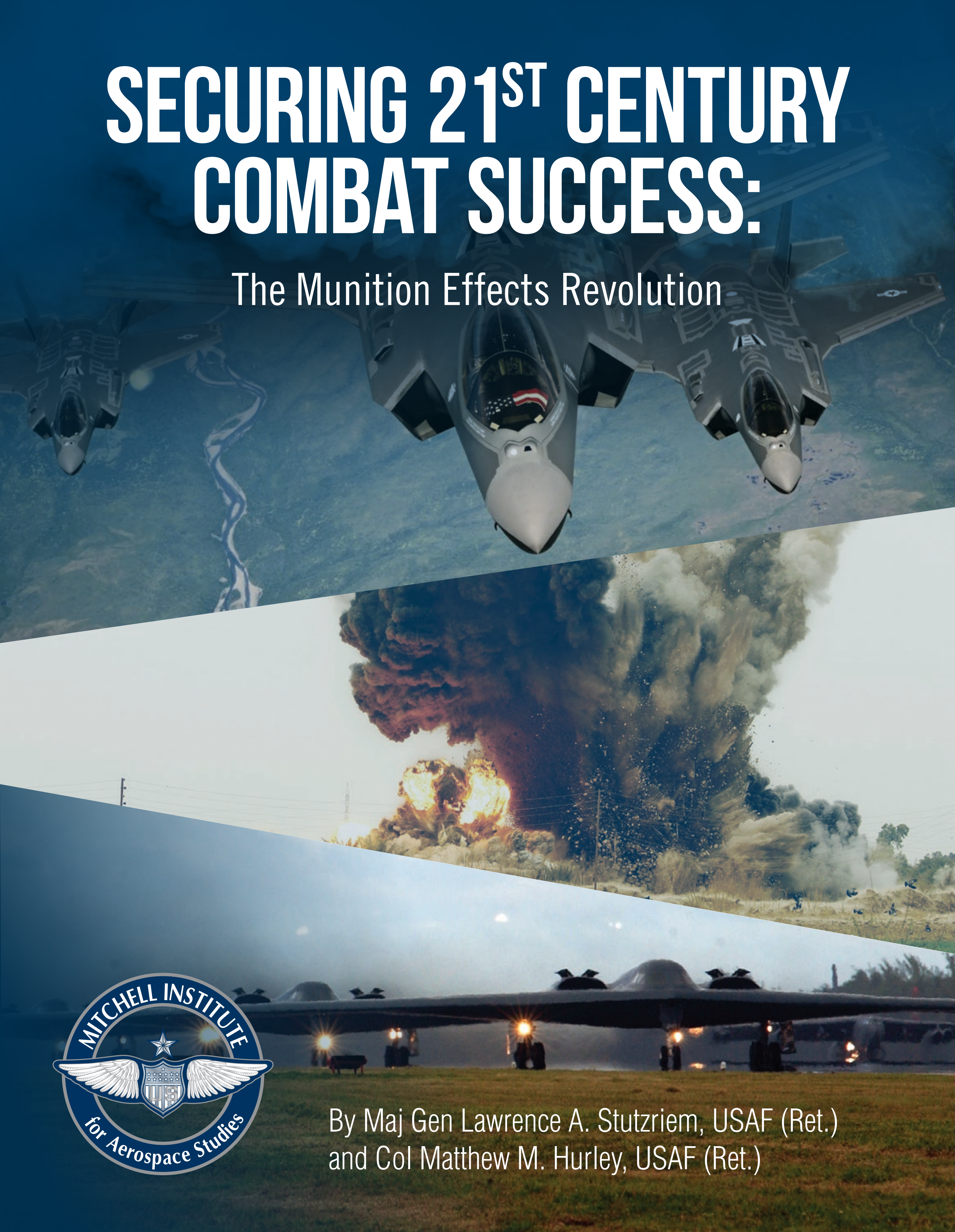

SECURING 21ST CENTURY COMBAT SUCCESS:

The Munition Effects Revolution

MITCHELL INSTITUTE for Aerospace Studies

By Maj Gen Lawrence A. Stutzriem, USAF (Ret.)
and Col Matthew M. Hurley, USAF (Ret.)

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The Mitchell Institute for Aerospace Studies

Air Force Association

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Col Matthew M. Hurley, USAF (Ret.), PhD, is a senior non-resident fellow with the Mitchell Institute. A career intelligence officer, Hurley completed a wide variety of assignments during his Active Duty service, to include tours with Air Mobility Command, Pacific Air Forces, US Air Forces in Europe, NATO, the Air Force District of Washington, US Forces Korea, Air University, and the Air Staff. Hurley has also deployed for duty on assignments in Southwest Asia, the former Yugoslavia, and the Horn of Africa. During his final assignments, he served at the Pentagon as the lead capabilities-based planner for Air Force Intelligence, Surveillance, and Reconnaissance (ISR), and also served as chief of Air Force ISR doctrine and policy. Hurley is a distinguished graduate of the Air Command and Staff College, Air Force intelligence officer training, and the US Air Force Academy Class of 1990. He has published and presented numerous articles and monographs regarding airpower history, operational design, and ISR. He resides in Hilliard, Ohio.

Front and back cover designs by Kristina Parrill; photos: US Air Force

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Foreword

Starting on January 17, 1991, the first night of Operation Desert Storm, American Airmen showed the world they had revolutionized what it meant to project military power through the large-scale use of precision strike weapons. Television audiences around the world saw video feed of guided munitions precisely strike carefully selected aim points to achieve desired effects and outcomes. The campaign's operations stood in stark contrast to the broad level of destruction that imprecise aerial bombardment incurred in past wars. From Desert Storm onward, one bomb for one target was the new concept that fundamentally shaped combat strategy in every subsequent conflict.

Nearly 30 years later, combat aviation is on the verge of a new kinetic strike revolution. With pin-point accuracy now an assured strike capability, the reality of modern aerial warfare yields expectations of even more versatile options for force employment. These options center around shaping the scale, scope, and vector of weapons to deliver highly customized kinetic results. In areas where collateral damage is a major concern, this might involve a very limited blast in a specific direction. If a target is hardened, then the destructive power of the weapon could be focused to negate that defense. In short, this revolution allows aircrews the opportunity to customize the kinetic effect of weapons to best attain the desired result—in real time.

Simultaneously, new technology is also allowing aircraft to carry more munitions that expand their capability. This is especially important given the need to make the most of every combat aircraft in an era where most combat aircraft are now "high demand, low density" assets. New technology also allows long-dwell aircraft like the MQ-9 Reaper or a B-52 Stratofortress to achieve a larger number of combat effects on a given sortie.

These aerial munitions advancements represent crucial advantages that amplify US aerospace power, capability, and capacity. This comprehensive study by Mitchell's Director of Research, Maj Gen Lawrence Stutzriem, USAF (Ret.), and Senior Fellow Col Matthew Hurley, USAF (Ret.), details the critical gains possible in the realm of aerial munitions, their effects potential, as well as recommended policy actions needed to meet the security challenges of the future.

Lt Gen David Deptula, USAF, (Ret.)
Dean, The Mitchell Institute for Aerospace Studies
September 2, 2018

Executive Summary

America's airpower arsenal is long overdue for a revolution in munition effects. The bomb body, a steel shell filled with explosive material, is relatively unchanged across the past 100 years. But some elements of modern munitions have significantly evolved—particularly guidance elements. Munition effects—the destructive envelope of heat, blast, and fragmentation—remain essentially unchanged.

While the revolution in precision guidance technology has enabled one modern B-2 to achieve what it took a raid of 1,000 B-17 Flying Fortress bombers to do in World War II, the fact remains that same "boom" from World War II-era bombs is simply more precise with today's weapons. Real-world requirements now demand a broader range of options regarding a munition's kinetic effect—the attributes of an explosion.

First, the recent wars in Iraq, Afghanistan, Syria, and beyond have repeatedly highlighted the need to limit collateral damage when attacking targets near innocent bystanders or in urban areas. Second, with near peer military power competition on the rise, warfighters also need the ability to bring extra kinetic power against aim points that may be extremely hard to destroy. Third, given the rise of real-time targeting, air crews generally do not know the kind of targets they will attack on a given mission when bombs are loaded on the ground. They require the ability to flexibly modify a munition's explosive effect in flight as given mission parameters may require. Otherwise, they may not be able to engage, which may result in the vanishing of a fleeting opportunity. This latter point is exceedingly important, for air component commanders cite that many target opportunities go untouched for want of a suitable munition at a given time and place. Aircraft loadout is fixed upon takeoff hours earlier based upon best available assumptions.

> New munition effects design can mitigate the reduced size and capabilities of the US Air Force by increasing flexibility and loadout with smaller munitions replicating the effects of today's larger ones.

To address these challenges and others, the Air Force Research Laboratory (AFRL) has translated warfighting priorities of the US combatant commands (COCOMs) into focus areas. This effort yielded the carbon-fiber BLU-129 munition—a pathfinder program aiming to meet greater warfighting needs through new effects design concepts such as variable yield, adapted effects, adjustable effects, and system of employment.

A key driver behind the need for enhanced munitions options is that combat aircraft are increasingly high demand, low density assets. The Air Force is currently operating the smallest and oldest aircraft force in its history. Additionally, current mission capable rates are low and pilots are in increasingly short supply. To best meet COCOM requirements amidst these constraints, it is crucial to ensure each sortie flown and every bomb dropped yields maximum potential. The margins simply do not exist to repeat missions that could have been successfully executed the first time had a broader range of kinetic options been available. New munition effects design can mitigate the reduced size and capabilities of the US

Air Force by increasing flexibility and loadout with smaller munitions replicating the effects of today's larger ones.

To fully realize the potential of the munitions effects revolution, investment will be required in key areas. These include advanced energetics, additive manufacturing (AM), and advanced developmental test and evaluation (DT&E) technology. Additive manufacturing is particularly important as an enabler of effects designs which were previously impossible to manufacture. The area of AM also promises to accelerate development and test cycles.

This study applauds recent efforts by Air Combat Command (ACC) and AFRL to engage with the defense industry to ensure munitions research and development (R&D) is aligned with warfighter requirements. Advancements will only occur if all stakeholders are working together. Prioritization and coordination must also occur on the Air Staff, which is why groups like the Air Force Warfighting Integration Capability (AFWIC) must ensure the potential of advanced munitions development is incorporated into the broader vision for aerospace power.

With all of this in mind, and after concluding the extensive research for this study, the Mitchell Institute submits the following recommendations for policymakers to consider to advance the near-term development of enhanced munition effects:

1. **Prioritize incentives and resourcing necessary to capitalize upon additive manufacturing.** New munition effects designs require AM. A further maturing of AM applications in munition effects design must be stimulated by targeted funding, incentives in acquisition, and import of AM innovation beyond the defense industry.

2. **Improve munitions developmental test and evaluation infrastructure**. The Air Force must craft a state-of-the-art template for weapons DT&E infrastructure. Congress must add the funds for this key enabler to operationalize advanced munition effects designs.

3. **Educate the COCOMs on the value of new munition effects designs.** Air component commanders must work with the Air Staff and AFRL to educate combatant commands on the value of new munition effects designs, how they can close capability gaps, and how they can be employed most effectively.

4. **Examine the potential for new munitions effects design to bolster overarching combat capacity—the "effects crisis."** New munition effects design can mitigate the effects shortage caused by force reductions, years of budget sequestration, and cuts to fifth generation aircraft buys without regard to their smaller payload capacity.

5. **Congress must prioritize both future capabilities and present wartime munitions requirements**. Ensuring an ample munitions stockpile and developing future munition effects capabilities demands a deeper level of investment from Congress. Current resources are stretched too thin under existing budget authorities.

6. **Ensure complementary, collaborative design between aircraft and munitions effects in the requirements, acquisition, sustainment, and budgeting processes**. AFWIC force-development guidance and acquisition policy must ensure aircraft and munitions effects are integrated programmatically, not through separate or sequential efforts. Weapons, the aircraft from which they are delivered, and the associated support infrastructure must be designed in a deliberate, collaborative fashion to ensure elements are working together for maximum desired effect.

7. **Ensure new munition effects designs are aligned to maximize opportunities afforded by new warfighting concepts such as the combat cloud.** As information's role in warfare continues to grow, it is crucial to ensure that munitions are designed to take advantage of improved battlespace knowledge while also contributing their own sensor data back into the combat cloud network.

8. **Promote "cost per effect" evaluation metrics versus "cost per bomb."** Few missions are executed by any single piece of hardware. The effectiveness and efficiency of mission effects packages can vary widely based upon various factors. AFWIC, ACC, and AFRL should assess "cost per effect"—an enterprise assessment of the true expense involved with undertaking a task for guiding munition development. If an investment will yield broad mission enhancements over another, it should be prioritized.

9. **Engineer a safe, secure, and transparent exchange of ideas involving munition effects designs between defense, industry, and academia.** Necessary gains will only occur if all involved actors are cooperating and collaborating in a positive fashion. Mission effect, not bureaucratic hurdles, must stand as the top priority in decision making as teams are assembled and programs are executed.

10. **Prepare Airmen now for new munitions effects designs.** To fully exploit new munition-effects designs, ACC must act now to adapt aircrew, weaponeer, and planning resources and training. Crews will only maximize their tools if they fully understand their potential. This will impact tactics, training, procedures, and force employment.

