Hard Armour Trade Space Analysis

A. Moser[1] and A. Geltmacher[1]

[1]U.S. Naval Research Laboratory, 4555 Overlook Ave., S.W., Washington, DC 20375
Alex.moser@nrl.navy.mil

Abstract. The U.S. Marine Corps primarily fields a single type of hard armour system called the Enhanced Small-Arms Protective Insert (ESAPI). The existing ESAPI plates are heavy and contribute to increased load bearing injuries and decreased mobility and survivability. These plates are engineered to stop specific threats at the designated threats' muzzle velocity. The primary and most severe threat for which the ESAPI is rated is rarely found in operation by either allied or adversarial forces. Also, the specific threats in most combat situations are predominantly and significantly under the threat's rated muzzle velocity. Thus, in 90% of battlefield scenarios these plates are overrated for penetration performance but significantly underperform with respect to mobility and overall survivability. As part of the Marine Corps mission, an attempt is being made to maintain adequate ballistic performance while decreasing plate weight, mobility, and overall survivability. The Hard Armour Trade Space (HATS) analysis evaluated ballistic performance information from armour vendor web sites and vendor proprietary information provided to the U.S. Naval Research Laboratory. Most vendor proprietary information typically consisted of ballistic test reports from a certified commercial ballistic test laboratory. The HATS analysis system consists of a database of 40 armour manufacturers, 234 hard armour plates, 42 prevalent ballistic threats, ballistic test data from threats for which each plate was tested, and scripts to perform analysis on the commercial-off-the-shelf plates in the database. The database provides over 1000 plate/threat performance combinations. The HATS analysis resulted in contribution to the ballistic requirements for a significant new lightweight armour plate procurement of over $260M for improved overall survivability.

1. Background

Dismounted ground troops carry 41kg (90lbs.) to 64kg (140 lbs.) or more in combat [1]. Such loads cause the Warfighter to sustain injuries from dismounting vehicles, even before entering contested spaces. With fatigue, cognitive abilities decline [2], as well. The excessive weight also decreases mobility. These factors, in combination, decrease over-all survivability. Thus, to decrease Warfighter load one approach is to decrease the weight of body armour.

Progress in armour development has progressively slowed over several decades, primarily from difficulties in finding materials with enhanced ballistic performance. An overall trend described by Dr. James Zheng, formerly of US Army/PEO Soldier, indicated improvements had approached an asymptotic limit as shown in Figure 1 [3]. Because of this, armed services development centres have recently focused on finding armour solutions that fit the threat scenario within specific operational environments. This typically reduces the weight requirement of armour, since the currently fielded US military body armour is required to stop a threat rarely seen in conflicted spaces. However, the trade-off between armour weight and survivability has previously been unquantified, and there had been a reluctance to transition to lighter weight body armour with reduced ballistic specification. A ballistic test is a clear metric on armour performance and is easily quantified through values such as V_{50} result. In contrast, survivability is less quantifiable, but is thought to be a function of mobility and, ultimately, body armour weight. Recently, progress has been made to better understand the link between armour weight, mobility, and survivability [4], and the results from these simulations show a strong correlation between weight and survivability.

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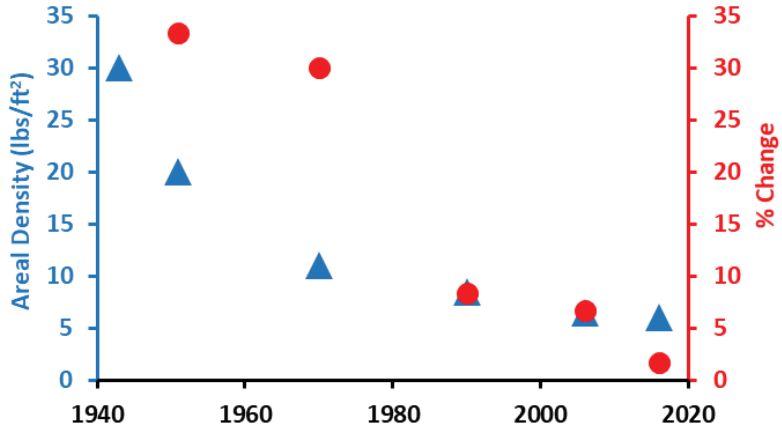

Figure 1. Plot of armour areal density as a function of development time reproduced from Fish et al [3]. The data indicates recent armour developments have been minimal.

