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A History of Flight Safe Discarding Sabot Rounds

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This paper outlines the development of saboted aerial gunnery rounds from their origins in conventional surface gun systems through today. Starting with the first medieval document describing a cannon firing a saboted fléchette, the evolution of sabots and saboted rounds is followed through widescale fielding in the 19th and 20th centuries. Changes in sabot materials, design philosophies and round performance are shown to have enabled anti-armor applications in surface gunnery. The tremendous innovations seen in these rounds are then juxtaposed to the lack of innovation in designs and configurations in aerial gunnery ammunition. Modern incarnations of aerial gunnery rounds are shown to have only incrementally evolved since they were first developed more than a century ago. This paper describes the practical and programmatic difficulties that plagued many aerial gunnery ammunition programs and why efforts to employ saboted rounds failed. Compounding these difficulties is the near complete divestment by the DoD in advanced aerial gunnery ammunition RDT&E since 1998. As a result, the ballistic coefficients of today's aerial gunnery ammunition are shown to be only incrementally better than those found in the first aerial pistol duels. The paper also describes modern, private efforts to modernize munitions for aerial gunnery given the absence of DoD leadership and funding. The Ballistic Aeromechanically Stable Sabot (BASS) rounds are shown to improve aerial gunnery dramatically with decreases in times of flight and large increases in range, kinetic energy and armor penetration capabilities. The paper concludes with a review of Federal government export approvals and international patent filings.

I. Nomenclature

AAL	=	*Adaptive Aerostructures Laboratory*
APDS	=	*Armor-Piercing Discarding Sabot*
APFSDS	=	*Armor-Piercing Fin Stabilized Discarding Sabot*
APFSDS-T	=	*Armor-Piercing Fin Stabilized Discarding Sabot - Tracer*
API	=	*Armor-Piercing Incendiary*
ARF	=	*Aeroballistics Research Facility*
BAA	=	*Broad Agency Announcement*
BASS	=	*Ballistic Aeromechanically Stable Sabot*
BLAM	=	*Barrel-Launched Adaptive Munition*
CEP	=	*Circular Error Probable*
CIWS	=	*Close-In Weapon System*
ERGM	=	*Extended-Range Guided Munition*
EXACTO	=	*Extremely Accurate Tasked Ordnance*
HEAT	=	*High Explosive Anti-Tank*
MADFIRES	=	*Multi-Azimuth Defense Fast Intercept Round Engagement System*
MASS	=	*Maneuvering Aeromechanically Stable Sabot*
RAP	=	*Rocket Assisted Projectile*
RDT&E	=	*Research, Development, Test, and Evaluation*
REAM	=	*Range-Extended Adaptive Munition*
SBIR	=	*Small Business Innovation Research*
SCREAM	=	*Shipborne Countermeasure Range Extended Adaptive Munition*
UAV	=	*Uninhabited Aerial Vehicle*

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II. Sabot Origins

The earliest archival document describing a cannon firing a bolt or fléchette (dart) with an associated sabot is the famous treatise of Walter de Milemete [1]. His "De Nobilitatibus, Sapientiis, et Prudentilis Regum" (Nobility, Wisdom and Prudent Conduct for Kings), was commissioned by Queen Isabella of France for her son Edward (later, King Edward III of England). The 1326 tome included many of the latest thoughts on warfare and war machines and, while the earliest archival source in the West, depicts a wide variety of tactics and weapons current to that era. Among the many devices presented was a "pot-de-fer" (fire pot), which is shown in Figure 1 being lit and expelling an arrow-shaped projectile from an opening. A leather wrap is wound around the projectile shaft, and served to transfer the energy from explosively expanding gasses to the flechette upon firing. This energy transfer allowed higher exit speeds to be obtained in this early incarnation of a saboted munition. While the terms "aeromechanical stability" and "kinetic energy" would not be documented for centuries, it is clear that the weaponeers of the day understood the importance of both. A similar fléchette (chambered) is also depicted in its 1326 companion book, "Secretum Secretorum" (The Secret of Secrets) [2]. Other contemporary documents describe similar powder-based siege weapons that were used by German knights in the 1331 siege of Cividale del Friuli (on the border of modern Italy and Slovenia today) [3]. These munitions—representing the first cannon projectiles recorded in the west—were not balls, full-bore shots, or bullet-shaped rounds, but aeromechanically stable, saboted fléchette projectiles. The projectiles were clearly designed with a high level of forethought and skill, outlining a deeper understanding of kinematics and energy conservation as it applies to ballistics.

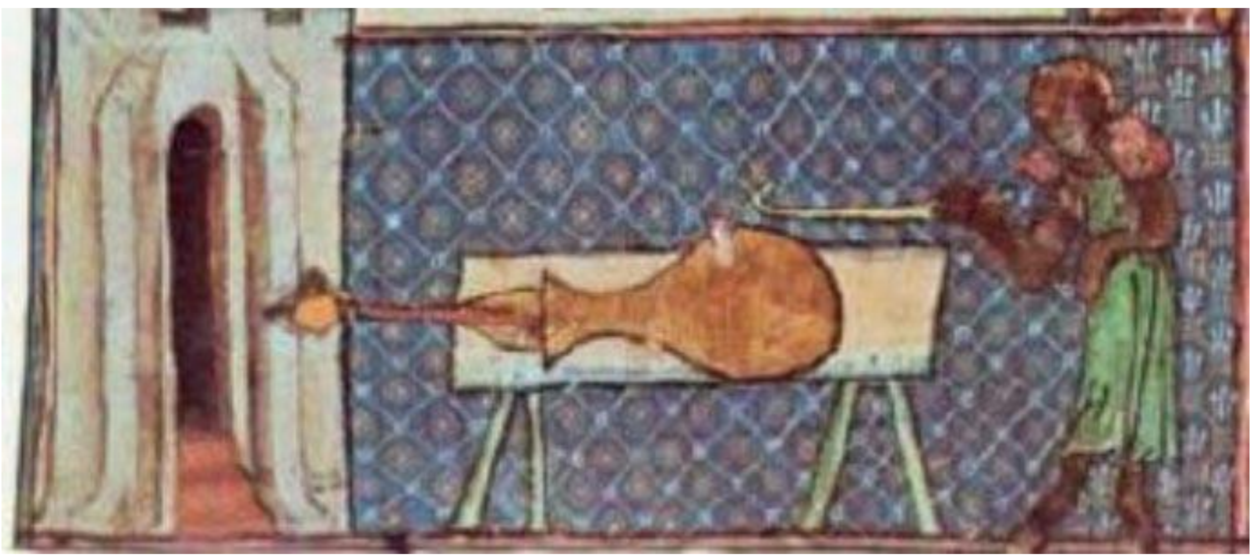

Figure 1: Walter de Milemete's 1326 Depiction of an Aeromechanically Stable, Saboted Fléchette [1]

A Review of Early Artillery

Full bore projectiles significantly predate saboted projectiles, some of the earliest incarnations enabled by the Chinese development of gunpowder and subsequent weapon systems like the fire lances of the Song dynasty (960-1279CE) [4]. The earliest depiction of a cannon is a sculpture from Sichuan province, China, dating to 1128 CE [5]. Cannon systems firing ball-type projectiles rapidly spread, becoming a common feature of battlefields in offensive and defensive combat, typically in sieges. Numerous records describe the purchase and use of a variety of *cannones de metallo* and lead balls during the warfare in Turin and Florence in 1326 and 1327 [6]. Other projectile types were also used with these full-bore cannon weapons, though less common. The ball-type projectiles typically used have severe wave drag penalties, but a detailed study of these phenomenon would not occur until formal study of artillery. As weapon system development began to rapidly advance, the interplay between tactics, command and command structures, and weapon system development became ever more intertwined. One famous example is none other than Napoleon himself; as a former artillery officer, who was successful in standing up its own service branch [7]. As a consequence of this interplay, command structures, weapons, and tactics advanced rapidly under unified commanders like Sénarmont. That a commanding general would be directly involved in the coevolution of ordnance and tactics speaks volumes of both the faith of a commander in his subordinates, but also the effectiveness of this class of weapon [8]. Many of Napoleon's victories were heavily supported by aggressive and innovative use of coordinated, concentrated artillery fire against enemy lines, often tearing through opposing infantry so effectively that supported calvary would face scant opposition as they rode through row upon row of the breeched enemy line [9].