Introduction

Advancements in aerial bombing since its operational introduction during the early days of World War I are nothing short of remarkable. The ability to routinely hit a precise set of coordinates anywhere around the world has revolutionized what it means to project combat power. In many ways, it represents the lynchpin of America's military might. However, modern combat requirements demand much more from air-delivered munitions.

While commanders can deliver a bomb to a specific aim point with utmost surety, modern combat demands even more nuanced kinetic effects. New requirements to project power in increasingly complex, dynamic circumstances against a broad range of targets means US Air Force and US military leaders need the ability to shape the explosive power of a bomb in highly nuanced, scalable ways. Desired effects could range from dialing blast power up or down, to shaping the direction and scope of a munition's explosion.

In many ways, this is an entirely new way to think about the next generation of weapons precision—precision effects—which extends far past precise coordinates, and instead focuses on the ability to manipulate kinetic effects. In an era where a single aircraft may be asked to strike a target where the avoidance of collateral damage is crucial, and then be sent to attack a hardened, deeply buried target on the same mission, a broad range of kinetic options are important. In fact, the desired outcome might not even be clear until a given target reveals itself. On top of this, US and allied operators often do not know the proximity of friendly forces and non-combatants until they have identified their aim point and its surroundings.

Investment in munition bomb bodies, key components that govern the nature of an actual explosion, has yielded limited incremental improvements in concept, design, and manufacturing. However, the essential kinetic force—the "boom"—is relatively unchanged.

Investment in munition bomb bodies, key components that govern the nature of an actual explosion, has yielded limited incremental improvements in concept, design, and manufacturing. However, the essential kinetic force—the "boom"—is relatively unchanged. Given a rise in real-world demand for more varied explosive effects, it is time for the Air Force to consider new technologies that can afford enhanced options.

Given the range and payload of modern aircraft, the force multiplication associated with such investment is tremendous. Today, a single B-2 Spirit bomber can precisely strike more than 80 independent targets.[1]

But imagine what could be achieved if each one of its 80-bomb loadout afforded a range of effects. The types of mission options available at the strategic, operational, and tactical level would expand dramatically. Airstrike options would no longer resemble taking a carpenter's hammer to a fight, but rather a range of effects could be called on—from a scalpel to a sledgehammer. Opportunities would also expand when considering other mission attributes, like long duration remotely piloted aircraft (RPA) missions. An MQ-9 might be on station upwards of a dozen hours. The potential range of missions it may encounter during that period could be significant. A more varied munitions toolkit equates to enhanced mission effects, a tighter kill chain, and more efficient power projection. Fighter-type aircraft, with smaller payloads, would also benefit, for they could expand the types of effects available on a limited number of weapon pylons.

It is important to understand the need for a broader set of kinetic options is not a fleeting requirement, but reflects an increasingly complex security environment in which low end operations will continue to persist, high end operations are becoming more dangerous, and the zone in between is melding into a complex hybrid of threat levels to US military forces. When it comes to conflicts against terrorist groups and non-state actors, commanders continue to struggle with political concerns to avoid collateral damage (CD) in operations. This has been an enduring constant when it comes to the counterinsurgency conflicts waged since the September 2001 terror attacks on the United States. Actions against the Islamic State (IS) typify these concerns, with American combat aircraft striking IS forces in the dense urban terrain of the Iraqi city of Mosul and the Syrian city of Raqqa. Enemy forces understood the self-imposed US force restrictions, and sought to take advantage of them. "[IS] has become so desperate that they have baited us to strike targets that will purposefully cause civilian casualties," said Air Force Lt Gen Jeffrey L. Harrigian, commander of ongoing air operations over Iraq and Syria, in May 2017.[2] "Bottom line, whether it's a deliberate or dynamic strike, the coalition strives to mitigate impacts to civilians throughout the targeting process, from identification, to validation, to the moment we release the weapon," he explained. More capable, advanced munitions would yield greater options to air commanders in such a scenario.

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On the other hand, the potential for highly kinetic and robust state-on-state conflict is becoming greater as security challenges grow in regard to dealing with nations such as Iran and North Korea, as well as Russia's meddling in Ukraine, and China's South China Sea military expansion. The Russians and Chinese, in particular, have observed American warfighting strategies over the last several decades and have sought to make their valued military facilities especially difficult to destroy. US commanders involved in future scenarios with these two potential adversaries may find themselves requiring exceedingly powerful munitions to eliminate these types of targets.

Further complicating matters is the now-popularized notion of "hybrid warfare," which offers no clear distinction between high-end battle and irregular warfare. Rather, as British-American strategic thinker Colin S. Gray has asserted, the United States and its allies likely will see a further blurring of warfare categories in the future.[3] Consequently, air operations must offer a more diverse range of weapon effects with greater real-time flexibility to succeed against adaptive adversaries operating in an increasingly complex conflict zone.

On top of these drivers, information's ascent in warfare is a further motivator driving the advanced munitions requirement. Through a concept known as the "combat cloud," the ability to gather information, process it rapidly, and disseminate it to relevant actors stands to radically enhance force employment options—honing the ability to place the right military capability at the proper place and time to maximize the likelihood of attaining a desired outcome.[4] This is a concept of an intelligence, surveillance, reconnaissance-strike-maneuver-sustainment complex that envisions a unified sensor-shooter grid linking all weapons-capable platforms in the air, at sea, on land, in space, and in cyberspace. Strike operations conducted in this combat cloud paradigm would experience time-compressed kill chains involving dynamic, rapid strikes with limited preplanning. To optimize the future potential of compressed kill chains against fleeting target opportunities, modern munitions must provide much greater flexibility than those currently in the US inventory. This requires what an observer might construe to be multi-function munitions. In actuality, it implies the creation of munitions where effects can vary according to the need.

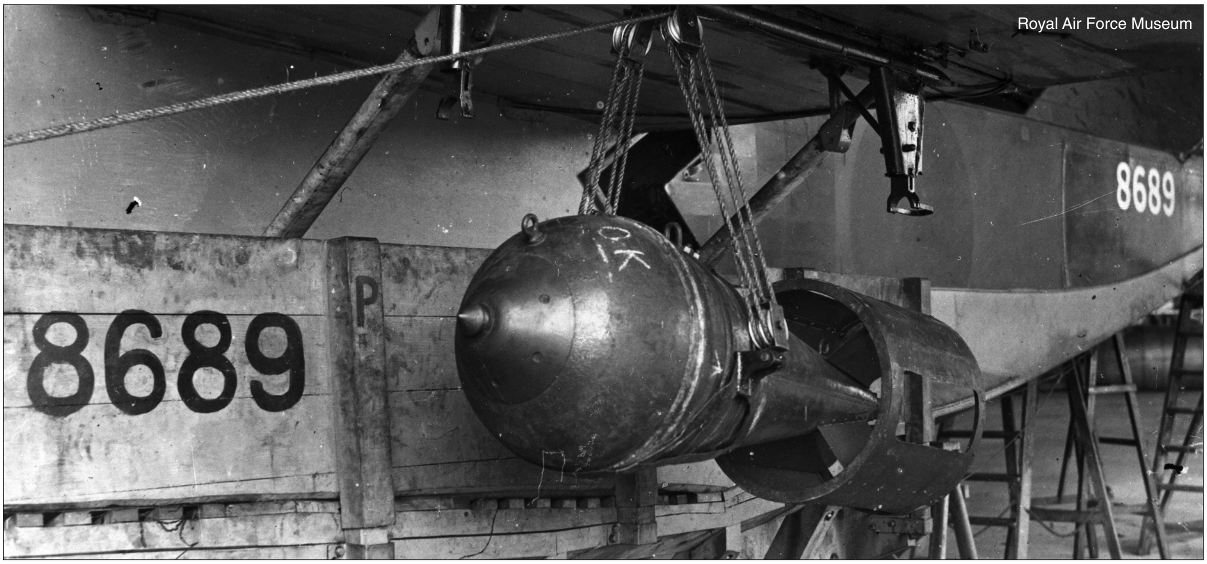
Finally, and less positive from a combat operations perspective, long-term underfunding of aircraft acquisition, modernization, and readiness is also driving the need for enhanced munition effects. The US Air Force aircraft force structure is the oldest and smallest it has been since the service's creation in 1947. This has created a capacity crisis simply described as an "effects shortage." With security challenges on the rise, and a small number of combat aircraft facing multiple, concurrent demands, every bomb dropped must maximize a desired effect.

To optimize the future potential of compressed kill chains against fleeting target opportunities, modern munitions must provide much greater flexibility than those currently in the US inventory.

Innovative munition design concepts have the potential to shape how the US will project power in the future, providing a crucial solution for multiple drivers: the scale and scope of future conflict; the effectiveness of the combat cloud concept; and the challenges precipitated by a high demand, low density combat aircraft inventory. A fundamental change in the conceptual approach to weapons development could lead to wide-reaching benefits, and is the down payment required to yield far more effective, efficient options for future US military operators.

Realizing these gains will require prioritized investment, though. Advances in materials, propulsion, explosives fill (also known as "energetics"), and manufacturing techniques offer pathways to more innovative and more flexible munition effects than were available in the past. While the Air Force is pursuing advances described in this study, increased emphasis, organizational support, and resources are needed to keep pace with the growth in the capability and nature of threats to US national security.

Background



Above: A British 520-pound bomb shown, circa early 1918, being winched onto a Curtiss *Large America* biplane flying boat.

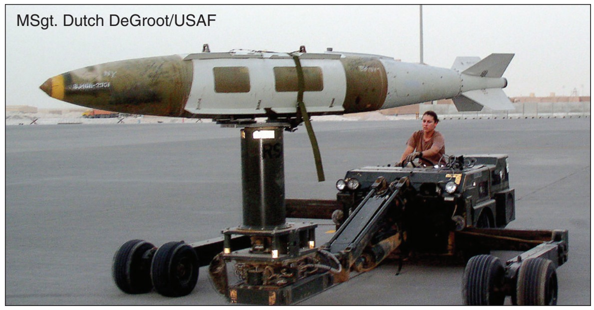
Today, fifth generation aircraft routinely take to the skies carrying third generation munitions. Said another way, the design of the munitions equipped on these aircraft may be far older than the pilots employing them. Given that the ultimate purpose of a warplane is to yield combat effects, investing millions in the most advanced aircraft will only do so much good if the tools they require to secure their objectives are outdated.

For example, the Mk-82 is a 500-pound general-purpose bomb with a TNT-based explosive encased in steel. It is a true workhorse in the aerial munition inventory and is rated for use in some of the Air Force's most advanced aircraft like the F-35 and B-2. Developed in the 1950s, the Air Force has used it in operations extending back to the Vietnam War.[5] Explosive fuel—the energetics—comprises about 50 percent of its weight. Fuses are required to detonate the energetics. Once triggered, the energetics fill detonates to create an envelope of heat, blast pressure, and casing fragmentation. By design, the envelope is not controllable, so in addition to affecting the intended target, the envelope also affects the target's surrounding vicinity. The Air Force has continued to employ the Mk-82 bomb body in present-day operations against IS, although today the weapon is fitted with a guidance package to allow precise placement on a desired impact point. Nonetheless, in the nearly 70 years since its introduction, the Mk-82 bomb body has seen only marginal improvements. Nor is it an outlier. The basic principles behind its construction and use are generally applicable across most of the US military's aerial bomb inventory.

The principles embodied in the Mk-82 date back to the beginning of combat aviation. During World War II, the AN-M64 was a similar mainstay munition that weighed about the same as the Mk-82 and employed a similar fixed-effects explosive envelope of heat, blast pressure, and casing shrapnel. Further back in airpower history, Britain's Royal Laboratory designed and manufactured a 520-pound bomb employed by primitive biplane bombers (see photo above).

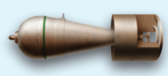
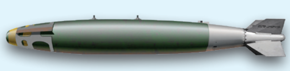
This study is not alone in signaling concern about the age of present-day munition technology. At the Air Force's 42nd Air Armament Symposium in 2016, an Air Force colonel made a poignant observation regarding the static nature of bomb design. He postulated that World War I and World War II flightline maintainers would not recognize many of the parts and pieces that comprise modern fighters and bombers. However, armament crews from those same conflicts would instantly understand the essential components and purposes of current bombs.[6]

Despite advancements in modern combat aircraft, antiquated munition-effects concepts limit mission potential. While the enduring usage of the fixed-effects bomb body is a tribute to the prescience of its design, it is increasingly failing to meet modern operational demands and adapt to constraints. The fixed-effects bomb lacks necessary flexibility and efficiency in the overall kill chain. There is also significant room for improvement when it comes to underlying logistics. The gap is widening between the capabilities of modern aircraft and the munitions they carry.



Above: A weapons loader prepares a GBU-31 Joint Direct Attack Munition for a B-1B sortie at a location in Southwest Asia. A Vietnam War-era Mk 84 bomb fitted with a GPS kit, despite advances in precision and accuracy, the essential components and bomb body of the GBU-31 have only marginally changed in the decades since the "Mark 80" series of general purpose munitions first debuted in combat.

Figure 1. The fixed-effects 500-pound bomb body across 100 years of conflict.

Conflict	500-pound Fixed-Effect Munitions	Fill to Weight	Fusing	Fixed Yield	Fixed Effects	Precision Guidance
1917 WWI		-50%	✔	✔	✔	No
1943 WWII		-50%	✔	✔	✔	No
1965 Vietnam		-50%	✔	✔	✔	No
1990 Desert Storm		-47%	✔	✔	✔	✔
2017 Inherent Resolve		-47%	✔	✔	✔	✔

Graphics: USAF, Lockheed Martin, Zaur Eylanbekov.

