AFRL-MN-EG-TP-2005-7414

Soft-Recovery of Explosively Formed Penetrators

David Lambert and 1Lt. Matthew Pope
Air Force Research Laboratory
Munitions Directorate
AFRL/MNMW
Eglin AFB, FL 32542-6810

Stanley Jones and Jonathan Muse
University of Alabama
Aerospace Engineering and Mechanics Department
Tuscaloosa, AL 35487

July 2005

AIR FORCE RESEARCH LABORATORY, MUNITIONS DIRECTORATE

Air Force Materiel Command ■ **United States Air Force** ■ **Eglin Air Force Base**

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED** *(From - To)*
26-07-2005	Conference Paper Preprint	Oct 1998 - Jul 2005

4. TITLE AND SUBTITLE
Soft-Recovery of Explosively Formed Penetrators

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62602F

6. AUTHOR(S)
David Lambert and 1Lt. Matthew Pope - MNMW

Stanley Jones and Jonathan Muse – University of Alabama

5d. PROJECT NUMBER
2502

5e. TASK NUMBER
12

5f. WORK UNIT NUMBER
31

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Air Force Research Laboratory
Munitions Directorate
AFRL/MNMW
Eglin AFB, FL 32542-6810

University of Alabama
Aerospace Engineering and Mechanics Dept.
Tuscaloosa, AL 35487

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Air Force Research Laboratory
Munitions Directorate
AFRL/MNMW
Eglin AFB, FL 32542-6810

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL-MN-EG

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-MN-EG-TP-2005-7414

12. DISTRIBUTION / AVAILABILITY STATEMENT
APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED

13. SUPPLEMENTARY NOTES This work was submitted to the National Defense Industrial Association, Ballistics Division for presentation at, and publication in proceedings of, the 22nd International Symposium on Ballistics, 14-18 November, Vancouver, BC, Canada. Two of the authors are U.S. Government employees working within the scope of their position; therefore, the U.S. Government is joint owner of the work. If published, the National Defense Industrial Association may assert copyright. If so, the Government has the right to copy, distribute, and use the work. Any other form of use is subject to copyright restrictions.

14. ABSTRACT
A model is presented to help in the design of a “soft-catch” device for safely recovering explosively formed penetrators (EFPs). The closed form analytic solution provides a means to extract drag coefficients within the various materials used in the soft-catch for predictive design and custom deceleration of a variety of kinetic energies and projectile shapes. The method for characterizing the media is dependent only on position-time data within the media and EFP projectile mass and shape information. Experimental data is presented for several EFP designs in parallel with the excellent agreement of the analytic model. The characterization process allows for subsequent optimization and prescription of soft-catch designs to capture the projectile for metallurgical analysis and validation of high-rate, constitutive material models.

15. SUBJECT TERMS
Soft-Catch, Explosively formed projectile, Drag-force model

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			David Lambert
Unclassified	Unclassified	Unclassified	Unlimited	9	**19b. TELEPHONE NUMBER** *(include area code)* 850-882-7991

Title: *Soft-Recovery of Explosively Formed Penetrators*

Authors: David Lambert[1]
Matthew Pope[1]
Stanley Jones[2]
Jonathan Muse[2]

[1]Air Force Research Laboratory, Munitions Directorate, 101 W. Eglin Blvd., Suite 135, Eglin Air Force Base, FL 32542
[2]University of Alabama, Aerospace Engineering and Mechanics Department, Tuscaloosa, AL 35487

A model is presented to help in the design of a "soft-catch" device for safely recovering explosively formed penetrators (EFPs). The closed form analytic solution provides a means to extract drag coefficients within the various materials used in the soft-catch for predictive design and custom deceleration of a variety of kinetic energies and projectile shapes. The method for characterizing the media is dependent only on position-time data within the media and EFP projectile mass and shape information. Experimental data is presented for several EFP designs in parallel with the excellent agreement of the analytic model. The characterization process allows for subsequent optimization and prescription of soft-catch designs to capture the projectile for metallurgical analysis and validation of high-rate, constitutive material models.