Independent artillery branches of armed forces would greatly aid in the development and detailed study of projectiles, weapons, and the interplay with tactics. Early branches formed in France, Prussia and England exemplify this land-based advancement. The study of artillery was also not limited to land warfare; advances in naval surface fire are not to be ignored as they too proved decisive in many sea battles of the era. Indeed, the Battle of Trafalgar and famously the decimation of the French fleet under Brueys d'Aigalliers by Nelson in the Battle of the Nile firmly intertwined surface fire and naval tactics, while capturing the attention of rules and the various bodies politic [10].

With the recognition that naval surface fire and land-based artillery were the "Kings of Battle," the quest for ever better performing rounds, more energetic powder, lighter guns and improved tactics were increasingly the focus of military advancement and scientific study. Breechloaders were essentially unknown till an obscure Swedish Diplomat and owner of a gun foundry made several important innovations in the 1830's. At the center of this advancement was, Martin von Wahrendorff (1789-1861), who was responsible for revolutionizing gunnery in several important ways. His inventions culminated in 15 patents (most on cannon technology) and he was among the first to patent a breech loading cannon [11]. Figure 2 shows a simple but effective way of opening and sealing the gun breech while allowing rapid loading of projectiles and charges. Although Von Wahrendorff was running a foundry in one of the most active iron ore producing countries of in the world at that time, the grades of metals available to him were limited in strength. He met this challenge with clever mechanical implementations of this ideas: loading the breech retention mechanism with a shear pin rather than threads as is the norm today. His gun was so successful that three years after patenting the design in 1837, the gun would be manufactured in his own gun works, and was adopted by the Swedish Army as the standard by 1854 [11] [12]. Today this innovation is remembered as the "Wahrendorff Breech."

Wahrendorff's second great contribution to gunnery was the inclusion of rifling in the barrel to aid in long range accuracy. This advancement was also accredited to Joseph Whitworth of the UK for independently developing rifled barrels. The embodiment of his famous invention was the Whitworth Rifle: one of the earliest examples of a dedicated sniper rifle [13]. Cavalli of Sardenia and Von Wahrendorff were both contemporaries, correspondents, and some claim, mutual admirers. Accordingly, it is no surprise that both independently invented rifled cannon barrels [14].

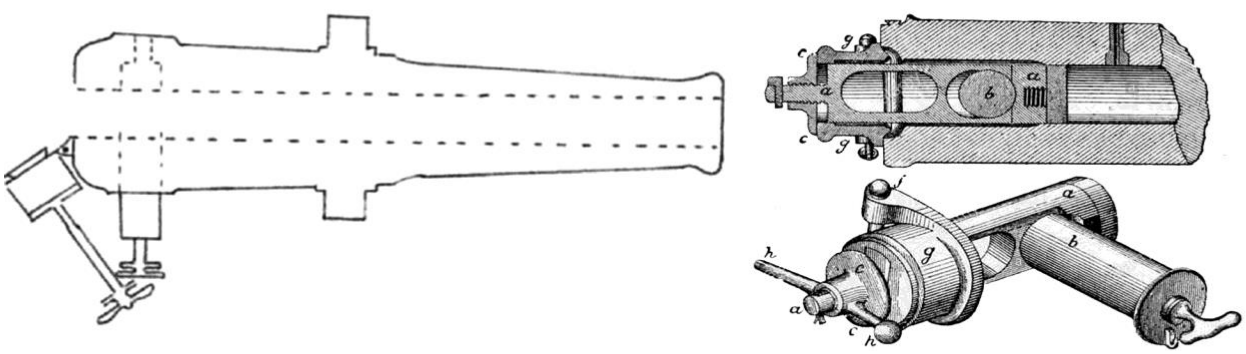

Figure 2: The Overall and Details of the Wahrendorff's Breech Loading Cannon [11] [12]

The importance of rifling to the gunnery systems of the day cannot be overstated. Variability in windage resulted in a given cannon shell that would fit more or less snugly in the barrel. While impacts to muzzle loaded systems were significant, impacts also extended breech loading guns. A tight-fitting shell was resistant to blow-by during barrel travel, and resulted in improved muzzle velocities; however, a tight-fitting shell could be hard to load and would exacerbate gun erosion. Conversely, a loose-fitting shell would induce lower wear levels, but result in increased balloting while traversing the barrel. This behavior, upon muzzle exit, results in increased excitation of barrel exit perturbations and increased the circular error probable (CEP) of the rounds downrange. To mitigate these effects, imparting spin along the gun major axis proved effective. In addition to reducing round CEP, the spin direction allowed for the firing of elongated, spin-stabilized rounds. These increased fineness ratio projectiles embody superior ballistic coefficients when compared to conventional cannon balls [11].

The final great innovation introduced by Von Wahrendorff was perhaps the most creative and addressed a major design challenge that is still a contemporary issue in gunnery design: breech sealing. As mentioned above, a properly fitting round can harness more of the kinetic energy of the powder, but the resulting reduction in blowby results in increased chamber pressures. Because peak pressures are greatest at the breech, sealing at that location was (and is) extremely important. Von Wahrendorff developed a curved plate that was inserted behind the projectile and charge, and ahead of the breech sealing plug. As the force of the powder explosion would hit the plate, it would deform and seal the breech. Clearly with these and contemporary innovations, the era of the modern cannon had begun.

Increasing Chamber Pressures and the Functions of Early Sabots

While Von Wahrendorff's plate, rifling, and breech-loading innovations had paved the way for improved cannon performance, countless inventors have since played a pivotal role in the evolution of modern incarnations of ammunition, guns, gunnery, tactics,... and sabots. Stemming from the Old French word for what is known today as a "clog" or "wooden shoe," sabots have evolved greatly since the first breech-loading cannon. By examining the patent gazettes, one can document a steady progression of sabot types and functionality. While the challenges with breech sealing had been met by the 1850's, sealing at the back of the projectile remained a challenge. With the noted improvements in breech sealing and advancements in charge chemistry, gun peak pressures increased to the point that nontrivial losses due to poor sealing about the projectile were noted. To mitigate the losses and accommodate barrel rifling, new families of sabots were developed. Houghton and Hubbell were two early innovators who experimented with different forms of lightweight, wooden sabots just prior to the US Civil War. Houghton described a paired sabot which sealed against gun gasses and transferred axial torque to the projectile while minimizing barrel wear [15]. This elementary form of sabot then directly addresses gun gas blowby while transferring rotational momentum to an "elongated ball." One feature of note is the back of the sabot is designed to expand as the round travels downbarrel. This is an artifact of the sabot being designed for muzzle-loading cannon which were common in the US Army during this time. Mechanisms to enhance sealing such as bore taper or choke would hinder the loading process, and could not be implemented as they could in breech-loader designs. Hubbell's invention was a clever way of gaining some of the advantages of a rifled barrel, but in a smooth-bore system. As the windage would blow past the wooden sabot, the cant angles of the "ribs" shown in Figure 3 were such that axial rotation would be initiated. As such the ball projectile would leave the barrel with a spin about the cannon longitudinal axis rather than any other axis that would typically increase CEP [16].

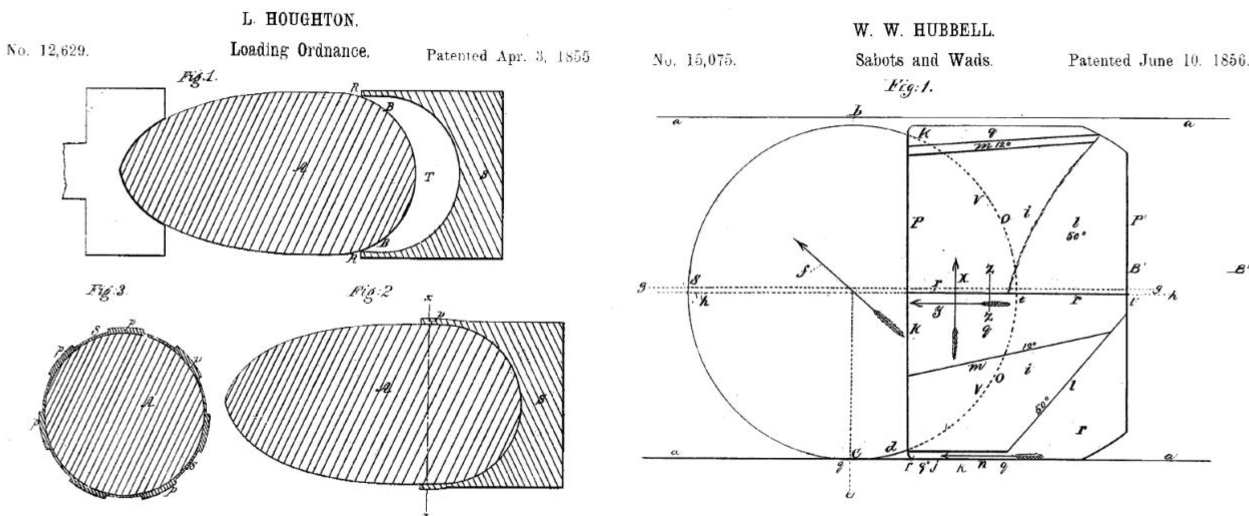

Figure 3: Sabots for Rifled and Smooth-Bore Cannon of the 1850's [15] [16]