The Effects of a Detonated Air-to-Ground Bomb Body

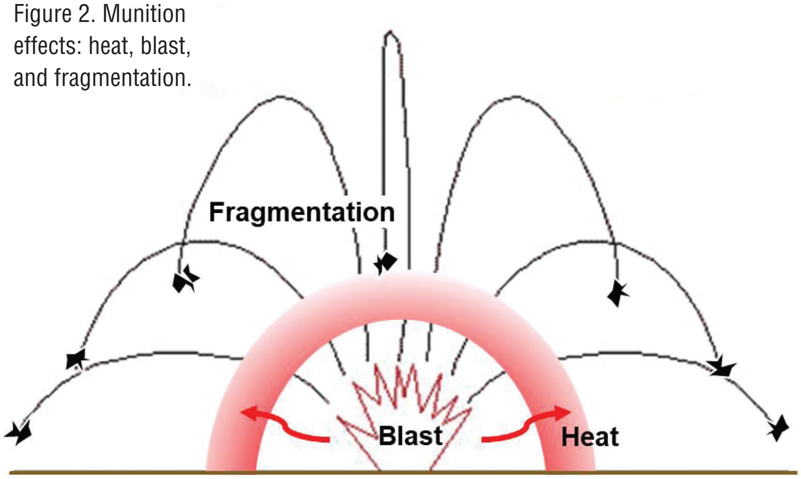
Although air-to-ground bomb bodies have undergone some improvements over the past decades, they are essentially unchanged in the effects they produce upon detonation. In the 13th century, the Chinese packaged gunpowder within shells. As the gunpowder burned, the shell pressurized and eventually burst. Since then, the effects of the "boom" have remained the central feature of munitions development.

Munition effects involve three distinct mechanisms: heat, blast, and fragmentation. Heat is a product of the chemical reaction. Blast is a destructive wave of gases produced in the surrounding atmosphere.[7] That pressure, when integrated over time, is called impulse, and impulse generally causes damage to machinery and especially structures.[8] Fragmentation is the dispersal of solid material, mainly the metal casing of the bomb body and packaging.[9]

While the exactitude of placing effects on a desired point has improved dramatically since the precision-guided munition (PGM) revolution that matured in the 1990s, the ability to tailor and focus those kinetic effects has lagged.

Over the past century, incremental innovations have improved the performance of air-to-ground munitions to some degree. Advances in fuel formulation have increased energy yielded per kilogram of energetics. Pre-fragmentation, the scoring of the bomb's body along its length and width, has enabled the casing to fracture into many smaller fragments and increased the area of lethality eightfold.[10] Bomb design can now also emphasize heat effects or blast effects over fragmentation. Traditionally, the damage imposed by bombs resulted from high-velocity fragments from the shattered bomb casing. Extreme heat and overpressure (blast effects) were only secondary variables—consequences of the explosion. But the effect of heat or overpressure can be useful in specific cases where shrapnel from traditional bombs would incur undesired collateral or other damage.

Figure 2. Munition effects: heat, blast, and fragmentation.



Graphic: Maj Gen Lawrence A. Stutzriem, USAF (Ret.)

While such advancements are important and should not be underappreciated, weaponeers and aircrews who employ today's most technologically advanced aircraft continue to rely on a common approach to pairing sufficient explosive power against a particular target in a linear fashion—such as larger or smaller bombs, or multiple weapons depending on the scale of desired effect.

Beginning in the 1960s, extensive testing and analysis yielded a series of Joint Munition Effectiveness Manuals to assist in calculating the number and type of fixed-effects munitions required to impair or destroy a particular class of target.[11] In an era of dynamic tasking, collateral-damage concerns, and urban warfare, such an approach lacks necessary exactitude. It also illustrates that no matter how "smart" the bomb's delivery mechanisms may be, the end effect comes down to the kinetic attributes of a weapon.

The Enduring Techniques of Shaping Munition Effects

Legacy munition designs, such as the Mk-82, yield a generally fixed envelope of blast, heat, and fragmentation (see Figure 2). However, the fixed effects of a detonation may be altered within limited parameters. One of the simplest means involves fusing. From the first decade of military airpower in the 1910s, innovations with fusing varied with respect to the altitude of detonation, such as exploding at or above the surface. Decades later, radar fuses provided further options regarding detonation altitude to optimize fragmentation and blast effects against specific target categories, such as troops in the open or concealed in foliage. Alternatively, the same bomb body detonated with a timing delay allows penetration into the surface to create greater fragmentation effects involving rock and soil or to disturb underground structures like bridge abutments or bunkers. Modern aircraft design affords aircrews an ability to select fusing options within the cockpit. However, once weapons are uploaded and aircraft are airborne, this fuse flexibility is usually limited and sometimes fixed, since load crews configure them to achieve optimum effects against a pre-planned category of targets. Although extensive research has improved fusing to support new munition design concepts involving selectable effects, the majority of fusing innovations to vary the fixed explosive envelope in use today predate the Vietnam War.

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Other techniques can also shape the effects envelope, including the angle of impact and the direction along which the munition is delivered, also known as the "attack geometry." Despite these methods, however, inherent limitations exist regarding fixed explosive design.

From a broader perspective, the shortfall in mission effects is driven by the changing parameters of modern war. Operations in urban areas, an increasingly common trait of modern conflicts, drives sensitivity to collateral damage, unintended civilian casualties, and heightened awareness regarding cultural sensitivities. The notion of pop-up targets is also a new driver in war, given advances in intelligence, surveillance, and reconnaissance (ISR) and the ability to command real-time targeting.

Aircrews in modern combat operations often must defer eliminating an important target due to concerns about secondary effects of collateral damage. Taking advantage of US and allied forces adherence to the laws of armed conflict, enemies have often tried to protect their forces by placing them in close proximity to facilities known to be off limits to US and allied forces to prevent their attack.

Alternatively, in some circumstances the US military has come up with innovative ways to beat the enemy at this game. In 1999, in northern Iraq, the Iraqi military moved some of its surface to air missile systems (SAMs) next to mosques to avoid being targeted by Operation Northern Watch (ONW) aircraft who were enforcing a no-fly zone—aircraft that Iraqi forces were threatening. In response, the ONW combined joint task force commander, then-Brig Gen David A. Deptula, directed his F-15E crews to load up inert 500lb GBU-12 laser-guided bombs. Upon hearing his direction, the crews were a bit puzzled—it wasn't normal to use a bomb with no explosive. However, Deptula pointed out that 500 pounds of concrete "going 500 miles an hour will ruin your whole day if it hits you." Deptula's point was that precision had rendered the explosive unnecessary if one could achieve a target kill with kinetic energy alone. His scheme worked, and the SAM next to the mosque was put out of commission with no damage to the building.[12]

As the ONW example shows, kinetic options designed to limit collateral damage, while still achieving primary mission goals, can prove exceedingly useful in some circumstances. They also rob the enemy of sanctuary and time since attacks can be prosecuted in a direct, rapid fashion. Adding non-explosive, kinetic power options to the inventory of weapons would be a welcome improvement over current explosive only options where some targets are literally observed for days, weeks, or even months before an opportunity for a suitable strike becomes available, owing to collateral damage concerns. A more rapid strike rate will lead to a greater preponderance of aircraft directed against a larger number of targets. Enemies under greater concurrent stress tend to fail rapidly, thereby helping US and allied forces gain a key advantage.

Although flexibility has long been a fundamental trait of airpower, the virtue remains limited in the airpower logistics enterprise.

Improved, more adaptable munitions are key to a fundamental of modern American warfare: ensuring operators and aircrews have the right tools for the job. Specialized munitions fill gaps where general-purpose weapons fail to provide necessary attributes. Thermobaric weapons maximize pressure and heat effects, for example. Deep penetrators are unique for their ability to withstand the forces of burrowing into the surface against deep and hardened facilities. Irregular warfare operations over the past 17 years have also spurred demand for smaller, more tightly focused effects envelopes. The Air Force's ISR community over this same period has served as a particular champion for smaller detonations, spurring vigorous development of smaller air-to-ground munitions.[13] But, while munitions with smaller explosive force may be more desirable in a permissive counterinsurgency environment involving urban warfare, the effects are still fixed, and cannot be shaped or vectored for a given situation. Once loaded on an aircraft, smaller munitions become extremely limited tools where more kinetic energy is needed to affect a target.

Dealing with the Limitations of Today's Munitions

When the United States kicked off combat operations in Afghanistan in late 2001, the event marked a new era in warfare defined by the real-time fusing of ISR data with the ability to rapidly strike targets—an element of the combat cloud construct. This real-time fusing was initially actualized with the arming of

Above: An MQ-1 Predator, armed with AGM-114 Hellfire missiles, flies a combat sortie over Afghanistan. By merging sensors and munitions on one airframe, the US marked a new era in warfare beginning in late 2001. Targets could be observed and prosecuted rapidly—in many instances, measured by minutes—instead of determined far in advance.

an MQ-1 Predator, an RPA that merged sensors and munitions on one airframe. This development yielded dynamic kill-chain processing, where warfighters could rapidly observe targets and prosecute them in rapid order—in some cases, in just minutes.

This process stood in stark contrast to previous conflicts, where targets were picked well in advance, and aircrews flew pre-planned missions with a separation between the intelligence-gathering on a target of interest and strike of the same target that would often be weeks or days, and at best multiple hours. Not only was new technology affording an improved approach to strikes, but mission requirements were demanding it. Defeating Taliban and al Qaeda forces in Afghanistan required taking advantage of fleeting opportunities. These adversaries, at the time, did not rely upon large, fixed industrial centers of gravity—Operation Enduring Freedom (OEF) was a combat operation in which enemy fighters embodied the core driver of the hostile force. Responding to this reality, the daily air tasking order (ATO) reflected more flexibility to support sharply tightened decision cycles to capitalize on emerging and fleeting target opportunities.[14] The lessons from the early months of OEF are still applicable to current operations today and are expected to be no less relevant in future wars, especially with the development of the sensor-shooter-effector collaboration afforded by the combat cloud.

In the current flexible environment of emerging opportunities empowered by ISR and dynamic command and control capabilities, the munitions available for striking targets are essentially those that were loaded before an aircraft's launch. Often, planners have determined those munitions to be optimum a day or more prior. They may also be what is available given current supplies.

Although flexibility has long been a fundamental trait of airpower, the virtue remains limited in the airpower logistics enterprise. In an environment demanding more flexibility for on-call target attacks, planners are compelled to use a "best estimate" for scheduling the availability of aircraft and munitions in order to position sufficient capability. Importantly, planners configure aircraft on the ground with a selection, or mix, of munitions. Maj Gen Duane A. Jones, USAF (Ret.), best summarized the reality of weapons logistics: "Today's successful logistician lives in the operator's world and is a student of both yesterday's requirement and tomorrow's need," said Jones, who served as director of logistics for US Central Command's air component command from June 2000 to August 2003 and was one of the Air Force's most combat-experienced logisticians during his time in uniform.[15] "That perspective enables the preemptory ordering and positioning of required munitions sometimes even before the requirement is stated," he said. Consequently, new munition designs with a range of options selectable in the cockpit would improve the availability of a bomb to be in a position to strike a target of opportunity with the desired yield or shape of the blast. It would transform the notion of a bomb from a binary asset—one that is dropped and yields a given effect, or not released and no effect is achieved—to something far more dynamic and customizable to a given set of circumstances.

When OEF kicked off in Afghanistan in 2001, the operation also marked the beginning of austere constraints the US National Command Authority imposed through US Central Command (CENTCOM) on airpower operations to limit collateral damage. As the mode of air operations shifted from pre-planned objectives to an arena of emerging targets, the command established strict protocols to assess the potential for collateral damage for each impact point. This included a five-level assessment process to determine collateral damage potential, assess whether damage might exceed thresholds, and consequently grant or withhold strike approval.[16] "We simply missed many opportunities because we could not meet the collateral damage constraints with the munitions available," said Maj Gen James O. Poss, USAF (Ret.), who served as director of intelligence for the air forces of the US-led coalition during OEF's opening phases. "Even the smallest bomb at 500 pounds was often too big," he said. Describing the methodology to gain strike approval—still in use after a generation of combat operations in the Middle East and Southwest Asia—Poss said "level three" was the most common method of collateral damage assessment, or "weaponeering estimate," that allowed mitigation of bomb effects to acceptable levels. "Under level three of the five-level target approval process, we could conduct basic modelling to determine how the envelope of the detonation would affect the target environment," he explained. Planners informally named the process "bug-splat analysis," as the pattern of effects from a general-purpose bomb body roughly resembles the shape of a butterfly smashed onto one's windscreen. "We then produced a graphic showing the blast and [fragmentation] pattern within the target environment to determine how the detonation would affect structures or bystanders in the vicinity. As a result of that analysis we were then allowed to mitigate collateral damage to acceptable criteria," he said.

...new munition designs with a range of options selectable in the cockpit would improve the availability of a bomb to be in a position to strike a target of opportunity with the desired yield or shape of the blast.

Poss explained there was limited flexibility in mitigating the potential unintended effects of even smaller munitions. "If the CDE [collateral damage estimate] was too high, we could try to adjust the attack heading or vary bomb fuse settings, but in way too many cases, we just couldn't do it," he said. Many times, such impromptu efforts to adjust weapons effects resulted in cases where assessments straddled the margins of acceptability. “We went through a second set of opinions at CENTCOM and they [command officials] often disapproved these types of targets and consequently we never struck the targets,” he noted. Adding to the complexity of modern airpower operations, level four of the assessment process required extensive modelling that, by definition, becomes irrelevant to the critical time demands of a dynamic targeting process.

