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The Aerial Gunnery Gap: Challenged Programs, New Combat Aircraft Opportunities and Designs

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This paper describes a yawning Aerial Gunnery Gap which has adversely affected combat aircraft designs, led to a number of avoidable program-threatening accidents and incidents, unnecessarily driven costs of modern combat aircraft and threatened mission effectiveness. The paper starts with an overview of robust aerial gunnery development which began in 1913 and continued till the late 1990's. The development of the M-50 and PGU-series ammunition are chronicled along with many research projects centered on extending ranges and increasing P_k which guided aircraft design and aerial engagement philosophies for decades. The last advanced aerial gunnery program pursued by the USAF is detailed along with an assessment of how close the USAF was to achieving the three main aerial combat holy grails related to gunnery: i.) Guided Offensive Aerial Gunnery, ii.) Counter-Missile/Defensive Aerial Gunnery, iii.) Aerial Indirect Fire Support. The cancellation of the Barrel-Launched Adaptive Munition (BLAM) program in 1998 was followed by a quarter-century of divestment in aerial gunnery RDT&E by the DoD. In that time, entire research groups were disbanded and critical, one-of-a-kind gunnery ranges and laboratories were dismantled. The paper shows how this gap has harmed US National Security, induced avoidable gun-related problems with aircraft like the F-35, led to debilitating restrictions on combat aircraft design approaches and trade spaces and produced nontrivial growths in weight, volume and life-cycle costs of combat airplanes and helicopters. The paper concludes with an assessment of current advanced aerial gunnery rounds and shows that nontrivial savings in combat aircraft program costs could be realized by promising new families of aerial gunnery ammunition along with novel aircraft designs.

I. Nomenclature

AAL	=	*Adaptive Aerostructures Laboratory*
AP	=	*Armor Piercing*
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*
ARDEC	=	*Armament Research, Development and Engineering Center*
ARF	=	*Aeroballistics Research Facility*
BAA	=	*Broad Agency Announcement*
BASS	=	*Ballistic Aeromechanically Stable Sabot*
BEF	=	*Ballistic Experimentation Facility*
BLAM	=	*Barrel-Launched Adaptive Munition*
CAS	=	*Close-Air Support*
CEP	=	*Circular Error Probable*
CEW	=	*Cost-Effective Warfare*
CIWS	=	*Close-In Weapon System*
EFP	=	*Explosively Formed Penetrator*

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ERGM	=	*Extended-Range Guided Munition*
EXACTO	=	*Extremely Accurate Tasked Ordnance*
FOIA	=	*Freedom of Information Act*
FSDS	=	*Flight-Safe Discarding Sabot*
GDS	=	*Gun Director Sight*
GE	=	*General Electric*
GOT	=	*Go onto Target*
HE	=	*High Explosive*
HEI	=	*High Explosive Incendiary*
HEAT	=	*High Explosive Anti-Tank*
LCC	=	*Life-Cycle Cost*
MADFIRES	=	*Multi-Azimuth Defense Fast Intercept Round Engagement System*
MASS	=	*Maneuvering Aeromechanically Stable Sabot*
P_k	=	*Probability of a Kill*
RAP	=	*Rocket Assisted Projectile*
RDT&E	=	*Research, Development, Test, and Evaluation*
REAM	=	*Range-Extended Adaptive Munition*
SAPHEI	=	*Semi-Armor Piercing High Explosive Incendiary*
SBIR	=	*Small Business Innovation Research*
SCREAM	=	*Shipborne Countermeasure Range Extended Adaptive Munition*
SD	=	*Self-Destruct*
SPO	=	*System Program Office*
T	=	*Tracer*
UAV	=	*Uninhabited Aerial Vehicle*
USAAF	=	*United States Army Air Forces*

II. Introduction: The First 80 Years of US Aerial Gunnery Development

25 years ago, decisions were made in the DoD which would significantly affect the maturation of critical combat aircraft technologies as they were just being born. [1] These technologies were centered on achieving the three great "holy grails" of aerial gunnery as laid down in the guidance briefing for the first guided aerial gunnery exploratory project undertaken by the USAF: i.) Guided Offensive Aerial Gunnery, ii.) Guided Counter-Missile/Defensive Aerial Gunnery, iii.) Aerial Indirect Fire Support [2]. If any of them would have been successful, dramatic changes to combat airplane and rotorcraft designs, tactics and programs would have been inevitable. This paper chronicles the events leading up to this time, the state of these technologies 25 years ago and technology maturation hence.

A. The Beginning: Airborne Pistols, Recoilless Antisubmarine Cannon to Stukas

As the first lethal class of airborne weapons for heavier than air craft, aerial gunnery was embraced by the US Army and others before aircraft were truly ready for aerial combat. The first air-to-air engagement between heavier-than-air craft, the first aerial bombardment, the first air-to-ground strafing and the first instance of associated air-defense gunnery all took place over Naco, Arizona and Naco Sonora during the Mexican Revolution in November of 1913. [3] [4] [5] These engagements would set the scene for so much of what was to follow in the coming World War. While the horrors of the war played out for all the world to see, many new technologies also appeared. [6] [7]

Fig. 1 World's First Dogfight over Naco, Sonora & Naco, Arizona, November 1913 [8]

As the First World War took off, innovations of many kinds were seen in gunnery, ammunition, gravity weapons and tactics to name a few. The boxes filled with dynamite and nails of Rader and Lamb's days were replaced by metal-shelled bombs with fuzes and tail kits. Pistols were replaced by machine guns and aircraft could carry much more than just one adventure-hungry soldier of fortune. WWI saw the use of a wide range of gun calibers between the 0.303 (7.7mm) of the Lewis guns up to 37mm recoilless cannon. [9] Fuzing technology became a high art and the use of tracers was obligatory for all sides as the effective distances became so great that spotting individual shells or gunnery streams with the naked eye was nearly impossible. Even larger calibers were used for antisubmarine warfare. The most noteworthy of them was the Davis Gun, invented by Commander Cleland Davis just prior to World War I in 1910. [10] The recoilless gun was produced in 40mm, 62mm and 76mm calibers, firing 2, 6 and 12lb shots respectively. While recoilless guns were (and are) relatively rare, they presented only negligible firing impulses to the airframe and allowed for comparatively large caliber shells to be fired at considerable muzzle velocities. Although the weapon was first produced prior to the Great War, the ammunition was quite sophisticated and included a variety of fuses, centrally located primers and flash tubes and even a "cup-nosed projectile" (which could possibly be an early forerunner of explosively formed penetrator (EPF) warheads in use today). [11]