As the American Civil War kicked off in the 1860's, advancements in metallurgy enabled better guns and exacerbated problems associated with windage as field artillery of the time was still dominated by muzzle loaders. This need drove continued munitions and sabot development. Swain's shell and sabot configuration shown in Figure 4 echoed many features that would be seen in modern incarnations of saboted munitions. His aeromechanically stable, spinning projectile was supported laterally by a split sabot (referred to as "packing," *D* in Figure 4) which also featured a metal pusher plate (*F*). These developments illustrate that by 1860, most of the major components seen in sabots for the century to follow had been implemented [17].

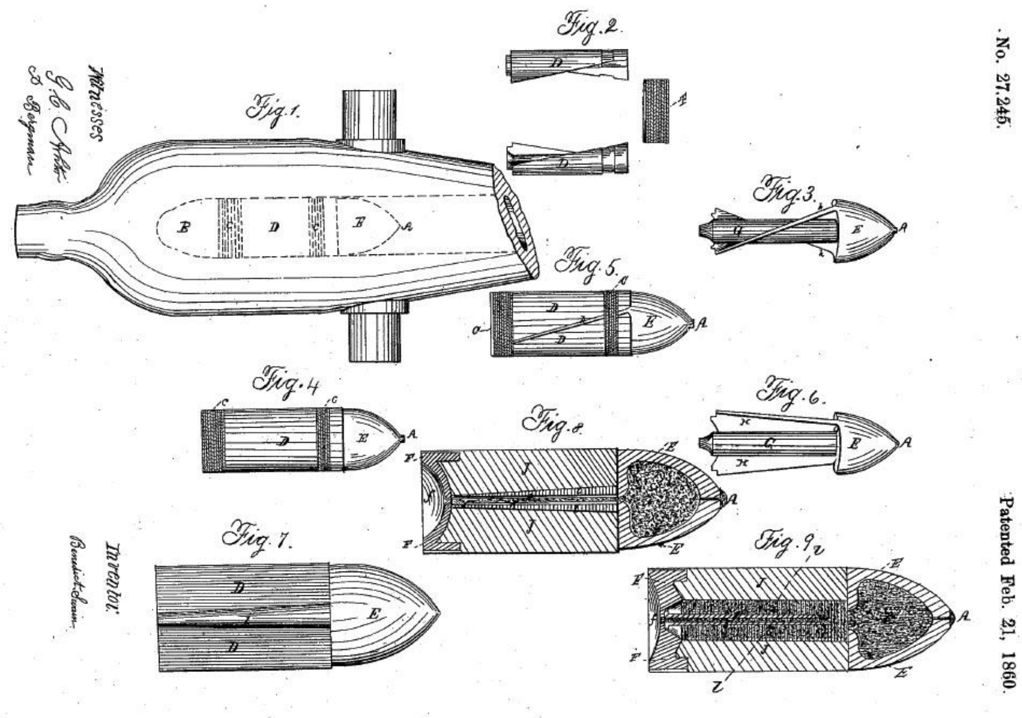

Figure 4: Sabot Design for Aeromechanically Stable, Spinning Projectile with Pusher Plate [17]

Sabot Design Evolution from US Civil War through Modern Warfare

Following the development occurring during the US Civil War, sabots of various configurations were employed to different degrees of effectiveness. Most of these systems added incremental levels of performance to otherwise well designed subcaliber munitions. The famed French weapon designer Edgar Brandt developed discarding sabot artillery shells and High Explosive Anti-Tank (HEAT) weapons during WWI [18]. A number of engineers who had worked for the Brandt left Paris for the UK after their company was nationalized in 1936. This group of engineers would join British engineers in developing anti-tank munitions. The Armor-Piercing Discarding Sabot (APDS) design of WWII enabled the effective penetration of armored vehicles of the day from smaller gunnery systems. Saboted munitions allow for the transfer of launch energy to a smaller, sub-caliber projectile, and the APDS projectile would then shed the sabot and drop the majority of the munition drag following barrel exit. As a result, the effective range and kinetic energy at range for these projectiles could be dramatically increased. In 1944, the APDS round was put in service for the British "QF 6-Pounder" antitank gun [19]. Figure 5 shows a contemporary 6lb APDS round and tungsten carbide core within the discarding jacket [20].

Figure 5: Armor-Piercing Discarding Sabot Tungsten Carbide Penetrator and Assembled Round [20]

Since the first of the successful APDS rounds, developments related to surface gunnery have been centered on improving round form factors, reducing the mass of the sabot while supporting clean separation, and the reduction of drag of the projectiles. Modern APDS rounds typically feature a high-density dart that is only a small fraction of the bore diameter, often coupled with a high speed, highly swept empennage [21] [22]. Around the dart is a gripper-interface, ensuring full energy transfer from the expanding gasses through the sabot to the subcaliber munition (*24*,

Figure 6). Upon barrel exit, the aerodynamic force against the forward face of the sabot pushes these relatively light segments out and away from the projectile, enabling a clean release. These aeromechanically unstable pieces then rapidly dissipate energy as they fall away from the projectile. Now in a low drag, high-fineness ratio configuration with increased muzzle energy, the range and energy imparted to target at range by the penetrator is greatly increased.

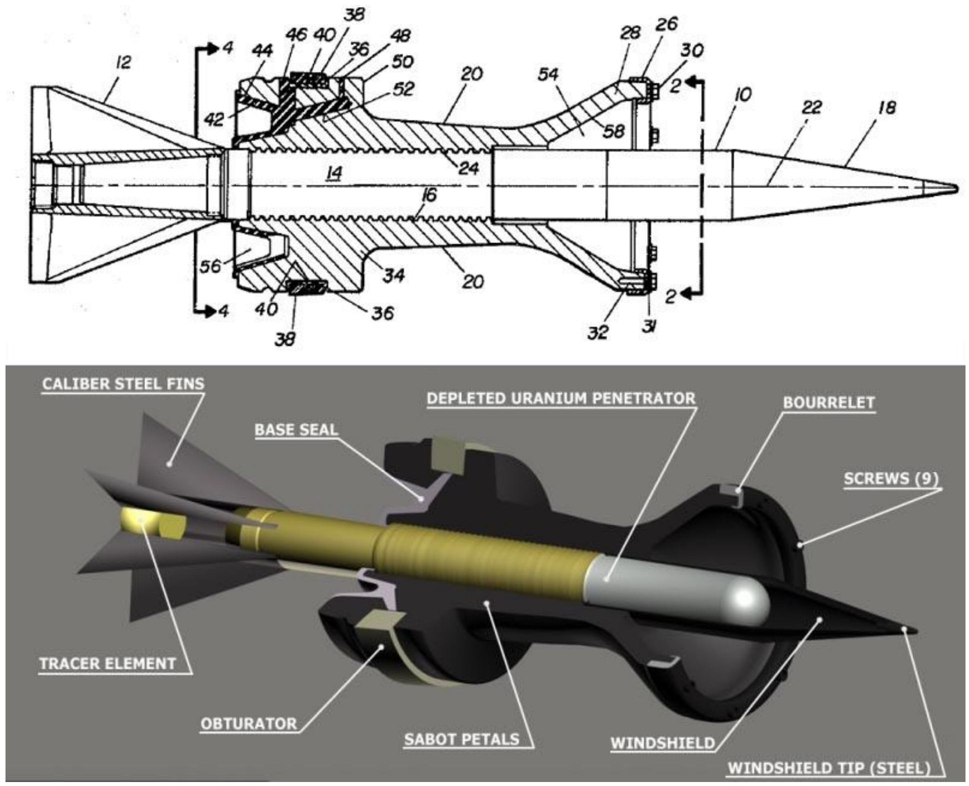

Figure 6: Modern Armor-Piercing Discarding Sabot Munition [21] [22]

III. Aerial Gunnery History and Challenges with Discarding Sabot Munitions

The first aerial engagement in recorded history was the famous encounter between Dean Ivan Lamb and Phil Rader over Sonoran skies in 1913 during the Mexican Revolution (1910 - 1920). A pair of mercenaries, the two were hired onto opposing sides of the conflict and are reported to have shot "at" each other, harming neither aircraft nor aviator. The thousand-foot duel twisted and turned for less than five minutes till each was out of ammunition and had to reload, but marked the beginning of a form of human struggle that continues to this day. Curiously, the engagement included both air-to-air combat and air-to ground strafing as Dean fired at the US Customs house in Naco, Arizona because: “Customs people are always irritating. [23]” Figure 7 shows the two contemporary aircraft that mixed it up in the skies that November afternoon.