An experimental study demonstrated a strong correlation between armour weight and mobility [5], in which a group of Marines were tasked to traverse an obstacle course carrying varying loads and in a rested and fatigued state. However, one must interpret these results carefully.

The plot in Figure 2 shows soldier's completion time through a typical military obstacle course used in training as a function of various armour configurations; the heaviest setup on the left side and the lightest on the right. One can see, for soldier's running a course in a rested state (blue) the reduction in time is less than 20% for a reduction in armour weight approaching 100%.

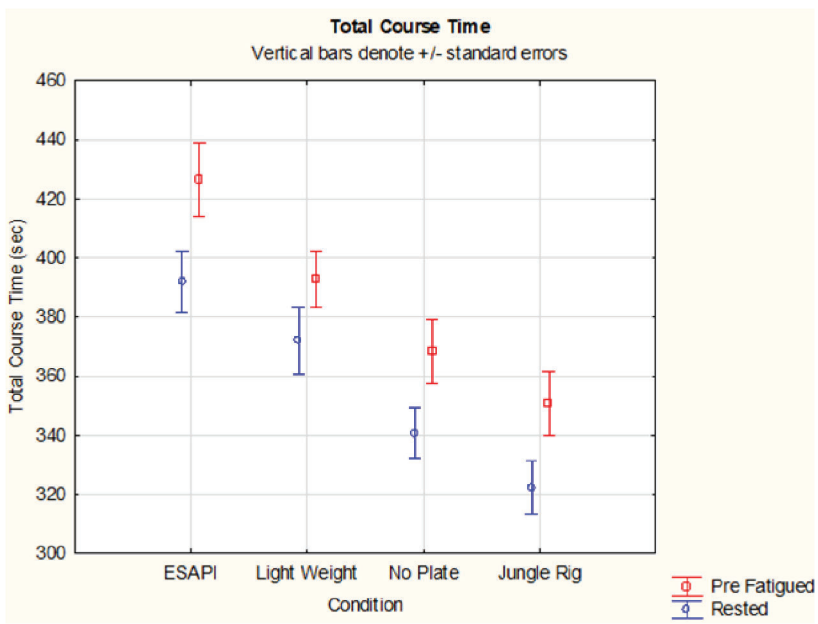

Figure 2. Results from a mobility test showing the importance a few shed kg has on mobility, and ultimately, survivability.

The trade-off between ballistic protection and mobility might lead one to believe reduction of armour weight is not worth the increased mobility. However, the most accurate metric is the total weight the soldier must carry, including the soldier's own body weight, compared to the mobility represented as time to course completion. Thus, a soldier weighing approximately 86kg (190 lbs.), carrying a minimal 90 lb load, including the full set of body armour results in a total weight of 127kg (280lbs.). Without the body armour or body armour vest the total weight is approximately 118kg (260 lbs.). This represents a weight decrease of only 7% yet the reduction in obstacle course time is approximately 17%.

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Thus, mobility is greatly enhanced for every ounce of mass shed and is likely to improve survivability significantly.

An endeavour was initiated to develop a hard armour trade scape analysis system (HATS) to determine the weight requirement for hard armour plates based on a set of threat, each at a specified velocity or distance down range from the muzzle. Other analytical models exist, but are not based on a large pool of experimental data [6,7,8]. The process used and subsequently described consisted of amassing known manufacturer hard armour plate data into a database and applying an analysis method which could capture intrinsic characteristics common among the known plates to determine the minimum required armour weight based on a user input threat set.

2. Database

A database was constructed using a well-established database development environment [9]. The criteria for entry into the database was as follows:

1) The company providing the armour was a U.S. company or resided in a country considered a close ally of the U.S.
2) The company of criteria (1) had to be a manufacturer of the plates and not merely a vendor/reseller of the plates
3) An exception to criteria (2) was if the vendor/reseller had exclusive rights to sell the plate from the manufacturer. In essence, the plate was specified/designed by the vendor and made by someone else.
4) An exception to criteria (3) was if the manufacturer was not a U.S. company or resided in a country considered an ally of the U.S.
5) The plates were required to be of nominal areal dimensions of a standard medium sized ESAPI plate.

