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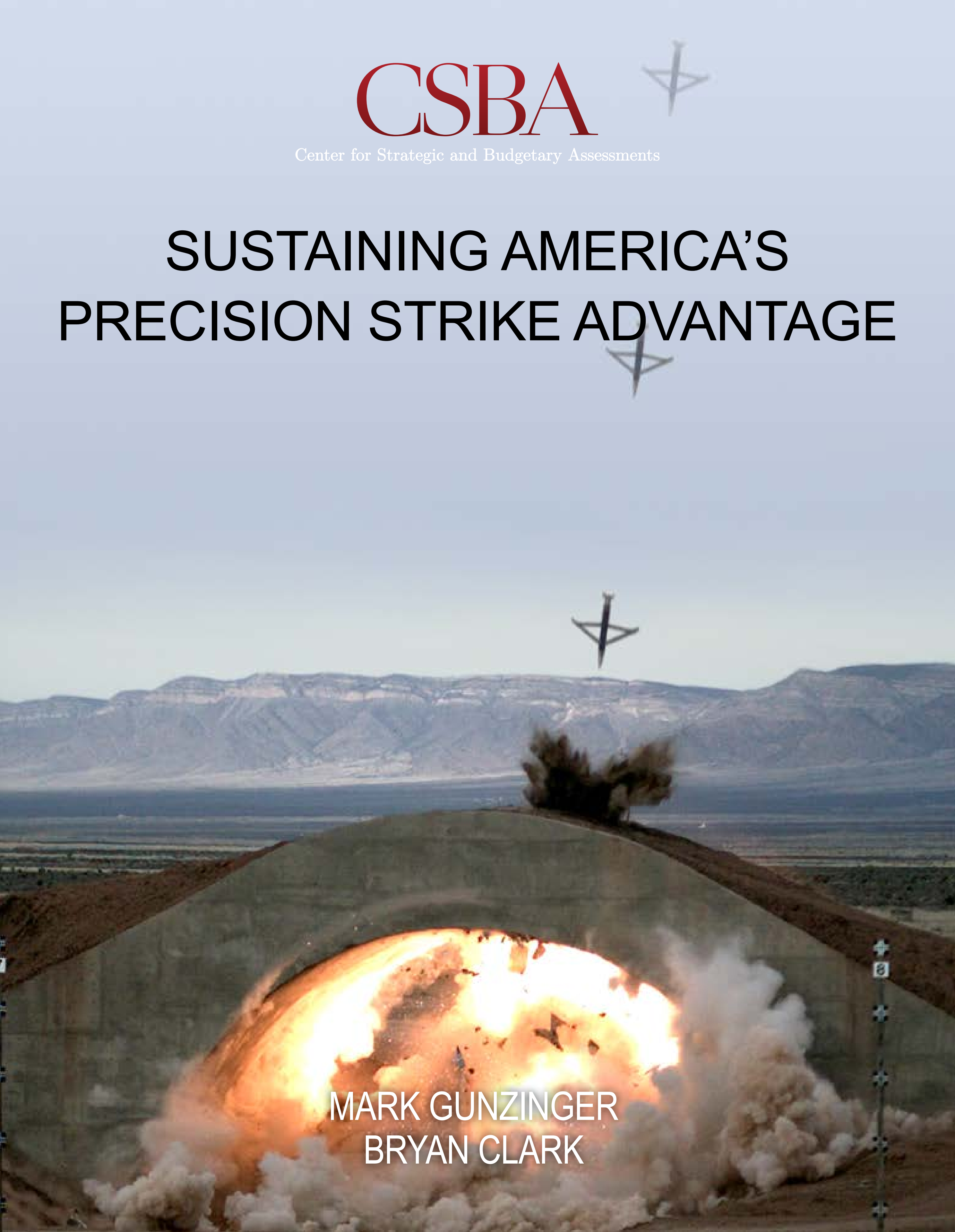
# SUSTAINING AMERICA'S PRECISION STRIKE ADVANTAGE



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## ABOUT THE CENTER FOR STRATEGIC AND BUDGETARY ASSESSMENTS (CSBA)

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# Executive Summary

The U.S. military has enjoyed an overwhelming advantage in precision strike since the end of the Cold War. The highly publicized use of laser-guided bombs and cruise missiles during Operation Desert Storm in 1991 heralded the potential for advanced precision-guided munitions to "dramatically increase the effectiveness of a fighting force."[1] Following Desert Storm, the Department of Defense (DoD) adopted a force planning construct developed during its "bottom-up" strategic review that prioritized the need to organize, train, and equip U.S. forces to deter, and if necessary defeat, conventional forces invading two U.S. allies or partner states nearly simultaneously.[2] This two-war planning construct assumed that future U.S. power projection forces would be able use large numbers of PGMs launched by aircraft, ships, submarines, and ground batteries to attack target sets with near impunity, much as they had during Desert Storm.

