

# History of Flight-Safe Discarding Sabot Rounds

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Oxford Brookes University  
Oxford, England

*AIAA SciTech Forum, San Diego, California*  
*3 – 7 January 2022*  
*Paper No HIS-08, 3609454*





**AFATL-TR-84-03**

# *Dedication:*

## **Historical Development Summary of Automatic Cannon Caliber Ammunition: 20-30 Millimeter**

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Dale M Davis  
MUNITIONS DIVISION

### *Dale M. Davis*

### *Director*

*USAF Munitions Division  
(1928 – 1988)*

JANUARY 1984

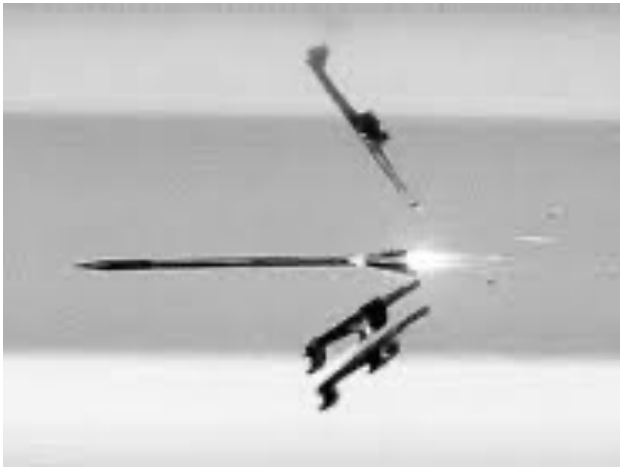
FINAL REPORT FOR PERIOD: 1952 - 1983

Approved for public release; distribution unlimited

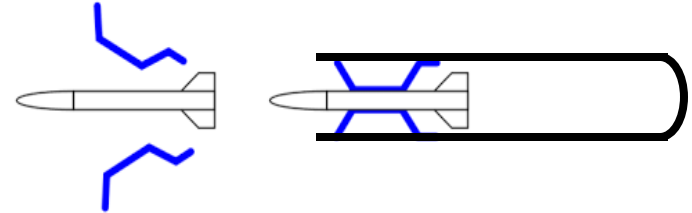


**Air Force Armament Laboratory**  
AIR FORCE SYSTEMS COMMAND \* UNITED STATES AIR FORCE \* EGLIN AIR FORCE BASE, FLORIDA

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***Sabot:***



*A light weight jacket or device which ensures the correct positioning of a dense bullet or cannon shell in the barrel of a gun, often falling away as it leaves the muzzle.*



# Structure:

- i. Artillery & Sabot Evolution***
- ii. Aerial Gunnery Evolution***
- iii. USAF Efforts to Design Advanced Flight-Safe Discarding Sabot Munitions***
- iv. Ballistic Aeromechanically Stable Sabot (BASS) Rounds***
- v. Conclusions***

# Why are Discarding Sabot Rounds Important?

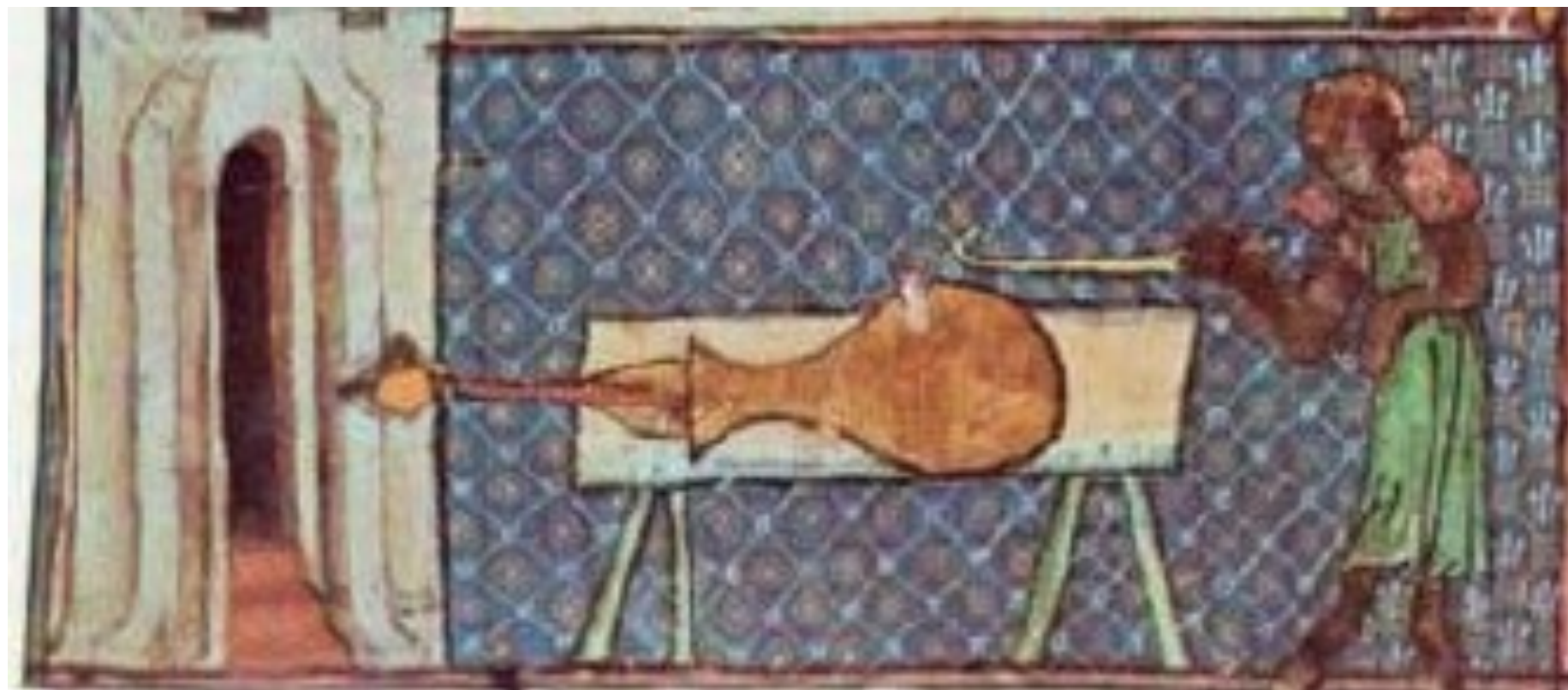
- **Improved:**  
*KE, HE, Range, Trajectory Flatness*
- **Reduced:**  
*TOF, CEP, Cost, Mass, Volume, Recoil*



# i. Artillery & Sabot Evolution

## *1st Archival Document Describing a Sabot*

1326 Treatise of Walter de Milemete



W. de Milemete, "The Treatise of Walter de Milemete: de Nobilitatibus, Sapientiis, et Prudentiis Regum," Christ Church, Oxford; digital ID: 3590ddc7-1ae2-4b23-b576-ec716fb24d01, 1326-1327.

Image Source:

<https://catalog.hathitrust.org/Record/002098083>

# i. Artillery & Sabot Evolution

## Early Artillery

- Song Dynasty (960 – 1279CE) Fire Lances
- Earliest Depiction of a Cannon 1128CE
- Cannones de Metallo Turin & Florence 1326/27



Chinese Rockets Repulse Mongols - 1232



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# i. Artillery & Sabot Evolution

## Early Artillery

- Napoleon: Artillery as a Service Branch
  - Tactics & Ordnance Coevolved
  - Highly Coordinated Artillery, Cavalry & Infantry
- Naval Surface Fire Evolved Simultaneously
- Battles of Trafalgar & Nile Cemented Importance of Naval Surface Fire

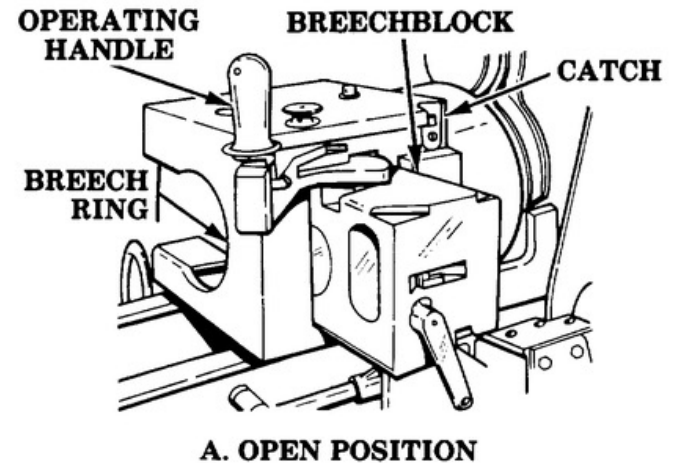
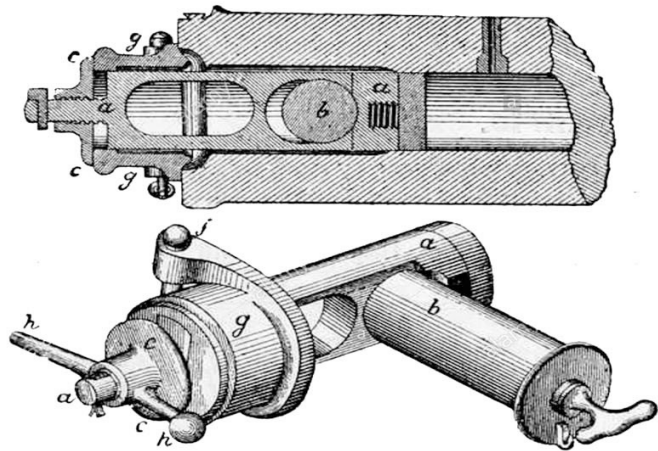
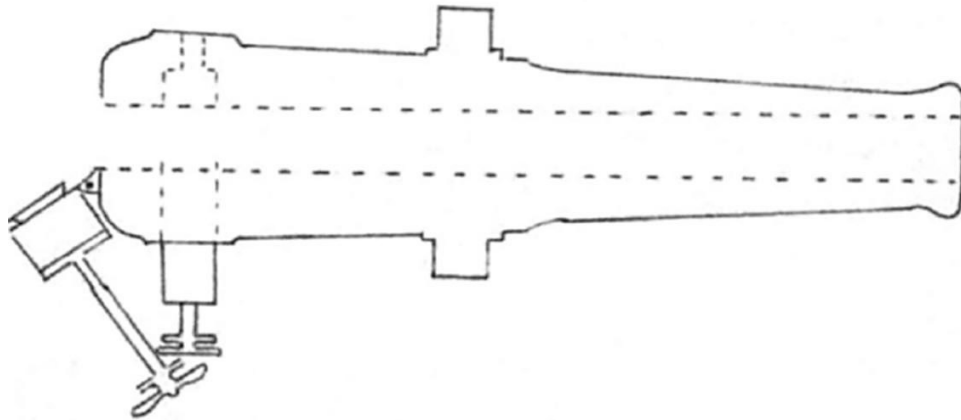




# i. Artillery & Sabot Evolution

## Early Artillery

- Von Warendorff's Breech Loading Cannon 1837 - 1854



- Von Warendorff & Whitworth's Rifling

- Von Warendorff's Breech Sealing

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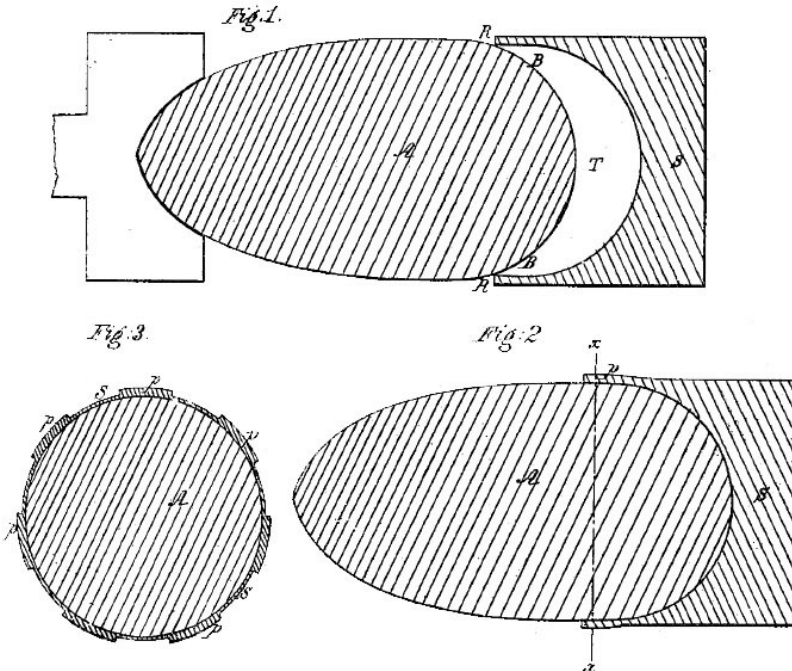