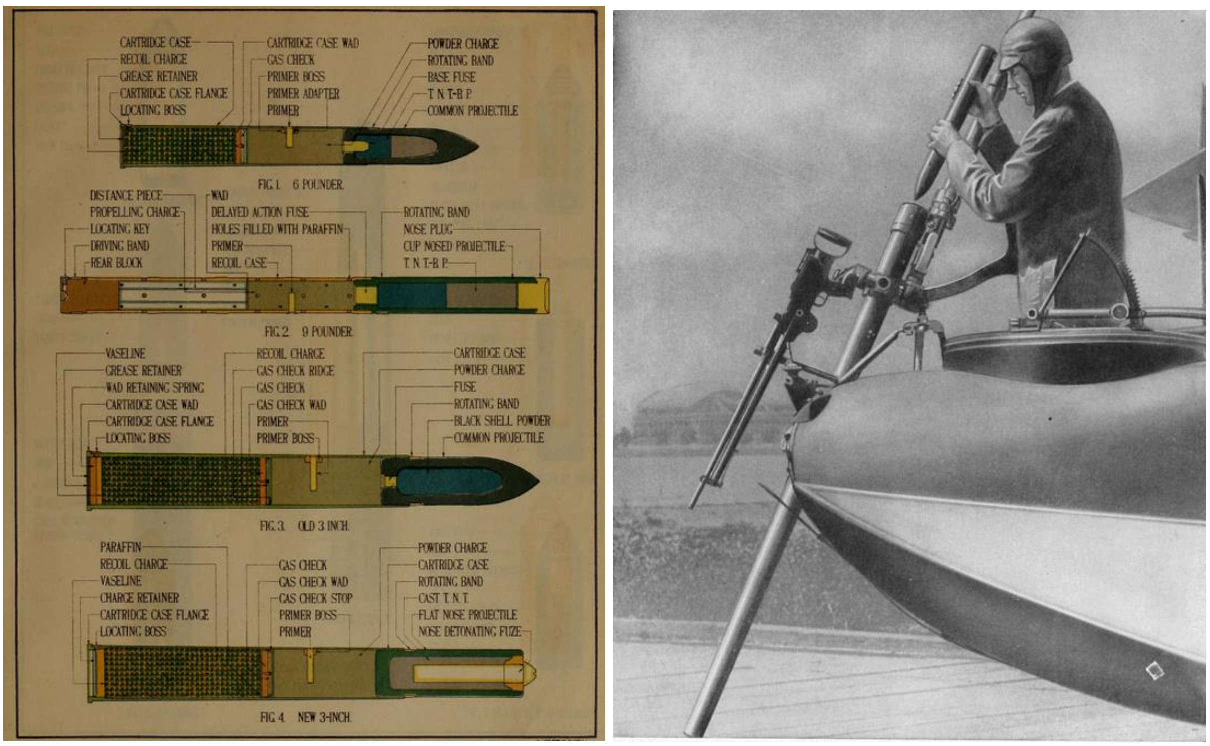

Fig. 2 Recoilless Ammunition and Davis Gun Ammunition and Mounted on a Curtiss J-N for Antisubmarine Warfare [12]

The rapid development of deadly airborne guns and ammunition of WWI was followed by an extended period of comparative moribundity during the interwar period for most armed forces around the world, save the Third Reich. As Germany was actively skirting, then flouting many of the terms of the Treaty of Versailles during the 1930's its war-related industries were flooded with contracts for the development of ever-more advanced tools of war, especially those associated with guns and ammunition. The Spanish civil war (1936 - 1939) provided an ideal opportunity for the Luftwaffe to test more ammunition and guns like the 7.92mm caliber Rheinmetall-Borsig Maschinengewehr MG-17 on the Henschel HS-123s, which were first invented in 1934. [13] Oddly enough, the Luftwaffe even provided 12 HS-123s to China which were used against the Imperial Japanese warships operating in the Yangtze River in 1938 during the Second Sino-Japanese war. Operational challenges of the HS-123 included poor range, speed and loadout. These difficulties were clearly noted as the Junkers Ju-87 Stukas co-evolved at the same time, with none of these issues and would eventually become one of the most effective and feared close air support (CAS) aircraft in history, also sporting multiple MG 17's. [14]

B. More Rapid Maturation: Aerial Gunnery and Ammunition Design During WWII

World War II saw many other advances in gunnery and ammunition including improvements in metallurgy, fuzing, tracer design and quality control which greatly improved reliability and lethality. By the middle of World War II, modern fuzed aerial gunnery ammunition had arrived. With fully integrated high explosive (high explosive, HE, shown in yellow below), a phosphor capsule just behind the fuze (incendiary charge, I shown in orange, below), and a tracer bay (T, shown in red below), one of the more advanced 20mm aerial dogfighting rounds had reached a state of technical maturity. The fuze was so advanced that a Zerleger (self-destruct, SD) feature was designed so that the rounds would detonate upon impact with structures like those found in aircraft and their skins, but would be inerted upon impact with the ground. This feature kept the spent shells from inducing collateral damage as many dogfights were held over German territory. [15]

Fig. 3 Minengeschoss 20mm (MG/"Mine Projectile") Self-Destruct, High Explosive Incendiary (HEI) with Tracer (T) with Phosphor Capsule (HE-yellow, I-orange, T-red)

The ammunition above (and its allied counterparts) was also designed to exactingly mark setback accelerations upon launch, then arm the round only after clearing the aircraft by more than 100m. This feature has since become standardized in most forms of aerial gunnery (at varying distances) today. By the end of WWII, fuzes for aerial gunnery and aerial gunnery ammunition had reached a high state of technical maturity, at least on the Axis side. [15]

During WWII, the US often fielded the derivatives of the 20mm Hispano-Suiza HS. 404 in a number of combat aircraft. Just prior to the war, the UK acquired a license to produce the gun as the Hispano Mk 1, fielded in the Westland Whirlwind in 1940. Experiences during the Battle of Britain solidified the utility of 20mm ammunition as smaller caliber guns had difficulty achieving kills at extended distances and canvas-skinned wings were far less vulnerable to smaller caliber rounds as they simply poked holes in the skin without doing serious damage. The Hispano Mk II replaced the eight 0.303 Browning machine guns in the Hawker Hurricane and so 20mm aerial gunnery was fully adopted and used by the British for nearly the entire war. By the end of the war, the HS gun had matured to the Mk V variant which would be fielded in the Hawker Tempest with an outstanding combat record. [15] [16]

The USAAC produced the Mk 1 under license starting in 1941, being fielded in the US as the M1. As with many products early in the war, it was extremely unreliable and tended to jam. Because the gun was a gas-unlocking blowback operating device, the ammunition had to be lubricated for the guns to operate properly. The M2 followed but was similarly unreliable as it, too, required lubrication and proper tolerancing. By the middle of 1942, the US had 40 million rounds of 20mm ammunition in storage and no reliable gun to fire them. Problems with reliability plagued American 20mm aerial gunnery systems during the entire war in spite of the guns being used in front-line fighters like the P-38. One of the ways around the 20mm problems was to make the gun just one of a number of guns as was the case in the P-38, which typically also included a cluster of 4 0.50 caliber machine guns as shown below:

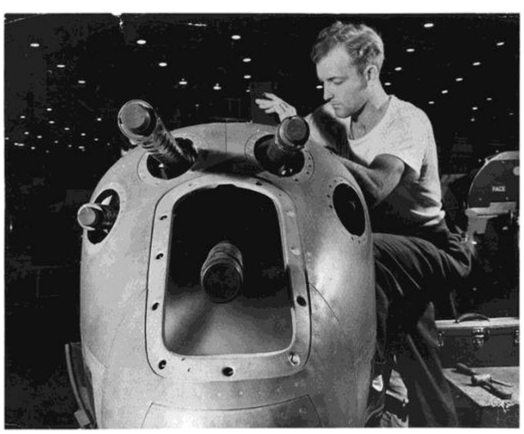

Fig. 4 P-38E Lightning Nose with Four .50 Caliber Browning M2 Machine Guns and One Hispano M2 20mm Autocannon [17]

Because of the relative success of the British gun systems, US design engineers watched technical developments closely and eventually adopted many features of the British Mk V in the AN/M3, but unreliability continued as combat was being pushed higher and higher in altitude, leading to frozen and jammed gun components. While the RAF had comparatively few problems with their HS guns, much of that is due to the proximity of the combat to home bases, environment and altitude ranges. Early in the war, RAF aircraft were fighting close to home and at relatively low altitudes. As the war raged on, USAAF aircraft would see far more dramatic altitude changes over flights as bombers regularly engaged targets from over 30,000 ft. Escort fighters would chase intercepting aircraft from high altitude to low, bringing cold-soaked guns to lower, far more humid altitudes which induced condensation and eventually frozen water in tightly toleranced components leading to (literally) "frozen" guns. Unfortunately, continual problems with US 20mm gun systems led directly to most US fighters using the AN/M2 .50 cal. Browning light-barrel HMG for most front-line fighters and bomber defensive gunnery. The AN/M3 would continue to be modified and incrementally improved. Although notoriously unreliable, it was used as late as 1975 in combat during the Viet Nam conflict in the A1E Skyraiders. [15]

