Estimating Ballistic Limits of Skin and Clothing for Projectiles

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Introduction-1

- This paper reports the development of an accurate correlation function for the ballistic limit velocity (that velocity for which there is a 50% probability of target perforation, V_{50}) over a wide range of projectiles striking bare skin and skin covered by various amounts and types of clothing.
- Accurate determination of the ballistic limit of skin and skin covered with various clothing is essential to accurate estimates of incapacitation levels by all models for incapacitation.
- Projectiles that must meet a requirement of being less-than-lethal (the non-perforation of skin, covered or uncovered) are just as demanding of an equally accurate determination of their ballistic limits.

Introduction-2

- The determination of being less-than-lethal (no breaking of the skin) used by the U. S. Army's Office of the Surgeon General is based on not exceeding a specified value of the ratio (for any projectile) of its kinetic energy to its presented cross-sectional area. This is for bare skin only
- As will be shown here, this ratio does not remain a constant over the range of projectile and skin properties for which it is necessary to determine the velocity limit for the perforation of skin.

Discussion-1

- Applicable data from eight studies were found in References 1- 5. A major issue with most of these sources is they give a range of velocities for “penetration” without a definition of “penetration”.
- Only Lewis *et al* (Ref. 5) reported the velocity and the perforation or non-perforation of the target skin and covering for each and every shot fired.
- This paper uses V_{50}, the velocity at which one-half of the tested projectiles will perforate the target and one-half will not, as the best estimate of the minimum velocity for perforation in the presence of velocity overlap.