Two factors reduced the chances of striking a valid target, said Poss. The first was the time it took for approval. Often, a fleeting target was not even worth the effort, due to knowing approval for the strike would not come before the collateral damage analysis was in hand. Other targets were lost due to target movement, or in the more common case, the target itself was lost. “Collateral damage estimates are perishable, and so are time-sensitive targets,” said Poss. The second factor involved the availability of suitable munitions.[17] Although there was a continuous distribution of US and coalition aircraft across an expansive area of operations in Afghanistan, most suitable munitions loads were not always available for the dynamic targeting environment. In the case where approval for a strike might limit options to a 500-pound-class bomb, there might be only 2,000-pound Joint Direct Attack Munitions available. The reverse was also true.[18] Munitions options did not support the required flexibility in the emerging mode of ISR-driven operations, said Poss. Coalition aircraft never struck between 70 percent and 80 percent of targets due to the disconnect between munitions suitability and availability as well as the nature of the target environment, estimated Poss, who now runs an ISR and RPA consulting firm and remains close to the ISR-driven revolution he helped pioneer.[19]

In Operation Inherent Resolve (OIR), the air campaign against the Islamic State in Iraq and Syria launched during the Obama Administration, concern for collateral damage became even more predominant and constraining.

ISR-driven operations have substantially matured since OEF’s early days, underpinning the design of more recent US military actions across the Middle East, Southwest Asia, and Northern Africa. In Operation Inherent Resolve (OIR), the air campaign against the Islamic State in Iraq and Syria launched during the Obama Administration, concern for collateral damage became even more predominant and constraining. “We will do everything we possibly can to keep those civilian casualties to a minimum,” said Maj Gen Peter E. Gersten in April of 2016.[20] Then overseeing coalition air operations in OIR, Gersten now commands the Air Force Air Warfare Center at Nellis AFB, NV. During the height of OIR strikes, coalition airplanes could not bomb many targets due to collateral damage concerns, including trucks transporting oil whose sale generated revenue for the IS, he later recalled.[21] The concern for even one truck driver’s death exceeded the collateral damage allowances under the then-rules of engagement (ROE). This excessive concern with collateral damage had the effect of leaving millions of Iraqis and Syrians exposed to the deprivations of IS for years. As a result, the OIR campaign to overthrow the IS moved at a snail’s pace, and the approach allowed the IS to fund their string of terror attacks and atrocities against innocent civilians by adding hundreds of millions of dollars to their operations. As succinctly put by Deptula, writing in a *Washington Post* opinion article, while unintended casualties of war are regrettable, “those associated with airstrikes pale in comparison with the savage acts being carried out by the Islamic State. What is the logic of a policy that restricts the use of air power to avoid the possibility of collateral damage while allowing the certainty of the Islamic State's crimes against humanity?"[22] Limited, gradual power projection is a recipe for grinding war. Quick victory, which minimizes suffering for innocent civilians, requires decisive power projection. This in turn requires a broader range of strike options.

SSgt Trevor T. McBride/USAF

An Air Force F-15E Strike Eagle fires flares during a June 2017 sortie supporting Operation Inherent Resolve. Between May 2015 and May 2016, US and coalition aircraft did not strike as many as 70 percent of some target opportunities in the campaign, according to OIR officials, due to a lack of suitable weapons or inability to mitigate their effects.

Operating under tight collateral damage constraints necessitated a great deal of tactical innovation, said Gersten, who coincidently worked with Poss in the combined air and space operations center during OEF. "Often, the smallest bomb could not meet weaponeering requirements," noted Gersten. "Had munitions existed with the ability to incapacitate only the vehicle and not the passengers, of course such an option would have accelerated progress. But, we also need to be ready for more hardened targets where potential for collateral damage is low," he said. During his tour in the combat zone, Gersten estimated that the coalition did not strike 60 percent to 70 percent of target opportunities due to a lack of suitable weapons, or the inability to mitigate their effects. "Yes, the suitability of munitions for a target, or having the right munitions in the right place, can lag behind the ability of ISR to identify targets," he said. Presented with the potential of a new regime of munitions more widely adaptable on the fly in terms of shape and size of their effects, Gersten said, "Of course. Whatever allows better exploitation of the capabilities and amazing flexibility of aircrews and their fourth and fifth generation aircraft will create a big step up in effectiveness."

In the fight against IS, the Air Force and its coalition partners have employed relatively inflexible munitions in an unprecedentedly complex operational environment. To allow a surge in close air support within urban areas, operators are configuring aircraft with "low-collateral" munitions loads. These include a version of the venerable Mk-82 bomb body only half filled with tritonal explosive (a mixture of TNT and aluminum powder) to allow a smaller, more suitable effects envelope. Additionally, workhorse aircraft like the F-15E Strike Eagle carry a mixed load of several or more distinctive munition types to ensure flexibility in flight so they meet tactical targeting needs on the ground. Aircrew familiar with current operations noted that, for most part, these mixed, low-collateral-damage munitions loads allow more aggressive prosecution of targets in areas of high CD concern.

However, when significant targets emerge in more-fortified positions, such weapons loads do not give aircrews adequate firepower to respond effectively.[23] While Airmen deserve tremendous credit for doing the most with their limited resources, the bottom line is that they deserve a more robust toolkit of options, not adaptations of munitions whose core design predates the advent of the Vietnam War.

This is not to say there have not been innovations in munitions in recent years that have adapted to the post-September 2001 operational environment. Since the start of OEF in 2001, munitions development has emphasized smaller explosive bombs, rockets, and rounds. For example, the Small Diameter Bomb (SDB) is half the size of the Mk-82 bomb body. The advantage is that through precision delivery technology, a well-placed smaller yield is roughly equivalent to a less precisely placed munition of higher yield. It also helps boost load-out on a given aircraft due to their respective size and weight. SDBs are also extremely useful due to their ability to glide long distances, thanks to integrated wings allowing aircraft to launch them outside threat rings in well-defended areas. While the smaller explosive yield is often more suitable in terms of minimizing collateral damage, this bomb also has its share of limitations. Gersten noted many cases where operators deemed even the SDB unsuitable given high potential for collateral damage.[24] In short, a smaller fixed-effects explosion often presents the same suitability problems as heavier munitions in many combat scenarios.

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Aircrew closest to a given conflict have perhaps the most salient perspectives about the suitability and availability of munitions in order to achieve the most favorable effects against a specific target. "We make it happen for the most part, but in other scenarios, the current approach might not be optimum," said one Airman familiar with ongoing OIR air operations over Iraq and Syria.[25] Given a hypothetical scenario where the balance between urban targets and interdiction targets varies widely, participating aircrew said the flexibility of their aircraft is affected by the limited flexibility of their munitions. They indicated they would need either to sub-optimize munitions loads by having a mix of effects, or to split up the aircraft to have specialized munition loads. "The ideal is to have munitions that can flex to both situations like 'dial-a-yield' or 'select-an-effect' where we can vary," said one of them. In this situation, aircrew could "dial down" the bomb body in explosive effect from its maximum designed potential.

The current paradigm for munitions design and acquisition is limiting opportunities to create combat effects, despite revolutionary advances in ISR, dynamic targeting, sensor-strike-enabled RPA, and a progressively more-integrated air control system. Within a combat environment increasingly characterized by a mix of low-CD operations and high-end strike needs, current munitions innovation efforts generally focus on modifying existing weapons and operating procedures, to include increased use of mixed loads to permit a more flexible range of options in the air. However, developmental pathways are currently focused on creating smaller explosions, while compromising maximum blast effect. From the edge of employment, experts agreed there is a need for a new regime of weapons effects that allows greater flexibility in all warfighting environments. It does no good to locate a target, fight into the zone of employment, and then wave off because a munition is not appropriate for the target.

Critically Separating Munition Effects from Precision Delivery

To understand the requirement for a new effects regime in air-to-ground munitions, one must strictly separate two concepts: precision employment and munition effects. Precision is a central characteristic of the modern American way of war. It is ubiquitous across the military services and their operating domains. While munition effects have remained relatively unchanged, precision employment of those munitions has greatly enhanced airpower effectiveness. Precision capabilities have leveraged the value of existing bomb bodies so greatly that munition effects innovation has not become a high priority.

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Precision Delivery

While weapons effects are generally similar—a fixed and marginally shaped envelope of heat, blast, and fragmentation—the ability to detonate those munitions at a specific point in space has transformed air campaign strategy and dramatically improved the effectiveness and efficiency of air operations. During World War I, the earliest incarnation of air-to-surface airpower was essentially a game of pitching horseshoes, except the pilot pitching the shoes was moving in three dimensions over the stake.[26] The earliest bombing tactics, lacking now-standard mechanisms such as radar and targeting aids, devolved into a matter of "chuck it and chance it."[27] By World War II, mechanical sighting methods, such as the Norden Bombsight—an advanced technology for its time—improved bombing results, but precision was astoundingly low relative to the performance of today's weapon systems. It was not uncommon during WWII to see some 1,000 B-17 or B-24 heavy bombers called upon to destroy a valuable target.

Munitions delivery techniques underwent considerable improvements throughout the Cold War, such as the introduction of radar-assisted bombing. During the final three years of the Vietnam War, guidance technologies opened a new chapter in precision. Throughout the conflict, unguided bombs hit their targets approximately five percent of the time. With introduction of the first generation of laser-guided bombs, that figure improved by nearly a factor of ten.[28]

Right: A 1972 reconnaissance photo of damage to the Thanh Hoa Bridge in North Vietnam, after a strike from US Air Force Paveway I Laser Guided Bombs. The bridge had been targeted with hundreds of sorties since 1965, none of which were successful prior to the use of LGBs—the introduction of which marked a dramatic improvement in munition accuracy.

A dramatic example of improving air-to-ground precision occurred against the Thanh Hoa Bridge, an important logistics chokepoint for North Vietnamese forces crossing the Red River south of Hanoi. Beginning in 1965, US pilots attempted to cut the bridge, flying hundreds of sorties and losing 11 aircraft in the process.[29] Finally, in spring of 1972, F-4 Phantom fighters carrying Paveway I laser-guided bombs (LGBs) put the bridge out of action, accomplishing with the precision-guided munition what had proved impossible in the hundreds of previous sorties against the target.

During that same period of experimentation and innovation in munitions delivery, advancing aircraft avionics were becoming part of the overall design of aircraft weapon systems. Profound innovations in avionics vastly improved the precision of unguided, gravity munitions that remained relatively unchanged in form and function from World War II. By the mid-1980s, top Air Force leadership clearly recognized the implications. Even as existing research and development (R&D) efforts focused on a new age of "smart weapons," Air Force Gen Robert W. Bazley, then-Pacific Air Forces commander, frequently observed that the Air Force's existing massive stockpiles of "dumb bombs" remained as relevant as ever on the pylons of "smart aircraft."[30] This basket of built-in avionics technologies, such as the continuously computing impact point projected onto a head-up display, rendered virtually every strike aircraft a precision airplane.[31] The United States dramatically demonstrated the revolution in precision delivery, especially improved laser-guidance technology, to allies and adversaries alike during Operation Desert Storm in 1991.

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One drawback to the LGB centered on the need for the aircrew and aircraft to continue illuminating the target with laser energy until weapon impact. This requirement placed the lasing aircraft in a vulnerable position, as the pilot flew a predictable flight path while the weapon remained in flight. Improved point defenses forced a change in overall concepts to delink the delivery aircraft from actively guiding the weapon. In addition, aircrews could not prosecute targets that smoke or clouds obscured using traditional laser-guided munitions.

A new generation of PGMs entered the inventory in the mid-1990s, known as the Joint Direct Attack Munition (JDAM). These bombs strapped GPS satellite-aided guidance kits onto standard "dumb bomb" cases. This allowed an all-weather, day and night "launch-and-leave" capability while attaining levels of precision as good as aircrew could clearly identify and map a geographic position. The JDAM also radically lowered the cost of precision. In terms of the precision and leverage GPS guidance affords, what took an armada of World War II bombers to achieve, such as the famous raid on the Schweinfurt ball bearing factory in Germany, could be accomplished by a single B-2 or two-ship of precision-delivery-capable fighters in a present-day combat operation.[32]

Precision is Assumed—Munition Effects Innovation Lags

Today, in OIR combat sorties, aircrews increasingly view precision and its reliability as a given. In fact, almost all Airmen flying today never flew in an Air Force where precision was not a given. "We don't need to drop more precisely," one Airman noted. "We are dropping closer than ever to friendlies or civilians and I've never had a problem. The issue is whether we have the right bomb hanging [on the aircraft] that we can use to kill the target without hitting civilians, especially in urban areas."[33]

While there is an urgent need to assure US precision capabilities in future combat environments against jamming, deception, and cyber operations, enhancements to capabilities to hit targets more exactly have likely reached a point of diminishing returns.

While there is an urgent need to assure US precision capabilities in future combat environments against jamming, deception, and cyber operations, enhancements to capabilities to hit targets more exactly have likely reached a point of diminishing returns. Traditional munition design and employment concepts are more likely to constrain the potential to increase airpower effects against adversaries in current and future battlespace environments. Consequently, as US defense officials max out the advantages of precision alone, they must begin to seriously address ways to tailor immediate kinetic effects once precision weapons detonate. As precise placement is assumed, Airmen and service members are now entering an area where the term "precision" comes down to the shape and power of the effect. This is the next logical step and it, too, will become ubiquitous over time. US and allied airpower is not about just projecting raw power. Instead, a developmental path is needed to move from precision in the placement of a detonation, to precision in achieving a desired effect—in essence, "precision effects."

