Flight Safe Discarding Sabot Ammunition: Configurations, Range Data, General Performance & IP Status

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KU THE UNIVERSITY OF KANSAS

Recognition:

Dr. Lauren Schumacher

Co-Inventor
Ballistic Aeromechanically Stable Sabot (BASS) Ammunition

Senior Systems Engineer, Raytheon

Structure:

i. *BASS Basics – Aeromechanics, Kinematics*

ii. *Design Philosophy & Configurations*

iii. *Basic Physics*

iv. *General Performance*

v. *Intellectual Property Filings, Claims & Status*

vi. *Opportunities*

Conventional Discarding Sabot Design Philosophy and Aeromechanics

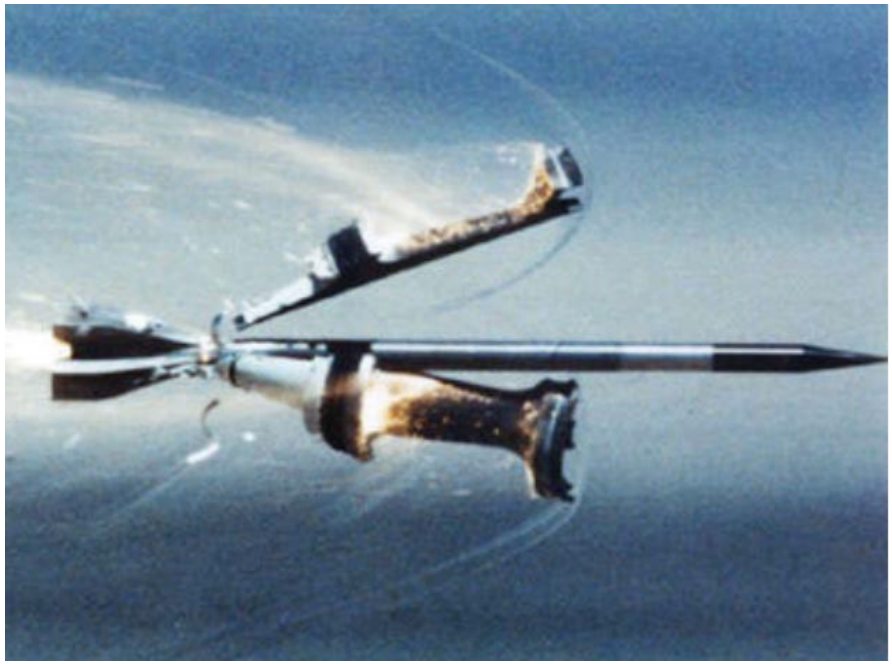
Flechette ammunition by its nature must be sabot launched. Herein lies another advantage and its major disadvantage. The advantage of sabot launch is, of course, that the projectile has a low sectional density while in the gun bore and can be easily accelerated to velocities not readily attainable with conventional shot. 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.

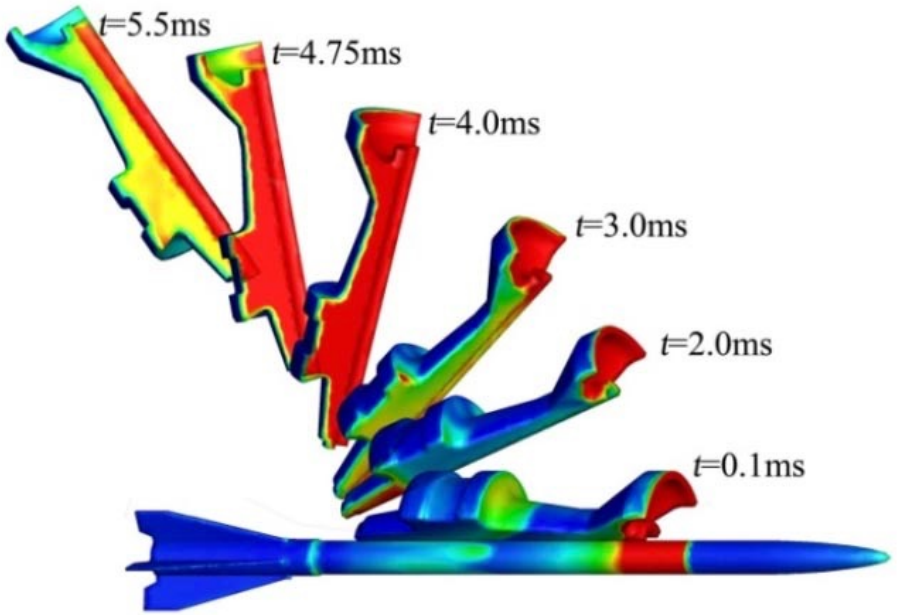
*-**Dale Davis**, Director, USAF Munitions Directorate 1984*

Problems with Aircraft & Sabots

Conventional Discarding Sabot

Aeromechanically unstable by necessity...





Problems with Aircraft & Sabots

Why a conventional sabot won't work for aerial gunnery

Dale Davis' Observations:

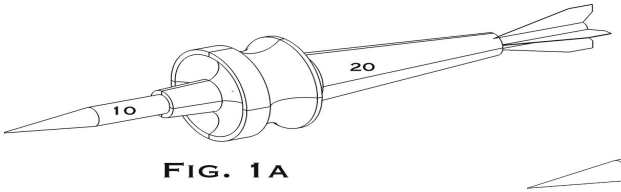


FIG. 1A

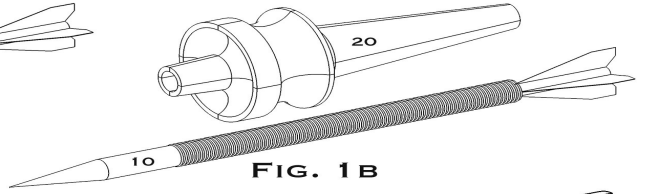


FIG. 1B

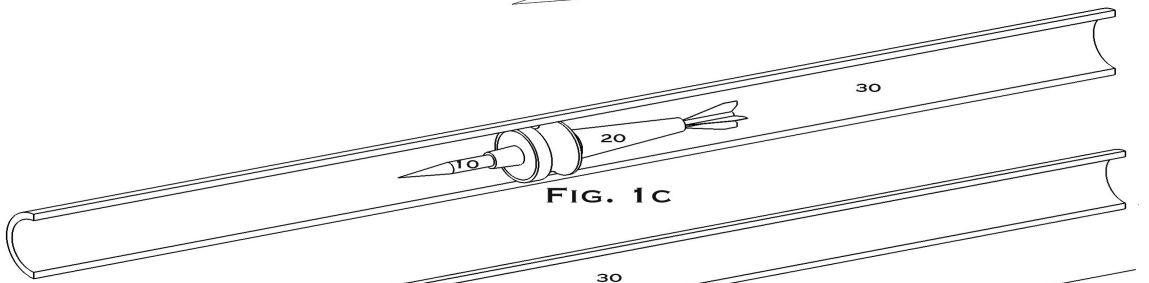


FIG. 1C

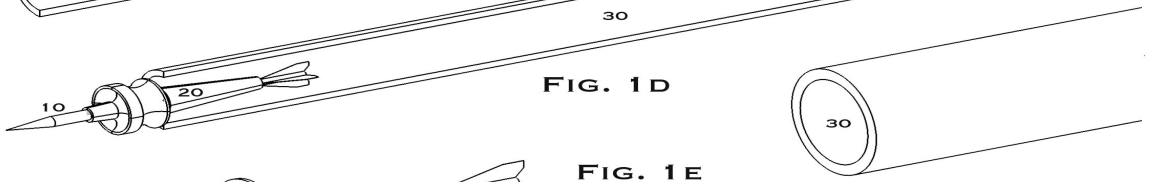


FIG. 1D

FIG. 1E

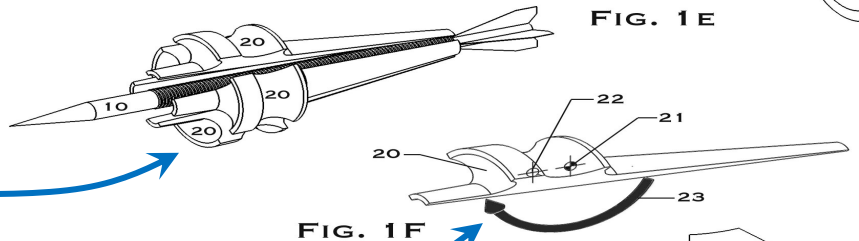


FIG. 1F

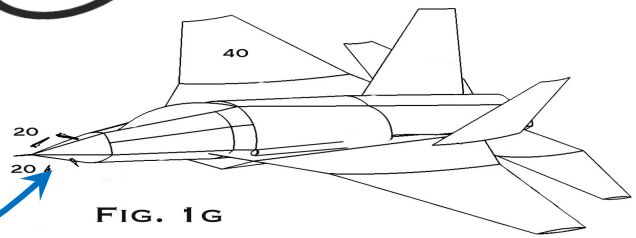


FIG. 1G

FIGURES 1

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

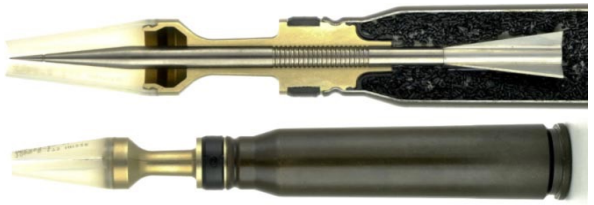
Aeromechanically unstable sabot pieces tumble