C. Postwar Combat Challenges: Dynamic Gunnery Research for Increased Altitude & Mach Numbers

By the middle of the Korean conflict, one thing was clear, superior aerial gunnery was necessary for air superiority. During the Korean conflict, the US would suffer 2,714 aircraft destroyed, and 4,055 casualties. As the early MiGs out turned, out-climbed and out-maneuvered early US jets, their victories mounted. It wasn't until the appearance of the F-86 Sabre that the tide turned. Most US aircraft over Korean skies during the conflict did not do well as can be seen in Table 1. The great exception, of course, is the F-86. The combat record of the F-86 is so stellar that the number of kills eclipses all other postwar victory records of all US aircraft. [18]

Table 1 US Aerial Kills During the Korean Conflict (1950 - 1953)

Aircraft \ Target	IL-10 -12	L-7 -9	PO-2	T-2	YAK-3 -9 -11 -15	Propeller no ID	MIG-15	Jet no ID	Total
F-80	5	-	-	-	9	-	6	-	20
F-84	-	-	-	-	1	-	10	-	11
F-86	2	6	-	9	1	-	834	-	852
F-94	-	-	-	-	-	2	1	1	4
F3D-2	-	-	1	-	1	-	4	-	6
F9F	-	-	-	-	2	-	5	-	7
Total	**7**	**6**	**1**	**9**	**14**	**2**	**860**	**1**	**900**

To help close the abysmal air combat record early in the Korean conflict, the USAF ramped up RDT&E efforts with respect to the development of not just jet fighters, but also specialized aircraft guns and ammunition. During WWII, many German fighters used larger 20 and 30mm cannon shells which allowed the aircraft to stand off their targets (like bombers with deadly defensive fire) and still achieve hits. Conversely, most Allied fighters (and defensive gunnery on bombers) used smaller, 0.50 caliber rounds which had less range, meaning that the fighters had to get closer. A problem with jet-age combat was that the aircraft speeds and altitudes were higher. This presented both opportunities and challenges to aerial gunnery. The higher altitudes and more rarefied air meant that higher caliber cannon shells could travel greater distances while maintaining suitable amounts of kinetic energy to hit a target. The volume of a cannon shell could accommodate a suitable amount of HE, so kill probabilities given a hit were high. The problem was that with low rates of fire, the probability of a hit was compromised. [19]

Fortunately, in 1946, the U.S. Army Ordnance Research and Development Service had issued a contact to General Electric for the design of a Gatling gun configured autocannon which was capable of rates of fire up to 7,200 rpm.

Following WWII, the US embraced 20mm ammunition and gunnery just as the Germans and British did during the war. The defensive gunnery on the B-36 fleet included 16 20mm guns on each aircraft, carrying a total of 9,920 rounds. While 20mm guns were being updated, the ammunition was maturing as well. At Eglin AFB in Florida, the USAF Armament Laboratory was working feverishly to develop a new family of ammunition specifically for combat above 40,000ft. During WWII, the US Army had developed a 1200 grain 0.60 caliber antitank cartridge at 3,500 fps. Development of the rounds would see the projectile necked up and down. [20] By 1950, GE delivered ten T45 guns of 0.60 (15.2mm) caliber for evaluation. Given an ever-increasing understanding of aerial combat in the jet age, the USAF asked for larger caliber guns. In 1952, GE delivered 20 and 27mm versions of the gun for evaluation. After extensive testing, the T171, 20mm gun was selected for further development. By 1956 the T171 had been standardized by the US Army and Air Force as the M61 20mm "Vulcan" aircraft gun. [21] This gun has since become The standard gun for modern USAF fighters and many abroad. Derivatives of the gun abound including 3-barreled M197 which saw so much use in Viet Nam and elsewhere on rotorcraft, many of which are still serving today like those in the USMC's AH-1Z fleet.

The post-war lessons learned from combat over Korea were not lost on the fledgling USAF. To wring out the best performance of the M61 Vulcan in high altitude combat, the USAF Armament Division oversaw the development of the M-50 series of 20mm ammunition. If one examines the rounds, it is easy to see that the form factor is not optimal for reducing drag, but rather it is optimized for maintenance of high internal volumes of HE at the expense of drag. This was deemed appropriate as high altitude combat as seen over Korea was conducted in rarefied atmospheres. The most common variants are the Armor-Piercing Incendiary (API) M53, Training Projectile (TP) M55, and High Explosive Incendiary (HEI) M56. [20]

For nearly a half-century, the M50 series ammunition was the primary aerial combat ammunition fielded in USAF aircraft. Although the M50 family of ammunition was the standard, there was constant pressure for higher speeds and greater effective ranges. Programs as early as 1972 were initiated by companies like Honeywell to develop lower drag rounds. Honeywell's "Quick" round was designed to shed as much as 25% of the round drag in supersonic flight. In the 1980's, a desire to "fix the drag problem" of the M50 family came to the fore as aircraft like the F-15 and F-16 were designed for aerial combat at a wider range of Mach numbers and altitudes than the Century-series fighters. Combat at lower altitudes, but high speeds were challenged by the high drag of the M50 family, so a new family of rounds designed for aerial combat with reduced drag was developed. In the Spring of 1992, the PGU-28 series of ammunition was fielded. [22] The figure below shows the nontrivial differences in shaping, volume of HE and configuration. The Semi Armor-Piercing High Explosive Incendiary (SAPHEI) PGU-28 was clearly designed for reduced drag with respect to the HEI M-56 as shown below:

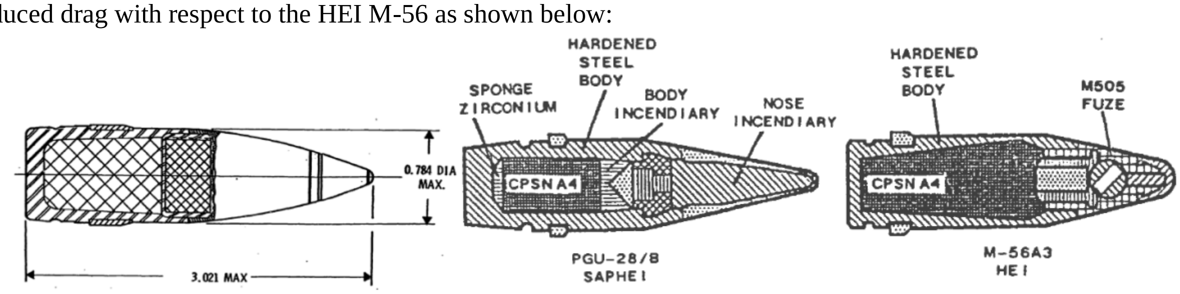

Fig. 5 Honeywell's "Quick" 20mm HEI Round (1972), PGU-28 (1992) and M-56 (1954) [22]

The difference in drag was immediately apparent as fighter firing tables in all USAF aircraft had to be updated. At typical aerial gunnery combat engagement ranges, nontrivial flight times were shaved off. The improvements in ballistics are obvious when one considers the times of flight and kinetic energy with range. With a Gun Director Sight (GDS) the PGU-28 round recommended engagement range is 4,000ft while the M56A3 recommended range is a full 25% shorter. [22] One of the primary reasons why gunnery ranges in air-to-air combat are limited is because of the required lead angle. If one considers a co-speed target at 300kts, 5,000ft MSL, 60° aspect from a slant range of 3,000ft will require a gun lead angle of 174mils for the PGU-28. The M56A3 will require 14% greater lead angle [22]. Timeliness of engagement was shown to be more important than simple volume of HEI materials within the round as air-to-air combat could take place in a variety of Mach numbers, altitudes, attitudes and tactical situations. Hess summed up the results:

When compared throughout the employment envelope, the PGU-28 is assessed to have an improved operational effectiveness of about 40 percent over the M- 56A3. [22]

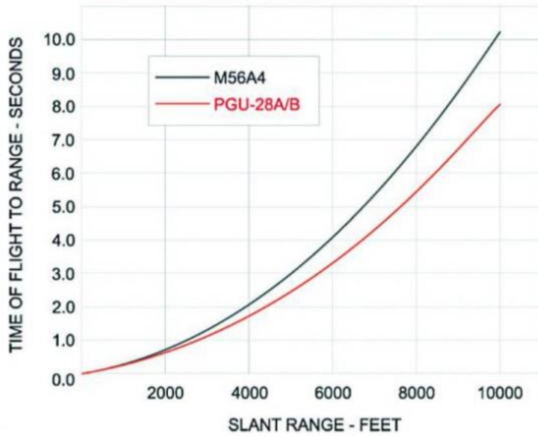

Fig. 6 Time of Flight (TOF) Reduction Due to Nontrivial Drag Reduction of PGU-Series over M50-Series Ammunition [23]