Munition-Effects Design Terms of Reference and Key Investment Priorities

Despite its importance, there has been no formal elaboration of many necessary terms of reference regarding the topic of next-generation munitions. Government and industry officials currently use several phrases to describe new munitions concepts, but there are no standardized labels to clearly align distinctions in effects design. Accordingly, to have a common terms-of-reference baseline, here are definitions this study has discerned for the five following categories of design:

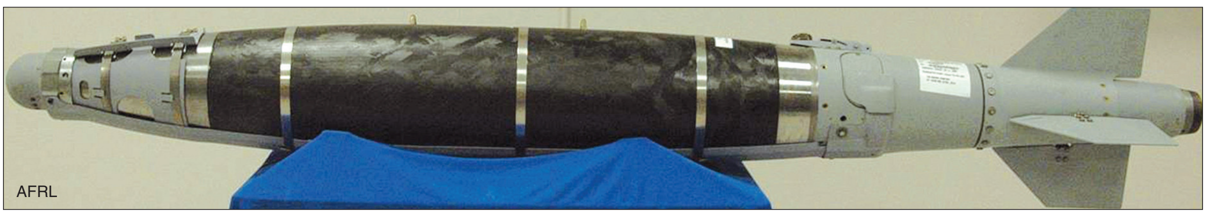
Variable-Yield Effects: This line of development seeks to achieve a tailorable range of explosive force from a single munition. For example, one could preset a 500-pound bomb body to detonate at its maximum explosive force, or alternatively, at a fraction of its full blast potential. Such a capability would offer several benefits. Variable-yield weapons improve operational flexibility across a range of target environments and collateral damage concerns. They are generally more suitable than fixed-effects munitions, where operators often "wave off" high-energy bomb bodies from targets in urban terrain or other areas of high collateral damage potential. The reverse is also true when attacking hardened targets that require more kinetic power. As aircrew participating in OIR have reported, low-CD munitions loads required to prosecute targets in urban areas have proven ineffective against targets requiring more energy to achieve desired effects.[34]

Below: A B-1B flies over northern Iraq after conducting Operation Inherent Resolve strikes in Syria, September 24, 2014. Aircrews flying OIR sorties have reported that low collateral damage (CD) munition loads required for targets in urban areas have proved less effective against targets needing more energy. Variable yield weapons would help improve both operational flexibility and relieve CD concerns.

From an operational-level perspective, the availability of variable-yield munitions throughout the 24-hour cycle of attack operations also increases the menu of munitions options featuring an appropriate level of kinetic effect for the target and its immediate environment. Offering substantial improvements to the efficiency of striking targets, variable-yield munitions will present a scalable—but preset—envelope of effects at detonation. The United States does not yet field variable-effects weapons, but AFRL's Munitions Directorate has identified such "tailored lethality/low-collateral-damage" munitions as a near-term priority.[35] There are some ideas as to how to do this, including having explosive elements require an electrical charge to induce combustion. One could also "print" the energetics through additive manufacturing techniques to allow a range of potential yields. Another option envisions burning off excess energetics during the time of flight, if selecting a lower yield. Consequently, operators could use the same bomb against a variety of targets depending on the scenario or context, and even render the weapon "inert" to avoid damage to pop-up noncombatant elements within the effects envelope.

Adapted Effects: This concept refers to innovative designs that create blast, heat, and fragmentation envelopes that differ from classic explosive effects. Rather, designers specifically adapted these munitions to provide optimum effects against a specific target class.

Below: The BLU-129 is an example of how AFRL is innovating in adaptive munition effects. The bomb has a carbon-fiber body that disintegrates, rather than fragments, when it detonates—delivering increased explosive power to a preset radius, and reduces damage and casualties related to fragmentation—and has been praised for its utility in Operation Inherent Resolve.


AFRL

The newly procured BLU-129, developed under the guidance of the Air Force's now-inactivated Air Armament Center, provides one current example of this capability. Based on the conventional Mk-82 "iron" bomb and originally designated the precision-effects 500-pound-class munition, or PL-82, the BLU-129 has a carbon-fiber body that disintegrates rather than fragments at detonation. This delivers increased explosive impulse to a certain radius where it rapidly drops to zero, thereby avoiding Mk-82-style fragmentation that can cause damage up to a mile away. The BLU-129 thus provides an effects envelope well-adapted to the urban battlespace, CD-averse situations, and "danger close" scenarios when employing ordnance in close proximity to friendly forces.[36] Aircrew employing the BLU-129 in support of OIR missions have praised its value, in particular its usefulness in extreme proximity to noncombatants and friendly forces.[37] The real question centers upon how the Air Force gains similar capabilities in the future, focusing on desired effects and not just blast.

The developmental "focused lethality munition," based on the GBU-39B small diameter bomb, also features a carbon-fiber-wound bomb casing that disintegrates upon detonation, producing more-devastating blast effects within a smaller confined volume. These adapted-effects munitions fill effects gaps at the highest end of collateral damage or friendly fire potential where there is need for a limited kinetic energy envelope and reduced level of fragmentation. Employing adapted-effects weapons in a "danger close" close air support situation—especially when friendly forces are aware of the inbound weapon, but the enemy is not—would provide much greater flexibility to prosecute targets in even the most restrictive environments.

Adjustable Effects: Unlike the previous two concepts, this line of development seeks greater flexibility in the effects envelope of a given bomb body. Such variability may mean changes in yield characteristics, but the idea is to tailor the actual effects envelope in other ways including blast size, shape, direction, and fragmentation characteristics. More-advanced adjustable-effects munitions would permit an intelligence targeteer to pass programming instructions across appropriate information links to dynamically adapt a weapon for optimum effects, based on the target, its environment, and relevant rules of engagement. Also, unlike the adapted-effects category, which features a unique but relatively fixed effects envelope, adjustable-effects munitions represent a far more difficult technological challenge. In its most exotic incarnation, a pilot or targeteer would be able to program a set of parameters to target any combatant more than five feet tall in the northeast quadrant of an adversary's conference room, for example. Such "effects vectoring" would permit operators to target and prosecute not just the right targets, but only the right targets, with an effects envelope they could adjust based on target analysis enabled by advancing ISR capabilities.

AFRL is exploring practical applications of what officials term "dialable effects," to include advanced air-to-surface munitions.[38] These types of weapons offer greater surety of avoiding friendly fire or collateral damage based on data acquired, fused, and disseminated throughout a combat cloud. If need be, operators again could render a weapon "inert" following launch due to pop-up indications of civilians or friendly forces in close proximity. Yet they could still effectively degrade or destroy a target itself via the kinetic power of the bomb casing striking the individual, vehicle, or aim point in question.

> Selectability requires an aircraft-to-munition interface. In its fullest capability, programming could pass across tactical data links directly from an ISR targeting cell or tactical air controller.

In-Flight Selectability: To ensure maximum airborne flexibility, this line of development envisions in-flight programming of options within the range of the payload's effects—the ability to adjust a weapon's yield or effects envelope in real time to respond to dynamic targeting situations. Selectability requires an aircraft-to-munition interface. In its fullest capability, programming could pass across tactical data links directly from an ISR targeting cell or tactical air controller. Selectability is assumed in variable-yield and adjustable-effects munitions for the majority of Air Force aircraft, but once dispensed, the selected effects envelope is fixed. A further extension of selectability allows changes while a weapon is in flight. This characteristic is required in future air-launched munitions to achieve maximum mission flexibility, whether in terms of weapon yield or the shape of the effects envelope. Given such flexibility, fifth generation and future aircraft will have the capability to interface with munitions after weapons launch, based on continuous ISR and rapidly changing conditions in a dynamic battlespace. For example, adversary forces could move through terrain where real-time ISR, combined with real-time weaponeering, would indicate a need to decrease blast size and pattern. The aircrew would then select new bomb settings in flight to allow a strike. As with adjustable-effects munitions, in-flight selectability offers much greater flexibility to avoid or prevent unintended damage and casualties, especially in the tight, intermingled urban battlespace.

System-of-Employment Effects: A generational leap in munition effects may well result from efforts to re-engineer the entire system of employment. Going well beyond the traditional bomb blast, this design concept seeks synergy from all aspects of design, including new energetics, the shaping of the effects envelope, most-advantageous detonation geometry, and options to sequence multiple warheads for greater destructive effect. In this line of development, designers would integrate all factors to achieve the highest level of effect with regard to concerns for weapon size, ROE, target class, and in-fight flexibility. The result would be an air-launched munition that offers commanders and operators the opportunity to select a tailored explosive yield, discriminate kinetic effects, produce a targeted effects envelope, and employ in-flight adjustability based on post-launch developments. Given the emergence of information-driven warfare, in which commanders and operators constantly monitor and update mission considerations, and the increasingly fluid nature of the projected battlespace, this all-encompassing capability is likely essential to future munitions.

Enhanced-lethality technology is one example of attainable capability in the near term through this approach. AFRL experimentation showed the ability to cut warhead sizes yet achieve the same effect against a class of targets.[39] Further development by industry includes a miniature PGM weighing less than 10 pounds, but with an enhanced-lethality warhead that, for specific target classes, can approximate the effects of much larger bomb bodies in current use. Against a single high-value target on foot, one such weapon would likely prove sufficient. But operators could also use multiple munitions if they required higher energy for a more fortified target. Also, rather than carrying a single 2,000-pound bomb, a similarly sized weapons carriage could conceivably carry hundreds of these smaller munitions. This level of magazine depth would allow the F-35 and current RPA to exert greater and more wide-ranging impact during a given mission.[40]

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While having the potential to mitigate the effects crisis caused by reduced numbers of aircraft and payload capacity, system-of-employment effects design could alleviate another emerging requirement for greater, or varied, effects at detonation. Increased use of hardening of potential targets around the world limits the effect of even 2,000-pound-class bombs. Boosting the effect of the 2,000-pound bomb body using the same payload capacity would create new options for an air commander.[41]

Assessing the Potential of New Munition-Effects Design Concepts

The previously mentioned and other novel developments in modern munitions would grant much greater flexibility and effectiveness than today's air-to-surface weapons offer. These capabilities would essentially "break the mold" of classic munitions employment and effects.

For example, a future conflict may see an F-35 or B-21 fly a pre-planned mission with 2,000-pound bombs to produce a high-order detonation against a fixed target. While en route, the pilot could receive direction to divert to a dynamic targeting mission against a key enemy mobile command and control node that has eluded attack. However, the theoretical node is located in the westernmost area of a hospital. While the Law of Armed Conflict explicitly permits targeting such a facility if an adversary is using it for military purposes, there are always significant political and public perception consequences in dropping such a powerful weapon into a protected civilian facility.[42]

Fortunately, the aircraft on this hypothetical mission would be armed with weapons featuring some or all of the attributes discussed in this study. In order to impact only the part of the structure that enemy forces are illegally using, ISR analysts send the appropriate munition parameters to the pilot, who accepts the programming into one of the bombs onboard. This programming shapes the magnitude and dimensions of the detonation. Given these adjustments and the selected aim point, the bomb's blast, heat, and fragmentation effects are directed exclusively into the enemy command and control center, with little damage to the overall hospital structure and few or no casualties among the civilian personnel within. The aircraft and its pilot then resume the initial mission.

Such a capability would generate tremendous flexibility when prosecuting fleeting or highly mobile targets. It would also optimize the utility of aircraft assets, with one aircraft able to effectively manage multiple taskings. The theoretical scenario involving the hospital above could have easily featured a senior terrorist figure in an urban environment; a mobile surface-to-air missile launcher parked in the shadow of an internationally recognized historical structure; a deeply buried and hardened target in an urban setting; or hostile formations in close proximity to friendly forces. In all cases, the capabilities envisioned for this next iteration of air-to-surface munitions would fulfill the desire to minimize the risk to innocents or friendly personnel. While flexible weapons effects can provide substantial benefits in the near term, the emergence of new command and control and ISR (C2ISR) concepts and technologies—including the combat cloud—will significantly enhance the operational effectiveness of munitions employment. The intended outcome would be to more effectively align strategy, technology, tactics, and tools. Conversely, relying on traditional concepts regarding weapons design, procurement, and employment will stifle the potential that the combat cloud and other C2ISR constructs offer in the information-driven warfare of the 21st century.[43]

The combat cloud concept, in particular, requires flexible-effects munitions that provide the greatest effect for the smallest payload, particularly in contested environments...

While these constructs will not eliminate the fog and friction of war, they do promise to increase targeting opportunities substantially and improve the likelihood of achieving operational objectives in any given scenario. The combat cloud concept, in particular, requires flexible-effects munitions that provide the greatest effect for the smallest payload, particularly in contested environments, high-CD situations, or friendly force "danger close" scenarios. Fighting in these conditions will demand a far greater reduction in the percentage of targets that the Air Force cannot prosecute today due a lack of munitions suitability or an insufficient number of weapons airborne and available for employment.

To summarize these points, Table 1 details an in-house Mitchell Institute assessment of the categories of design concepts for munition effects. It rates how each design improves flexibility of effects, retains an option for maximum energy detonation, and provides increased levels of suitability and availability in a dynamic targeting environment. Importantly, it also gauges each category for its potential to increase the number of payload effects on individual aircraft and for its ability to raise overall effects across each cycle of the air tasking order.

