

Hypersonic Aerial Gunnery Ammunition

A hypersonic aircraft is shown in flight against a blue sky with scattered white clouds. The aircraft is firing a missile, which is depicted as a long, multi-colored streak (yellow, orange, red) extending across the sky. The background features a range of mountains and a valley with some buildings and greenery. In the foreground, the blurred silhouette of a gun or missile launcher is visible.

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Outline:

- i. Motivation***
- ii. Aerial Gunnery History... Condensed***
- iii. Technology Breakthrough: Flight Safe Sabots***
- iv. BASS & MASS Round Design Philosophies***
- v. Aerodynamics, Aeromechanics, FEM, Bench Testing***
- vi. Range Shots, Performance, Trades***
- vii. Intellectual Property Filings, Claims & Status***
- viii. Opportunities***

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Adaptive Aerostructures Laboratory

- **Specialize in "Prime Mover" Military Technologies:**

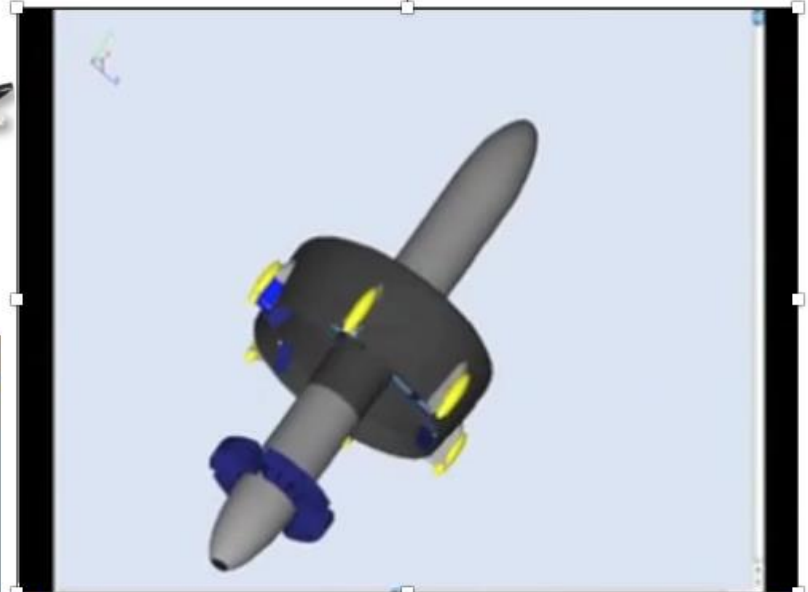
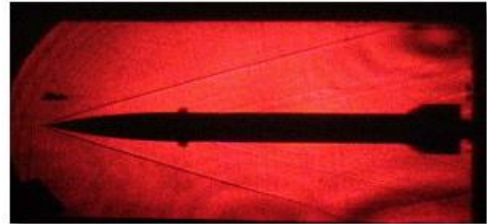
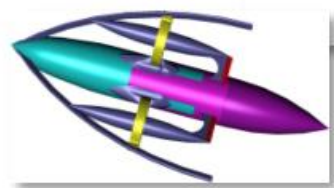
- Ultra-high performance drones
- Invisible drones
- Hovering missiles
- Guided ammunition 4 – 155mm
- Hypersonic ammunition
- Acoustic Vector Sensors

- **Advanced Commercial Technologies:**

- Adaptive Aerocompliant Surfaces
- Commercial Drones
- Toys

- **IP Protection & Litigation**

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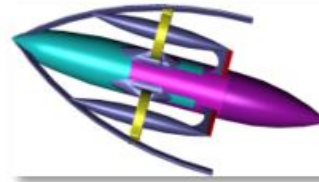
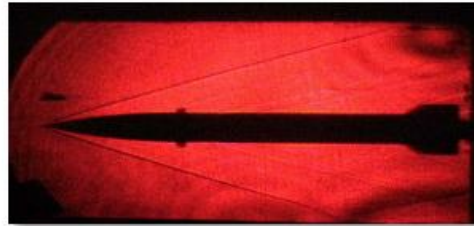
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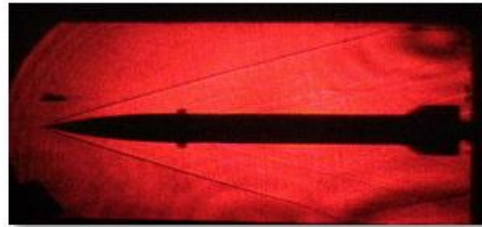
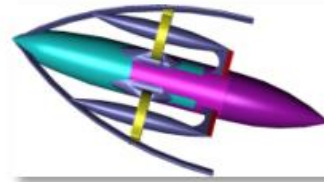
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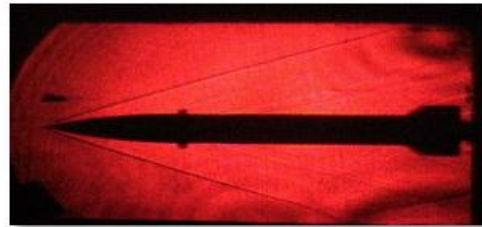
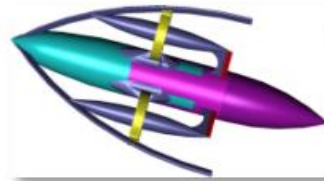
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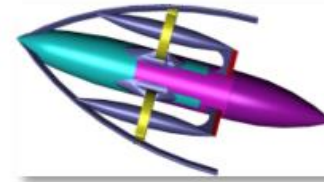
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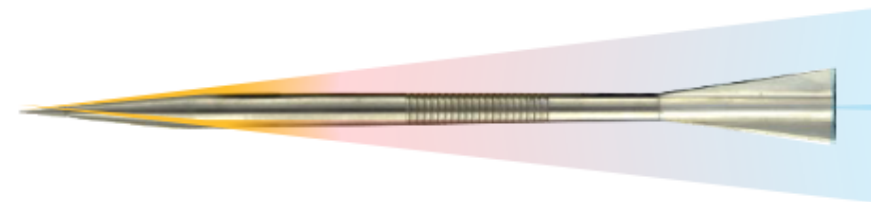
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1. Motivation: Why Hypersonic Aerial Gunnery Ammunition?

- Large expansion in mission effectiveness & force multiplication
- Increased range, KE, lethality, P_k , flat fire
- Reduced TOF, CEP, system weight, volume, airframe MGWTO & LCC



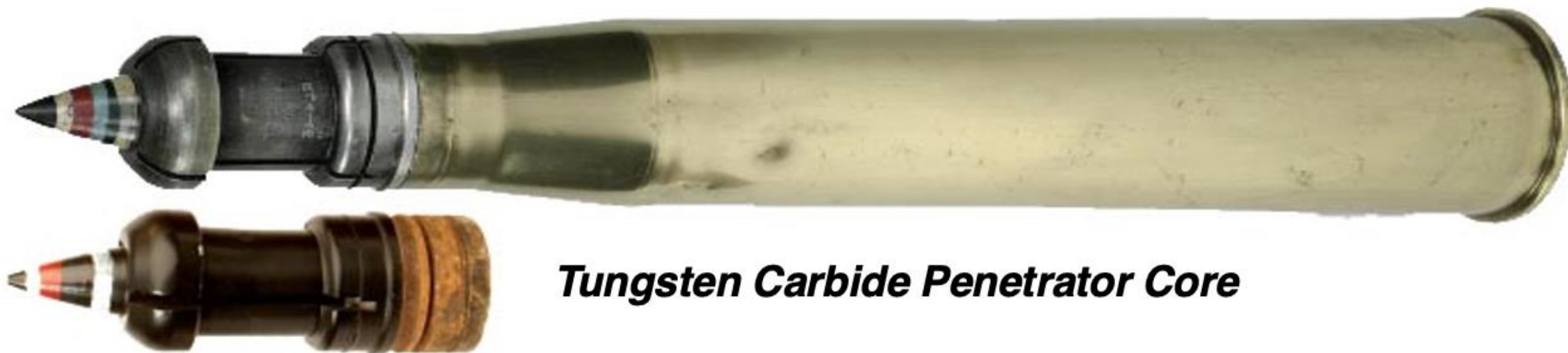
2. Aerial Gunnery History (condensed)

- 1st Recorded sabot rounds: 1326
- 1913: 1st Air-to-Ground Strafing, Bombardment, Air-to-Air Combat from Heavier-than-Air Craft
- Critical during WWI, II

2. Aerial Gunnery History (condensed)

British QF 6-Pounder Antitank Gun 1944

Armor-Piercing Discarding Sabot (APDS Round)

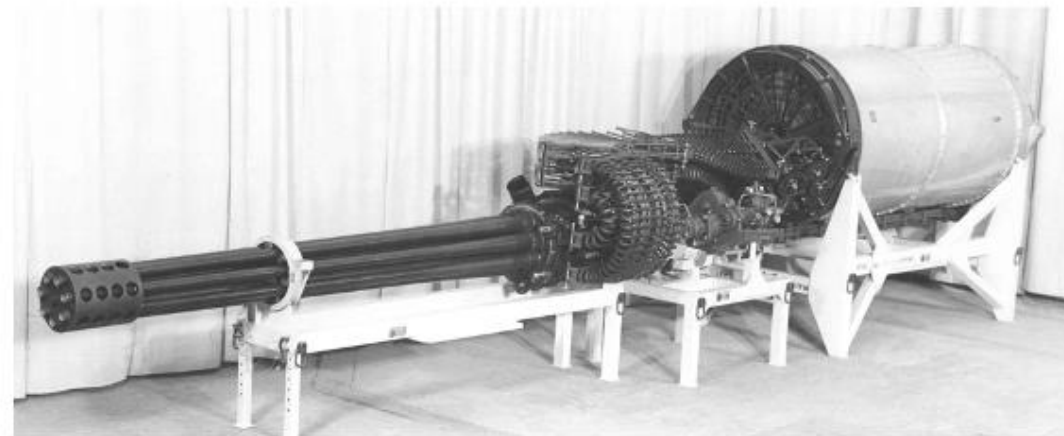


Tungsten Carbide Penetrator Core

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2. Aerial Gunnery History (condensed)

- Post-War, 949.5/1130.25 (84%) of aerial victories are gun kills
- Specialized rounds for aerial combat developed 1950's (M50 family)
- M61 & derivative Gatling guns evolved 1950's forward
- GAU-8 & PGU-13/14/15 developed for A-10

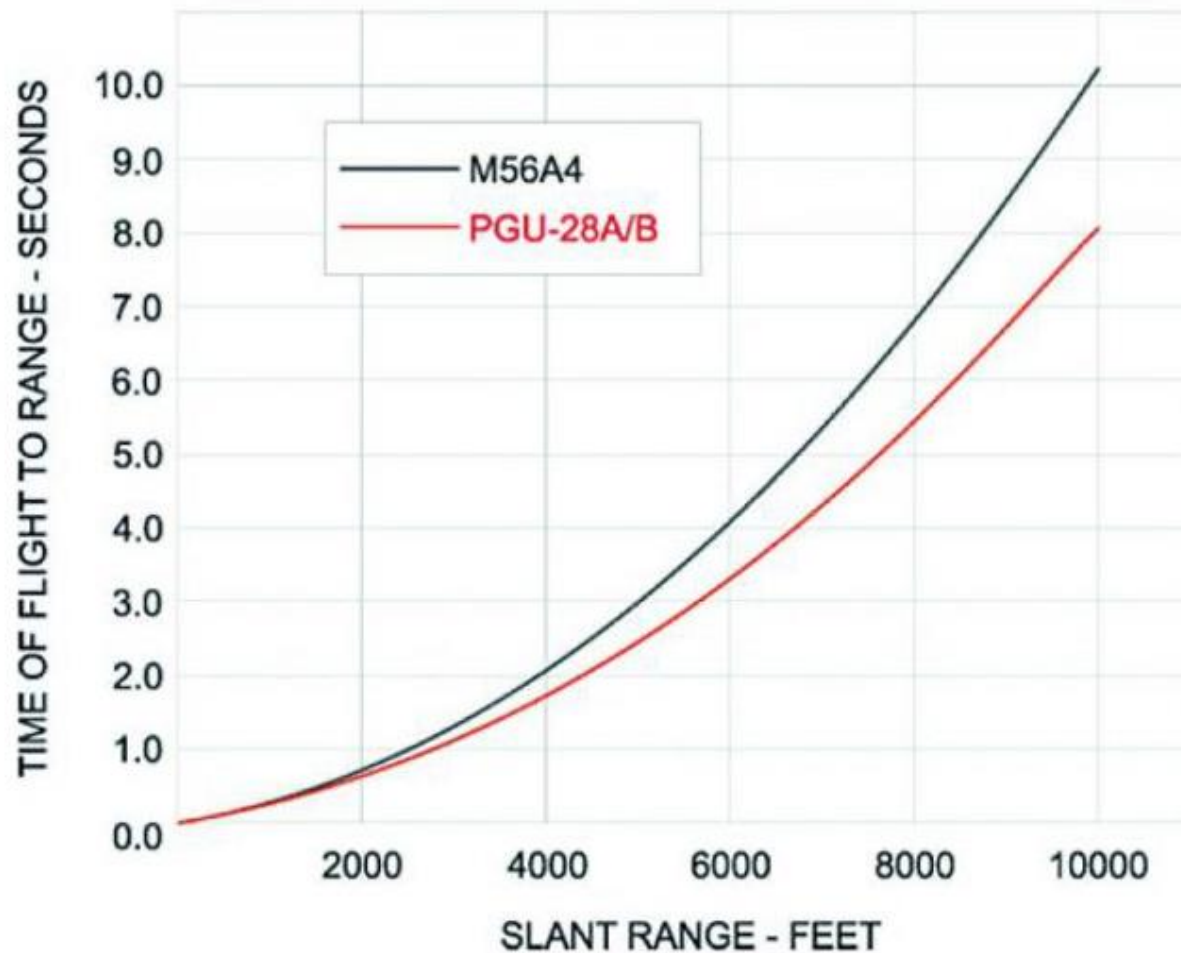


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2. Aerial Gunnery History (condensed)