# i. Artillery & Sabot Evolution

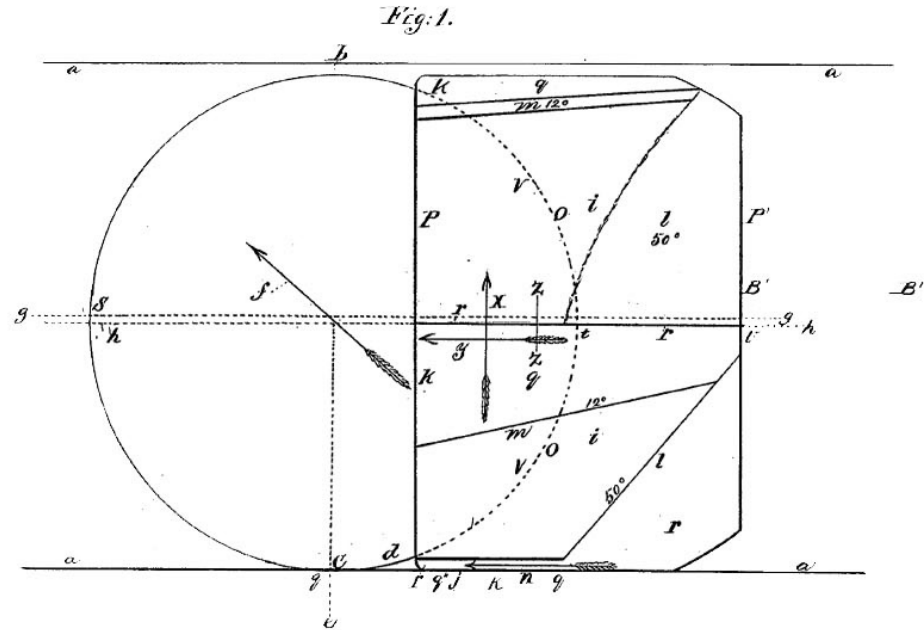
## Early Artillery

• Increasing Chamber Pressures & Functions of Early Sabots – 1850's

L. HOUGHTON.  
Loading Ordnance. Patented Apr. 3, 1855.  
No. 12,629.



W. W. HUBBELL.  
Sabots and Wads. Patented June 10, 1856.  
No. 15,075.



# i. Artillery & Sabot Evolution

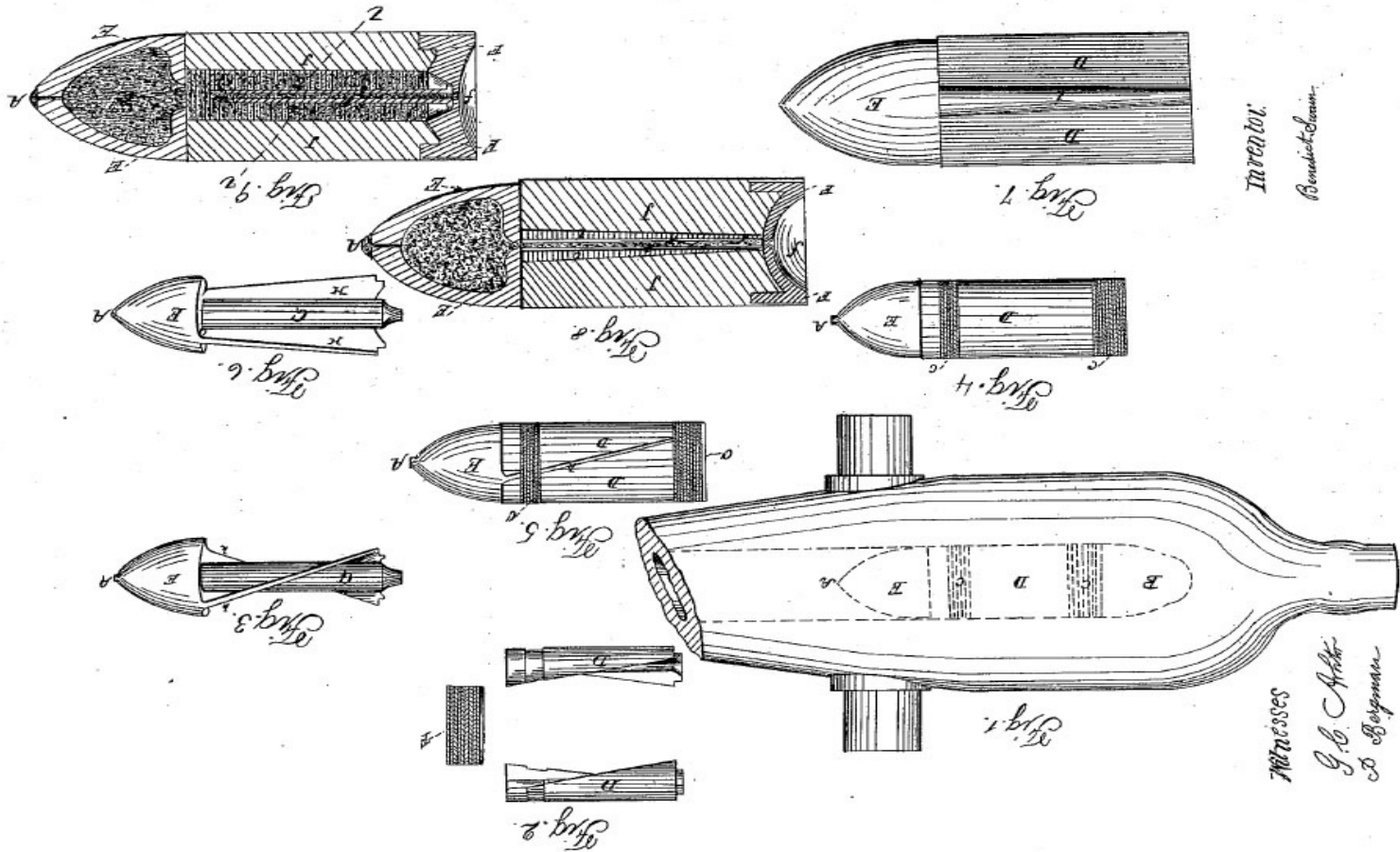
## Early Artillery

- Aeromechanically Stable Spinning Projectile with Pusher Plate 1860

B. SWAIN.  
Shell.

No. 27,245.

Patented Feb. 21, 1860.



Inventor.  
Benjamin Swain.

Witnesses  
G. C. Archer  
D. Boyman

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# i. Artillery & Sabot Evolution

## US Civil War – Modern Sabots

### 695 Years of Sabots...

### Not one suitable for aerial gunnery

W. W. HUBBELL  
Sabots and Wads.  
No. 15,075.  
2 Sheets—Sheet 1.  
Painted June 10, 1866.

Inventor: W. W. Hubbell  
Witnesses: General G. H. & J. P. ...

C. W. STAFFORD  
Projectile.  
No. 39,180.  
Patented July 7, 1863.

Inventor: C. W. Stafford  
Witnesses: ...

C. ARICK  
Projectile.  
No. 39,190.  
Patented July 24, 1863.

Inventor: C. Arick  
Witnesses: ...

J. R. N. OWEN.  
PROJECTILES FOR SMOKE-LESS GUNS.  
No. 125,040.  
Patented Sept. 11, 1877.

Inventor: J. R. N. Owen  
Witnesses: ...

United States Patent [19] (11) Patent Number: 4,833,995  
Götz et al. [45] Date of Patent: May 30, 1989

[15] FIN-STABILIZED PROJECTILE  
[17] Inventors: Udo Götz, Troninger, Dietrich Hoffmann, Anita Flüg, both of Schramberg; Adolf Armbruster, Aishalden, all of Fed. Rep. of Germany

[73] Assignee: Messer-Werke Oertrand GmbH, Oberndorf, Fed. Rep. of Germany

[21] Appl. No.: 887,527  
[22] Filed: Jul. 14, 1986  
[23] Foreign Application Priority Data  
Jul. 28, 1985 [083] Fed. Rep. of Germany ... 353585

[31] Int. Cl.<sup>4</sup> ... F42B 13/16; F42B 31/00  
[32] U.S. Cl. ... 102/521; 102/524; 102/527  
[51] Field of Search ... 102/520-525; 102/501; 244/3.23-3.3

[56] References Cited  
U.S. PATENT DOCUMENTS  
3,228,315 1/1966 Thompson ... 244/3.24

16 Claims, 1 Drawing Sheet

May 27, 1969 W. ENGEL ET AL. 3,446,147  
CALLING FOR THE SABOT OF A PROJECTILE  
Filed March 1, 1967 Sheet 1 of 2

Inventors: W. Engel, R. ...  
Witnesses: ...

Jan. 5, 1965 D. S. REED ET AL.  
AMMUNITION SABOT  
Filed Nov. 15, 1962

Inventors: David S. Reed, Rex E. Dickey  
Witnesses: ...

HEGGE ET AL. 3,148,472  
SABOT FOR HIGH VELOCITY FIREARMS  
June 11, 1962

Inventors: ...  
Witnesses: ...

United States Patent [19] (11) 4,18  
Campoli et al. [45] Feb. 12, 1979

[15] DISCARDING SABOT MUNITION  
[17] Inventors: Ralph F. Campoli, Miss H.H. Elie L. Barrows, Morris Plante, John W. Bassett, Lake Hopatcong, all of N.J.; Edward G. Steiner, Irving, Iowa; Thomas A. Lynch, Waterloo, Iowa; Gary M. Miller, Waterloo, Iowa

[73] Assignee: The United States of America as represented by the Secretary of the Army, Washington, D.C.

[21] Appl. No.: 885,715  
[22] Filed: Mar. 15, 1978  
[23] Foreign Application Priority Data  
F42B 13/16  
U.S. Cl. ... 102/500  
[51] Field of Search ... 102/501, 102/507

[56] References Cited  
U.S. PATENT DOCUMENTS  
3,023,165 11/1971 Raton et al. 102/503  
3,081,246 5/1976 Luther et al. 102/503  
4,100,582 5/1978 Hoop et al. 102/503  
4,146,004 2/1979 Campoli et al. 102/503

5 Claims, 4 Drawing Figures

United States Patent [19] (11) 4,284,008  
Kirkendall et al. [45] Aug. 18, 1979

[15] DOUBLE RAMP DISCARDING SABOT  
[17] Inventors: Richard D. Kirkendall, Harry de Groot, William W. Dravich, Arlington; Leslie D. Kukulinski, Chicago; Bruce P. Burns, Hartford, Conn.; all of Ill.

[73] Assignee: The United States of America as represented by the Secretary of the Army, Washington, D.C.

[21] Appl. No.: 30,318  
[22] Filed: Apr. 12, 1979  
[23] Foreign Application Priority Data  
U.S. Cl. ... F42B 13/16  
U.S. Cl. ... 102/521; 102/520; 102/529

[56] References Cited  
U.S. PATENT DOCUMENTS  
3,003,216 10/1961 Bony ... 102/503  
1,113,002 11/1965 Taylor ... 102/500.7

9 Claims, 4 Drawing Figures

Image Source: https://patents.google.com/

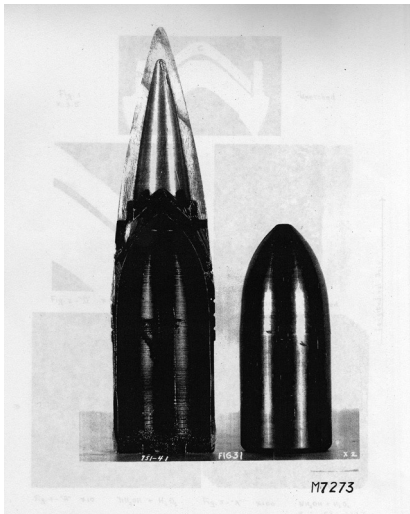
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# i. Artillery & Sabot Evolution

## US Civil War – Modern Sabots

### Edgar Brandt

1st to Develop Discarding Sabot Artillery Shells, WWI



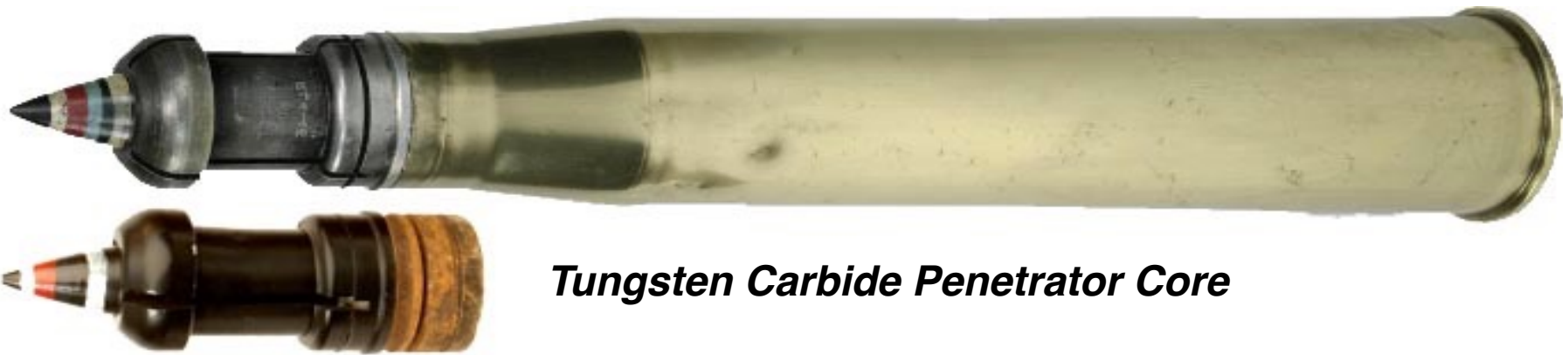
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# i. Artillery & Sabot Evolution

*US Civil War – Modern Sabots*

***British QF 6-Pounder Antitank Gun 1944***

***Armor-Piercing Discarding Sabot (APDS Round)***

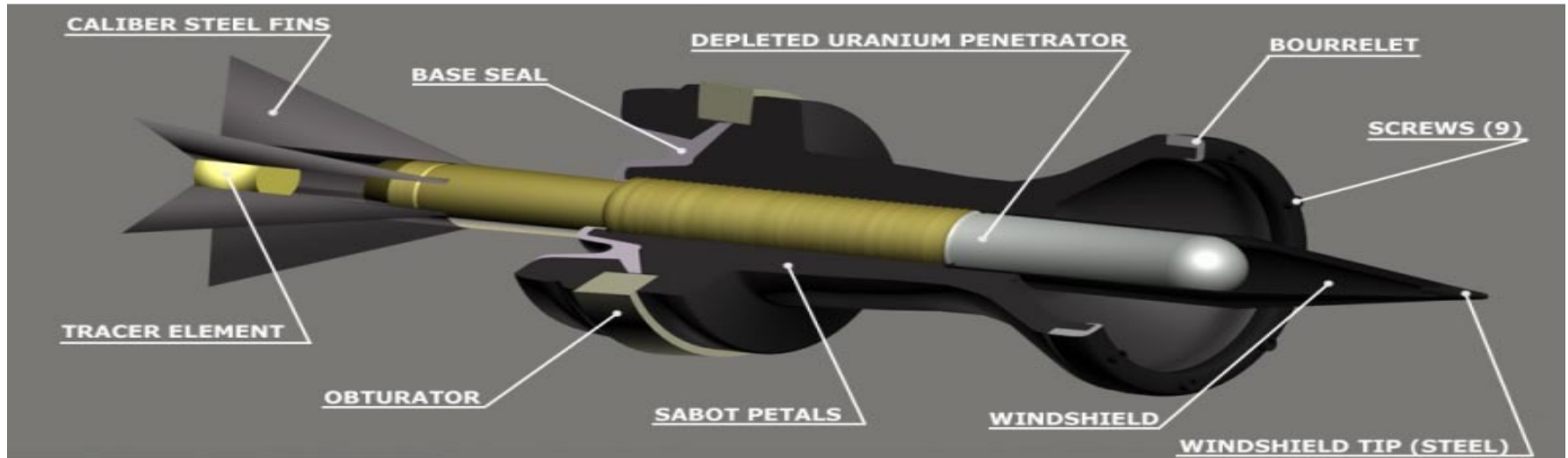
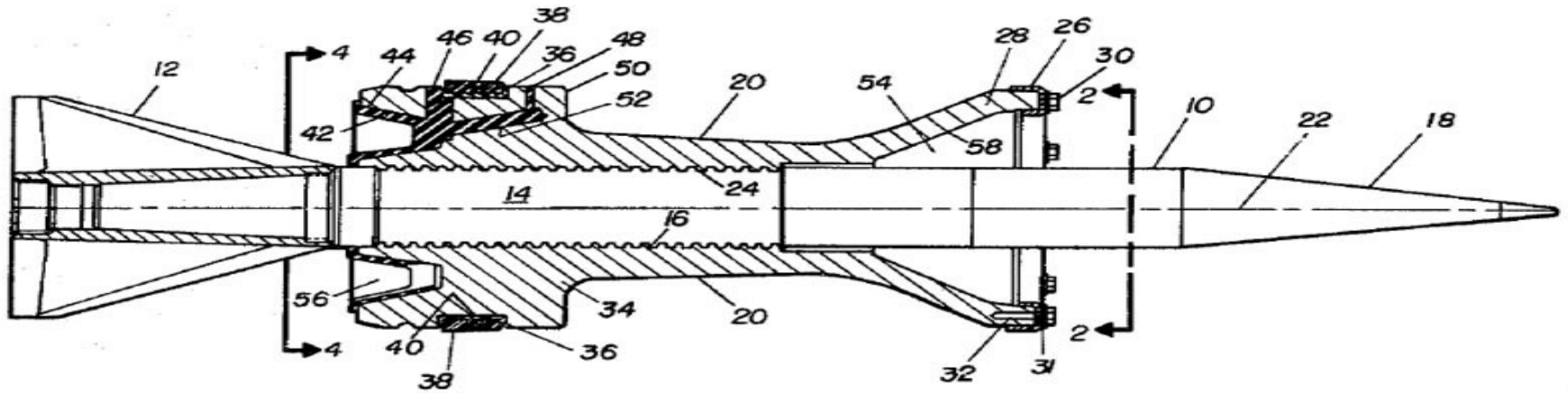