Table 1: Potential Value of Munition-Effects Design to Operational Requirements

Operational Requirement / Effects Design	Flexibility of Effects[1]	Option for Max Energy Detonation	Suitability for Dynamic Tasking[2]	Availability for Dynamic Tasking[3]	Effects per Platform Payload Capacity	Effects per ATO Cycle
Variable Yield	**MED**	**YES**	**HIGH**	**HIGH**	**LOW**	**MED**
Adapted Effects	**LOW**	**N/A**	**HIGH** (for limited target, CD, or mission niche)	**HIGH** (for limited target or CD niche)	**MED** (for limited target, CD, or mission niche)	**MED** (depending on share of niche targets)
Adjustable Effects	**HIGH**	**YES**	**HIGH**	**HIGH**	**LOW**	**HIGH**
System of Employment[4]	**LOW**	**YES**	**MED**	**LOW**	**HIGH** (**VERY HIGH** for long-dwell RPA)	**HIGH**

Note 1: Flexibility of effects is the degree to which one can shape the effects envelope, including yield, directionality, fragmentation pattern, and lethality radius.

Note 2: Suitability means a munition can create a desired effect within the target environment and associated rules of engagement. An innovative effects design can produce a wider range of suitability.

Note 3: Availability refers to the presence of munitions in proximity of a target of opportunity. Innovative effects design can increase chances of availability, if distributed across the flow of platforms.

Note 4: System-of-employment (SOE) design seeks synergies in portions or across the entire strike architecture to maximize effects on a target. Warheads are one component of overall design; therefore, SOE can produce the same effect of traditional munitions with significantly less warhead weight. SOE designs could include fixed effects, variable yield, or adjusted effects. Current development in this area is generally limited to fixed effects, and the assessments above factor into this assumption.

Battlespace Changes and Emerging Requirements for New Munition Effects

For the past 27 years, continuous airpower operations have primarily reflected a spectrum of combat in a dynamic, ill-defined battlespace nearly completely devoid of high-end military competitors and threats. More recently, the Department of Defense (DOD) has begun to seriously address the long-neglected area of peer warfare. This refocus on modernization and readiness at the higher end of the conflict spectrum does not reduce the requirement for munition-effects innovation. In fact, it further heightens it. A number of features in the future combat environment facing US and allied forces will demand an even more rapid advance toward an air-to-surface effects revolution. They include:

More recently, the Department of Defense (DOD) has begun to seriously address the long-neglected area of peer warfare. This refocus on modernization and readiness at the higher end of the conflict spectrum does not reduce the requirement for munition-effects innovation. In fact, it further heightens it.

A Complex, Blended Battlespace: The future battlespace will continue to reflect an adaptive use of tactics and strategy by a range of adversaries. Many conflicts will likely feature hybrid irregular warfare and tactics encountered across the Middle East since the United States and its allies invaded Iraq in 2003. However, major conventional operations against a uniformed peer—or near-peer adversary—will involve much greater challenges, and the United States must be prepared to contend with those as well. US defense officials must also give due regard to the likelihood that militia and terror groups will exploit the instability that conflict introduces in any area of the world. US aerospace forces must therefore be prepared to engage threats throughout the full range of military operations, from counterinsurgency and counter-terror actions, to campaigns against hybrid adversaries, to high-end campaigns that mitigate some lower end concerns while elevating others. As Russia's 2014 invasion of Ukraine illustrated, even a major nation state may choose to advantageously harness the gray zones of armed conflict.

Law of Armed Conflict and Human Shielding: The United States and its allies will continue to abide by the moral and ethical boundaries set forth in the Law of Armed Conflict and other international conventions. In contrast, potential adversaries and their surrogates are increasingly likely to pursue an asymmetric approach to blunt US airpower capabilities. They will take advantage of Western values that constrain risks to civilians and other protected persons by blending into civilian populations, sheltering in religious and cultural sites, and shielding their forces with civilians. Such illegal methods, combined with negative repercussions of collateral damage in the global media space, have increasingly conferred strategic benefits to irregular adversaries, and encouraged them to pursue these practices further to limit airpower effectiveness.

To work within the limits of current munition effects, the OIR Joint Task Force has relied on extreme workarounds to avoid collateral damage. One example involves the use of non-explosive concrete-filled bombs (just as was utilized in Operation Northern Watch against Iraqi missile batteries). Another replicates a tactic that the Israel Defense Forces developed called "roof knocking" that features use of small explosive charges to warn of impending strikes to encourage civilians to flee.[44] Despite these operational innovations, there continues to be a pressing need for new approaches to these modern day combat challenges. In a November 2015 *USA Today* opinion article, Deptula, the Mitchell Institute's dean, detailed a lack of progress against the IS at the time.[45] Air strikes against the IS in Syria on average numbered four sorties a day at that point, compared to over 1,200 a day during Operation Desert Storm, he noted. Furthermore, the IS essentially operated in a sanctuary constructed by increasingly unrealistic US collateral-damage constraints. Deptula concluded that America's enemies in the conflict "are exploiting our humanity to impose their terror." Since then, significant recent operational changes have allowed higher fidelity identification of hostile forces in urban environments, while low-CD loads and the adapted-effects design modification to the BLU-129 munition have enabled more aggressive prosecution of IS targets. Deptula further noted that extreme avoidance of collateral damage merely extended the destruction that IS causes. Nonetheless, he insisted the US would always adhere to the established international norms of modern conflict, and seek to limit harm to non-combatants. Innovative munition effects can provide increased freedom of action under a range of politically imposed CD constraints.

New Munition-Effects Design Concepts:

The BLU-129 is one of the earliest examples of precision lethality. It is different than other "reduced collateral damage" weapons that are just downloaded versions of long-enduring munitions. In contrast, the BLU-129 yields high-energy lethality within a limited radius. Not only does it have much higher lethality in the near field than a Mk-82, outside that lethal footprint its probability of kill drops from assured to nearly zero. Its effects, relative to the Mk-82, are analogous to the difference between a sniper bullet and a hand grenade. Like a sniper round, it is low collateral because it delivers precision effects, not because it is low lethality. A high-impulse design allows a single round to have the same effect against a structure as four to five Mk-82s. While new munition design concepts may come with higher per-unit costs, a holistic cost analysis must consider improved efficiency where fewer bombs are necessary per target, savings associated with collateral damage avoidance, and overall system effectiveness in achieving operational-level objectives.

However, an Air Force fighter pilot and former project manager working with munitions concepts at the Defense Advanced Research Projects Agency (DARPA), the Pentagon's cutting-edge weapons development shop, cautioned that smaller fixed-effects munitions are "good for the current war, but not to the exclusion of other types of war."[46] Indeed, the United States must restore balance in its capability to contend with both high-end targets and irregular adversary tactics, such as human shielding, said Deptula in a 2017 interview. "It makes sense to gain more flexibility in munition effects so as not to be sub-optimized for one narrow segment across the range of military operations," he said.[47] Accordingly, the United States must always guard against projecting just enough power to potentially lose a conflict. If prudent options do not exist to project the power necessary to win, this may signal that armed engagement may not be a smart option. This is also a key reason why US Airmen need better munition options.

ISR-driven Operations and the Evolution of the Combat Cloud: No matter how accurate, any precision munition will fail to yield desired effects if aimed at an irrelevant or counter-productive target. For example, if the ISR enterprise misidentifies a schoolhouse as an adversary barracks, an advanced precision-guided munition will most likely hit that facility with eye-watering precision, but generate no benefit—and would likely result in political and public detriment to the US.

Nor is this example academic, as demonstrated by the accidental US strike in 1999 against the Chinese embassy in Belgrade, Serbia during Operation Allied Force. Extant and emerging technologies could likely mitigate this possibility in the future, as the advance of information and data fusing technology affords significant synergy between previously isolated hardware, software, and intelligence processes. The power of a highly integrated information enterprise is expected to transform the entire operational structure of modern warfare. This combat cloud would extend operational innovation already underway, and promises a substantial increase in combat effectiveness.

The combat cloud represents a cohesive, ubiquitous battle management system of systems linking all assets, from aircraft to ships to satellites to ground vehicles and other sensors in every domain.[48] This concept means to resolve current difficulties in rapidly moving data to decision in war, and its ultimate objective is a secure, multi-level enclave through which any user can access, process, and fuse data from all available sources, thereby enabling operators to use all relevant information in real time.[49] The concept also envisions the ability to be self-forming and self-healing when realized. With ports and nodes resident in every platform, the combat cloud can withstand the loss of one or many, leading to graceful degradation in the face of enemy attempts to shut it down. Much as the most effective cyber attacks against the civilian internet have shown, the loss or shutdown of even a great many nodes simply results in the rerouting of prioritized traffic through surviving paths and does not halt the network's functioning, even with some temporary localized functionality loss.[50] Meanwhile the resident data receive constant updates and scrubbing for errors and are ubiquitously available anywhere, anytime.[51]

To fully realize the value of information age warfare, the United States must address increased flexibility of munition effects across all payloads available in the battlespace.

The concept offers the potential to optimize effects in the battlespace by employing the best strike asset armed with the most suitable munition—and in the shortest possible time. Since information residing in the combat cloud will be ubiquitous and distributed in near-real time, greater efficiencies accrue when tasking platforms and associated munitions of any domain or service. To fully realize the value of information age warfare, the United States must address increased flexibility of munition effects across all payloads available in the battlespace. The United States could gain revolutionary benefits with munition flexibility today, though, with proper attention and investment—long before the combat cloud becomes a reality.

The Leverage of Long-Dwell Remotely Piloted Aircraft: For the foreseeable future, long-dwell sensor-shooter aircraft, such as the MQ-9 Reaper RPA will leverage the speed at which operators can target emerging opportunities. However, even when integrated with smaller sized munitions like the SDB, current

RPA still face two operational limitations. First, as previously explained, even an SDB is constrained in environments involving medium-to-high collateral damage potential. Conversely, if the payload is modified for low collateral damage opportunities, more-fortified targets or less-constrained scenarios will not be optimally attacked.

Secondly, there remains a mismatch in current RPA mission endurance and the number of effects these aircraft can create across a spectrum of targets. Because of the long period of time RPA can stay aloft there is a high likelihood that their weapons capacity may be expended before their mission duration is complete. Advanced weapons would allow RPA to fully exploit their inherent duration capabilities. Munitions development must adapt to evolving RPA concepts of operation within the broader template of ISR-driven operations. As munitions design is improved to allow more effects per payload, and therefore more-flexible combat potential across a range of targeting opportunities, US military and defense officials must ensure that armed RPA development takes place in tandem to reduce or eliminate future capability disconnects.

In working to understand airpower, it is crucial to recognize that achieving desired effects is always the top priority, a different objective than mere destruction. This requires providing leaders options to achieve theater objectives effectively and efficiently.

A Summary of Emerging Munitions Requirements

In working to understand airpower, it is crucial to recognize that achieving desired effects is always the top priority, a different objective than mere destruction. This requires providing leaders options to achieve theater objectives effectively and efficiently. To this end, Air Force officials have worked to define capability gaps, and depend on science and technology (S&T) initiatives across government and industry to engineer a broad range of solutions. But severe resourcing constraints have significantly hampered progress, even as peer competitors close capability gaps that once defined US airpower preeminence.

In 2006, the Air Force issued a flight plan that recognized the need for significant initiative in munition effects. Specifically, the plan highlighted that "composite warhead casings and specially formulated energetics can provide tailored weapon effects, low collateral damage, and safer (insensitive) munitions."[52] Since then, officials at Air Combat Command have taken the lead to define munitions capability gaps, which the Air Force's Global Precision Attack Core Function Team formally articulates.

Perspectives from Air Combat Command

As the Air Force's major command tasked with training, organizing, and equipping the air combat arm of the service, ACC is well attuned to the requirements for today's Airmen to fight modern wars, while also working to forecast and establish plans to meet future warfighting needs. This includes munitions challenges. While there is progress in this regard, funding limitations stand as the primary factor limiting necessary progress in advanced munitions development.

On the positive side, improved transparency in S&T activities in both government and industry is helping to fill these capability gaps, according to James A. Dunn, ACC's deputy director of requirements.[53] The command is working to share its plans with industry, and now hosts periodic technology information exchanges to review independent industry research and development, he said. Also, ACC's requirements directorate has significantly enhanced its collaboration with the Air Force Research Laboratory to prioritize the focus of S&T efforts in developing solutions. ACC has included new munition effects in its capabilities gap analysis, and Dunn highlighted the requirement for selectable effects and multimode warheads.[54]

However, an overarching concern pivots on capacity. In an era where highly contested environments will increasingly define operating environments, attributes such as low observable stealth technologies will be more important than ever. These aircraft, when flying in the most dangerous phases of a campaign, will be carrying their munitions in internal bays to preserve their low signature. This will limit carriage capacity for a period of time before efforts to reduce the threat allow use of external hard points, thus boosting weapons carrying capacity. Any effort to reduce munitions size, while still preserving kinetic effect, will prove exceedingly useful in ensuring limited weapons stores capacity can still meet strike demands—this is all about finding ways to fit more kinetic effects in a given space.