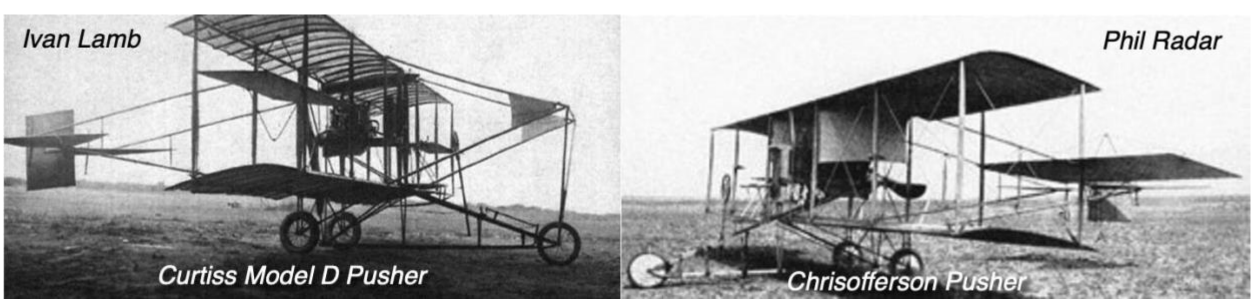

Figure 7: Aircraft of the World's First Dogfight, 30 November 1913 [23]

While Lamb and Rader's aerial duel was less than deadly, the weapons they used could indeed have inflicted harm. Both were reported to have been armed with 0.45 cal. 1909 Colt New Service revolvers, most likely firing 45 cal. ball ammunition, shooting wide of each other, emptying their clips. Since this earliest exercise in aerial gunnery, ammunition that is used for air-to-air and air-to-ground combat has evolved little in overall configuration, though the mounting schemes have adapted. Aerial gunnery still exclusively uses full bore projectiles, and other than internal component modifications, the overall projectile scheme and form factor has seen little significant development. Figure 8 shows the configuration of the first rounds used in aerial combat 108 years ago and one of today's most modern aerial gunnery rounds. The reader is asked to contemplate the two aircraft above and think of all of the innovations that have come to aviation in the past century... then think of the changes that have come to aerial gunnery in the same time period. Advancements in aeromechanical modeling, impact mechanics, and structural dynamics have led to incremental improvements (most notably in materials, energetics and arrangement of internal projectile components) but many objective aerospace design engineers would be hard pressed to point to any truly innovative configuration changes in the ammunition used for aerial gunnery [24] [25].

Figure 8: Aerial Gunnery Ammunition 1913 and 2021 [24] [25]

When one tracks the advances in aerial gunnery from WWI forward, it is easy to see a plethora of gun development in a range of calibers. While 7.92, 9mm, 45 cal. and 50 ca. weapons were used throughout the war, curiously enough, the Germans even fielded a 20mm autocannon aboard several aircraft. The most famous among them was the Becker Type M2 20 mm cannon fielded on the Gotha G1 as seen in Fig. 9 below.

Figure 9: 20mm Becker Autocannon in the Front of a Gotha G.1 [26]

The Americans were late to enter and used mostly allied equipment as its aircraft industry was not nearly as developed as that of the Europeans. The interwar period saw a dramatic drawdown in the Weimar Republic, followed by the explosive growth and development of the Third Reich. One of the most famous ground attack aircraft ever in history, the Junkers Ju-87 Stuka evolved from 1933 through the war. While only initially armed with 7.92mm offensive and defensive guns, it would later be retrofitted with 37mm cannon pods. In the hands of fabled Stuka pilot Hans Rudel, the Ju-87G would prove quite effective in the last stages of the war.

During the interwar period, the American aviation industry also developed a forward-looking ground attack aircraft that also sported 37mm cannon. The Bell YFM-1 Airacuda was decidedly less successful than its German counterpart. Poor maneuverability associated with large size made it highly vulnerable. A pair of laterally displaced gunners was indeed a unique innovation, but the tendency of the 37mm guns to fill the gun pods with choking gun gasses rendered them dangerously unusable. Throughout the war, a number of gun calibers were used in a variety of positions on the airframe, but all would fire conventionally configured ammunition.

Conventional Sabots: Aeromechanically Unstable by Design

A prime reason why the aerial gunnery munition designs and subcaliber munition development for use in aerial combat has stagnated is a function of sabot convention. Sabot pieces are designed to rapidly and cleanly separate from a projectile while perturbing the subcaliber munition as little as possible (minimizing CEP at extended ranges). From Figure 9, it is apparent that conventional sabot petals separate out and away from an armor-piercing dart rapidly, enabled by the aftward relative placement of the center of gravity to the aerodynamic center of pressure. This is by definition an inherently unstable longitudinal and/or directional aeromechanical design. If one were to watch the full separation event over an extended period of time, erratic petal trajectories resulting from this instability combined with atmospheric perturbations cause large scatter in component trajectory tracing [27]. Starting less than one body length away from the projectile, the petal momentum from the initial separation event is sufficient to cause tumbling in excess of 180° a number of times. This high drag maneuver quickly dissipates the sabot energy, decelerating the components with hundreds to thousands of g's. This behavior is by design, allowing for rapid airspeed bleed off of an unstable flight body with no defined angle of aerodynamic trim. This energy dissipation is critical to current implementation of land-based sabot munitions in proximity to friendly forces. In naval applications, flying sabot pieces are known to have damaged various structures adjacent to guns and pose danger to nearby personnel. Areas adjacent to Close-in-Weapon Systems (CIWS) are typically off limits to deck personnel during firing for this reason.

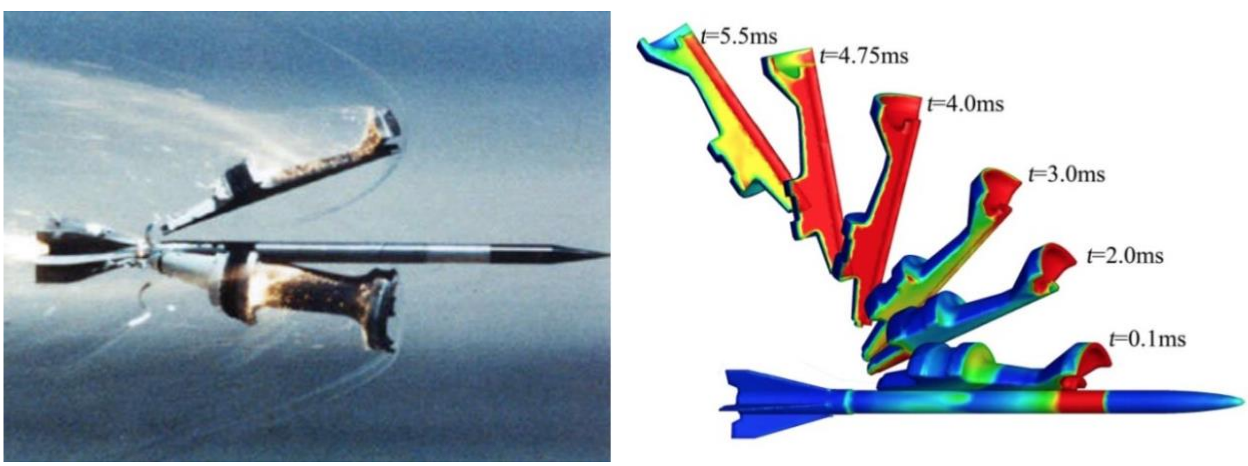

Figure 9: Sabot Discard of an Armor-Piercing, Fin-Stabilized Discarding Sabot (APFSDS) [27]

Flight Safety: The Great Show Stopper

One of (if not The) greatest treatises on aerial gunnery and mid-caliber ammunition development was penned by Dale Davis of Eglin AFB in 1984, just as the A-10/GAU-8/PGU-13/14/15 programs were reaching maturity and being widely fielded [28]. Dale Davis worked for the USAF Munitions Directorate from 1952 through his retirement in 1984. He was part of every major USAF gunnery effort in that time and played a critical role in the development of the GAU-8 and its ammunition. His outstanding volume contains an excellent summary of the major programs of the time. As a gunnery expert, he was well aware of the importance of flechette ammunition and sabots (both discarding and non-discarding) and captured his thoughts on the subject eloquently:

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* [28].