DoD's subsequent strategic reviews have reaffirmed the need for the U.S. military to prepare for fighting two major conflicts in separate theaters. The Pentagon's latest strategic assessment, the 2014 Quadrennial Defense Review (QDR), concluded the nation should maintain a military that "could defeat a regional adversary in a large-scale multi-phased campaign" while deterring or spoiling the offensive of a second opportunistic aggressor.[3] The 2014 QDR shared another characteristic with most of DoD's post-Cold War strategic reviews: it focused primarily on the size of its force and major force modernization programs, and it excluded a serious assessment of the numbers and kinds of PGMs needed to conduct future operations.[4]

1 Office of the Secretary of Defense (OSD), *Report on the Bottom-Up Review* (Washington, DC: DoD, October 1993), p. 9.

2 Ibid.

3 OSD, *Quadrennial Defense Review 2014* (Washington, DC: DoD, March 2014), p. 22. Acknowledging the limitations of a smaller force driven by reduced defense spending, however, the QDR changed requirements for the second of the two wars to "deny the objectives of—or impose unacceptable costs on—another aggressor in another region." The 2014 QDR report also acknowledged, "Modern warfare is evolving rapidly, leading to increasingly contested battlespace in the air, sea, and space domains—as well as cyberspace—in which our forces enjoyed dominance in our most recent conflicts." Ibid., p. iii.

4 The Deep Attack Weapons Mix Study (DAWMS) conducted during the 1997 QDR is a notable exception.

This failure is troubling, since the effectiveness of America's precision strike operations over the past twenty-five years has not gone unnoticed. Military competitors have exploited the proliferation of precision guidance technologies to field their own PGMs. China has developed a reconnaissance-strike complex capable of attacking U.S. naval forces at over-the-horizon (OTH) ranges and threatening U.S. air bases and ports throughout the Western Pacific. China, Iran, and others potential adversaries have also developed air and missile defenses, electronic warfare systems, and other active countermeasures to prevent U.S. strike systems and the PGMs they launch from reaching targets. Passive countermeasures such as making weapon systems mobile and hardening or deeply burying important facilities threaten to further degrade the effectiveness of U.S. precision strikes. Combined, these active and passive countermeasures could force the U.S. military to fly more strike sorties and expend larger numbers of PGMs in future wars.

## Report Purpose and Scope

The dynamic between two militaries that each have PGMs and precision defensive capabilities can be called a "salvo competition." In this competition, both combatants seek to gain the advantage by improving their capabilities to attack with precision and/or defend against precision strikes.

This report uses a salvo competition framework to assess new operational concepts and PGM technologies that could sustain the U.S. military's precision strike advantage in future conflicts. To bound the scope of the salvo competition challenge, the report focuses on the U.S. military's air and maritime strike capabilities. This limitation is not intended to diminish the importance of ground-based strike systems such as the Army Tactical Missile System (ATACMS) in future wars. The report also focuses on the offensive dimension of the salvo competition. Opportunities for DoD to more effectively defend against precision air and missile strikes will be the subject of future CSBA research.

## New Operational Concepts

This report concludes that simply using more current-generation PGMs to compensate for an enemy's precision strike defenses would be prohibitively costly. Instead, the Pentagon should create new operational concepts to increase the size or survivability of strike salvos. Possible approaches include:

- **Tunneling Operations.** DoD should make widespread use of inexpensive munitions to "tunnel" through air and missile defenses in future operations. Forcing enemies to expend their best defenses against cheap, expendable weapons could reduce the density of defenses sufficiently to allow follow-on PGMs to reach their targets. Using expendable decoys and jammers as part of a tunneling operation would further deplete an enemy's precision defenses while improving the survivability of U.S. PGM salvos and strike platforms.

- **Collaborative Weapons Operations.** Weapons capable of coordinating their operations after launch could help maximize target damage and compensate for weapons lost in flight. This would enable the U.S. military to use smaller PGM salvos to achieve greater effects than larger, non-collaborative salvos. While some PGM collaborative operations can be done manually today, DoD should pursue future weapons that are capable of autonomously communicating and coordinating with each other to greatly enhance the effectiveness of its precision strikes.

