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New Attack Aircraft Designs and Tactics Enabled by Discarding Sabot Aerial Gunnery

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This paper outlines how advanced discarding sabot aerial gunnery can provide increased weapon effectiveness in a number of currently employed tactics as well as enabling new developments in aircraft design and gunnery tactics. This paper examines the origins of ground attack aircraft, currently fielded aircraft and tactics, as well as newly designed aircraft and advanced tactics made possible by advanced munitions. New advanced discarding sabot rounds can achieve the same lethality as much larger guns such as the GAU-8 at a reduced caliber, size, and weight. The reduced recoil, size, and weight allow for an innovative side firing gun placement allowing for new orbiting firing modes to be employed that both allow for a safer engagement of the enemy as well as reducing the number of assets required on station. The two aircraft presented in the body of this report were designed to incorporate these innovative gunnery systems thereby outperforming current light attack aircraft competitors as well as the larger and more capable A-10 Warthog and AC-130 family of attack aircraft. In addition, the effective reduction in equivalent airframe size and operating cost is outlined compared to the AT-6 Wolverine and A-29 Super Tucano in addition to the A-10 Warthog. Finally, the cost for both soft and hard target engagements were analyzed using currently fielded light attack aircraft as well as the two innovative designs presented demonstrating that the use of advanced discarding sabot gunnery greatly reduces costs of engagement.

I. Nomenclature

AP = *Armor Piercing*
BAGS = *Ballistic Aerial Gunnery Solver*
BASS = *Ballistic Aeromechanically Stable Sabot*
CAS = *Close Air Support*
CEP = *Circular Error Probable*
DoD = *Department of Defense*
MANPADS = *Man Portable Air Defense System*
RTB = *Return to Base*
SFC = *Specific Fuel Consumption*

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II. Attack Aircraft: Origins, Evolution

The importance of light attack aircraft was understood as early as World War I during which pilots dropped fléchettes and small ordnance at ground forces in an attempt to disrupt enemy supply lines and attack enemy trenches in the hopes of breaking the stalemates often developed in them. However, the first true light attack aircraft were not developed and extensively used until World War II.

A. The First Air-to-Air and Air-to-Ground Engagements

In late November skies over the rough-and-tumble twin border towns of Naco, Arizona (1910 pop. 517 [1]) and Mexico, aerospace history was made. The pair of dusty Sonoran trading posts would serve as a backdrop for four important aerospace milestones. The towns were so rough that in 1899, Mexican consul Mascareñas proposed constructing a "steel fence between neighboring border the cities" to "...deter contraband and prevent cattle rustling [2]." In 1912, an adventuring newspaper man, writer, and cartoonist for the San Francisco *Examiner,* Phillips (Phil) Dwight Rader (1890 - 1918) would wander to the Southeast Arizona border towns in search of fortune and adventure. A part-time soldier of fortune and aviator with only a handful of introductory flights in his logbook, he would sell his skills as an airman to the local comandante [3]. At the time, the Mexican Revolution (1910 - 1920) was in full swing. The forces of Mexican Dictator José Victoriano Huerta Márquez (1850 - 1916) had laid siege to Naco, Sonora. Occupying (or defending) the town itself were the Constitutionalist forces of José Venustina Carranza de la Garza (1859 - 1920) [4]. Upon arrival in Naco, Rader was promptly hired to fly for the Huertistas. Following the arrival of his Christofferson Pusher, Rader began reconnaissance flights of the Carrancista forces within Naco in late September 1913 [5]. Such is the first aerospace milestone achieved: Aerial Reconnaissance of Enemy Combatants by a heavier-than air craft. While anything but decisive in the battle, the sight and sound of an aircraft overhead brought great consternation and drew much ground fire by Carrancistas (resulting in another military milestone: air defense gunnery). This groundfire in turn forced Rader to fly at exceptionally high altitudes for the day:

> *"A plane came over the town flying very high, nearly two thousand feet. Every man with a gun opened fire as it passed to the Eastward, without doing any damage. General Hill was greatly excited as to what effect it might have on his men, but I calmed him somewhat by promising to shoot it down as soon as I had a plane."* [5]

The Huertistas which had hired Rader were quick to turn up the pressure on General Benjamin Hill (1874 - 1920) and the Carrancista forces he commanded to defend Naco. Constructing crude bombs of blasting caps and dynamite, Rader made several passes over Naco, *dropping four bombs doing no material damage except to frighten nearly all the revolutionists to death* [5]. Such is the second aerospace milestone: aerial bombing of enemy troops by a heavier-than-air craft.

While the Huertistas had engaged Rader, a second aviator mercenary, Col. Dean Ivan Lamb (1886 - 1955), had similarly made his way to Naco and had been hired by Gen. Hill. Following the arrival of his Curtiss Model D and given his promise above, the scene was set for the first aerial dog fight:

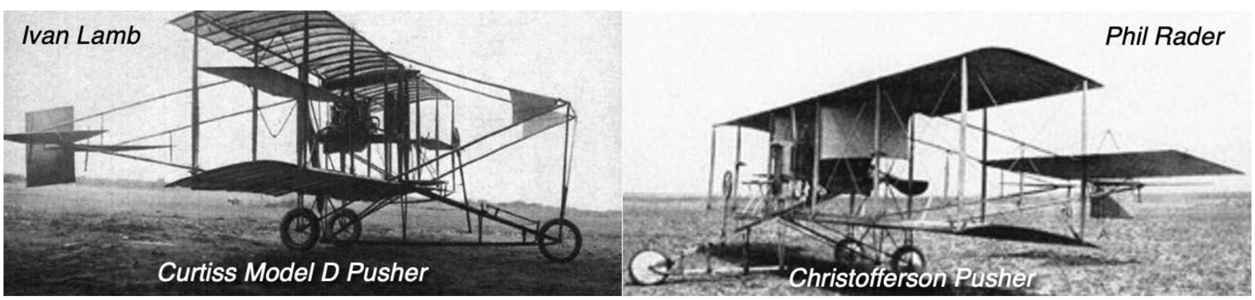


Figure 1: Aircraft of the World's First Dogfight, 30 November 1913 [6]

> *"Early one morning while making a reconnaissance, I saw the enemy plane and edged over in its direction... He then drew a pistol and fired downward, below my machine. We then fired spaced shots until our guns were empty at about the same time."* [5]

The aerial tumult clearly excited and thrilled commanders and ground troops on both sides, but was less than deadly. Unknown to the belligerents, both Rader and Lamb were longtime friends and made sure this aerial gun duel looked impressive but was not fatal. Still, a third aerospace milestone had been achieved: air-to-air combat. The final great milestone was claimed by Lamb as he was returning to the Carrancistas camp: he decided to reload and fired into the Customs house from above because *Customs people are always irritating* [6]. Such marks the fourth aerospace milestone: aerial strafing of an enemy target.

As the air war in Europe kicked off the following year, it started with a similar form of "brotherhood of the air" as seen between Lamb and Rader. Enemy forces were reconnoitered, pilots on either side would wave, then fly on to land behind their respective lines. By the end, the conflagration would generate legends of the air, revolutionize aircraft designs, solidify aerobatic dogfight tactics (many still bear the names of aviators of the time) and induce countless murderous engagements [7]. The guns used in aerial combat would become lighter and specialized for shooting through propellers. Bombs would grow empennages and become aeromechanically stable. One of the more deadly weapons inducing indiscriminate carnage was the fléchette. These small metal darts were dropped by the thousand on enemy trenches, effectively raining steel through helmets, bones, horses, vehicles, and etc. While no single weapon system was decisive in WWI, least of all airborne weapons, fléchettes added to the misery and bloodshed on both sides.

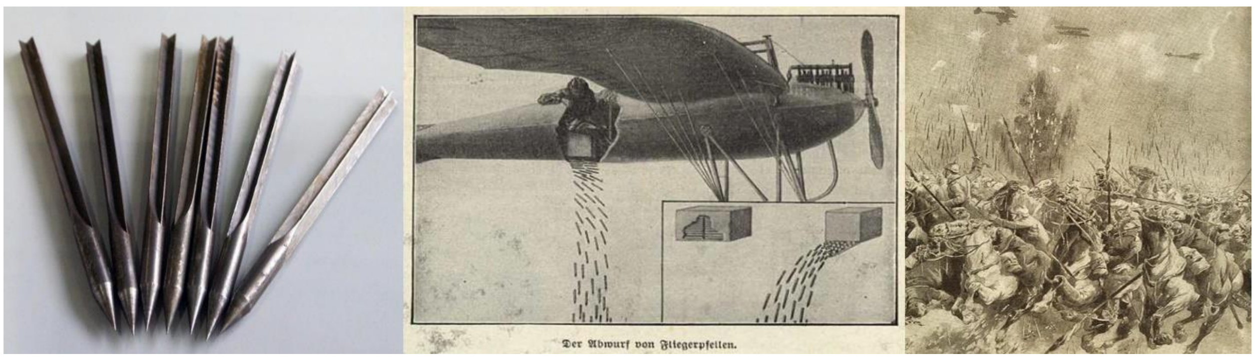


Figure 2: Air-to-Ground Attack via Fléchettes during WWI [8]

B. From Tactical Bombing to Dedicated Ground Attack Aircraft

Based on the lessons learned in WWI about the need for more precise and faster methods of ground attack than could be provided by large scale bombers, ground attack aircraft were designed and utilized to great success by all sides in WWII. The Germans, fearing the stalemates of WWI, developed a new method of warfare: Blitzkrieg, or “lightning war,” relying on fast mechanized units to push through an opponent’s line of defense and get behind enemy lines before a proper defense could be mounted. To this end, light attack aircraft were developed to help ground forces.