Clearly, the munitions experts of the day fully understood the challenges and were wrestling with issues related to airframe strike and engine ingestion. One would be hard pressed to find a flight crew that would willingly fly through a debris field comprised of material that could damage windshields and fowl engines. Figure 10 shows such a sabot debris field of a typical combat helicopter after firing conventional mid-caliber APFSDS rounds under nominal forward flight speeds and atmospherics [29]:

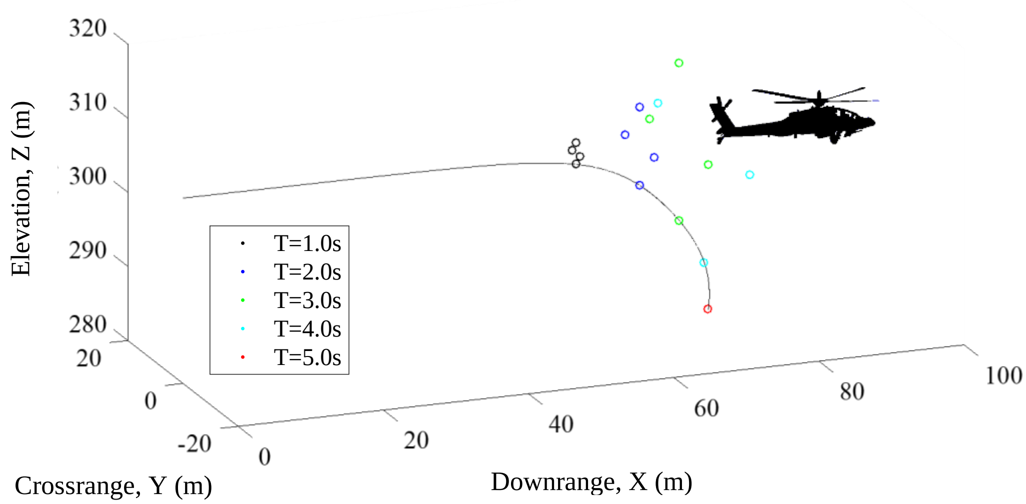

Figure 10: Helicopter Flying through Simulated Debris Field of Conventional Sabot Pieces [29]

Given similar sabot dynamics for fixed-wing aircraft of all flight speeds, it is easy to see that flight safety is the primary reason that discarding sabot rounds are not used in aerial gunnery.

IV. USAF Efforts to Design Flight-Safe Discarding Sabots and Advanced Mid-Caliber Munitions

As described in [28], many USAF technologists tried for decades to develop flight-safe discarding sabots and high-performance mid-caliber munitions for aerial gunnery. USAF investigators like their predecessors were keenly aware that the performance of the GAU-8 30mm autocannon on the A-10 would have to be improved by the integration of discarding sabot rounds, though flight safety remained a chief concern. The Big Problems: Tumble, Airframe Strike, Engine Ingestion and Fouling

The First Approach: Sabots that Disintegrate into Small Plastic Pieces

Sabot material has evolved from its early origins in leather and wood, then progressing through metals like aluminum and magnesium, culminating in reinforced and monolithic plastics. With storied past in a number of different materials and integration schemes, USAF investigators attempted to make sabots that separated into many small particles upon muzzle exit. The rational was that the lightweight pieces of plastic would not damage the aircraft as it would fly through the debris field. A test of this concept demonstrated that the plastic easily melted as fragments progressed through the last compressor stages just upstream of the combustor. Just as airflow on wings can be destroyed by ice accumulation, a similar phenomenon occurred as the engine lost both efficiency and power. This severe engine fouling was unacceptable so the effort was discontinued [28].

Sabot Diverters

The next approach was to make sabot diverters that would direct sabot pieces away from the projectile and allow them to egress harmlessly below the aircraft. This method would in theory keep debris well away from critical airframe parts, especially engines. In 1970, this approach was attempted on a 20mm cannon and ten years later on a 30mm autocannon. It was found that the required sabot splitters were heavy, reducing the energy that could be imparted to the projectile. Additionally, they were about 95% efficient... leaving 5% of the sabot pieces to survive the splitter and cause potential damage to the launching aircraft. From a typical A-10 loadout, more than 50 rounds worth of sabot pieces would typically form a debris field in front of the aircraft.

Figure 11: Typical Navy 30mm Saboted Ammunition 30x173 NM225 APFSDS-T [30]

A case study involving a common surface sabot munition highlights the challenges associated with using a sabot splitting mechanisms: the NM225 APFSDS-T is shown in Figure 11 [30]. Clearly, the sabot of the NM225 must be strong enough to transfer launch forces along a short, 35mm length of the fléchette. This acceleration is non-trivial as the round is accelerated with barrel pressures of 50,000 - 60,000psi (3,400 - 4100 atmospheres). The materials needed to withstand these kinds of loads form the crux of the problem.: if a sabot petal is strong enough to survive launches on the order of 80,000g's of acceleration and effectively transfer these loads, then it's more than strong enough to damage the airframe. The sabot components that are therefore not successfully deflected away by splitters in aerial applications are therefore unacceptable due to the dangers they pose to the aircraft.

USAF investigators also noted the sabot strippers only worked with high spin rates. The high fineness ratio projectiles they encased (with low bending stiffness) such as DU penetrators were found to bend. Accordingly, this most promising approach was also found to be unsuitable for aerial gunnery because of inherent structural mechanics problems [28].

Hybrid Rocket-Assisted Projectiles

Given failed attempts to incorporate sabots into mid-caliber munitions, USAF investigators explored other methods to gain range and kinetic energy [28]. One alternative is to use rocket assisted projectiles (RAP): historically tested by a number of groups including the Germans in WWII. The German ballisticians of the day observed that the 28cm K5 gun range could be extended from 62km (38.6mi) to 86.5km (53.8mi) by incorporating RAP. By using a sabot-launched arrow shell, the range could be stretched to an incredible 146km (91mi). Thiokol was contracted to build 30mm RAP shells with small rocket motors that were shown to survive 80,000g setback accelerations, 100,000RPM spin rates and 60,000psi (4100atomosphere) chamber pressures. The increased round complexity and associated expense—the integration of fléchette with integral rocket motors—would result in performance on par with the standard PGU-14 penetrator. While the RAP configuration aided in boosting kinetic energy and range following muzzle exit, the reduction in powder volume required to incorporate the munition reduced the muzzle velocity: making the relative performance a wash. As the RAP effort progressed, an AAI design demonstrated increased performance at 6,000 ft range, but the additional round complexity and cost was seen as prohibitive.

Drag Fumers

Several general trends were noted by USAF investigators, most notably that in a well-designed shell, the nose generates roughly 50% of the drag, 10% is skin friction and 40% is base drag [28]. If the base drag could be mitigated, then range and kinetic energy at range could be significantly increased. One effective means of reducing basedrag is with the incorporation of a mechanism to pressurize this region: for instance, with a drag fumer. While a good concept, the practicality of a 30mm round equipped with a drag fumer was also shown to be prohibitive for similar reasons to the RAP. Reduction in powder to physically incorporate the system coupled with the complexity of launch triggering significantly increases the cost of the shell with only incremental performance benefits. Accordingly, these efforts were abandoned as well.

Rotating Bands

Given successive challenges with significant round alteration, USAF investigators settled on incremental improvements to overall performance provided by rotating bands. By exploring a variety of materials from monolithic metals to polycarbonate, nylon, polyethylene and other materials, a series of workable band configurations were settled upon. While not providing dramatic improvements, incremental improvements in muzzle velocity and gun wear were noted with only very small increases in cost per round.