- **An Emphasis on Long-range Strike Operations.** To sustain its sortie capacity, the U.S. military should shift toward conducting a larger proportion of its strike operations from locations on land and at sea that are out of range of most cruise and ballistic missile threats.

- **Different uses for Short-Range Aircraft.** In future salvo competitions, DoD should preferentially use fighter aircraft with limited ranges and small PGM payloads to defend forward bases and conduct counterair operations. These operations would enable large strike platforms to penetrate target areas and to use short-range PGMs that are, on average, smaller and less expensive than long-range cruise and ballistic missiles.

- **New Basing Approaches.** DoD should pursue concepts for operating fighters from highly dispersed posture inside contested areas. This could complicate an enemy's ability to target U.S. fighter forces as well as increase U.S. fighter sortie rates for counterair and attack missions.

- **A Shift from Direct Attacks to Short-range, Standoff Strike Operations.** To counter increasingly capable point defenses, even stealthy strike aircraft will need to launch attacks from standoff ranges. With today's PGM portfolio, this would require aircraft to launch large, long-range standoff weapons such as cruise missiles that can be carried in much smaller numbers compared to most "direct attack" PGMs.[5] The U.S. military should instead shift toward using small, short-range standoff attack PGMs that will allow its strike aircraft to avoid lethal point defenses and maximize the number of weapons they can carry.

## Capability Implications

This report also recommends initiatives that take advantage of existing and emerging weapons technologies to increase the U.S. military's strike effectiveness against enemies with PGM defenses, to include:

5 For the purposes of this report, PGMs with a range of 50 nautical miles (nm) after launch or release from an aircraft are considered direct attack weapons. Direct attack PGMs can be unpowered, such as the Joint Direct Attack Munition (JDAM) that can glide for up to 13 nm depending on its altitude at release. Direct attack weapons, such as the Small Diameter Bomb (SDB) can also have wings that deploy after release, and be powered by small engines or rockets to extend their range.

- **Short-Range, Standoff Attack PGMs.** DoD should shift from a munitions inventory that now primarily consists of short-range, direct attack PGMs to a PGM mix that is weighted toward short-range standoff weapons that would allow strike platforms to avoid lethal point defenses protecting targets. This may require DoD to develop new standoff PGMs and possibly modify existing direct attack PGMs with small, inexpensive engines to extend their ranges after launch.

- **Smaller, Multi-Mission Weapons**. Smaller PGMs that are able to attack a wider range of targets can increase the salvo size and mission flexibility of platforms—particularly ships—that cannot easily replenish their weapons magazines. The Navy's current PGM portfolio is predominantly composed of single-mission (e.g., strike, anti-ship, anti-air) weapons with relatively large warheads. This limits the salvo sizes of its ships and inhibits their ability to support changing mission priorities during deployments without first returning to a secure port to replenish or change their weapon loadouts.

- **Survivable PGMs.** DoD should develop and field stealthy PGMs that can maneuver to avoid threats, and/or fly at hypersonic speeds (above Mach 5) to reduce the time available for defenders to react. Technologies are sufficiently mature to support the development and production of air-launched hypersonic cruise missiles that would create new advantages for the U.S. military against enemies with sophisticated air and missile defenses.

- **PGMs That Can Attack Multiple Targets.** To increase the strike potential of a single aircraft or missile sortie, DoD should take greater advantage of submunitions and warheads that give PGMs the capability to attack multiple targets per weapon. These "volumetric" weapons could carry smart submunitions individually capable of finding and homing in on targets, or warheads that use High-Power Microwave (HPM) energy to degrade or destroy electronic components inside enemy weapon systems.

- **PGMs for Challenging Targets.** DoD should increase investment in PGMs that are effective against moving, relocatable, hardened, or deeply buried targets. New PGM guidance systems and sensors will enable PGMs to find and attack moving or relocatable targets with fewer cues from external sources after launch. Advances in materials and high explosives could lead to new PGMs that have the penetrating power of much larger and heavier weapons to service deeply buried or hardened targets.