Armour input into the database typically consisted of an array of plates comprised of various designs and constructions, but the most prevalent consisted of either all steel plates, all polymer (Dyneema or Spectra or similar variant), all ceramic plates, or a combination of ceramic and polymer. Differing covered and foams were incorporated into plates, but these variants contributed little to ballistic performance.

Most armour plates had associated detailed ballistic test reports either obtained directly on-line or through proprietary agreement with the company providing the information. Excluding some minor variance in the data, most were obtained with the use of a soft armour surrogate as a backing material in front of a standard Roma Plastilina.

The database structure is shown in Figure 3 and consists of 15 relational database tables containing a total of 110 fields and thousands of records (2033 records). It contains personal armour plates from 38 U.S. and allied armour manufacturers down selected from an initial field of 108 vendors/manufacturers. It contains a total of 229 unique armour systems ranging from NIJ level III through IV+, and included some plates with capability to stop special threats. The tables were linked together using a variety of rules and/or programmatic processes.

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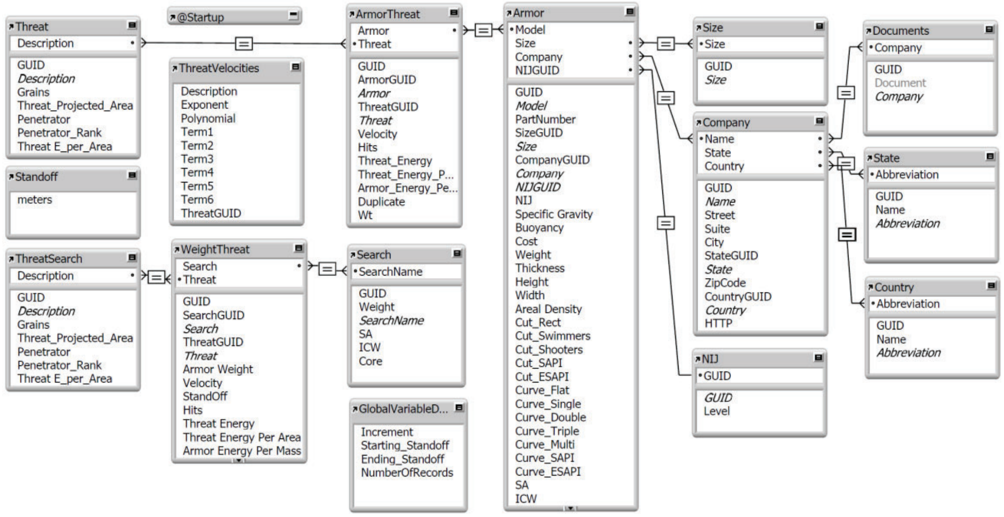

Figure 3. Trade space analysis database tables, fields, and relationships.

Armour plate weights ranged from 0.744kg (1.64 lbs.) to 4.45kg (9.8 lbs.) for medium sized plates, thicknesses from 4.8mm (0.19in.) to 33mm (1.3in). It consisted of 38 different threat types, from shotgun slugs, through NIJ level IV+ threats[1]. Since each plate was typically tested for multiple threats, the database contained ballistic test data from over 1086 armour/threat combinations.

The front-end user input section of the database is comprised of a search/analysis capability, is described in detail later, and is shown schematically in Figure 4. The user can create and save a set of search criteria based on a set of threats and associated velocity/stand-offs from muzzle. The search can be for plates known to defeat all threats in the threat set at or about the designated velocity/stand-off or those inferred to defeat the threats based on analysis of each plate's ballistic data and other parameters.

[1] NIJ IV+ is not a standard NIJ level, but presented by several vendors to represent protection against not only M2 AP threat, but other threats such as the 7.62x39 BZ API and 7.62x54R B32 API.