Tubular Projectiles

In the mid-1970's a number of tubular projectiles were considered, proposals submitted, and projects funded. At the heart of the project was the idea that nose and base drag could be reduced by drilling a hole through a projectile. The fundamental problem with this approach is that the associated flow within the tube would choke at supersonic speeds, often boosting drag levels to far beyond the levels of a solid round as the round essentially becomes a flying Pitot tube. This dynamic, is well known to aerodynamicists who study internal flows, but had to be rediscovered by USAF investigators in the mid-1970's as several programs were started with high hopes, but by the program's end, was considered: "Like so many technological phenomena of academic interest, it is difficult to find a real application for it."

The Final Aerial Sabot Development Attempts

Despite the incremental improvement efforts conducted by the USAF, evidence of the importance of flight safety in sabot design did not entirely fade before the turn of the century. Two patents awarded in the late 1980s and early 1990s show the desire for a flight safe sabot and development effort continued on some level through this time. The “Delay Discarding Sabot Projectile” by Meyer and the “Saboted Projectile” put forth by Burnette in 1989 and 1993 respectively, both attempted to describe a single piece sabot system that was designed to minimize potential harm to the aircraft [31] [32]. While flight safety was an issue, neither the Meyer nor Burnette sabots were aeromechanically stable. Because of high levels of aeromechanical stability with little chance of suppressing a tumble-event post penetrator release, the unfavorable dynamics seen in Fig. 10 would have been seen if ever flight tested. These concepts are shown in Figure 12.

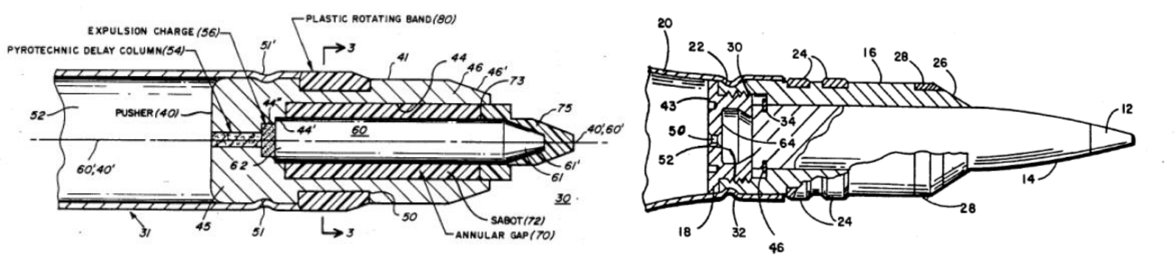

Figure 12: Meyer and Burnette Aerial Sabot Concepts [31] [32]

While neither of these munitions were fielded—likely due to the shortcomings discussed above and in [29]—they represent the continued interest in improving aerial gunnery in the 1980's and mid-1990's with the inclusion of subcaliber penetrator integration. They Meyer concept, relying on a pyrotechnic charge to eject a spin stabilized projectile, would have had unacceptable CEP levels at range due to perturbation dynamics at separation, insufficient atmospheric gust perturbation rejection, and reduced spin and angular momentum imparted to the projectile. The Meyer sabots are neither directionally nor longitudinally aeromechanically stable in the implementation disclosed, and would therefore have unfavorable dynamics that would make trajectory tailoring of the sabot nearly impossible after the separation event. Similar challenges are encountered in the bourrelet design proposed by Brunette [29]

Barrel-Launched Adaptive Munition

In 1995, the Air Force kicked off its first guided aerial gunnery munition effort. The Barrel-Launched Adaptive Munition (BLAM) program was commissioned to investigate basic translational flight control on a conical 10° half-angle, 37mm round. Several test articles were made to explore bandwidth and control power in high Mach regimes. Wind tunnel testing showed good control of nose deflections at rates in excess of 200 Hz. Freeflight testing in the USAF Aeroballistic Research Facility (ARF) at Eglin AFB, FL demonstrated 7 ft crossrange translations could be generated over the 800 ft long range. Figure 13 shows the internal configuration of the BLAM [33]. The program surpassed all technical goals and was set to progress to further stages of development. Unfortunately, rather than ring in a new era of aerial gunnery munition modernization and advanced RDT&E, it marked the end of advanced aerial gunnery munition development for more than two decades [33].

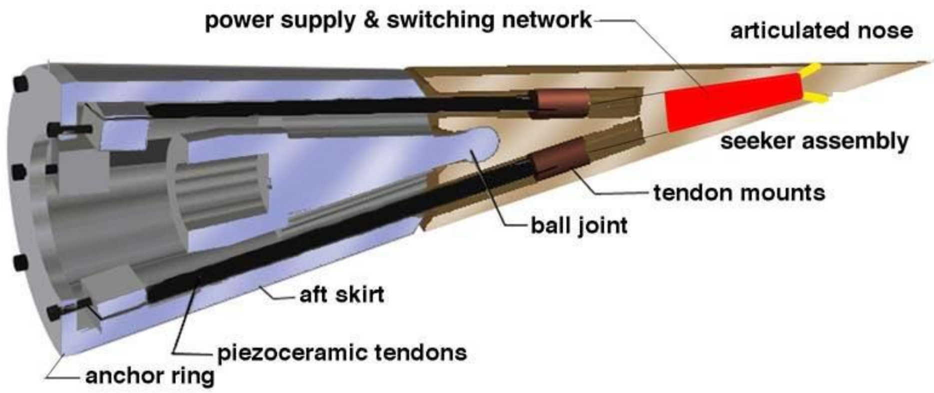

Figure 13: BLAM Internal Arrangement (1997) [33]

The abandonment of advanced aerial gunnery ammunition RDT&E is so complete that the USAF has ceased to maintain the nation's only fully instrumented mid-caliber aerial gunnery range. After being scavenged for parts, the facilities at Eglin AFB are now effectively derelict ruins. It should be no surprise that the entire USAF lacks the ability to develop even basic aerial gunnery ammunition (let alone any advanced ammunition). As the AFRL Chief Scientist put it:

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

-***David Lambert*** *AFRL Chief Scientist, (via J. Ellison) 2021* [34]

While references were given to the other branches of the armed forces, none appear to have active advanced aerial gunnery ammunition programs, as has been the case for more than two decades. Repeated information requests have yielded no programs of record for advanced aerial gunnery ammunition development across the DoD in this time period. The outside observer can only conclude that aerial gunnery ammunition has essentially "fallen through the cracks" as the USAF abandoned its former role as a technology leader and none of the other branches have picked up the slack. All indications are that the Navy, USMC and Army perceive aerial gunnery ammunition as technologically stagnant "commodities" to be purchased in bulk rather than critical weapon systems to be methodically developed and constantly improved. This very clearly renders the US Armed Forces highly vulnerable to technological surprise and unable to take advantage of technologies that are rapidly maturing around the world.

Advanced Guided Munitions for Surface Forces... None for Aircraft

Following the BLAM efforts through current research focus areas, the US Army has poured countless millions into large caliber advanced munitions: encompassing programs like the 155mm guided XM982 artillery shell and mortars like the XM395 [35] [36]. RDECOM-ARDEC at Picatinny Arsenal also sponsored several guided bullet programs at the turn of the century which were then folded into DARPA's EXACTO program of the late 2000's and early teens, eventually leading to the world's first guided 0.50 caliber bullet [37] [38] [39]. The Army even sponsored several advanced, guided mid-caliber rounds including the 25mm Light Fighter Lethality program which was to be launched from a soldier's forearm (as is often seen in some sci-fi/action movies) [40]. The Navy also joined in the development of advanced guided munitions with programs like its 5" (127mm) EX171 Extended Range Guided Munition (ERGM) [41]. The DARPA/Navy Shipborne Countermeasure Range Extended Adaptive Munition (SCREAM) program was a 25mm guided round saboted up to be launched from a 40mm gun as a defense against sea-skimming missiles [42]. An active DARPA-Navy program, the Multi-Azimuth Defense Fast Intercept Round Engagement System (MAD-FIRES) program is similarly centered on a mid-caliber munition for defense against anti-ship missiles and UAV swarms [43] [44]. A 57mm test article of the munition is shown below:

Figure 14: DARPA-Navy-Raytheon MADFIRES 57mm Test Round [44]

While advanced, guided ammunition for Army and Navy surface gunnery in small, medium and large calibers have been robustly pursued, a gaping RDT&E hole has been made apparent: centering on aerial gunnery. Nothing has been done for aircraft: nothing for rotary-wing assents, nothing for fixed-wing. If one looks over the preceding two+ decades of programs of record, announcements, targeted BAA's and SBIR topics it is painfully obvious that aerial gunnery has been completely left in the dust. It is essentially frozen in time with air-to-air and air-to-ground ammunition of today being based on WWII configurations. The Marine M53 and M56 rounds in the AH-1/M197... which were actually designed during WWII [28]. While there are many reasons why the Army, Navy and Air Force have ignored advanced aerial gunnery ammunition development, an adequate treatment of this politically charged topic is beyond the scope of this work. General Genatempo addressed one facet of the problem quite eloquently:

Weapons are the "beer money" of the Air Force.
When times are good, there's money for it. When times are not, there's not.

