Soft-Recovery of Explosively Formed Penetrators

December 2005

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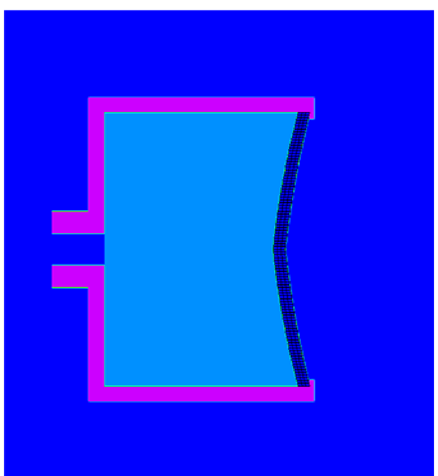
Outline

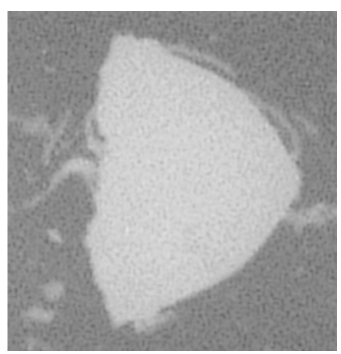
- Introduction
- Model Description
- Experimental Setup
- Results
- Discussion/Conclusions

Why Soft-Recovery?

- Improved design of EFPs (Explosively Formed Projectiles) using state-of-the-art constitutive descriptions require *ab initio* information of the high-rate, multi-axis stress deformation path
  - Explosive shock effects
  - Predominate crystallographic orientation (i.e. texture) and its dynamic evolution
  - Classical flash radiography and high-speed photography only captures geometry information
- Collaboration with Dr. Paul Maudlin, Los Alamos National Lab., TCG-I

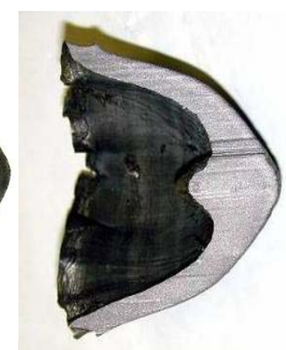


Example EFP Formation

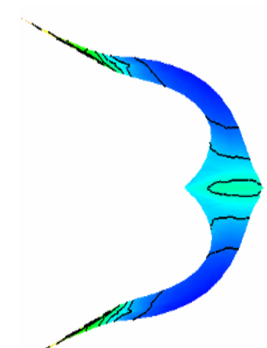


Flash Radiograph of an EFP in flight

Recovered EFP



Cross-section of recovered EFP



Code simulation, EPIC Anisotropic MTS

Developmental Engineering Tools
3D, Anisotropic Material Descriptions

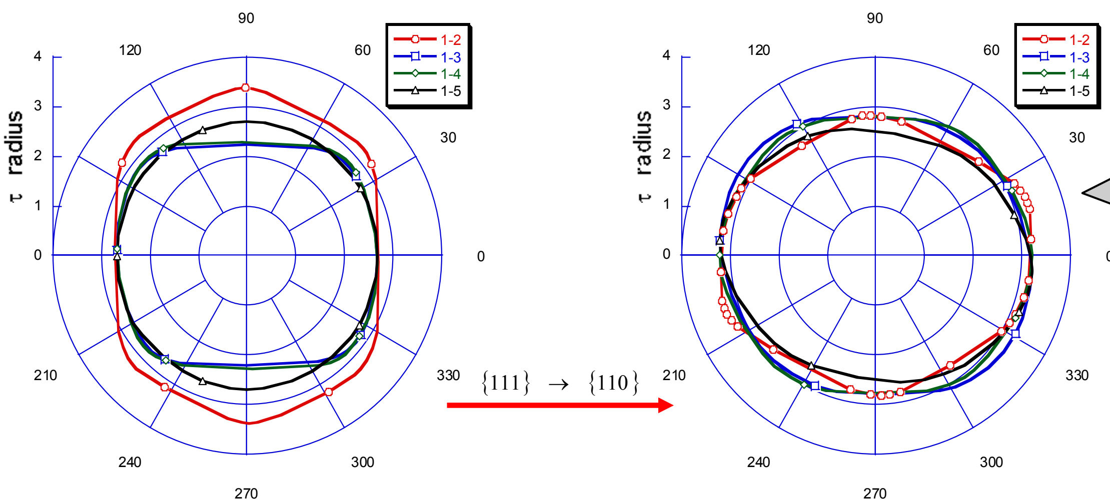
Material Processing
- **Conventional**
- **Unconventional**