***Tungsten Carbide Penetrator Core***

# i. Artillery & Sabot Evolution

*US Civil War – Modern Sabots*

## **Modern Armor-Piercing Discarding Sabot Mmunition**



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## II. Aerial Gunnery Evolution

*1st Aerial Battle 1913*

*Dean Ivan Lamb & Phil Rader  
Soldiers of Fortune  
Naco, Sonora & Naco, Arizona*





# II. Aerial Gunnery Evolution

## THE INCURABLE FILIBUSTER

*Adventures of* COLONEL DEAN IVAN LAMB

*Illustrated by* PAUL BROWN



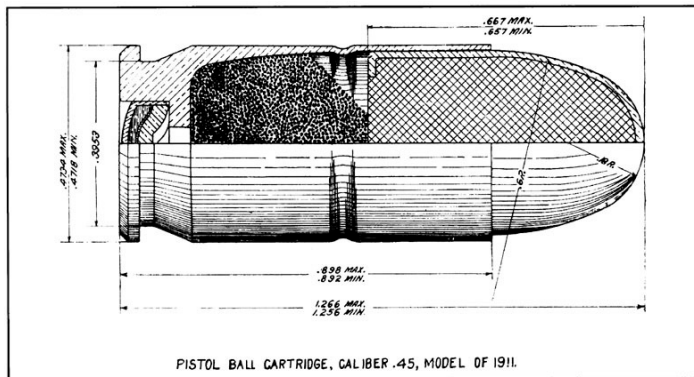
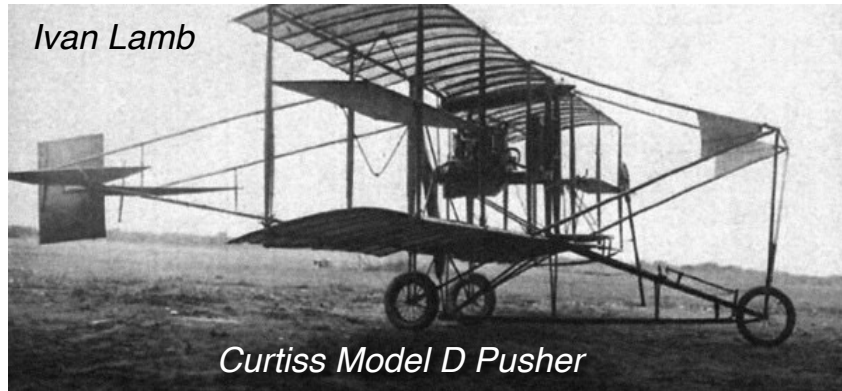
FARRAR & RINEHART  
INCORPORATED  
PUBLISHERS NEW YORK



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# II. Aerial Gunnery Evolution

## 1st Gun Duel



The drawing above, from a 1918 "Manual of the Automatic Pistol Caliber .45 Model of 1911," illustrates components of the original military .45 ACP loading—a 230-gr. bullet traveling at 855 f.p.s.



Model 1906 .45 Revolver Ball cartridge



US Army Colt 0.45 1909

Image Source [https://en.wikipedia.org/wiki/.45\\_ACP](https://en.wikipedia.org/wiki/.45_ACP)  
<http://www.cartridgecollector.net/45-colt-m1906>

Image Source [https://en.wikipedia.org/wiki/M1911\\_pistol](https://en.wikipedia.org/wiki/M1911_pistol)

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## II. Aerial Gunnery Evolution

***1st Air-to-Ground  
Bombardment from  
Heavier-than Air Craft***

***1st Air-Defense Gunnery***



***Box of Dynamite &  
Nails***





## II. Aerial Gunnery Evolution

**1st Air-to-Ground Strafing:**

**US Customs House  
Naco, Arizona**



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## II. Aerial Gunnery Evolution

### 1st Air-to-Ground Strafing:

*US Customs House  
Naco, Arizona*

*"Customs people are always irritating." –  
Dean Ivan Lamb*





## II. Aerial Gunnery Evolution

### *Aerial Gunnery WWI*



**20mm Becker Autocannon in the Front of a Gotha G.1 [26]**



## II. Aerial Gunnery Evolution

### *Interwar Aerial Gunnery*



**JU-87G-1 with 37mm Cannon (1937 – 1945)**

## II. Aerial Gunnery Evolution

### *Interwar Aerial Gunnery*



**Bell XFM Airacuda "Heavy Fighter" with 37mm Cannon (1937 – 1945)**





# II. Aerial Gunnery Evolution



WWII



20mm P-38 Lightning Autocannon

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# II. Aerial Gunnery Evolution

## Today

### F-35



Image Source: <https://www.youtube.com/watch?v=69Nv3FIHNK0>

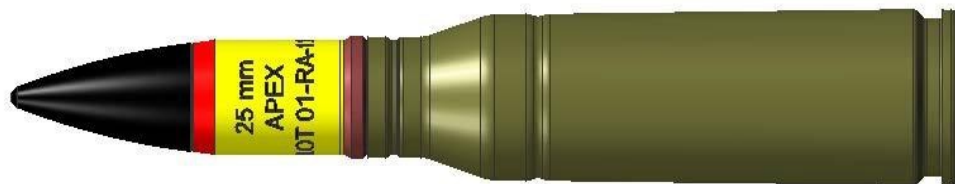
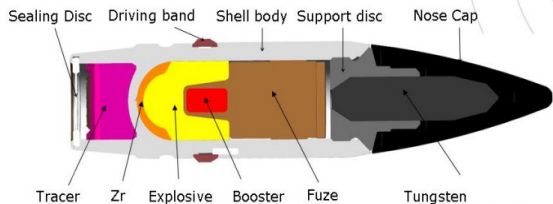


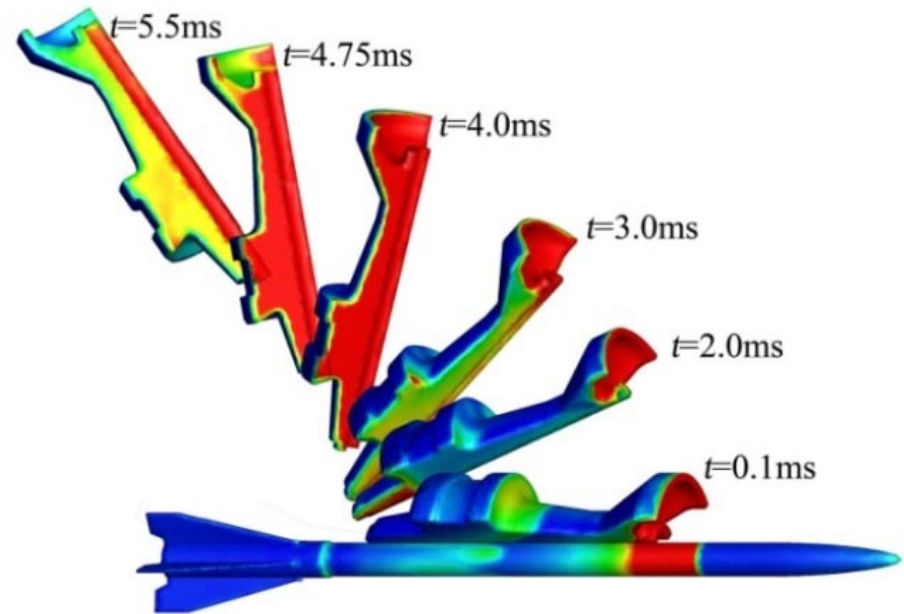
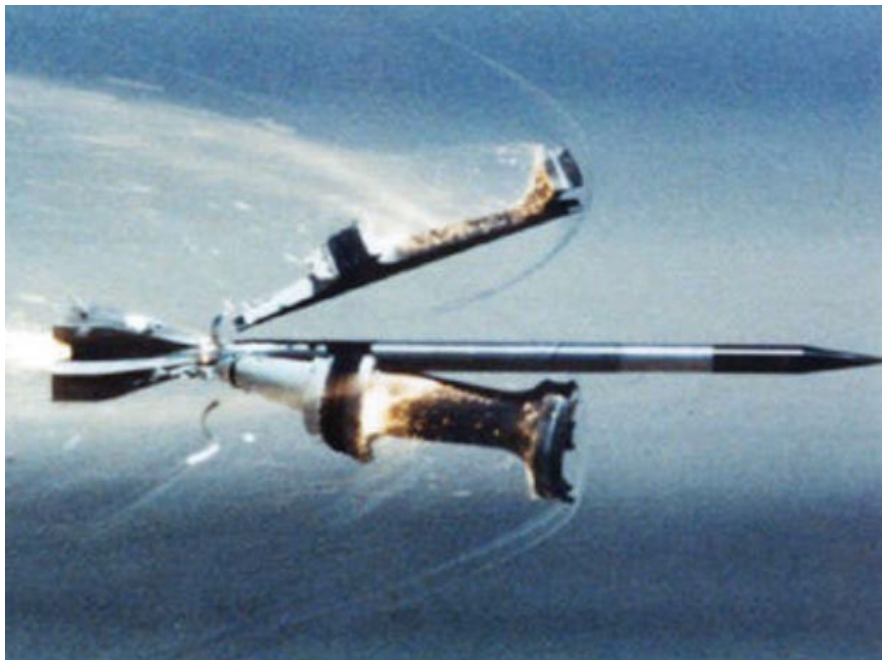
Image Source: McConkie, Jim, "Qualification Testing of the PGU-47 Armor Piercing High Explosive Incendiary-Traced 25mm Cartridge," NDIA Armament Systems Forum 27 April 2016