INTRODUCTION

The design of explosively formed penetrators (EFP) requires knowledge of the dynamic deformation processes that the initial liner material experiences from explosive shock acceleration through to the final formation of the aerostable geometry. The EFP designer uses physics-based codes with finite element or finite difference numerical schemes, along with constitutive descriptions and equation-of-state models for high-fidelity modeling of these devices. Typical validation of the design codes, or 'hydrocodes', includes comparison of the EFP formation calculations with experiment diagnostics such as flash radiography and synchro-ballistic photography. However, these diagnostics only provide data on the external shape and little physical information on material properties of its post-explosive launch state. The ‘soft-catch’ is an apparatus designed to safely decelerate and recover the projectile intact for characterization of its material properties at its end state.

Traditional constitutive model properties are derived from a series of classical uniaxial stress tests, such as quasi-static tension and compression strength and high-rate (but still uniaxial stress condition) split-Hopkinson pressure bar. None of the calibration tests invoke the shock conditions produced by the explosive launch environment of the EFP nor the triaxial stress and high-rate strain conditions of the initial EFP liner deforming into the final aerostable projectile.

The soft-catch apparatus has been used previously [1], but this effort presents a more in-depth analysis to understand its design and utility. Two significant contributions are introduced here. The first and primary contribution is a method of characterizing the media used within the soft-catch to allow one to prescribe its physical construct and resulting deceleration history. A mathematical description based on a drag force law is proposed and the model’s constants are calibrated. The second contribution is the inclusion of a water section (at the appropriate location along the soft-catch) for terminating the projectile flight and insure thermal quenching and preservation of material microstructure. The quenching process secures the metallurgical conditions of the projectile for post-test analysis and comparison with higher fidelity constitutive descriptions that are currently under development.

The paper begins with a description of the drag force model and mathematical analysis required to characterize the media and projectile constants. This is followed by a presentation of EFP experiments and diagnostic requirements within the soft-catch to calibrate the model. Then, the data and analysis method is given with comparisons made between the model and experiments. Finally, summary and conclusions are made with recommendations of follow-on efforts.

THE DRAG FORCE MODEL

The mathematical model is based on observations presented by Allen, et al [2] and initial application of the model to a specific EFP design showed promising results [3]. Allen, et al observed that the forces on the noses of the penetrators were derived from two distinct force regimes. Rigid body penetration is assumed and verified in the experiments through negligible mass loss. Above a critical velocity, v_c, the force acting on the nose of the projectile was proportional to the square of the local speed, as shown in Eq. (1).

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

Below the critical velocity the force followed a classical Poncelet form [4],

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

In these equations, m is the mass of the projectile, v is the current velocity of the projectile, A is the cross sectional area of the shank of the projectile, ρ is the density of the target medium (i.e. soft-catch matieral), C_D is a dimensionless drag coefficient, β is a coefficient having the dimension of density, and R is a target strength factor having the dimension of stress.

For this effort, the experimental data was obtained for the initial media in the soft-catch and not available in the denser media where the projectile came to rest; thus, the assumption is made that the equation of motion described in Eq. (1) is valid for the analysis and calibration. The subsequent derivations are based on the assumption that the projectile remains above the critical velocity through the majority of the media. This assumption will be re-addressed following application to the soft-catch and comparison to the experiments. Another inherent assumption of this model is that the drag coefficient is not dependent on velocity. The ensuing solution and good agreement of the model results with experiments indicate that this is a reasonable assumption.

Two independent integrals, velocity-distance and velocity-time, are found by direct integration of Eq. (1),

$$\frac{1}{2}\frac{C_D A\rho}{m}z = \ell n\left(\frac{v_0}{v}\right) \tag{3}$$

and

$$\frac{1}{2}\frac{C_D A\rho}{m}t = \frac{1}{v} - \frac{1}{v_0} \tag{4}$$

where v_o is the impact velocity of the projectile and z is the penetration depth measured from the face of the target.