**Ammunition for the More Modern Jets:
Better Form Factor, Reduced HE**

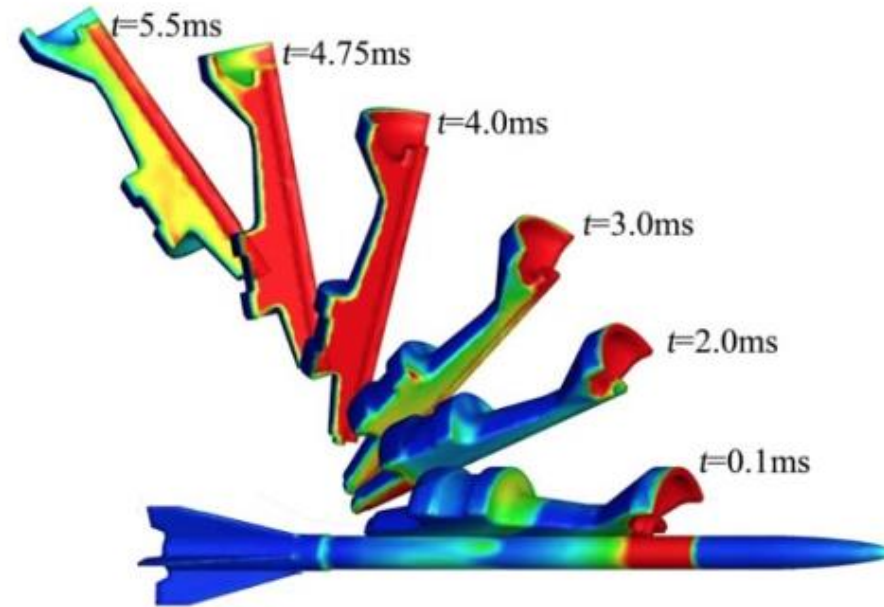
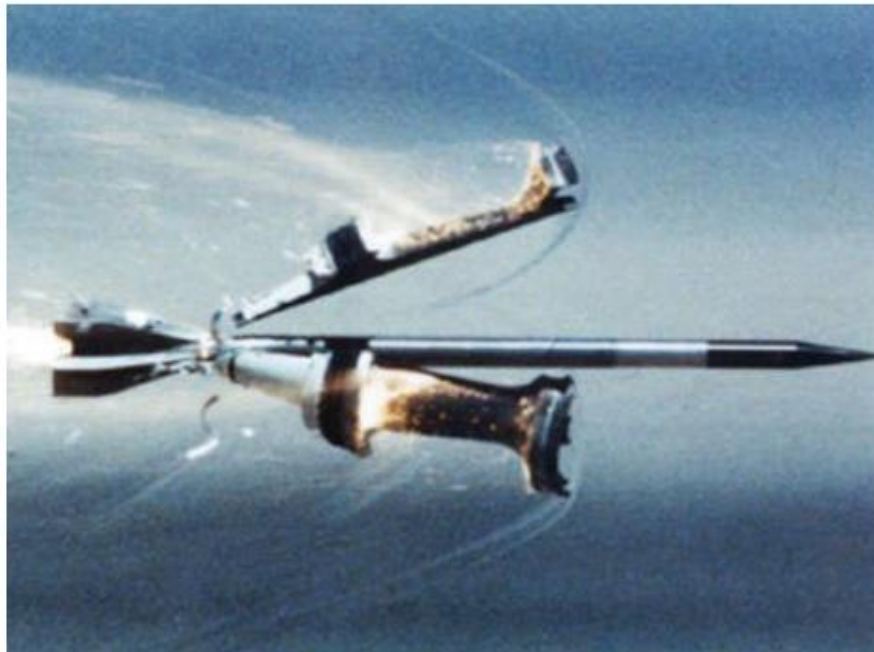
- PGU-28 fielded 1992



2. Aerial Gunnery History (condensed)

Problems with Aircraft & Sabots

Conventional Discarding Sabot
Aeromechanically unstable by necessity...



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2. Aerial Gunnery History (condensed)

- **USAF worked hard to develop sabotred aerial gunnery rounds 1970 – 1998**

Conventional Discarding Sabot Design Philosophy and Aeromechanics

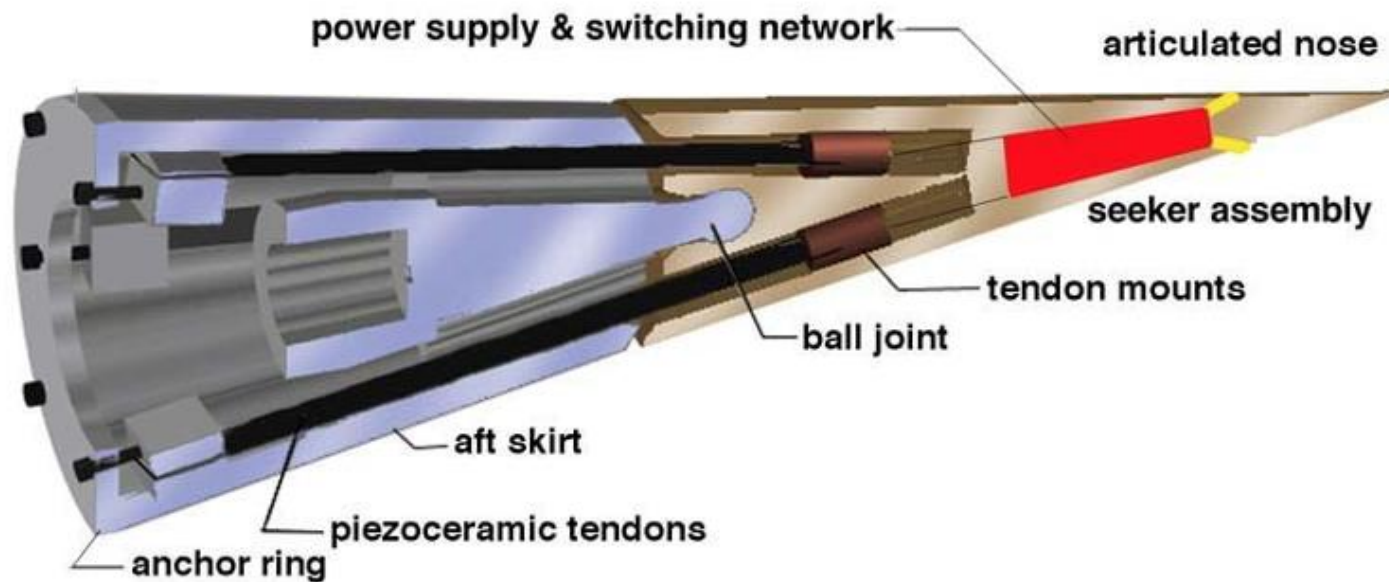
The disadvantage of sabots is that they must be discarded at muzzle exit, and these rapidly decelerating sabots pose an unacceptable hazard to launching aircraft.

-Dale Davis, Director, USAF Munitions Directorate 1984

Historical Development of Automatic Cannon Caliber Ammunition 20 – 30mm 1952 - 1983

2. Aerial Gunnery History (condensed)

- **USAF developed 1st guided aerial gunnery round prototypes 1995 - 1998**
- ***Barrel-Launched Adaptive Munition (BLAM) Program 1995 - 1998***



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2. Aerial Gunnery History (condensed)

1948 Key West Agreement:



Section VI - Functions of the United States Army

Primary Functions

1. a. To defeat enemy land forces.
- b. To seize, occupy and defend land areas.



Section VI - Functions of the United States Air Force

Primary Functions

1. b. To gain and maintain general air supremacy.
- c. To defeat enemy air forces.
- d. To control vital air areas.
- e. To establish local air superiority except as otherwise assigned herein.

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1998: USAF ceases all advanced/guided aerial gunnery & sabotaged ammo. RDT&E

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The AFRL does not have an S&T portfolio in ammunition.

-David Lambert AFRL Munitions Directorate Chief Scientist, (via J. Ellison) 2021

3. Breakthrough: Problems with Aircraft & Sabots

Why a conventional sabot won't work for aerial gunnery

Dale Davis' Observations:

Conventional sabot pieces are designed to be aeromechanically unstable, by necessity, to separate from projectile

