Multicomponent Structures for Ballistic Protection

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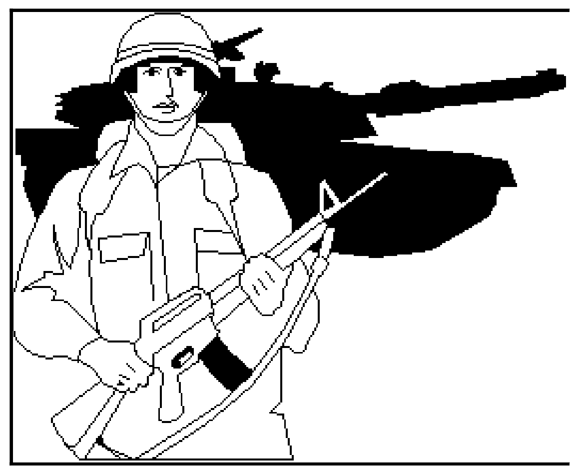
Body armor has 2 fields of application

- Police and government officials
  - Rated projectile threats (handguns, long guns)
  - Light, concealable, flexible

- Military applications
  - Rated threats from explosion fragments
  - Directed projectile threats



Body armor developments

- **Used since ancient times**
  - **wood, copper, bronze, iron, steel**
- **Advent of guns eliminated armor until recently**
- **WWII aircraft reintroduced**
- **Vietnam - ceramic, textile**

Early Military Standards

- US Army
  - range = 5 feet
  - witness plate 6 “ behind armor target
  - penetration of armor + plate = fail
  - no plate penetration = pass
  - determine max velocity at which pass occurs
- US Navy
  - range = 5 feet
  - no witness plate
  - target penetration = fail
  - no pentration by a projectile= pass
  - fragment penetration without projectile penetration = pass

Current vest types

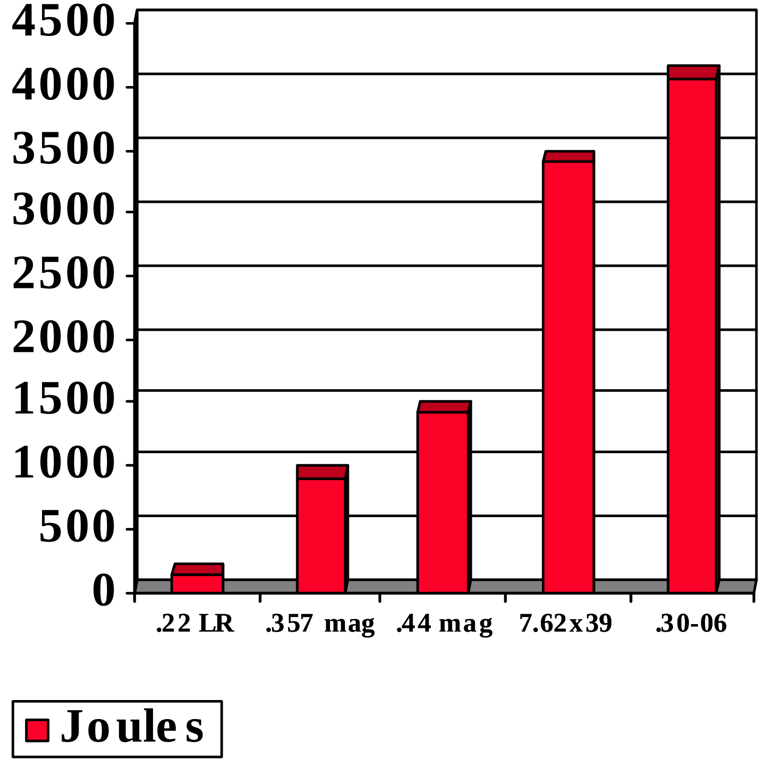
- Mostly textile materials
- Many imperfections exist
- Vests are uncomfortable
  - weight
  - flexibility
  - moisture transport
- Engineered for specific threats

NIJ Standard ratings

Threat level	**Caliber**	**Projectile description**	**Mass (Gm)**	**Velocity (m/sec)**
I	.22 Long rifle .38 Special	Lead ball	2.6 10.2	320 259
II-A	9 mm .357 Magnum	FMJ Jacket soft pt.	8.0 10.2	332 381
II	9 mm .357 Magnum	FMJ Jacket soft pt.	8.0 10.2	358 425
III-A	9 mm .44 Magnum	FMJ Semi-wadcut	8.0 15.55	426 426
III	7.62x39 mm .308 Winchester	FMJ	9.7	838
IV	.30-06	Armor piercing	10.8	868