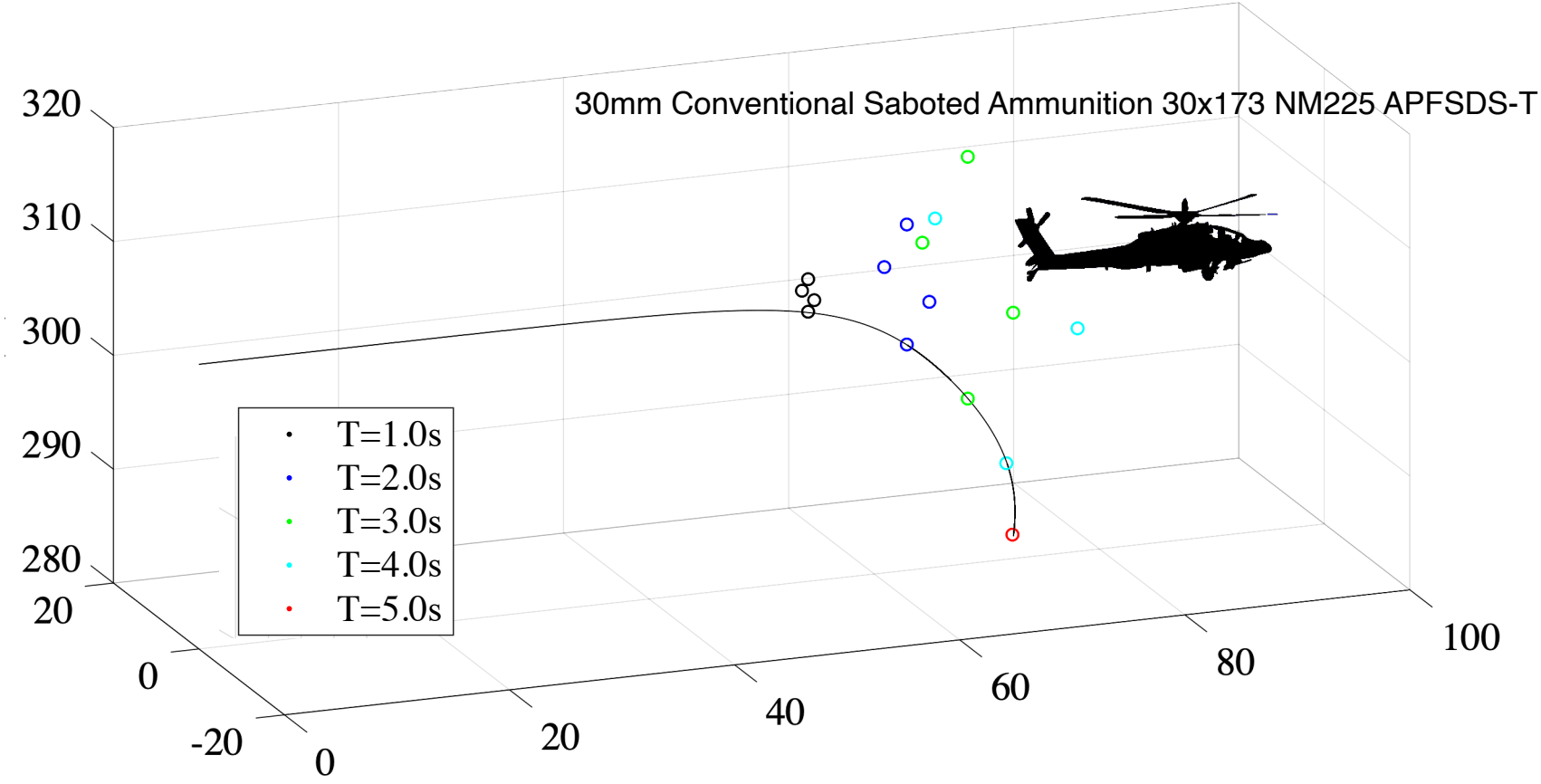
...and strike airframe/engine

Image Source: PCT/IB2020/053899

Problems with Aircraft & Sabots

The Great Show Stopper for conventional sabots:
Flight Safety

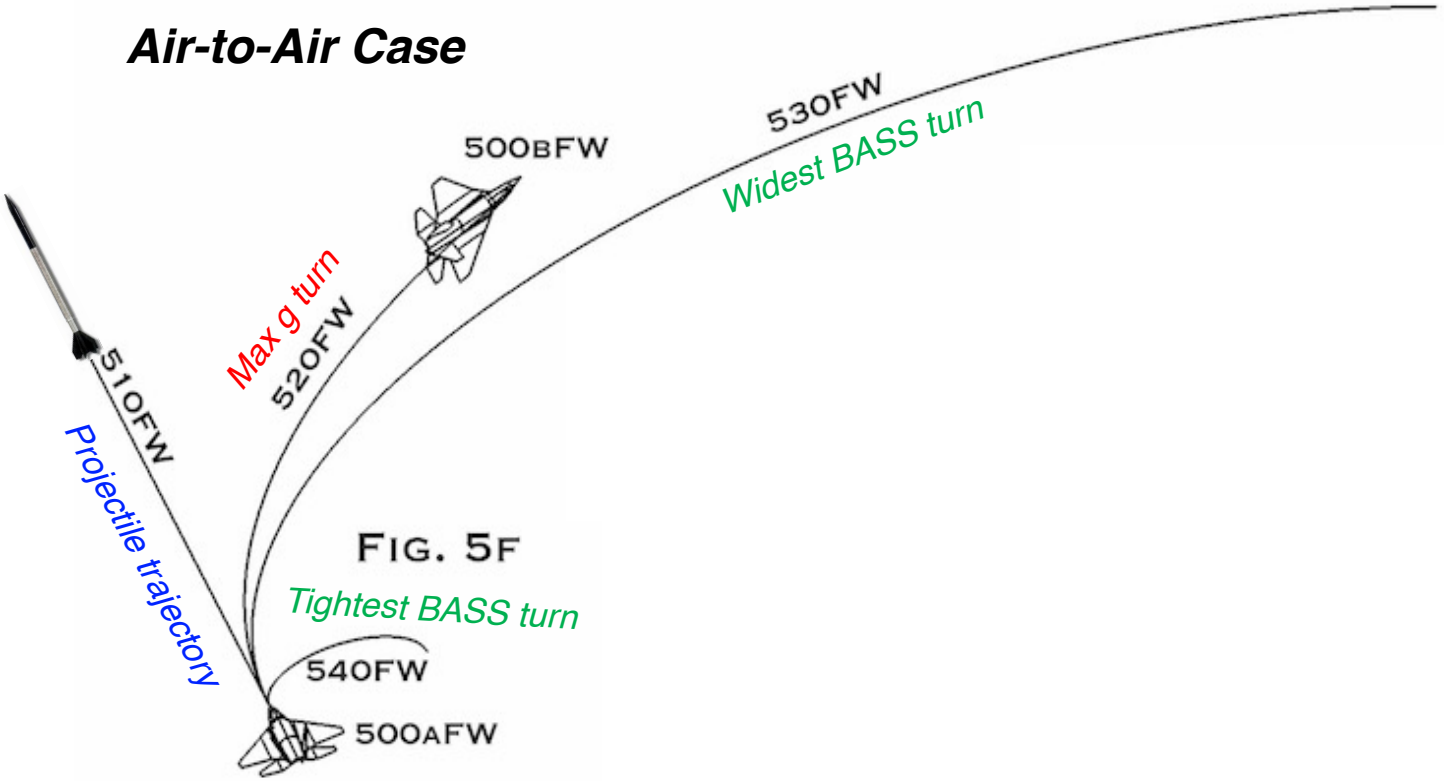




I. BASS Basics – Aeromechanics, Kinematics

BASS Rounds: Design the Sabot to clear the launching aircraft

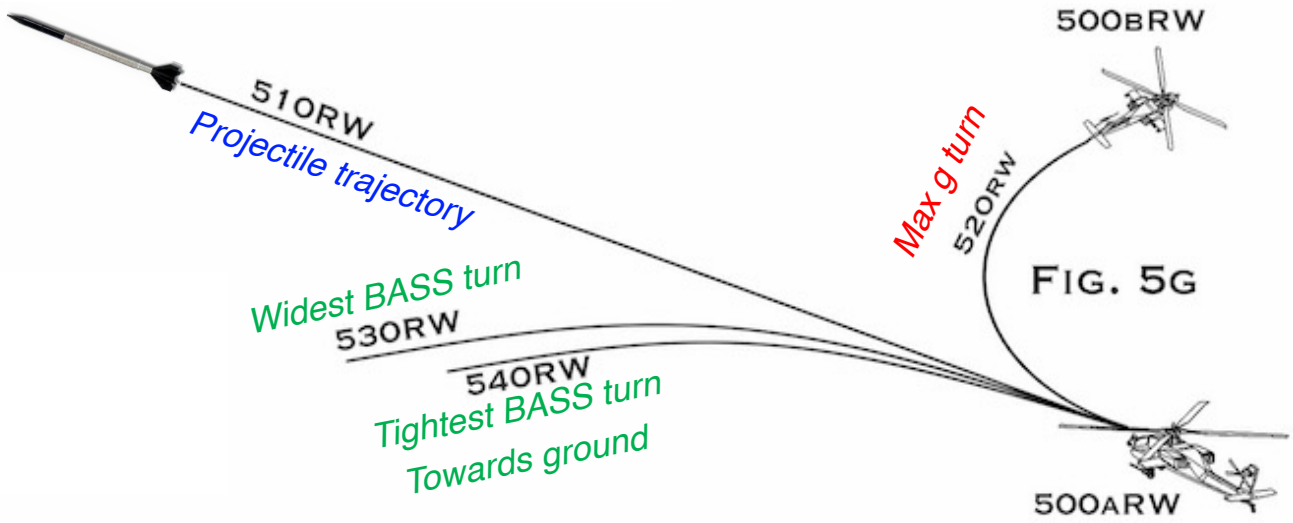
Air-to-Air Case



I. BASS Basics – Aeromechanics, Kinematics

BASS Rounds: Design the Sabot to clear the launching aircraft

Ground Attack Case



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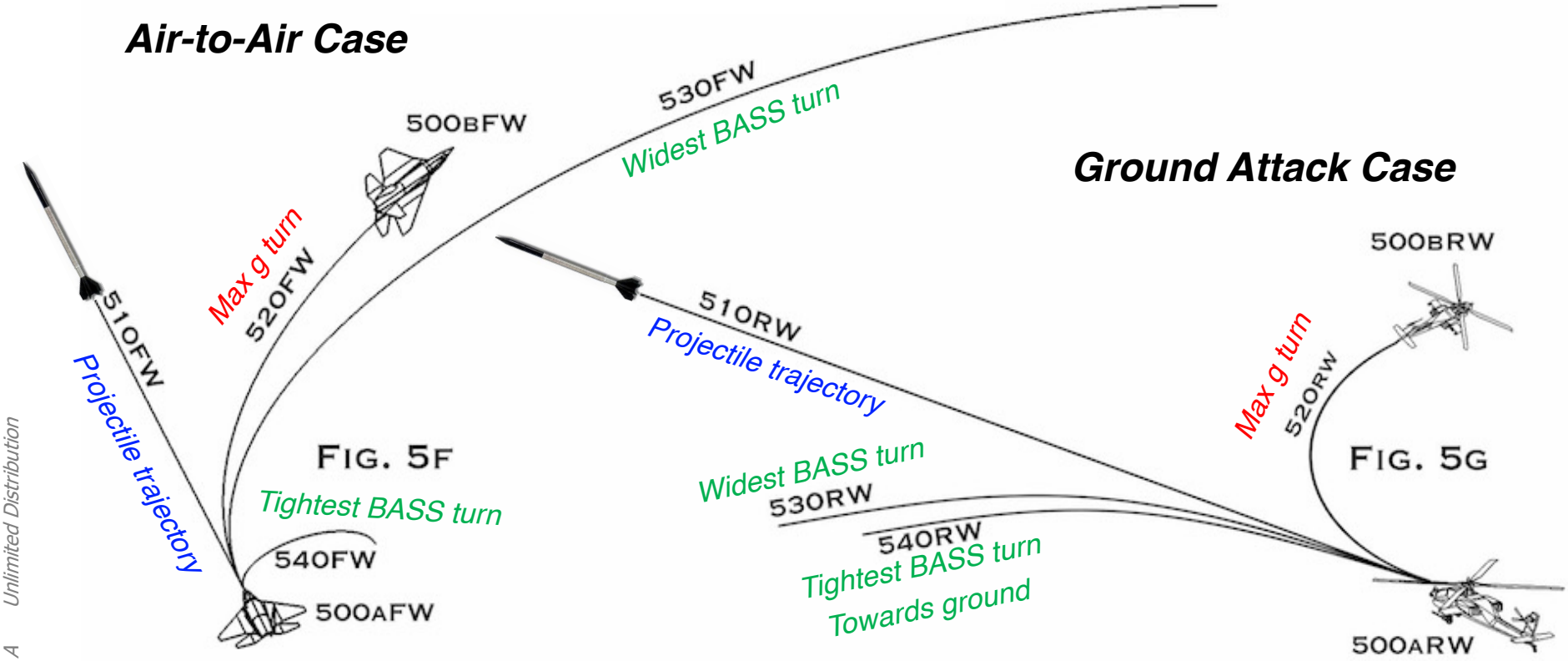

Image Source: PCT/IB2020/053899

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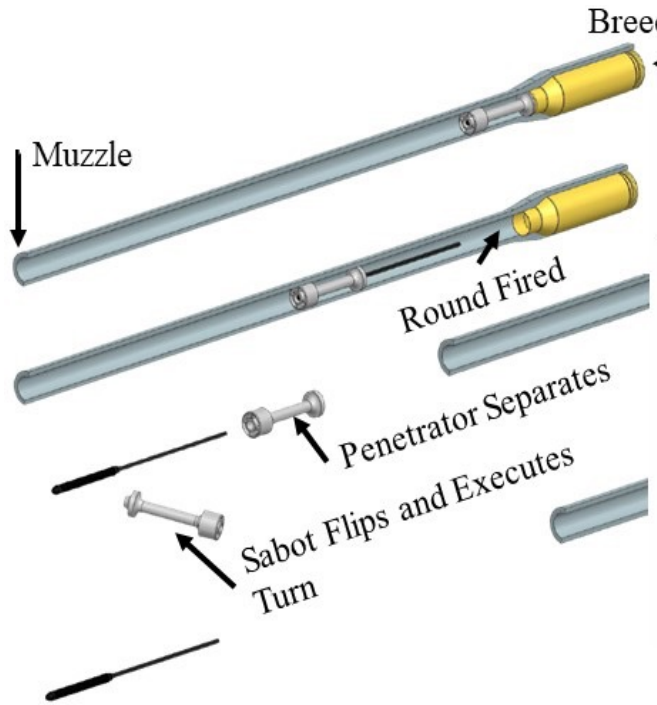
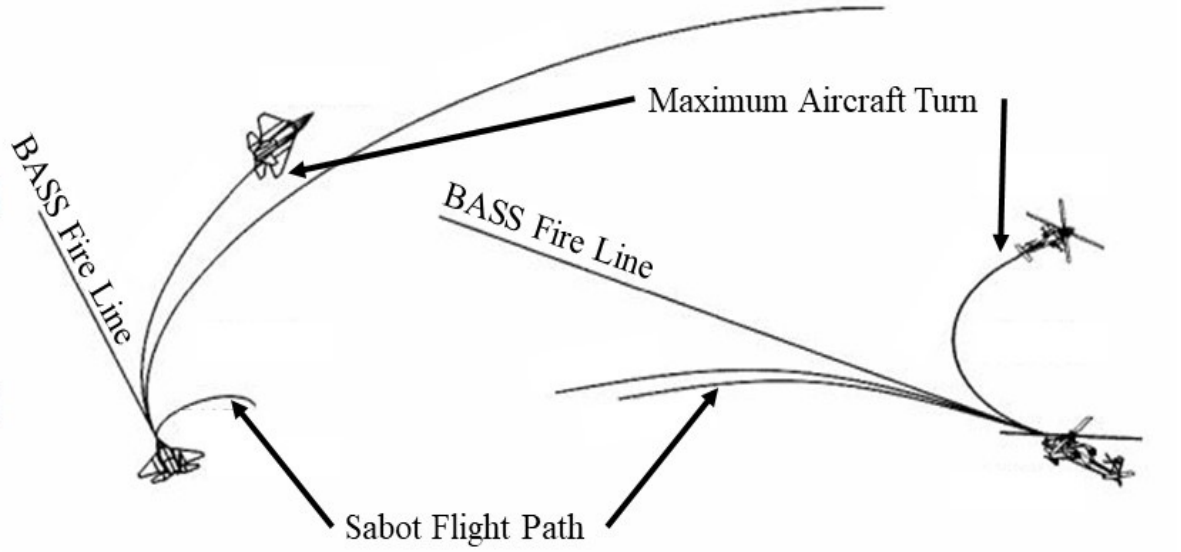
BASS Rounds: Design the Sabot to clear the launching aircraft





I. BASS Basics – Aeromechanics, Kinematics

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

How safe?
FAR-23: 10^{-6} air-to-air
FAR-25: 10^{-9} ground attack

II. Design Philosophy

1. Use BASS configuration to increase KE at combat relevant ranges & range at usable KE as much as possible;

2. Render sabot flight safe by flying clear of launching aircraft & wingmen;

3. Maintain more HE volume & lethal effects than conventional/target round;

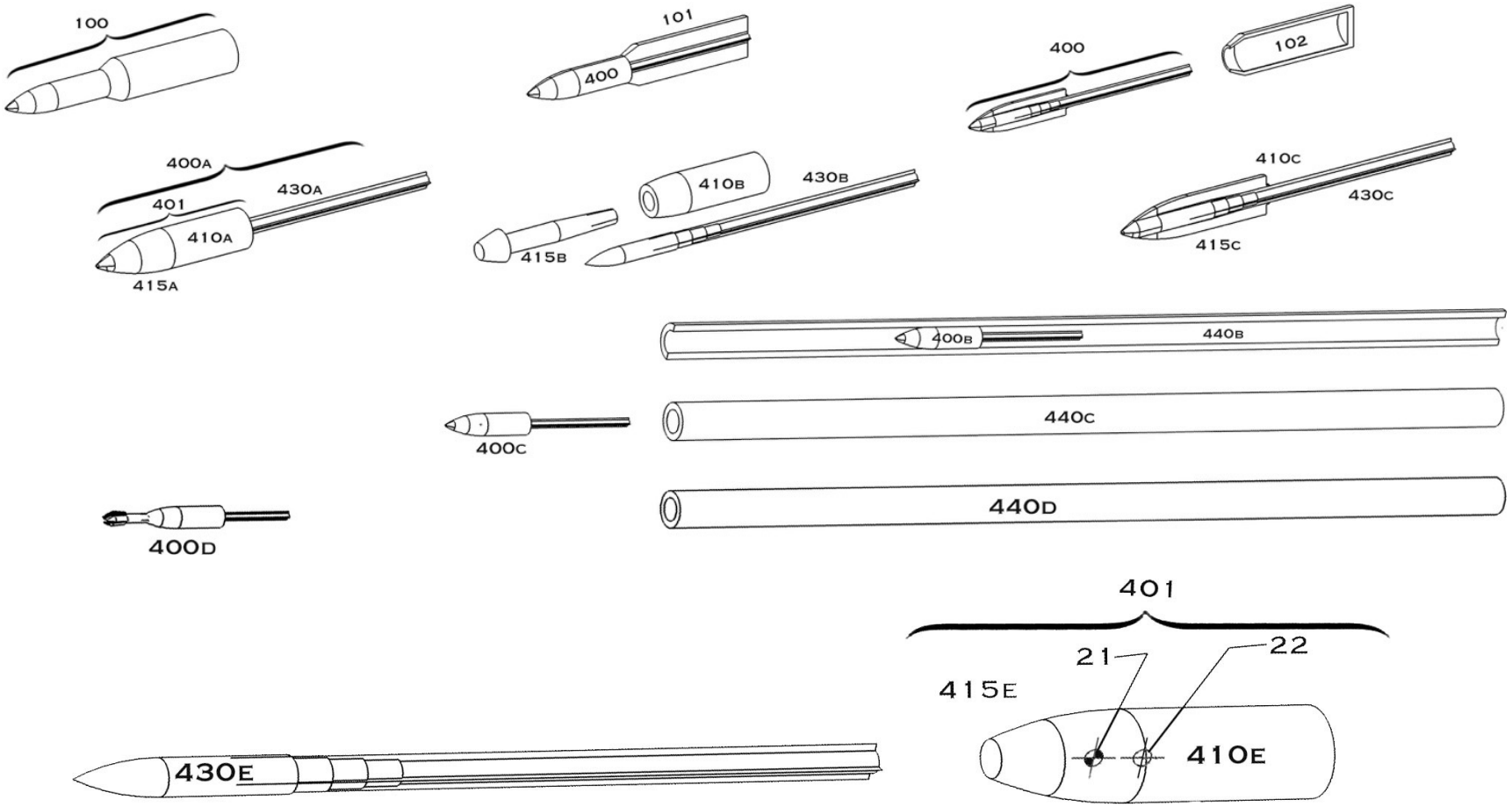
4. Cut CEP by reducing gust sensitivity;