Unlimited Distribution  
Distribution A



## II. Aerial Gunnery Evolution

### *Conventional Discarding Sabot Design Philosophy and Aeromechanics*



Distribution A Unlimited Distribution



## II. Aerial Gunnery Evolution

### ***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*

# II. Aerial Gunnery Evolution

**Why a conventional sabot won't work for aerial gunnery**

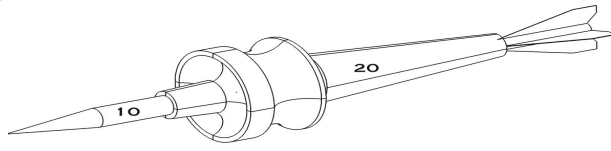


FIG. 1A

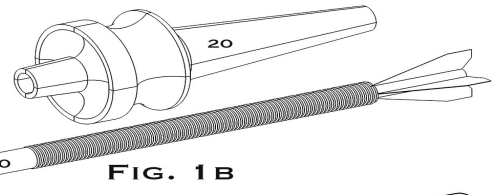


FIG. 1B

**Dale Davis' Observations:**

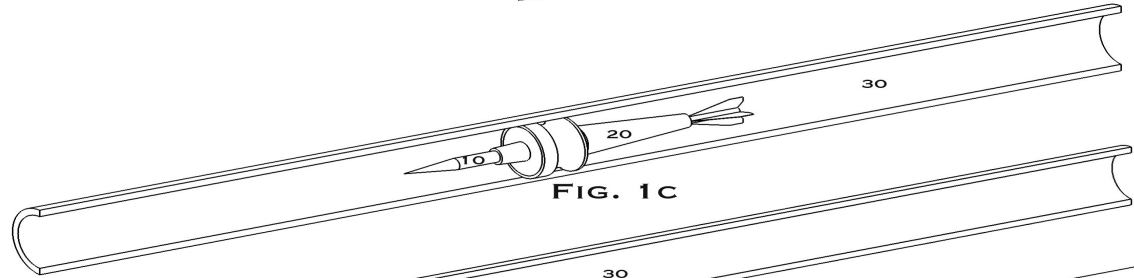


FIG. 1C

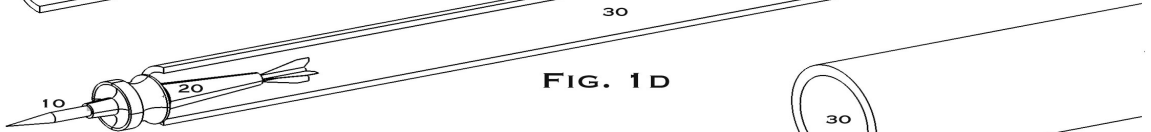


FIG. 1D

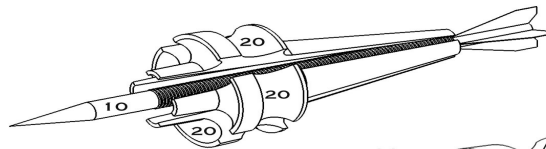


FIG. 1E

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

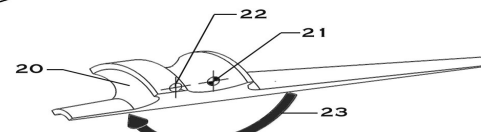


FIG. 1F

*Aeromechanically unstable sabot pieces tumble*



*...and strike airframe/engine*

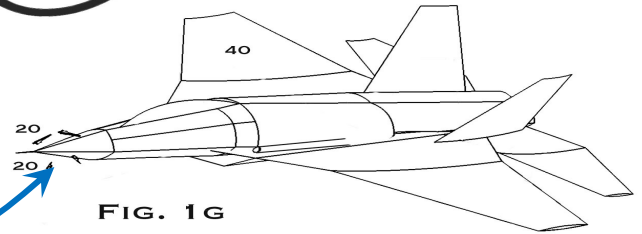


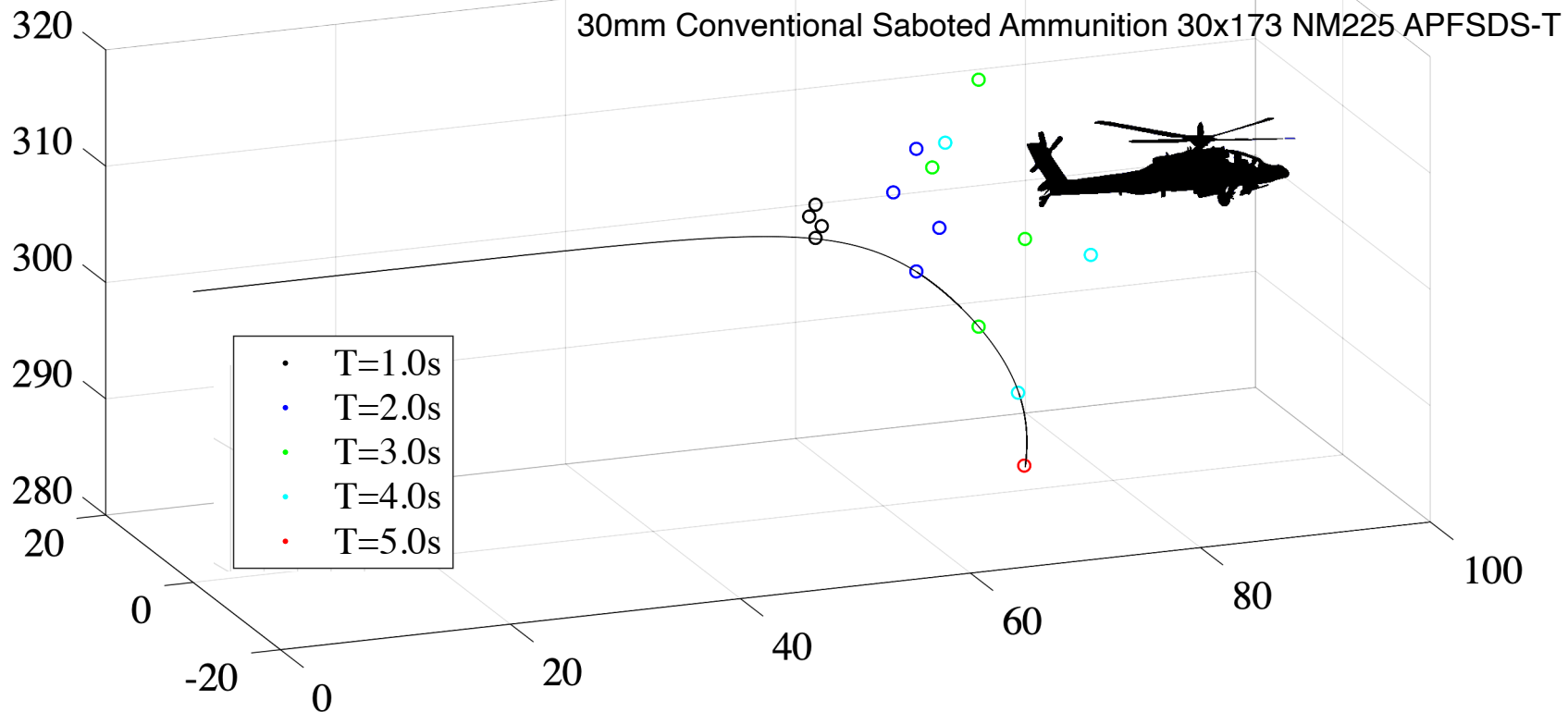
FIG. 1G

FIGURES 1

Image Source: PCT/IB2020/053899

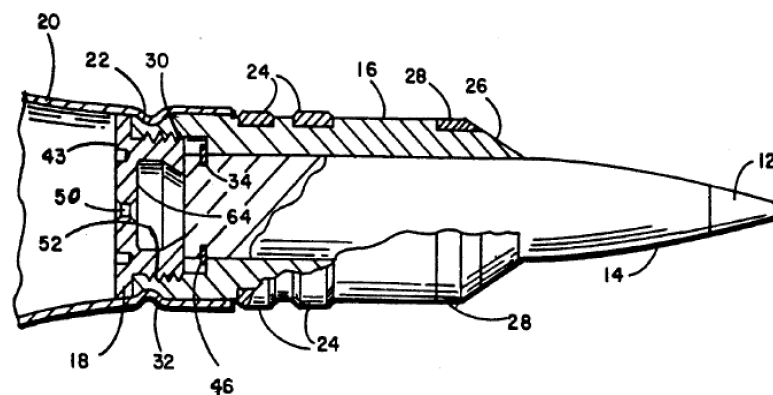
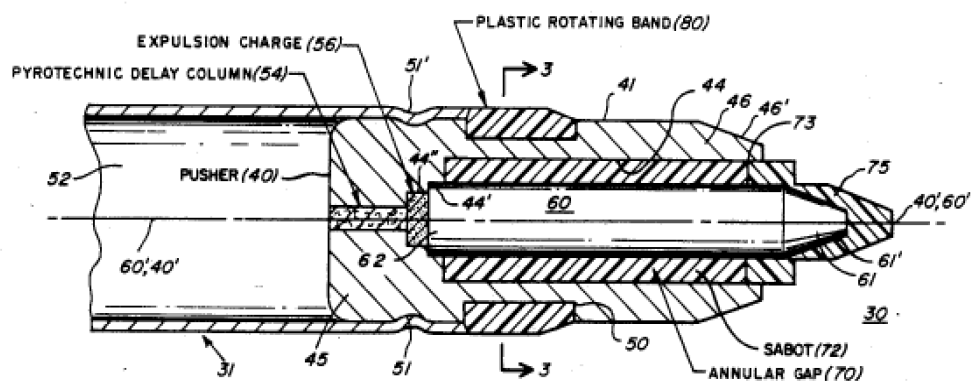
## II. Aerial Gunnery Evolution

### *The Great Show Stopper: Flight Safety*



# III. USAF Advanced Munitions Efforts

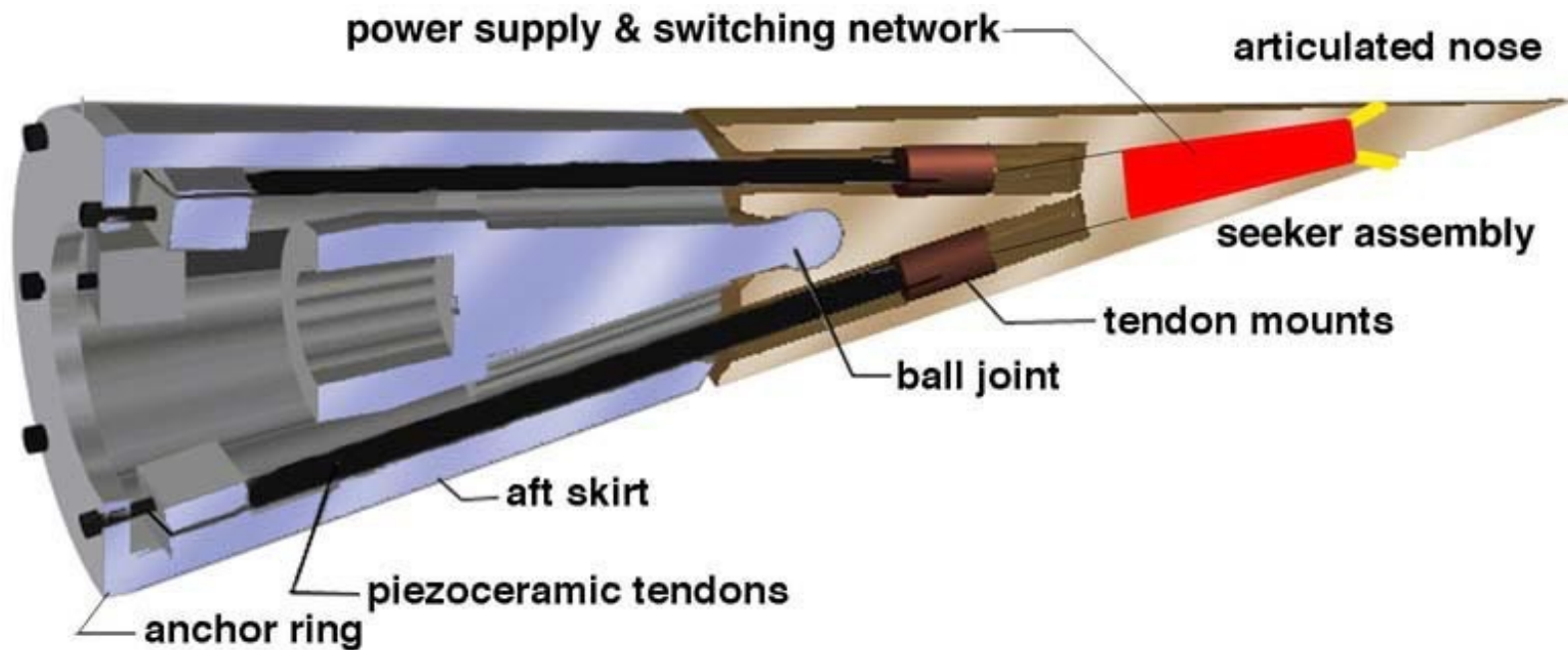
- *Tremendous Activitiy 1952 – 1998*
- *Sabot Diverters*
- *Hybrid Rocket-Assisted Projectiles*
- *Drag Fumers*
- *Rotating Bands*
- *Tubular Projectiles*
- *Disintegrating Sabots*
- *Meyer & Burnette Sabots*





# III. USAF Advanced Munitions Efforts

- **Barrel-Launched Adaptive Munition (BLAM) Program 1995 - 1998**



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## III. USAF Advanced Munitions Efforts

- ***Advanced DoD Aerial Gunnery Ammunition Programs 1998 - Present***



## III. USAF Advanced Munitions Efforts

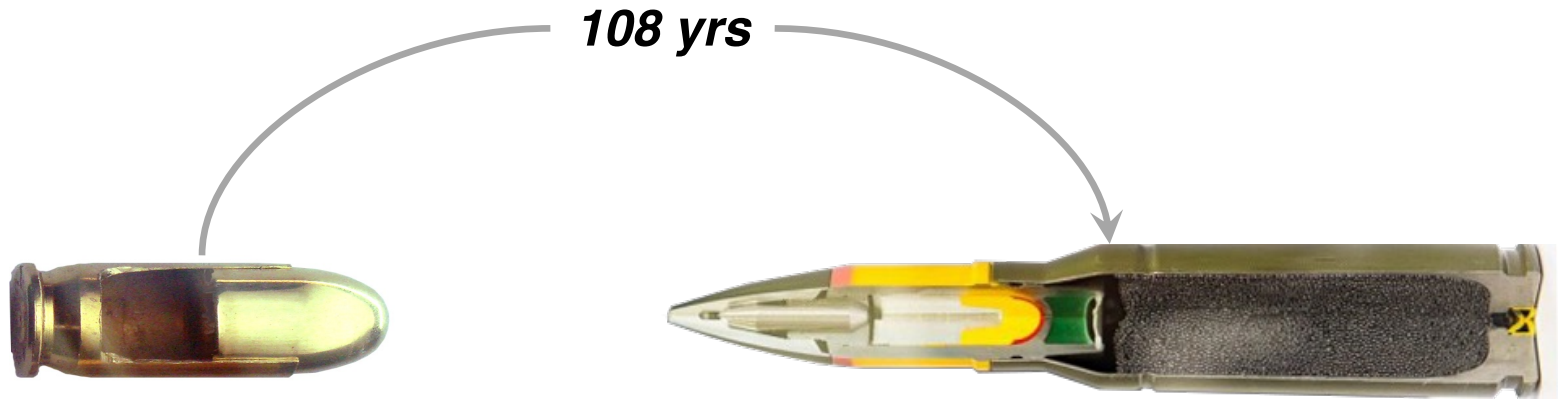
- ***Advanced DoD Aerial Gunnery Ammunition Programs 1998 - Present***

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

*-David Lambert AFRL Chief Scientist November 2021*

# III. USAF Advanced Munitions Efforts

## *Conventional Aerial Gunnery Ammunition has Barely Evolved*



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Image Source:  
Image Source [https://en.wikipedia.org/wiki/.45\\_ACP](https://en.wikipedia.org/wiki/.45_ACP)

Image Source:  
<https://www.f-16.net/forum/viewtopic.php?f=54&t=52628&start=75>

# III. USAF Advanced Munitions Efforts

*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

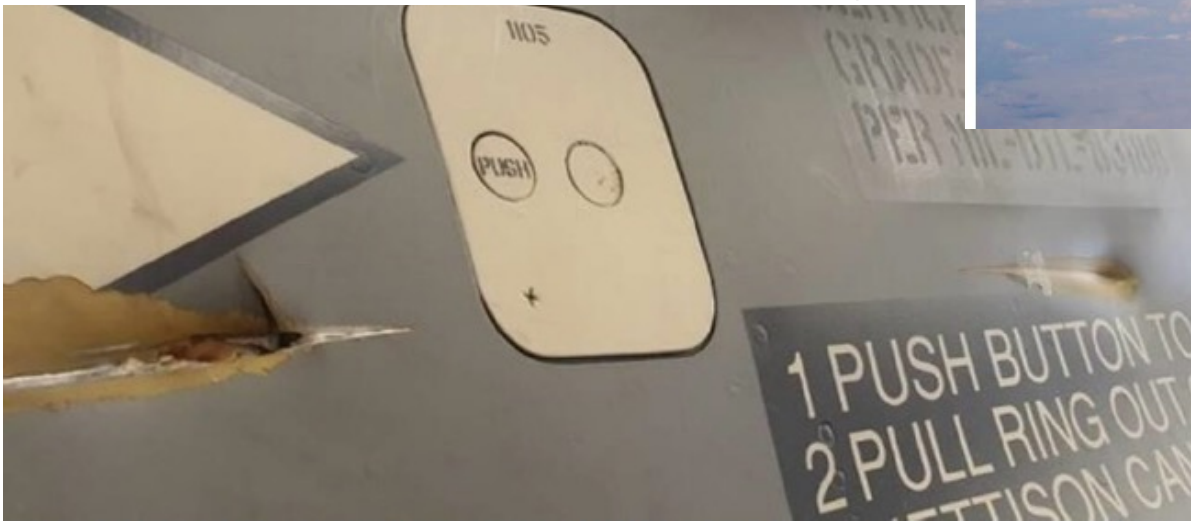


Military Culture

## Dutch F-16 makes emergency landing after plane shoots itself

J.D. Simkins

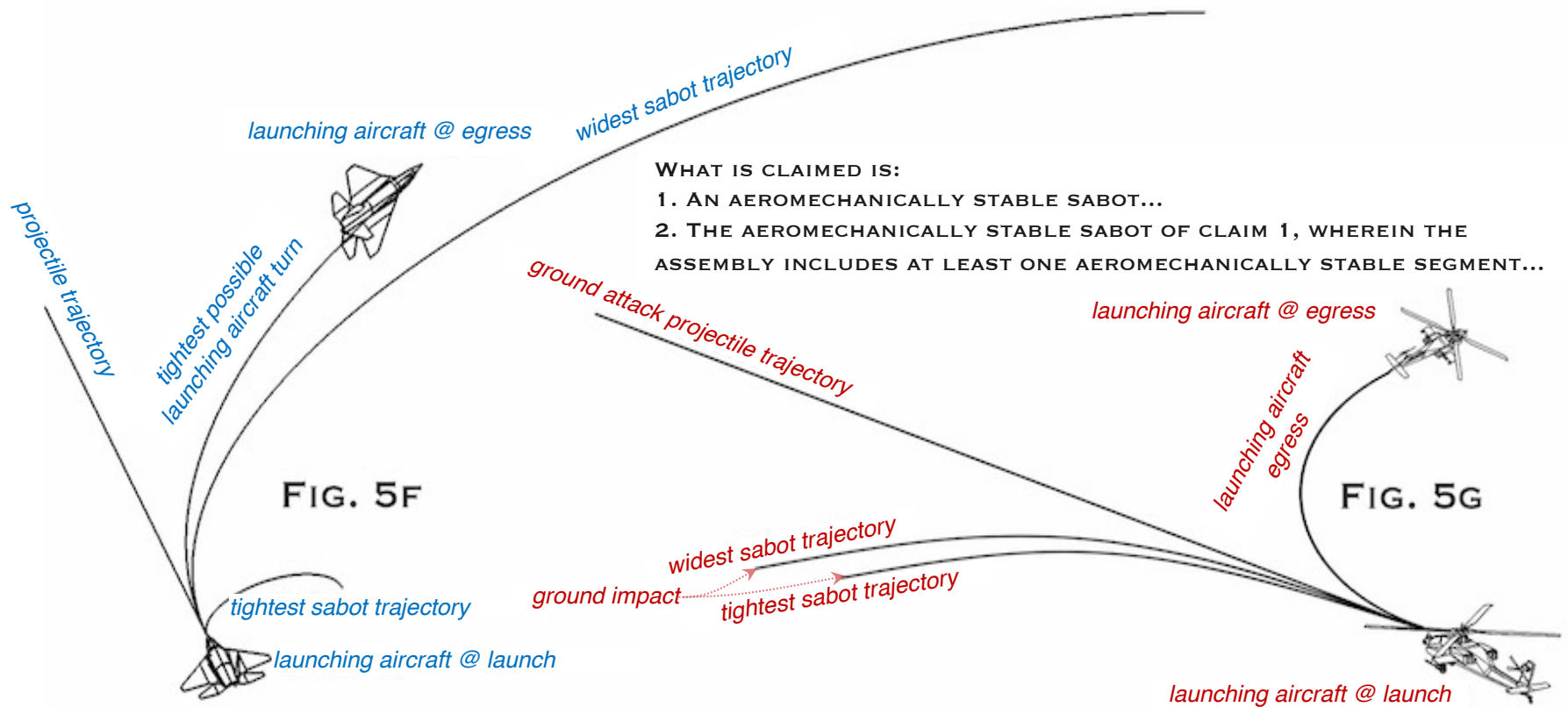
April 8, 2019



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.