Aeromechanically unstable sabot pieces tumble

...and strike airframe/engine

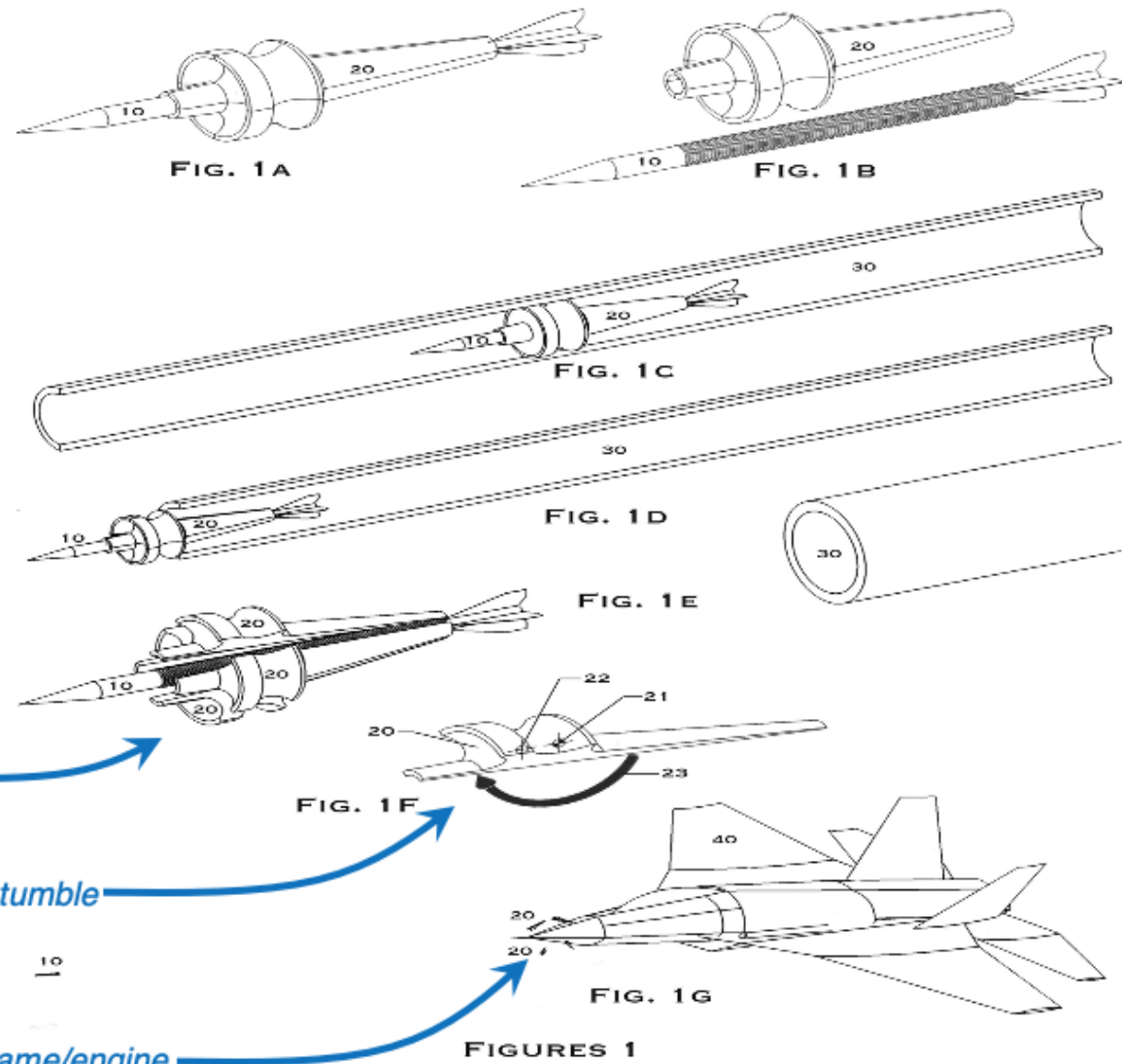
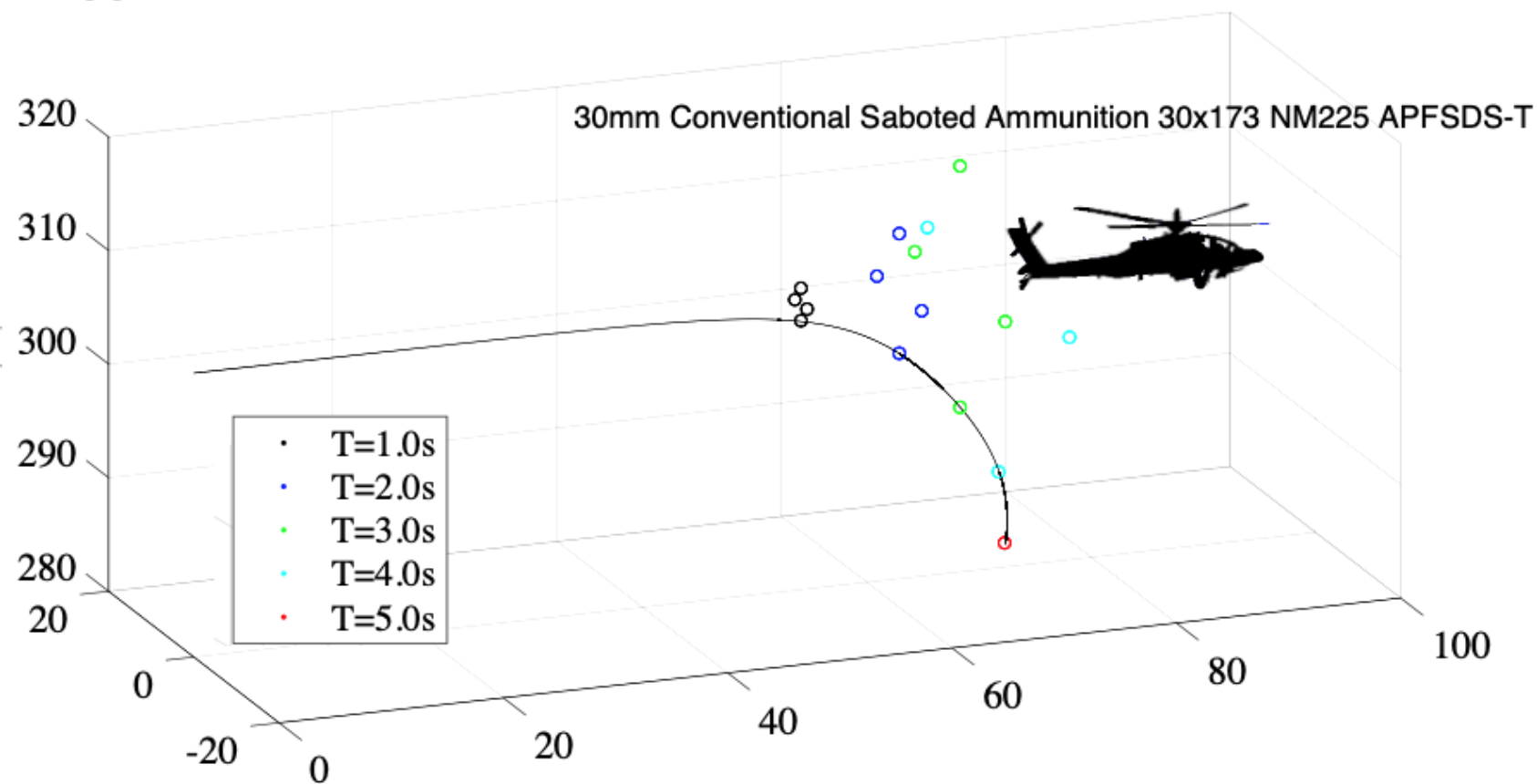


Image Source: PCT/IB2020/053899

3. Breakthrough: Problems with Aircraft & Sabots

*The Great Show Stopper for conventional sabots:
Flight Safety*



3. Breakthrough:

Ms. (now Dr.) Lauren Schumacher



2016 Co-Inventor

Ballistic Aeromechanically Stable Sabot (BASS) Ammunition

Maneuvering Aeromechanically Stable Sabot (MASS) Ammunition

Senior Systems Engineer, Raytheon

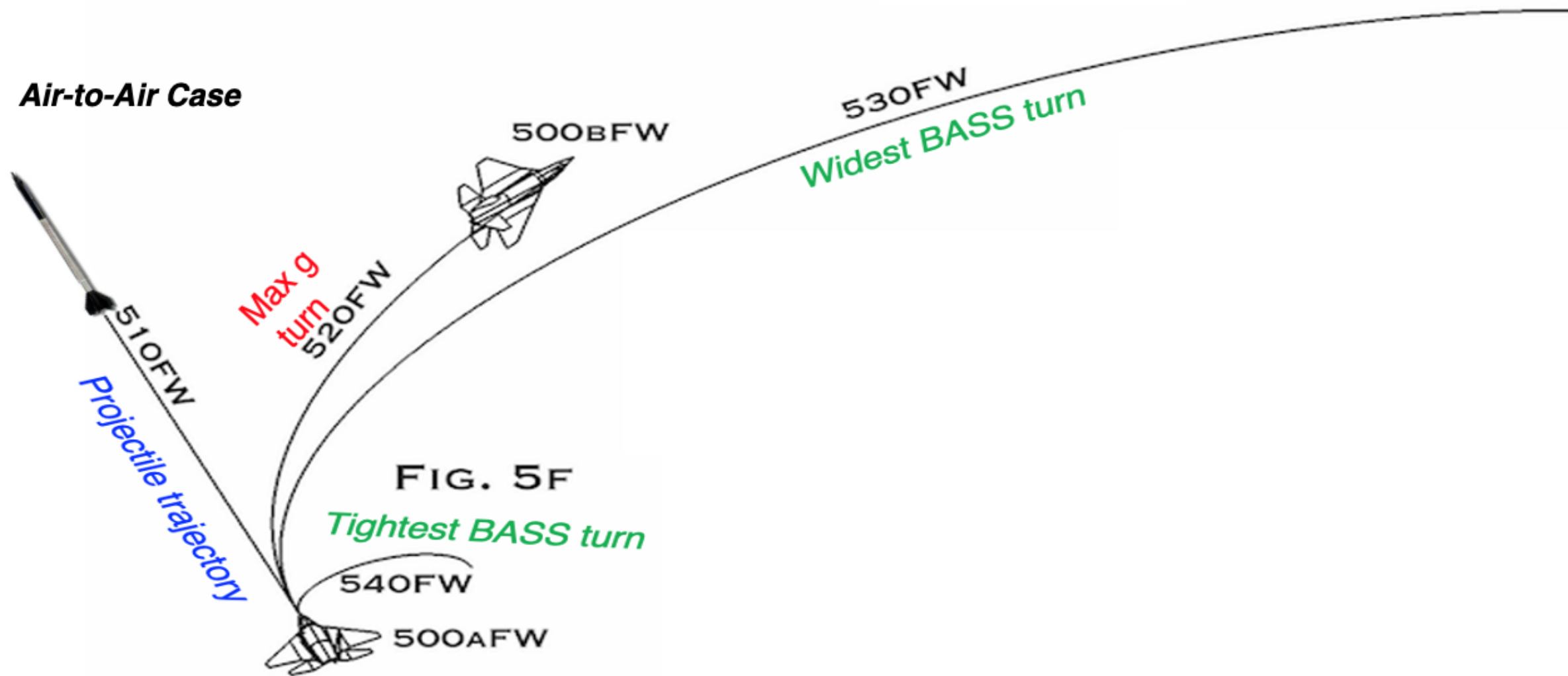
3. Breakthrough:

BASS Rounds: Design the Sabot to clear the launching aircraft

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Air-to-Air Case

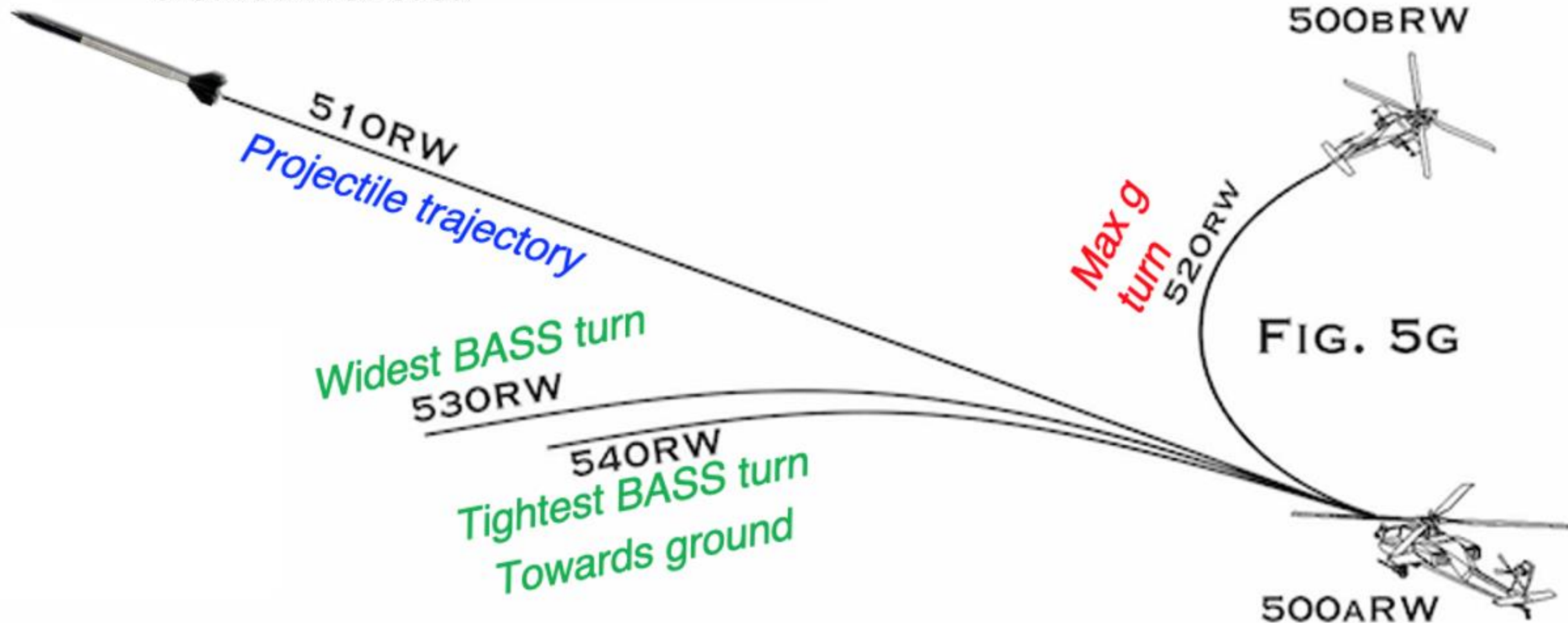


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3. Breakthrough:

BASS Rounds: Design the Sabot to clear the launching aircraft

Ground Attack Case

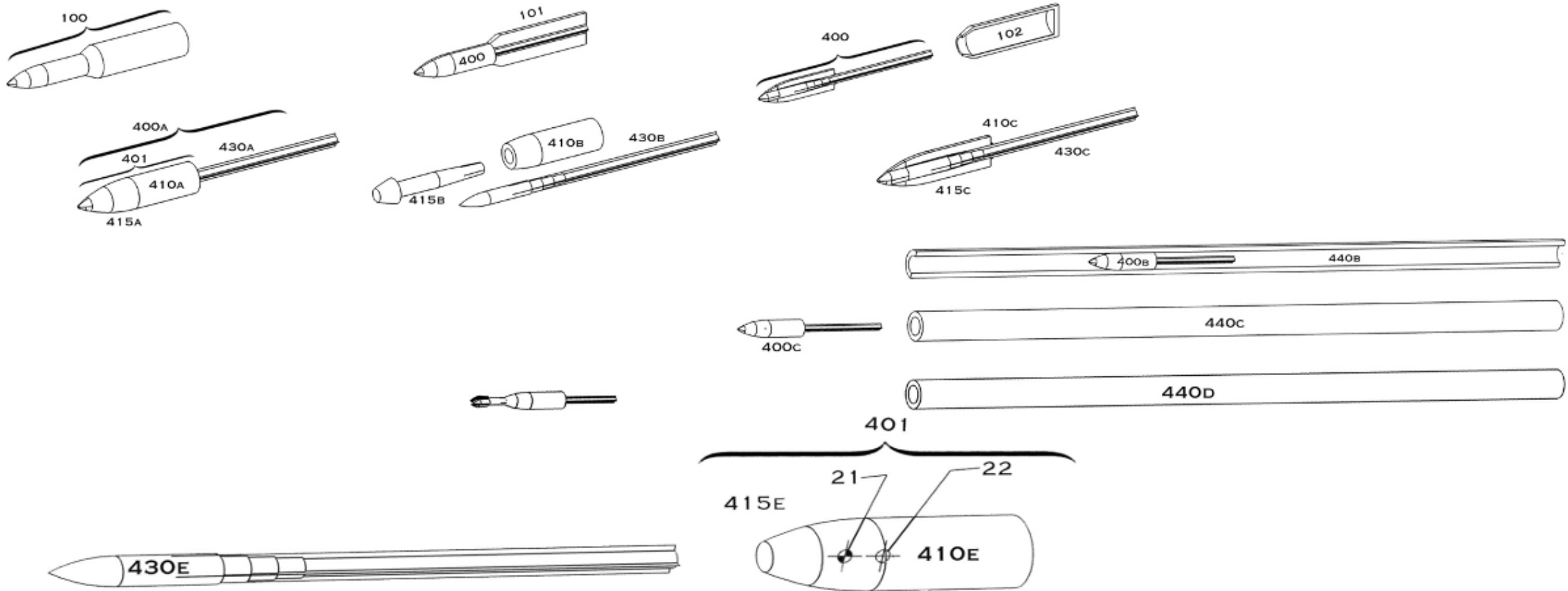


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4. MASS & BASS Rounds

What is claimed is:

1. An aeromechanically stable sabot...



54 major families, >1,000 species covered in expansive patent filings

4. MASS & BASS Rounds

Today's Aerial Gunnery Ammunition Design Philosophy

Design space for fuze, HE, I, shaped charge, tracer etc.