5. Maintain full compatibility with existing guns & barrels.

II. Design Philosophy

What is claimed is:

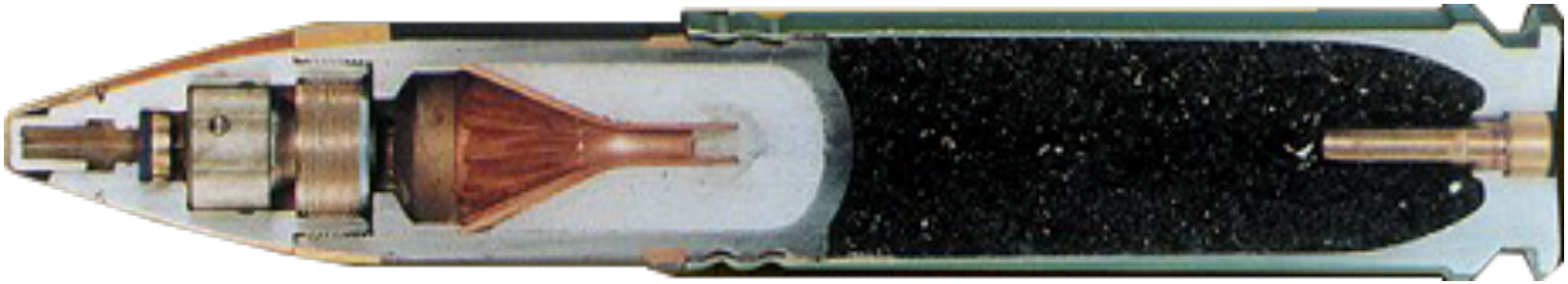
1. An aeromechanically stable sabot...



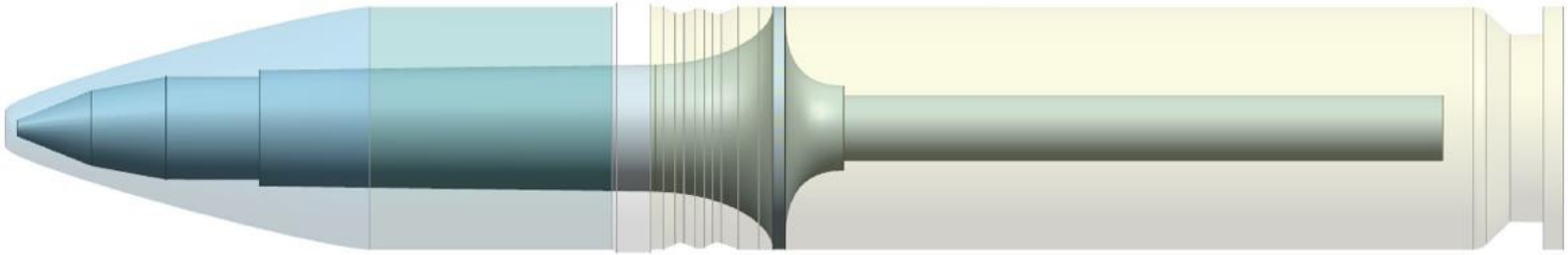
54 major families, >1,000 species covered in expansive patent filings

II. Design Philosophy

Today's "Advanced" M789 Aerial Gunnery Round



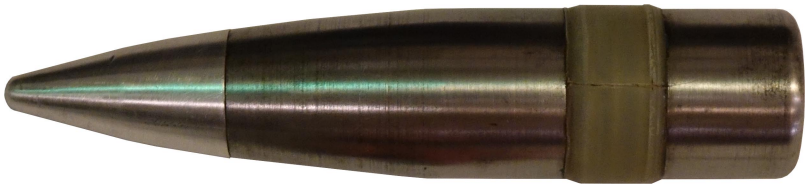
BASS Round: Sub-caliber flechette goes into powder, seated in sabot

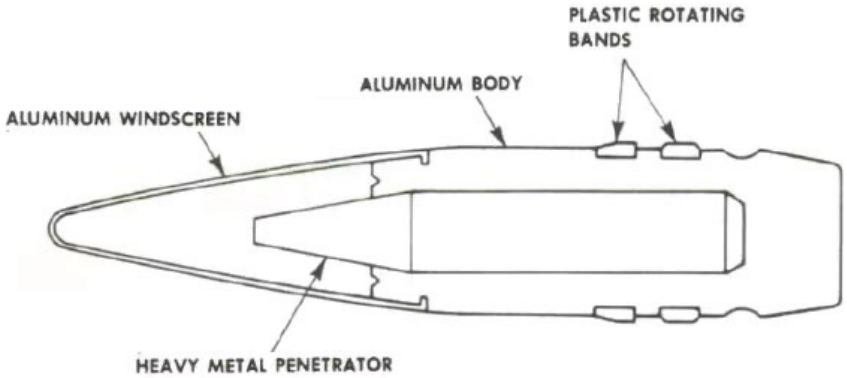


II. Design Philosophy

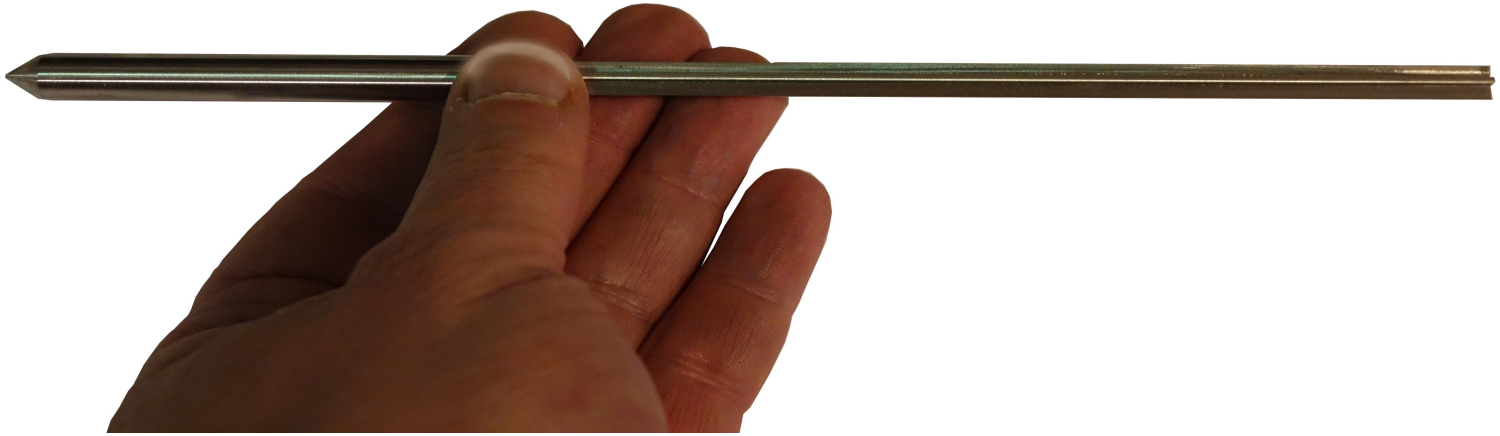
Today's "Advanced" Aerial Gunnery Round

PGU-14





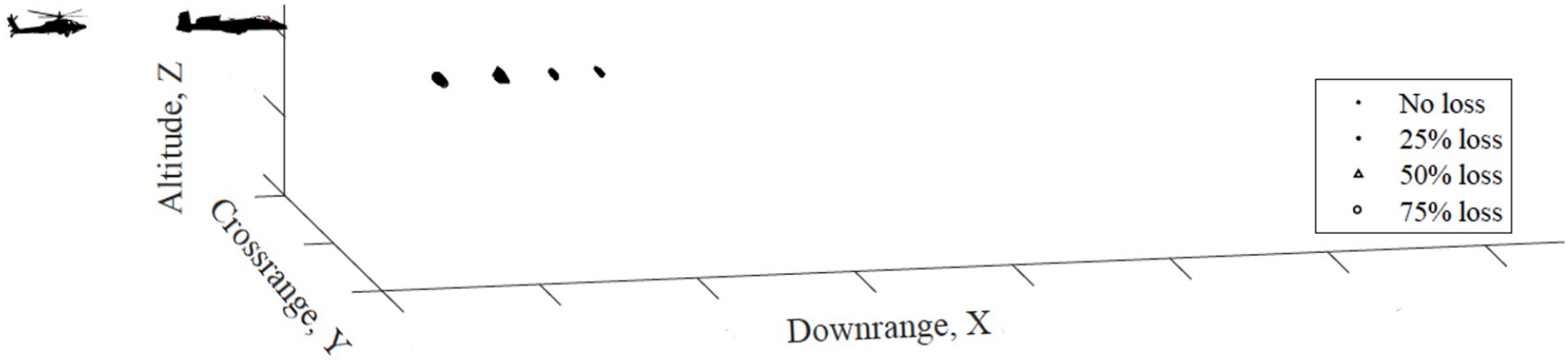
BASS 2081 Flechette/penetrator



III. Basic BASS Physics

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

1 Sec.



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.

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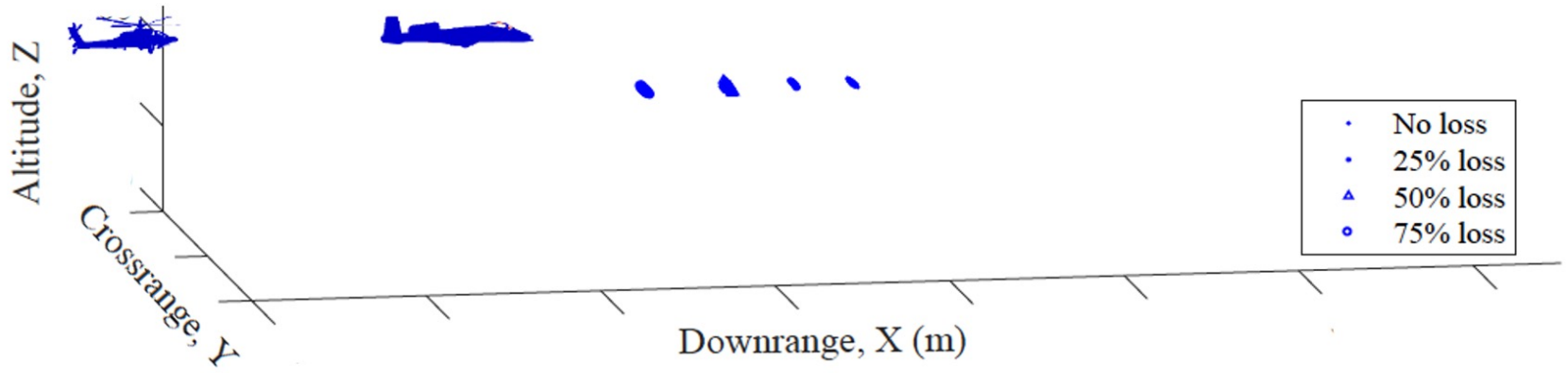
2 Sec.