Figure 3: Junker Ju-87 [9]

The first light attack aircraft fielded by German forces was the Ju-87, or Stuka, to great success. The Ju 87 first flew in 1935 with around 6,000 aircraft being produced. It had a crew of two (a pilot and a rear gunner) and was powered by a 1,200 hp V-12 inverted, liquid-cooled Jumo 211 piston engine. The aircraft had an empty weight of 5980 lb. and a max takeoff weight of 9560 lb. The Ju 87 was used throughout the war as a dive bomber and ground attack aircraft, with many modifications and configurations. The aircraft had two forward 7.92 mm MG 17 machine guns and one rear 7.92mm MG 15 machine gun. Additionally, the Ju 87 could carry up to a 500 lb. bomb or 4 x 110 lb. bombs under the wings. Two large 37 mm gun pods could also be mounted to points under the wing [8].

Figure 4: HS 129 [9]

Later in the war Germany required a new, more powerful light attack aircraft that could effectively take out armored vehicles, leading to the development of the HS 129. The HS 129 first flew in 1939, with 865 being produced. The HS 129 had a crew of one and had an empty weight of 8863 lb. with a max takeoff weight of 11,574 lb. The HS 129 was unique in that it was a heavily armored with the plane designed around a large “bathtub” of steel that encompassed the cockpit and nose of the aircraft. Even the canopy was steel with only small windows, slanted heavily to deflect bullets. The aircraft was continually up gunned as tank armor improved. The aircraft was originally equipped with 2 x 7.92 mm MG 17 machine guns in the nose, but later models equipped 2 x 13 mm MG 131 machine guns instead. The belly of the aircraft was originally configured to carry 4 x 110 lb. fragmentation bombs, but a belly gun pod soon replaced the bombs and mounted 2 x 20 mm MG 151/20 cannons, then later a single 30 mm cannon, and finally a 75 mm Rheinmetall PaK 40 anti-tank gun theoretically capable of destroying any tank in the world at the time. In addition, the wings could accommodate 2 x 110 lb. bombs on underwing hardpoints. Unfortunately, the HS 129 was plagued with engine problems, first using two low-power German Argus AS 410 V-12 air-cooled engines generating 459 hp each and later two French 14-cylinder Gnome-Rhone 14M air-cooled radial engines generating 691 hp each, neither of which generated adequate power [8].

The United States also developed light attack aircraft in WWII, the first of which was the P-40 Warhawk. It first flew in 1938 with 13,738 aircraft being produced by the Allied Powers. The P-40 had a crew of one and was powered by a V-12 liquid-cooled Allison piston engine producing 1,240 hp. With an empty weight of 5,922 lb. and a max takeoff weight of 9,200 lb., the P-40 was equipped with 6 x 0.5 in. M2 Browning machine guns in the wings as well as the capability to mount up to 2,000 lb. of bombs across three hardpoints. The P-40 was also an exceptional fighter with over 200 Allied fighter pilots becoming aces flying in the P-40 including at least 20 double aces [8].

Figure 5: P-40 [8]

The P-47 Thunderbolt was later developed as a light attack aircraft, with its first flight in 1941 and 15,636 being produced. The P-47 had a crew of one and was powered by an 18-cylinder air-cooled radial piston Pratt and Whitney R-2800-59 engine producing 2,000 hp. With an empty weight of 10,000 lb. and a max takeoff weight of 17,500 lb., it carried 8 x M2 Browning machine guns, up to 2,500 lb. of bombs across three hardpoints, and 10 x 5-in unguided rockets. The P-47 was especially well-suited for ground attacks with an armored cockpit and radial engines which were more damage tolerant than comparable liquid-cooled engines [8].

Figure 6: P-47 Thunderbolt [8]

In addition to using designs produced by the United States, the United Kingdom used the Hawker Typhoon as a light attack aircraft. First flown in 1940 and with 3,317 being produced, the Hawker Typhoon had a crew of one and was powered by a liquid cooled 24 piston Napier Sabre IIA producing 2,180 hp. With an empty weight of 8,840 lb. and a max takeoff weight of 13,250 lb., the aircraft was equipped with 4 x 20 mm Hispano MK II cannons and could carry 8 x RP-3 unguided rockets as well as up to 2 x 1000 lb. bombs [8].

Figure 7: Hawker Typhoon [8]

Similarly, the Soviets developed the Il-2 as a light attack aircraft in addition to using aircraft developed by the United States. The Il-2 first flew in 1939 with 36,183 produced. The aircraft had a crew of two (a pilot and a rear gunner) and was powered by a liquid cooled V12 Mikulin AM-38F engine producing 1,720 hp with an empty weight of 9,755 lb. and a maximum takeoff weight of 14,021 lb. The Il-2 was equipped with 2 x forward firing 23 mm VYa-23 cannons, 2 x forward firing 7.62 mm ShKAS machine guns, and a single rear turreted 12.7 mm UBT machine gun. In addition, the Il-2 could be equipped with 8 x RS-82 rockets and 6 x 220 lb. bombs in wing bomb bays and underwing mounts [8].

Figure 8: Il-2 [8]

After WWII the light attack aircraft role was taken by the carrier-based A-1 Skyraider in the United States. The first flight of the A-1 was in 1945 and it remained in service until 1985 with 3,180 being produced. The plane had a crew of one (although variants had up to a crew of three) and was powered by an 18-cylinder air-cooled radial Wright R-3350-26WA engine producing 2,700 hp, with an empty weight of 11,968 lb. and a max takeoff weight of 18,106 lb. The A-1 Skyraider was equipped with 4 x 20 mm AN/M3 cannons and 15 external hardpoints with a capacity of 8,000 lb. It had the ability to carry combinations of bombs, torpedoes, mine dispensers, unguided rockets, and gun pods [8].

Figure 9: A-1 Skyraider [8]

Figure 10: OV-10 Bronco [8]

Later light attack aircraft include the OV-10 Bronco, a twin turboprop light attack and observation aircraft that first flew in 1965 and is still in limited service with 360 produced. The aircraft has a two-man crew and is powered by two Garrett T76-G-420 turboprop engines producing 1,040 hp each with an empty weight of 6,893 lb. and a max takeoff weight of 14,444 lb. The OV-10 is equipped with either a single 20 mm M197 cannon or 4 x 7.62 mm M60C machine guns in addition to having five fuselage and two underwing hardpoints capable of carrying combinations of 7 or 19 tube 2.75 in FFars rockets, AIM-9 Sidewinders, or up to 500 lb. of bombs [8].

Modern attack aircraft include the Brazilian EMB 314 Super Tucano, which is a light attack aircraft, and the United States' A-10 Thunderbolt II, which is not a light attack aircraft but has been an extremely successful attack aircraft. The EMB 314 Super Tucano first flew in 1999 with at least 200 produced and is still in production. The aircraft has a crew of two (a pilot and a navigator) and is powered by a Pratt and Whitney PT6-A-68C turboprop generating 1,604 hp with an empty weight of 7,055 lb. and a max takeoff weight of 11,605 lb. The EMB 314 is equipped with 2 x internal 12.7 mm FN Herstal machine guns with 5 external hardpoints (two under each wing and one under fuselage) with a capacity of 3,300 lb. with the capability of carrying rockets, missiles, bombs, and electronics [8].

Figure 11: EMB 314 Super Tucano [8]

Figure 12: A-10 Thunderbolt II [8]

The A-10 first flew in 1977 and is still in wide service with 716 aircraft produced. The plane has a crew of one and is powered by two GE TF34-GE-100A turbofans producing 9,065 lbf with an empty weight of 24,959 lb. and a max takeoff weight of 50,000 lb. The A-10 is unique in that it is built around its massive 30 mm GAU-8/A rotary cannon, with an additional 11 hardpoints (8 underwing and 3 belly stations) providing a capacity of 16,000 lb. of rockets, missiles, bombs, and sensors in many combinations. The A-10 is extremely tough, surviving up to 23 mm armor piercing and high explosive rounds with a double redundant hydraulic flight system and a mechanical back up system if hydraulics are lost. The cockpit and critical parts of the aircraft are protected by 1,200 lb. of titanium aircraft armor similarly to the armored "bathtub" of the HS 129. In addition, the front windscreen and canopy are built to resist small arms fire [8].