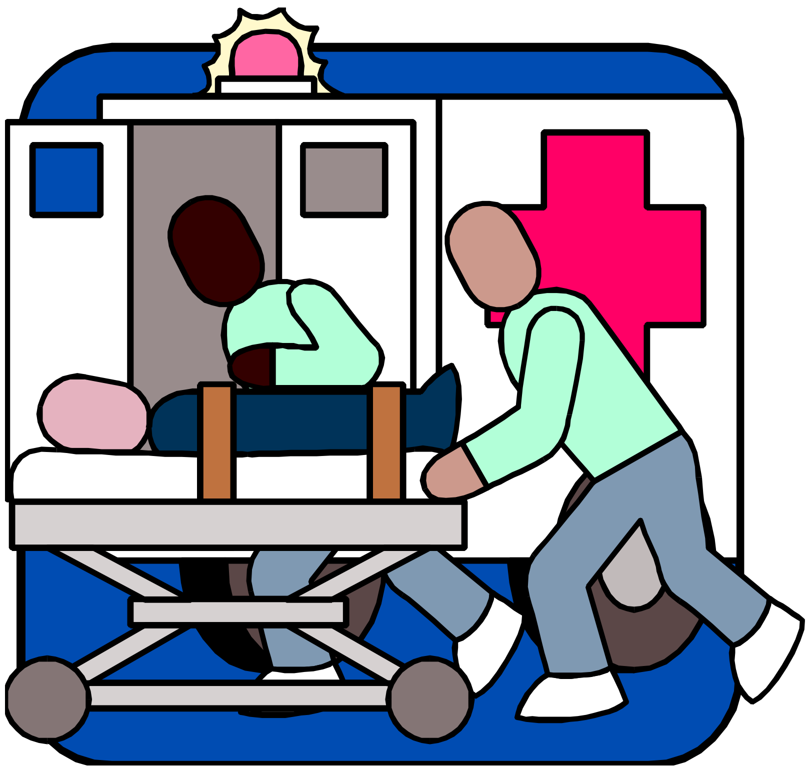
What the ratings mean

- .22 LR = 133 Joules
- .357 Mag = 903 Joules
- .44 Mag = 1416 Joules
- 7.62 mm = 3406 Joules
- .30-06 = 4068 Joules



Is meeting the NIJ standard enough?

- Only 8 out of some 600 legal ammunitions are represented (excludes > 100 military types and frangibles*)
- Ballistic resistant materials are tested on a flat surface. Human bodies are curved
- Up to 44 mm (1.73") of penetration of the fabric into the body plane is permitted *after* ballistic event termination!



*A frangible completely disintegrates inside its target. While easier to terminate with a ballistic vest than metallic projectiles, the effect of a frangible in the absence of ballistic protection is horrible. Frangibles also deliver 100% of their residual energy as trauma effects after disintegration on a ballistic protection surface. They are becoming standard issue ammunition to SWAT teams, Navy SEAL units etc. Some have doubtless found their way into civilian possession.

Early medical evaluations of trauma effects[2]

The Goldfarb et al live animal tests (1976)

In experiments at US Army Aberdeen Proving Grounds, 40 to 50 kg goats were used to model 70 kg humans

Goats were given protective ballistic fabric coverings and shot with .38 caliber (Level I) ammunition.*

Experimental Assumptions

1. Damage level of organs will be similar between goats and humans if forces and impact areas are the same
2. Goats experience the same aftereffects as humans
3. Because of thicker chest walls, humans experience less damage than goats.**

2. Bridgman,M. and Crotty,E., senior research project report, Auburn University, May 1999. Includes the following 10 slides as well.

*The experiments were terminated in 1977 and findings were generally discredited because of cruelty to animals considerations.

** Complete verification of the assumption is not documented.

Some fallacies in the assumptions

1. Humans react differently after ballistic injuries.

2. Orientation of human organs are different

Parts of the assumptions were tested

Water penetration studies were performed on test animals and autopsied shooting victims.

Vital areas examined were

1. Lungs
2. Liver
3. Kidneys
4. Spleen

Results of tests

1. The lung and spleen yielded essentially the same values for both the goat and the human.

2. The goats’ kidneys and livers were penetrated about twice as easily as the human’s

3. It was *assumed* that humans will incur less kidney and liver damage than goats

Shortcoming of test: **All material testing was performed at threat Level 1 with a .38 caliber revolver.**

Heart tissue damage

Goat was in a sitting position in a rack wearing a Kevlar protective garment.

The goat was monitored by EKG during the test.

Upon ballistic impact on the test animal, EKG registered possible heart damage.

24 hours later, the goat was sacrificed, and upon autopsy, a 1.5 cm hole in the outer lining of the heart was found.

Spinal cord injuries

4 impacts into the Kevlar armor over the goat’s spine created holes in the skin and subcutaneous tissue.

It also fractured the spine

Some goats exhibited weak movement during recovery from anesthesia.

Neurological consultants believed that an impact over the spine of a human might cause immediate weakness or even contusion of the spinal cord

Pulmonary cavity effects

Animal was stabilized, holding left front leg in extension

Blood gases were monitored before and after impact

All goats were sacrificed 24 hours after impact and autopsied

The largest contusion found in the lung was around 45cc

This amount of damage related to humans would equate to less than 100cc

This impact may cause fractured ribs in humans as it did with 3 of the tested goats

Abdominal effects

7 central impacts over the liver caused contusions averaging 50cc

This injury in humans could cause bleeding in the stomach cavity and abdominal pain

If blood is found in the abdomen, surgery would be recommended

The liver wound incurred with a ballistic jacket would be extremely minor, with a surgical mortality of 5% compared to a rate of up to 60% without a jacket

Spleen damage

The impact over the spleen was very difficult to achieve due to its small size

Three attempts were made, one shot showed no damage, one missed completely, and the other showed a 2 cm contusion at the lower border of the spleen

The spleen is easily damaged. A direct hit over the spleen in a human would probably cause a contusion or blood clot under the outer layer of the spleen, requiring surgery.

Other Threat Level I tests

Other tests were performed with .22 caliber ammunition, to compare results with the previous tests with .38 caliber.