- **A PGM Inventory Sized for Future Salvo Competitions.** Finally, DoD should evaluate the sufficiency of its PGM stocks to support future strike operations against enemies that have precision strike countermeasures. DoD spends, on average, less than half a percent of its annual budget on PGM procurement. If this continues, U.S. forces may not have enough weapons to conduct sustained strike operations against a large target set in a contested environment. While major programs to develop next-generation aircraft and sea-based strike platforms have garnered a great deal of the Pentagon's attention and resources, it is time to acknowledge that these platforms will only be as effective as the PGMs they deliver.

# Introduction

The U.S. military has enjoyed an overwhelming precision strike advantage in the conflicts it has fought since the end of the Cold War. Facing relatively unsophisticated adversaries with limited defensive capabilities, it has been able to attack targets using large numbers of aircraft-delivered "direct attack" PGMs and missiles launched from ships, submarines, and ground batteries with impunity.[6] The effectiveness of America's precision air and missile strikes over the last twenty-five years has reinforced a belief that using as few as one or two PGMs against a single target is the new normal for modern warfare. This "one weapon, one target" mentality has also helped to justify serial cuts to the Pentagon's air and naval strike forces as well as its ground artillery.

The success of America's precision strike operations did not go unnoticed by military competitors, who exploited the proliferation of precision guidance technologies to field their own PGMs. China has developed a reconnaissance-strike complex that is capable of attacking U.S. naval forces at over-the-horizon ranges and threatening U.S. air bases and ports located throughout the Western Pacific. Iran has fielded ballistic missiles that can reach targets across the Middle East and multiple variants of anti-ship cruise missiles (ASCMs) that can be launched from coastal batteries, fast attack craft, and aircraft. Non-state actors in highly volatile or contested areas are also gaining access to guided rockets, artillery, mortars, and missiles (G-RAMM), which could significantly increase risk to U.S. forces. The Department of Defense now invests billions of dollars each year to counter guided weapon threats that pose a "cost-imposing challenge to U.S. and partner naval forces and land installations."[7]

China, Iran, and other potential adversaries have also developed active and passive defenses to reduce the effectiveness of U.S. precision strikes. Air and missile defenses, electronic warfare

6 The Department of Defense describes a PGM as "a guided weapon intended to destroy a point target and minimize collateral damage." DoD, *Joint Interdiction*, Joint Publication 3-03 (Washington, DC: DoD, 2011), p. GL-4. For the purposes of this report, PGMs with a range of 50 nm after launch or release from an aircraft are considered direct attack weapons. Direct attack PGMs can be unpowered, such as the Joint Direct Attack Munition, or JDAM, that can glide for up to 13 nm depending on its altitude at release. Direct attack weapons, such as the Small Diameter Bomb can also have wings that deploy after release, and be powered by small engines or rockets to extend their range.

7 OSD, *Quadrennial Defense Review 2014*, p. 7.

systems, and other active countermeasures are designed to prevent U.S. strike systems and their weapons from reaching designated targets. Passive countermeasures, such as creating highly mobile weapons systems and hardening or deeply burying fixed infrastructure, threaten to further degrade the effectiveness of U.S. precision strikes. Combined, these active and passive countermeasures could force the U.S. military to fly more strike sorties and expend larger numbers of PGMs in future wars.

The emergence of potential adversaries with PGMs as well as effective countermeasures against precision strikes has serious implications for DoD. The dynamic between two militaries that each have PGMs and capabilities to counter one another's strikes can be called a salvo competition. In this competition, both combatants seek to gain the advantage by improving their capabilities to attack with precision while defending against their opponent's precision attacks.

## Report Approach

This report uses a salvo competition framework to assess concepts and weapons technologies that could help the U.S. military maintain its precision strike advantage. It focuses on the offensive dimension of the salvo competition, and it assesses new operational concepts and the potential for leveraging existing and emerging weapons technologies to maintain or create new advantages in the future. Opportunities for DoD to more effectively defend against precision air and missile strikes will be the subject of future CSBA research.

Assessments in this report assume that passive and active countermeasures will significantly reduce the probability of damage (PD) of U.S. PGMs against their designated targets. DoD defines PD as the "probability that damage will occur to a target expressed as a percentage or as a decimal" to gauge the effectiveness of munitions against particular targets.[8] Passive precision strike countermeasures, such as camouflage, deception, hardening, burying, or otherwise fortifying targets that may be attacked by U.S. forces, could reduce PGM probability of damage values.