C. Precision Bombing: Close-in and Dangerous, or Standoff and Costly

As described above, gravity weapons originated in WWI, when pilots hand released fléchettes, hand grenades, and even bricks from the cockpits of their planes in attempts to disrupt the enemies below. As aircraft rapidly developed and became more capable, munitions design accelerated and gravity weapons grew larger and more powerful. A list of modern 250lb and 500lb gravity weapons can be seen in Table 1 below. These are the size and weight of gravity weapons seen in modern ground attack aircraft.

Table 1 U.S. 500 and 250lb Bombs [9]

500lb		
Designation	**Description**	**Cost**
Mk82	Low-Drag General Purpose High Explosive	$2,082.50
Mk82 Snakeye	Low-Drag Close Air Support High Explosive	
BLU-111/B	Low-Drag General Purpose Stable High Explosive Thermal-Protective Coating on BLU-111/B (Navy)	
BLU-111A/B		
BLU-126/B	Low Collateral Damage Bomb	
BLU-129/B	Composite Low Collateral Damage	
GBU-38(V)1/B	All-Weather Precision-Guided Mk82	$25,000

GBU-38(V)2/B	All-Weather Precision Guided BLU-111	
GBU-38(V)3/B	All-Weather Precision-Guided BLU-126/B	
GBU-38(V)5/B	All-Weather Precision-Guided BLU-129/B	
250lb		
Designation	**Description**	**Cost**
Mk81	Low-Drag General Purpose High Explosive	$2,082.50
Mk81 Snakeye	Low-Drag Close Air Support High Explosive	
GBU-29	Precision-Guided General Purpose High Explosive	$25,000
GBU-39/B	Precision-Guided Glide Bomb	
GBU-39A/B	Precision-Guided Glide Bomb	

Although still effective, the deployment of such weapons is costly. Additionally, the deployment of gravity weapons often leaves the aircraft extremely vulnerable. External weapons increase the radar cross section of aircraft substantially, and even if the bombs are in a bomb bay the deployment will require the opening of the bomb bay doors and thereby an increase in radar cross section. In addition, the deployment of gravity weapons often requires an aircraft to be either directly over their target if the bombs are not guided, and still relatively close to the target even with guided bombs. Finally, their deployment often results in significant area effect damage which is becoming increasingly dangerous in modern urban warfare.

D. The High Cost of Missiles

The solution to many of the problems of bombs comes in the form of modern missiles seen in Table 2 below. They offer significant standoff ranges compared to bombs, have a lower CEP, are faster to target, and can be more precise in their targeting and area of effect damage. However, they do not solve the issue of increasing the aircraft's radar cross-section, and they also are extremely costly, even more so than bombs, as seen in Table 2 below. Nonetheless, this has been a price modern militaries have been willing to pay as we have seen an increase in weapons platforms primarily using missiles such as the Predator and Reaper UAS.

Table 2: U.S. Guided Missiles [8] - [9]

Designation	Description	Target	Cost
AGM-114K/K2/K2A Hellfire II	SALH	Land	$150,000
AGM-114N Hellfire (MAC)	SALH, MMWR	Land	
AGM-114R Hellfire II (Hellfire Romeo)	SALH	Land	
AGM-114R9X Hellfire	SALH	Land	
AGM-65(A-K) Maverick	EO, IIR, SALH, CCD	Land	$17,000-$110,000
AGM-84 Harpoon	SSR	Ship	$1,406,812
AGM-84K SLAM-ER	INS, GPS, CGD	Land	$500,000-$3,033,468
AGM-88E AARGM	ARG	Land	$870,000
AGM-88F HCSM	ARG	Land	
AGM-88G AARGM-ER	ARG	Land	
AGM-119 Penguin	SSR	Ship	Unknown
AGM-176 Griffin	SALH, GPS, INS	Land	$127,333
AGM-179 JAGM	SALH, MMWR	Land	$324,805

III. Strafing and Orbiting Attack Aircraft Today -- Configurations, Tactics

Modern ballistic aerial gunnery has evolved into two different methods, employing either a strafing or an orbit attack path. Both paths provide challenges discussed in the following sections.

A. Superior Strafing with Egress Challenges: The A-10 Solution

The most well-known aircraft using a strafing attack method is the A-10. This method involves a direct, low strafe of the target often due to fixed weaponry on the aircraft. The benefits of this method are that it only requires a single pilot, and it is often very accurate with direct line of sight to the enemy and friendlies. However, this method does bring the aircraft in close proximity to the enemy position, thereby endangering the aircraft and crew. This is especially dangerous as when pulling out of a strafing attack the hot exhaust off the engines presents an ideal target for surface-launched heat seeking missiles. The A-10 has developed an advanced method of strafing to deal with this where two or more aircraft operate in opposing circular orbits and then strafe the enemy as seen in Figure 13. This method results in lower and lower time between strafing attacks on an enemy position (depending on how many aircraft are involved). However, the danger still exists after the last strafing run. In addition, this method is costly as it requires multiple assets on station.

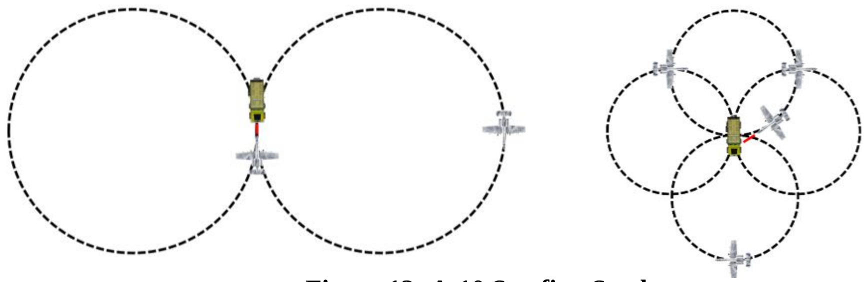


Figure 13: A-10 Strafing Stacks

B. Advantages of an Orbit with Size, Weight and Cost Challenges: The AC-130 Solution

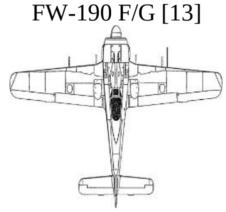
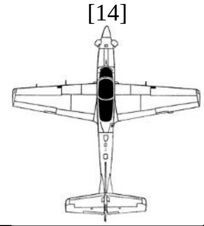
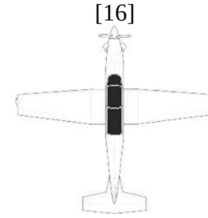
The second method that has evolved is an orbital firing method. This method involves an aircraft entering a large, high-altitude circular orbit around a target where a gunner can fire out the side of the aircraft at enemy positions below. The obvious advantage is that this attack method brings the aircraft away from immediate hostile fire. However, this is costly in that it requires at least one other occupant in the aircraft as a dedicated gunner. The AC-130 is the most iconic aircraft currently operating in this mode, as seen in Figure 14.

Figure 14: AC-130 Firing [10] [11]

IV. Light Attack Aircraft Today, Low Cost and Small, but Effective?

In so many ways, the light attack aircraft of today represent only an incremental improvement at best over front-line ground attack aircraft seen 75 years ago. Indeed, the P-51 Mustang and FW-190 F/G compare very favorably to the EMB 314 Super Tucano and AT-6 Wolverine:

Table 3 75 Years of Attack Aircraft Design Evolution?

	P-51 Mustang [12] 	FW-190 F/G [13] 	EMB 314 Super Tucano [14] 	AT-6 Wolverine [15] [16] 
Year	1945	1945	2020	2020
Max Gr. Weight	12,100lb	10,803lb	11,905lb	10,000lb
Empty Weight	7,635lb	7,055lb	7,055lb	5,890lb
Useful Load	4,465lb	3,748lb	4,850lb	4,110lb
Vmax	383kts	352kts	320kts	316kts
Ferry Range	1434nmi	540nmi	1542nmi	1725nmi
Max. Power	1,720hp	1,953hp	1,604hp	1,600hp

If one examines Table 3 it is hard to believe that 75 years have elapsed and the performance of two front-line ground attack aircraft of 1945 are roughly the same as the two major competitors in today's light attack aircraft competition. Even with all of the improvements in materials, analysis capabilities, and powerplants, the loadouts, maximum rates of climb, maximum range, and combat turn radii are essentially unchanged, while maximum speeds have actually dropped.

A. Small Size, Very Small Loadout

From Table IV.1, it is easy to see that the useful load fraction of light attack aircraft being proposed today is around 41%. If one examines the specifications of the A-10 Warthog, this 45-year-old aircraft design has a CAS useful load fraction of 47% [17]. With 22,000lb of loadout including more than 1300 rounds, the Warthog is often hailed as the gold standard of ground attack aircraft in service today. Given that the light attack aircraft under consideration today are two-seaters, while the A-10 is a single-seat aircraft, the respective loadouts are even more compromised. Indeed, the light attack aircraft under consideration today can carry less than 1/5th the ordnance of the A-10.