Design space for propellant, primer, etc.

4. MASS & BASS Rounds

Today's Aerial Gunnery Ammunition Design Philosophy



Components laid out in full-bore shell for mission at hand, cartridge case filled



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4. MASS & BASS Rounds

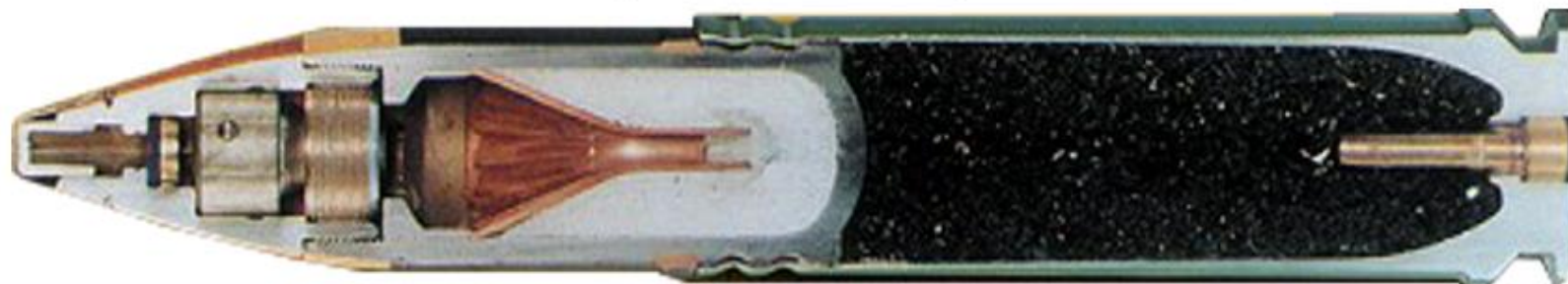
Today's Aerial Gunnery Ammunition Design Philosophy



Components laid out in full-bore shell for mission at hand, cartridge case filled



Band(s) fitted to shell, then mate to cartridge case & crimped at case joint



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4. MASS & BASS Rounds

MASS & BASS Design Philosophy



- HE/I volume set by blast effects requirements
- Armor penetration & longer ranges achieved by high ballistic coefficient flechette
- Use decoupling of bore & projectile to maximize objectives while minimizing cost, recoil, caliber, etc.

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4. MASS & BASS Rounds

MASS & BASS Design Philosophy

Start Point: M789 HEDP



4. MASS & BASS Rounds

MASS & BASS Design Philosophy

Start Point: M789 HEDP



Eliminate air, low-stress metal, shrink fuze, stretch HE, add W or DU nose



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4. MASS & BASS Rounds

MASS & BASS Design Philosophy

Start Point: M789 HEDP



Eliminate air, low-stress metal, shrink fuze, stretch HE, add W or DU nose



Stretch more to full length, maintaining HE volume & effects, leave clearance for flash hole



4. MASS & BASS Rounds

MASS & BASS Design Philosophy

Reshape flechette for sabot compatibility



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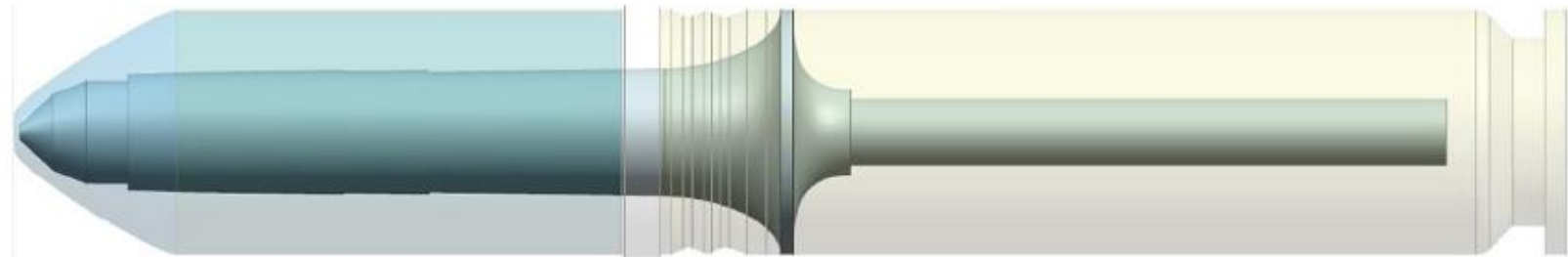
4. MASS & BASS Rounds

MASS & BASS Design Philosophy

Reshape flechette for sabot compatibility



Run MDO including sabot, flechette, gun(s), aircraft and optimization vector



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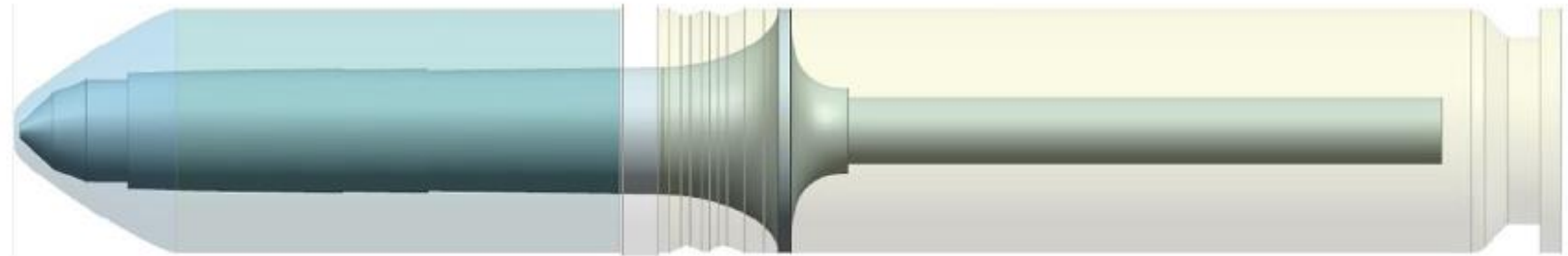
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MASS & BASS Design Philosophy

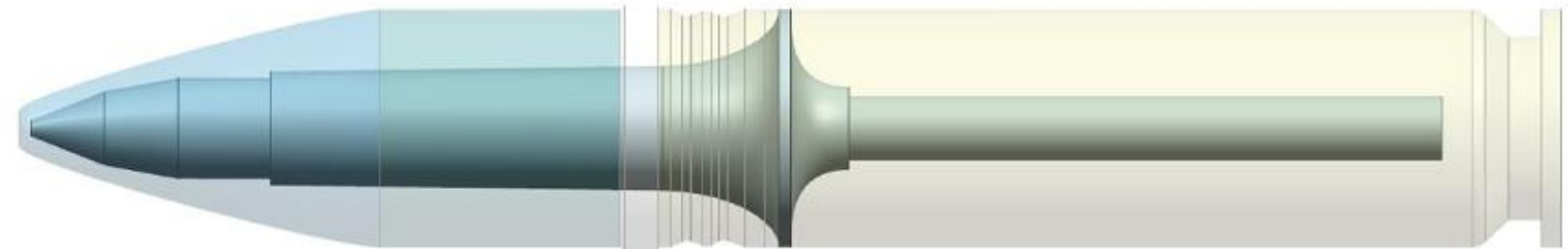
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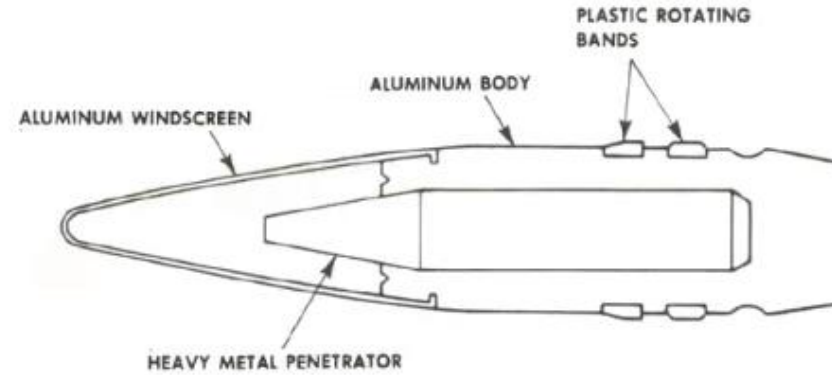
Send to Class II analysis & optimization



4. MASS & BASS Rounds

Today's Aerial Gunnery Round

PGU-14



BASS 2081 Flechette/penetrator



5. Modeling & Testing

- *Conceived 2016 & reduced to practice*
- *Modeled in CFD, FEM, DATCOM & PRODAS*
- *Tested on Shock Table, Wind Tunnel, Range*
- *>100 rounds fired, currently @ TRL-6*



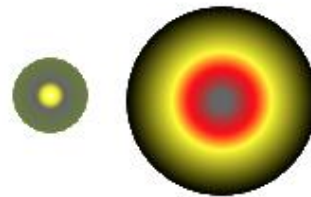
5. Modeling & Testing

Top-Level Drag and Stability Characteristics

Flechette

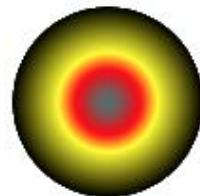


X-Sectional Area of PGU-14 >> Flechette



Supersonic Drag ~ proportional to X-Sectional Area, $Drag_{PGU14} \gg D_{Flechette}$

PGU-xx



5. Modeling & Testing

Interior Ballistics:

System Modeling & Design:

- FEM calibrated with fielded-round dynamic shock modeling;
- Numerical simulation of sabot and projectile assembly through muzzle exit with initial dynamic perturbation.

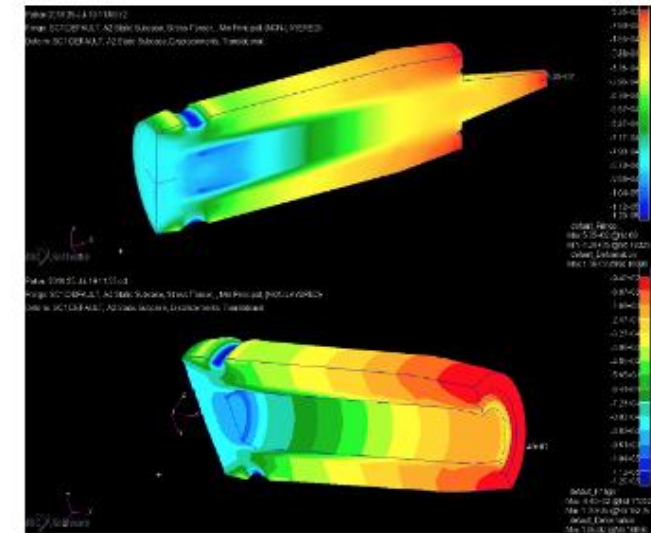
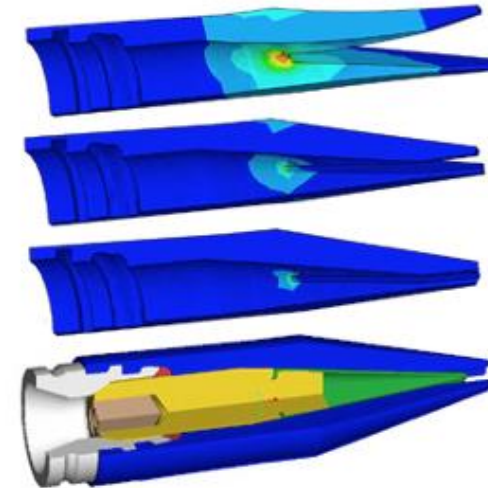


Image Sources:
<https://www.sws-llc.com/structuralanalysis1.htm>
http://www.mycity-military.com/uploads2/154453_716860609_Zececiv_Dispersion_PGU-14_ammunition%5B1%5D.pdf

5. Modeling & Testing

Aeromechanics:

- Six-degree of freedom aeromechanical modeling of munitions of varied geometry and stability schemes through high angles and angular rates with the potential for deploying surfaces;
- Initial structural and aeromechanical design of a preferred configuration of the BASS system for penetrator and cargo rounds.