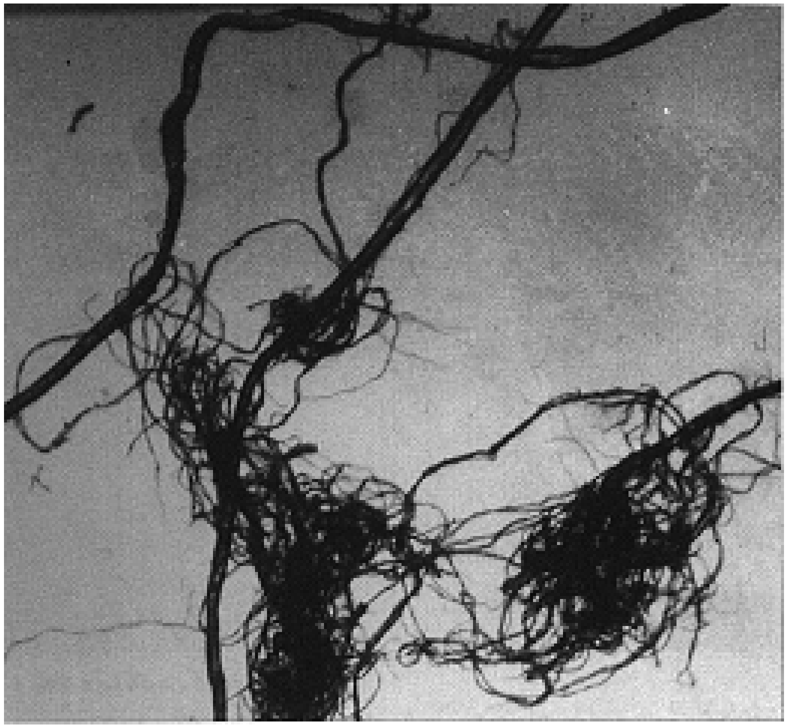
The tests with .22 caliber showed ballistic resistant vests to be very successful in lowering the effects of blunt trauma

Energy absorption by polyamides

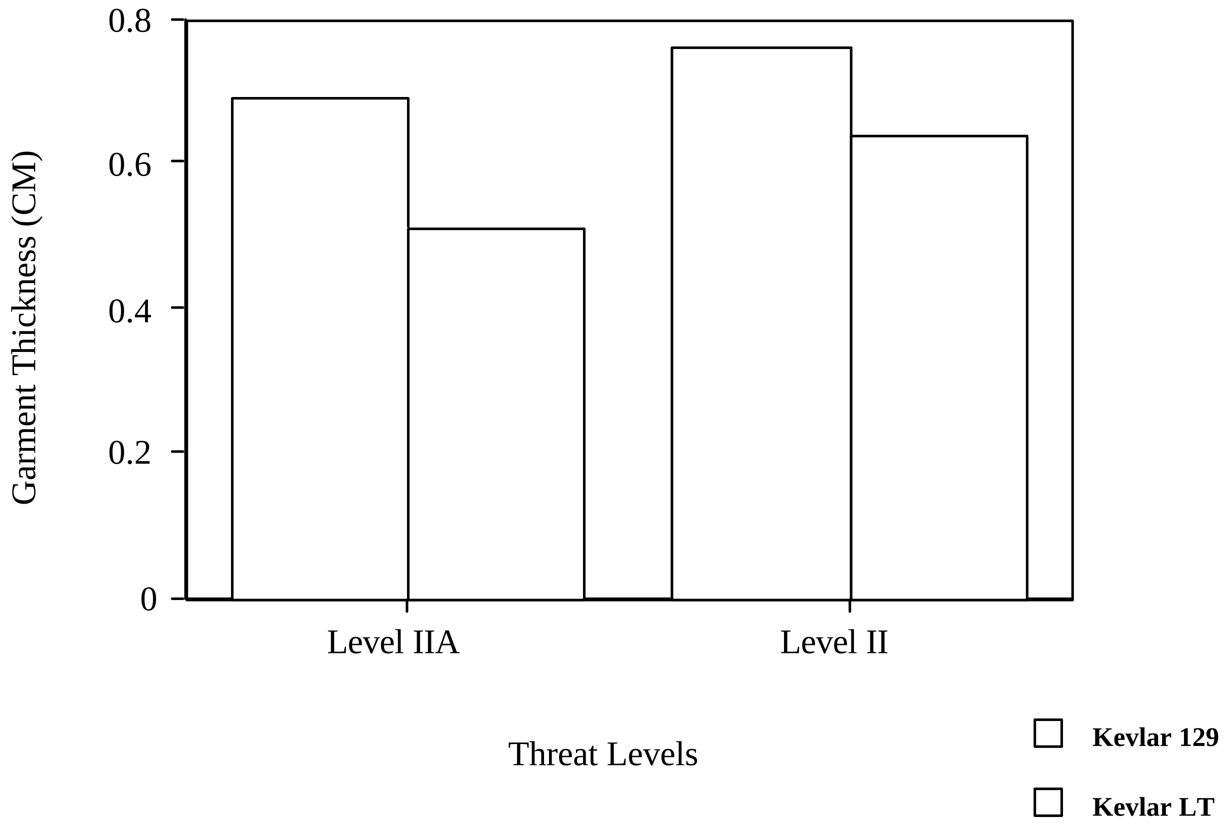
- Tensile strength = 5.9 - 9.8 gpd
- Elongation to break = 15 - 28 %
- Young’s modulus = 21 - 58 gpd
- Specific gravity = 1.14

Energy absorption in aramids

- Tensile strength
  - 23-28 gpd
- Elongation to break
  - 2.5 - 3.5 %
- Young's modulus
  - 500 - 900 gpd
- Specific gravity = 1.44
- Fibrillates on impact



New generation aramids



Energy absorption in HPPE

- Tensile strength
  - 30 - 40 gpd
- Elongation to break
  - 2.5 - 3.6 %
- Young's modulus
  - 1400 - 2400 gpd
- Specific gravity = 0.97
- Usually uniaxially wrapped and resin encased

