to assess likelihood of forearm fracture/traumatic amputation. Arm in two positions, at the handle of the prodder and close to surface near the mine.

Very simple eye simulant using foam adhesive pads to capture particles striking the eye rather than a direct assessment of injury.

Posture: prone

Range: Centre of the mine to accelerometer in the rig 1.0m Fingers of hand/arm models 300mm from centre of charge. Head position as dictated by thorax. B12 gauge (prone) as ear position on head

Orientation: All tests were performed with the mannequin facing the explosion, simulating a mine prodding or mine excavation procedure.

Sand density grading and moisture content measured. Moisture content of representative sample of chalk determined.

Note: It is important to note that these trials were performed as part of a project supporting an urgent requirement where time-scales were extremely short. It was not possible to optimise some of the models in the time available.

UPPER BODY PROTECTION SYSTEM

Detailed Description: Various in-service and concept blast protection systems were tested as well as visors, in various positions from up to fully down, Goggles/wraps and with/without helmet. A number of types and thickness of textile (Aramid) sleeves for arm protection, loose and tight were tested.

Projected Area: not measured.

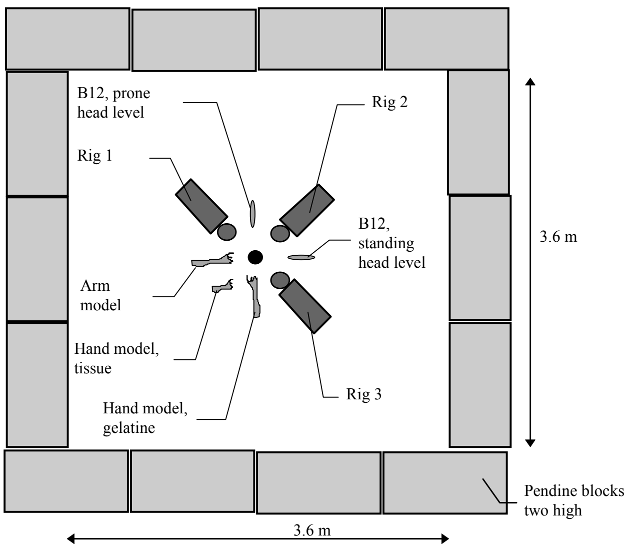
Notes:

PHYSIOLOGICAL MONITORING

Description in Detail: N/A

Control:

DIAGRAM SHOWING SURROGATE POSITION



REFERENCES

None available at time of printing.

TITLE: ASSESSMENT OF PROTECTION LEVEL OF PPE AGAINST FRAGMENTATION AND BLAST MINES – MARCH-APRIL 1996 – DRDC SUFFIELD, CANADA

TEST OBJECTIVE(S)

Assessment of the protection level of an EOR4/MCS4 suit against fragmentation and blast mines.

THREAT CONDITIONS

Charge mass: PMR-2A, M16, M18 and PMA-1 mines

Charge geometry: Defined by mine type

Placement of charge: PMA-1 was buried in soil; PMR-2A was placed on its stake, M16 was allowed to bound and M18 was placed as per manufacturer specifications.

Depth of burial: 2 cm for PMA-1

Initiation point: As per mine design

Charge type: As manufactured.

Notes:

SOIL CONDITIONS

Soil type: Dry soil with low moisture

Soil container dimensions: A small crater was excavated and refilled with unfrozen soil

Soil replacement: After each test

Compaction: Lightly packed

Notes: The soil was kept indoors until ready for the test, then placed in its crater; no attempt was made to dry the samples.

POST PROCESSING AND ANALYSIS

Injury Assessment Criteria: Bowen et al for pressure; head acceleration; fragment hits and penetrations.

X-ray: not used

CT scan: not used

Dissection: n/a

Anthropometry: Defined by the Hybrid II

Filters/Electronic Post processing: Simple Butterworth filter to remove high frequencies above 10 kHz

Notes: Ear pressure and head acceleration were recorded only for selected tests (mostly vs blast mines).

INSTRUMENTATION

Pressure gauge: Kulite pressure transducer were mounted through the head box of Hybrid II.

Regular video: yes

High-speed video/film: High speed film used at 2000 to 5000 frames per second.

Flash x-ray: not used.

Accelerometer: 3 axis in the head of the Hybrid II.

Strain gauge: not used.

Load cell (uni-axial/multi-axial): not used.

Displacement: not computed.

Temperature: not monitored, except for outside air temperature.

Signal conditioning: Butterworth low-pass filter at 10 kHz

Data acquisition: Pacific system at 1 MHz

Notes:

SURROGATE

Description: Hybrid II 50th percentile male

Posture: Standing upright and lying prone for fragmentation tests; lying prone for blast tests.

Range: 0.5 m up to 10 m from charge.

Orientation: Most tests were performed with the mannequin facing the explosion, but some tests were also performed with the mannequin facing away (rear strikes).

Positioning/Measurement System: Steel supports were used for the standing position, while the mannequin were self supporting for the prone position.

Surrogate Calibration: none

Anthropometry: Defined by the Hybrid II

Notes: -/-

UPPER BODY PROTECTION SYSTEM

Detailed Description: Med-Eng Systems EOR4/MCS4 development suit, which was a lightweight version of their EOD 7 suit; the EOD 7B helmet and accessories were used for selected tests.

Mass: Approximately 25 kg

Fitting: The equipment was fitted tightly to the body.

Projected Area: not measured.

Control: n/a

Notes: -/-

PHYSIOLOGICAL MONITORING

Description in Detail: Not applicable

Control: -/-

DIAGRAM SHOWING SURROGATE POSITION

REFERENCE(S)

Bergeron, D.M., Walker, R.A., Bourget, D. and Makris, A., Testing of the EOR4 Mine Clearance Suit against Anti-Personnel Mines, Suffield Report 651, July 1996.

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Mine blast
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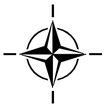
Models
Overpressure
Protective clothing
Sands
Shock waves
Simulation
Soft Body Armour
Soil properties
Soil tests

14. Abstract

The protection of dismounted soldiers against anti-personnel (AP) land mines has been a focus of Military Forces for many years. Since World War II, a significant amount of resources has been invested in developing personal protective equipment (PPE) against this threat. However, the past ten years has seen an intensified effort to solve the problem, which has led to the emergence of new PPE. It was soon recognized that common international procedures to evaluate and assess the performance of this equipment was needed. In 2000, the NATO RTO decided to pool the knowledge and experience of its members to develop a common understanding of the physics at play during a mine explosion and the resulting human injuries. This database would then be used to define common methods to test PPE against AP mines. This was the mandate of Task Group HFM-089/TG-024.

This report presents the results of TG-024. It provides background information about mine explosions and the injuries they inflict on their victims. This sets a reference against which the reader can assess the discussion on test methodologies. This discussion is broken down in three sections. The first describes the basic elements that a test methodology must have. The second addresses methods designed to test PPE that protects the lower extremities. The third is focussed on PPE that protects the upper body. Following this discussion, the report presents the TG recommendations with respect to test methods for the assessment of PPE performance against AP blast and fragmentation mines. Finally, conclusions are presented along with a brief recommendation for future work. The report is supplemented with several annexes that contain information relating to mines, past experience of the participating nations, mine injuries, etc., which were too detailed for inclusion in the main text.



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