Earth Fixed $\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{bmatrix} = q_b \begin{bmatrix} U \\ V \\ W \end{bmatrix}$

Body Linear Momentum $\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} = \frac{1}{m}(m\dot{g} + \dot{F}) - \bar{\Omega} \times \bar{V}_b$

Body Angular Momentum $\begin{bmatrix} \dot{P} \\ \dot{Q} \\ \dot{R} \end{bmatrix} = [J]^{-1} \left(\begin{bmatrix} L \\ M \\ N \end{bmatrix} - \begin{bmatrix} 0 & -R & Q \\ R & 0 & P \\ -Q & -P & 0 \end{bmatrix} [J] \begin{bmatrix} P \\ Q \\ R \end{bmatrix} + \sum_{i=1}^N (J_i \dot{\Omega}_i + J_i \bar{\Omega}_i + \bar{\Omega}_i \times H_i) \right)$

Body Orientation $\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -P & -Q & -R \\ P & 0 & R & -Q \\ Q & -R & 0 & P \\ R & Q & -P & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix}$

Fin to Body Orientation $\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & 0 & 0 & -r \\ 0 & 0 & r & 0 \\ 0 & -r & 0 & 0 \\ r & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad \dot{r}_i = n_i \left(I_{xxi} + \frac{mb^2}{4} \right)^{-1}$

Source of relationships:
<http://www.songho.ca/math/quaternion/quaternion.html>
https://en.wikipedia.org/wiki/Rotation_formalisms_in_three_dimensions

$\Phi_b = \rho_\infty V_\infty \sin(\theta)$

$\frac{F}{A} = \Delta P = \rho_\infty V_\infty \sin(\theta)^2$

$c_p = \frac{\Delta P}{q} = 2 \sin^2(\theta)$

$c_{pb2} = \frac{P_{0,2} - P_{0\infty}}{q} = \frac{P_{0,2} - P_{0\infty}}{\frac{\gamma}{2} \rho_\infty M_\infty^2} = \frac{2}{\gamma M_\infty^2} \left(\frac{P_{0,2}}{P_{0\infty}} - 1 \right)$

$c_p = c_{pb2} \sin^2(\theta)$

$c_p = c_{p0} \sin^2 \theta = \left(\frac{[\gamma+1]^2}{4\gamma} \right)^{\frac{\gamma}{\gamma-1}} \frac{4}{\gamma+1} \left(\frac{2}{\gamma M_\infty^2} \right) \sin^2 \theta$

$\frac{d\bar{V}}{dt} = -\frac{1}{2m} \rho S V c_{D0} \bar{V} + \frac{1}{2m} \rho S c_{D0} (V^2 \bar{R} - (\bar{V} \cdot \bar{R}) \bar{V}) - \frac{1}{2m} \rho S D c_{Dpa} \left(\frac{I_{yy}}{I_{xx}} \right) (\bar{R} \cdot \bar{R}) (\bar{R} \times \bar{V})$

$+ \frac{1}{2m} \rho S V D (c_{Nq} + c_{N\dot{\alpha}}) (\bar{R} \times \bar{R}) + \bar{g} + \bar{\omega}$

$\frac{d\bar{\omega}}{dt} = \frac{1}{2I_{yy}} \rho S V D c_{Mq} (\bar{V} \times \bar{R}) + \frac{1}{2I_{xx}} \rho V S d^2 c_{Npa} (\bar{R} \cdot \bar{R}) (\bar{V} - (\bar{V} \cdot \bar{R}) \bar{R})$

$+ \frac{1}{2I_{yy}} \rho S V D^2 (c_{Nq} + c_{N\dot{\alpha}}) (\bar{R} - (\bar{R} \cdot \bar{R}) \bar{R}) + \frac{1}{2I_{xx}} \rho S V D^2 c_{Np} (\bar{R} \cdot \bar{R}) \bar{R}$

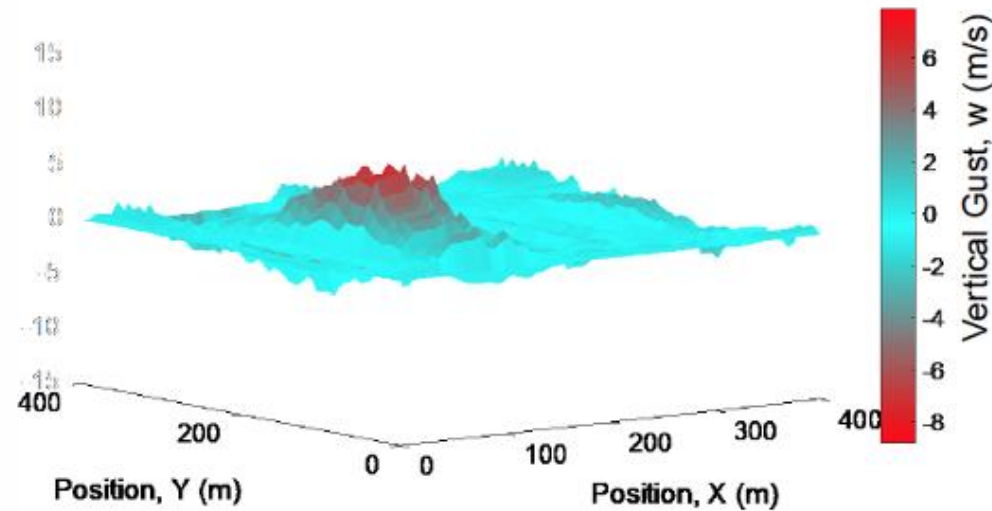
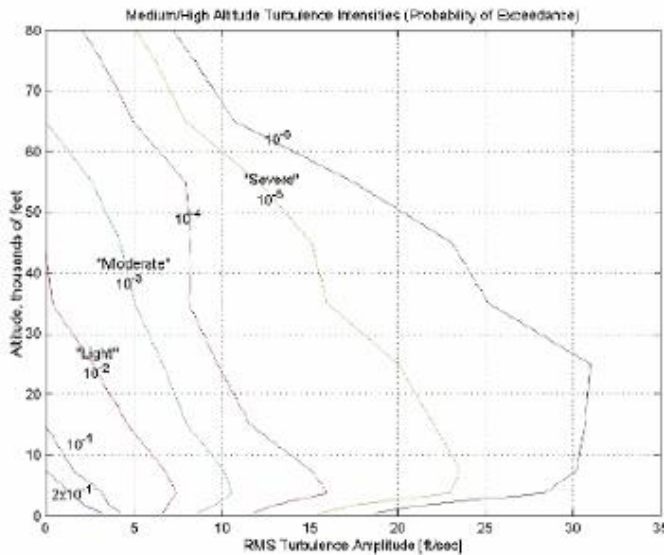
$+ \frac{1}{2I_{yy}} \rho S V^2 c_{N\dot{\alpha}} D \bar{r}_p \bar{R}$

Distribution A Unlimited Distribution

5. Modeling & Testing

Aeromechanics:

- Quaternion DE until small angle assumption oscillation
- Pseudo-steady state 6DOF exterior ballistics model for projectile and sabot
- Von-Kármán gust field for scatter analysis downrange (MIL-F-8785C)
- Conventional sabot modeling with empirical data

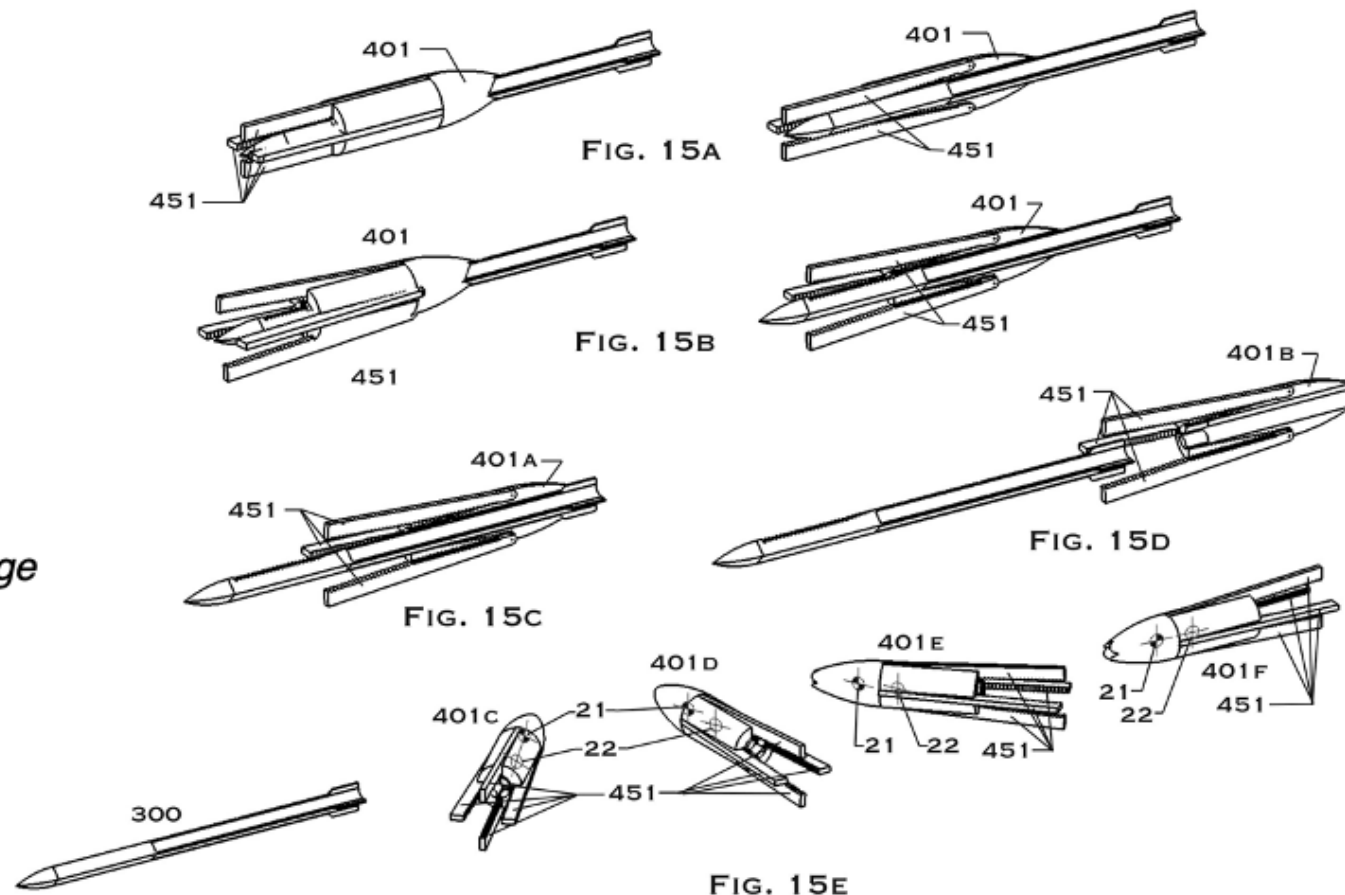


5. Modeling & Testing

Exit Dynamics

Sabot Separation event

- Transfers loads during launch
- Separates cleanly from projectile
- Clears launching aircraft & proceeds downrange in an aeromechanically stable configuration