A major variable factored into PD estimates is the probability that PGMs will arrive at targets after they are launched from strike platforms. The probability of arrival (PA) for PGMs was nearly 100 percent during post-Cold War conflicts against enemies that lacked effective air and missile defenses.[9] Average PGM PA values may be far lower against adversaries that have active defense weapon systems capable of intercepting individual PGMs.

The emergence of effective precision strike countermeasures should prompt a rethinking about how the U.S. military conducts its future strike operations. Attempting to compensate

8 Probability of kill (Pk) has also been used to describe weapon effectiveness. Pk implies the desired effect of a weapon is to totally *destroy* a target, whereas damage criteria for targets can also include destroying or degrading its "functional or operational capability . . . to perform its intended mission" using kinetic or non-kinetic (e.g., cyber or electronic warfare) means.

9 This is, excluding errors such as inaccurate targeting information or material failures of strike capabilities that prevented PGMs from reaching their designated targets.

for precision strike countermeasures by simply using more of the kinds of PGMs DoD has procured over the last fourteen years may be ineffective. The vast majority (96 percent) of these munitions were short-range, direct attack PGMs such as air-delivered JDAMs. Platforms using direct attack munitions must maneuver or fly close to their intended targets, which could bring them within the effective range of enemy point defenses that protect specific "vital elements and installations."[10] Moreover, future strike operations that depend on using larger numbers of direct attack PGMs against target sets protected by advanced point defenses may be cost prohibitive.

Approaches that compensate for an enemy's precision strike countermeasures by simply launching more weapons could also require DoD to deploy more ships and aircraft than it now operates. Furthermore, attempts to simply use greater numbers of PGMs would be complicated by the fact that DoD must prepare to project power from U.S. territory to distant fronts. The need to deploy and sustain more ships and aircraft over global ranges would require costly investments in additional inter-theater lift capabilities, refueling ships and aircraft, and other supporting logistics infrastructure.

## Report Roadmap

This report is organized into six chapters that focus on new operational concepts and PGMs for air and maritime forces that could help the U.S. military to sustain its precision strike advantage in future salvo competitions. This focus is for the purpose of reducing the scope of the report and is not intended to diminish the importance of ground-based precision strike capabilities such as the ATACMS.

Chapter 1 briefly summarizes advantages created by precision-guided munitions. Chapter 2 assesses how a PGM salvo competition could affect U.S. strike operations. Chapter 3 then illustrates the challenges related to using more aircraft sorties and munitions, or "precision plus mass," to compensate for reduced PGM probability of arrival values.

The next two chapters assess alternatives to precision plus mass. Chapter 4 summarizes operational concepts that could help offset the effectiveness of active and passive defenses against PGMs. Chapter 5 uses a salvo competition framework to evaluate the advantages of developing new PGMs that are more survivable, smaller, and more lethal, as well as the advantages of PGMs that have greater range and/or the potential to create a wider range of effects compared with weapons now in DoD's inventory.

Chapter 6 concludes by summarizing issues that may inhibit DoD from evolving its PGM inventory to be more effective in future salvo competitions.

10 DoD describes point defenses as surface-to-air missiles and other weapon systems that protect specific "vital elements and installations." DoD, *Joint Airspace Control*, Joint Publication 3-52 (Washington, DC: DoD, 2014), p. GL-11. Advanced point defense systems could have effective ranges of a hundred miles or more against non-stealth aircraft.

CHAPTER 1

# Advantages of Precision-Guided Munitions

## The March to Precision

Guided munitions in various forms have been in use for over seventy years. Some historians mark the Royal Air Force's use of air-delivered acoustic homing torpedoes in May 1943 as the dawn of the guided weapons era.[11] Other World War II-era guided weapons were equipped with early inertial navigation systems (INS), radar seekers, or were directed to targets by human controllers using radio links. In July 1943, Germany deployed an air-delivered FRITZ-X radio-controlled anti-ship bomb, which "generated early anxiety about the future survivability of U.S. surface combatants, particularly aircraft carriers."[12] The subsequent development of more advanced guidance systems led to munitions that could strike targets with far greater precision compared to the rudimentary guided weapons of World War II. Today, PGMs equipped with internal guidance systems that receive precision navigation information from satellites, datalinks, and multi-spectral terminal seekers enable U.S. forces to attack targets with near-pinpoint accuracy.[13]

11 A former Air Force chief historian has observed: "The precision weapon era may be said to date to 12 May 1943 when a Royal Air Force Liberator patrol bomber dropped an Mk 24 acoustic homing torpedo that subsequently seriously damaged the [German submarine] U-456, driving it to the surface where it was subsequently sunk by convoy escort vessels." Dr. Richard P. Hallion, *Precision Guided Weapons and the New Era of Warfare*, APSC paper number 53 (Fairbairn, Australia: Air Power Studies Centre, April 1997), p. 8, available at http://www.fas.org/man/dod-101/sys/smart/docs/paper53.htm.