Physical Characterization
Grain size
Chemistry
Crystallography

Mechanical Characterization
Low Rate & High Rate
Temperature
Uniaxial
Taylor Impact

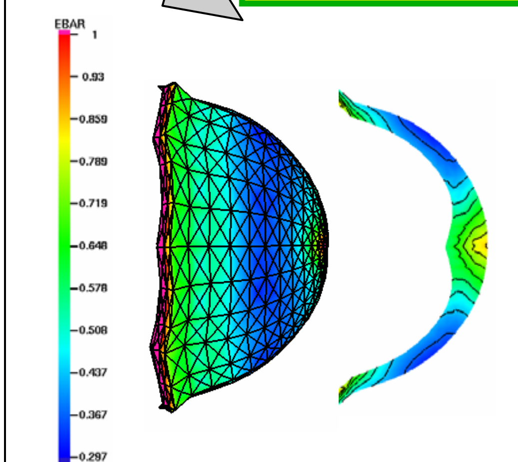
Explosive Metal Forming Experiments
Shock loading
High-rate
Tri-axial stress

Yield Surface Projections



Initial

Recovered Projectile



Calculations by Dr. Paul Maudlin, LANL, under TCG-I "Computational Mechanics and Material Models", EPIC-3D

The Approach Taken Here

- Apply a simplistic, but adequate equation-of-motion for the projectile through the media
- Arrange mathematical relationships that relate to the physical experiment and instrumentation capability
- Conduct experiments from which the data is used to calibrate the soft-recovery media
- Compare results of the general model with specific experiments
- Use the model and calibrated media constants for tailored design and construct of soft-recovery apparatus