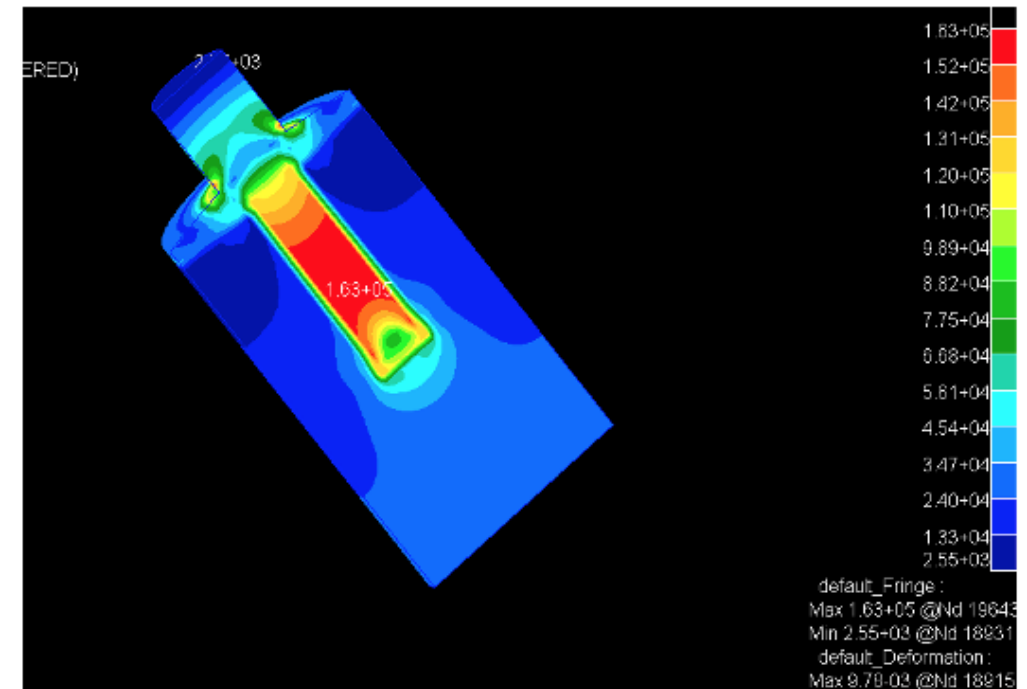
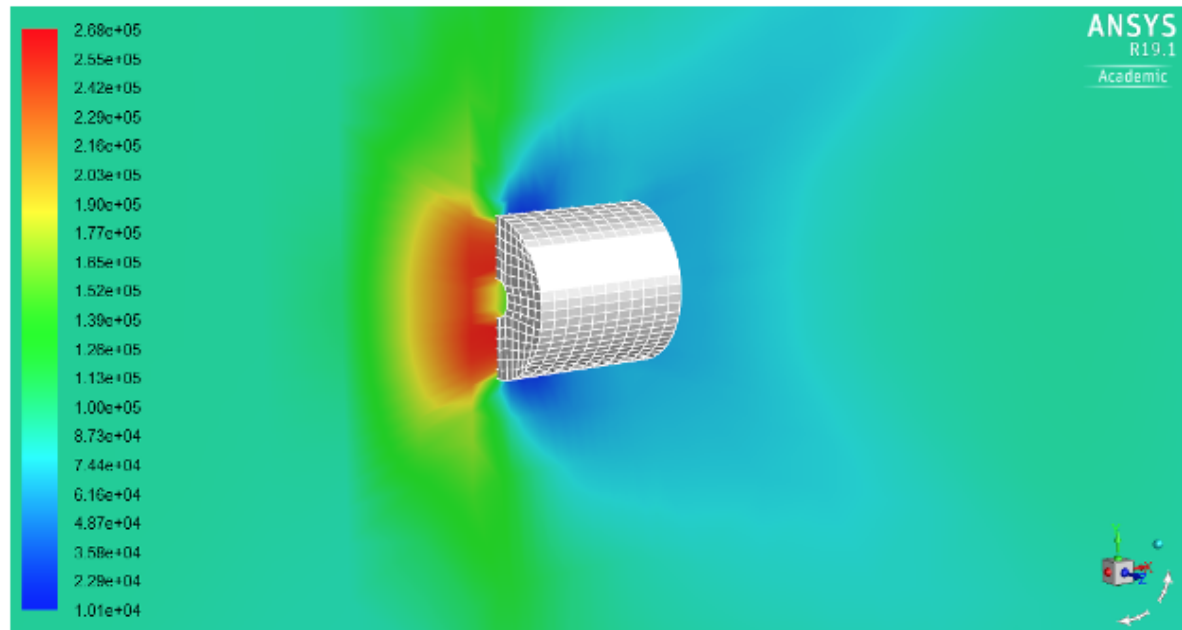
FIGURES 15

Image Source: PCT/IB2020/053899

5. Modeling & Testing

Computational Fluid Dynamics (CFD)

- Drag, center of pressure and aerodynamic center locations identified with α sweeps



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5. Modeling & Testing

Wind Tunnel Verification:

- Center of pressure and aerodynamic center locations identified with α sweeps

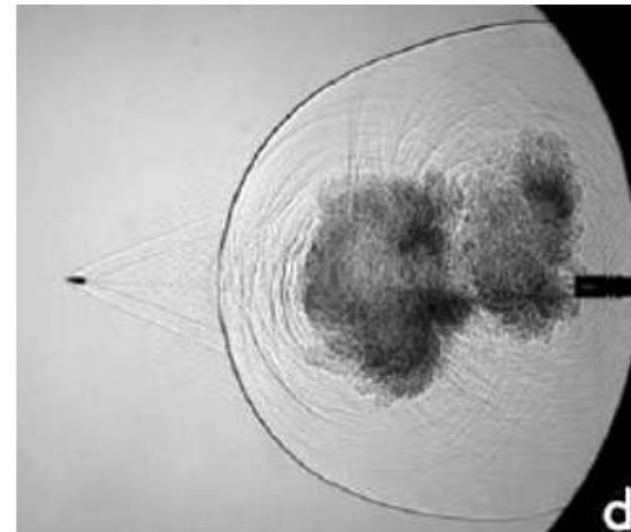
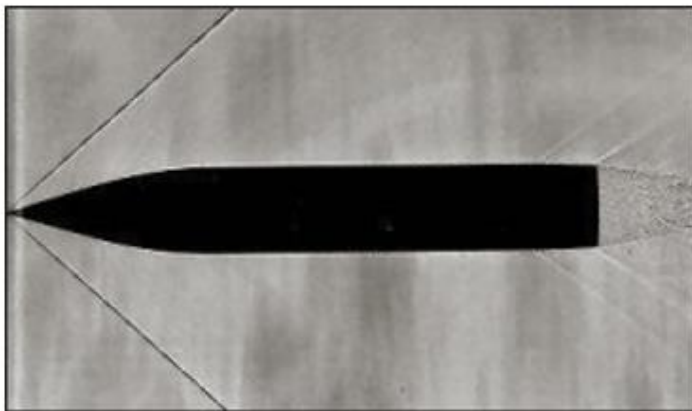


Image Sources:
<https://nuclearprojects.com/blog/schlieren-flow-visualization/>
https://www.researchgate.net/figure/Focused-shadowgrams-of-223-automatic-rifle-fire-a-sharply-focused-b-defocused-1m_fig3_226053639

5. Modeling & Testing

Range Testing



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5. Modeling & Testing

Range Testing



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5. Modeling & Testing

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5. Modeling & Testing

Range Testing

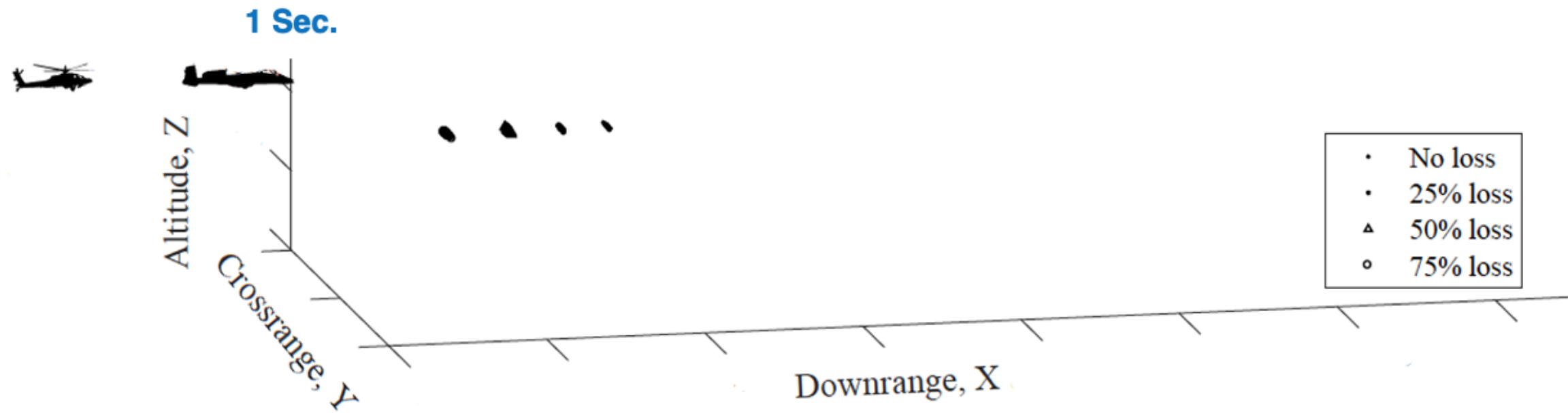


Distribution A Unlimited Distribution

6. BASS Performance

Flight Safety/Airframe Strike Check

AH-64 & A-10 Sabot separation Modeling (99% atmospheric)



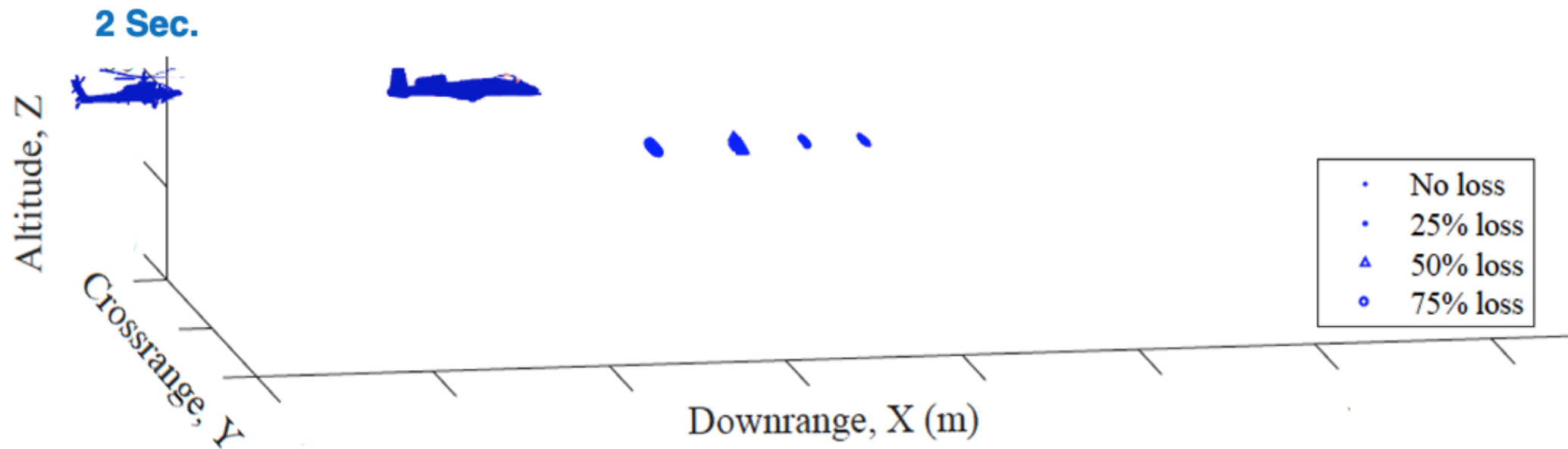
Source: Schumacher, L. N., "BASS Medium Caliber System Modeling: Proof-of-Concept and the Future of Aerial Gunnery with Advanced Munitions," Ph.D. Dissertation Defense, 29 June 2020, The University of Kansas Aerospace Engineering Department, Lawrence, Kansas.