Discussion-2

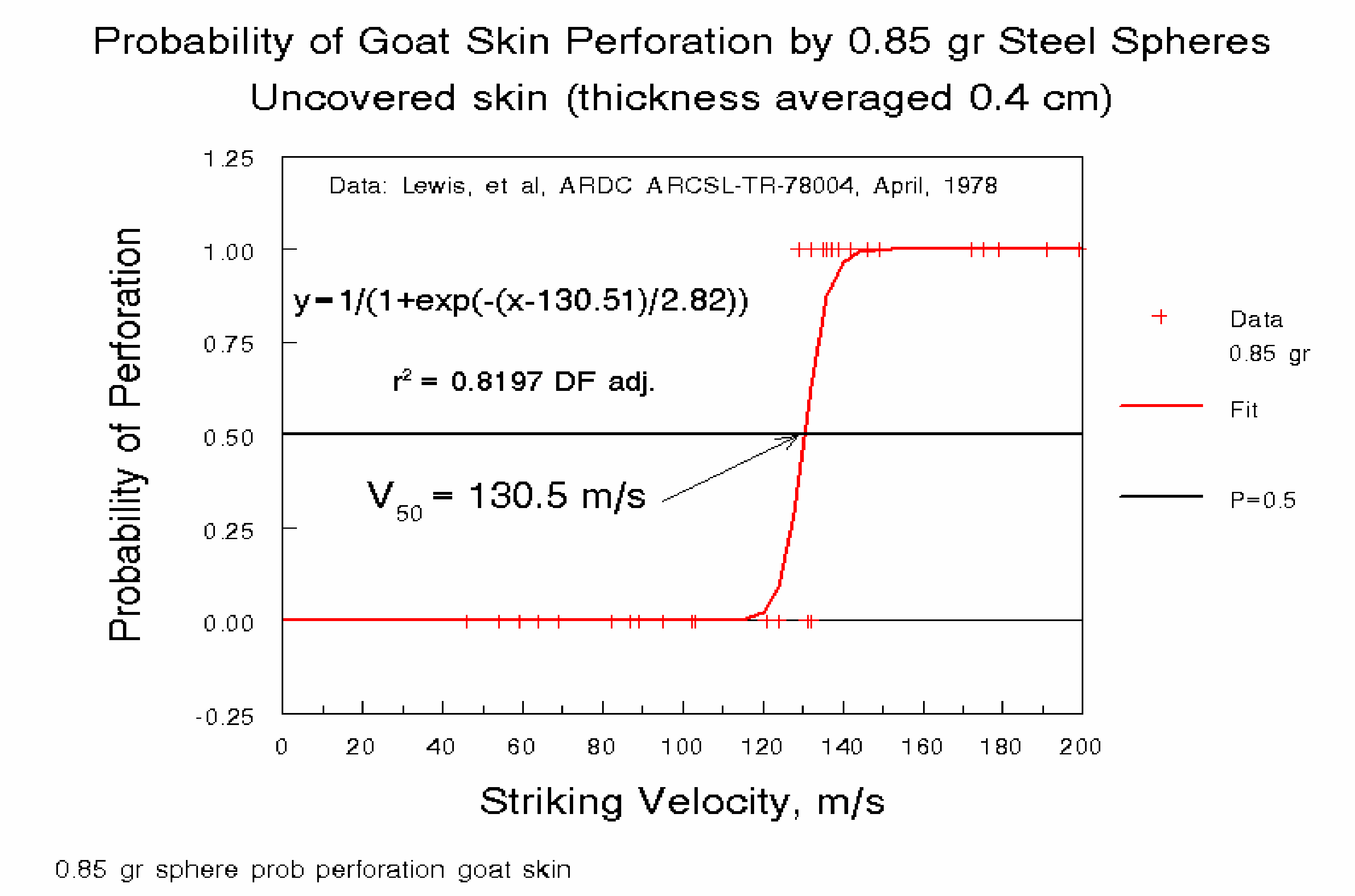

Fig. 1 Example of Probability of Perforation vs Striking Velocity

Discussion-3

- For the sources with only velocity spreads it was necessary to provisionally use the mean of the spread to approximate V_{50}. This provisional use was shown to be reasonable when the data from the sources and the data from Lewis *et al* for which the more exact method was used correlated equally well.
- MacPherson (Ref. 2) used sectional density as a correlation parameter and he showed good results for bare skin. The data in Kokinakis and Sperrazza (Ref. 3 and 4) and in Lewis, *et al* (Ref. 5) that include bare skin and various clothing layers could not be correlated using only projectile sectional densities.
- It is clear that target skin and covering properties also need to be included in the correlation parameter. The obvious starting point is to use a perforation parameter, analogous to the penetration parameter defined for flight,

Discussion-4

$$P \equiv 2m/(\rho t A_p)$$

where,

ρ = target density　　t = target skin and covering thicknes

m = projectile mass　　A_p = projectile average presented area

Discussion-5

- The average presented area of a stable projectile is the maximum cross-sectional area perpendicular to the flight axis, and it is the average presented area for an unstable projectile. It has been proven (e.g., Ref. 7) that for any shape composed of non-concave surfaces that the average presented area is given by:

$$A_p = \underline{\text{Total Surface Area}} / 4$$

- The one exception found in the data used was for unstable cubes (Refs. 4 & 5). The differences in skin thicknesses used between Ref. 4 and Ref. 5 still allowed good correlation of all cube data, therefore, attention shifted to the effective area.
- Empirically, and **only for the case of bare skin**, dividing the cubes' average presented area by 3.37 brought the tumbling cubes back into line with the other shapes when perforating skin and with cubes perforating cloth-covered skin.

Discussion-6

- This suggests the needed area reduction is not due to an incorrect average area but it is the result of the cubes sometimes striking primarily with a point or edge. This creates very high stress concentrations in the bare skin.
- The fact that an area reduction is not needed when the skin is cloth-covered supports this hypothesis. Cloth pushed in front of the cube (even as loose pieces) effectively blunts edges and corners and reduces stress concentrations.

Modeling Clothing-1

- Clothing properties can often be input directly into the model as the product ρt is exactly the areal density usually used to describe the “weight” of clothing.
- The way to account for multiple clothing layers of different areal densities is to determine the effective areal density of all the layers, $(\rho t)_{eff}$.