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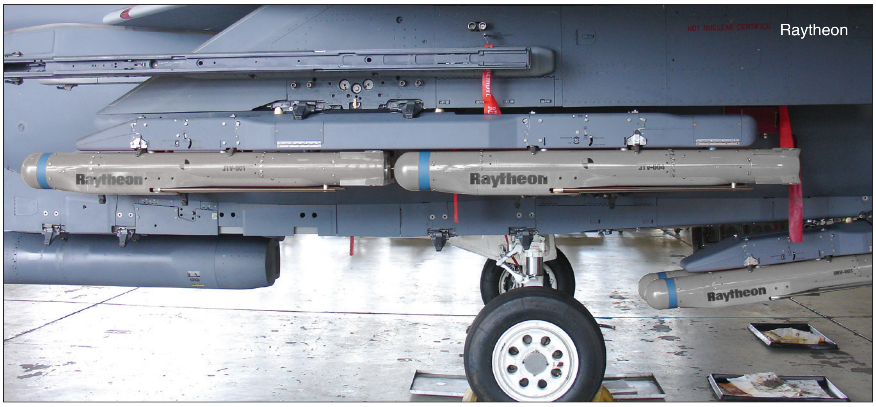
Nor is a desire for more munitions in a smaller space constrained to fifth generation fighters. RPAs like the MQ-9 possess tremendous dwell time which allows them numerous opportunities to engage targets, with mission duration often outlasting weapons stores. If more munitions can be carried onboard available pylons, then the utility of each RPA will rise.

This desire to pack more effects on each aircraft also ties to variables in the broader combat air force. Budget pressures and competing priorities have seen aircraft inventories decline sharply. For example, during 1991's Operation Desert Storm, the Air Force possessed 134 fighter squadrons. Today, it has just 55. Things are even worse with the bomber force, with inventories down to just a total of 157 long range strike aircraft. Today's combat bomber forces are largely defined by the qualifiers "old" and "small." This means the remaining aircraft must yield maximum positive effects, especially in an era when regions in Asia, Europe, the Middle East, and Africa each present unique, concurrent security challenges.[55]

Changing operational mission demands, paired with a diminished aircraft inventory are prompting efforts to boost the number of potential bombs available onboard aircraft at any given time. Building more new aircraft like the F-35 and B-21 at a faster rate is a crucial step in filling this shortfall. However, it is also critical to incorporate new munition designs.

There are bright spots in this effort to boost loadout per airframe, with the Air Force pursuing new efforts like StormBreaker, formerly the SDB II. Four of these bombs occupy the space once reserved for a single weapon, while also offering increased flexibility like their long reach through their ability to glide to the target. The goal is to "scale up" rather than "scale down" bombs per airframe, said experts familiar with ACC requirements.[56] Given that smaller munitions risk reducing blast power, aircrews have the option of using more weapons against a given target if more energy is required. As current operational personnel explain, the preference is to combine the effects of multiple smaller weapons, rather than carry a single 2000-pound weapon and "dial down" to a low-collateral blast.[57] If combat conditions change and demand more concerted, forceful striking power, bigger bombs can be loaded. The objective is to have choices—both in terms of the number of effects and their scale.

Right: The Air Force is pursuing efforts such as the StormBreaker munition (pictured on an F-15E Strike Eagle), formerly known as the Small Diameter Bomb-II, in order to address capacity concerns on modern combat aircraft. Four of these weapons can fit in a space normally reserved for a single munition, while offering operational flexibility due to their ability to glide long distances to a target.



While these gains should be applauded, it is also important to highlight that a significant gap between mission requirements and available options persists. Tight fiscal constraints continue to restrict progress toward a broader munition-effects revolution. Demands to modernize Air Force air-to-surface munitions designed to prevail in a potential peer conflict, and the imperative to restore legacy munition inventories depleted by nearly two decades' worth of constant combat are stretching available funding to the limit. These priorities must be met. However, this places extreme pressure on available funding to press forward with a new, advanced regime of munition-effect designs. "For the foreseeable future, we will continue to live with the fixed effects we have at takeoff and adapt those effects by burying it or varying the height of burst," said an Air Force munitions requirements expert.[58] This perspective, however, reflects far too much focus on budget-driven constraints versus what it will take to successfully fight and win future wars. ACC leaders understand these problems and recognize that marginal modifications to existing munitions proposals fall short of netting necessary capability gains. This is causing resistance to serious reprogramming of available funding. Only transformational concepts can gain traction in the current tight fiscal climate.

Shortly after taking command of ACC in March 2017, Air Force Gen James M. "Mike" Holmes indicated he wanted ideas from industry to address capacity and capability gaps. However, those ideas needed to address a severe gap in capability, not simply a modest improvement in performance, he said.[59] Consequently, requirements experts are doing what they have done for two decades: defining capability gaps under a de facto directive to do more with less. This only works as long as the security environment allows. Given that US adversaries have a vote in this process and are largely setting the pace, the US is assuming imprudent levels of risk. Capabilities required tomorrow require significant lead time, planning, and investment. The time to commit to real progress is now.

Perspectives from the Air Force Research Laboratory

In the not-so-distant past, a perception existed in some Air Force and DOD communities that AFRL was, to a degree, disconnected from the operational Air Force, primarily due to a lack of linkage between how research advances lead to implementable operational outcomes. In addition, the AFRL Munitions Directorate at Eglin AFB, FL faced significant budget reductions due to the mistaken perception that weapons research had plateaued. Fortunately, the directorate, then under the leadership of John S. Wilcox, took far-sighted action to address the relevance of AFRL's S&T efforts. "We needed to understand operational capability gaps and drive S&T objectives and technical challenges to mitigate the gaps," he recalled in late 2017.[60] The transformation required a much closer relationship with the warfighter and better internal processes to structure collaboration across the span of S&T providers. Consequently, the directorate shifted its focus to operationally focused outcomes. This change of emphasis required a systems engineering mindset that considered the entire range of operational mission phases, rather than the pursuit of compartmented research objectives isolated from one another.[61]

AFRL leadership underwrote the new approach, and is pressing continual dialogue to ensure operational gaps drive AFRL initiatives. Proof of this outcome is already evident. At the 42nd Air Armament Symposium in November 2016 in Fort Walton Beach, FL, comments from Maj Gen Robert D. McMurry Jr., then-AFRL commander, were in close sync with ACC requirements. He explained that there must be an offset to the smaller carriage capacities of a smaller inventory of fifth generation aircraft to increase the number of deliverable effects. Additionally, McMurry said that S&T work must advance to make weapons more effective in combat with less collateral damage, primarily through selectable effects and smaller components, all while maintaining affordability.[62] McMurry established selectable/dialable effects as one of eight enabling capabilities for both global precision attack and close air support.[63]

AFRL's new focus has also expanded beyond immediate challenges. The staff and leadership of the Air Force's research arm fully appreciates that tomorrow's wars may look far different than today's challenges.

AFRL's new focus has also expanded beyond immediate challenges. The staff and leadership of the Air Force's research arm fully appreciates that tomorrow's wars may look far different than today's challenges. The threefold increase in AFRL's munitions-related funding from Fiscal 2011 to Fiscal 2020 is a response to rapid improvements in the defensive capabilities of peer adversaries. In addition, most of this funding increase goes towards future weapons programs, rather than merely resolving the current effects crisis.[64] The AFRL Munitions Directorate is now also working to address capability gaps that can be resolved by more flexible and effective bomb body effects through other funding sources, such as Office of the Secretary of Defense-sponsored joint capability technology demonstrations.

Enabling a Munition Effects Revolution

With the need for new munition effects pressing, it should be noted the technology to achieve these advances is actually mature in many areas. A range of technical and conceptual innovations will help aid the development and procurement of a new generation of conventional air-delivered surface attack munitions.

For example, the Air Force might be able to refine or replace post-tritonal explosives such as AFX-757—which the BLU-109C/B contains and future BLU-137/B "bunker buster" bombs will carry—to produce blast agents that better lend themselves to directed, adaptable, and tailored effects.[65] Kinetic agents currently undergoing development, such as CL-20, could offer even greater effects for air-delivered weapons if designers can overcome challenges like explosive sensitivity.[66] Air Force officials should also study advances by civilian industry in explosive application, including precision blasting, extremely powerful nanoexplosives such as "fullerenes," and control of blast-induced vibration, for possible use in future munitions.[67] In particular, the mining, drilling, and civil engineering sectors are communities that have made progress in many potentially relevant areas.[68] Capitalizing on these civilian innovations may result in considerable savings for the Air Force and the DOD, more broadly, in research, development, test, and evaluation (RDT&E). At the same time, the Air Force should continue to invest in the ongoing development and deployment of other advanced—and compactly powerful—micro- and nanoexplosives, as the defense establishment has been doing for years.

Back in 2002, Andrzej W. Miziolek, a research physicist with the Army, asserted that the chemistry of current energetics had reached a limit. In contrast, he wrote that "nanoenergetics can store higher amounts of energy than conventional energetic materials and one can use them in unprecedented ways to tailor the release of this energy so as to maximize the lethality of the weapons."[69] This is particularly relevant given the push to downsize weapon size to increase carriage capacity. It may prevent a degradation in explosive power inherent with reducing the scale of a weapon with conventional energetics.

Emerging nanotechnologies also offer great potential in the development of future munition casings. Nanomaterials—particularly "nanotubes" and fullerene-based materials—have been shown to exhibit far greater strength-to-weight characteristics than traditional metals and composites.[70] A compound munition body composed of nanomaterials, with traditional (and weaker) bomb body materials placed in determined areas, may provide one way of modifying the direction and shape of a weapon's effects.

Additive Manufacturing

However, this vision is not limited to the material that gives a bomb its bang, or how that bomb directs its effect. Even greater potential lies in the manner through which the Air Force develops, produces, and fields air-to-surface munitions.

One of the most significant developments in this regard is the advent of additive manufacturing (AM). This innovation begins with a computer model, and then produces three-dimensional objects by applying successive layers of material (e.g., liquid, powder, sheet material) to fabricate a final predetermined form. The AM field encompasses many more familiar concepts including not only 3-D printing, but also rapid prototyping and direct digital manufacturing. The potential is boundless. Using AM, one can produce any three-dimensional object, even one incorporating a variety of different materials. To illustrate, companies currently use AM to fabricate end-use products such as medical and dental implants, automobile components, and even fashion products.[71] The aerospace firm Aerojet Rocketdyne's "Rocket Shop" has made steady and sometimes impressive strides in AM applications for engine and propulsion system testing, prototyping, and manufacturing. These applications include 3-D printing key components of the AR1 rocket engine that the United States eyes as a contender to replace the Russian-built RD-180, which is currently used in Atlas V boosters to lift national security payloads into orbit.[72] Meanwhile, General Electric's aviation division, currently the world's largest supplier of jet aircraft engines, is working to produce fuel nozzles using AM rather than the traditional methods of casting and welding metal.[73] In a similar vein, Norsk Titanium is using a 3-D printing technique known as "rapid plasma deposition" to produce components for the Boeing 787 Dreamliner.[74] The Air Force is also pursuing efforts to additively manufacture aircraft components.[75]

The demonstrated feasibility of additive manufacturing in industrial endeavors indicates its potential to enable munitions designs previously deemed impossible to construct. The Air Force has long investigated the incorporation of AM techniques into weapons RDT&E. "We've been working on printing [munitions] for the past five to 10 years," said John Corley, AFRL's core technical competency lead for ordnance sciences. Such AM-fabricated weapons would be lighter and smaller than current munitions, while producing similar kinetic effects with a lower explosive yield. "Workhorse munitions for us are 500-pound and 2,000-pound munitions, but we'd like to get to a 100-pound munition, for instance, that has the same output as a 500-pound bomb," Corley explained.[76] Reducing weapon size and weight offers obvious advantages in terms of sortie generation requirements: more bombs per aircraft increases effects per-aircraft, thereby reducing overall sortie count, and keeping more Airmen and aircraft out of harm's way. It also reduces overall costs in terms of fuel, maintenance, and other logistical necessities. Further, fifth generation aircraft, such as the F-22, F-35, and future B-21—all

Right: An F-35 from the 34th Fighter Squadron drops a GBU-12 LGB over the Utah Test and Training Range, February 25, 2016. Efforts to reduce weapon size and weight are critical for increasing the effectiveness of fifth generation aircraft, as they would carry all their weapons internally in contested combat environments. Smaller, equally potent munitions would allow aircraft like the F-35 to hit more targets per sortie.

of which carry weapons internally in contested environments—could prosecute more targets given a greater number of smaller, but equally potent, munitions. RPA load out could also increase.

Aerospace and defense firms have likewise expanded the horizons of AM when it comes to manufacturing munitions. In one case, a leading defense firm has developed a prototype air-to-surface weapon composed of 80 percent AM-produced components, propulsion, guidance surfaces, and control systems. "You can design internal features that might be impossible to machine," said Raytheon engineer Travis Mayberry, who is researching future uses of AM for munitions production. "We're trying new designs for thermal improvements and lightweight structures, things we couldn't achieve with any other manufacturing method," he said.[77] This is a major development, for a bomb's performance is fundamentally tied to its design and construction—AM changes core assumptions in this process.

Additive manufacturing offers significant advantages and efficiencies to weapons design, since rapid prototyping and re-prototyping will significantly reduce the cycle time of test iterations, lower costs, and ultimately improve weapon-aircraft integration.