Today, most military tacticians think only of missiles when considering air-to-air combat. While they are certainly effective, there is much more to the story. Since the end of WWII, American aviators have scored 1125.75 aerial victories. Of those, only 15% are attributed to missile shots. The rest were the almost exclusively the result of aerial gunnery. Some other interesting facts of post-war aerial combat include the record of the venerable F-18 which has made its name as a front-line fighter (and notable Hollywood movies). Oddly enough, it is credited with the same number of air-to-air kills as the A-10 (using its powerful GAU-8 30mm cannon) which is not designed for air superiority, but close-air support (CAS). [18]

One of the most famous gunnery programs the USAF engaged in was the integration of the GAU-8 and the development of the PGU-13/14/15 series of ammunition for the A-10 Warthog. The aforementioned gun kills by the A-10 were had at nontrivial ranges of 5,000 ft. [24] [25] While the gun has seen the most utility in the A-10 and has gained a great deal of notoriety, the GAU-8 was actually developed by the US Navy for a Close-In Weapon System (CIWS). Fairchild designers were clearly thinking "outside the box" when they spec'd the gun and wrapped an aircraft around the giant system (giving them the edge over the YA-9 which only sported the 20mm M61 Vulcan. The problems were in the details. Gun gas erosion, hung rounds, barrel wear, loader fittings, and many other problems were evident early in the A-10 program. This led to a nontrivial amount of interaction between the System Project Office (SPO) and the Armament Division. Friction between the A-10 SPO and the Armament Division was well documented as the gun and the airframe matured simultaneously, overcoming aforementioned issues. The Armament Division proved critical in A-10 maturation, with some "challenged" dynamics along the way. Armament Division Director Dale Davis summed up the working relationship:

SPOs have a bad habit of not listening to good advice from experienced people.
-***Dale Davis**, Director USAF Armament Division* [20]

Although the A-10 airframe, gun and ammunition problems persisted for several years, they were eventually overcome. Today, the aircraft is seen as one of the finest CAS fixed-wing aircraft ever fielded. As the A-10/GAU-8/PGU-13/14/15 issues were being worked, many advanced ammunition configurations were researched in the USAF Armament Division. The division and its personnel proved to be extremely innovative, producing a stream of new designs and technologies. Caseless Ammunition was among the more interesting projects as the division tackled some very thorny issues.

Cases serve many purposes they seal the chamber, protect propellant from contamination,
serve as flame barriers, accept and transmit handling loads, serve as heat sinks, etc.
In caseless systems, other provisions must be made to serve these functions.
-***Dale Davis**, Director USAF Armament Division* [20]

Telescoped ammunition was an innovation which was intended to increase round ranges by bringing rounds closer to the ideal Sears-Haack shapes without compromising powder volume and maintaining aeromechanical stability. The

Division also researched combustible cartridges in an effort to support the GAU-7 program. Much progress was made in the development of ever higher velocity rounds, but problems with gun barrel and muzzle debris persisted. [20]

Nontrivial efforts were made to develop flechette ammunition. Flechette ammunition had been used by armies for more than 7 centuries and were ubiquitous for ground combat for reasons relating to basic physics. [26] [27] [28] [29] [6] In short, a tremendous amount of energy is invested in a dart-shaped projectile (flechette). This flechette in turn possesses a far greater ballistic coefficient, which increases total range and kinetic energy at all ranges. The Division worked hard to make flechette-configured projectiles a reality. Dale Davis summed up the opportunity and challenges associated with discarding sabot flechette ammunition:

> *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. For this reason, flechette ammunition has never been used from forward-firing aircraft.*
> *-**Dale Davis**, Director USAF Armament Division* [20]

The Division experimented with sabot diverters, sabot strippers, disentegrating sabots and many other configurations. Experiments with plastic sabot ingestion on engines showed sabot parts glazing engine components, reducing performance and fouling combustors. Several designs of an aeromechanically unstable unspun projectile within a discarding sabot were undertaken. The Burnette and Meyer sabots were similarly configured, but tended to have severe dispersion problems following sabot separation. [30] [31] After several decades and many millions of dollars of work, discarding sabots for aerial gunnery were eventually abandoned as "infeasible."

To extend ranges via a different drag mitigation mechanism, ring projectiles were explored. Unfortunately, it was discovered that choked central projectile flow induced substantially more drag than had been predicted. Drag fumers were explored as a mechanism to shed base drag, which typically makes up roughly 40% of a given projectile's drag. A number of experiments were successfully conducted with drag fumers and related Rocket Assisted Projectiles (RAP), but in the end, it was shown that the trades against internal HE and propellent did not show substantial improvements and induced some adverse effects like increased dispersion.

Experiments with a wide variety of obturating and sealing bands were successful in demonstrating greater round sealing for interior ballistics. They were shown to reduce barrel erosion, increase muzzle velocity and facilitate suitable levels of rotational acceleration upon muzzle exit to provide good spin stabilization over the course of a normal engagement. Ablative cooling, squeeze bore and plastic case ammunition were among the many innovations explored by the USAF Armament Division during the lead-up to the fielding of the PGU-13/14/15 and PGU-27/28 families ammunition. Clearly, the first four decades of post-war progress in aerial gunnery were extremely dynamic. [20]

III. 5 Years of Dynamic Progress Towards the Holy Grails of Aerial Gunnery

In 1992 the USAF Armament Directorate began exploring whole new classes of materials as it continued the march towards ever more capable aerial gunnery ammunition. Projects centered on the use of adaptive materials and structures were let for air-to-air missiles, gunnery and gravity weapon flight control. [32] Subscale flight control surfaces for such weapons were demonstrated in the laboratory and on the benchtop, setting the scene for more robust exploration (below).

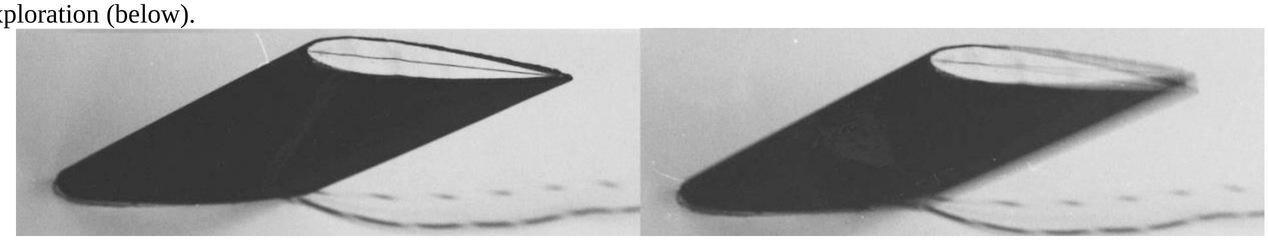

Fig. 7 High Speed Piezoelectric Missile Fin (1993) [32]

The performance of the self-contained piezoelectrically driven missile fins was impressive: Deflections of ±10 deg, with a corner frequency in excess of 125 rad/s for under 100mW of power at speeds through Mach 0.8. At the same time, piezoelectrically controlled helicopter rotor blades, airplane flaps, rudders and ailerons were being methodically matured. [33] In 1995, the Air Vehicles branch of the Armament Directorate, WL/MNAV kicked off a new program to pursue three ambitious goals related to aerial gunnery. [2] The principal author of this document supported this effort to develop:

i.) Guided Offensive Aerial Gunnery ii.) Counter-Missile/Defensive Aerial Gunnery iii.) Aerial Indirect Fire Support

The then Branch Chief, explained that if any of the three were successful, it would revolutionize not only the concept of aerial gunnery, but associated combat aircraft designs and tactics into the foreseeable future. From this basic concept briefing and guidance was spawned the Barrel-Launched Adaptive Munition (BLAM) program. [2] To demonstrate that basic flight control of a maneuvering cannon shell could be achieved, a 10° half-angle conical projectile of 37mm in base caliber was designed, modeled, fabricated, bench, wind tunnel and range tested.