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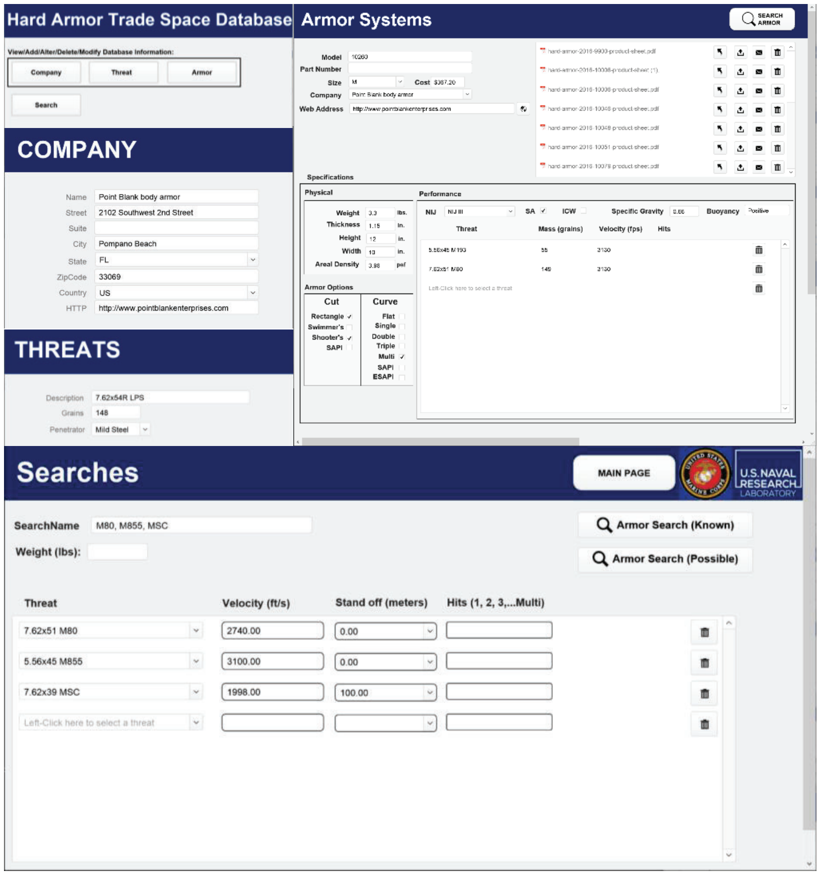

Figure 4. Hard Armour Trade Space analysis system comprised of a database built from a common database development system. Shown (upper left) the main page, the page for Company input, and Threat input, (upper right) Armour system input, and (lower) the search page for finding the required armour.

The result of the search is either a table of plates known to defeat the most aggressive threat in the threat set or a table of plates likely to defeat the most aggressive threats in the threat set and also a minimum medium ESAPI format plate weight required to defeat the most aggressive threat in the threat set. Further filtering and sorting can be applied to the tables upon user input to target specific desired attributes such as plate total weight range, buoyancy characteristic, and specific armour plate cut.

The results obtain for plate systems known to defeat specific threats is straightforward and requires a typical database record lookup. However, determination of the armour systems inferred to defeat the user input threat set and the minimum armour plate weight required is more involved.

As seen in Figure 5 for a single threat at muzzle velocity, without adequate transformation of the data, no clear determination of armour performance is possible. The upper left plot in Figure 5 shows armour weight as a function of threat velocity producing a scatter plot without any significant trend. Similarly, the remaining representations of the data within the database, armour areal density as a function of threat velocity, energy, or projected energy (as shown in Figure 6) produces similar ambiguous results.

The plots in Figure 5 all use extrinsic parameters for the data representation of the armour systems. Ultimately, transformation of the data to an intrinsic parameter similar to toughness would enable comparison of each armour system relative to another.