B. Cost of a Single Turboprop Engine, Trainer Conversion: Low Caliber Wing Gun Pods, Low Standoff Distance, Low KE Gunnery

The single tractor engine configurations of the attack aircraft competitors under consideration today presents a nontrivial challenge with respect to gun positions and caliber. Because firing a gun through a propeller is not a realistic option, gun positions are forced to be laterally displaced beyond the propeller tips. This in turn means the guns will be mounted via some mechanism fairly far out on the wings. The P-51 and FW-190 solve this by integrating the 0.50 cal. and 20mm guns within the wing, with recoil vectors lining up almost precisely with the vertical position of the wing elastic axis. What is more is that because the FW-190 and P-51 used piston engines, the amount of wingspan consumed by fuel tanks less than 1/3 of the wingspan. Figures IV.1 shows that because the ground attack aircraft of today use comparatively thirsty turboprop engines, fuel tanks are necessarily larger; accordingly, their wings are wet to approximately the 70% span. Aside from survivability concerns, this design issue presents problems with respect to gunnery: the P-51 designers carved out roughly 50% of their wingspan to accommodate guns and ammunition. Indeed, the P-51 could carry 1840 total rounds of 0.50 cal. ammunition between six machine guns [12]. The EMB 314, on the other hand, has only 2 0.50 cal. guns with just 250 rounds each. Clearly the compromise between fuel volume, machine gun form factor, and ammunition volume has led to unfavorable compromises in modern times.

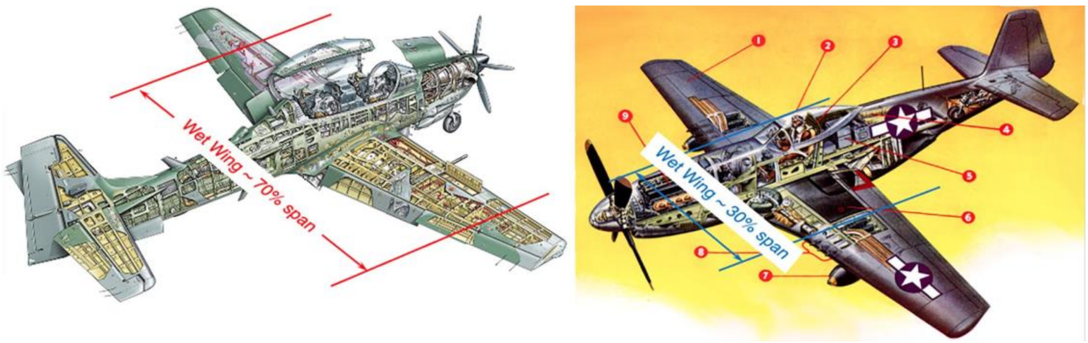


Figure 15: Trade Between Engine Type and SFC Driving Fuel Tank Volume vs Gun and Ammo Volume

While it is easy to show that lower SFC drives fuel tanks to be smaller, freeing up wingspan for internal accommodation of guns and ammunition, what is less obvious is the effect of accommodating guns far from the wing elastic axes. Indeed, several nontrivial problems are evident. First, because the 20mm gun pods generate on average more than 50kJ (37k ft-lb) of recoil energy per round, nontrivial torques are applied at appreciable distances from the elastic axis. The associated recoil torque alone will cause gun barrel sighting deviations. Given limited recoil distances, structural impulses are more sharp-edged than high stroke guns. This in turn excites wing torsional vibration modes. Because phasing between guns is not possible, CEP levels will be greater than body-mounted gun systems which suffer from none of these dynamics. In addition to troublesome CEP at range, the rounds simply run out of energy. If one examines the 0.50 BMG round energy with respect to range, it is easy to see the round loses roughly 1/2 of its kinetic energy by 600m. Given that the 0.50 cal. round exits the barrel with 1/12th the energy of a PGU-14, the gold standard for engaging many ground targets, its effectiveness against many targets is less than assured.

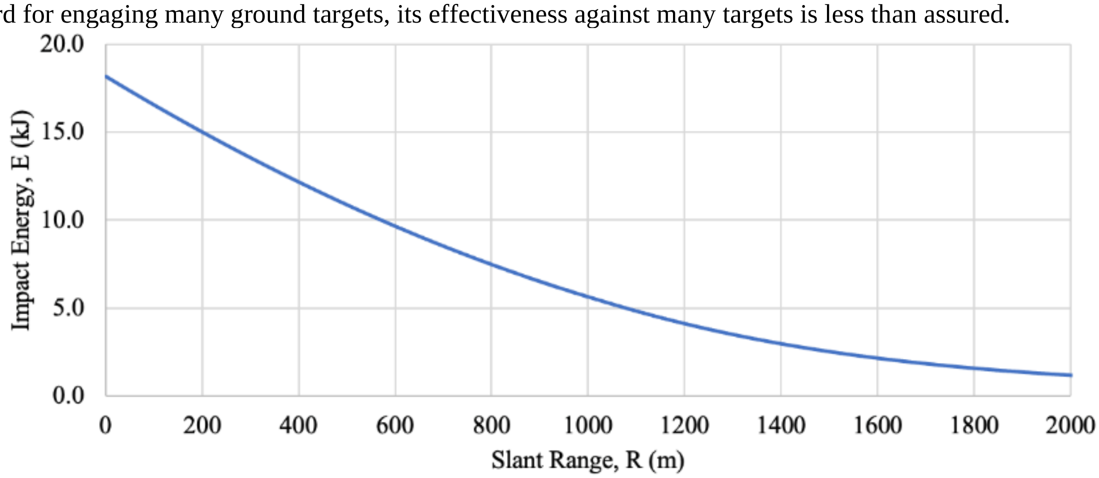


Figure 16: 0.50 Cal. BMG Round Energy Decay with Distance

C. Close-In and Vulnerable

While guided bombs like the GBU-39 can have a range in excess of 150km (93mi), the small loadout makes light attack aircraft less than ideal platforms for hauling large numbers of bombs [18]. Missiles like the AGM-114 Hellfire cost $74,500 each, which makes them far too costly for many situations to say the least [19]. When examining the maximum cost effectiveness per kill of bombs, rockets, missiles, and aerial gunnery, a single well-placed cannon shell can knock out vehicles and individuals; accordingly, the most cost-effective method of target engagement is via aerial gunnery. That said, the costs are often quite high. First, given the low caliber guns like 0.50 cal. bullets built into light attack aircraft of today, the aircraft must advance quite close to the target for suitable engagement. While a ground-based 0.50 cal. gun effective range is only 1,000 yards (0.9km), when airborne the range shrinks to 250 - 400 yards (229 - 366m) [20].

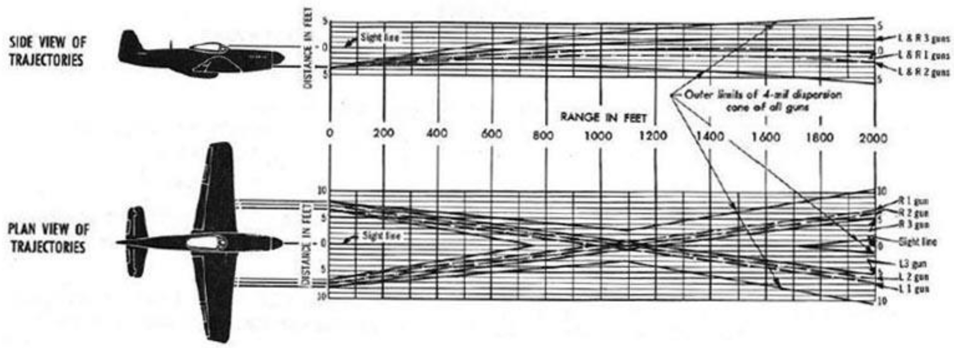


Figure 17: P-51 Gunnery Convergence Diagram with 6 0.50 Caliber AN/M2 Browning Machine Guns [20]

If one examines the threats that will be faced by light attack aircraft, foremost among them will be MANPADS missiles like the 9K333 Verba (SA-25). Because 0.50 caliber guns disperse more than 4 mils at ranges in excess of 500yds (460m) (above), the attacking aircraft must get very close to the target. Given that the SA-25 can hit targets out to 3.5nmi (6.5 km) at altitudes of up to 15,000ft (4.5km), it is easy to see that light attack aircraft strafing targets with small, 0.50 caliber or conventional 20mm rounds are very vulnerable [21].

V. The Solution: Twin Engine Configurations with Advanced Discarding Sabot Ammunition

Two designs were put forth by the University of Kansas design teams to answer the request for proposal issued by AIAA for the Undergraduate Austere Field Light Attack Aircraft. Both proposals followed the twin engine design philosophy, offering greater flight safety and superior gun integration options than their single engine competitors. Additionally, both designs incorporated variations of the newly developed BASS round system. While the overall design considerations for the two aircraft addressed similar concerns regarding flight safety and performance, the design approaches differed in several key ways, most notably in the use of ducted turboprops on the Dragoon [8] and jet turbine engines on the Chimera [22]. Figure 18 and Figure 19 on the next page show the two designs put forth by the University of Kansas.