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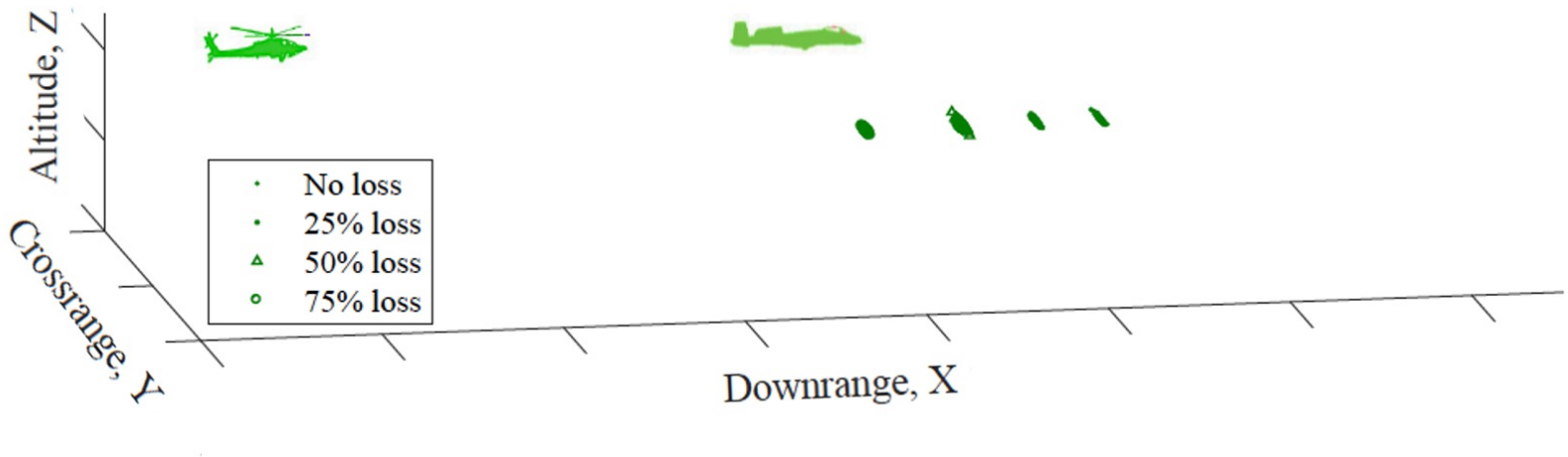

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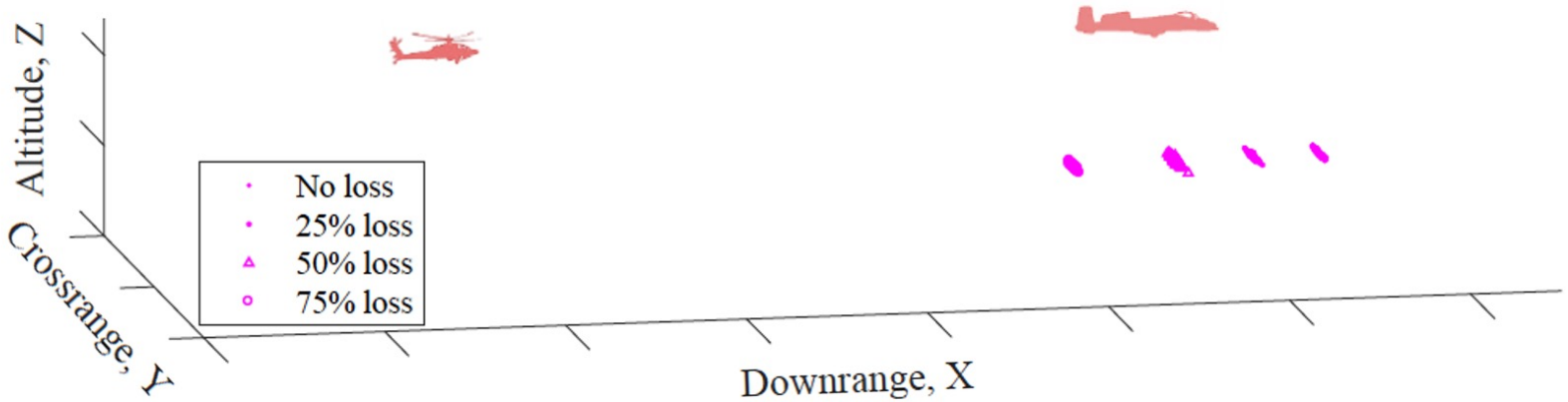

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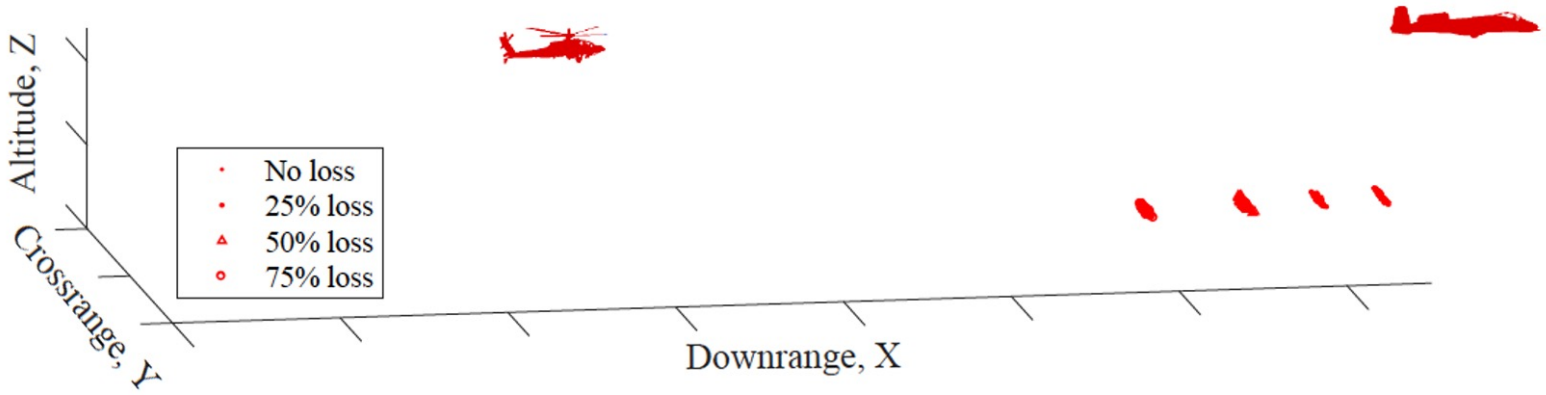
5 Sec.



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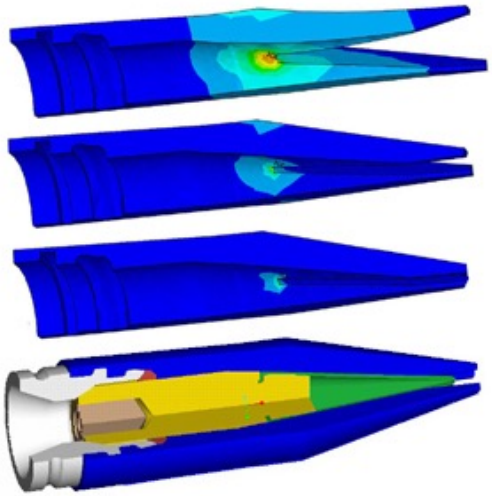
III. Basic BASS Physics

Interior Ballistics

Modeling, Analysis & Testing



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_Zecevic_Dispersion_PGU-14_ammunition%5B1%5D.pdf

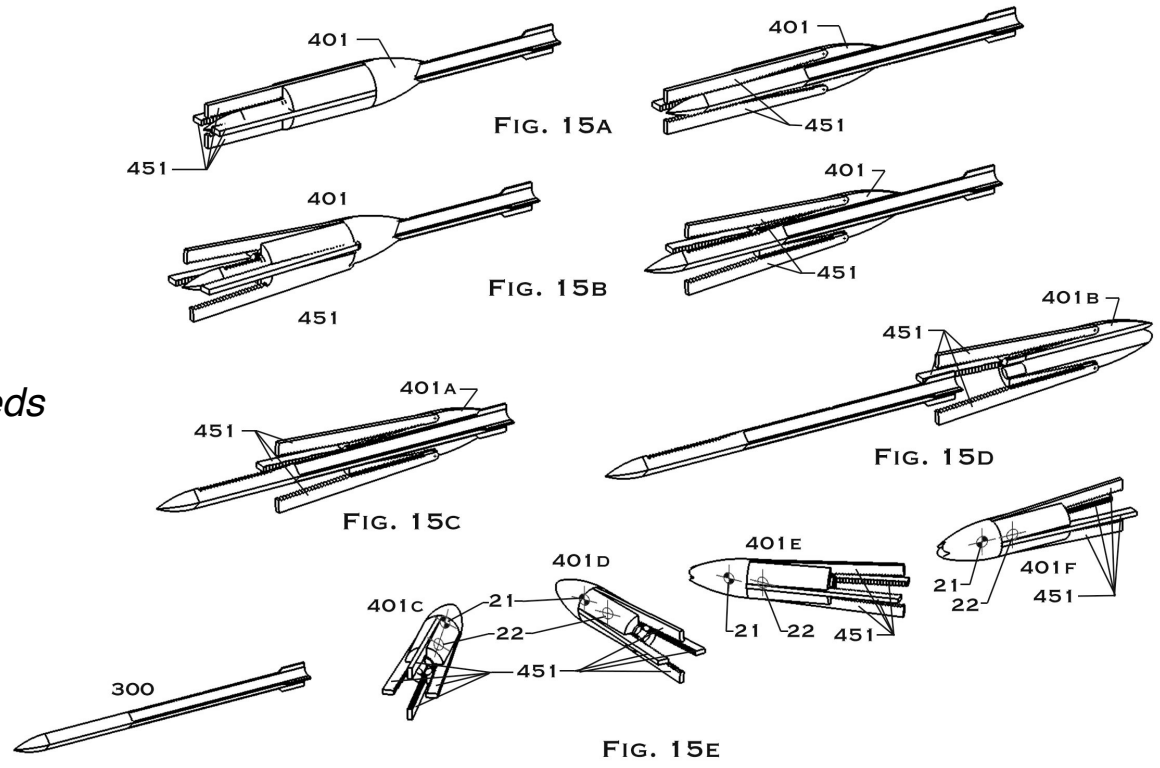
III. Basic BASS Physics

Exit Dynamics

Sabot Separation event

Ballistic Aeromechanically Stable Sabot (BASS)

- *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

III. Basic BASS Physics

Freeflight Aeromechanics

Modeling, Analysis & Testing

System Modeling & Design:

• 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

$$\begin{bmatrix}\dot{X}\\ \dot{Y}\\ \dot{Z}\end{bmatrix} = q_b^* \begin{bmatrix}U\\ V\\ W\end{bmatrix} q_b$$

Body Linear Momentum

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

Body Angular Momentum

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

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

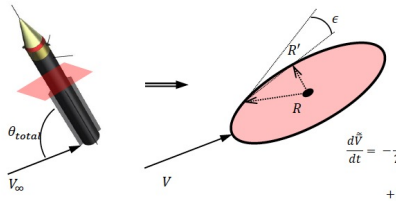
$$\begin{bmatrix}\dot{q}_0\\ \dot{q}_1\\ \dot{q}_2\\ \dot{q}_3\end{bmatrix}_i = \frac{1}{2}\begin{bmatrix}0 & 0 & 0 & -r\\ 0 & 0 & r & 0\\ 0 & -r & 0 & 0\\ r & 0 & 0 & 0\end{bmatrix}\begin{bmatrix}q_0\\ q_1\\ q_2\\ q_3\end{bmatrix}_i \qquad \dot{r}_i = n_i\left(I_{zz_i} + \frac{mb^2}{4}\right)^{-1}$$

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

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

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

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



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

$$c_P = c_{P_{0,2}}\sin^2(\theta)$$

$$c_P = c_{P0}\sin^2\theta = \left(\left[\frac{(\gamma+1)^2}{4\gamma}\right]^{\frac{\gamma}{\gamma-1}}\frac{4}{\gamma+1} - \frac{2}{\gamma M_\infty^2}\right)\sin^2\theta$$

$$\frac{d\bar{V}}{dt} = -\frac{1}{2m}\rho S v C_D \bar{V} + \frac{1}{2m}\rho S C_{L_\alpha}\left(V^2\hat{X} - (\bar{V}\cdot\hat{X})\bar{V}\right) - \frac{1}{2m}\rho S D C_{N_{pa}}\left(\frac{I_{yy}}{I_{xx}}\right)(\bar{h}\times\hat{X})(\hat{X}\times\bar{V}) + \frac{1}{2m}\rho S V D\left(C_{N_q} + C_{N_\alpha}\right)(\bar{h}\times\hat{X}) + \bar{g} + \bar{\Lambda}$$

$$\frac{d\bar{h}}{dt} = \frac{1}{2I_{yy}}\rho S V d C_{M_\alpha}(\bar{V}\times\hat{X}) + \frac{1}{2I_{xx}}\rho V S d^2 C_{M_{pa}}(\bar{h}\cdot\hat{X})(\bar{V} - (\bar{V}\cdot\hat{X})\hat{X}) + \frac{1}{2I_{yy}}\rho S V D^2\left(C_{M_q} + C_{M_\alpha}\right)(\bar{h} - (\bar{h}\cdot\hat{X})\hat{X}) + \frac{1}{2I_{xx}}\rho S V D^2 C_{l_p}(\bar{h}\cdot\hat{X})\hat{X} + \frac{1}{2I_{yy}}\rho S V^2 C_{l_\delta} D\delta_F\hat{X}$$

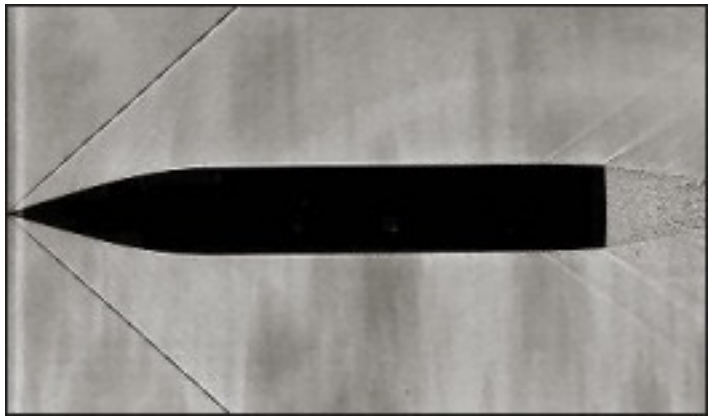
III. Basic BASS Physics

Freeflight Aeromechanics

Modeling, Analysis & Testing

Experimental Validation:

• Wind tunnel verification of preferred BASS sabot geometry center of pressure and aerodynamic center location with angle of attack changes.