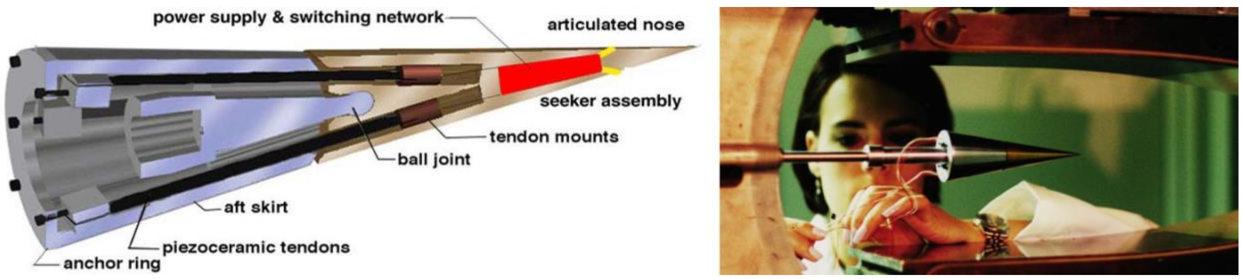

Fig. 8 Barrel-Launched Adaptive Munition (1995 - 1998) [34]

The piezoelectric tendons were designed to withstand more than 50,000g's of setback acceleration and were shown to be able to pitch the nose around the ball joint at rates in excess of 1000 rad/s for less than 100mW of total power draw. [35] [36] Wind tunnel testing showed steady, controllable balanced deflections through Mach 3. [37] Freeflight testing showed large, controlled deviations over the 700 ft long Aeroballistic Research Facility (ARF) at Eglin AFB. [38] [39] [40] By 1998, all three of the major goals for advanced aerial gunnery (above) were well on their way to being achieved, had demonstrated a string of strong technical successes with no adverse characteristics or "show stoppers." The 1998 BLAM final report and associated AIAA papers which had been approved for public airing and associated presentation estimated nontrivial range increases with full-bore projectiles fired from the AC-130's M102, 105mm howitzer while in a right-hand orbit (rather than the usual left-hand orbit for direct fire missions). [37] [36] This new form of indirect fire support promised to significantly change the way that soldiers on the ground would be supported, with indirect fire, which was a plus, but also opened the Pandora's box of interservice rivalry. [1] [40]

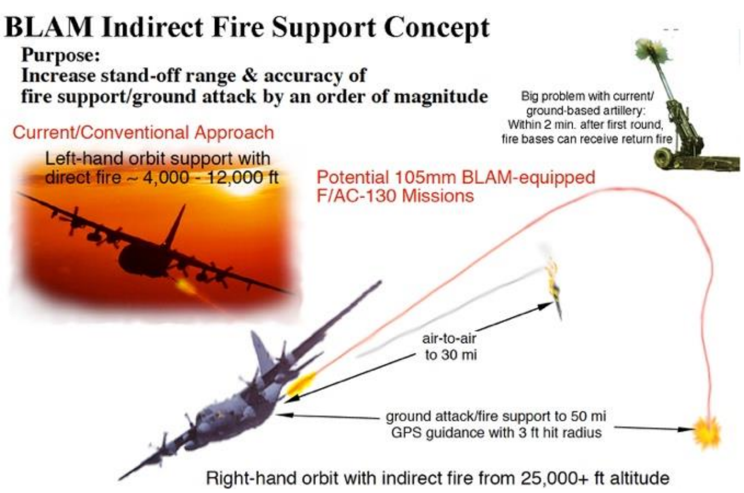

Fig. 9 BLAM Indirect Fire Support Concept (1998) [37] [36] [41]

From Ref. [40] it was obvious that the hardest parts of the technologies underpinning guided aerial gunnery had been successfully designed and reduced to practice in the BLAM and associated programs. All of the other technologies related to structures, aerodynamics, interior and exterior ballistics and GNC had been in place for many years as they were matured in many families of hard- and soft-launched munitions. From beam-rider concepts to Go

Onto Target (GOT) guidance, the only major missing piece was high bandwidth, high control authority, low power flight control, compact flight control actuator mechanisms that could survive setback, setforward, and balloting accelerations. What is more is that the SSDC and USAF had supported the development of hypersonic guided gunnery and had successfully demonstrated Mach 6 launches of conical projectile prototypes which were suitable for integration of hypersonic GNC packages. [42]

The three main goals above were well on their way to being achieved and a new era of aerial gunnery was just around the corner. In October of 1998, abruptly and without warning, the BLAM program and all related efforts within the Munitions Division were cancelled as orders came from above branch to do so. [1] Not only was the BLAM program itself shut down, but over the following 25 years, all advanced guided hard-launched munitions work within the AFRL and the USAF as a whole would effectively cease to exist including all hard-launched GNC development efforts, actuators, flight-safe sabots or hypersonic rounds. A Freedom of Information Act (FOIA) revealed that over the past 25 years, the USAF has not issued a single BAA or RFP calling for or supporting the development of advanced guided aerial gunnery. The complete divestment from this entire family of weapon systems and all ammunition development within the USAF is summed up eloquently by the current Munitions Directorate Chief Scientist:

The AFRL does not have an S&T portfolio in ammunition. [43]
*-**David Lambert** AFRL Munitions Directorate Chief Scientist, (via J. Ellison) 2021*

In addition to closing down the entire advanced USAF ammunition portfolio, unique research installations including the Aeroballistic Research Facility (ARF) would be left derelict, stripped of instrumentation and starved of trained personnel. This once extremely active research branch of the USAF now lacks the ability to even start to support new families aerial gunnery munitions. Additionally, the lack of resident expertise has crippled its ability to properly evaluate new gun systems developed by contractors and quantify their performance from an engineering standpoint, which is critical for aircraft design. [43] While some may argue that USAF ammunition and gunnery development and evaluation at Hill AFB, UT is sufficient, the lack of a properly instrumented gunnery range, dearth of resident expertise and very public gun-related troubles with the F-35 indicate the contrary. The admonitions of Ref. [20] are hauntingly apparent as the USAF is making the precise mistakes that Dale Davis warned about nearly 40 years ago. These sentiments were also very publicly summed up by General Genatempo:

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.. [44]
*-**Brig. Gen. Anthony Genatempo** USAF PEO for Weapons*

It can also be argued that recent costly disasters like the F-35 nearly shooting itself down because of a prematurely exploding PGU-32 SAPHEI round just after barrel exit could have been prevented by proper round (gun and fuze) development in a facility like the ARF. [45] [46] [47] These problems are just the tip of the iceberg as the challenged GAU-22 and its difficult integration have led to such tremendous issues that the whole $1.7T aircraft program itself is being threatened as its congressional adversaries seize upon its woes. [48] [49] [50] [51]

While the USAF divested itself from aerial gun and ammunition RDT&E, the branch which was then tasked to pick it up was the US Army Armament Research, Development and Engineering Center (ARDEC) in Picatinny, NJ according to Ref. 5 of [1]. It was explained that the above branch decisions were fundamentally rooted in interservice rivalry and justified by the impression that aerial gunnery ammunition was simply a commodity to be purchased rather than a critical component of an airborne weapon system in need of constant maturation Ref. 5 of [1]. If one examines the 1947 Key West agreement and its postcedants, the USAF and Army missions are clear: [52] [53]

Section VI - Functions of the United States Army [52]
<u>Primary Functions</u>
1. a. To defeat enemy land forces.
b. To seize, occupy and defend land areas.

Section VI - Functions of the United States Air Force [52]
<u>Primary Functions</u>
1. b. To gain and maintain general air supremacy.
c. To defeat enemy air forces.
d. To control vital air areas.
e. To establish local air superiority except as otherwise assigned herein.