Rapid prototyping is another benefit afforded by AM, which could help teams quickly experiment, and in doing so, speed fielding of new capabilities. The idea centers around rapidly converting a digital design into an actual working product. This promises to slash the time and cost required to develop and test virtually any product.[78] In one particularly poignant example, a research team at Aachen University in Germany has used AM to fabricate all exterior and some interior components for a prototype electric car, which it designed, built, and tested in less than a year, compared to the typical six years in the automotive industry.[79]

Bringing speed and agility back to defense production would be a most welcome capability. As a point of reference, the GBU-39B small diameter bomb took nine years to progress from requirement to delivery, four of those devoted to development and testing—a period that AM-enabled rapid prototyping could considerably shorten.[80] Rapid prototyping also offers other advantages, such as enabling swifter iterative design to correct identified flaws (i.e., "re-prototyping") and reducing the material scrap and re-work inefficiencies inherent in traditional prototyping practices.[81]

Testing and Experimentation

Beyond prototyping and manufacturing, opportunities exist to improve munitions testing and experimentation. In particular, the Air Force must explore how to modernize the developmental test and evaluation (DT&E) process. The service must also expand munitions "arena testing" in order to better analyze weapon effects and efficiency. The rationale for these recommendations is that there will continue to be a need to harness more advanced analytics to evaluate the performance of advanced air-to-surface munitions against the full range of potential targets.[82] This applies especially to weapons meant for precise calibration in their kinetic output, and focus in their blast, heat, and fragmentation effects.

With ongoing air campaigns now taking place in several areas of operation around the globe, the Air Force should also investigate opportunities to test new munitions operationally in a combat environment. Additive manufacturing offers significant advantages and efficiencies to weapons design, since rapid prototyping and re-prototyping will significantly reduce the cycle time of test iterations, lower costs, and ultimately improve weapon-aircraft integration.

Logistics and New Munition-Effects Designs

Finally, The US Air Force cannot project power in a sustained fashion without an effective, efficient logistics process. New munition designs may offer distinct benefits in this regard. First and most apparent, the development of smaller, lighter weapons incorporating innovative casing materials and more-energetic explosive agents would reduce the airlift, sealift, and ground transportation required to deliver these weapons to expeditionary forces abroad. Wherever stored or staged, these munitions would require a smaller footprint for the same number of effects. Second, advances in AM and materials may offer new logistics flexibility. For a given contingency or crisis situation, there is likely an optimal mix of prepared weapons and just-in-time weapons or associated components printed in, or near, deployed locations which can be called upon quickly. Any reduction in logistics requirements or time to satisfy warfighter demand has implications for improvements in speed, cost, and overall warfighting effectiveness as well as reductions in the vulnerability of those stocks.

Policy and Investment Recommendations

In order to achieve any of the above-mentioned imperatives, changes are necessary in regard to munitions investment strategy. Defense officials need to place far more emphasis on matching the pace of munitions design to the capabilities inherent in fifth generation and future aircraft designs, which will employ these weapons in a dramatically transformed operational environment. The current path in air-to-surface munition-effects design is not dissimilar to the leap in capability the Air Force eventually achieved when it transitioned from reliance on mass "dumb" bomb employment to precision-guided munitions. While pathfinding programs such as the BLU-129 are underway, more education, effort, and resources are needed to advance new munition-effects designs—as well as their enablers. The Mitchell Institute believes the following policy and investment recommendations could accelerate this transition:

1. **Prioritize incentives and resourcing necessary to capitalize upon additive manufacturing.** Additive manufacturing promises to be the technology that allows munition-effects designs and fabrication that was not previously possible. AM has potential to reduce manufacturing costs, logistics burdens, and DT&E timelines—and can move munitions acquisition a step closer to the "speed of combat" sought by the defense acquisition community and operators alike. The Air Force must pursue AM more aggressively, fund AM innovation in defense applications, and stimulate industry innovation. Incentives for AM innovation should be a standard fixture in munition acquisition strategies.

2. **Improve munitions developmental test and evaluation infrastructure**. The Air Force must continue to modernize its weapons DT&E infrastructure to support the rapid deployment of advanced munitions. While the Air Force should protect and, where possible, accelerate current resourcing for infrastructure modernization at Eglin AFB, FL, much more funding is needed. AFRL should establish a cross-functional infrastructure and capability design team that will produce a next-generation template for munitions DT&E.

3. **Educate the combatant commands on the value of new munition-effects designs.** Numbered air force commanders, tasked as COCOM air component leaders, should work with the Air Staff and AFRL to educate combatant commands on the increased capability new munition-effects designs can bring to bear in combat. Combatant command officials may not understand the potential of these effects enough to factor them in when formulating their integrated priority lists. Considering that the 500-pound bomb body has remained relatively unchanged in its characteristics for decades, these COCOMs may need information about munition improvements that may mitigate the effects shortage in high-end operations, and offer greater effects flexibility for lower end operations.

4. **Examine the potential for new effects designs to mitigate the air combat "effects crisis."** Ongoing discussions within the Air Force, especially Air Combat Command, have shown that the service faces an air combat "effects crisis" expected to last for an extended period.[83] New munitions concepts can mitigate the air combat effects shortage caused by force reductions, years of budget

sequestration, and cuts to fifth generation aircraft buys without regard to their smaller payload capacity. Lighter, more compact, and more flexible weapons that can approximate or improve upon the effects of existing bombs—not simply smaller munitions—will assist in mitigating the shortage of overall aircraft munitions carriage capacity. While increased investment is critical to meet COCOM needs for more smaller munitions in lieu of half-filled and concrete-filled temporary operational solutions driven by tight constraints on collateral damage, this approach does not address the air combat effects shortage related to executing high-end war plans.

5. **Congress must recognize that the cost of non-stop combat operations cannot choke off resources for new munition-effects designs**. Under mandates to replenish munition stockpiles depleted by long-enduring combat operations, and to modernize a drastically reduced and aged aircraft inventory, Air Force resourcing is at a dangerously low level for new munitions development. Some key technology areas are on extended life support-level funding, while potential adversaries have made significant gains in developing their own new munitions. The Air Force must fill today's weapons stockpiles, but budget authority must allow the service to rapidly exploit new munition-effects design concepts to offset capability gaps that could project forward for decades if not addressed.

6. **Ensure complementary, collaborative design between aircraft and munitions effects in the requirements, acquisition, sustainment, and budgeting processes**. Since at least 2011, AFRL has publicly highlighted that munitions development lags behind aircraft development, creating significant challenges that substantially limit aircraft design capabilities.[84] Acquisition policy and top-level force-development guidance that Air Force Warfighting Integration Capability (AFWIC) officials formulate must ensure aircraft and munitions effects are fused programmatically, and are not separate or sequential efforts. The Air Force must vigorously defend this principle throughout the institutional and fiscal turmoil of modernization, whether a result of programmatic changes, budget fluctuations, force structure adjustments, or technological challenges. Gold-standard analysis and complete transparency must exist when force structure is adjusted to ensure Air Force officials can express the resulting impacts across the range of military operations to decision makers in the DOD and on Capitol Hill.

7. **Concurrently develop new munition-effects designs and new warfighting paradigms such as the combat cloud.** As the DOD formulates developmental principles for making the combat cloud concept operational, advanced munition effects must be a co-developed capability, not an afterthought or secondary priority. Employing the combat cloud's operational design in combat with older generation munitions will limit the ability of US forces to pair a compatible weapon from scheduled loadouts in flight with vastly increased strike opportunities. Munitions must be more flexible in terms of shaping munition effects to a wider range of target types and environments. As noted previously, from 2001 to 2018, air commanders observed large percentages of targets that aircraft could not strike because of munition incompatibility. The Air Force should work with the Pentagon's Office of Net Assessment to ensure officials put forward principles involving future operational concepts across the US military services to guide munitions design concepts concurrently.

8. **Promote "cost per effect" evaluation metrics versus "cost per bomb."** AFWIC, Air Combat Command, and AFRL officials should examine the metric of "cost per effect" in order to guide future munition choices and development. As this study explains, a regime of new munition-effects design creates benefits beyond pairing a more effective munition with a desired impact point. Greater system efficiencies, kill-chain flexibility, loadout, and potential logistical benefits are relevant to a full-value assessment, no matter the resulting acquisition strategy. Importantly, Air Force officials must also factor the cost of indiscriminate effects into how they determine value, as new munition-effects designs and their flexibility reduce this cost in both dollars and strategic impact. At the same time, advocating new munition-effects designs requires clear comparisons with older effects designs. Air Force Public Affairs and Legislative Affairs representatives need to understand and communicate the operational advantages of new munition-effects designs well beyond the "boom."

9. **Engineer a safe, secure, and transparent exchange of ideas involving munition-effects designs between the Department of Defense, the military services, industry, and academia.** Both Air Force officials and DOD representatives have said they need to better engage the aerospace industry to explain requirements and solicit ideas to address capability gaps. Many in industry opined that these efforts were not particularly useful for understanding where to focus limited funds for independent research and development. Understandably, on the US government side, there is sensitivity to allegations of unfair access—which could result in eventual litigation, such as protests and disputes. Of late, however, a marked change has occurred in Air Force and DOD engagements with industry and academia. As cited earlier in this study, ACC has raised the priority of industry engagement to include technology information exchanges.[85] US Special Operations Command (SOCOM) also operates a system that welcomes unsolicited proposals, and staffs them to parts of the organization with subject-matter interest. AFRL, as well, has increased its focus on mapping capability gaps. A senior Air Force official explained these efforts only succeed to the extent that the right service personnel support them, specifically those who possess appropriate operational expertise and a realistic understanding how emerging technologies can enhance current operations concepts, or create new ones. The Air Force should convene a working group to re-formulate the structure and rule set to achieve vigorous cross-flow of information and ideas with the defense industry. This effort should include recommendations for modifying the Federal Acquisition Regulation (FAR), the approval of new legislation guiding DOD acquisition, and changes to Air Force instructions to facilitate the prompt delivery of maximum value to the warfighter. Ultimately, this study concludes that systemically engineering a safe and secure exchange of ideas between defense, industry, and academia will feed a revolution in munition effects more than any other single initiative.

10. **Prepare Airmen now for new munition-effects designs.** Higher performance munitions that afford flexible effects will not take hold without changing the way weaponeers and aircrews execute their planning. This will require adequate forethought, as these weapons enter service and eventually become routine tools of modern war. While training will be necessary, Air Combat Command should work now to experiment with the value of flexible-effects munitions and prepare resources needed to adapt training and planning activities to exploit the value of new munition-effects designs fully.

Conclusion

American airpower provides a global set of capabilities for deterrence and, when needed, a decisive force in war. During a century of maturation, America's Air Force became the indispensable element for all successful military operations. The Air Force also continues a strong tradition of affording unique policy options that cannot be replicated through force projection in other domains. However, continuous employment of US airpower in combat operations since the start of Desert Storm in 1991 has harmed modernization and readiness efforts. As the costs of war and nation building since September 2001 have climbed to trillions of US dollars, the resulting squeeze on defense resourcing has yielded an Air Force increasingly defined by gaps between real world demands and available capabilities.

The Air Force's inventory of airplanes has fallen by nearly half its size at the end of the Cold War, with large portions dating back to the Eisenhower Administration. The American technological edge relative to potential peer competitors, at the same time, is shrinking, if not gone in some areas. While this occurs, long-term tasking of airpower capabilities against terrorist groups in locations around the world looks to continue unabated. Competitive, highly lethal military systems are improving and proliferating, placing finite Air Force capabilities at increased risk in the hands of potential adversaries. These factors led to a stunning conclusion articulated in the Air Force's *Air Superiority 2030 Flight Plan*: "The Air Force's projected force structure in 2030 is not capable of fighting and winning against this array of potential adversary capabilities."[86]

> The Air Force's inventory of airplanes has fallen by nearly half its size at the end of the Cold War, with large portions dating back to the Eisenhower Administration. The American technological edge relative to potential peer competitors, at the same time, is shrinking, if not gone in some areas.

The United States will not be able to restore its Air Force overnight. Lawmakers, US military service leaders, and DOD officials must do more to increase the effectiveness of the existing Air Force inventory and clear obstacles to speed modernization. It is critical that a lack of resources not starve a potential revolution in munition effects, which will greatly aid these efforts. New design concepts for munitions will increase airpower efficiencies and effectiveness, expanding the potential effects that the current combat aircraft inventory provides. Said another way, advanced munitions will provide a vastly improved range of options at the strategic, operational, and tactical levels of war.

Fortunately, methods of defining capability gaps have vastly improved. Increased transparency gives more centers of innovation the opportunity to respond. In tandem, the Air Force has re-tracked its science and technology efforts involving munitions to go after defined capability gaps. A new and robust system that fosters an exchange of ideas between the Air Force, the DOD, industry, and academia will feed a munition-effects revolution.

At the same time, an enduring commitment is required to inextricably link aircraft and munitions development, and reverse the disconnect that occurred with the development of fifth generation aircraft. The F-35 is not simply an improved fighter aircraft; rather, it is a technological and operational innovation for information-age warfare. In spite of that potential, the F-35, for the foreseeable future, will drop bomb bodies with fixed effects not much different than those Airmen released from aircraft in generations past. The same will likely be the case for the Air Force's new next-generation bomber, the B-21.

Airpower is long overdue for a revolution in munition effects, a revolution that is technologically feasible and within grasp of today's Air Force and defense leaders. If prioritized, a powerful era of precision munition effects is feasible in the near to medium term. Failure to capitalize on this potential will result in suboptimal modification of present-day munitions to achieve increasingly discrete desired effects. If unchanged, future air campaigns and joint combat operations run the risk of increased collateral damage; friendly fire incidents; a prolonged munitions effects shortage; and warfighter frustration regarding missed targeting opportunities. While this Band-Aid approach may have proved adequate—albeit suboptimal—in contemporary low-intensity conflicts, it is crucial to remember that those conflicts did not involve peer-level military threats—threats the United States will most certainly face in the future. Given what is on the line, the time to act is now.

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