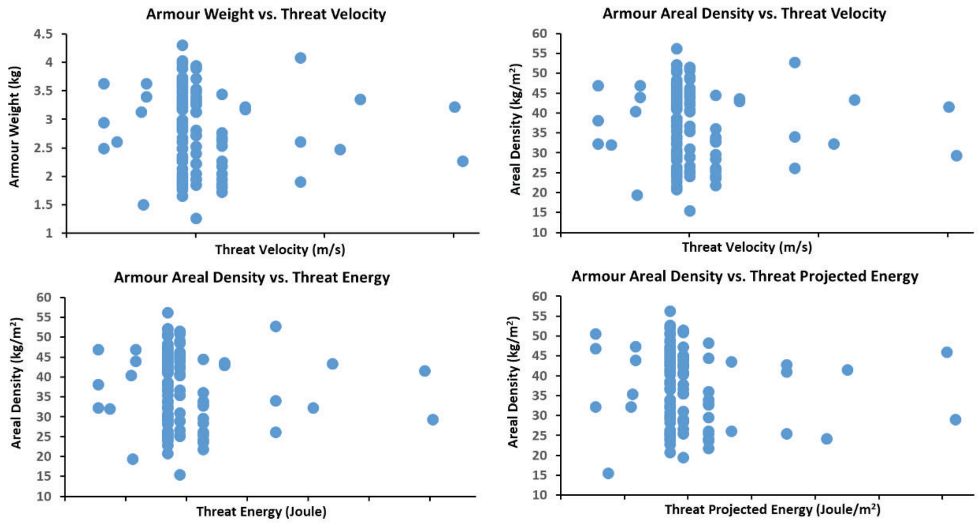

Figure 5. Representations of armour performance against a specific rifle threat. Each horizontal axis represents similar range but with differing units. These data representations make it difficult to infer any useful information.

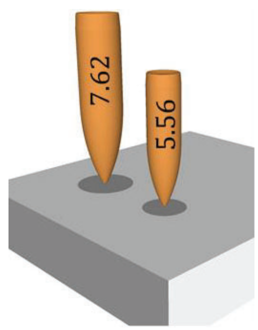

Figure 6. Schematic showing projected cross-sectional area of two different threats onto armour front surface.

The area projected by the threat onto the armour defines the armour volume in which the threat energy is absorbed. This assumption is justified because the greatest strains to the armour, greatest surface area transformation of the ceramic strike face and, ultimately, the greatest percentage of the threats kinetic energy is absorbed in this volume. If one represents the data as a plate energy absorbed per unit volume, this enables comparison across plate systems having undergone ballistic tests with differing threats. This metric is, effectively, a per-mass representation of toughness. To create this representation of the data, the threat projected energy (Joule/cm^2) is divided by the plate areal density (gm/cm^2) to obtain the effective per- mass 'toughness' of the armour system (J/gm). This representation of the armour systems against a specific threat is shown in the left-hand plot of Figure 7, and follows a $y = x^{-n}$ relationship. The inverse relationship is shown on the right-hand side of Figure 7 and follows a $y = m\,x$ relationship. This representation allows us to find the armour with the lowest areal density; lowest values along the y-axis and the armour with the greatest mass- toughness (lowest values along the x-axis).

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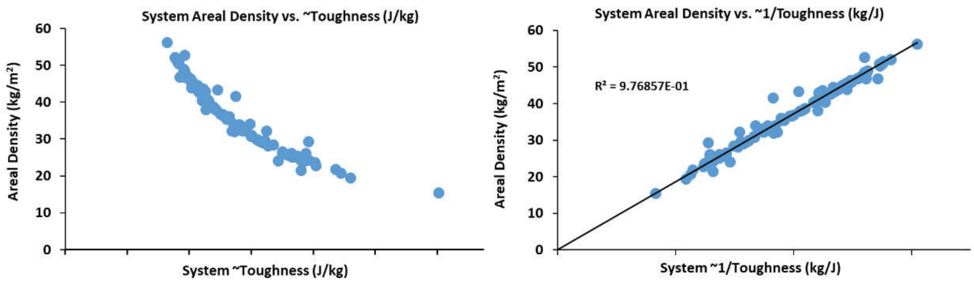

Figure 7. Data from Figure 6 transformed to show armour performance trend. (left) Data from the lower right plot of Figure 6 normalized by dividing the threat projected energy by the area density to produce an armour 'toughness' metric. (right) the same data from the plot on the left but representing the inverse 'toughness'.