# IV. BASS Rounds

## Ballistic Aeromechanically Stable Sabot (BASS) Rounds



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...

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Image Source: PCT/IB2020/053899

US & international patent priority date: 4/26/2019



## IV. BASS Rounds

### ***Ballistic Aeromechanically Stable Sabot (BASS) Rounds***

- ***Conceived & reduced to practice outside of the DoD RDT&E system, 2016 – Present***
- ***Modeled in CFD, FEM, DATCOM & PRODAS***
- ***Tested on Shock Table, Wind Tunnel, Range***
- ***>100 rounds fired, currently @ TRL-6***
- ***US & International Patents Filed***
- ***Federal Government Approved Export & Exported***

*How safe?*

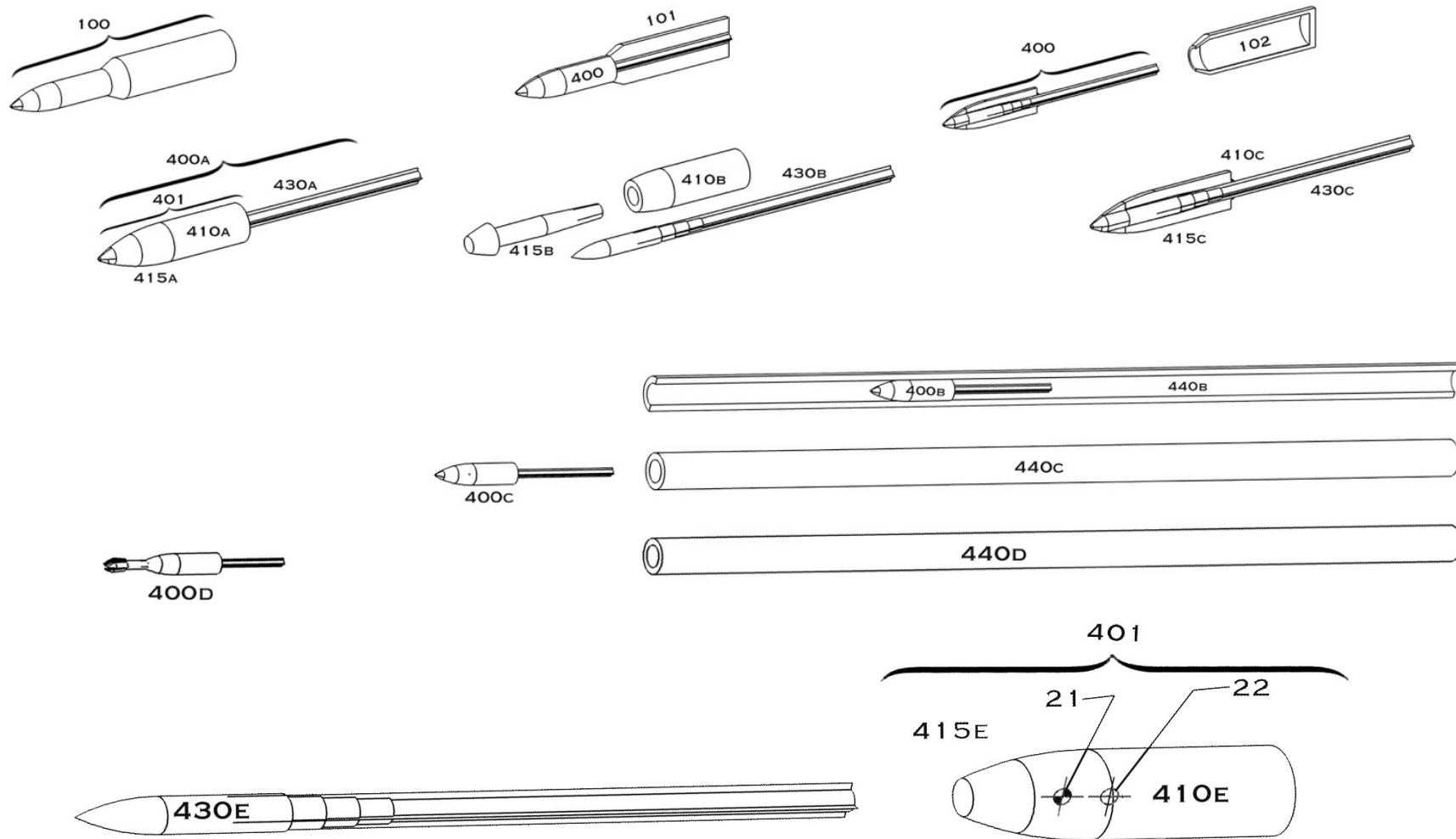
*FAR-23:  $10^{-6}$  air-to-air*

*FAR-25:  $10^{-9}$  ground attack*



# IV. BASS Rounds

*What is claimed is:  
1. An aeromechanically stable sabot...*



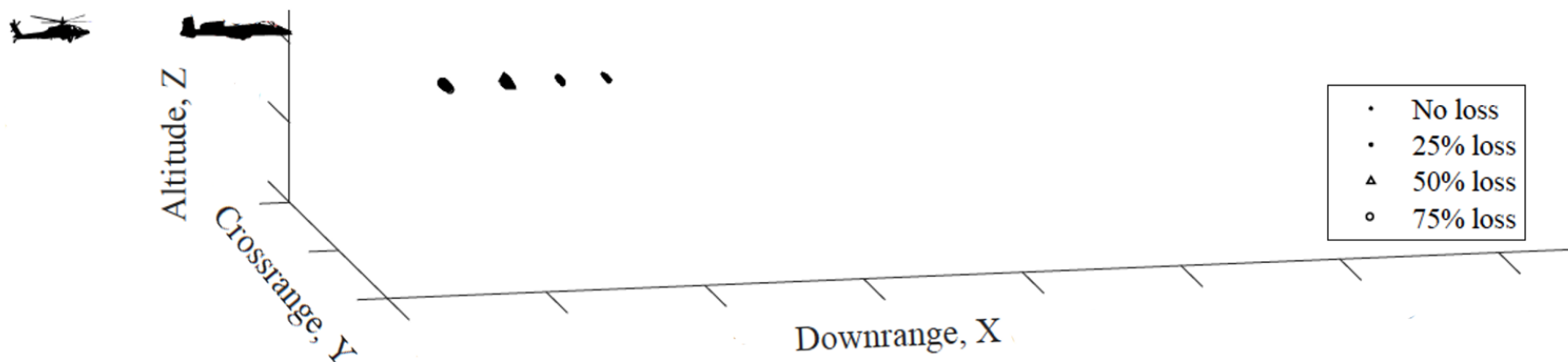
*54 major families, >1,000 species covered in expansive patent filings*

## IV. BASS Rounds

# BASS Sabot Aircraft Clearance

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

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.

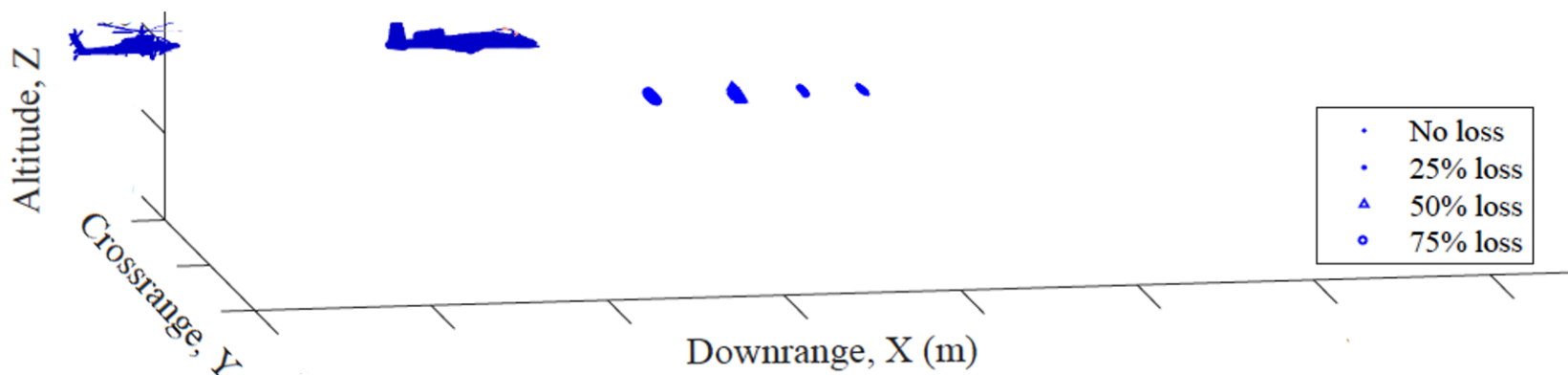




## IV. BASS Rounds

# Scatter & Flight Safety Verification

2 Sec.



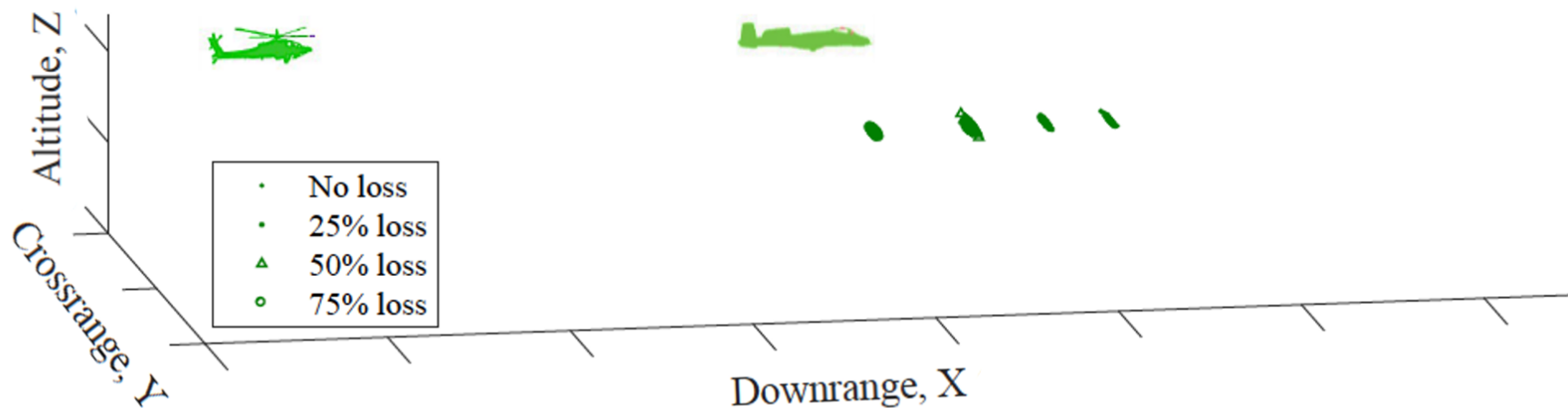
Source: Schumacher, L. N., "BASS Medium Caliber System Modeling: Proof-of-Concept and the Future of Aerial Gunnery with Advanced Munitions," Ph.D. Dissertation Defense, 29 June 2020, The University of Kansas Aerospace Engineering Department, Lawrence, Kansas.

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## IV. BASS Rounds

# Scatter & Flight Safety Verification

3 Sec.

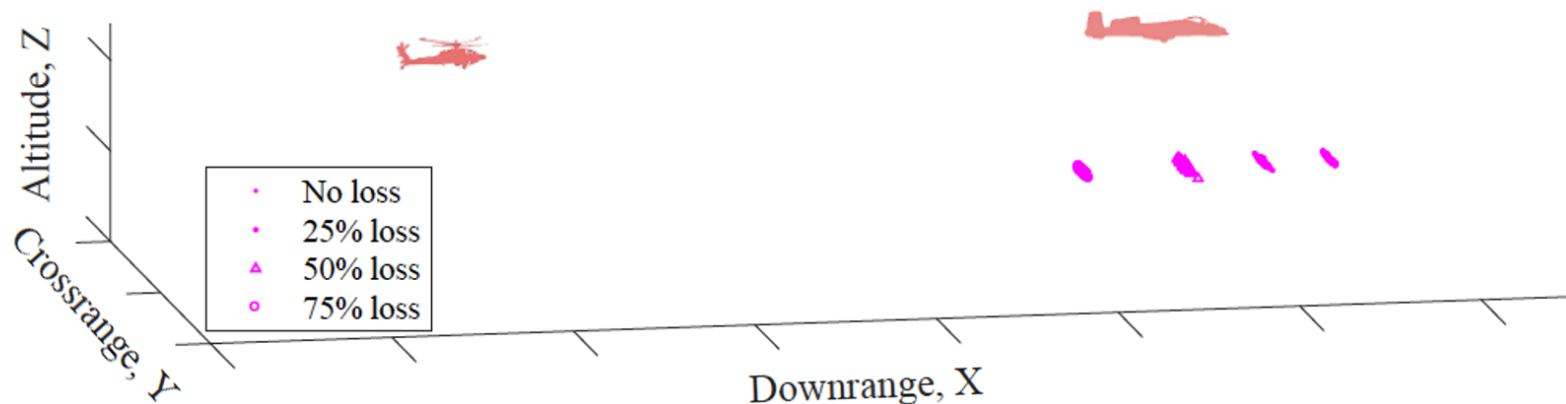


Source: Schumacher, L. N., "BASS Medium Caliber System Modeling: Proof-of-Concept and the Future of Aerial Gunnery with Advanced Munitions," Ph.D. Dissertation Defense, 29 June 2020, The University of Kansas Aerospace Engineering Department, Lawrence, Kansas.

## IV. BASS Rounds

# Scatter & Flight Safety Verification

4 Sec.

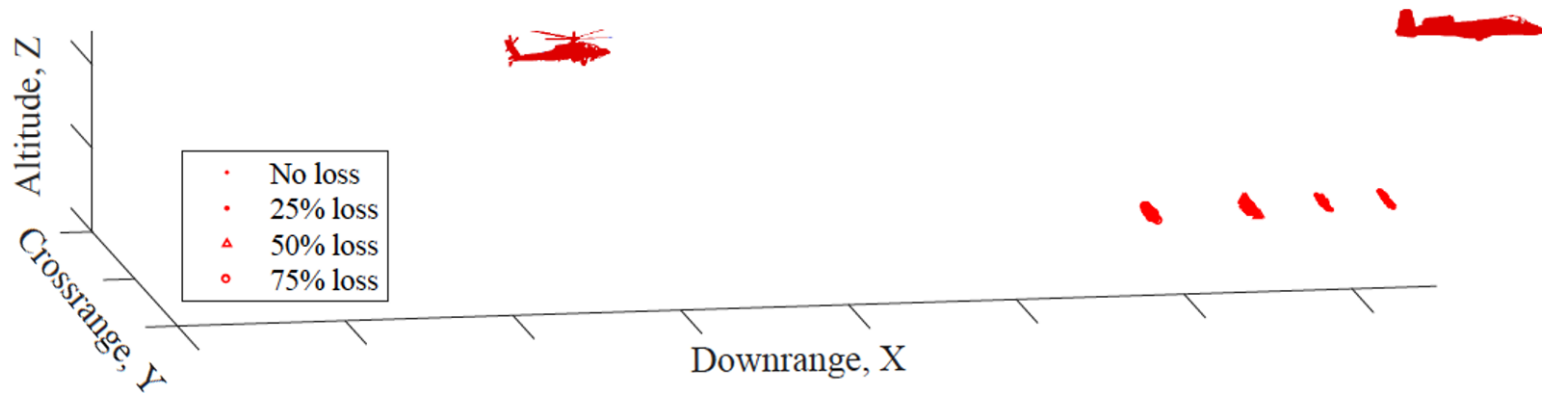


Source: Schumacher, L. N., "BASS Medium Caliber System Modeling: Proof-of-Concept and the Future of Aerial Gunnery with Advanced Munitions," Ph.D. Dissertation Defense, 29 June 2020, The University of Kansas Aerospace Engineering Department, Lawrence, Kansas.