12 Barry D. Watts, *The Maturing Revolution in Military Affairs* (Washington, DC: Center for Strategic and Budgetary Assessments, 2011), p. 21.

13 See Barry D. Watts, *The Evolution of Precision Strike* (Washington, DC: Center for Strategic and Budgetary Assessments, 2013).

The maturation of precision guidance technologies also created opportunities to develop weapons to defend against air attacks. In the 1950s and early 1960s, the U.S. military fielded the Hawk surface-to-air missile (SAM) and Tartar ship-based SAM to intercept aircraft. For its part, the Soviet Union developed and widely exported its "SA" series of SAMs, including SA-2 missiles, which gained notoriety when they were used to shoot down an American U-2 surveillance aircraft in 1960.

Since the 1960s, the proliferation of more advanced SAMs and guided anti-aircraft fires has increased the risk to aircraft that must penetrate enemy territory to strike targets. To reduce "the risk of detection and loss of aircraft and aircrews while increasing the probability of successful attacks" in contested areas, the U.S. military fielded stealth aircraft capable of penetrating denied areas. They likewise fielded new standoff PGMs that could be launched by aircraft, ships, and ground launchers from secure locations.[14] Further, the maturation of miniaturized INS, map-matching capabilities for enroute navigation, and small turbofan engines enabled the development of very long-range standoff PGMs such as the Tomahawk Land Attack Missile (TLAM).


Developmental Tomahawk cruise missile in 1983

## U.S. Direct Attack and Standoff Attack PGMs

DoD now fields a host of direct attack and standoff attack PGMs. These can be grouped into three categories:

- "Direct attack" PGMs are short-range weapons that require launch platforms to be within range of enemy point defenses protecting specific "vital elements and installations."[15] For the purposes of this report, PGMs with a range of 50 nm after launch or release are categorized as direct attack weapons. They can be unpowered, such as the JDAMs that can glide up to 13 nm depending on its altitude at release. Some direct attack weapons such as the Small Diameter Bomb use wings that deploy after launch to extend their range and/or are powered by small engines or rockets.

- "Short-range, standoff attack" PGMs fly for longer distances after release compared to direct attack munitions. These PGMs allow penetrating aircraft to deliver them from ranges that reduce the aircraft's exposure to point defenses protecting targets. For the purposes of this report, short-range, standoff attack PGMs have ranges between 50 nm and 400 nm. This category includes unpowered, short-range standoff weapons with

14 DoD, *Joint Interdiction*, pp. II-2, II-3.

15 DoD, *Joint Airspace Control,* p. GL-11.

wings that deploy after release, such as the AGM-54 Joint Standoff Weapon (JSOW), or powered cruise missiles, such as the Joint Air-to-Surface Standoff Missile (JASSM).[16]

- "Long-range, standoff attack" PGMs have sufficient range to permit their launching platforms to avoid area defenses protecting large areas from attack.[17] For the purposes of this report, this category includes PGMs with ranges that exceed 400 nm, such as JASSM-Extended Range (JASSM-ER) cruise missiles and TLAMs. Because ships are often unable to maneuver close to target areas, most ship-launched strike weapons fall into this category.

Appendix 1 summarizes direct attack and standoff PGMs that are now operational or will soon join the U.S. military's inventory.

## Advantages of Precision

**Precision has redefined the meaning of mass.** Perhaps the most obvious advantage afforded by the large-scale use of PGMs is the decrease in the number of sorties and munitions needed to attack large, geographically dispersed target sets. During World War II, the combination of inaccurate aircraft navigation systems and unguided munitions required Allied forces to use large formations of bombers and fighters to ensure a fraction of their combined payloads would hit target areas.[18] Substituting mass for precision, airmen flew hundreds of strike sorties and dropped thousands of unguided bombs to ensure targets were destroyed. As combat aircraft navigation and targeting systems improved in the 1950s and 1960s, the number of unguided weapons and sorties needed to effectively strike targets decreased significantly. This trend continued as DoD integrated precision guidance systems such as laser seekers, INS, and Global Positioning System (GPS) receivers into its gravity bombs and cruise missiles (see Figure 1).[19]