Figure 18: Dragoon Austere Field Light Attack Aircraft [8]

Figure 19: Chimera Austere Field Light Attack Aircraft [22]

A. New Capabilities from Advanced Discarding Sabot Ammunition

Sabot systems have been used for hundreds of years and offer several advantages over solid rounds. The purpose of sabots is to transfer the energy of a large caliber firing system into a subcaliber penetrator. This transfer of energy is typically accomplished in one of two ways, namely, non-discarding and discarding sabots [8].

In non-discarding sabot systems, the shell design incorporates a subcaliber penetrator of a dense and hardened material, often tungsten or depleted uranium, wrapped in standard lead or similar shell materials. Upon firing the assembly travels down range and impacts a target. At impact, the soft outer layer of the shell flattens and dissipates, while the penetrator continues through armor to cause damage. While effective, non-discarding sabots have several disadvantages. The first of these is the drag profile of conventional rounds. At supersonic speeds, cross-sectional area has major implications on drag. This means the external sabot being carried downrange pays drag penalties with little to no benefit at impact. The second disadvantage stems from the stabilizing spin used by conventional rounds. This spin, coupled with the shape of typical cannon shells, makes conventional rounds susceptible to being blown off course by gusts [8].

Discarding sabot systems address the drag penalties of non-discarding sabot systems by only firing the penetrator downrange. In historical and currently fielded systems, upon exiting the barrel the sabot around the penetrator breaks into several pieces and is cast aside. This system works well for ground-based assets, but presents a problem for airborne gunnery platforms in that the sabot pieces form a debris cloud in front of the firing aircraft and any sister craft in the area. The BASS system addresses this issue by utilizing a single piece aeromechanically stable sabot. Upon exiting the barrel, the sabot flips end over end and executes a turn tighter than any aircraft are capable of executing, thereby removing itself from the flight trajectory of the aircraft. Figure 20 below shows the firing procedure for the BASS system [8].

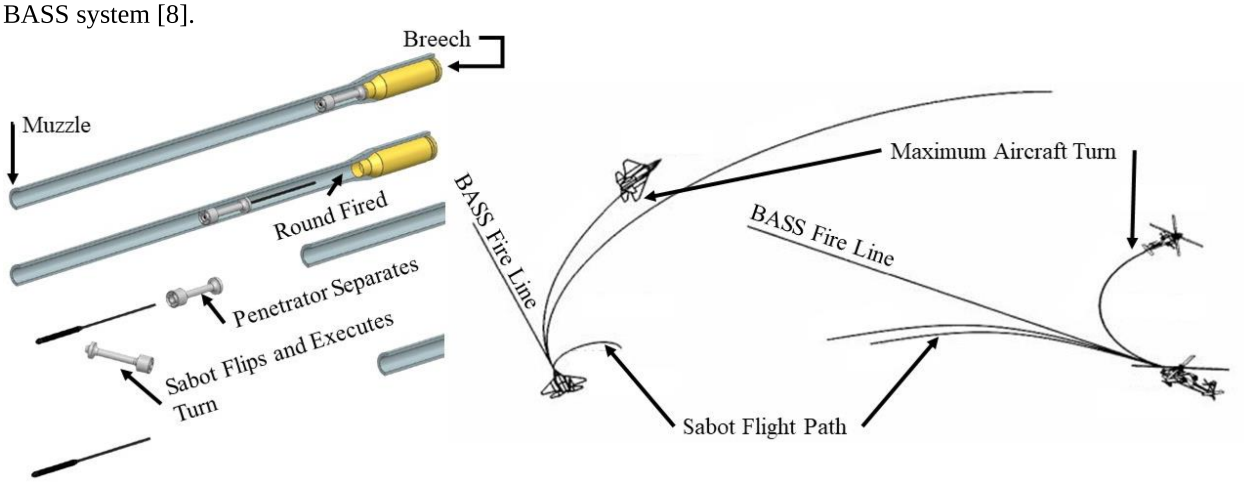


Figure 20: BASS Firing Diagram [8]

B. Strafing to Overmatch A-10

In the design of both example aircraft, unique ballistics codes were developed and used to evaluate the downrange effectiveness of a sweep of hard launch calibers. In addition to the time step performance characteristics, the analysis tracked the time of flight, kinetic energy, and armor penetration capabilities. Figure 21 below shows the armor penetration capabilities graph generated by the designers of the Dragoon using BAGS. Note that this code was created using publicly available shell data and basic ballistic physics [8].

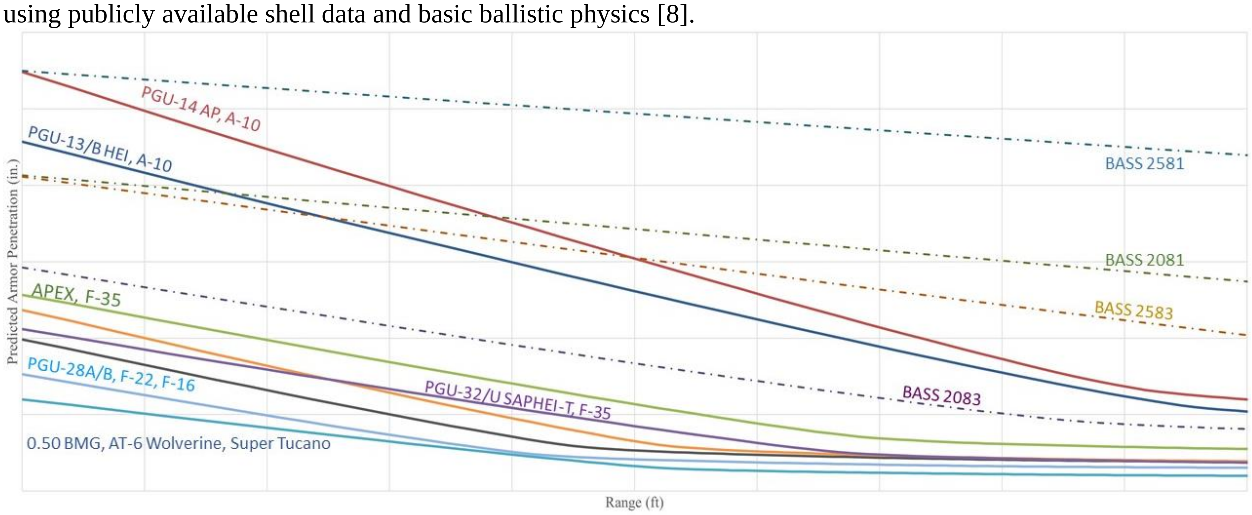


Figure 21: Armor Penetration (in.) vs Range (ft) [8]

"Smaller caliber guns than 30mm might do something, but they really couldn't engage all targets. Only the A-10 can do that. A 0.50 cal gun against most of what we were up against would be worthless."
-Col. Roger Disrud, USAF A-10 Pilot & Top Gun, Ret.

Using this data, the Dragoon design put forth was designed to utilize the 25mm variant of the BASS rounds. This round was selected for its sustained armor penetration capabilities at range. As shown in Figure 21, the BASS 2581 AP variant surpasses the abilities of the A-10 at an engagement distance of just under 3,000 ft and continues to outperform the PGU-14 for the rest of the flight regime [8]. The Chimera fields the 20mm variant of the BASS round. The smaller variant carries less recoil forces and a lower weight price, but also suffers lower effectiveness against enemy armor. At long ranges in the 7,000ft region, the BASS 2081 AP variant does eclipse the armor penetration of the PGU-14, but the performance remains less than the larger BASS round [22].

C. Orbiting Fire to Overmatch the AC-130

Both the Dragoon and Chimera platforms can slew their respective cannon platforms up to 90 degrees off body axis and enter a pylon turn to mimic the engagement style of the larger AC-130. In this engagement style, the increased range capabilities of the BASS family of hard launch munitions becomes a major advantage over conventional munitions currently employed by the AC-130 platform. Figure 22 below was also generated with BAGS and taken from the design report of the Dragoon and tracks the performance of the rounds currently fielded on the AC-130 and examples of conventional rounds versus the abilities of the BASS system when deployed in an orbit attack mode.