Four of the five specific primary functions of the USAF are directly related to the conduct of air combat and the design, development, maintenance, fielding, and use of supporting weapon systems while the Army functions are centered on the conduct of land combat. It is difficult to reconcile the USAF's abandonment of advanced aerial gunnery RDT&E given its Key West mandated missions and that that aerial gunnery is responsible for 84% of post-war air victories and is a primary tool for prosecution of CAS missions to this day. [18]

While the USAF ceased advanced aerial gunnery RDT&E efforts over the past quarter-century, the US Army embraced advanced guided gunnery in support of ground forces by numerous small-arms and large caliber projects. Among the earlier efforts was the Range-Extended Adaptive Munition (REAM) project of 2001. [54] The REAM program successfully rolled BLAM technology into GNC packages for direct line-of-sight guidance of .40 caliber munitions which had been saboted up to .50 cal. as shown below:

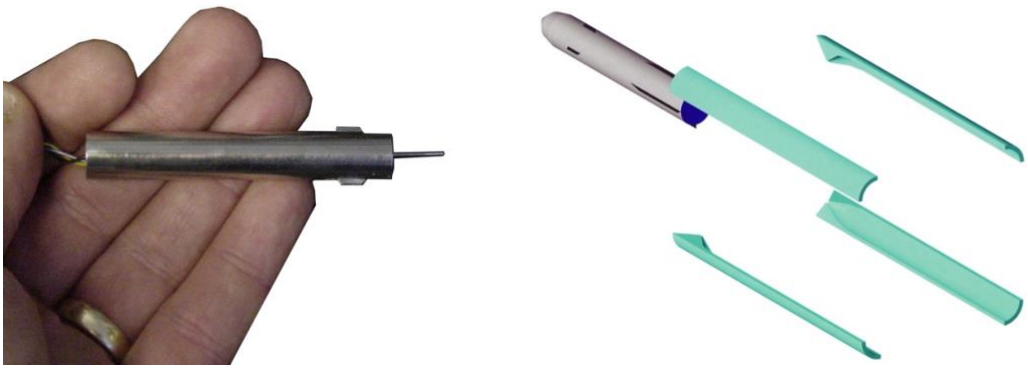

Fig. 10 Range-Extended Adaptive Munition (2001) [28]

The DARPA/Navy Extreme Accuracy Tasked Ordnance (EXACTO) program which was a similar .50 caliber sniper round with the same design specifications as the REAM program showed concretely that small caliber ammunition could be successfully guided. [55] Mid-caliber ammunition for surface combat was matured with programs like the US Army ARDEC Light Fighter Lethality (LFL). [56] The Navy was folded into a guided Close-in-Weapons System (CIWS) round of 25mm caliber saboted up to 40mm. The US Navy/DARPA Shipborne Countermeasure Range-Extended Adaptive Munition (SCREAM) showed extremely high control authorities at high Mach numbers and high rates. [57] Guided high caliber hard-launched munitions like the 155mm M712 have been fielded for more than 40 years. [58] More modern guided rounds include the 155mm M982 Excalibur, M1156 Precision-Guidance Kit, and the 120mm XM 395 guided mortars. [59] [60] Because the Army is not tasked with conduct of aerial combat (which would be counter to the functions described in the Key West Agreement), it is no surprise that not a single guided aerial gunnery program has been pursued by that branch over the past quarter-century. From the above programs and others, it is clear that advanced guided ammunition and associated gunnery has been, is being and will be developed for nearly all major forms of combat conducted by the DoD, save aerial combat. One inescapable conclusion is that given that all of the supporting technologies for development of guided aerial gunnery are well established and available, the DoD and its top brass are primed for a nontrivial technological surprise.

IV. New Opportunities for Aircraft Designs with Advanced Munitions

Although the DoD abandoned advanced guided aerial gunnery programs years ago, private entities and academia have continued research in this area. A steady stream of discoveries, models, tests, inventions and patents have come over the past two decades. These inventions include fully hardened flight control actuators that are capable of near 100% electrical-to-mechanical conversion efficiencies and designs for integration in subsonic and supersonic munitions. [61] Among the most significant has been the invention of Flight-Safe Discarding Sabot (FSDS) ammunition. This class of ammunition achieves the formerly impossible goal that the USAF labored so long and hard to meet, described by Dale Davis in Ref. [20]. Two basic branches of FSDS munitions have been identified: Ballistic Aeromechanically Stable Sabot (BASS), and Maneuvering Aeromechanically Stable Sabot (MASS) ammunition. [62] [63] [64] [65] [18] These classes of ammunition have undergone analytical and computational modeling in FEM and CFD, were reduced to practice and physically built and wind tunnel tested, shock table tested and range tested. The API versions of the BASS rounds are currently at TRL-6. [66] [67] [68] The way they fundamentally function is that a saboted flechette projectile exits the barrel at a comparatively high speed, then separates. The aeromechanically stable sabot turns harder than the aircraft could possibly turn, but not so hard so as to impact the launching aircraft. In the air-to-air case, the sabot could be actively guided to steer clear of the launching aircraft and wingman. In the air-to-ground case, the sabot is simply designed to dive for the ground. This dynamic is shown in Ref. [69] and below. [28] [29] [70] [71] From the figure below, it is clear that a fundamental change in aerial combat using aerial gunnery is being prescribed. While only unguided rounds are pictured below, it is obvious that a FSDS flechette can also be guided. The combination of FSDS technology and the aforementioned guidance packages is particularly potent as high speeds, low TOF, tight CEP and extended ranges are all supported. This invention and all of its derivatives are of high importance to both combat fixed- and rotary-wing aircraft.

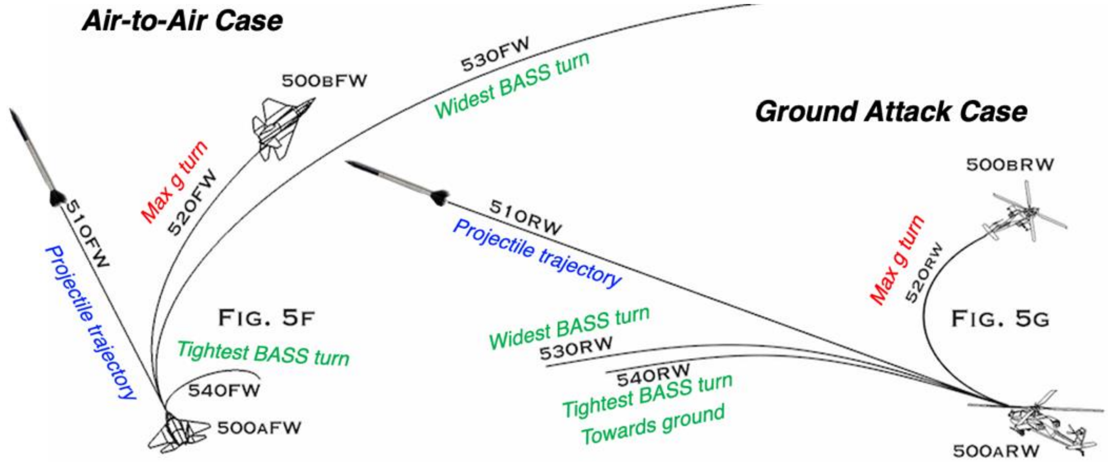

Fig. 11 Operational Concept of BASS Ammunition [6] [70] [71]

The nontrivial improvements in aerial gunnery are seen most obviously in a comparison of ballistic coefficients. Starting with the first air-to-air engagements in 1913, it is easy to show that modern ammunition used for aerial gunnery (like the M50, M789 and PGU series ammunition) has hardly improved at all given more than a century of RDT&E. [6] [71] The best Army and Navy rounds are all discarding sabot flechette rounds. The foremost of them are the US Army's APIFSDS antitank rounds. Although the ballistic coefficients of the 20mm BASS rounds are not quite as good as the best Navy and Army ammunition, they are orders of magnitude better than the best that is used today:

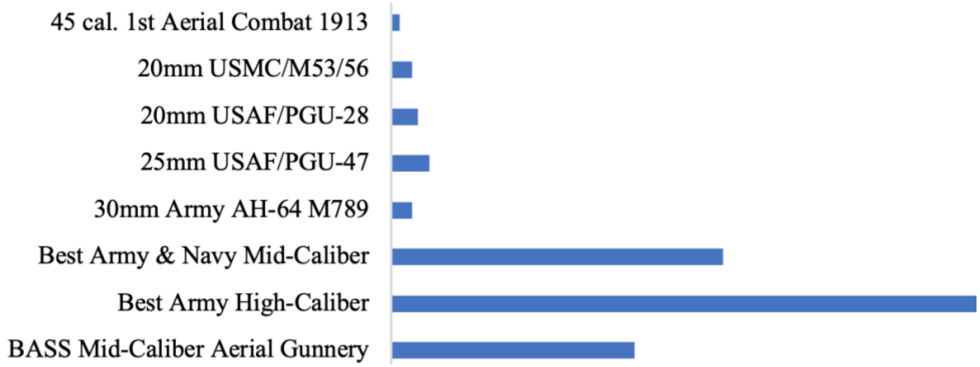

Fig. 12 Relative Ballistic Coefficients of "Modern" Ammunition used for Aerial Gunnery (M50, M789, PGU-series), the Best Flechette-Configured Army and Navy Rounds and BASS Rounds [70]

Given vastly superior ballistic coefficients, the TOF and kinetic energy at range are similarly outstanding. When one examines typical aerial gunnery rounds like the M50 and 20mm PGU-families, it can be seen that the times of flight with respect to BASS rounds are considerably greater. Similarly, when one examines the kinetic energy with distance, it is shown that the 20mm M50 and PGU families simply run out of kinetic energy at reasonable ranges. The 20mm BASS flechettes, however have such low drag in flight that they exceed the kinetic energy of the 30mm PGU-14 ammunition at extended ranges. The implication of this superior performance is that standoff performance of the BASS rounds is also superior. Given an aeromechanically stable configuration, BASS rounds are also shown to possess far tighter CEPs, meaning that targeting at extended ranges is highly viable. In air-to-ground modes, the KE overmatch with respect to the PGU-14 family of rounds implies an interesting dynamic: An aircraft equipped with 20mm BASS rounds can penetrate thicker armor than the A-10. Another interesting dynamic is that because the BASS rounds leave the airframe around Mach 3 relative to the airframe and they don't slow down very much with range, they are shown to have times of flight at distance far lower than missiles and rockets like the 2.75/70mm Hydras and AGM-114 Hellfires which leave the airframe with a relative speed of zero. At range, it takes less than 1/3 the time to engage targets with BASS rounds, rather than Hellfires. Given the thousand+ fold difference in acquisition costs, BASS rounds clearly support the concept of cost effective warfare (CEW). Because a number of families of aircraft like the FARA and F-35 are supposed to take over the A-10 CAS mission, this could potentially be actually realized. The figures below show the TOF and KE trends with range of a variety of munitions.

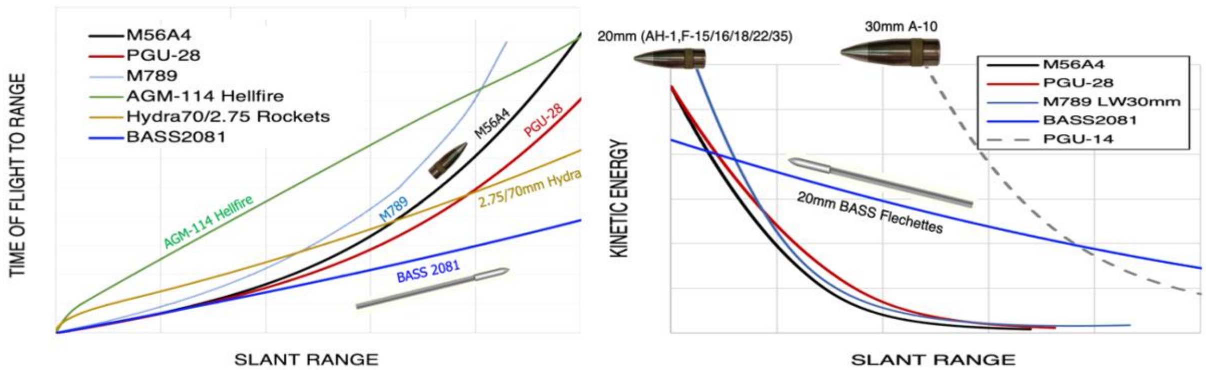

Fig. 13 Operational Advantages of BASS Ammunition

Given the differences in raw ballistic performance of the various rounds and implications for combat effectiveness, it is simply a matter of time till the BASS family of rounds is at least investigated by the DoD for aerial gunnery applications. What is also clear is that there exists a profound Aerial Gunnery Gap between the performance of the guns and ammo that the DoD fields in its aircraft and the most advanced ammunition currently under development.

V. The Gunnery Gap: Implications for Coming Combat Aircraft Designs, Sizing and Program Costs

One of the principal characteristics for gun integration in combat aircraft is the consideration of recoil forces. There are several relatively common calibers and guns that are used in a variety of combat rotary- and fixed-wing CAS aircraft. These include the M193, M134, GAU-19 and M61 of 5.56mm, 7.62mm, .50 caliber and 20mm respectively. Cartridge mass and gun weight are also critical factors as shown in the figure below:

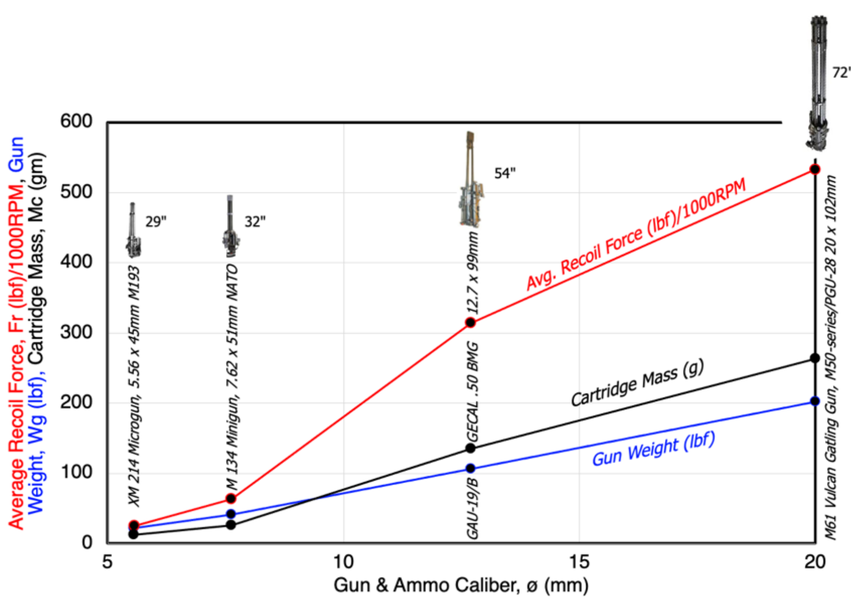

Fig. 14 Effects of Reduced Caliber on Recoil Forces, Gun Weights and Cartridge Masses for Various Gun Calibers [72]

Because the superior performance of BASS rounds shown in Fig. 13, it is now possible to effectively "downgun" a given aircraft design and achieve the same performance. It is interesting to note that the USAF originally considered a 25mm gun for the F-15, but wound up downgunning to 20mm for a number of reasons, not the least of which was that the caseless ammunition was proving hard to develop and the recoil forces on the airframe were deemed excessive at prescribed rates of fire. Given that the F-35 is suffering nontrivial problems because of its 25mm gun, it may be time to consider downgunning as well to something like the venerable M61 Vulcan cannon. Of course, to do so would give problems in attacking ground targets... unless BASS rounds were used.