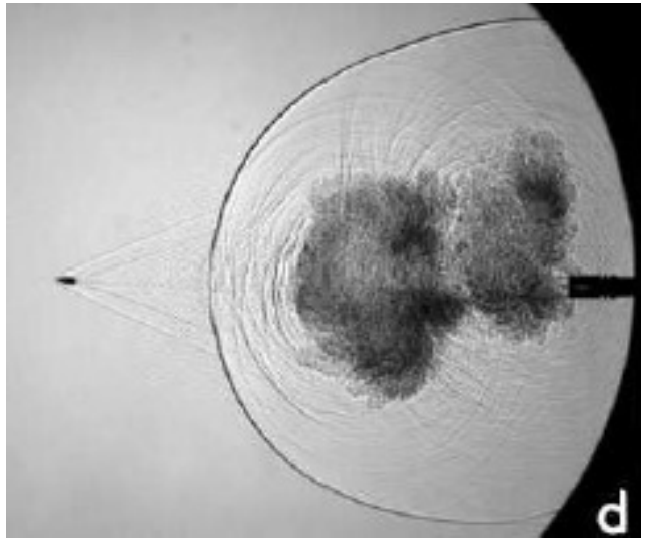


Image Sources:
https://nuclearprojects.com/blog/schlieren-flow-visualization/
https://www.researchgate.net/figure/Focused-shadowgrams-of-223-automatic-rifle-fire-a-sharply-focused-b-defocused-1m_fig3_226053639

III. Basic BASS Physics

Projectile Aeromechanics & CEP Fundamentals

General Configurations

Old Munitions:

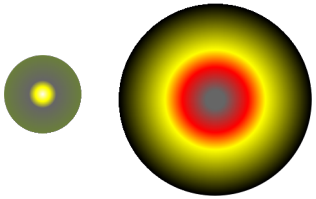
BASS Flechette

III. Basic BASS Physics

Projectile Aeromechanics & CEP Fundamentals

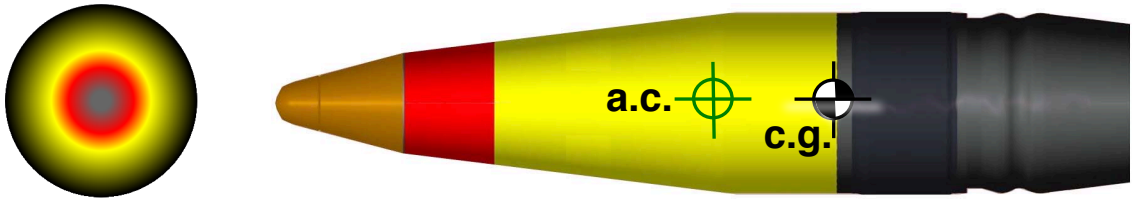
Flechette

X-Sectional Area of PGU-14 >> Flechette



PGU-xx

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

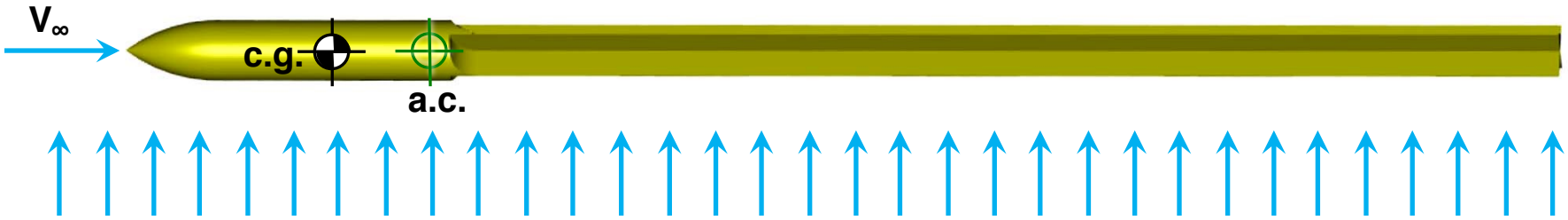


III. Basic BASS Physics

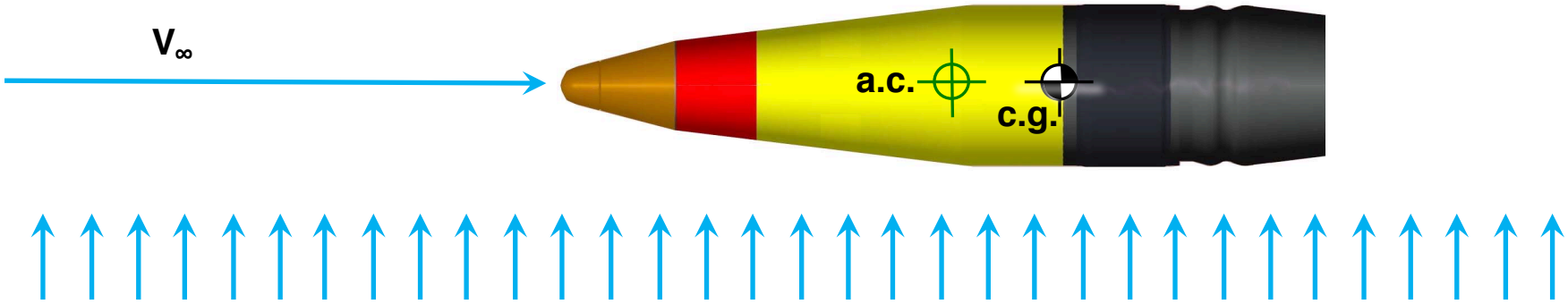
Projectile Aeromechanics & CEP Fundamentals

Flechette

Instantaneous introduction of lateral gust

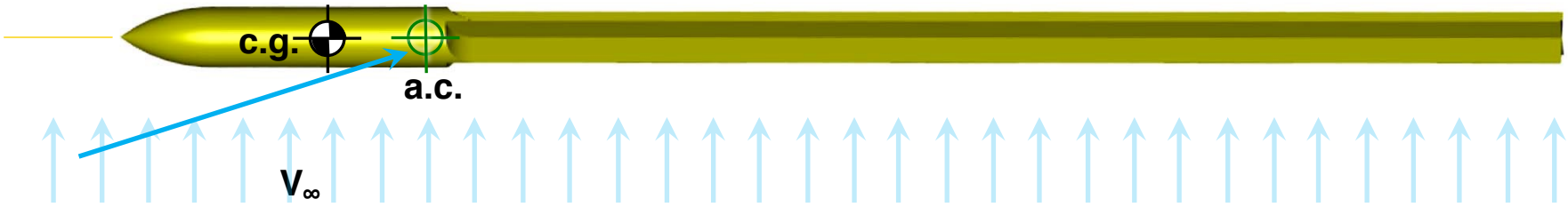


PGU-xx

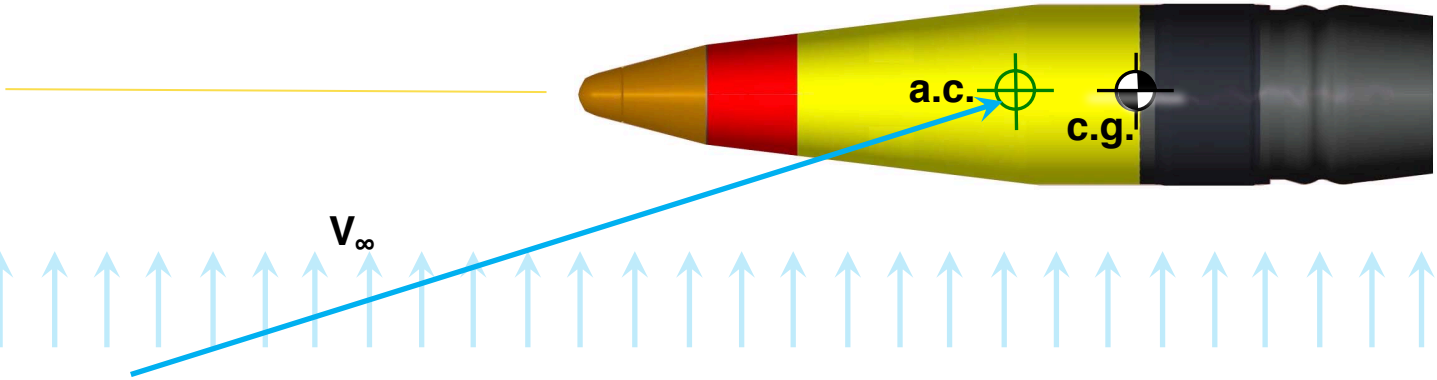


III. Basic BASS Physics

Projectile Aeromechanics & CEP Fundamentals

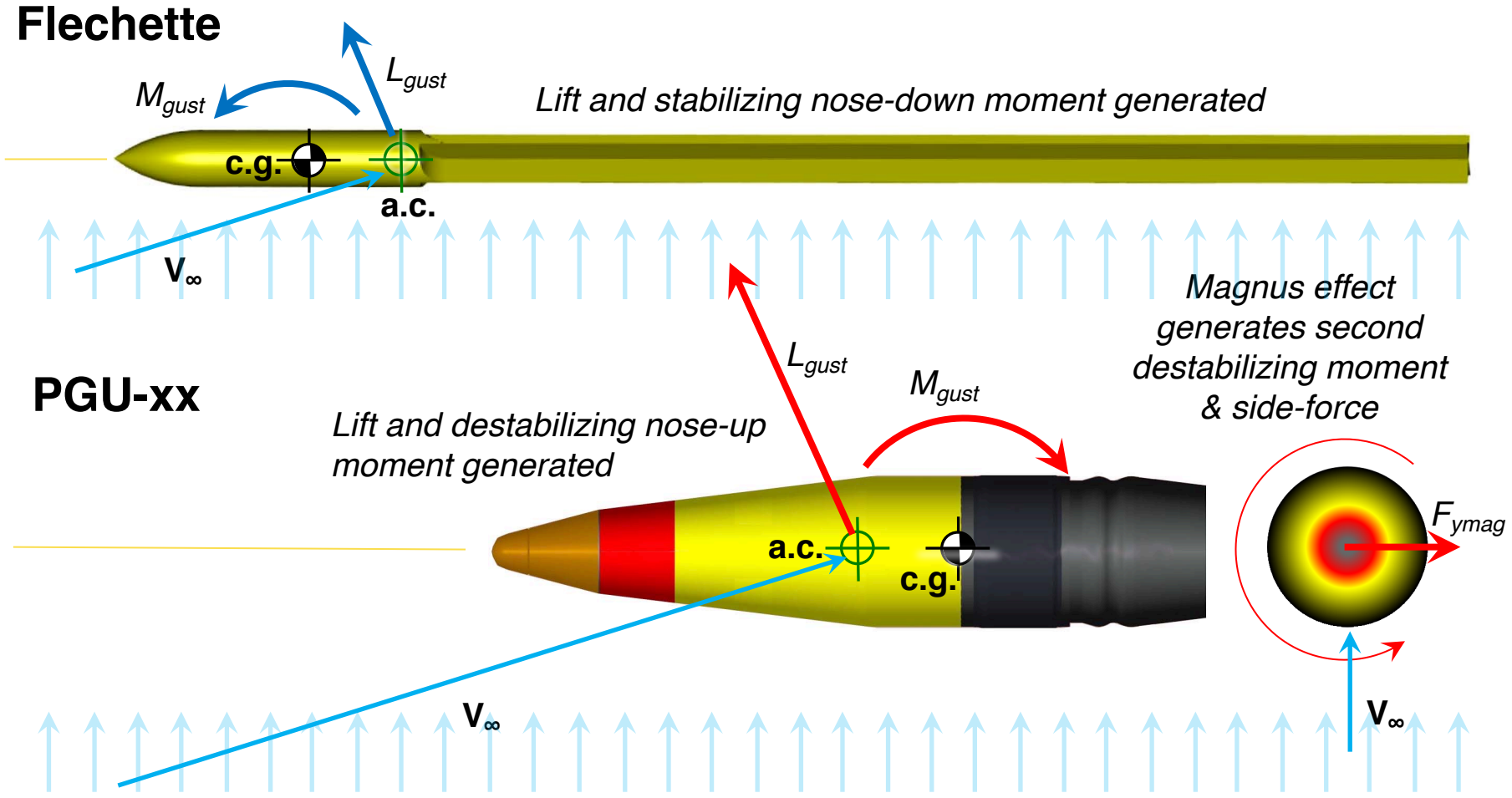


PGU-v



III. Basic BASS Physics

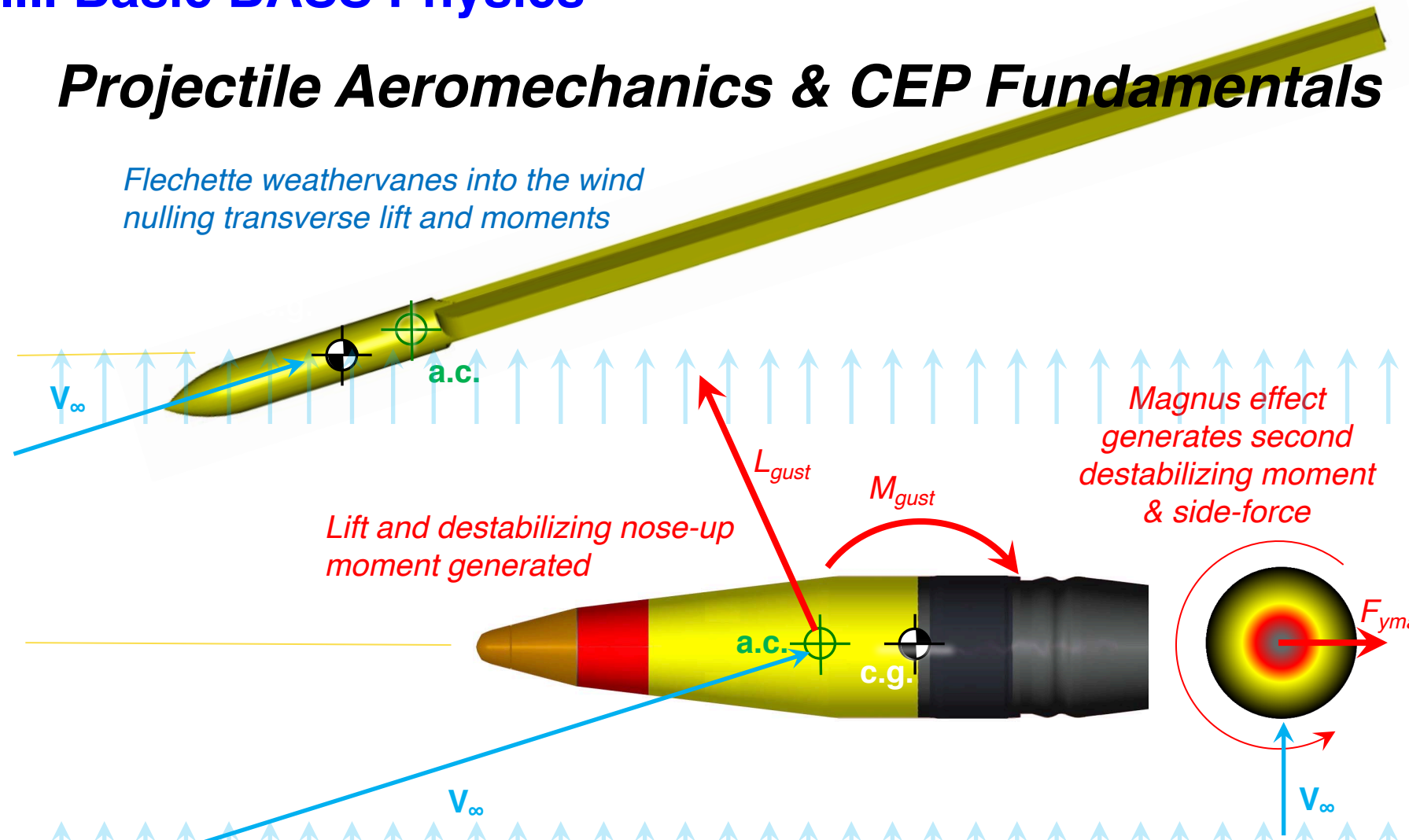
Projectile Aeromechanics & CEP Fundamentals