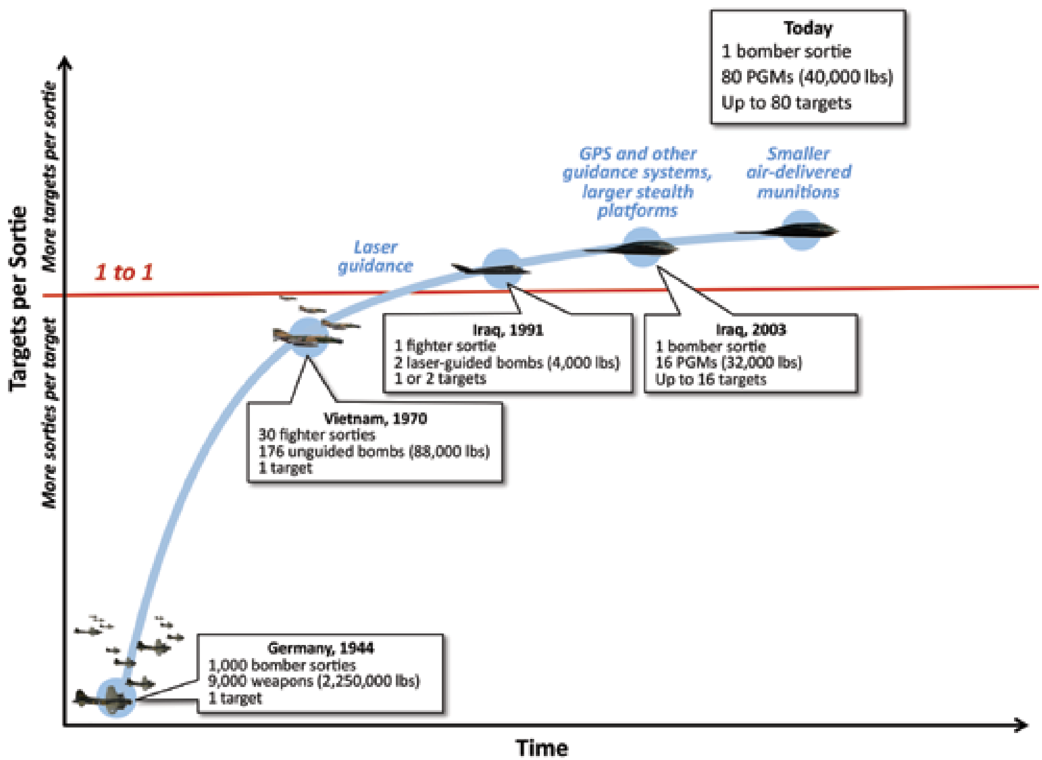
16 JSOWs may have a range of 65 nm or slightly more depending on the altitude and airspeed of their releasing aircraft. See "AGM-154 JSOW (Joint Standoff Weapon) and JSOW-ER," in Robert Hewson, *Jane's Weapons: Air-Launched 2014–2015* (London: IHS Global, 2014).

17 DoD, *Countering Air and Missile Threats,* Joint Publication 3-01 (Washington, DC: DoD, 2012), p. D-7.

18 According to official estimates of the effectiveness of bombing operations in the European Theater, "only about 20 percent of the bombs aimed at precision targets" fell within 1,000 feet of their aimpoints. United States Strategic Bombing Survey (USSBS), *Summary Report,* (European War) (Washington, DC: U.S. GPO, 1945), p. 13.

19 To be fair, many targets attacked by Allied aircraft during World War II were large facilities such as industrial complexes. While attacking similar targets today would likely require the use of multiple PGMs, total weapons and sorties needed to do so effectively would still be far less than the number of unguided munitions needed during World War II.

## FIGURE 1. FROM SORTIES PER TARGET TO TARGETS PER SORTIE




During the 1991 Desert Storm air campaign, laser-guided bombs delivered by U.S. F-111 and F-117 fighter-bombers hit 85 percent and 80 percent of their targets respectively, compared to 53 percent for F-16s and 42 percent for F/A-18s delivering unguided weapons.[20] According to the Gulf War Air Power Survey:

> Desert Storm witnessed a fundamental change in the tactical and technological means of causing a given amount of destruction to a specific target. Previously, the requisite level of destruction could be increased by increasing the mass of bombs dropped, by improving the inherent accuracy of the bombing platform, or both. In Desert Storm, the availability of precision-guided air-to-surface munitions, particularly laser-guided bombs (LGBs), caused a fundamental rethinking of the means of achieving the destruction goal.[21]

Since Desert Storm, PGMs have constituted roughly 60 percent of all munitions dropped by U.S. aircraft in major air campaigns (see Table 1).