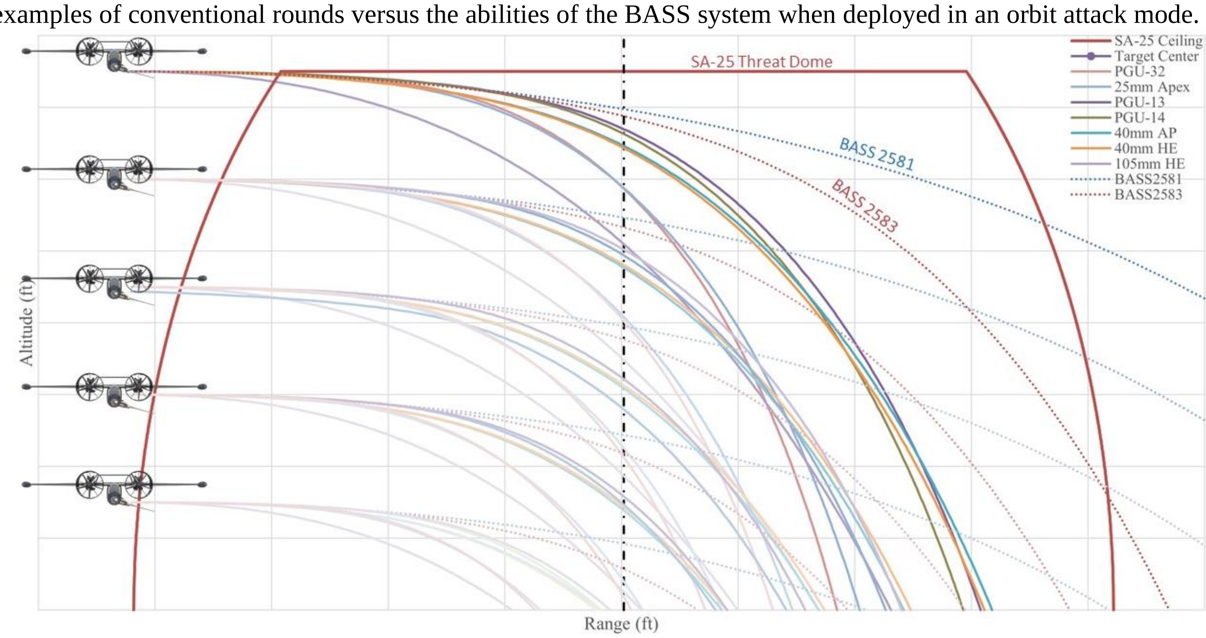


Figure 22: Orbit Mode Conventional Rounds vs BASS Rounds [8]

Figure 22 shows that the reduced drag profile of the BASS family of rounds exponentially increases the range of target engagement ability for aircraft that can field them in combat. The pink lines denote the threat dome of the Russian-built SA-25 shoulder launched surface to air heat seeking missile. Figure 22 shows that for orbit style engagements, to effectively engage targets at the center of the threat dome aircraft equipped with conventional rounds must operate either at high altitudes or within the threat dome itself [8].

These limitations present aircraft with two unfavorable options of engagement. At high altitudes, rounds will have longer flight times to impact targets. This increases the chance of changing wind conditions negatively impacting the flight of the rounds, leading to a larger CEP. In constantly changing battlefield dynamics, large CEPs are avoided at all costs, as the reduction of accuracy poses a threat of accidental fratricide. This CEP increase can be reduced by moving the airborne asset closer to the target center, but the trade-off is to place the support aircraft in the threat dome of enemy fire. For slow moving and less agile platforms like the AC-130, this is undesirable.

The BASS round's enhanced range capabilities address both of these limitations. As mentioned in Section A of this chapter, the BASS round is designed to alleviate increases in CEP due to gusts. Shown in Figure 22, the BASS rounds' increased range over conventional hard-launched munitions allows aircraft fielding BASS rounds to hit targets over large portions of the SA-25 threat dome while remaining out of range of return fire. This increase in standoff range capability serves to increase survivability and reduce ground observables of the aircraft while engaging targets.

"Orbiting fire is better than strafing fire. The reason is that orbiting fire can both suppress and engage. Strafing fire alone engages, then for the majority of the time the aircraft is circling around, the bad guys are able to return fire, move and engage friendly forces and aircraft. If an AC-130 was overhead and knew where both we and the bad guys were, we knew we would all be safe."

-Prof. Adrian Lewis, US Army Special Forces Major, Ret.

D. Orbit and Strafe Engagement Capabilities and Influence on New Aerial Gunnery Tactics

The designs put forth to meet the AIAA request for proposal have unique implications for the future of air to ground engagements. Because both aircraft can transition between engaging targets both in strafing runs and orbit fire, they have the potential to reshape the methods used by the aerial gunnery community. The environment surrounding battlefields often impacts the effectiveness of close air support, limiting where and when certain assets can be employed. Modern battlefields are more fluid than those of history, as advances in vehicles and armor have led to dynamic environments which can change in the span of seconds. Flexibility of engagement allows aircrews to adapt their aircraft to the changes on the ground rather than transitioning support responsibilities to other platforms.

This ability to transition from between engagement styles allows both the Dragoon and Chimera platforms to engage in traditional strafing runs if the combat environment requires, however their ability to slew their primary armament combined with their long loiter time make them valuable as orbit fire overwatch assets. As shown previously in Figure 22, the BASS rounds used on both platforms give both the Dragoon and Chimera the range and engagement power to overmatch the AC-130 at a fraction of the cost of the current orbit overwatch vehicle, making them an attractive option from both the close air support perspective and from the military budget perspective.

Figure 22 below demonstrates a single ship implementation of the Dragoon and Chimera platforms as overwatch orbit support vehicles. In this deployment, the aircraft enters a left-hand orbit above the threat dome of the SA-25 and similar anti-aircraft missiles. From this point, the vehicle can target various enemies both within and outside its orbit radius, as well as reacting to threats from outside ground forces. This performance is enabled by using the BASS rounds which, in addition to giving increased anti-armor capabilities, give the weapons systems on the Dragoon and Chimera accurate ranges greater than those achievable by the AC-130 platform. By remaining outside of the SA-25 threat dome, the danger to the asset is mitigated and the target zone exit challenges imposed on the A-10 platform is alleviated.

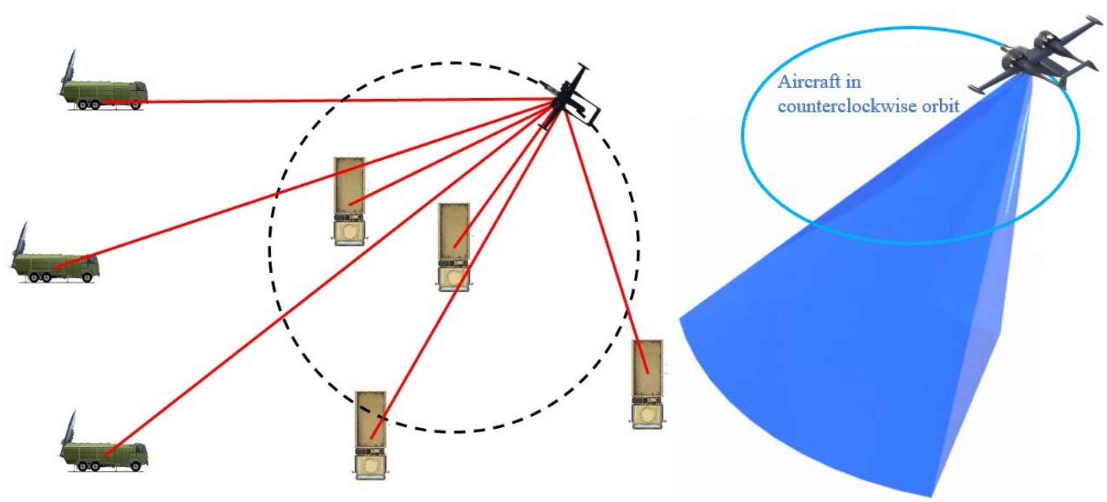


Figure 23 Single Ship Orbit Engagement of Multiple Targets

Further, advances in targeting computer systems, in addition to the advances in munitions, allow designs like the Dragoon and Chimera to change the dynamic of multi-ship formations by utilizing vertically stacked formations. Applicable to extremely dangerous or very high-profile target zones, this formation poses more risk to the operating group as it requires multiple assets on target but allows for a dedicated aggressor aircraft to provide uninterrupted ground support. In this formation, the commanding aircraft climbs to an altitude above the threat dome imposed by the SA-25 and similar surface to air missiles and enters a right-hand orbit with the cannon slewed away from the target zone. From this position, the gunner can use the side-firing capabilities of the aircraft to scan for and suppress enemies located outside of the immediate target zone. While the commanding aircraft takes up this position, the sister ship enters a slightly smaller radius anti-clockwise orbit at a lower altitude still above the SA-25 threat dome. From this position, the gunner can identify and engage targets and threats within the target zone. Networked fire control computers allow both aircraft to continuously engage and suppress enemies for the entire duration of the engagement. Since the computers can track where both aircraft are located, they can automatically interrupt fire when allied aircraft are in the line of fire to prevent friendly fire. Figure 24 below shows an example of vertically stacked formations using the Dragoon aircraft, with the command aircraft's higher altitude denoted in orange.