## IV. BASS Rounds

# Scatter & Flight Safety Verification

5 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.

## IV. BASS Rounds

# 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.

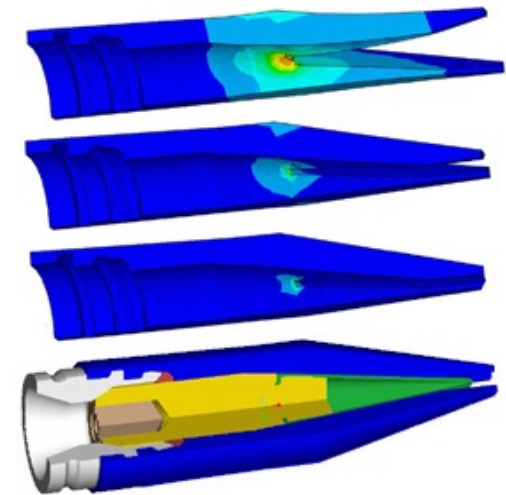


Image Sources:

<https://www.sws-llc.com/structuralanalysis1.htm>

[http://www.mycity-military.com/uploads2/154453\\_716860609\\_Zececiv\\_Dispersion\\_PGU-14\\_ammunition%5B1%5D.pdf](http://www.mycity-military.com/uploads2/154453_716860609_Zececiv_Dispersion_PGU-14_ammunition%5B1%5D.pdf)

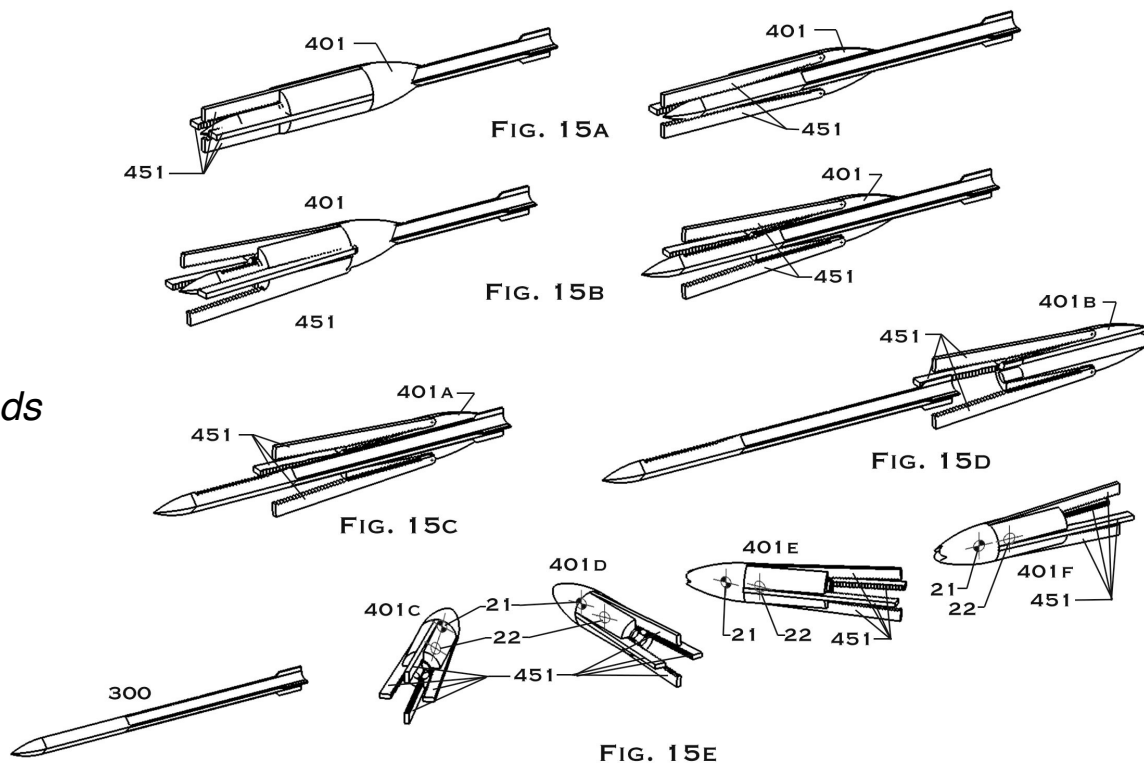
## IV. BASS Rounds

# 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

# IV. BASS Rounds

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

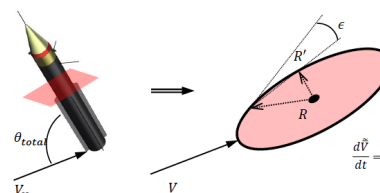
Body Linear Momentum  $\begin{bmatrix} \dot{U} \\ \dot{V} \\ \dot{W} \end{bmatrix} = \frac{1}{m}(m\bar{g} + \bar{F}) - \bar{\Omega} \times \bar{V}_b$

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

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

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



$c_{p_{0,z}} = \frac{P_{0,z} - P_{\infty}}{q} = \frac{P_{0,z} - P_{\infty}}{\frac{\gamma}{2} \rho_{\infty} M_{\infty}^2} = \frac{2}{\gamma M_{\infty}^2} \left( \frac{P_{0,z}}{P_{\infty}} - 1 \right)$   
 $c_p = c_{p_{0,z}} \sin^2(\theta)$   
 $c_p = c_{p_0} \sin^2 \theta = \left( \frac{(\gamma+1)^2}{4\gamma} \right)^{\frac{\gamma}{\gamma-1}} \frac{4}{\gamma+1} \left( \frac{2}{\gamma M_{\infty}^2} \right) \sin^2 \theta$

$\frac{d\bar{V}}{dt} = -\frac{1}{2m} \rho S V C_D \bar{V} + \frac{1}{2m} \rho S C_{L\alpha} (V^2 \bar{X} - (\bar{V} \cdot \bar{X}) \bar{V}) - \frac{1}{2m} \rho S D C_{N\beta} \left( \frac{\partial yx}{\partial x x} \right) (\bar{h} \cdot \bar{X}) (\bar{X} \times \bar{V})$   
 $+ \frac{1}{2m} \rho S V D (C_{Nq} + C_{N\dot{\alpha}}) (\bar{h} \times \bar{X}) + \bar{g} + \bar{a}$   
 $\frac{d\bar{h}}{dt} = \frac{1}{2I_{yy}} \rho S V D C_{M\alpha} (\bar{V} \times \bar{X}) + \frac{1}{2I_{xx}} \rho V S d^2 C_{M\beta} (\bar{h} \cdot \bar{X}) (\bar{V} - (\bar{V} \cdot \bar{X}) \bar{X})$   
 $+ \frac{1}{2I_{yy}} \rho S V D^2 (C_{Mq} + C_{M\dot{\alpha}}) (\bar{h} - (\bar{h} \cdot \bar{X}) \bar{X}) + \frac{1}{2I_{xx}} \rho S V D^2 C_{I\beta} (\bar{h} \cdot \bar{X}) \bar{X}$   
 $+ \frac{1}{2I_{yy}} \rho S V^2 C_{I\alpha} D \delta \bar{X}$

Source of relationships:  
<http://www.songho.ca/math/quaternion/quaternion.html>  
[https://en.wikipedia.org/wiki/Rotation\\_formalisms\\_in\\_three\\_dimensions](https://en.wikipedia.org/wiki/Rotation_formalisms_in_three_dimensions)

Unlimited Distribution

Distribution A

## IV. BASS Rounds

# 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.

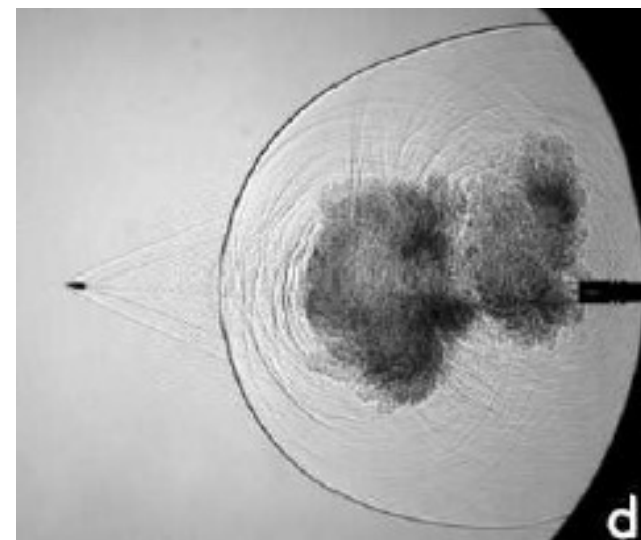
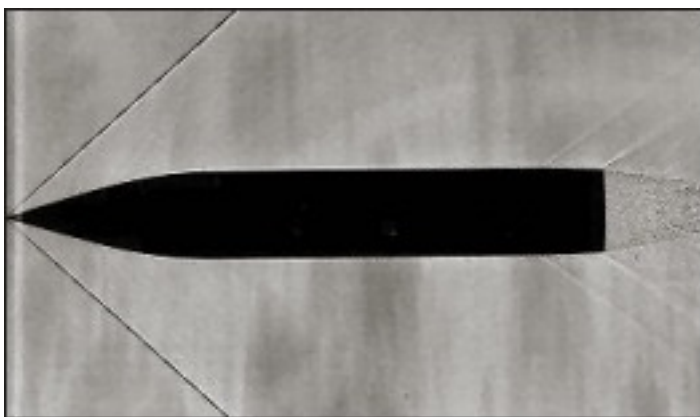


Image Sources:

<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](https://www.researchgate.net/figure/Focused-shadowgrams-of-223-automatic-rifle-fire-a-sharply-focused-b-defocused-1m_fig3_226053639)





# Freeflight Aeromechanics

## *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.



Distribution A Unlimited Distribution



## IV. BASS Rounds 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.



# Freeflight Aeromechanics



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.

Distribution A Unlimited Distribution

# Freeflight Aeromechanics

## Modeling, Analysis & Testing

### Performance Analysis:

- Projectile and sabot tracking downrange in full gust atmospherics
- Juxtaposition with aircraft trajectories and establishment of “stay-out” zones
  - 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

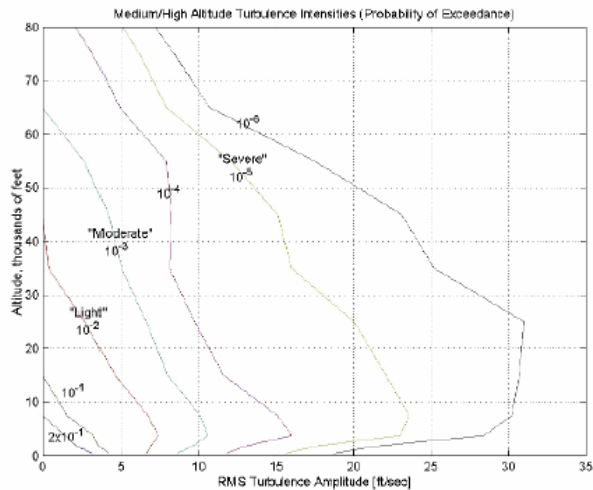
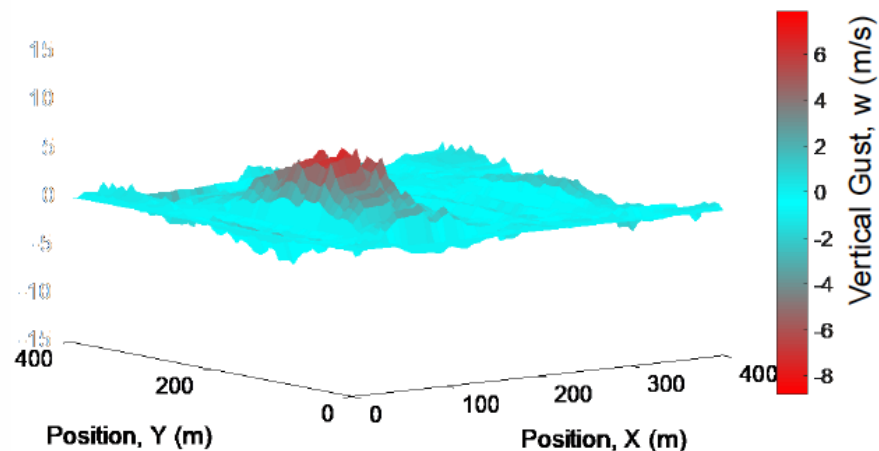


Image Source: MIL-HDBK-1797





# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals

### General Configurations

#### BASS Flechette



#### PGU-14



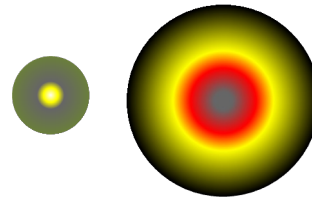
# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals

### Flechette

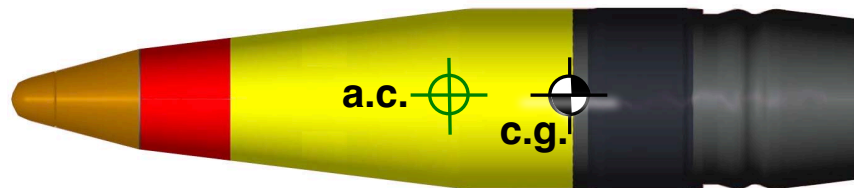
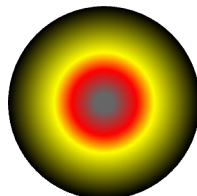


*X-Sectional Area of PGU-14 >> Flechette*



### PGU-14

*Supersonic Drag ~ proportional to X-Sectional Area, Drag<sub>PGU14</sub> >> D<sub>Flechette</sub>*

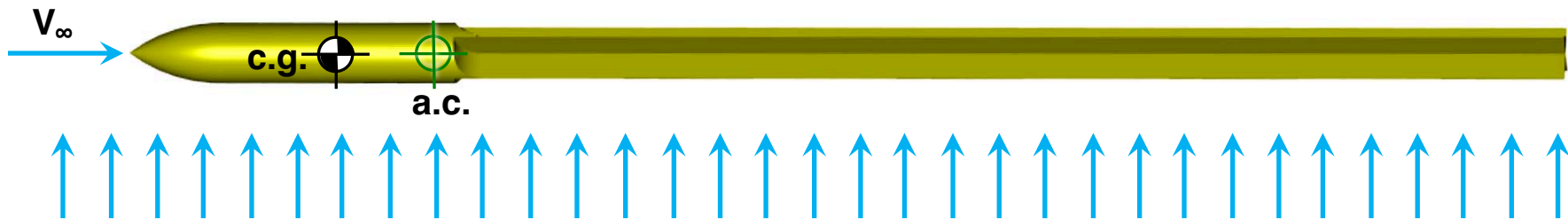


# Freeflight Aeromechanics

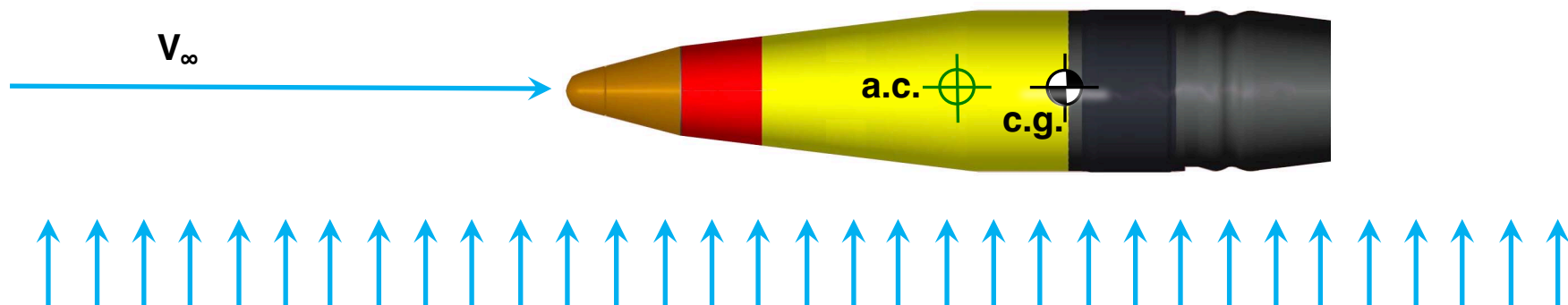
## Projectile Aeromechanics & CEP Fundamentals