In addition to helping the F-35 program, the opportunity for downgunning has other implications. A FARA or AT-6 Wolverine fielded with 20mm BASS rounds could outperform the A-10. In addition to providing more kinetic energy and armor penetration capability at range with a smaller round, the effects on the airframe are nontrivial: The gun bay, ammo bay and feed mechanisms all shrink. This in turn reduces the overall weight and volume of the aircraft, reducing drag further, inducing further shrinkage. If one considers LO, then the tremendous jump in RCS must be considered. Given that the AMRAAM bays doors are open for no less than 8 seconds during missile launch, the three+ order of magnitude jump in RCS may be less than ideal, especially during active combat. [73] If high-caliber guided BASS or MASS rounds are used, then there is no jump in RCS as the rounds are fired. What is more is that with guided BASS or MASS rounds, there is no delay between trigger pull and weapon egress. Ref. [73] shows there is at least a 4 second delay between initial door opening and missile clearance beyond aircraft nose. In that time, normal muzzle velocity BASS or MASS rounds will have traveled 4km. Ref. [64] [65] [66] [74] The AMRAAM won't catch up with the 20mm BASS round for another 10km. A high caliber BASS round will maintain lower TOF than the AMRAAM, all the way out to the AMRAAM max. range. If one considers delivery of indirect fire high caliber weapons with the capabilities of the GBU-39, then the airframe need no bay doors, but will be able to accomplish the same performance with a 6" (155mm) diameter RCS-shielded hole in the fuselage accommodating the barrel muzzle. The airframe weight savings between a small hole and 12 ft+ long bay door is rather profound. When one considers all of the aforementioned characteristics and the performance of the F-35, against a BASS-equipped equivalent aircraft the notional "F-36," then some interesting effects are seen, below:

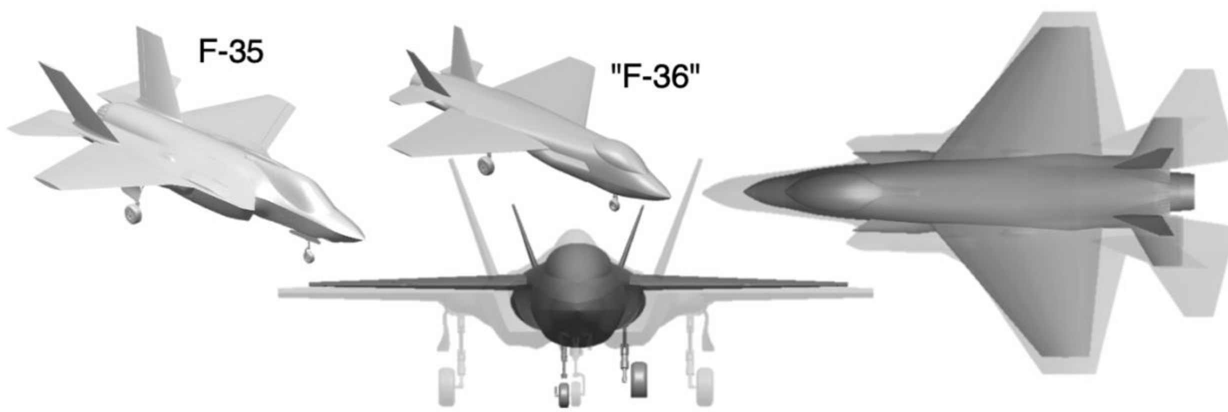

Fig. 15 Improvements in Aircraft Designs from BASS Ammunition:
Airframe Shrinkage, Weight Reductions, and RCS Mitigation using the Techniques of Ref. [75]

Ref. [67] examined the airframe shrinkage due to BASS rounds and estimated a total program cost savings of 16% using the methods of Ref. [76]. The highest estimates for BASS and MASS ammunition RDT&E is on the order of $200M from start to finish. This indicates a return on investment of more than a thousand-fold. Assuming the estimates are off by an order of magnitude, the savings to be realized are still 100:1.

Of course, in addition to raw program cost savings, is the enhancement of mission effectiveness. The increase in standoff ranges to beyond MANPADS range is a considerable benefit. If one considers other aircraft like an MQ-9, then the mission utility can be expanded greatly. If one considers a belly ball turret as was used on the OV-10 Bronco in the 1960's, then a ball-turreted M197 at beyond MANPADS range would have more armor penetrating capability than the GAU-8 on the A-10.

Fig. 16 OV-10 Bronco with Ball Turret M197 20mm 3 Barrel Gatling Gun, Conventional Figure-8 Type Target Engagement and Orbiting Fire Possibilities

Given that orbiting fire from smaller guns on smaller aircraft is now possible for both suppression and engagement, it is imperative to overlay the SA-25 threat dome on top of the BASS round strike profile as seen below in Fig. 17. In less time than the Verba takes to arm the missile and ready it for firing, it could be engaged from more than 4 miles away.

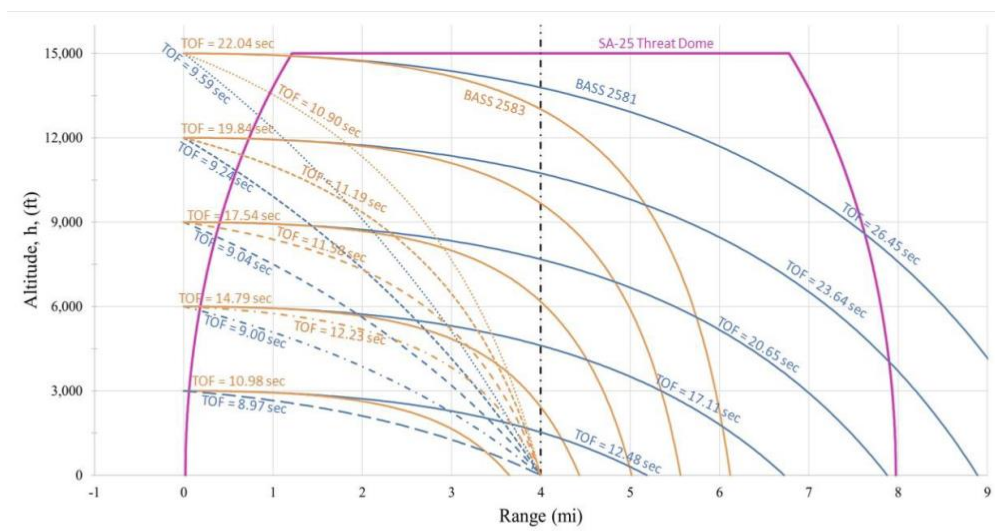

Fig. 17 SA-25 Threat Dome Well Covered by 20mm BASS Rounds with Times of Flight under 9 sec.

VI. Conclusions

From 1913 through 1992 aerial gunnery RDT&E was extremely robust with hosts of new innovations coming at regular intervals. From 1993 through 1998, highly advanced guided aerial gunnery research efforts were poised to dramatically change the very nature aerial combat. In 1998, the DoD fundamentally divested itself from all advanced guided aerial gunnery research efforts, disbanded research groups and left critical research infrastructure derelict. From 1998 through today, guided aerial gunnery efforts in private companies and research groups has continued and spawned whole new ammunition with unique properties and capabilities. By using Flight Safe Discarding Sabots, effective ranges, times of flight, kinetic energies and armor penetration capabilities are dramatically improved, overmatching current ammunition and some missile systems. The net effects of guided FSDS configured rounds, particularly those using Ballistic Aeromechanically Stable Sabots (BASS) is that nontrivial shrinkage in combat aircraft designs can now be realized with respect to conventionally armed combat aircraft. Reductions in gun and ammunition weight, volume and recoil forces reduce the overall weight, volume and costs of combat aircraft. The F-35 program could have saved an estimated 16% in life-cycle costs (LCC) if guided BASS rounds were to be fully developed and implemented. It is also shown that smaller aircraft with smaller gun systems equipped with BASS rounds can now do the jobs of larger combat aircraft. This indicates that smaller attack airplanes and rotorcraft and uninhabited aerial vehicles (UAVs) can engage more targets per dollar than is currently the case.

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