Mathematical Model

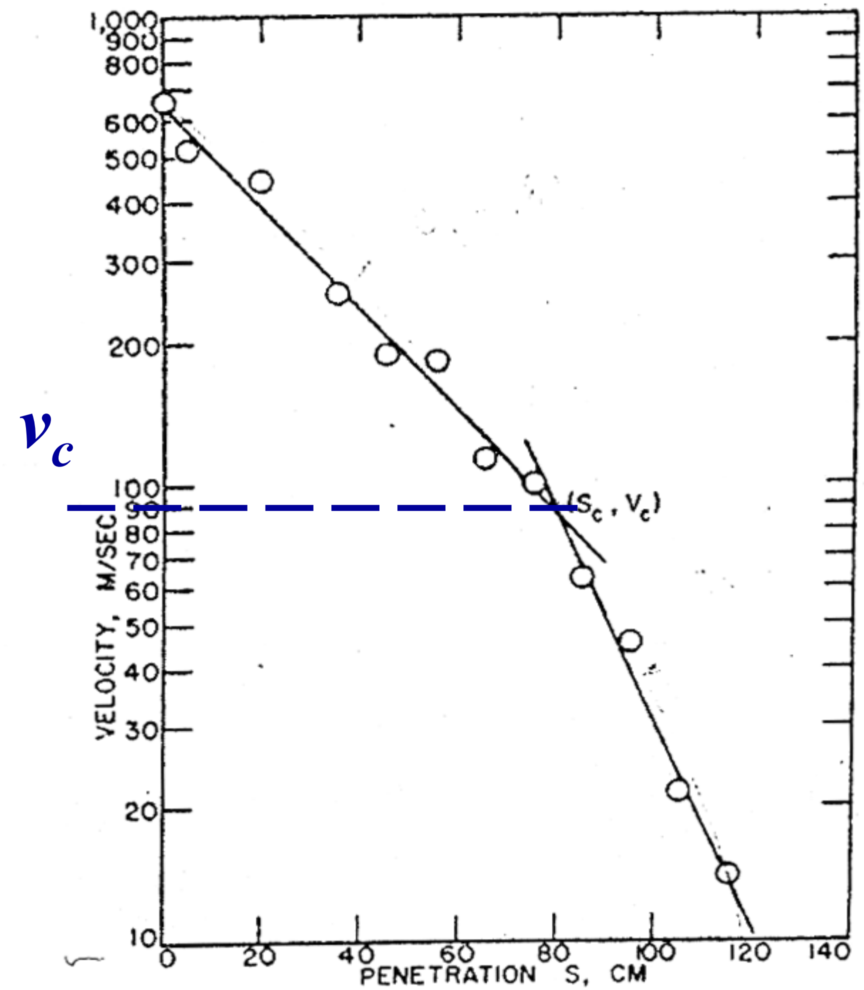
Region 1: Drag Force Model

$$m\dot{v} = -\frac{1}{2} C_D A \rho v^2 , \quad v > v_c$$

Region 2: Poncelet Form

$$m\dot{v} = -A(\beta v^2 + R) \quad , \quad v < v_c$$

- ***m is mass of the projectile***
- ***v is current projectile velocity,***
- ***A is projectile cross-section area***
- ***ρ is the density of the target medium***
- ***C_D is a dimensionless drag coefficient***
- ***β is a coefficient (dim. of density)***
- ***R is a target strength factor (dim. of stress)***



Allen, et al. J. Applied Physics, 1957

Mathematical Model (cont'd)

Assumptions made on the solution:

- **Model will be applied for soft-catch sections where $v > v_c$**
- **Drag coefficient is not dependent on velocity**

Direct integration of the Drag-Force model gives:

$$\frac{1}{2}\frac{C_D A\rho}{m} z = \ell n\left(\frac{v_0}{v}\right)$$

and

$$\frac{1}{2}\frac{C_D A\rho}{m} t = \frac{1}{v} - \frac{1}{v_0}$$

where:

- z ***is the displacement into that section of the soft catch***
- t ***is the experimentally obtained time at the displacement*** z
- v_o ***is the entrance velocity to that section***
- v ***is the exit velocity from that section***

Mathematical Model (cont'd)

- By dividing the prior two equations, a single relationship is obtained, *dependent only on parameters* that can be directly obtained during an experiment.

$$\frac{z}{t}\left(\frac{v_0}{v}-1\right)=v_0\ell n\left(\frac{v_0}{v}\right)$$

where:

- ***z is the displacement into that section of the soft catch***
- ***t is the experimentally obtained time at the displacement z***
- ***v_o is the entrance velocity to that section***
- ***v is the exit velocity from that section***

Solution Steps

Step 1:

$$\frac{z}{t}\left(\frac{v_0}{v}-1\right)=v_0 \ell n\left(\frac{v_0}{v}\right)$$

Is applied to each catch section with experimental time-position data, using Newton's method for convergence on an iterative root solution to get the ratio v_o/v, where v_o is the exit velocity from the previous section and v is our unknown

Step 2:

$$\frac{1}{2}\frac{C_D A\rho}{m}z=\ell n\left(\frac{v_0}{v}\right)$$

The ratio v_o/v is then put back into this equation to obtain a C_D for each penetrator/soft-catch material combination

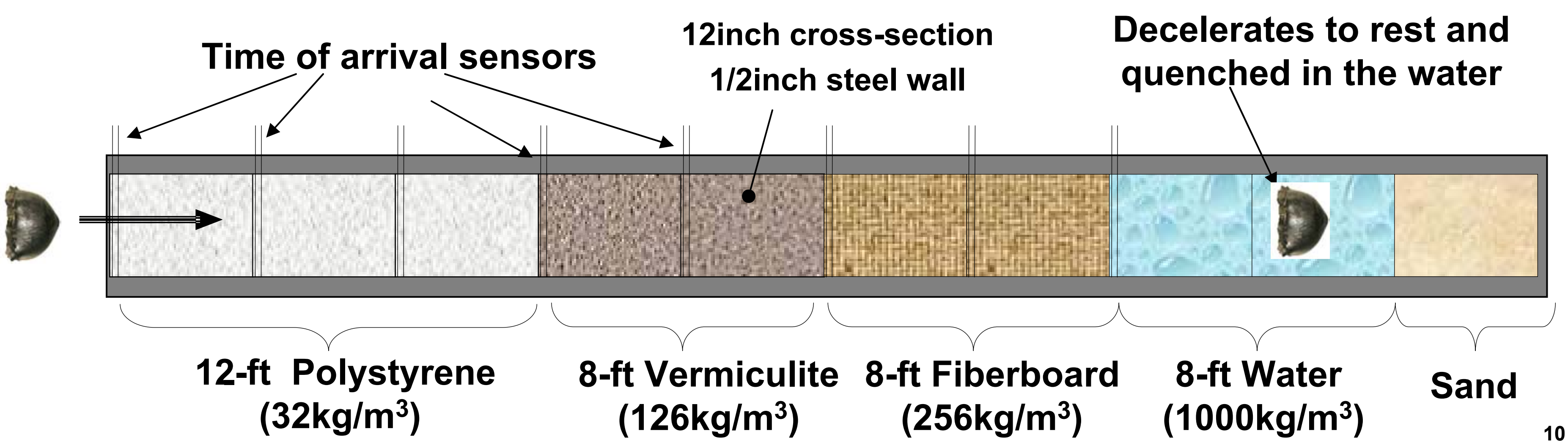
Step 3:

$$\frac{1}{2}\frac{C_D A\rho}{m}t=\frac{1}{v}-\frac{1}{v_0}$$

The C_D for sections of each material are averaged, and then used to obtain an estimated exit time, t, for comparison to the experimental values

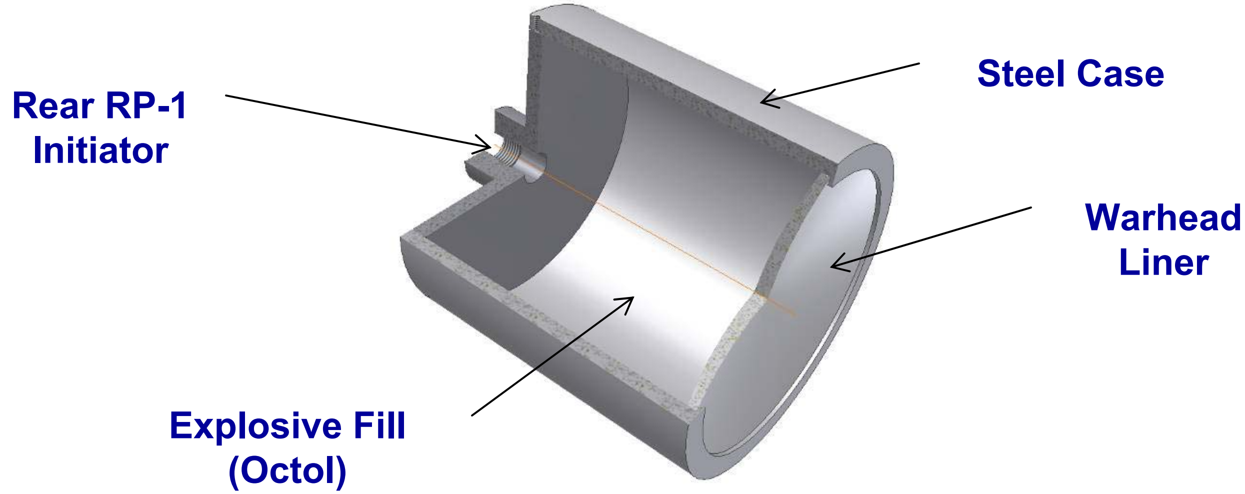
The Soft-Catch Process

- A gradient in the media density safely decelerates the projectile
- Instrumented shotline captures the time, position, and velocity data to feed the transcendental relationship
- The section of water not only provides a gradual increase in media density, but also serves to quench the projectile
- Dual, orthogonal radiographs were used in pre-impact, free-flight to establish external geometry and entrance velocity



Experimental Setup

1. **Three warhead liner types were shot**
   - 3 shots with "Tantalum Design 1"
   - 2 shots with "Tantalum Design 2"
   - 1 shot with "Cu EFP"
2. **Fine Grain Octol explosive (65%HMX, 35% TNT)**
3. **Design was for a simple 'fold-over' projectile**
   - Explosive shock conditions
   - Representative strain-rate and strain paths