### Flechette

*Instantaneous introduction of lateral gust*



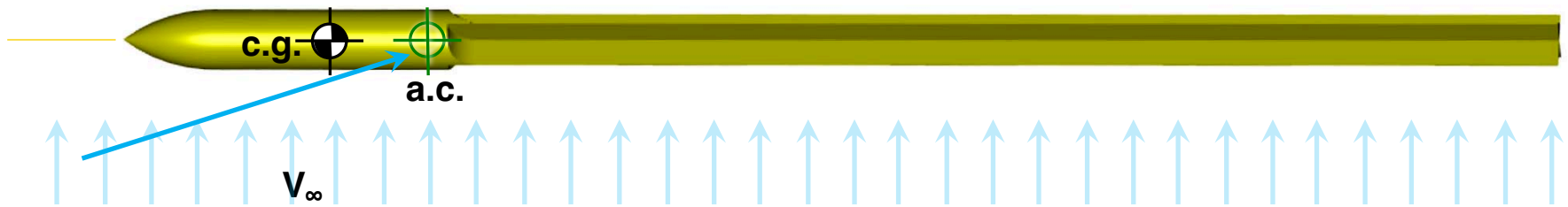
### PGU-14



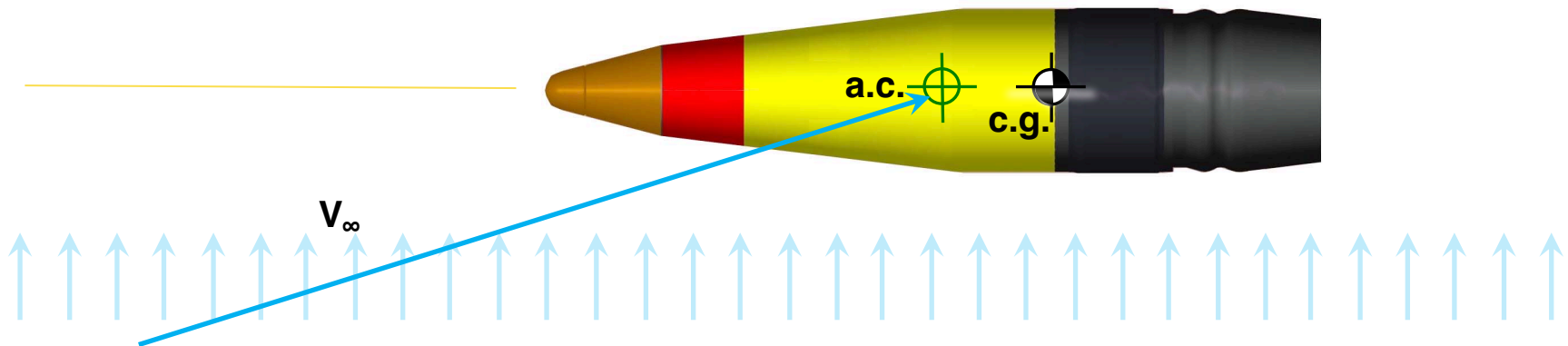


# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals



PGU-14



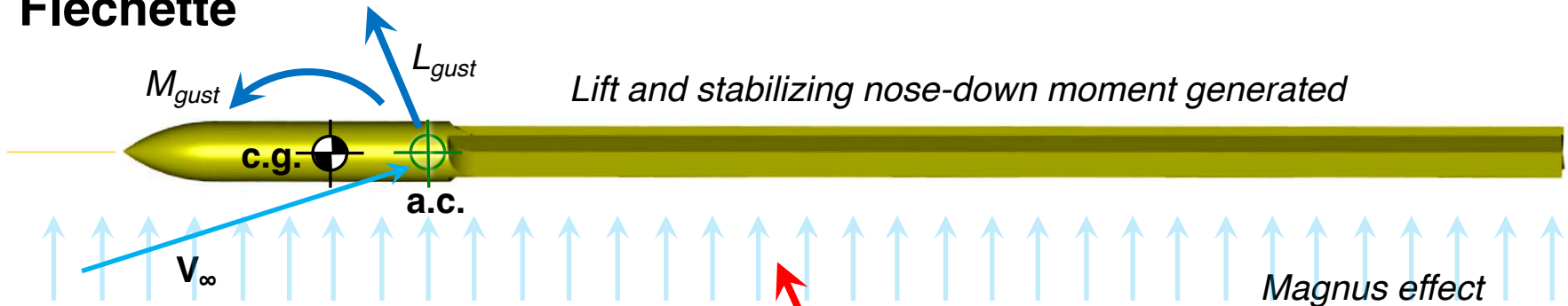
Distribution A Unlimited Distribution



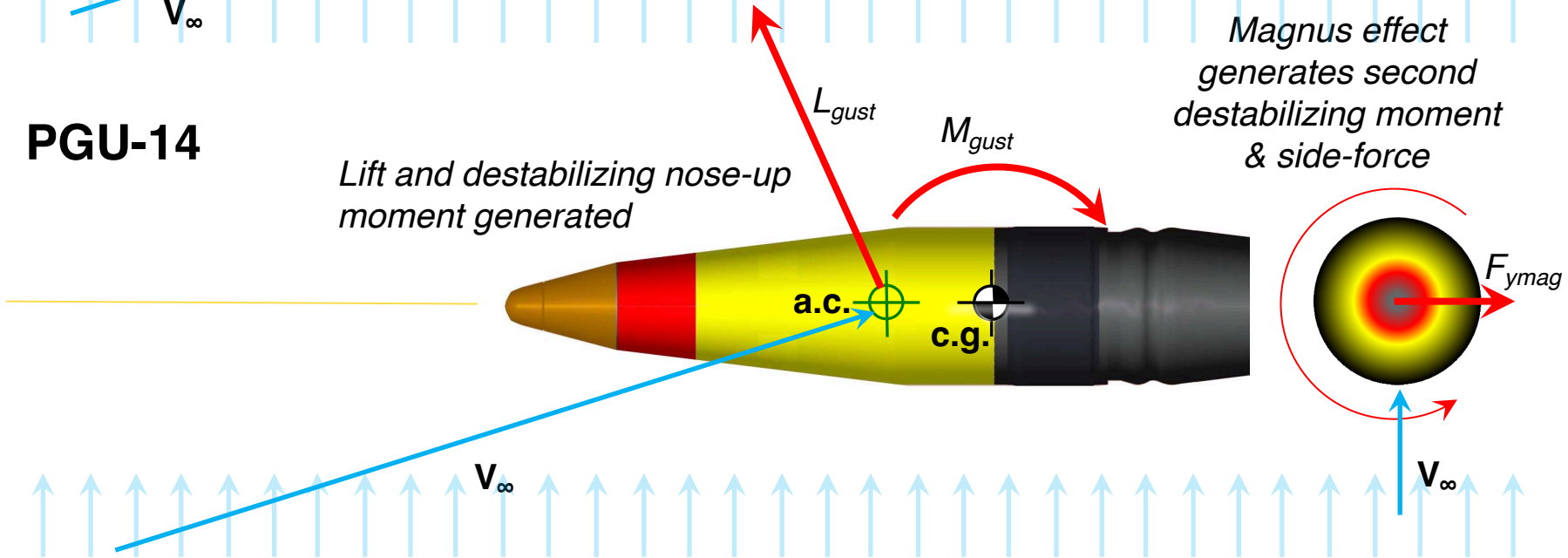
# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals

### Flechette



### PGU-14

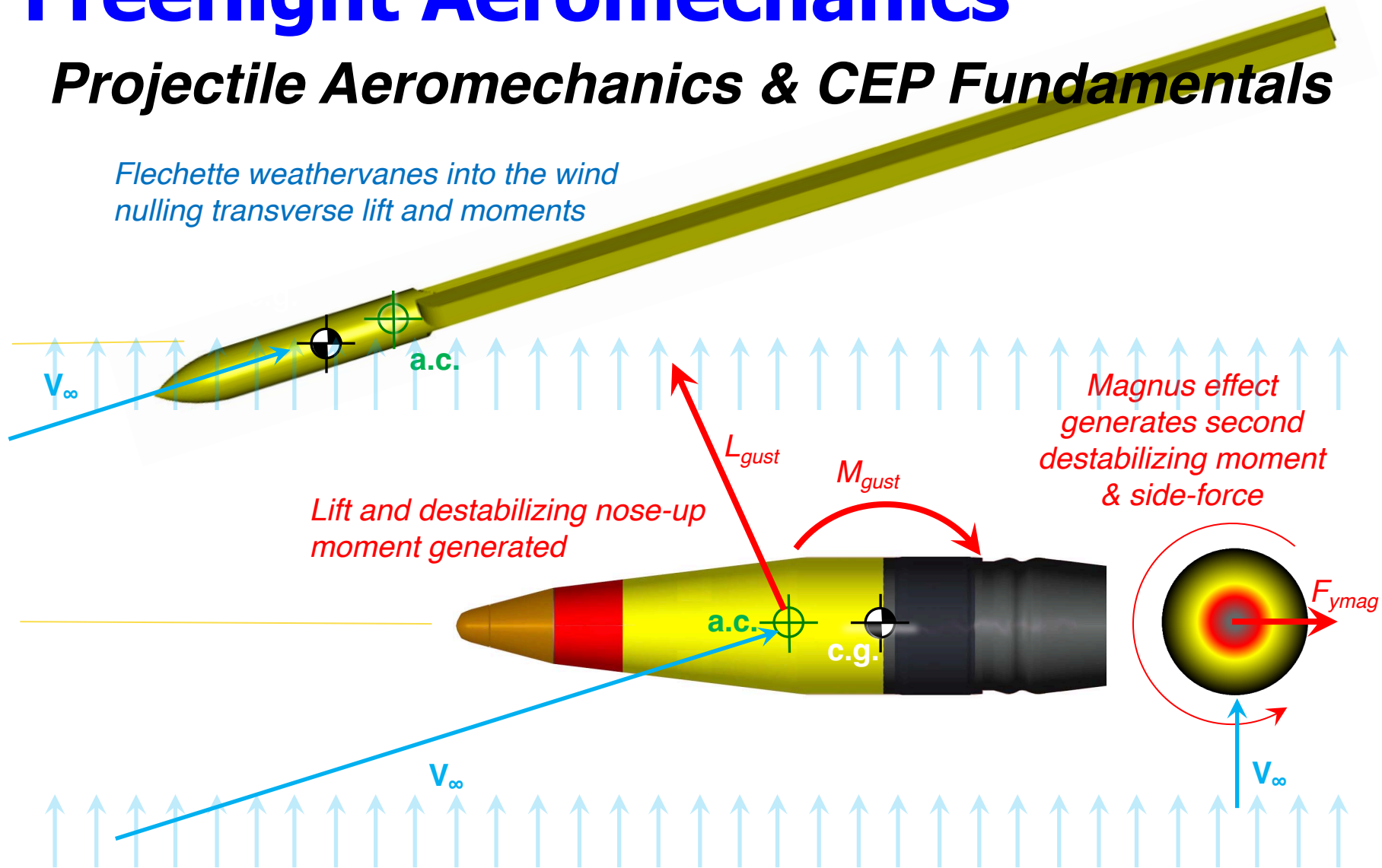


Distribution A Unlimited Distribution

# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals

*Flechette weathervanes into the wind  
nulling transverse lift and moments*



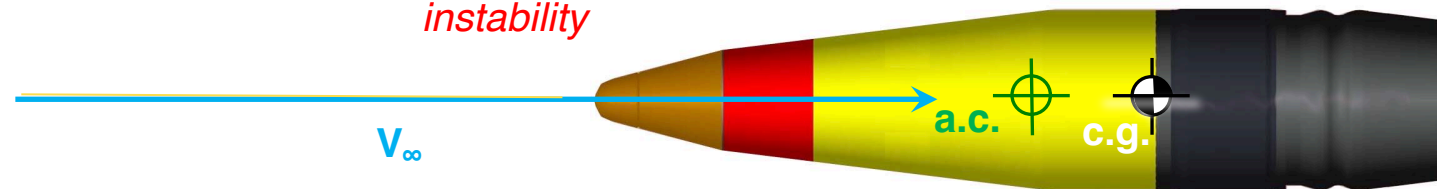
# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals

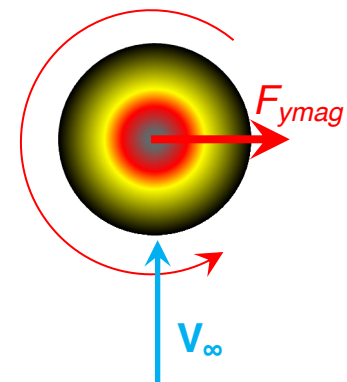
*Flechette experiences lift and moments in the opposite direction, often nulling flight path deviations*



*Dynamic modes (precession, nutation) excited given low  $Cmq$  & inherent instability*