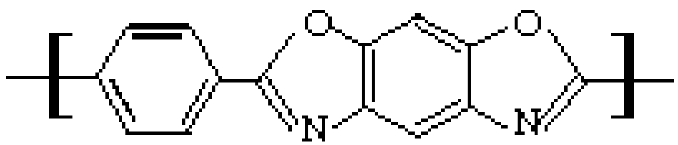
New Generations of HPPE Fibers

Characteristic	SK65	SK66	SK77
Specific gravity	0.97	0.97	0.97
Tenacity cN/dtex	31	33	40
Modulus cN/dtex	970	1010	1400
Break Elongation	3.6%	3.7%	3.7%
Work to Break Index	90	100	135
Sonic Velocity m/sec	9800	10000	12000

Characteristics of DSM Dyneema® HPPE Fibers

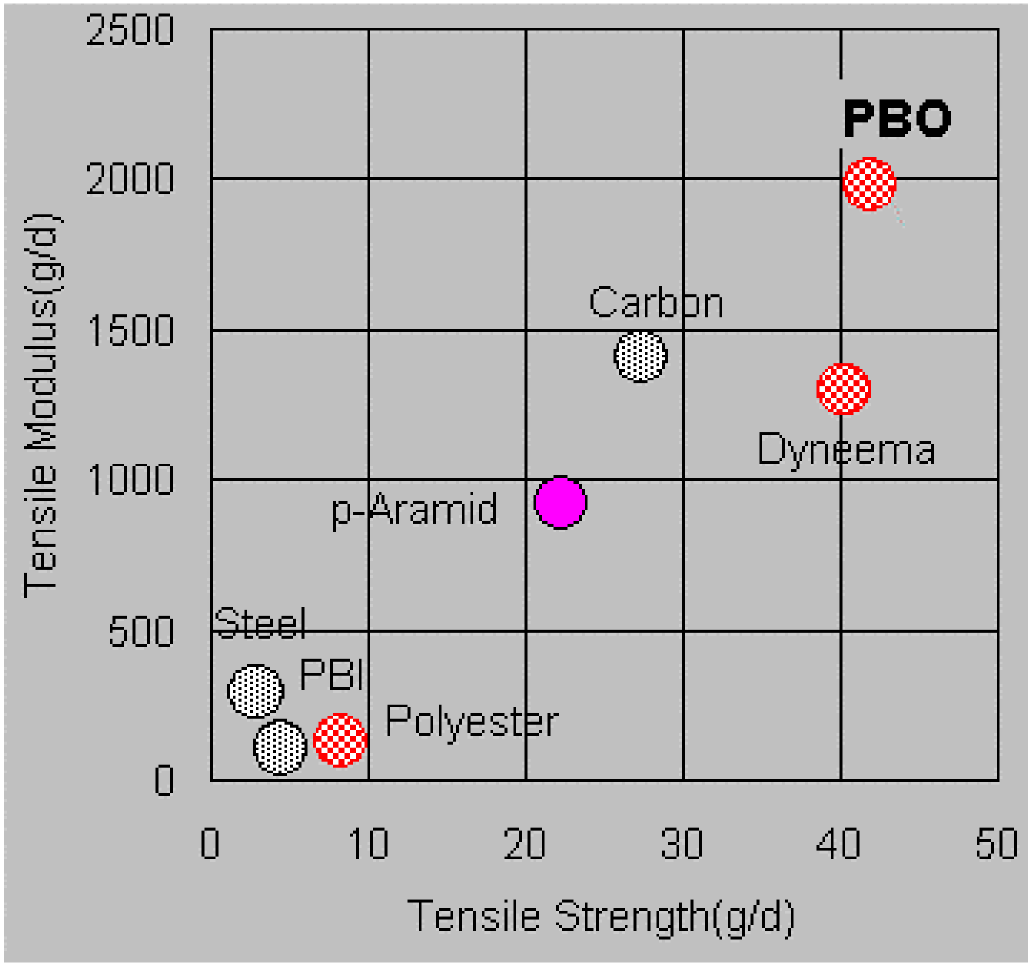
PBO Fibers

- Newest fiber types on the market
- Currently marketed by Toyobo (Japan)
- Tradename “Zylon”



Poly(p-phenylene-2,6-benzobisoxazole), or PBO structure
[http://www.toyobo.co.jp/e/seihin/kc/pbo]

PBO Characteristics [http://www.toyobo.co.jp/e/seihin/kc/pbo]



Energy absorption mechanisms:
Woven fabric

- Sonic velocity of strain wave
  - $v = \sqrt{F/\mu}$
  - $v = \sqrt{E/r}$
    - F = impact force; μ= density
    - E = modulus; ρ = specific gravity
- Energy = $0.5\, m_p\{V_s^2 - V_r^2\}$
  - $= E_{strain} - E_{absorbed}$ (Cunniff 1996)
- $E_{absorbed} = 0.5 \int E\varepsilon^2\, dt$ (Chocron-Benloulo et al 1997)
    - But $F dt = E\varepsilon\{nsl\}\cos \phi\, d\phi$; n=yarns, s=caliber, l=layers