Interestingly, one observes a plate that seems to significantly outperform others. This armour system with the lowest areal density and greatest toughness is separated from the other performers. Further investigation revealed the plate's ceramic component was significantly smaller than that of a standard medium ESAPI plate and was backed by a standard sized polymer backing. Thus, one must still carefully screen outliers because they can distort the desired result. In this case, the manufacturer represented the armour as a standard size plate, when, in fact, functionally this was not the case.

Figure 8 demonstrates armour systems perform differently against different threats. Each threat's performance is plotted against the plates with which it was tested. The most severe threats are those with the largest slope.

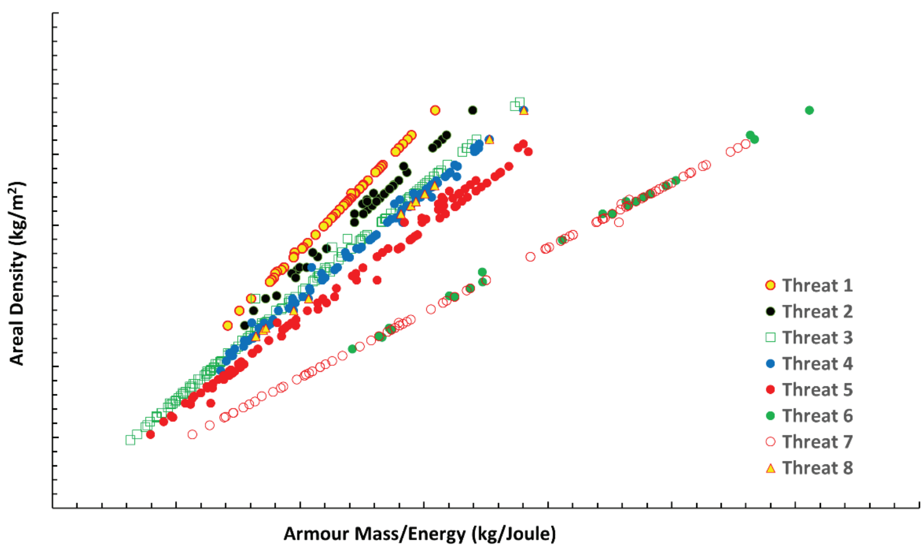

Figure 8. Plot of armour areal density vs the armour mass per unit energy which the armour system is known to absorb based on ballistic test reports. Each point represents a specific armour system/threat pair for which the armour was tested.

3. Results

One can use the database/analysis system to determine the weight requirement for a plate with specific ballistic performance characteristics. Recently, the United States Marine Corps had a requirement for a light weight plate able to stop four different threats, each at a different velocity. The number of ballistic tests to determine the required weight would be time consuming and costly, and since the tests would likely be from a limited lot of plates, the results would be less certain than those from a source utilizing a large dataset of armour plates.

Analysis to determine a feasible plate weight based on USMC threat requirements was quickly performed using the HATS tool. The results of the analysis informed the threshold and objective areal density requirements of the Lightweight Plate Performance Specification. A solicitation was published to which several vendors submitted proposal packages. Each submission was evaluated individually and independently for ballistic and non-ballistic conformance to the requirements by a Source Selection Evaluation Board. The Protective Group, a Point Blank Company, was awarded the contract to produce the USMC Lightweight Plate [10].

4. Conclusion

ESAPI plate system is capable of stopping severe threats typically not found on the battlefield and, as a result, is much heavier than needed for survivability optimization. A lighter armour system, capable of stopping more common and less severe battlefield threats, significantly improves Warfighter mobility and survivability. Without extensive knowledge of the existing armour plate data from a large vendor dataset, determination of the optimal armour weight and ballistic performance is time consuming and expensive.

Using the Hard Armour Trade Space analysis system, armour system performance and weight were tailored for a balance between ballistic performance and mobility to optimize overall survivability for a specific mission and operation theatre. This system has taken armour system physical parameter information and ballistic performance data and transformed it into a more intrinsic form of energy-per-unit-mass or the inverse. This allows for evaluation of plate performance against threats for which it was not ballistically tested and enables determination of a potential best performing plate.

The resulting lightweight plate solicitation by the USMC is one example of armour optimization, but each specific mission could have different requirements and armour optimal weight. The HATS system could find use by other organizations for each of their mission requirements in the future.

Acknowledgments

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