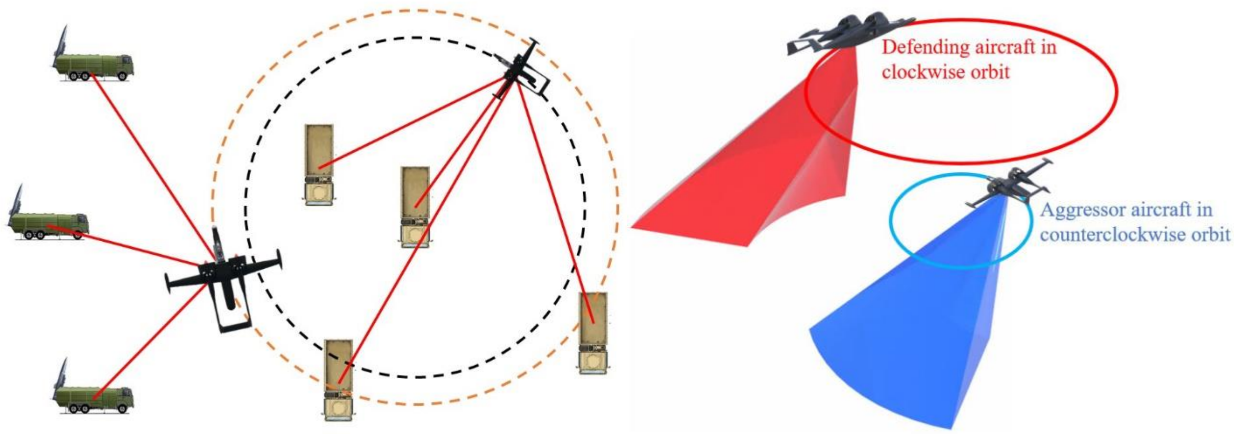


Figure 24: Two Ship Multi-Direction Engagement of Multiple Targets Using Networked Fire Control

Finally, the cannon used onboard the Dragoon, the M242 Bushmaster, has two unique characteristics that have direct impacts on the effectiveness of orbit-firing Dragoon aircraft. The M242 has an electrically driven firing mechanism rather than the recoil or hydraulically driven systems common in other attack aircraft. This system facilitates the unique dual feed mechanism fitted as standard on the M242. The dual feed allows gunners to switch rounds between AP and HE rounds while firing to adapt to changing battlefield conditions. For example, when engaging a hard target such as a tank or armored personnel carrier, the gunner may select AP rounds, but while suppressing enemy soldiers, the HE rounds may be more effective. This electric system also enables the gunner to adjust the firing rate of the cannon while flying, allowing for suppressive fire rates to be increased to take advantage of the engagement angle during the orbit path [8].

E. Weight, Acquisition, Direct Operating and Life Cycle Costs Matching Conventional Light Attack Aircraft

Table 4 shows the weight and cost analysis generated for competing attack aircraft by the Dragoon design team. The chart shows that, while acquisition cost is a factor in the life cycle costs of aircraft designs, suppressing direct operating costs is the most effective way to reduce the overall cost of operating the aircraft over the course of its lifetime.

Table 4: Weight and Cost Analysis of Competing Attack Aircraft [8]

Aircraft	AT-6 Wolverine	A-29 Super Tucano	A-10 Thunderbolt II
W_{TO} (lbf)	10,000	11,905	50,000
Cost of Acquisition "Roskam"	$7.78 M	$9.35 M	$42.7M
Direct Operating Costs ($/hr)	$1,000 – $2,500	$1,000	$20,000 - $60,000
Life Cycle Costs/ Unit (15,000hr)	~ $22.8 M - $45.2 M	~ $24.4 M	~ $343 M - $943 M

Both the Dragoon and Chimera designs used the design philosophy of suppressing operating costs to minimize life cycle costs. Table 5 and Table 6 on the next page show the cost analysis of the two designs.

Table 5: Dragoon Cost Analysis [8]

	50 Units Cost ($)
Airframe Engineering Design	$38.73 M
Development and Support	$9.18 M
Flight Test Aircraft	$198.33 M
Flight Test Operations	$13.95 M
Test and Simulation Facilities	$72.27 M
RDT&E Profit	$16.26 M
Cost to Finance RDT&E Phases	$12.65 M
RDT&E Total Cost	$7.3 M
Total Manufacturing	$462.7 M
Total Acquisition	$509 M
Estimated Price per Airplane	$19.0 M
Fuel, Oil, and Lubricants	$160.8 M
Direct Personnel	$2.81 B
Indirect Personnel	$1.38 B
Consumable Materials	$240.8 M
Operating Cost (1,200 Hrs.)	$6.90 B
Operating Cost Per Hour	$3,962
Life Cycle Cost	$8.72 B

Table 6: Chimera Cost Analysis [22]

	Item	50 Units Cost ($)
Research, Development, Test, and Evaluation	Airframe Engineering and Design	$26.5 M
	Development, Support, and Testing	$7.8 M
	Flight Test Airplanes	$148.5 M
	Flight Test Operations	$2.1 M
	Test and Simulation Facilities	$53.6 M
	Financing	$29.8 M
	Profit	$29.8 M
	Total R.D.T.E Cost	**$298.2 M**
Acquisition Costs	Airframe Engineering and Design	$13.4 M
	Program Production	$490.8 M
	Flight Test Operations	$11.2 M
	Financing	$57.3 M
	Profit	$57.3 M
	Manufacturing	$572.7 M
	Total Acquisition Cost	**$630.0 M**
	Price per Airplane	**$18.5 M**
Operating Costs	Fuel, Oil, Lubricants (1,200 flight hours/yr)	$42.5 M
	Consumable Materials	$286.4 M
	Direct Maintenance Personnel	$1.9 M
	Indirect Personnel	$477 M
	Spare Parts	$366.9 M
	Maintenance Depot	$366.9 M
	Miscellaneous Items	$146.8 M
	Total Operating Cost	**$3.7 B**
	Operating Cost per Hour	**$2795/hr**
Life Cycle Cost	Research, Development, Test, and Evaluation	$298.2 M
	Acquisition Cost	$30.0 M
	Operating Costs	$3.7 B
	Disposal	$46.4 M
	Life Cycle Cost	**$4.6 B**

These graphs show that while the initial cost of acquisition for the Dragoon and Chimera, $19 million and $18.5 million, respectively, is more than the competing light attack aircraft, the AT-6 Wolverine and the A-29 Super Tucano, both platforms carry acquisition and life cycle costs that are fractions of the costs to purchase and operate A-10s while outperforming the A-10 in attack runs. Figure 25 below tracks the cost of acquisition in blue and the life cycle cost in orange of the Dragoon and Chimera versus their current competitors [8], [22].

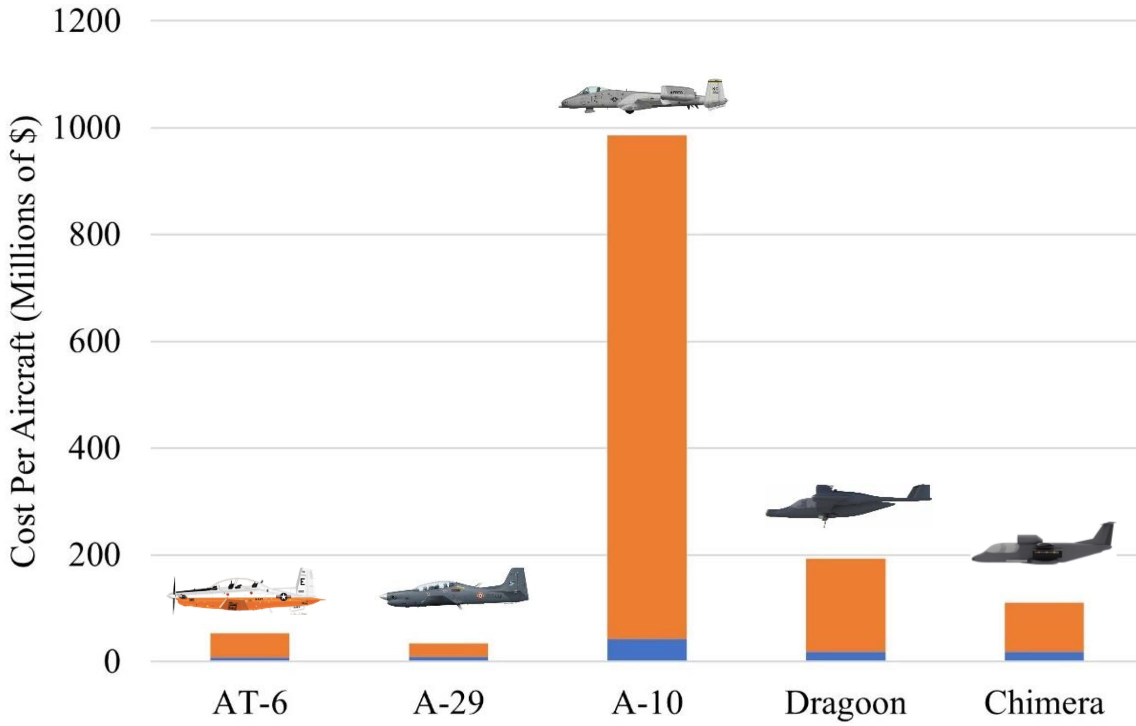


Figure 25: Cost Comparison Tracking Acquisition Cost (Blue) and Life Cycle Cost (Orange) [8] [22]

F. Engagement Cost Estimations Matching Conventional Light Attack Aircraft

In addition to having reduced acquisition and life operating cost compared to the A-10, the BASS munition implementation allows for a reduced engagement cost. Figure 26 and Figure 27 below estimate the engagement cost of 1,000 soft targets and 100 hard targets respectively based on the DoD fiscal year 2021 ammo budget estimates [23]. For comparison the mass equivalent of 20 and 50 12.7 mm rounds was used when analyzing soft target engagements.