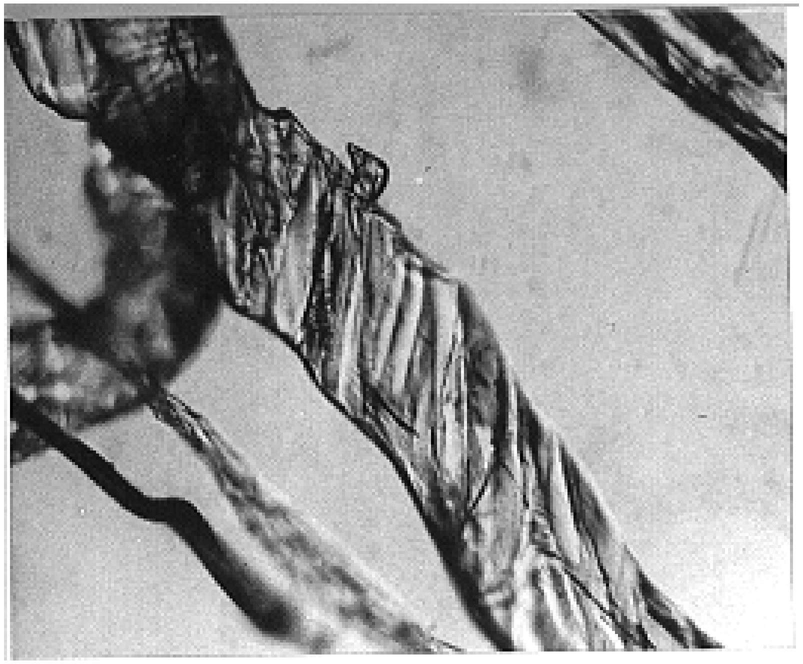
Fragment defense

- Strong weight advantages for nonwoven fabrics over woven fabrics (8+lbs)
- Current vests are unitary fiber types. Initial commercial introduction of nonwoven -

  (DSM “Fraglite”)
- Initial suggestion for blended fiber nonwoven use - (1992, Thomas)

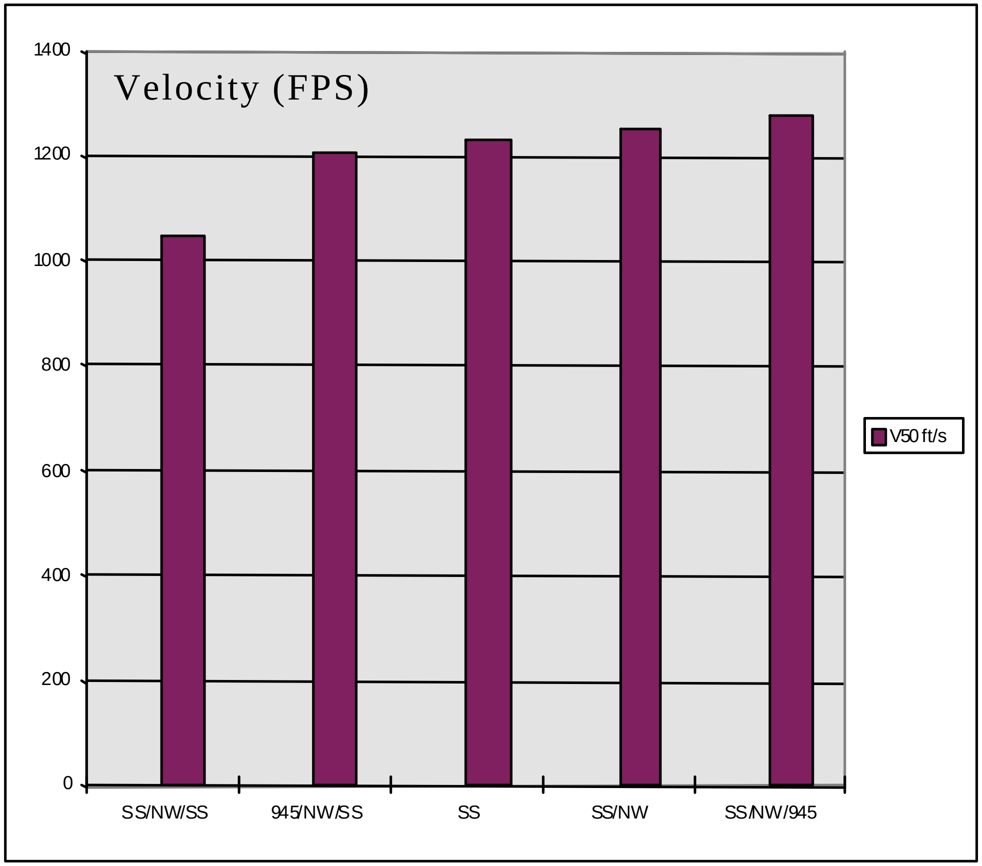
Energy absorption in HPPE, aramid blends

- Radiated strain energy
  - transferrred by aramids and HPPE outside impact
- Fibrillation of aramids
- Phase change induced in HPPE