Modeling Clothing-2

- Effective areal density is computed as:

$$(\rho t)_{eff} = \sum_{1}^{i} (\rho t)_i \; = \; \sum_{1}^{i} \rho_i t_i$$

or combine the forms as required by the available data.

Fitting the Data-1

- The actual data points fitted are given in Table 1 and were computed from the values of skin thickness and density and clothing areal density reported, when available. When not available, average values of the reported data were used.
- Table 1 arranges the parameterized data by experimenter, type of projectile, and the makeup of the target covering (bare skin, skin plus 2-layer clothing (summer uniform), or skin plus 6-layer clothing (winter uniform). The final fit using a nonlinear method is described next.

Results-1

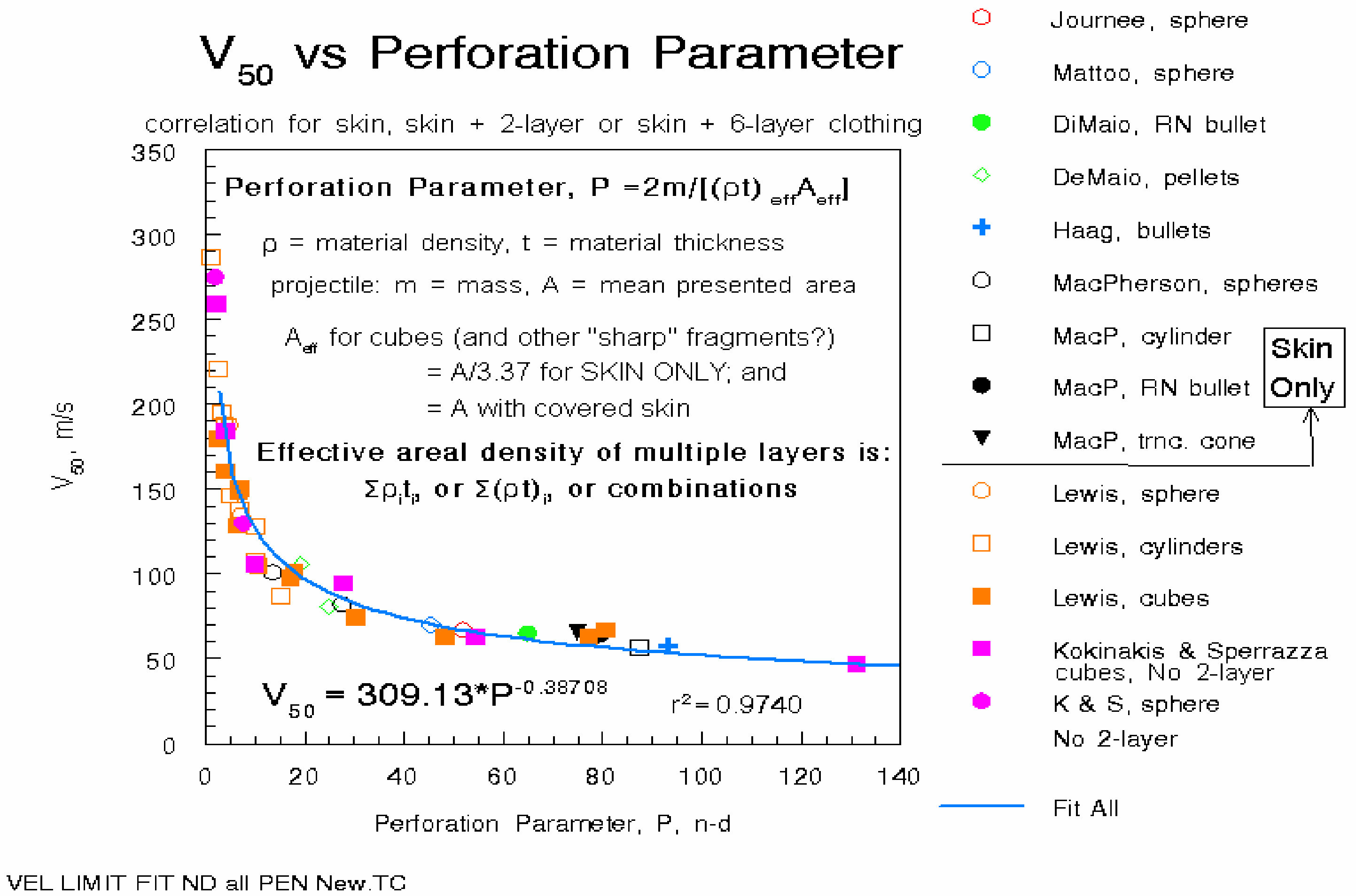

Figure 2. V_{50} vs Perforation Parameter

Results-2

- When densities, thicknesses, and/or areal densities are not available for the estimates that need to be made, use a skin density of 1.06 gm/cm^3 and a skin average thickness (based on all the sources) of 0.31 cm and the clothing areal densities from Lewis *et al* (Ref. 5).

Target Skin and Covering	Effective Areal Density, $(\rho t)_{eff}$
	gm/cm^2
skin	0.33
skin + 2-layer summer uniform	0.49
Skin + 6-layer winter uniform	1.30

Compare Correlation and Energy/Area-1

- Given this correlation equation, the approach using striking energy divided by projectile presented area is a constant that defines the ballistic limit can be shown to be less accurate even when accounting for target skin and covering properties.

Compare-2

- Using energy equals one half mass times velocity squared, the correlation equation yields the following:

$$E_{50}/A_{eff} = 2^{-(1-2b)}\, a^2\, (\rho t)_{eff}^{-2b}\, (m/A_{eff})^{(1+2b)}$$

where, a is the multiplier and b is the exponent of P in the fitting equation, $(\rho t)_{eff}$ is the effective areal density of the target skin and covering, and m/Aeff is the projectile's mass over its presented area. It is clear for any given target skin and covering E50/Aeff cannot be a constant when m/Aeff varies since b = -0.38708 and, therefore, (1+2b) is not zero. A constant ratio requires b = -1/2. A fit using this value was tried and yielded a poorer fit, as expected.

Conclusions-1

- It is necessary to include target skin and clothing areal density in the correlation parameter to allow the results from different layers and types of clothing to be collapsed into the same curve for predicting V_{50}.