III. Basic BASS Physics

Projectile Aeromechanics & CEP Fundamentals

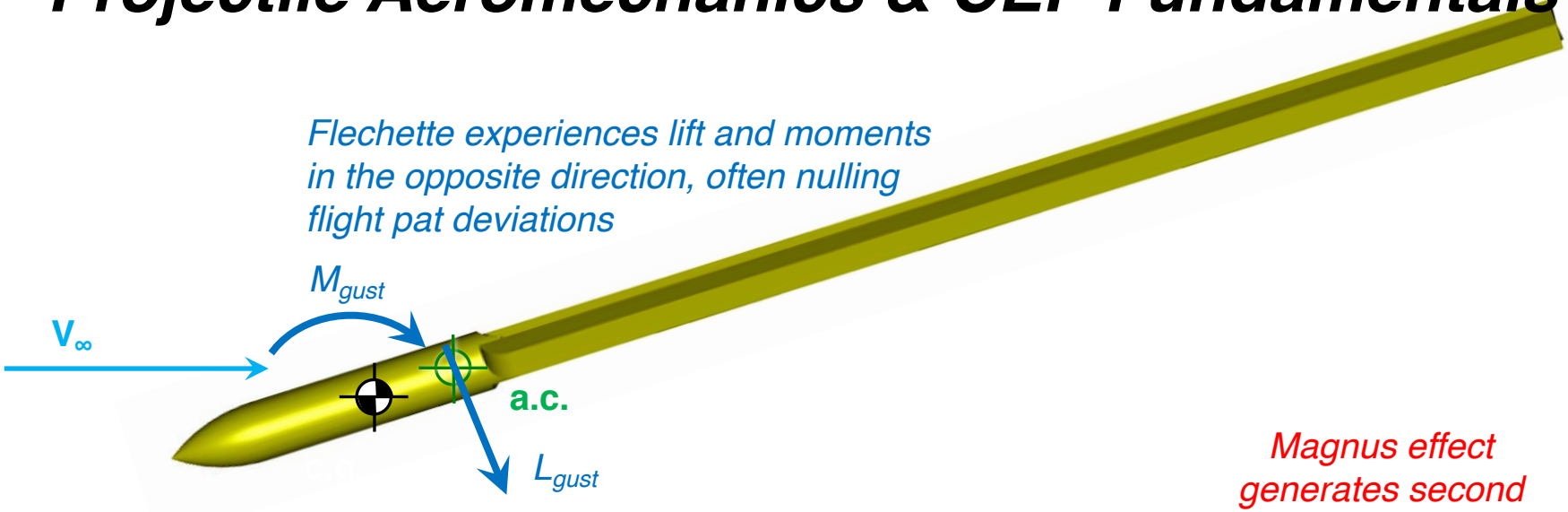
Flechette weathervanes into the wind nulling transverse lift and moments



III. Basic BASS Physics

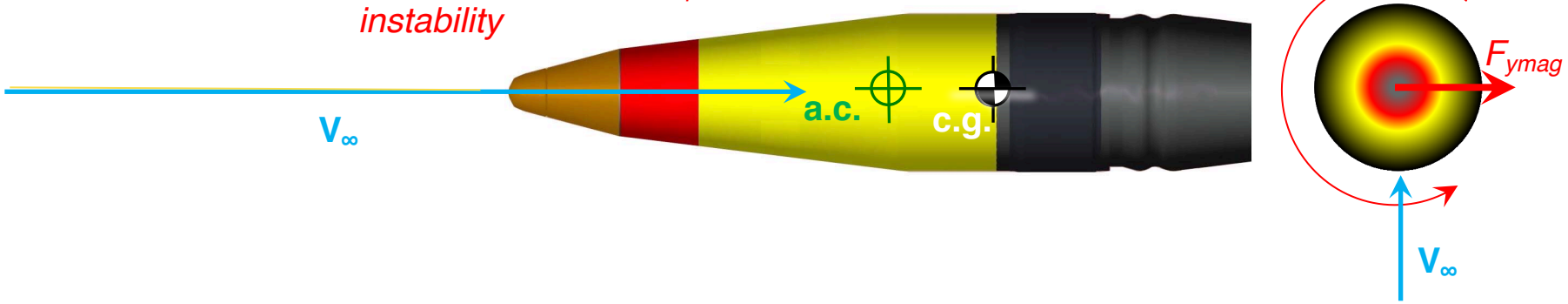
Projectile Aeromechanics & CEP Fundamentals

Flechette experiences lift and moments in the opposite direction, often nulling flight pat deviations



Dynamic modes (precession, nutation) excited given low C_{mq} & inherent instability

Magnus effect generates second destabilizing moment & side-force



III. Basic BASS Physics

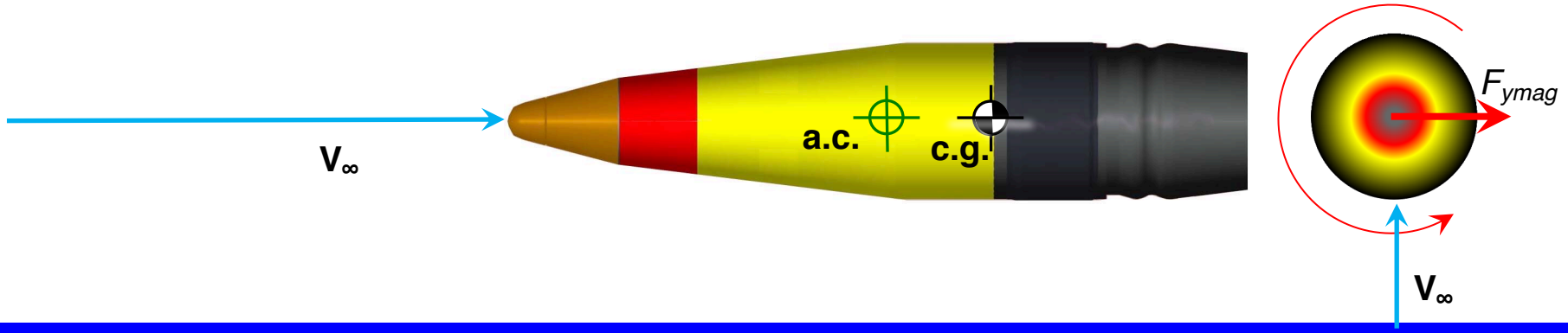
Projectile Aeromechanics & CEP Fundamentals

Flechette

Flechette returned to steady-state flight close to original flight path (maintaining very small CEP)

PGU-xx

CEP greately increased due to steady-state and dynamic effects



IV. BASS Performance

Modeling, Analysis & Testing

Experimental Validation:

- Full scale range testing of preferred BASS configuration w/muzzle exit dynamics;
- Structural verification of BASS components via soft catch.

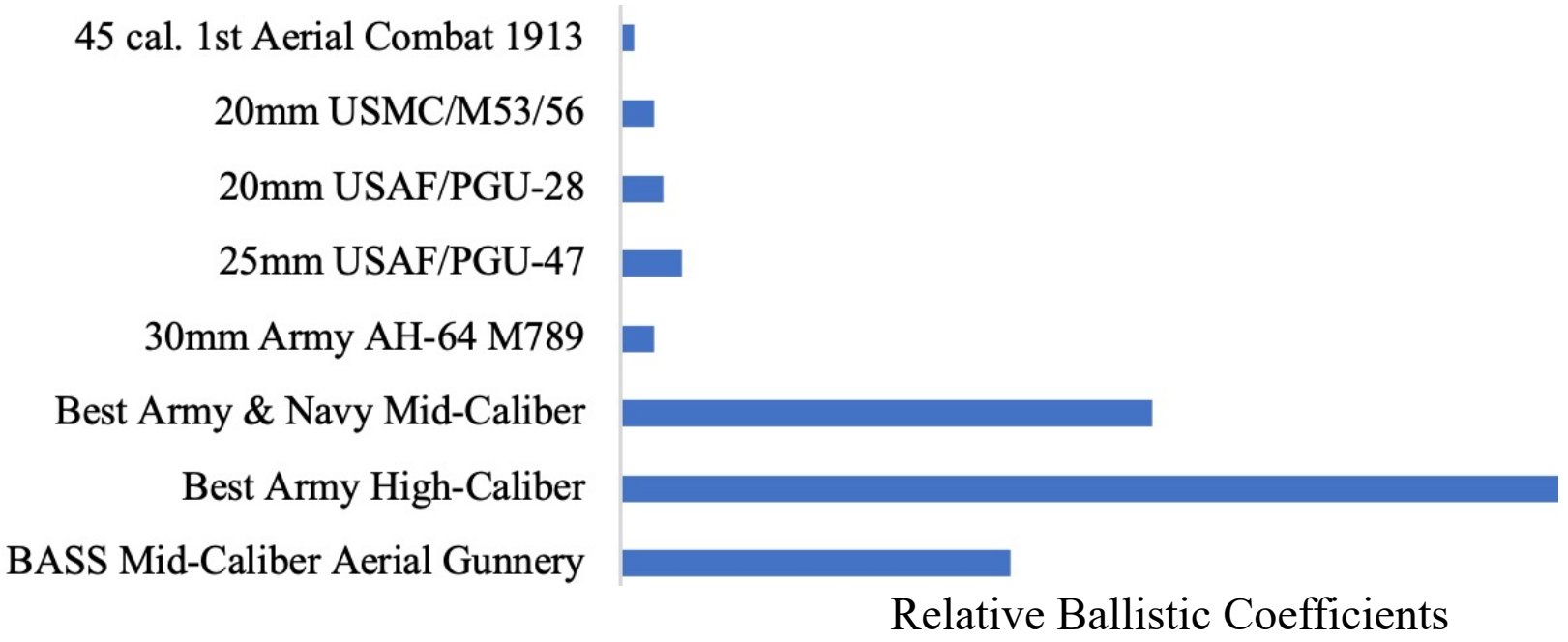
IV. BASS Performance

Range Shots

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

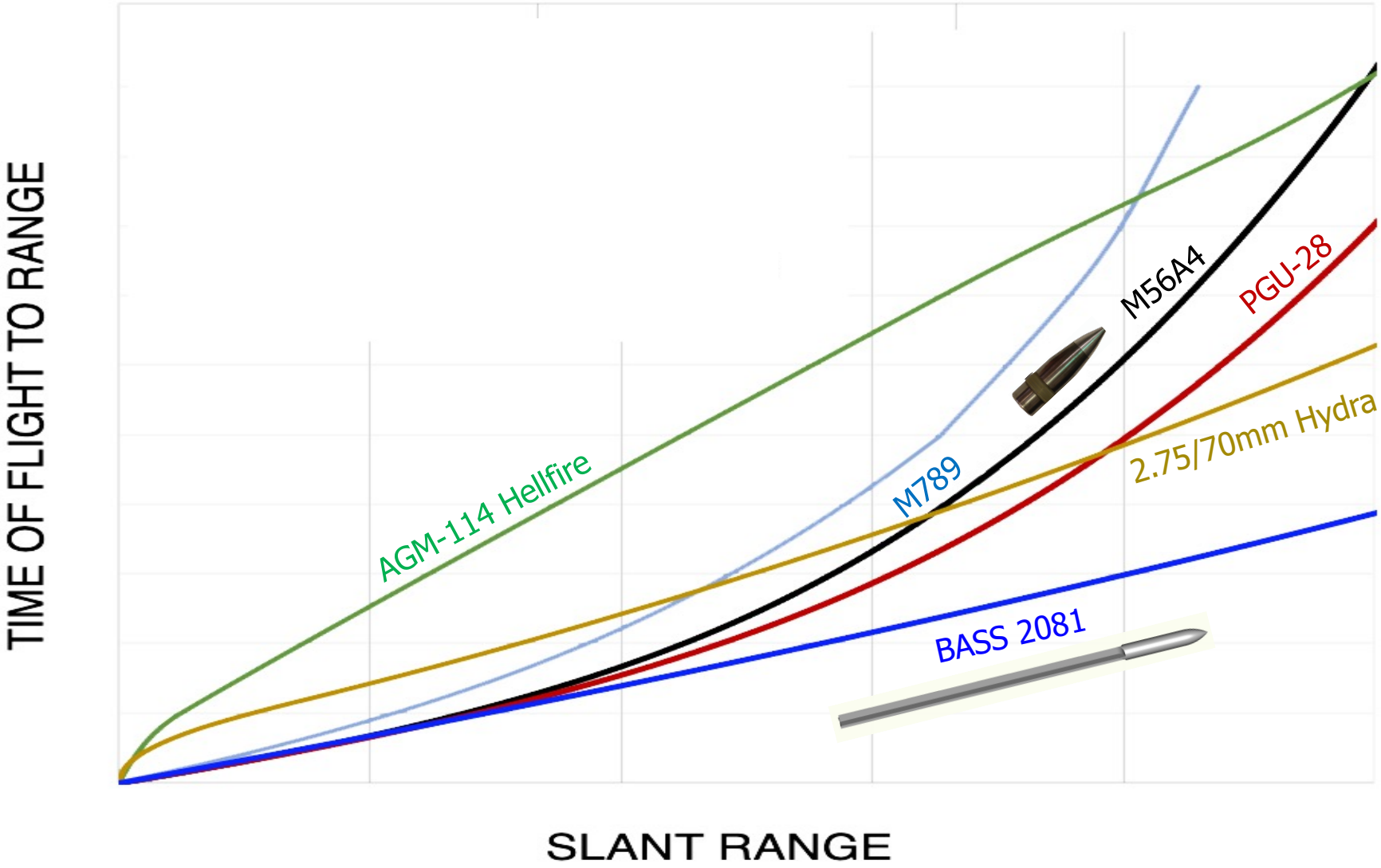
IV. BASS Performance

BASS Rounds Represent the First Major Advance in Ballistic Coefficients for Aerial Gunnery Ammunition in Over a Century