Dividing Eq. (3) by Eq. (4) reduces the set to a transcendental equation, Equation (5), in which the ratio v_o/v is the unknown, but can be found using standard root finding methods for specific values of z, t, and v_o.

$$\frac{z}{t}\left(\frac{v_0}{v} - 1\right) = v_0 \ell n\left(\frac{v_0}{v}\right) \tag{5}$$

Now, C_D is determined from either Equation (3) or (4). Once the C_D is found for a projectile-media combination it can be used for predictive design purposes in further experiments. The next section describes the experiments, EFP projectile and the layout of the soft-catch apparatus.

EFP EXPERIMENTS

The experiments consisted of placing an EFP warhead behind a blast-stripping wall and firing past dual, orthogonal flash radiography stations into the soft-catch apparatus. The standoff from warhead to soft-catch allowed a flight time of just over 3-ms to ensure full formation (complete at nominally 0.50-ms) and establish a steady-state velocity that is documented by the radiograph stations. The soft-catch media had electronic contact screens, velocity screens, distributed at intervals along its length that the projectile triggered for recording the time-position data. This data is the essential element to characterizing the media in accordance to model.

The Explosively Formed Penetrator Design

Three sets of EFP designs were used for application of the model and extraction of drag coefficients. The first two types were of a tantalum material and were relatively close in formation response. The Ta designs were a simple reverse folding projectile that had relatively low velocity of approximately 1.4 km/s in order to increase the probability of catching without adverse deformation and stability within the soft-catch media. The difference in the Ta designs were material specification, i.e. constitutive response, resulting in different degree of collapse, hence, different cross-sectional area and coefficients of drag. The two Ta designs created a nearly hemispherical shape.

The third design was a copper projectile with velocity of 2.03 km/s and an aerostable shape more representative to a tactical, long-standoff EFP. The three designs and the resulting experimental data provide a degree of robustness to the model and allow for confidence in the drag-force assumption.

The Soft-catch Apparatus

The design of the soft-catch was initially based on previous successes and limitations on the physical lengths viable within the test site. A 47-ft (14.3-m) long square channel pipe of 12-in cross-section and 0.5-in wall thickness was used to contain various soft-catch media. The steel tube was to prevent the projectile from escaping laterally during the recovery process. Additionally, the cross-section was kept small and used a density gradient to keep the projectiles from achieving a high angle of incident and force them to the middle, desired path of the soft-catch media. The media of study had only a 6-in lateral dimension with layers of fiberboard and plywood surrounding it within the steel tube. This concept is analogous to the construct fiber optic cable that internally reflects the light back down the centerline. Here, if the projectile began to exit the central media (intended path) it would encounter the higher density surrounding material and be directed back to the center pathline.

The pathline, or longitudinal direction, consisted of lengths of selected media to provide an increasing mass density and strength to bring the projectile to rest. The media consisted of expanded polystyrene (32 kg/m^3), Vermiculite® (126 kg/m^3), fiberboard (256 kg/m^3), water (993 kg/m^3), and sand, respectively from entrance onward. Each experiment had a slight variation in the length of these materials and each came to rest in different media. The goal was to end up in the water section of the apparatus in order to thermally quench the projectile and prevent post-shot annealing, recrystallization, and/or grain-growth from the thermalization of internal energy absorbed during the high-rate formation process. A typical construct of the soft-catch apparatus is given in Figure 1, showing locations of the velocity screens for obtaining the time-position data.