- An excellent correlation has been found for V_{50} (ballistic limit) using a physically meaningful non-dimensional combination of projectile and target skin and covering properties (named here the perforation parameter).
- This correlation has been demonstrated for a wide range of projectile shapes, dimensions, and masses for bare skin and skin covered with multiple layers of differing clothing.

Conclusions-2

A power law very well fits this general new correlation.

$$V_{50} = 309.13\,P^{-0.38708}$$

$r^2 = 0.9740$

Conclusions-3

- This fit has direct application with improved accuracy and generality for determining the safe limit for less-than-lethal projectiles for bare skin and skin covered with various clothing.
- It is also essential to determining levels of incapacitation. All incapacitation models must compute or be provided with the velocity variation with distance through the specified target.
- The velocity losses from clothing, etc. are required to provide the correct initial velocity condition.
- Now that the form of a good fit to the data is known, it also demonstrates that the quantity – striking energy divided by projectile presented area – cannot be made a constant without producing a poorer fit to the data, even when accounting for skin and clothing properties.

Recommendations-1

- It is recommended the perforation performance of unstable cubes and other unstable “sharp-edged” projectiles be investigated further to see if the “cutting” hypothesis proposed here for the skin only case can be confirmed or some other explanation found. Special attention should be given to the evidence that clothing appears to eliminate this effect.

Recommendations-2

- The sources used in this analysis supported the skin or covered skin target differently. Some did not specify how, others stretched the target in a frame, and still others backed up the target with a gelatin block. A test series with the same backing for all targets should be conducted.
- Since how V_{50} is best used to estimate the remaining velocity of a projectile that has excess striking velocity is still being debated, tests should be conducted without a support behind the target and the exit velocity measured. Parenthetically, the most common suggestion for estimating remaining velocity is based on energy: $V_{out} = \sqrt{(V_{in}^2 - V_{50}^2)}$.