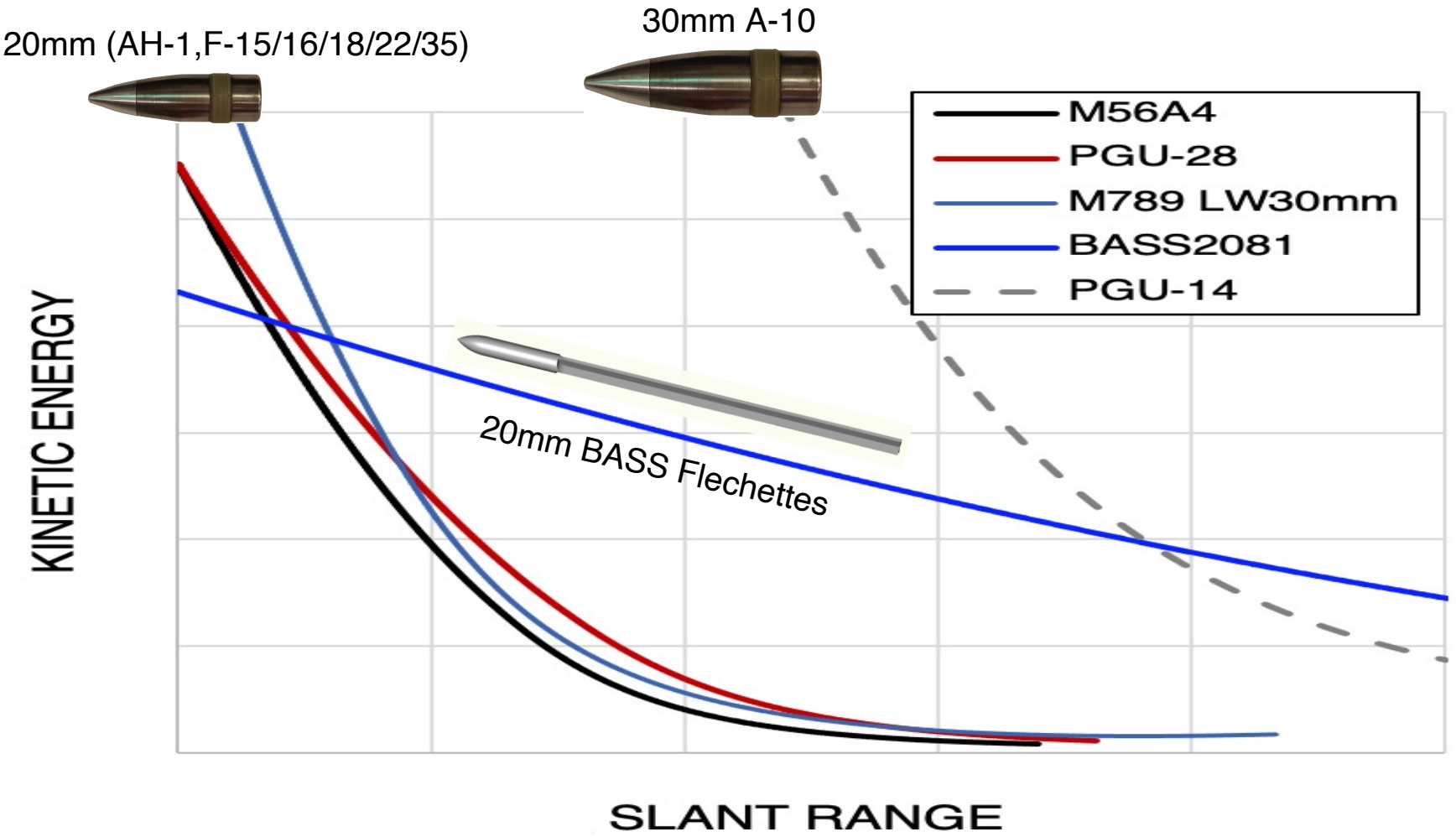
IV. BASS Performance

Lowest TOF of modern A-G systems



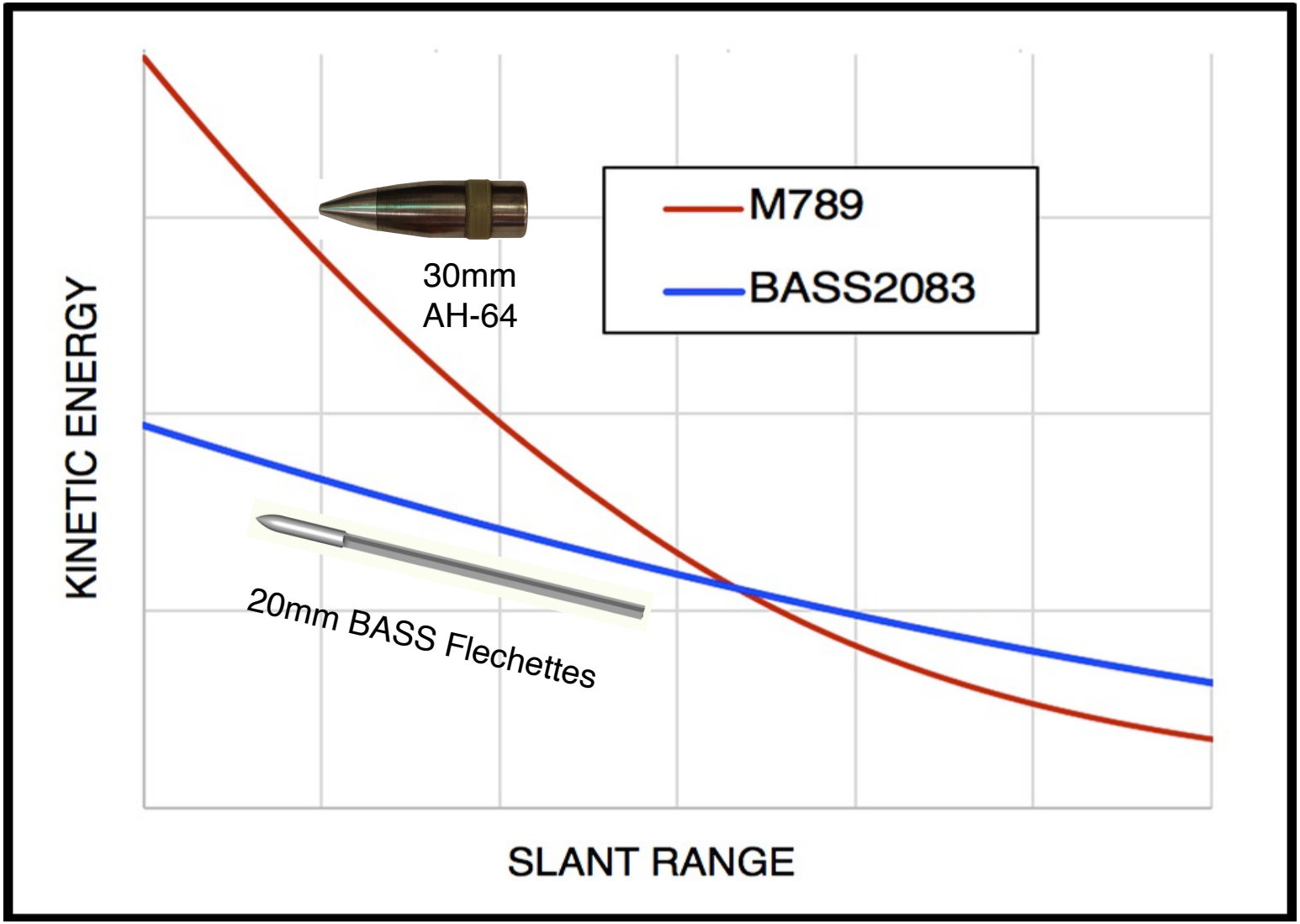
IV. BASS Performance

20mm Performance Comparison



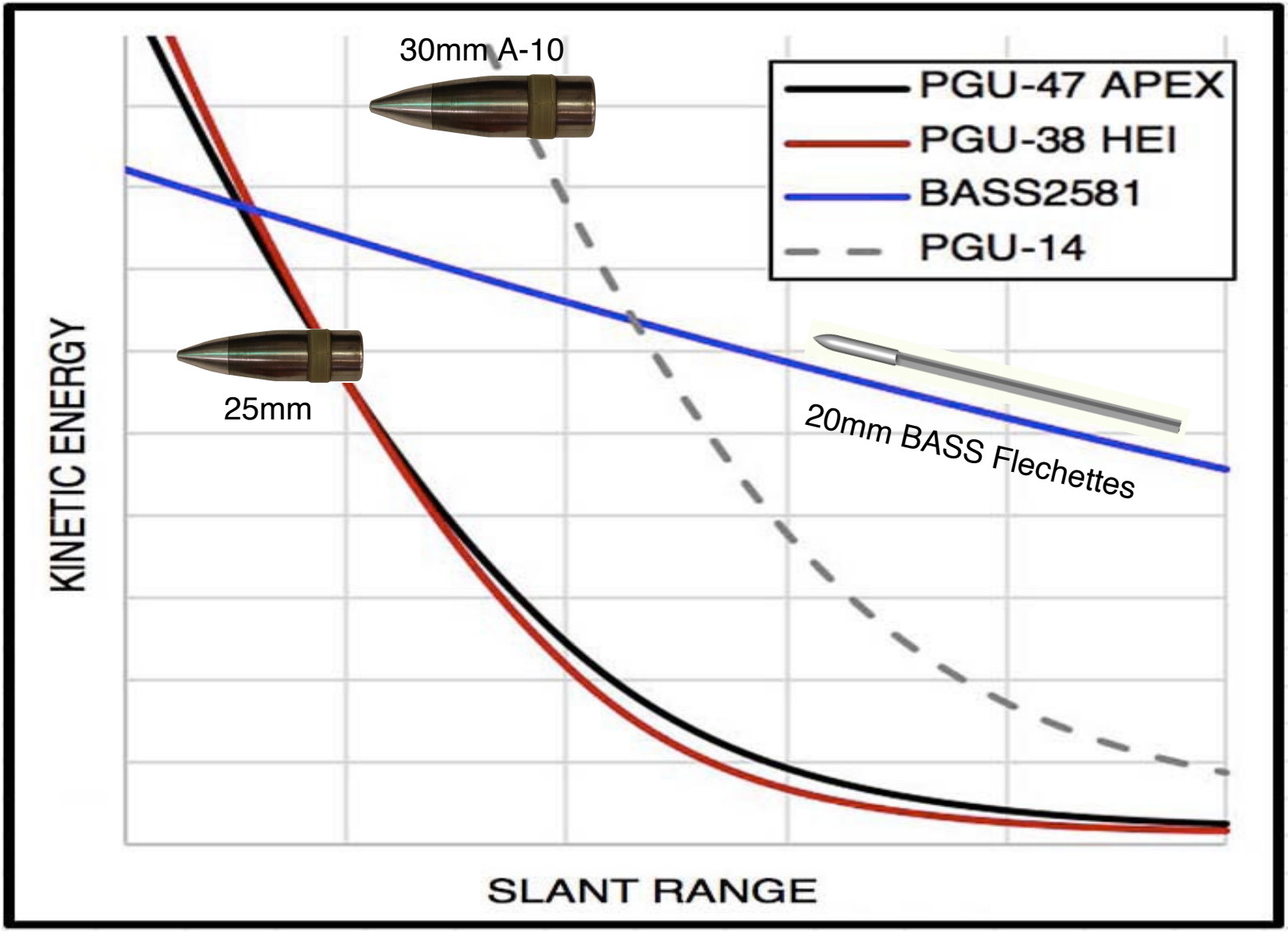
IV. BASS Performance

20 – 30mm Performance Comparison (same HE & effects)



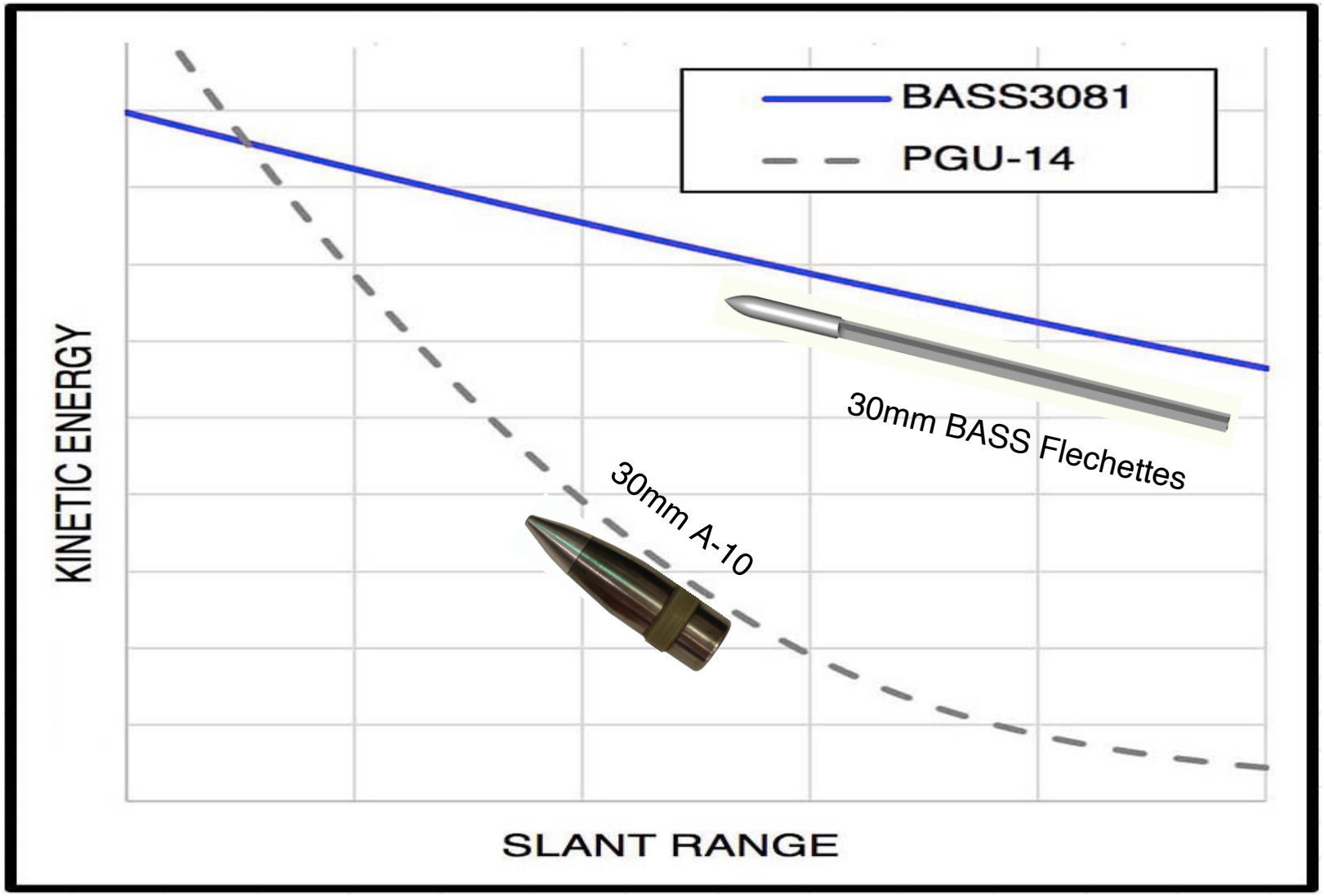
IV. BASS Performance

25mm Performance



IV. BASS Performance

30mm Performance



IV. BASS Performance

Enabling Technology for Light Attack, Rotorcraft & UAV Gunnery

Smaller guns w/BASS rounds do the job of much larger guns w/conventional rounds

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Enabling Technology for Light Attack, Rotorcraft & UAV Gunnery