Distribution A

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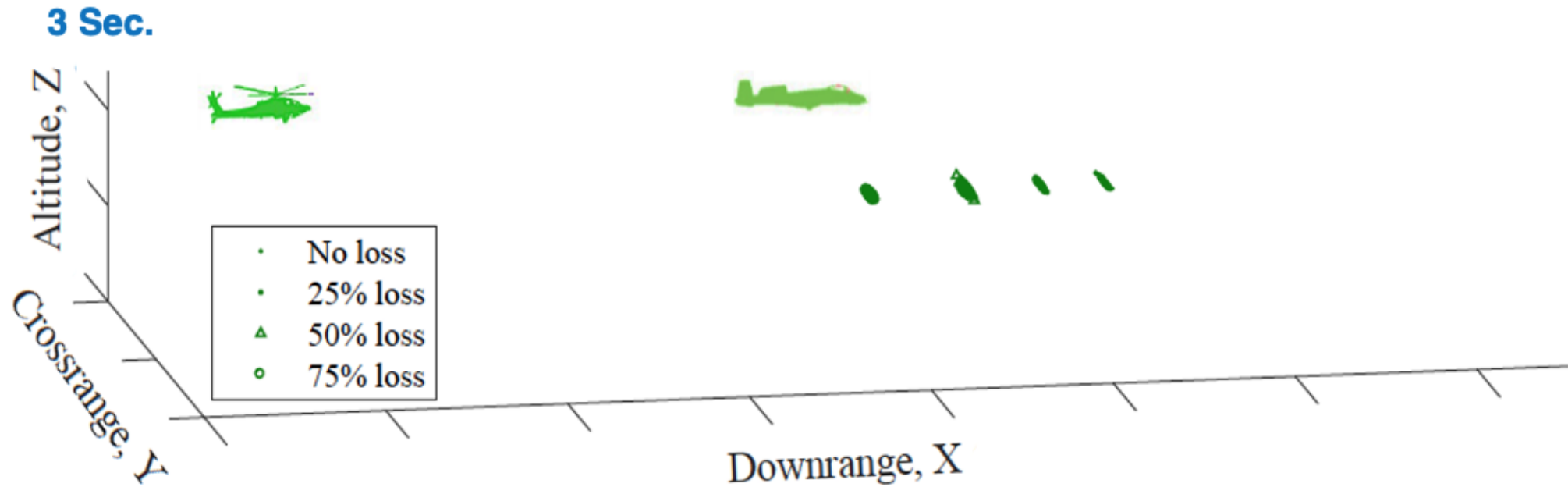


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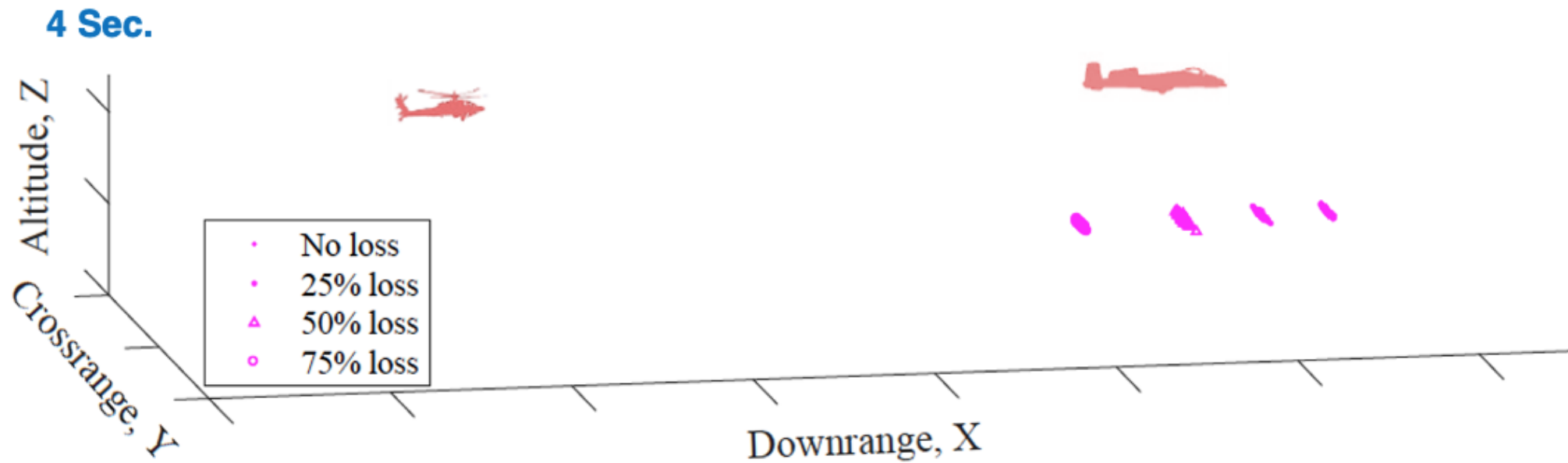
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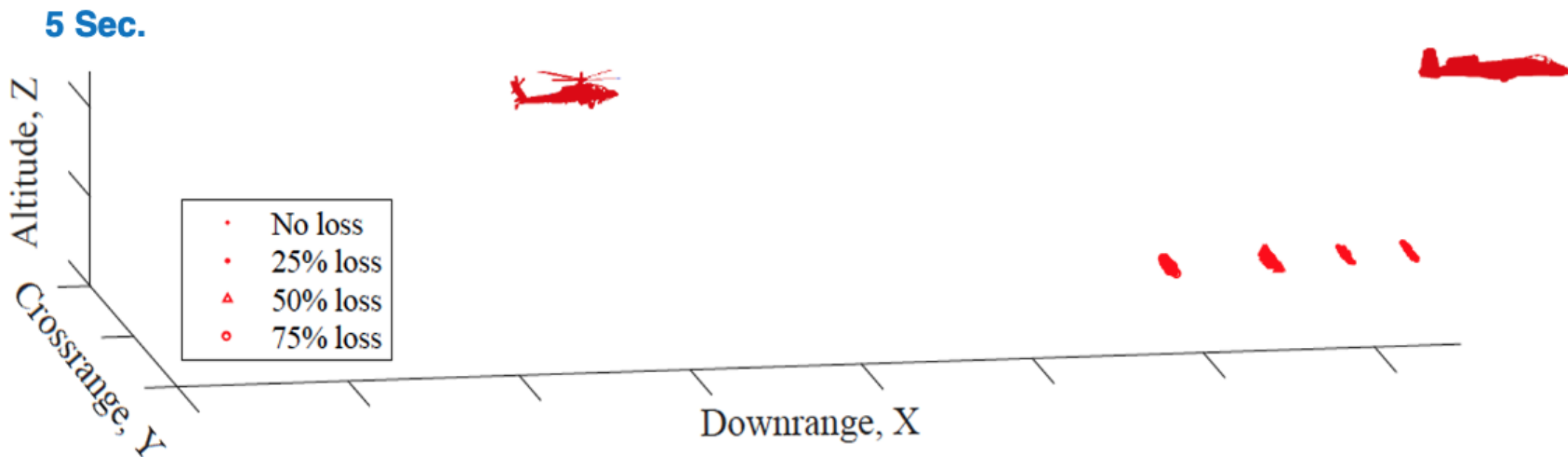
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Distribution A Unlimited Distribution