Nonwoven enhanced armor for handgun threats

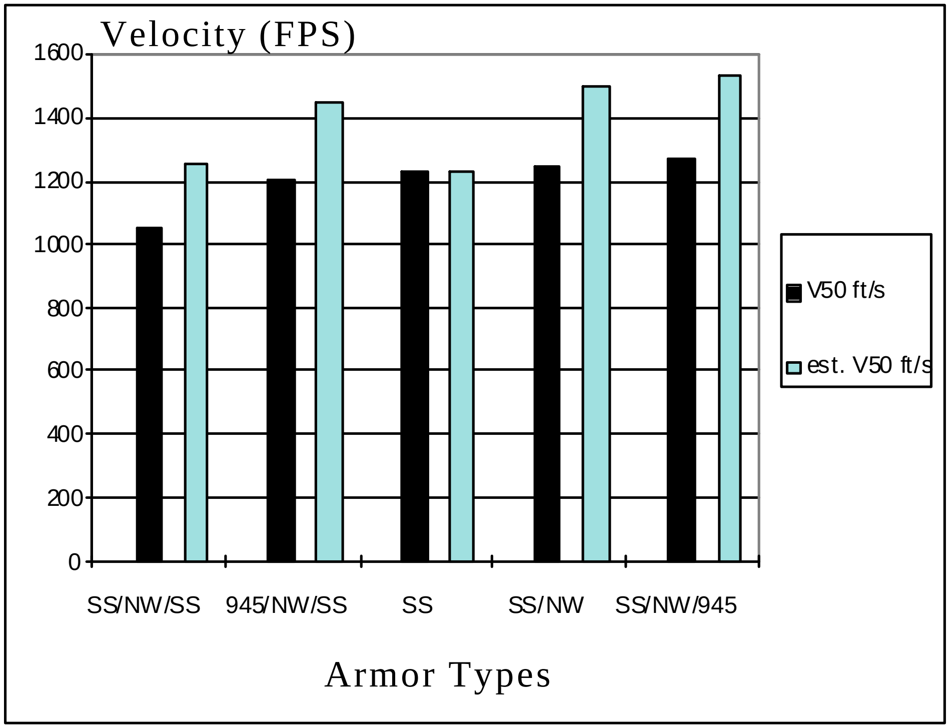
- Lighter weights were attempted
  - Reductions from 12 oz/sqft to 10.5 oz/sqft
- NW + Spectra shield proved unsatisfactory
- NW + woven proved superior
- **Shield+NW+woven was best**



Armor Types

Anticipated improvements with current generation fibers*

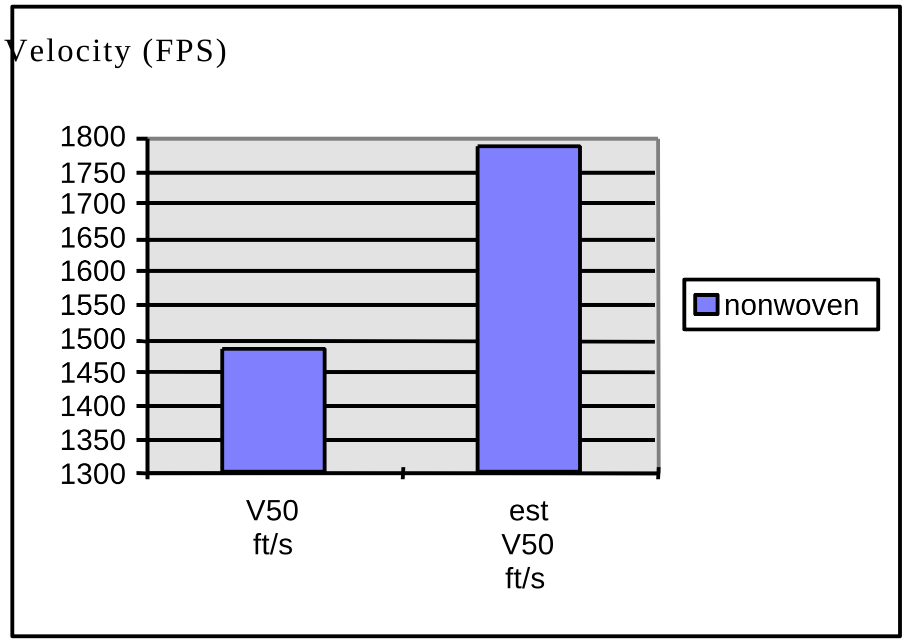
- Newer fiber types have 17 - 20 % greater breaking strength
- Tensile moduli are correspondingly higher
  - Manufacturers say no elongation loss or increase occurs



* Includes Spectra 2000 and Kevlar 229 types

Projected fragment armor improvements

- The current “best” protection velocity is 1780 fps (50/50 aramid/HPPE blend)
  - .22 cal fragment simulating projectile
- Original Kevlar 29 = 1275 fps
- Original (1991) blend gave 1425 fps (Spectra 1000, 2nd quality and Kevlar 29)



Armor Types

Energy absorption mechanisms:

Solid plates (1)

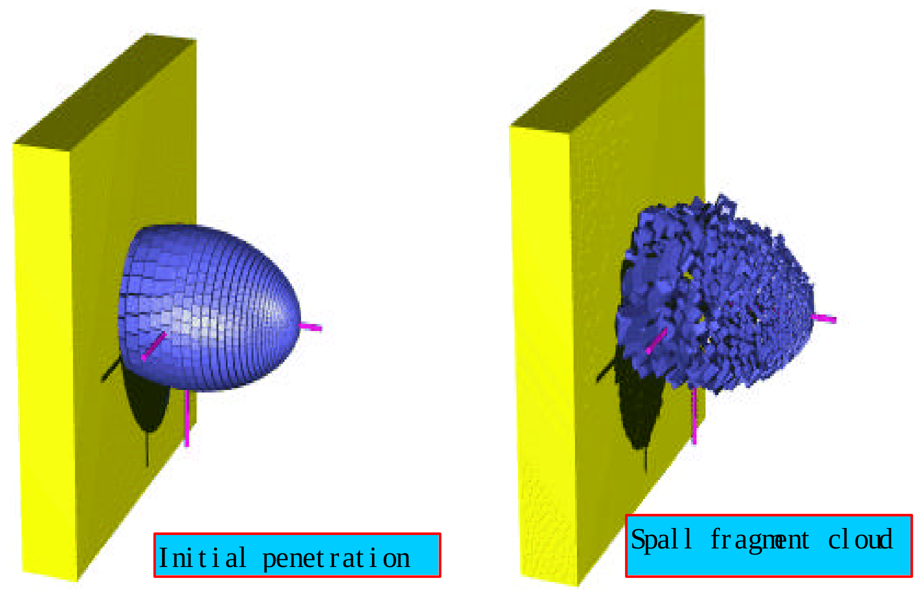
- $E_i = 0.5\ mV_p^2$
  - (initial condition)
- $E_a = 0.5\ \{mp \bullet ma/(mp+ma)\}\ V_a^2$
  - (impact condition)
- Retardation effects (drag)
  - $R = A\ \rho\ V^2$ (Bachmann and Goldsmith 1978)
  - $R = C_d\ A\ \rho\ V^2$ (Cunniff 1996;aerodynamics)
    - A= ø area; ρ= plate density; Cd=drag coeff.; V=velocity