*Magnus effect generates second destabilizing moment & side-force*



# Freeflight Aeromechanics

## Projectile Aeromechanics & CEP Fundamentals

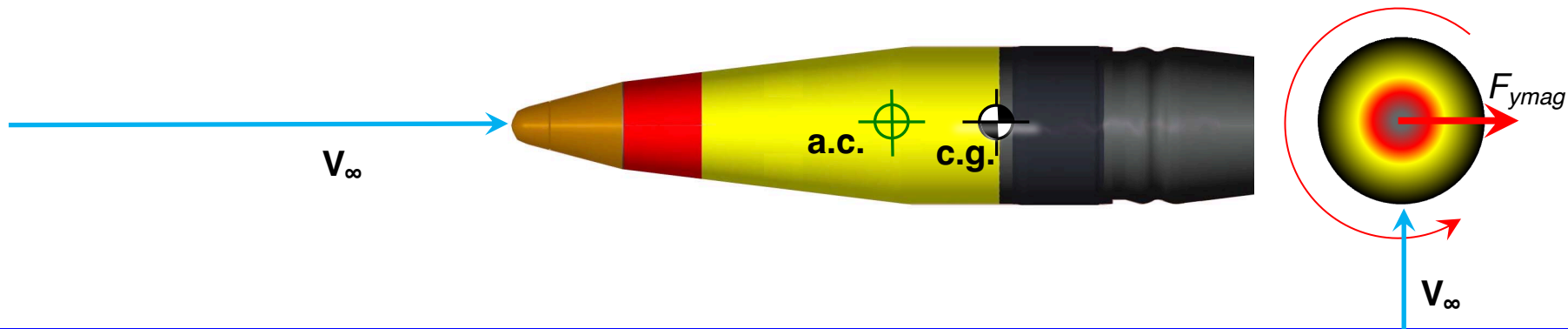
### Flechette

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



### PGU-14

*CEP greatly increased due to steady-state and dynamic effects*

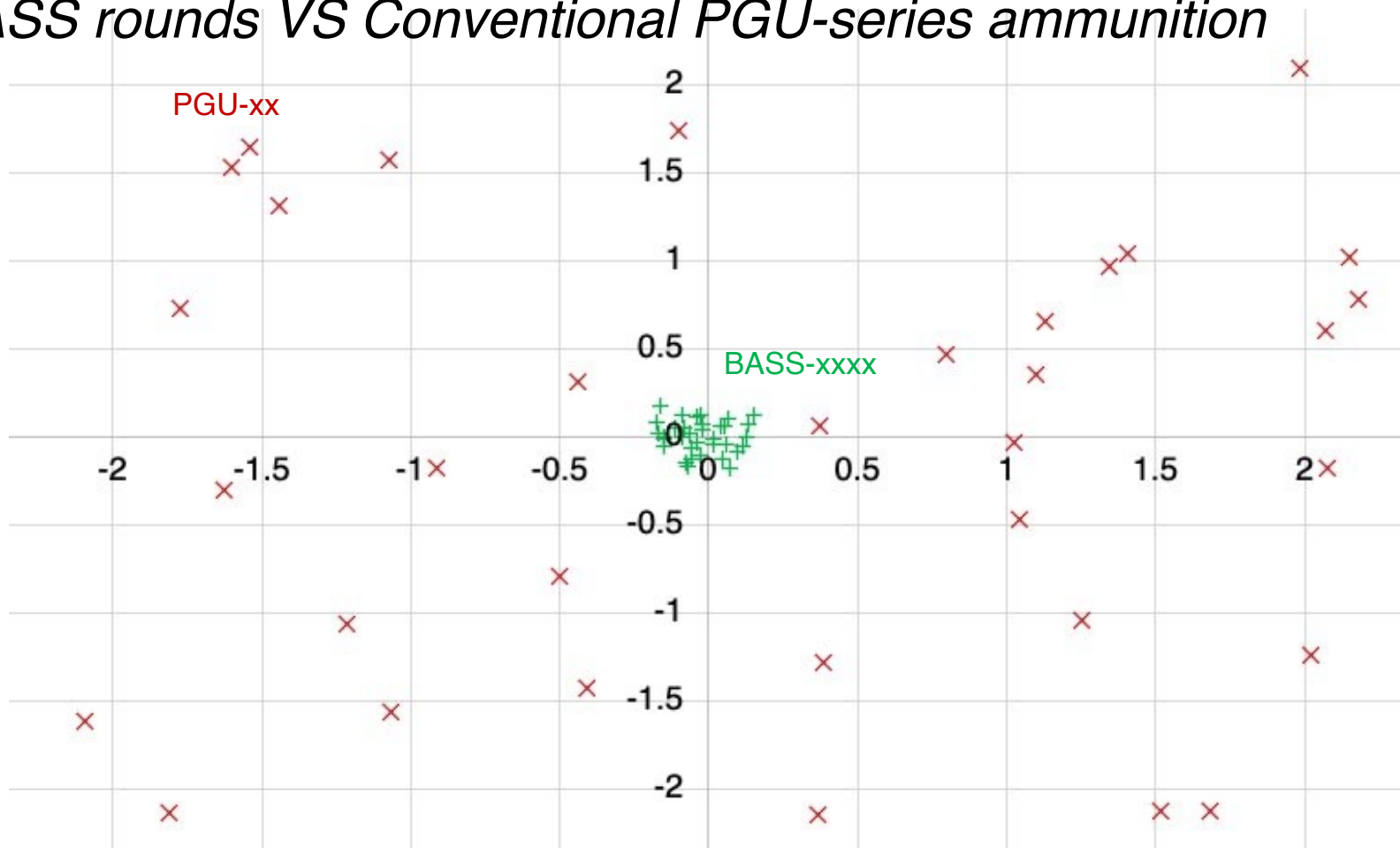




# Freeflight Aeromechanics

## CEP Comparison:

*BASS rounds VS Conventional PGU-series ammunition*

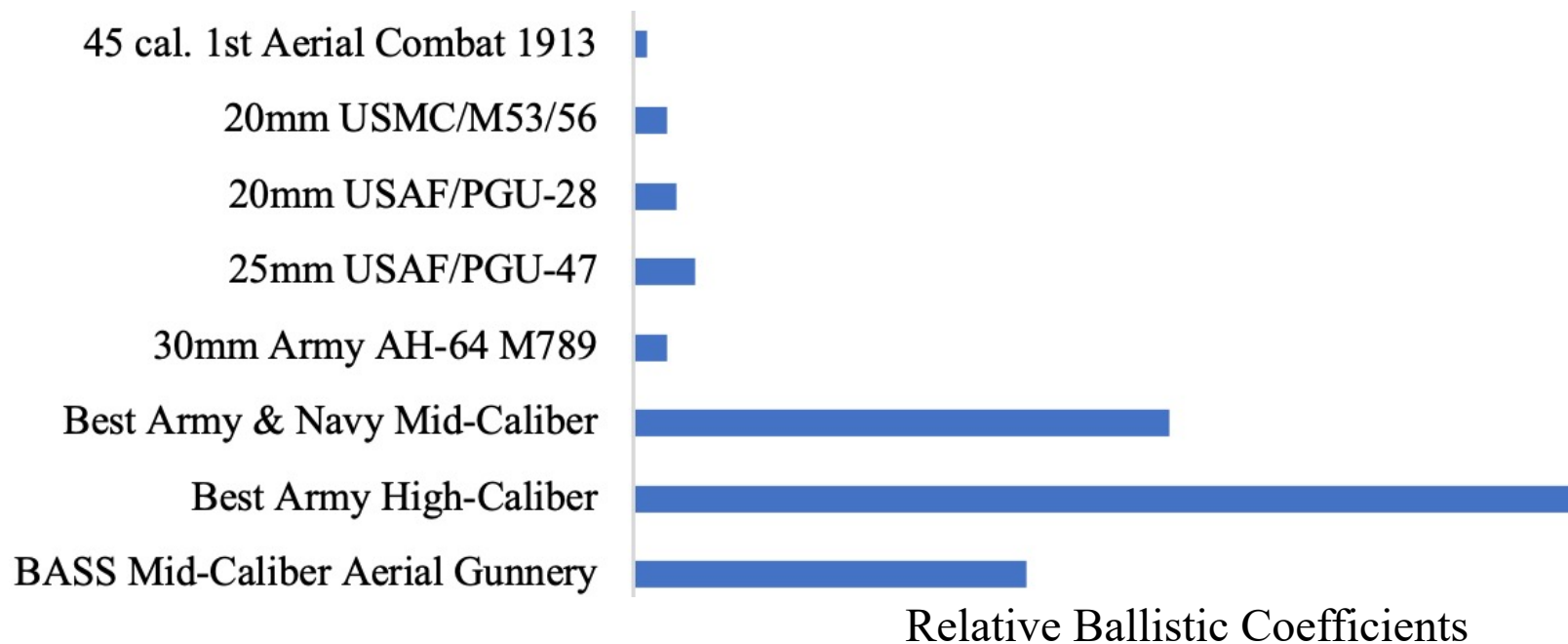


90% gust field for both round families

Distribution A Unlimited Distribution

## V. Conclusions

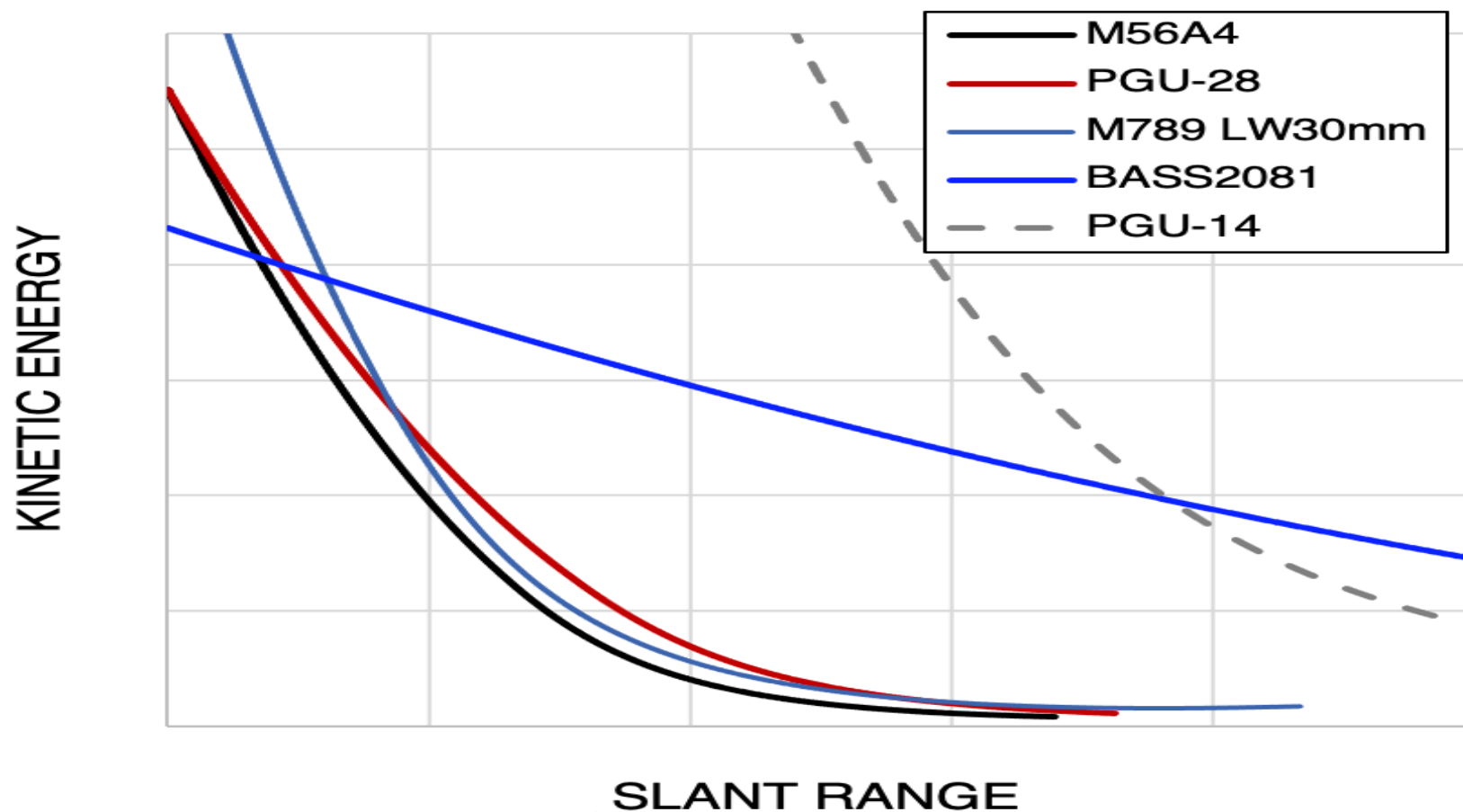
***BASS Rounds Represent the First Major Advance in Ballistic Coefficients for Aerial Gunnery Ammunition in Over a Century***



Relative Ballistic Coefficients

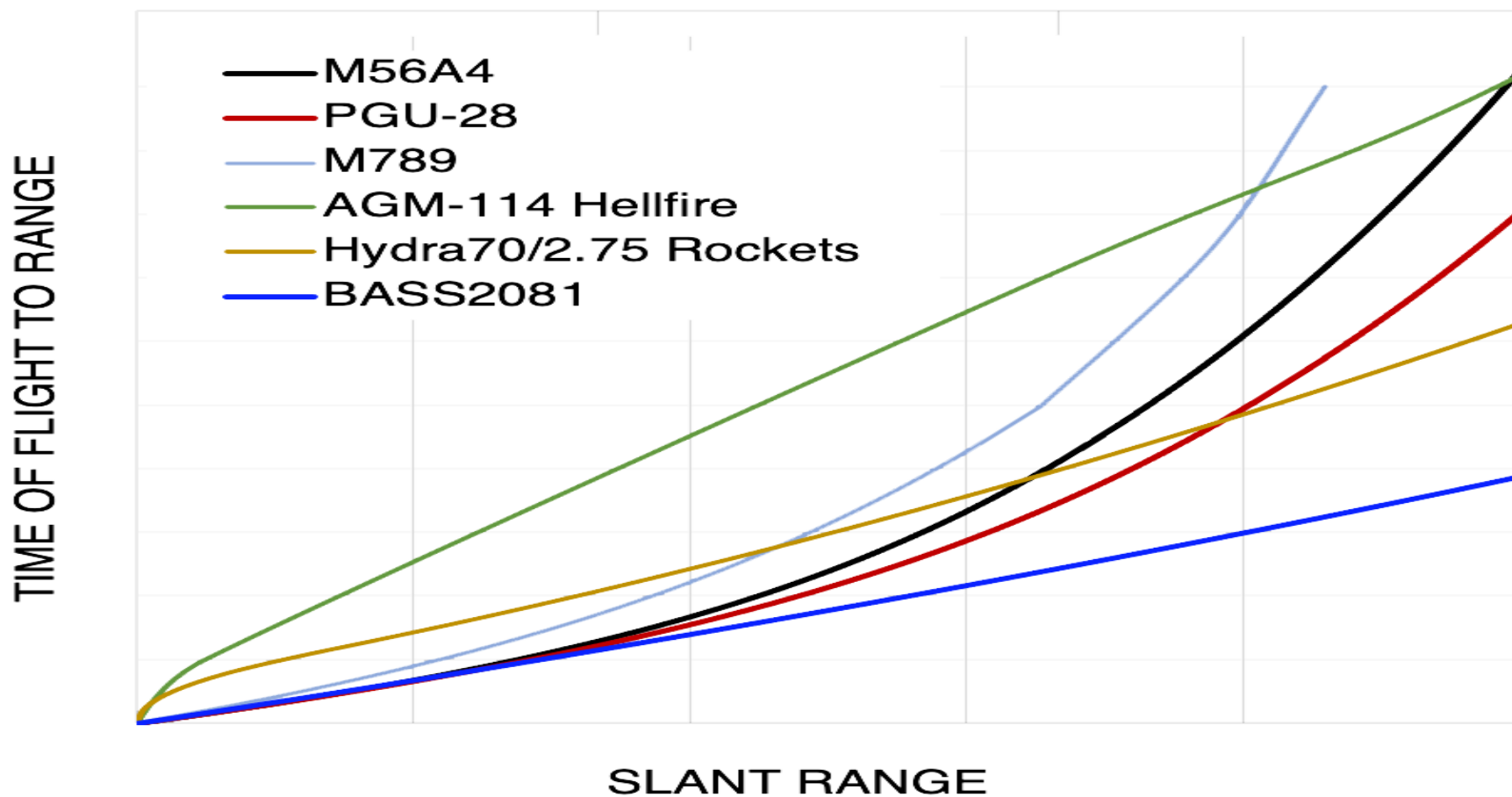
# V. Conclusions

## *Flight Safe Discarding Sabot Ammunition Promises Dramatic Improvements in Aerial Gunnery*



# V. Conclusions

## *Flight Safe Discarding Sabot Ammunition Promises Dramatic Improvements in Aerial Gunnery*







# Questions?