References

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Table 1-1. Ballistic Limit Velocity vs Perforation Parameter by Source, Type, and Target Skin and Covering

P, n-d	V_{50}, m/s								
	Journee	Mattoo	DiMaio		Haag	MacPherson			
	sphere	sphere	round nose bullet	BB pellet	various shaped nose bullets	sphere	cylinder	round nose bullet	truncated cone nose bullet
	skin	skin	skin	skin	skin	skin	skin	skin	skin
51.82	67.1								
45.33		70.1							
64.82			65.0						
24.82				81.0					
19.21				106.0					
93.18					57.3				
13.55						101.0			
27.48						82.0			
87.27							56.4		
79.30								64.0	
74.94									65.5

Table 1-2. Ballistic Limit Velocity vs Perforation Parameter by Source, Type, and Target Skin and Covering

P, n-d	V_{50}, m/s								
	Lewis, Coon, Clare, and Sturdivan								
	sphere 0.85 gr	sphere 0.85 gr	sphere 0.85 gr	cylinder 0.5 in length	cylinder 0.5 in length	cylinder 0.5 in length	cylinder 1.0 in length	cylinder 1.0 in length	cylinder 1.0 in length
	skin	skin + 2-layers	skin + 6-layers	skin	skin + 2-layers	skin + 6-layers	skin	skin + 2-layers	skin + 6-layers
7.15	134.6								
4.82		188.0							
1.82			259.1						
4.88				146.4					
3.29					195.3				
1.24						286.5			
10.12							107.2		
6.86								137.5	
2.57									220.5

Table 1-3. Ballistic Limit Velocity vs Perforation Parameter by Source, Type, and Target Skin and Covering

P, n-d	V_{50}, m/s								
	Lewis, Coon, Clare, and Sturdivan								
	cylinder 1.5 in length	cylinder 1.5 in length	cylinder 1.5 in length	cube steel 4 gr	cube steel 4 gr	cube steel 4 gr	cube steel 16 gr	cube steel 16gr	cube steel 16 gr
	skin	skin + 2-layers	skin + 6-layers	skin	skin + 2-layers	skin + 6-layers	skin	skin + 2-layers	skin + 6-layers
15.09	87.2								
10.16		127.8							
3.83			187.7						
30.20				74.8					
6.72					148.1				
2.54						180.0			
48.16							62.7		
10.65								104.7	
6.74									150.5

Table 1-4. Ballistic Limit Velocity vs Perforation Parameter by Source, Type, and Target Skin and Covering

P, n-d	V_{50}, m/s							
	Lewis, Coon, Clare, and Sturdivan						Kokinakis & Sperrazza, 1965	
	cube tungsten 16 gr	cube tungsten 16 gr	cube tungsten 16 gr	cube steel 64 gr	cube steel 64 gr	cube steel 64 gr	cube steel 2.1 gr	cube steel 2.1gr
	skin	skin + 2-layers	skin + 6-layers	skin	skin + 2-layers	skin + 6-layers	skin	skin + 6-layers
80.50	67.0							
17.88		101.3						
4.02			160.5					
77.14				62.9				
17.12					97.5			
6.45						128.4		
27.74							94.5	
2.09								259.0

Table 1-5. Ballistic Limit Velocity vs Perforation Parameter by Source, Type, and Target Skin and Covering

P, n-d	V_{50}, m/s					
	Kokinakis and Sperrazza, 1965				Kokinakis & Sperrazza, 1967	
	cube steel 16 gr	cube steel 16 gr	cube steel 225 gr	cube steel 225 gr	sphere steel 0.85 gr	sphere steel 0.85 gr
	skin	skin + 6-layers	skin	skin + 6-layers	skin	skin + 6-layers
54.38	62.8					
4.10		184.0				
131.11			47.2			
9.89				106.0		
7.61					129.9	
1.92						275.0