Energy absorption mechanisms:
Solid plates (2)

- R = a negative force vector
- $R = m_{proj} (d^2s/dt^2)$
  - $(d^2s/dt^2) = (C_d\ A\ \rho\ V^2)/\ m_{proj}$
  - $= V\ dv/ds$
- $dv/ds = (C_d\ A\ \rho\ V)/\ m_{proj}$
- The difficulty lies in the determination of
  - decrease in projectile mass
  - decrease in drag coefficient

Ceramic or metal plate armor spall

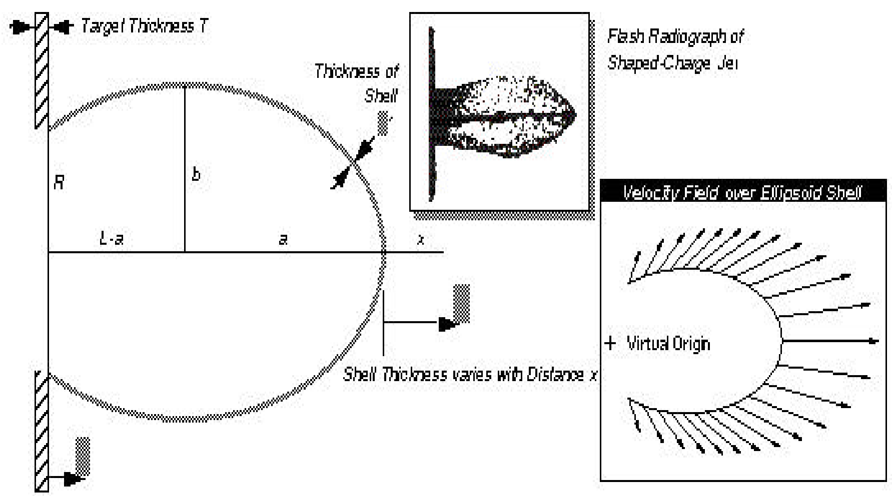
- As the projectile penetrates the armor
  - fragmentation (shatter) occurs
  - momentum is transferred to the particles
  - a spall cloud forms
- $V_{spall} = \sqrt{2 E_a (m_p + m_a) r C_d A / m_p \bullet m_a}$



US Army, ARL Website

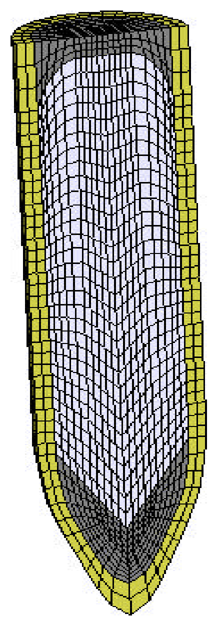
US Army research (ARL Website)

- Most work has been statistical
- New research is developing a stochastic model
- Experimental work uses flash radiographic image capture
- Still only applied to vehicle armor



Armor piercing projectiles

- Most serious threat to military personnel with body armor
- Some are in general public circulation
- Designed as multicomponent (eg)
  - copper sheath
  - lead tip (spall generator)
  - carbon steel interior



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Inducing chaos

- A trajectory is a highly ordered kinetic path
- Targets are destroyed by release of the kinetic energy where the projectile is aimed
- Destabilization can result in degradation of lethality, kinetic energy transfer

Application of a chaos approach

- Lyupanov function describes behavior of motion in chaotic states
  - uses a “strange attractor”
  - sensitive to initial conditions
  - allows exponential divergence of neighboring trajectories
- Applying this function could generate an optimized condition for unstable trajectories

The Lyupanov Function

- Estimated by $d(t) = d_0\ (t)\ e^{\lambda t}$
- d_0 defines the x, y plane path separation at initial condition
  - a function of projectile stability at impact
- λ = a variable such that
  - negative values indicate chaotic conditions
  - non-negativity indicates stability (z or target direction)

Determining λ

- A spectrum of Lyupanov exponents exists such that $l = \lim_{t \to \infty} \frac{1}{t} \ln \frac{d(t)}{d(o)}$
- o is a trajectory function prior to chaos
- The first estimate of the exponent which is usually made is

$$l = \left[1 / t_n - t_0 \right] \sum_{k=1}^{N} \ln \frac{d(t_k)}{d(t_{k-1})}$$

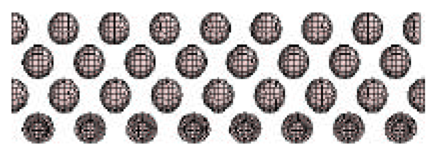
- k = range of dimensions

Determining geometry of the “strange attractor”