Results from Applying the Model

TABLE I. DRAG COEFFICIENTS, C_D, FOR ALL EFP TYPES

	Polystyrene (ρ = 32.0 kg/m^3)	Vermiculite© (ρ = 126.4 kg/m^3)	Fiberboard (ρ = 256 kg/m^3)
Ta Design 1 (avg. of 3 shots)	0.777	1.534	0.395
Ta Design 2 (avg. of 2 shots)	0.84	0.88	0.86
Cu EFP (1 shot)	0.77	0.94	0.76

Comparison with the Theory

TABLE II. MODEL COMPARISON WITH "TA DESIGN 2, SHOT 1"

Tantalum Design 2, Shot 1: Impact Velocity = 1440 m/s					
Media	Experiment Velocity (m/s)	est. Exit Velocity (m/s)	Experiment Exit time (us)	est. Exit time (us)	Difference in time (%)
Polystyrene	1395	1381	437	432	-1.1%
	1382	1324	878	883	0.6%
	1273	1270	1357	1353	-0.3%
	1229	1218	1853	1844	-0.5%
	1212	1168	2356	2355	-0.1%
	1146	1120	2888	2888	0.0%
Vermiculite	1039	941	3475	3482	0.2%
	872	791	4174	4190	0.4%
	721	665	5019	5032	0.3%
	615	559	6010	6033	0.4%
	512	469	7201	7225	0.3%
	419	395	8656	8644	-0.1%
Cellotex	325	280	10529	10488	-0.4%
	235	198	13119	13092	-0.2%

- **Excellent results validate the assumption of simple drag-force relationship,** $v > v_c$
- **Note, penetration velocities are below that reported in Mayfield, et al for** v_c

Recovered Projectiles

Shot	Impact Velocity (m/s)	Recovered Mass (kg) (%initial)	Location Recovered	Cross-section	Picture
Ta Design 1 Shot 1	1423	0.726 (83.4%)	12-in into sand		
Ta Design 1 Shot 2	1397	0.720 (82%)	24-in into sand		
Ta Design 1 Shot 3	1389	Not Available	18-in into water	Not available	
Ta Design 2 Shot 1	1440	0.738 (92.6%)	41-in into fiberboard		
Ta Design 2 Shot 2	1422	0.761 (93.4%)	60-in into fiberboard		
Cu EFP	2030	0.409 (90.8%)	fiberboard section		

Discussions/Conclusions

Areas for further investigation:

1. Determine if the tacit assumption that $v > v_c$ used is valid
   - Find v_c in these media
2. Determine if C_D is independent of velocity as assumed (velocities were in a relatively narrow band)
   - Find C_D for a wider range of velocities in each media and compare
3. Use constants for predictive design of soft-catch build up and capture higher velocity, more tactical (collapsed) projectiles

Discussions/Conclusions

An alternative approach to calibrating projectile/media constants:

1. **Construct a soft catch with just one catch material at a time to obtain C_D for all velocities above and below v_c**
2. **Place velocity screens at closer intervals for better resolution such that v_c might be obtained**

Total penetration depth $z = S$ is found when $v = 0$, i.e. projectile comes to rest

The original equations of motion can be arranged to solve for total penetration into the single media and extract v_c

$$S = \frac{2m}{C_D A \rho} \cdot \ln\left(\frac{v_o}{v_c}\right) + \frac{m}{2\beta A} \cdot \ln\left(\frac{\beta v_c^{\ 2}}{R} + 1\right)$$

Summary

- A simple theory has been successfully applied for the design of a soft-catch apparatus
- Model, thus far, yields excellent agreement with experimental time data
- Further experiments needed to support underlying assumptions
- These interest items will be the subject of future experiments

Sources

[1] Draxler, V.C. 1993. “Softcatch Method for Explosively Formed Penetrators,” presented at the 44th Meeting of the Aeroballistic Range Association, Munich, Germany, September 13-17, 1993.

[2] Allen, W.A., E.B. Mayfield, and Morrison, Harvey L., 1957. “Dynamics of a Projectile Penetrating Sand,” *J. Applied Physics*, 28(3):370-376, 1957.

[3] Poncelet, J.V. 1829. *Cours de Mecanique Industrielle*, 1829.

[4] Allen, W.A., E.B. Mayfield, and Morrison, Harvey L., 1957. “Dynamics of a Projectile Penetrating Sand, Part II” *J. Applied Physics*, 28(11):1331-1335, 1957.