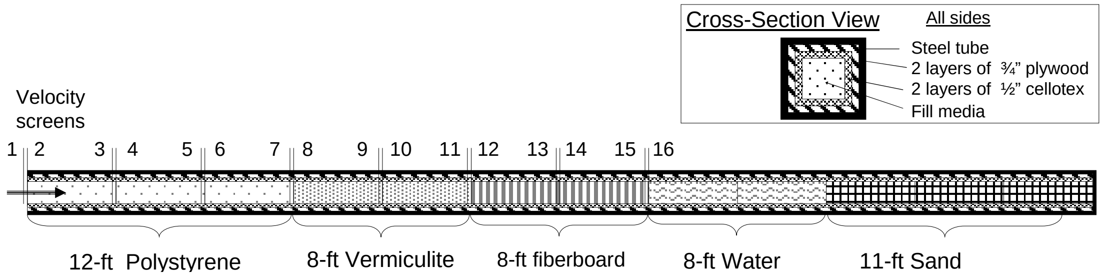

Figure 1. Example Construct of the Soft-Catch Apparatus

APPLICATION OF THE MODEL TO THE EXPERIMENTS

Equation (5) was applied to each section of similar material in the soft-catch using the time-position experiment data. The transcendental equation was solved using Newton's Method for fast convergence in an iterative root solution of $v_{exit}/v_{entrance}$ where v_{exit} is the velocity exiting a specific section of media and $v_{entrance}$ is the velocity going into the section. As the equation was applied to subsequent sections along the soft-catch, the $v_{entrance}$ was taken as the v_{exit} of the previous section. The drag coefficients, C_D, from each EFP design are given in Table I. The data from "Ta Design 1" was taken directly from that of Ref. [4] for completeness, while the results from "Ta Design 2" and "Cu EFP" are added as new results.

Once C_D has been determined, the Eqs. (3) and (4) are used to calculate estimated times and velocities for comparison to the experiments. Again, details for "Ta Design 1" shots are given in Ref. [4], but those of the other EFPs are given in Tables II-IV to show how well the model compares.

The cross-section, density, and mass of each projectile were obtained for comparing estimates (Eqs. (3) and (4)) of the time-velocity profiles to the experiments. An "equivalent" cross-sectional area of each recovered projectile was obtained using a shadowgraph method along with a reference object. High-contrast digital photographs were taken of the projectiles (and reference object) resting upright on a back-lit surface. Image processing software was used to get the number of pixels occupying their cross-sectional area and calculate equivalent area.

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

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%

TABLE III. MODEL COMPARISON WITH "TA DESIGN 2, SHOT 2"

Tantalum Design 2, Shot 2: Impact Velocity = 1422 m/s					
Media	Experiment Velocity (m/s)	est. Exit Velocity (m/s)	Experiment Exit time (us)	est. Exit time (us)	Difference in time (%)
Polystyrene	N/A	1365	438	440	-0.6%
	N/A	1311	893	920	-2.9%
	1270	1258	1368	1400	-2.3%
	1172	1208	1863	1880	-0.9%
	1089	1160	2378	2400	-0.9%
	1016	1113	2914	2960	-1.5%
Vermiculite	847	940	3511	3560	-1.4%
	762	793	4218	4280	-1.5%
	620	670	5055	5080	-0.5%
	538	566	6046	6064	-0.3%
	423	478	7221	7198	0.3%
	495	403	8612	8640	-0.3%
Cellotex	N/A	288	10408	9872	5.4%

TABLE IV. MODEL COMPARISON WITH "CU EFP"

Copper aerostable projectile: Impact Velocity = 2030 m/s					
Media	Experiment Velocity (m/s)	est. Exit Velocity (m/s)	Experiment Exit time (us)	est. Exit time (us)	Difference in time (%)
Polystyrene	2030	2027	10	10	0.2%
		1729	1336	1314	-1.7%
	1692	1727	1348	1324	-1.8%
		1594	2062	2064	0.1%
Vermiculite	1562	1589	2075	2077	0.1%
		1350	2879	2875	-0.1%
	1269	1347	2895	2888	-0.2%
		956	5257	5064	-3.7%
Fiberboard	781	946	5283	5086	-3.7%
		509	7216	6846	-5.1%
	564	504	7252	6881	-5.1%

Discussion of the Results

The results in Tables II-IV show excellent agreement between the calibrated model and experiments. The maximum difference occurs in the fiberboard/Cellotex media where just over 5% difference in the time-of-arrival at the location of the velocity screen was calculated. The fiberboard also happens to be the media where the least amount of data was obtained and was also where cumulative problems and errors occur.