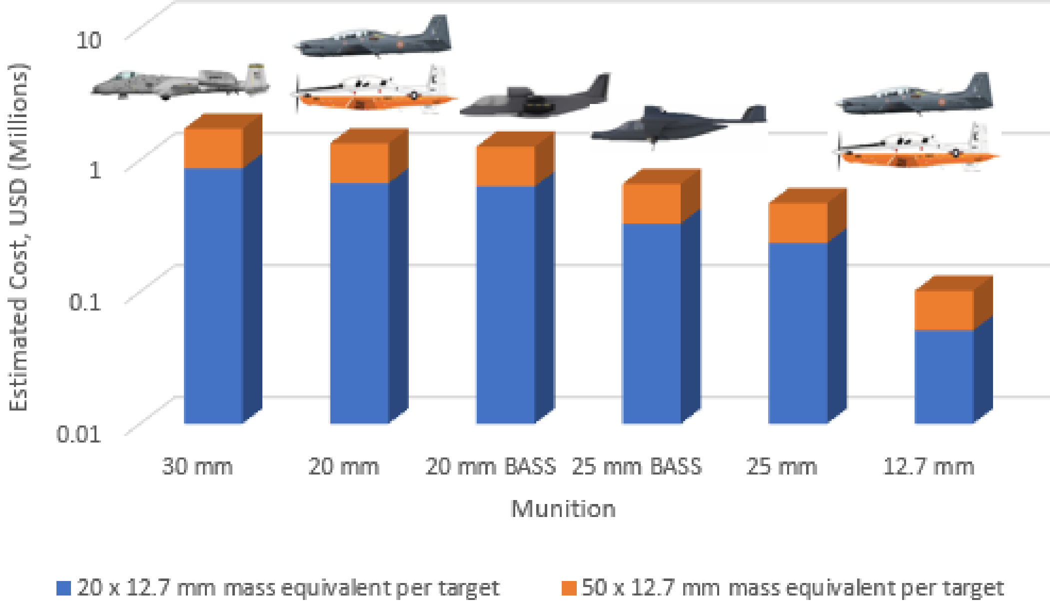


Figure 26: Estimated engagement cost of 1,000 soft targets with various munitions

Figure 26 above would seemingly lend credit to the current light attack philosophy shown in the Embraer A-29 Super Tucano and AT-6 Texan II. The former has two 12.7 mm machine guns in the wings, and both can support gun pods carrying additional 12.7 mm machine guns or larger caliber guns such as a 20 or 25 mm. However, the use of these greatly increases the cost of engagement and gun pods by nature will have a much larger CEP than integrated gun systems. While the 12.7 mm round does clearly have the lowest cost per engagement for soft targets, there are two hidden realities that limit the actual effectiveness of such a weapon.

The first reality is that even the A-29 with its two 12.7 mm guns can only hold a maximum of 250 rounds for each gun. This results in 12 soft targets at 20 rounds/engagement or a mere 5 soft targets at a 50 rounds/engagement estimation before having to either RTB or use much heavier and costly munitions on the pylons such as a Hellfire or Mk. 82 bomb. Aircraft like the A-10 Warthog and the proposed Dragoon and Chimera design are built around the gun and thus can carry a much larger amount of ammunition (1,174, 1900, and 2,500 respectively). In addition, the 20, 25, and 30 mm round mass equivalent to the 20 or 50 12.7 mm rounds results in far less rounds needing to be fired for the same effect.

In addition, to engage a soft target with a 12.7 mm gun the pilot must strafe the enemy position nearly at ground level due to the limited downrange performance shown in Figure 21. This results in putting the relatively fragile airframes of a light attack aircraft into dangerous proximity to enemy combatants where they could suffer catastrophic failure even from small arms fire. The A-10 mitigates this by adding large amounts of armor and redundancy to the aircraft which, although proven effective, is costly and does often require them to operate in packs to protect each other when climbing after engaging a target as discussed in Chapter III. The Dragoon and Chimera designs mitigate this problem through an orbit firing mode that allows the aircraft to remain out of harm's way without the costly armor and redundancy that the A-10 requires.

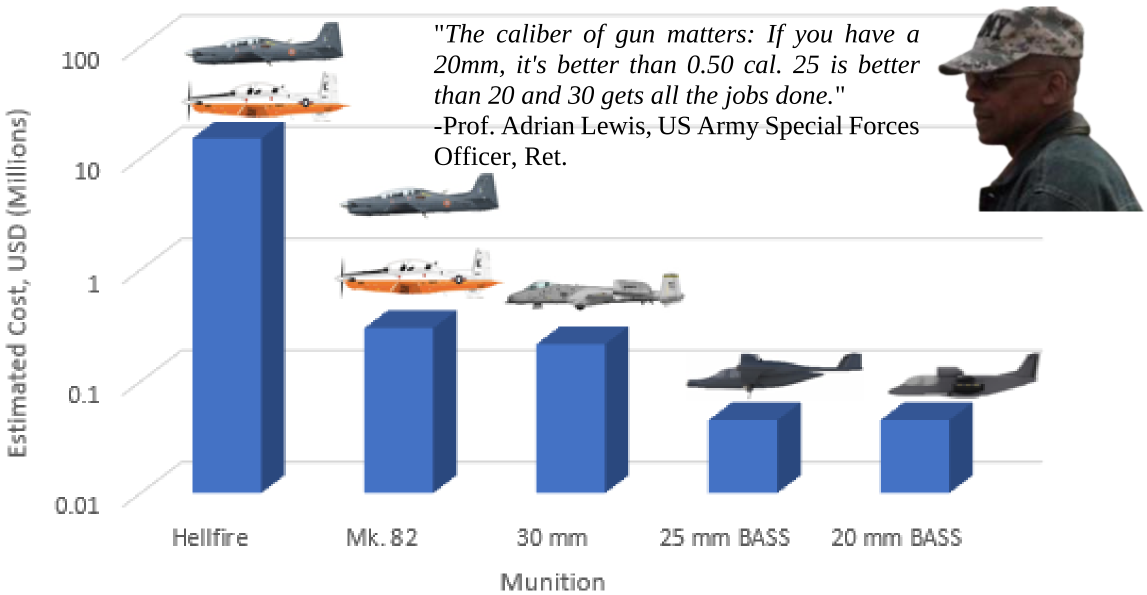


Figure 27: Estimated engagement cost of 100 hard targets with various munitions

Figure 27 paints a much grimmer perspective to the A-29 and AT-6 Texan II which are forced to rely on costly pylon-mounted munitions such as the Hellfire and Mk. 82 to engage hard targets, whereas high caliber and high penetration rounds can destroy the same target at a fraction of the cost. It is this type of analysis that indicates why aircraft like the A-10 have remained in use far past their original estimated service life and are undergoing costly retrofits and re-winging processes to keep them active. However, designs like the Dragoon and Chimera using innovative BASS munitions can perform just as effectively as the A-10 at engagement distances while having a fraction of the cost of both the projectile and the airframe. In addition, light attack aircraft such as the A-29 and AT-6 once again suffer from a lack of ordnance as they have limited hardpoints and useful load in turn limiting their hard target engagements to single digit numbers before having to RTB.

G. Advanced Capabilities: Global Remote Deployment, Remote Operation

Both the Dragoon and Chimera were designed to be global deployment capable. In the Chimera platform, the maximum ferry range of the aircraft was designed to be over 2,500nmi. This range allows the platform to direct deploy across the Atlantic Ocean and from there to any theater it is needed [22].

In the Dragoon design, a unique munitions pod was designed to carry all missile and gravity weapons internally. This reduces drag on the airframe and gives the aircraft extended range compared to those with external stores. Additionally, the removable design of the pod facilitates faster ground turns when reloading. When deploying the aircraft, the weapons pod can be replaced with an extended range fuel tank giving the Dragoon platform a direct deployment range of over 8,000nmi [8].

Both platforms have provisions for remote crew capabilities in the future, specifically for long haul deployments. When configured in this manner, both aircraft gain approximately 1,000nmi additional range [8].

VI. Conclusions

The use of Advanced Discarding Sabot Aerial Gunnery has the potential to reshape the future of air to ground combat. This report introduces the effectiveness of these rounds and illustrates two potential deployment platforms. With today's current military push to limit accidental injury and damage to non-combatants and friendly forces, the use of aerial gunnery is likely to once again become a major method of target engagement due to high accuracy of damage deliverance when compared to explosive engagements. Reducing the cost of target engagement is also a major consideration for military leadership, and the cost savings of employing highly effective cannon shells over missiles or gravity weapons strengthens the argument in favor of advancements such as the BASS family.

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