6. BASS Performance

Relative Ballistic Coefficients

45 cal. 1st Aerial Combat 1913



20mm USMC/M53/56



20mm USAF/PGU-28



25mm USAF/PGU-47



30mm Army AH-64 M789



*Aerial
Gunnery
Ammunition*

Distribution A Unlimited Distribution

6. BASS Performance

Relative Ballistic Coefficients



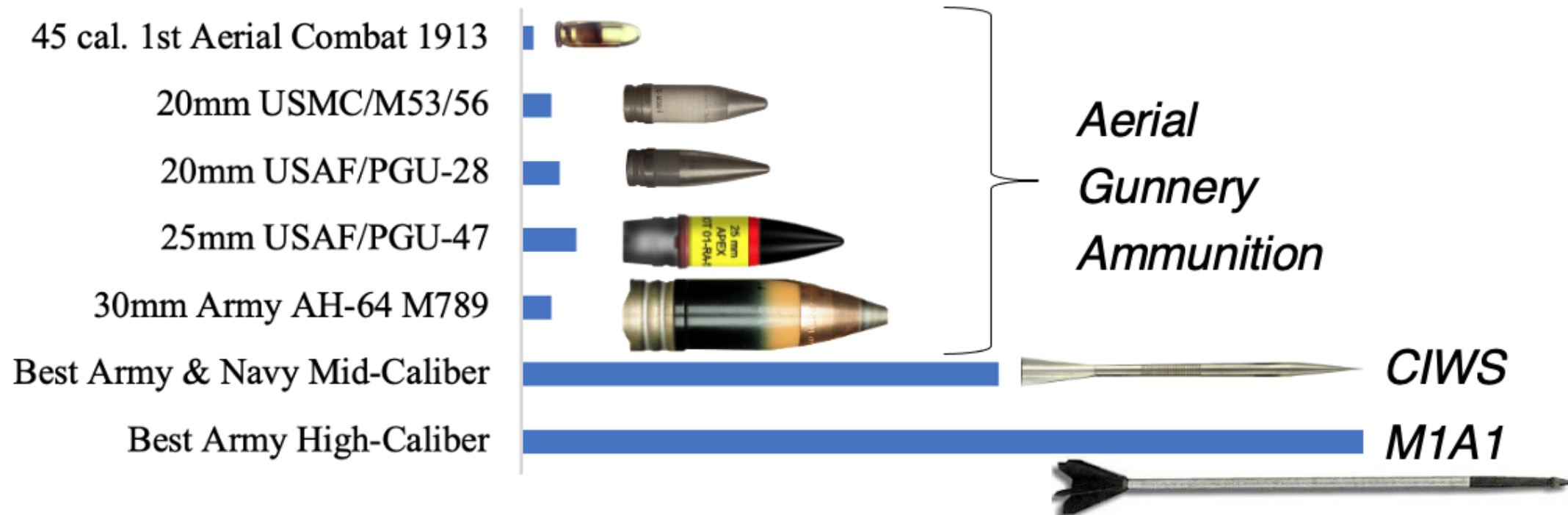
100 yrs



Distribution A Unlimited Distribution

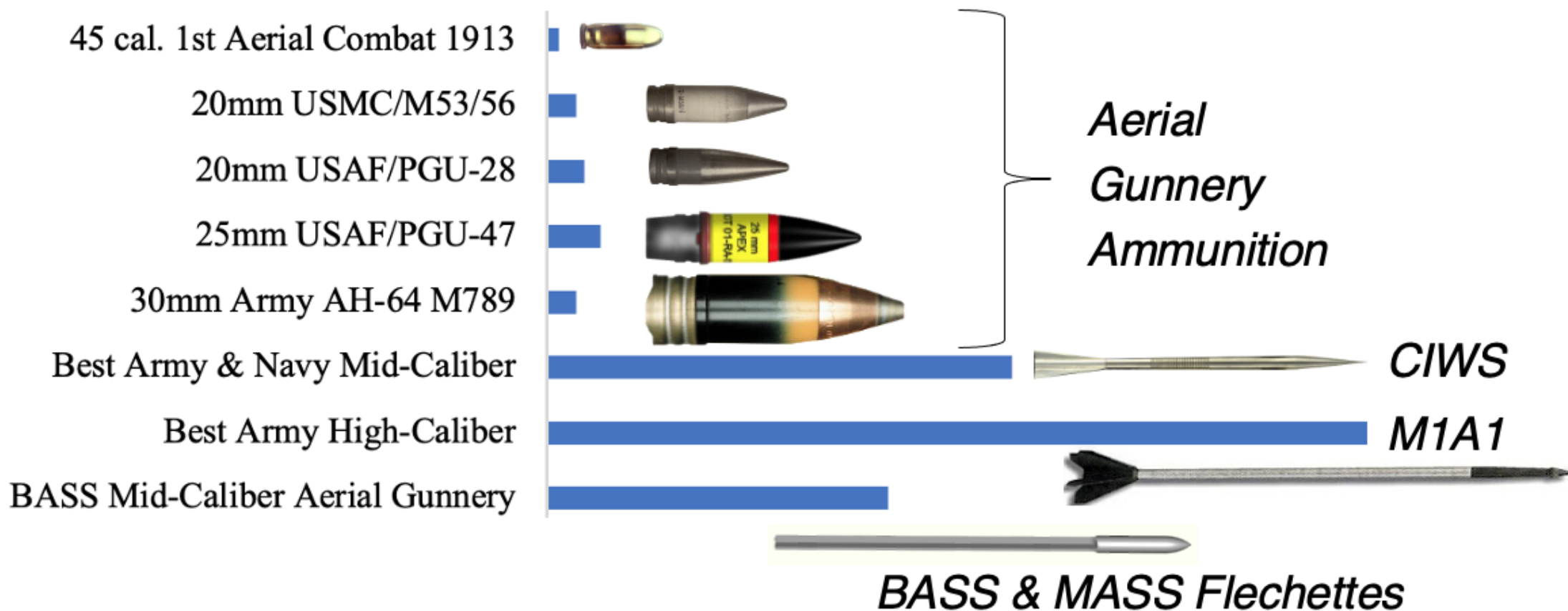
6. BASS Performance

Relative Ballistic Coefficients



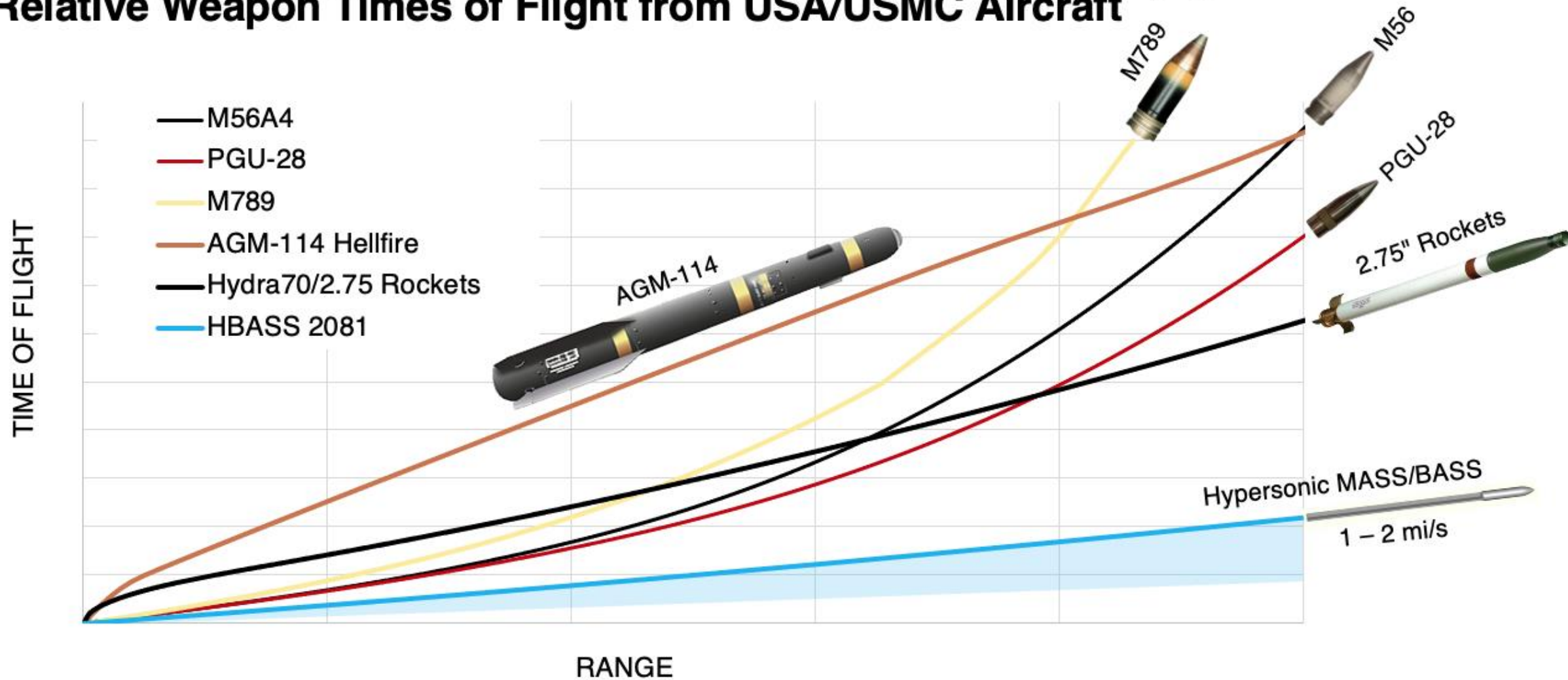
6. BASS Performance

Relative Ballistic Coefficients



6. BASS Performance

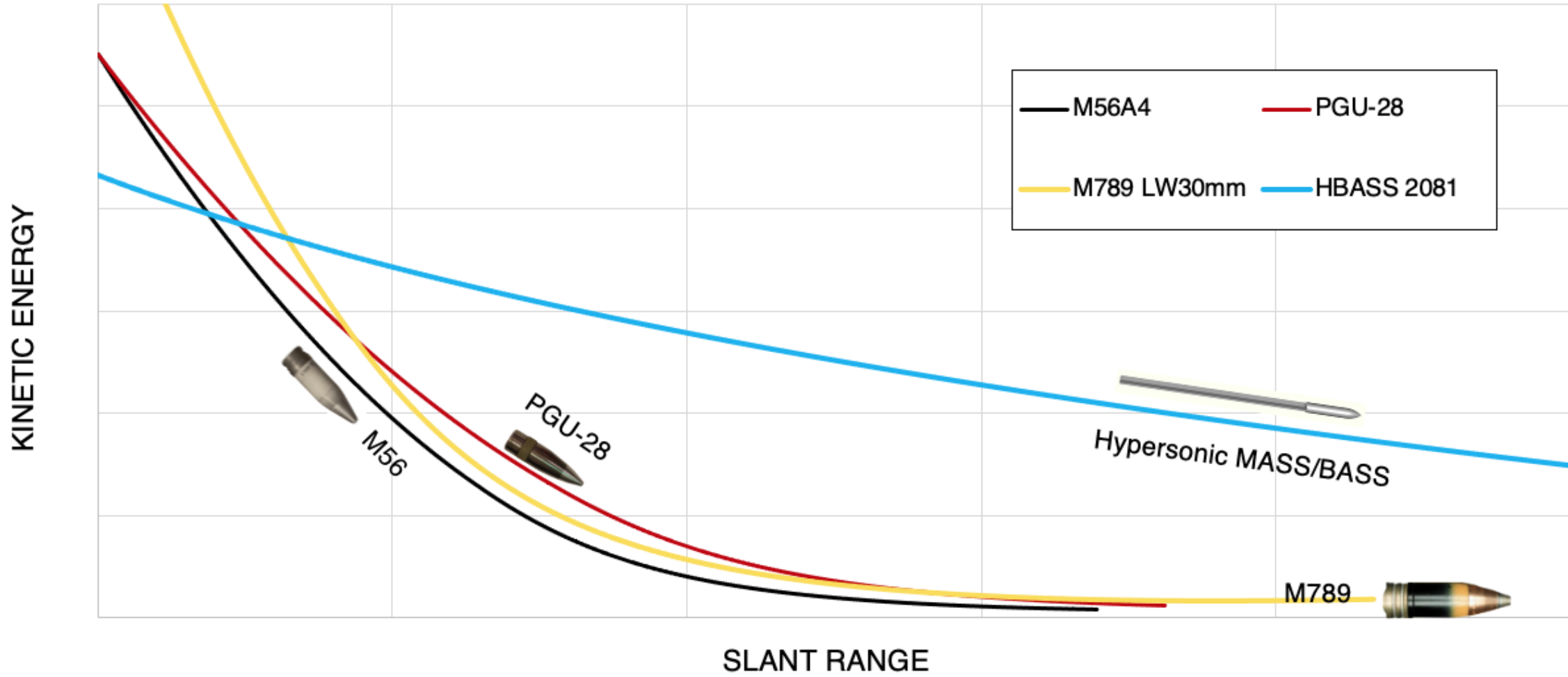
Relative Weapon Times of Flight from USA/USMC Aircraft



Distribution A Unlimited Distribution

6. BASS Performance

Relative Weapon Kinetic Energy from USA/USMC Aircraft



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7. Intellectual Property Staatus

WHAT IS CLAIMED IS:

- 1. AN AEROMECHANICALLY STABLE SABOT...**
- 2. THE AEROMECHANICALLY STABLE SABOT OF CLAIM 1, WHEREIN THE ASSEMBLY INCLUDES AT LEAST ONE AEROMECHANICALLY STABLE SEGMENT...**

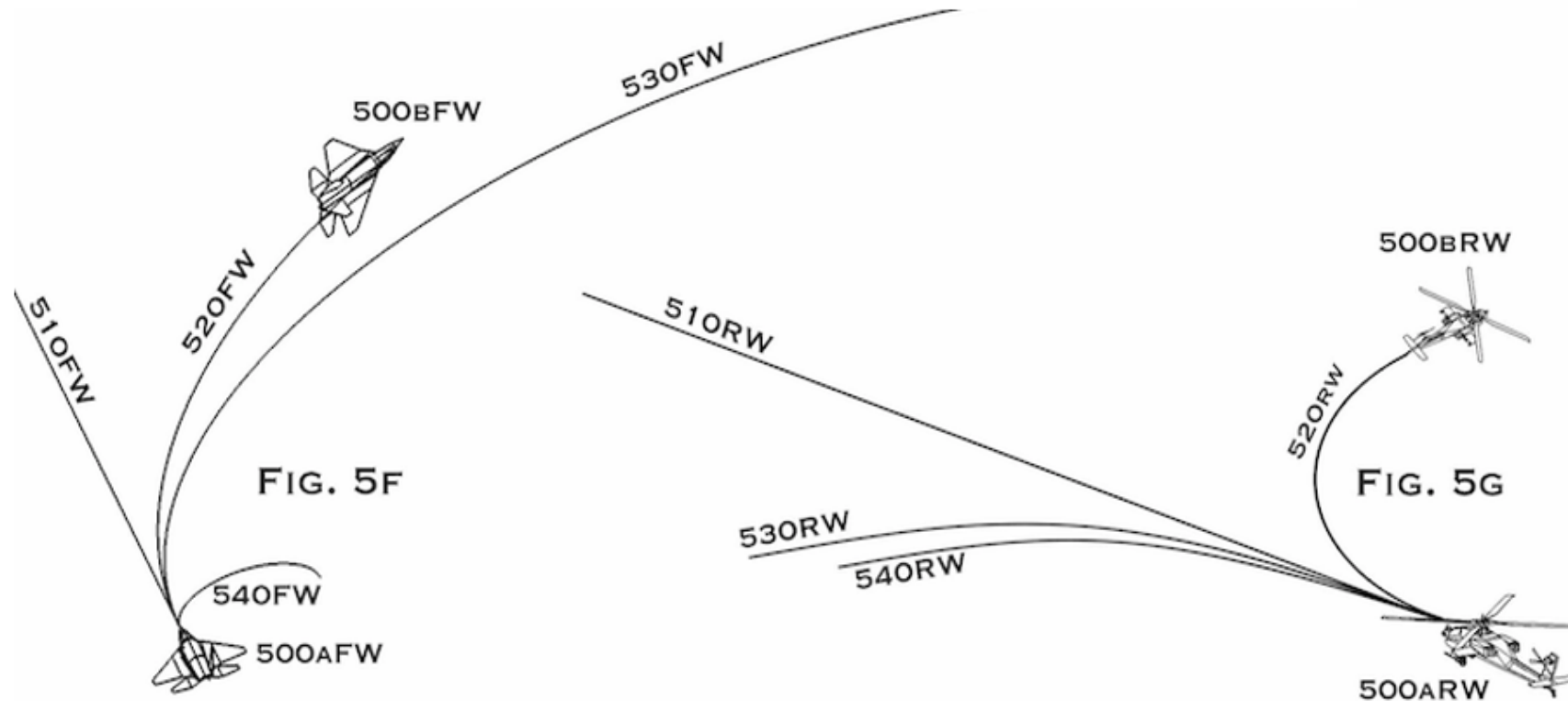


Image Source: PCT/IB2020/053899

Invented 2016

Modeled 2017

Reduced to practice 2018

Pat. priority date: 4/26/2019

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8. Opportunities

Attack Rotorcraft

AH-64 (M789 30 x 113mm) AH-1 (M56 20 x 102mm) FARA



Fixed-Wing Attack Aircraft

A-10 (PGU-14 30 x 173mm)



Multi-Role Fixed-Wing Aircraft

F-15, F-16, F-18, F-22 (PGU-28 20 x 102mm)

F-35 (PGU-47 25 x 137mm)



Gunships

AC-130 (25mm, 40mm, 105mm)



Armed Drones

MQ-9, MQ-?, Bayraktar TB2, Shadow...



8. Opportunities ...Nontrivial chance of capturing a substantial part of the market

US Army: (DoD FY 2019 Budget Exhibit P-1 FY 2019, P. A-17C)

20, 25, 30mm \$113M/yr



USMC: (DoD FY 2019 Budget Exhibit P-1 FY 2019, P. N-20C)

20, 25, 30mm \$34M/yr



US Air Force: (DoD FY 2019 Budget Exhibit P-1 FY 2019, P. F-19C)

20, 25, 30mm+ \$193M/yr



8. Opportunities KU Aerospace: open for business...

- **Exclusive & non-exclusive licenses available for:**

- US, Europe-Wide, Germany, Norway, Australia, UK, Netherlands, France, Belgium, Spain, Italy, Japan, Korea, Singapore

Approved by the Federal Government for export

- **Engineering support: 3+ yr acceleration, data sets** (as allowed by law)

- On site support up to 2 yrs

- **Operational Units:**

- "What's possible – whole new mission sets" briefings (ITAR restricted)

- **Corporate Labs:**

- "What's possible" briefings (ITAR restricted & open)

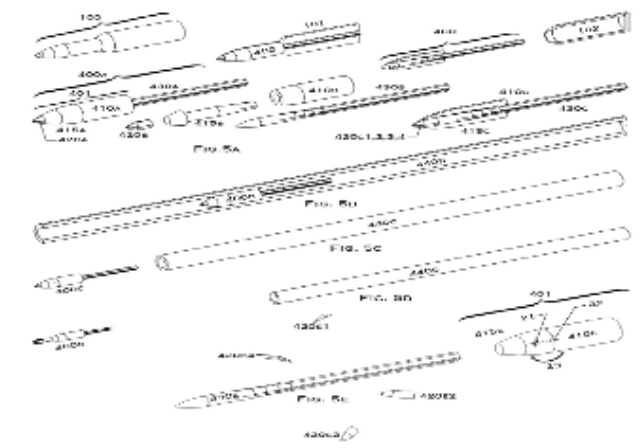
- Short courses (1 hr to 2 days)

- Patent/IP structure, legal offense/defense planning & weaponization

- **Government Labs:**

- Next research steps & navigating 15 CFR § 700 to 700.93 DPA

- Short courses (1hr to 2 days)



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Questions?

Visit us at Booth 412

Wed. 21 Sept. 3:30 – 3:50pm Level 4, Room 18D

Outgunning the A-10 With an Apache or Fara:
New Flight-Safe Discarding Sabot Ammunition for Attack Rotorcraft