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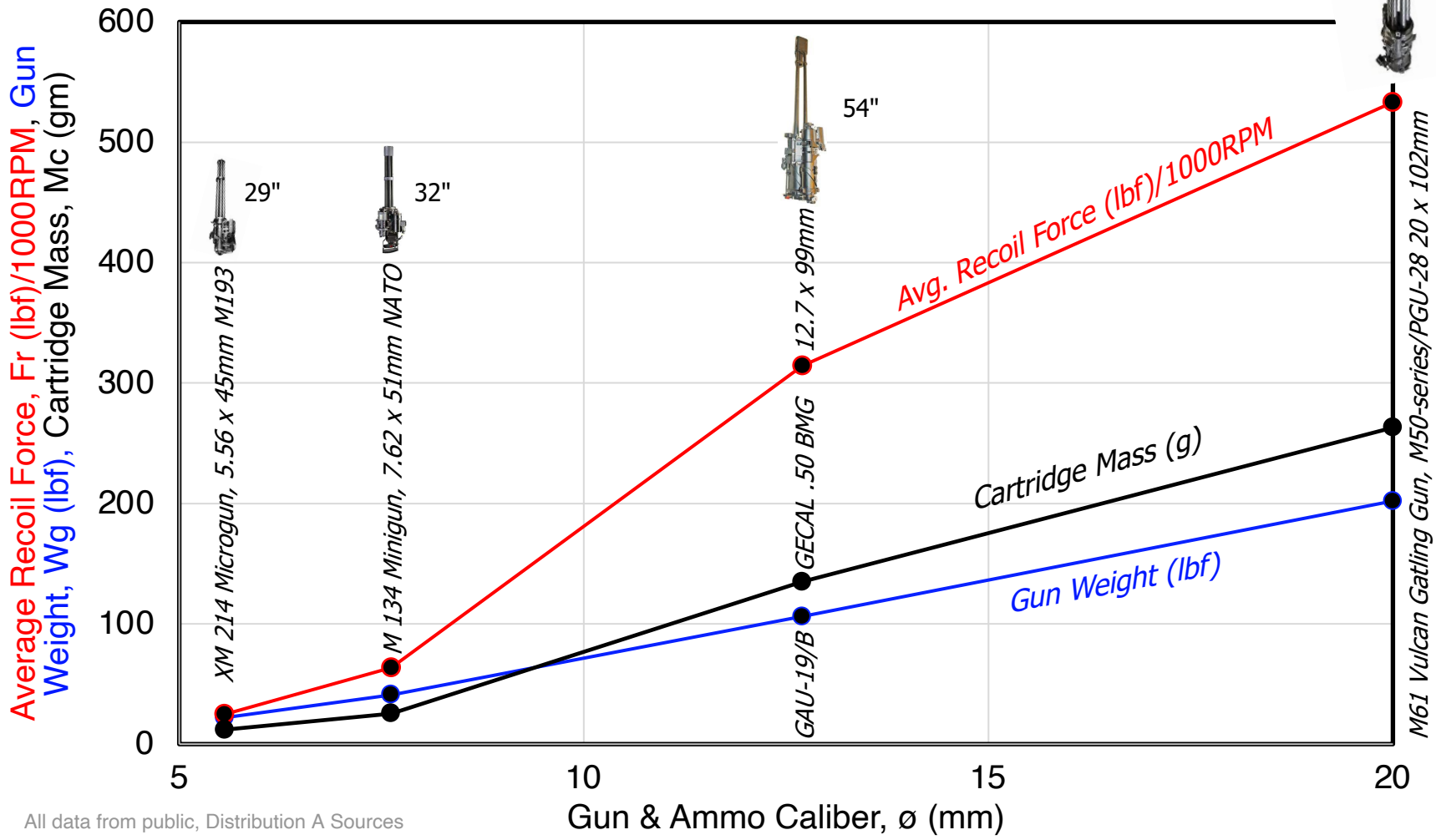


All data from public, Distribution A Sources

V. Intellectual Property Status

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…

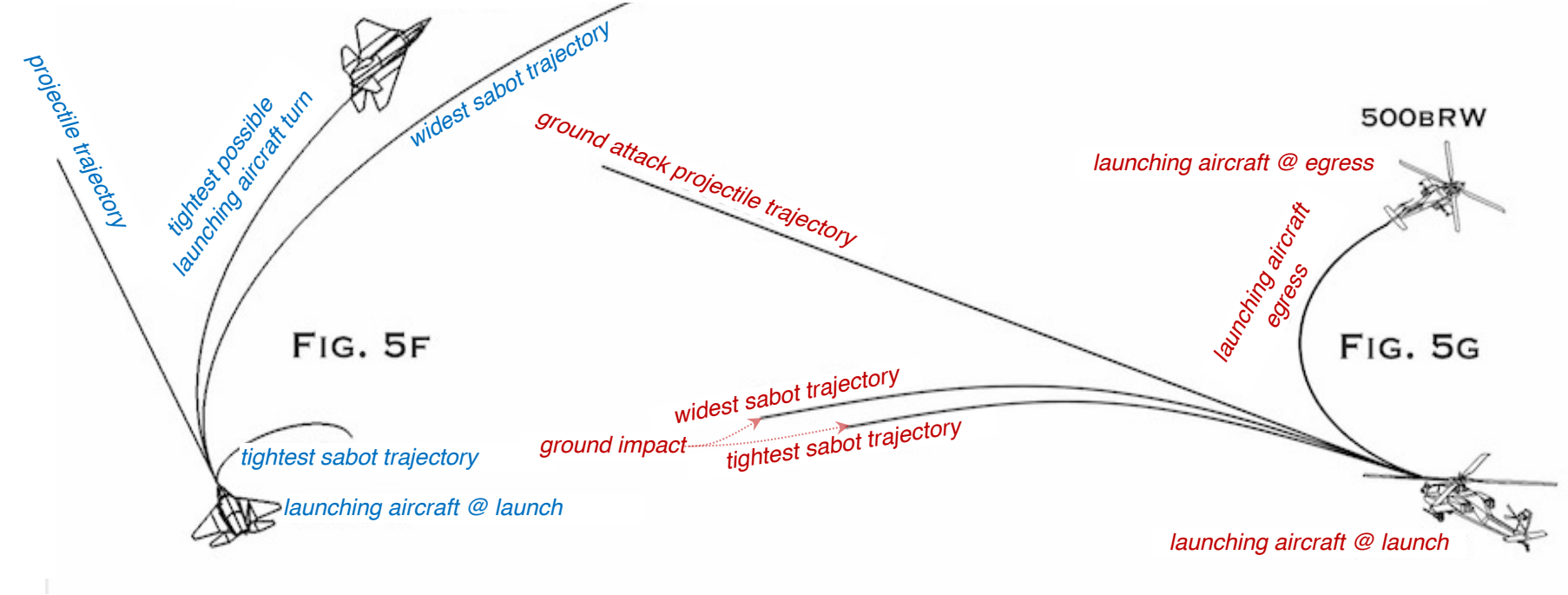
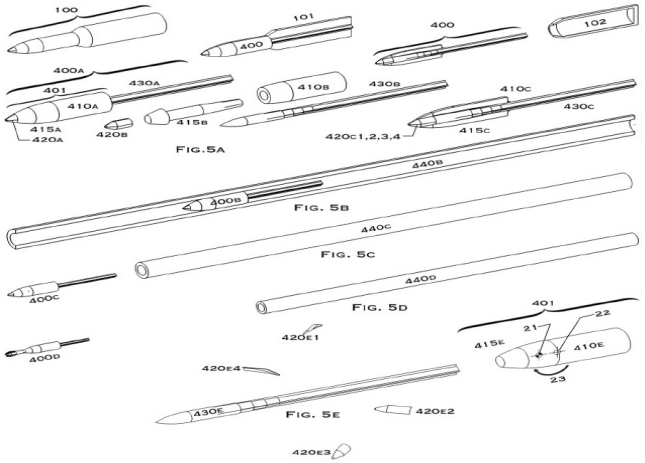


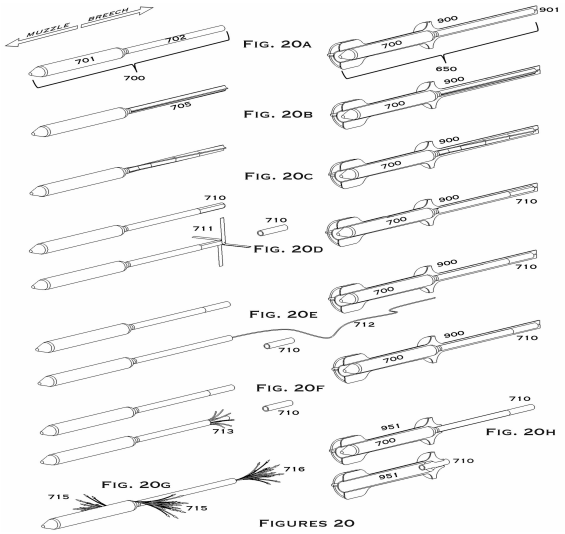
Image Source: PCT/IB2020/053899

Invented 2016
Modeled computationally & analytically 2017
Reduced to practice 2018
US & international patent priority date: 4/26/2019

V. Intellectual Property Status

- **Strong, Broad US Patents Filed 2019, 2020**
- **Fed. Government Granted Export License & Exported**
- **Patents filed in: US, Europe, Germany, Norway, Australia, UK, Netherlands, France, Belgium, Italy, Spain, Japan, Korea, Singapore**





PROVISIONAL PATENT APPLICATION 62/839,551 26 APRIL 2019 PRIORITY DATE

25 FIGURES, 83 CLAIMS, 80 PAGES

PCT FILING PCT/IB2020/053899 24 APRIL 2020

> 54 FAMILIES 3+ SPECIES WITHIN EACH FAMILY: 33 FIGURES, 130 CLAIMS, 106 PAGES

FEDERAL GOVERNMENT APPROVED FOR EXPORT & EXPORTED ENABLING BASS TECHNOLOGY & DESIGNS

VI. 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...

VI. Opportunities

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

VI. 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)*

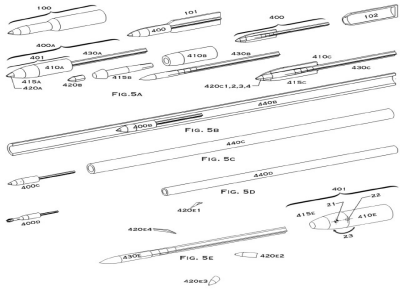
20, 25, 30mm $34M/yr

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

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

VI. 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

- ***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)

Questions?

History

How flight safe is current aerial gunnery?

Whoops, an F-35 Accidentally Shot Itself

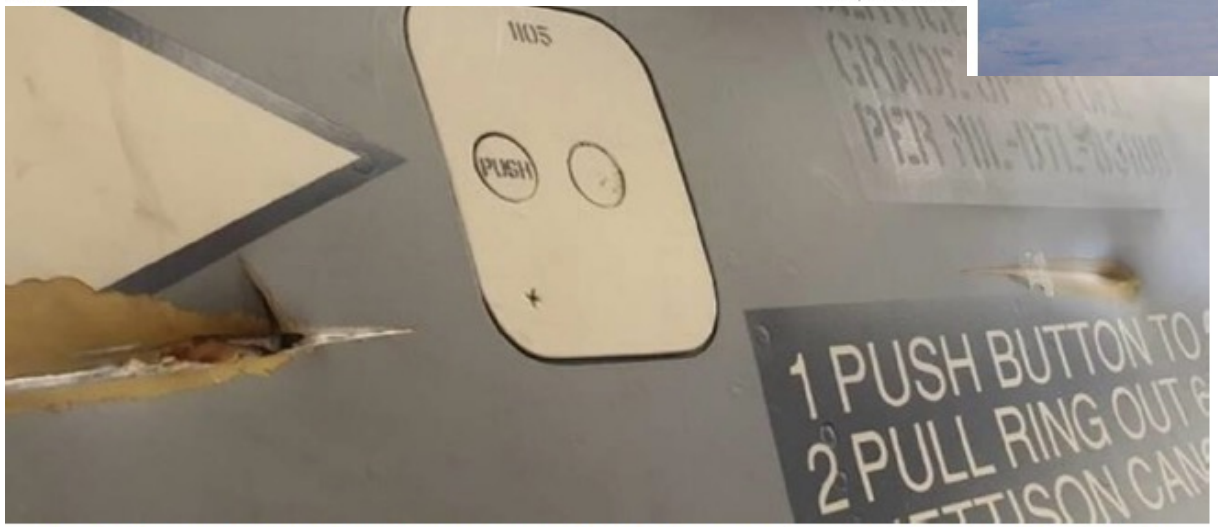
Poor plane can't catch a break.

// BY KYLE MIZOKAMI MAR 25, 2021

Military Culture

Dutch F-16 makes emergency landing after plane shoots itself

J.D. Simkins April 8, 2019



Task and Purpose, "This is Real: A Dutch F-16 Fighter Shot Itself With Its Very Own Vulcan Cannon," The National Interest, 9 April 2019.