The projectiles can accumulate debris on their noses which interfere with the electrical contact method of the velocity screens. Erroneous data has dramatic effects on the root of transcendental equation, Eq. (5), forcing keen user interpretation of the recorded waveforms. Additionally, drag forces are increased with media density and any aerodynamic instability is magnified. This resulted in some of the projectiles deviating off of the central shotline – where the 4-inch by 4-inch velocity screens were located – and not activating the screen in the intended manner. All of the projectiles reported here were observed to have followed a "nose-forwared" trajectory; i.e. not tumbling or rotating through the media.

Table V lists all the experiments along with the location of where they were recovered and a picture of their final shape. Flash radiographs of each in free-flight just before impact were compared with the recovered projectile to ensure the media did not further deform or erode them. Mass loss of the recovered projectiles was not due to the soft-catch procedure. It was a result of losing the outer radius of the EFP liner during explosive shock acceleration, typically 5%-10% of the liner.

One shot, "Ta Design 1", "Shot 3", had the projectile end up, as desired, in the section of water. This was achieved after examining the results of the previous two "Ta Design 1" experiments and adding an additional 1.2 m section of Vermiculite. The projectile was quenched and at room temperature when recovered within 10-mins of explosive launch. The projectile was delivered to Los Alamos National Laboratory for metallurgical investigations and the validation of advanced constitutive and plasticity theories. Their analysis showed the material did not experience post-shot temperature effects and that capturing it in the water section was desirable.

Recommended Further Studies

Further studies will examine the time-position data and differentiate the curve-fit equations to extract velocity and acceleration histories. From this, the equation of motion, Eq. (1), can be used to quantify the drag force and compare with relation to the material strengths. This process will help ensure the deceleration forces don't exceed that which plastically deform or shear the projectiles.

It is also desirable to explore the model, Eq. (2), for velocities under the critical velocity. Ref. [3] indicated that projectiles fired into sand at nominally 600-700 km/s had a critical velocity in the 70-100 m/s range. Further experiments are warranted to explore the critical velocity for the EFPs and media reported here and ensure the tacit assumption above v_c was valid, as well as, calibrate what would be the termination phase of the model. This would give a complete tool from which to design the soft-catch from beginning to end.

TABLE V. PROJECTILES FROM ALL EXPERIMENTS

Shot	Impact Velocity (m/s)	Recovered Mass (kg) (%initial)	Location Recovered	Cross-sectional area	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		

CONCLUSIONS

A one-dimensional analysis of projectile deceleration has been presented that correlates closely with EFP warhead experiments. The analysis produced drag coefficients for a variety of projectile velocities and shapes. The model then accurately replicated time of arrival and velocity histories through the soft-catch media with discrepancies of only 5.4% or less. The two goals of this effort were met by successful calibration of the soft-catch media and the capture of a projectile in the section of water for quenching and preserving the material state of the "as formed" condition. This process and its excellent results make it a useful design tool for further experiments and recovery of EFP projectiles.

DISCLAIMER

Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Air Force. This research was sponsored by the Munitions Directorate, Air Force Research Laboratory.

REFERENCES

---

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 H.L. Harvey. 1957. "Dynamics of a Projectile Penetrating Sand," *J. Applied Physics*, 28(3):370-376, 1957.
3. Pope, M., B. Martin, D. Lambert, S. Jones, and J. Muse. 2005. "Analysis of a Soft Catch for Conventional Warheads," presented at the 2005 ASME Pressure Vessels and Piping Division Conference, Denver, CO, July 17-21, 2005.
4. Poncelet, J.V. 1829. *Cours de Mecanique Industrielle*, 1829.