***-Brig. Gen. Anthony Genatempo** USAF 2019 [45]*

V. Ballistic Aeromechanically Stable Sabot (BASS) Discarding Sabot Aerial Gunnery Rounds

Although the DoD has essentially abandoned advanced aerial gunnery munitions RDT&E, work continues internationally. Given the wide range of advanced guided munition programs within the US and abroad, development of guided aerial gunnery munitions is just a matter of time. It is also easy to see that the DoD has set itself up for a colossal "technological surprise" in this area as many foreign armed forces, companies and governments are not as constrained by internal and inter-service politics as is the case in the US. Fortunately, there are a handful of laboratories in the US that have had the foresight to keep pioneering in this area, like the University of Kansas' Adaptive Aerostructures Laboratory (AAL).

Laying the Groundwork: Small-Arms Guided Munition Developments

Following the abandonment of advanced and guided aerial gunnery efforts by the USAF in 1997, the AAL switched to supporting US Army guided 0.50 cal. bullets via the REAM program, which would eventually lead into the DARPA-EXACTO program [37] [39]. Because the AAL was the principal non-Federal lab contracted to develop guided aerial gunnery rounds 26 years ago and has been working steadily on the topic ever since, it is currently resident to (arguably) the nation's technical "memory" and repository of expertise on the subject. While funding has waned, progress has continued: Indeed, the world's fastest, full-proportional, gun-hardened flight control actuators were designed, developed, wind tunnel, shock table, range tested and patented in 2011 [46]. More importantly, the guided small-arms work led directly to more important innovations.

Invention is the Mother of Necessity: Guided Rounds Lead to Flight-Safe Discarding Sabot Discovery

As efforts related to guided aerial gunnery continued within the AAL, configurations of beam-riders were taking shape. During this exercise, a series of profound discoveries were made: The first was that full-bore guided rounds exhibited severely compromised performance. Because the round density was lower than a conventional round, range, loadouts and penetration capabilities were simply unsatisfactory. The second major discovery was that there existed no flight-safe discarding sabot configuration. The observations of Dale Davis [28] simply rang ever more true. It was impossible to conceive of a conventional sabot configuration that wouldn't threaten the aircraft and/or its engines... that is until something new was invented. Although the design of a guided aerial gunnery round itself is not particularly hard, a suitable sabot for such a round is. The answer to this challenge: the Maneuvering Aeromechanically Stable Sabot (MASS) and its unguided variant, the Ballistic Aeromechanically Stable Sabot (BASS) rounds, were conceived and reduced to practice. The enabling discovery behind these concepts was not simply a device, but a totally new philosophy in sabot design, which led to many families of workable sabots for aerial gunnery. The key to the many families of flight-safe sabots for aerial gunnery is explained in detail in the multiple IP filings with the USPTO, all based on Claim 1:

What is claimed is:
1. An aeromechanically stable sabot... [47]

Aeromechanical stability is at the heart of the invention. Once aeromechanical stability of the sabot is achieved, then the flight path of the sabot can be tailored and/or controlled.

BASS Configurations, Reduction to Practice and Testing

While the AAL and its personnel were centered on developing guided munitions for aerial gunnery, the invention of flight-safe sabots for aerial gunnery may prove to have a more profound and lasting influence on aerial combat than near term guided munition advancement. Figure 15 shows the overall configuration of a conventionally configured MASS/BASS cartridge (100). If the sabot-projectile combination (400) is separated from the shell casing and powder (101/102), then it becomes obvious that the form factor of the projectile (430) is much higher aspect ratio than a conventional round as it takes the form of a fléchette from more than a century ago. A full-hard force-transfer sleeve (415) transfers launch loads to the fléchette during launch as seen in Figure 15 [47].

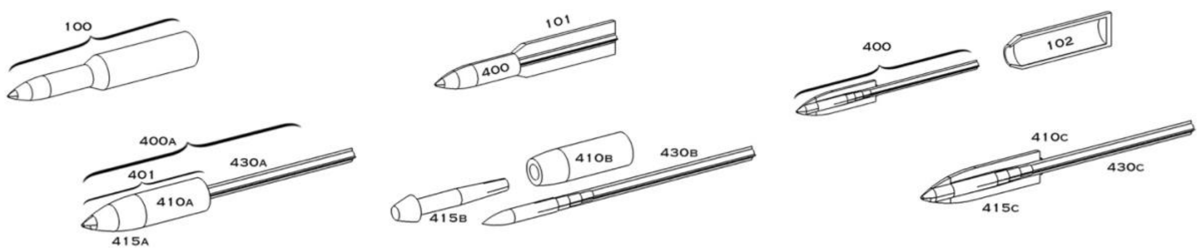

Figure 15: General Configurations of One Family of MASS/BASS Rounds and Sabots [47]

As the sabot-projectile combination (400) travels down the barrel, gun gasses act on the base of the sabot, pulling the fléchette down the entire length of the barrel. Upon muzzle exit, aerodynamic drag causes the sabot to slide backwards, down the length of the projectile (400D) as shown in Fig. 15.

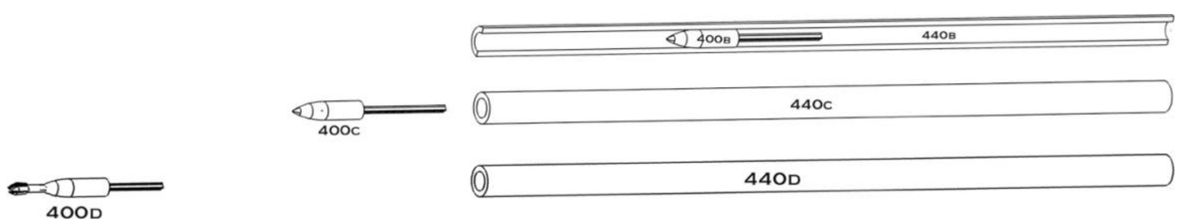

Figure 16: Muzzle Exit and Initiation of Sabot Separation from MASS/BASS Fléchette [47]

Eventually, the fléchette (430) and sabot (401) separate completely and fly as two aeromechanically stable bodies. To achieve this, like the fléchettes of WWI, the center of gravity is far ahead of the aerodynamic center, thereby lending inherent static longitudinal and directional stability. As the post-separation sabot also flies independently away from the launch platform, it too exhibits inherent aeromechanical stability, with the center of gravity (21) is placed well ahead of the aerodynamic center (22) in all flight regimes.

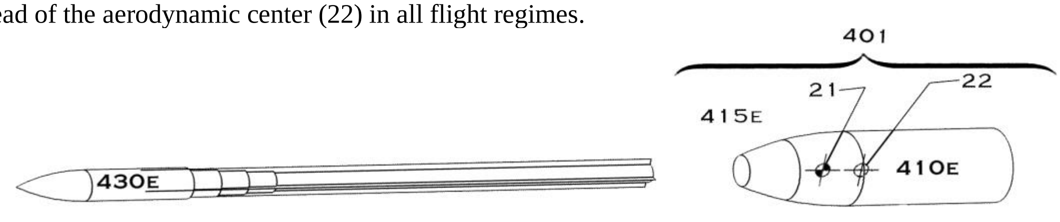

Figure 17: Sabot Separation and Freeflight Event from MASS/BASS Fléchette [47]

As the scope of this compilation is historic in nature, the reader is referred to the following references to detail the sabots and projectiles performance [48] [49] [50] [51] [52] [53] [54] [55] [56]. These references highlight the computational and analytical modeling, wind tunnel testing, and demonstration article testing on the range of the BASS munitions. To summarize these works, BASS rounds can more than double effective ranges, holding all other round characteristics steady. Similarly, the aforementioned references show that smaller caliber BASS ammunition can now outperform higher caliber conventional ammunition. Indeed, it was shown that 20mm API BASS rounds have more impact energy and armor penetration ability than 30mm GAU-8 ammo. at typical engagement ranges.