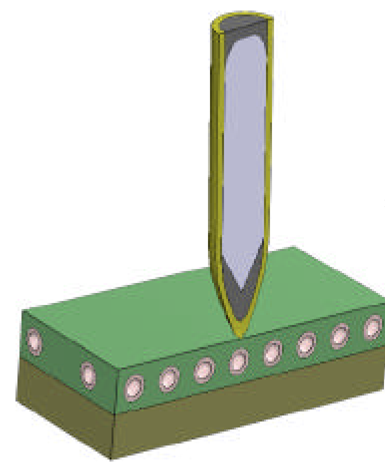
- Discrete elements of space are assumed to be a “hypercube” of dimension “e” on each side
- If number of hypercubes = N(e)
  - N(e) varies as e^{-d} where
  - D=dimensions present
- In our case we want dz/dt -> 0
  - desired dimensionality = 2

A flexible hard armor media

- Generation of multiple simultaneous paths
- Projectile spreads, fragments
- Spall cloud redirected by internal geometrics
- Fragment defense by nonwovens



Deflecting geometrical surfaces



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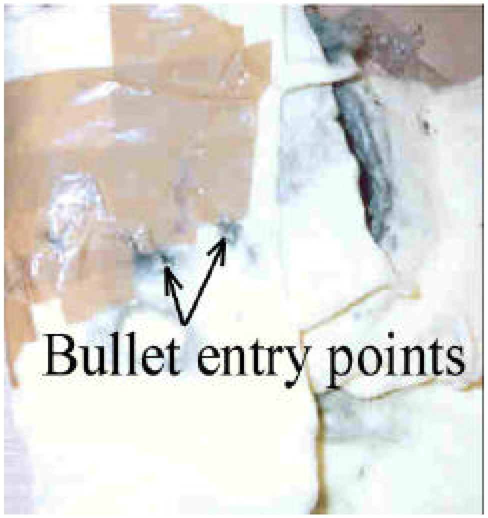
Embedded hard elements in flexible media

* Jeff Simon, SRI International; Mel Miller, The Protective Group

Test Results - Prototype Level 4



Prototype armor insert showing results of 2 hits
by .30-06 caliber APM2; range = 6 yards; hit spacing < 1”

Test Results (Level 3 API) **AK-47**

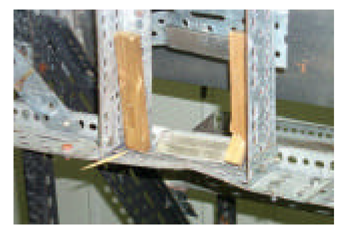
- Standard = 14” x 14”
- Hit survival = 6 (lead core)
- 6” x 6” sample used
- 6 hits stopped
- 2 hits in ***one*** bullet hole
- 3 hits in ***another*** bullet hole

Test Results (Level 4) **.30-06 APM2**

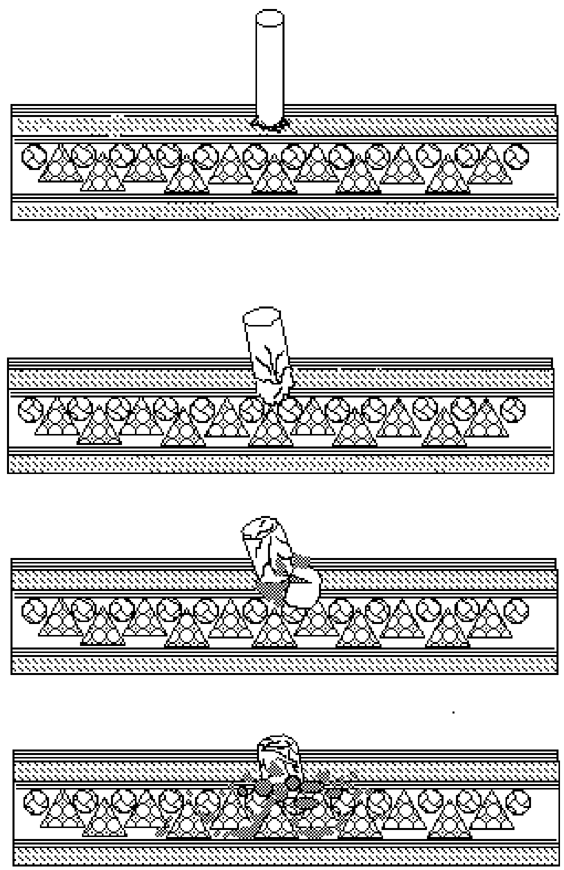
- Standard = 14” x 14”
- One hit survival
- 6” x 6” sample used
- 6 hits stopped
- 5 hits in ***one*** bullet hole

Test Results **12.7 mm Russian API**

- Standard (undefined)
- Survival (impossible)
- 6” x 6” sample used
- Direct hit stopped
- 15 meters range
- We broke the Army’s test mounting stand
- ***(Sorry!!!)***



Projectile Impact Sequence



In the initial stages of the impact, the projectile enters the vest in the normal manner, with standard ballistic resistant fabrics or thin, high strength ceramic plates distorting the leading end and increasing the projectile drag as it enters.

Upon entry into the geometrics zone, the projectile is turned by the deflecting surfaces.

As it continues along the path, the initially turned leading end is deflected into other paths while the trailing end has not yet experienced the torquing action of the shock waves in the projectile body.

The front portion begins to disintegrate, clearing the way for the rear section to be deflected along similar reverse torqued paths until the projectile is finally totally destroyed and comes to rest in the geometric layer.

In initial tests with this media, both 7.62x39 mm Russian and .30-06 US rifle ammunition have been destroyed at 15 meters distance and less without the use of ceramic front plate facings on the armor package. Both ammunition types were destroyed in multi hit test conditions. Research on this concept to create a flexible, comfortable, rifle resistant body armor is continuing.

The next prospects for “protects”

Oooh! At’s a byoooty
Let’s pick ‘er up ‘n kiss ‘er!