Patenting and Export License

While it is certainly unfortunate that the US Department of Defense has left an entire branch of defense-related technology unexplored and therefore undeveloped, this technology gap has been partially filled by private industry and higher ed. Currently, the Federal Government has granted an export license and exported the critical designs of BASS ronds internationally, so claiming any form of confidentiality or security restrictions as applicable to these designs will be challenging to support. International patents have been filed on the critical enabling designs, of which there are more than 54 families of designs with 3 - 12 species within each family. Astute companies and branches of the DoD desiring to maintain parity with others would be well advised to negotiate at least a non-exclusive license. Proactive companies and branches of the DoD desiring an advantage over others should negotiate an exclusive license covering countries of interest.

Importance for Existing Aircraft and Upcoming Aircraft Development Programs

When one considers existing aircraft, the idea that simply by changing ammunition, improvements in system effectiveness and new mission spaces may be defined is alluring. If an AH-1 is equipped with 20mm API BASS rounds, it would be able to match an A-10 at typical ranges in energy on target. If one considers current competitions like the Future Attack Reconnaissance Aircraft (FARA), then it is obvious that a tactical advantage over the other team can be gained by licensing BASS technology [57]. Given that the F35 gun troubles are now widely acknowledged in the public domain: theoretical applications of the BASS system to this platform may mitigate many of these concerns. It would be possible to down-gun the F-35 to a 20mm M61 Vulcan, reducing recoil so as to mitigate some of the structural issues the system, without loss in energy on target [58]. Additionally, the BASS rounds are inherently aeromechanically stable which allows them to fly in flatter fire trajectories at vastly extended ranges. This would help solve some of the widely reported accuracy issues the gun is experiencing [59]. The reduction in caliber would also enable the F-35 to carry 400 rounds rather than the <190 round loadout it now boasts. There are similar upgrade paths for the AC-130 and all existing rotary- and fixed-wing combat aircraft that is equipped with a gun. One effect of using saboted flechette counfigured rounds is that they times of flight are dropped dramatically. Figure 18 shows that the total amount of kinetic energy retained by a 20mm BASS round is so great that it even surpasses the energy of the 30mm PGU-14 at range:

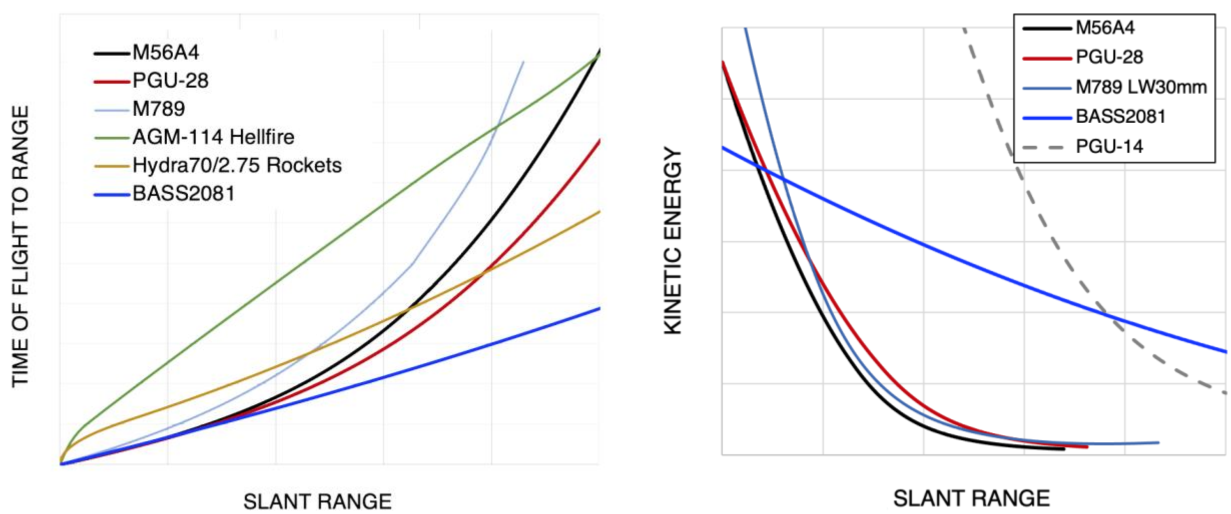

Figure 18: Times of Flight (ToF) and Kinetic Energy (KE) Comparison of 20mm BASS Rounds and Conventional Weapon Systems Fielded Today

In the end, the most fundamental reason why flight safe discarding sabot aerial gunnery ammunition so seriously outperforms conventional ammunition is simply related to ballistic coefficient. Figure 19 shows that given the past 108 years of aerial engagements, the ballistic coefficients of rounds fielded today have only incrementally improved with respect to the pistol ammunition fired in 1913. The BASS rounds conversely have ballistic coefficients that are on the same order of magnitude as the best round fielded by Army and Navy ground forces.

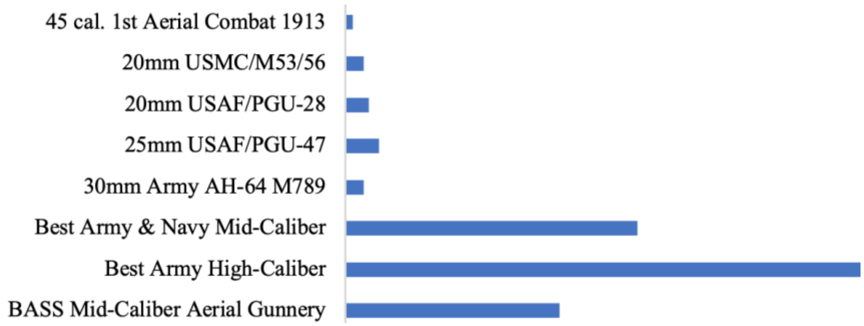

Figure 19 Relative Ballistic Coefficients of the First Rounds used in Aerial Combat (1913), Currently Fielded "Modern" Aerial Gunnery Rounds and Discarding Sabot Rounds including BASS Flechettes

Things to Come: Aerial Gunnery with Missile Performance Leading To Smaller, Lower Cost Combat Aircraft

While the near-term solutions to unguided aerial gunnery are profound, the longer-term possibilities given guided aerial gunnery are astounding. References [48] [49] [50] [51] [52] [53] [54] [55] [56] show how multiple targets can be engaged with missile-like ranges and missile-level Pk values while shrinking airframe weapon bay sizes. This system compression implies new aircraft may be cut as much as 30% in weight, volume, and life-cycle cost given the same mission performance. In addition to added offensive capabilities, guided shells that use underexpanded pyrophoric rockets would make ideal guided flares for airframe decoy and defense. High caliber MASS systems are shown to be so capable that coverage of targets hundreds of miles away from an aircraft like an AC-17 are certainly within reach with indirect fire support. Given self-defense capabilities of MASS-equipped aircraft at extended ranges, it is certainly possible to conceive the next step in aerial gunnery: The FAC-17. Most importantly, References 48-56 showed clearly that for every dollar spent on advanced aerial gunnery munitions development, the taxpayer would save two to four orders of magnitude more money.

VI. Conclusions

Sabot development and subcaliber munitions have enabled increased gunnery performance from its origins in 1326 through the present. The earliest sabots were devoted to launching fléchette rounds at high enough speeds to breech medieval fortifications. Later improvements addressed \problems like gun gas blow-by, round centering and spinning around the gun longitudinal axis for range accuracy. Since the first aerial gunnery battle of 1913, the bullets and cannon shells have evolved very little. Today, the general configuration of most rounds used for aerial combat are of the same general configuration as the 0.45 cal. rounds used more than 100 years ago. While there existed a dynamic period of munitions development for aerial gunnery between roughly 1952 and 1997, a period of near complete technological stagnation has gripped the area since, within all branches of the US armed forces. However, entities outside of the Government have continued exploring the area. The result is that a number of important patents have been filed and granted export licenses during this time. The technology described therein, related to aeromechanically stable sabots, has been shown to dramatically improve range, impact energy, armor penetration capabilities, while shrinking recoil forces, cartridge and gun sizes and gun gasses over conventional hard launch systems. In the end, this munition innovation that lends such superior performance has come full-circle, with the advanced subcaliber munitions harking back to the historical fléchettes fired long ago.

Acknowledgments

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