20 United States Government Accountability Office (GAO), *Operation Desert Storm Evaluation of the Air Campaign* (Washington, DC: GAO, June 1997), pp. 118–121. The GAO's analysis compared the effectiveness of F-111Fs and F-117s using various types of LGBs against 49 common targets attacked during Desert Storm.

21 U.S. Air Force, *Gulf War Air Power Survey*, Volume IV, Part I: *Weapons, Tactics, and Training* (Washington, DC: Government Printing Office [GPO], 1993), available at http://www.afhso.af.mil/shared/media/document/AFD-100927-067.pdf, p. 252.

### TABLE 1. MUNITIONS USED IN MAJOR U.S. POST-COLD WAR AIR CAMPAIGNS

| Conflict | Unguided Bombs | Precision-Guided Munitions | | |
|---|---|---|---|---|
| | Number Used | Total Number PGMs Used | % of Total Munitions Used | PGM Per Target Ratio |
| **1991 Desert Storm** | 210,900 | 17,162 | 7.5 | 1.9 : 1 |
| **1999 Allied Force** | 2,334 | 3,590 | 60.6 | 2 : 1 |
| **2003 Iraqi Freedom** (reported April 2003) | 9,127 | 19,269 | 67.8 | 1.5 : 1 |

In 2003, coalition air forces supporting Operation Iraqi Freedom used an average of 1.5 PGMs per target,[22] a weapons-to-target ratio that World War II airmen could only have dreamed of. Instead of thinking in terms of how many sorties are needed per target, strike planners now "expect one platform to be able to create multiple effects against a range of targets in one mission."[23] This leap-ahead in strike effectiveness has led some warfighters to claim that giving standoff and direct attack munitions precision guidance has "redefined the meaning of mass" in modern strike warfare.[24] In other words, while many aircraft payloads were needed to successfully strike targets before the advent of precision weapons, today the "mass" of weapons needed for strikes has decreased by orders of magnitude and can often be carried by a single aircraft.

**PGMs are force multipliers**.[25] Successful guided cruise missile and laser-guided bomb strikes in 1991 during Operation Desert Storm heralded the force-multiplying potential of PGMs. Although less than 8 percent of munitions used during the Desert Storm air campaign were precision-guided, their effectiveness against Iraqi tanks and air defense systems demonstrated that PGMs could have as significant an impact on warfare as machine guns did during World War I and armored vehicles did during World War II. Just as mechanized firepower largely replaced the need to overwhelm an enemy with massed manpower, PGMs provide small units with the same or better striking power as much larger, non-PGM equipped forces.

Today, munitions with precision guidance enable combat aircraft to strike many targets in a single sortie and ships to attack multiple targets simultaneously. Precision guidance also

22 USCENTAF Assessment and Analysis Division, *Operation Iraqi Freedom—By the Numbers* (Shaw AFB, SC: U.S. Air Force, April 30, 2003), p. 11, available at http://www.afhso.af.mil/shared/media/document/AFD-130613-025.pdf.

23 Air Commodore Tim Anderson, "UK Long Range Offensive Air Power for 2020 and Beyond," *The Royal Air Force Airpower Review,* Winter 2006, p. 47.

24 Colonel Phillip S. Meilinger, *10 Propositions Regarding Air Power* (Washington, DC: Air Force History and Museums Program, 1995), pp. 41, 45.

25 The Defense Department has defined the term "force multiplier" as "a capability that, when added to and employed by a combat force, significantly increases the combat potential of that force and thus enhances the probability of successful mission accomplishment." *DoD, Department of Defense Dictionary of Military and Associated Terms,* Joint Publication 1-02 (Washington, DC: DoD, November 8, 2010), p. 142, as amended through May 15, 2011.

enables U.S. forces to use smaller weapons that can destroy or mission kill specific targets. This has the force-multiplying effect of increasing the number of PGMs that can be delivered by individual strike platforms.

Perhaps the most significant indication of the force-multiplying potential of PGMs is the steady draw-down in the size of DoD's combat air forces. Increased sortie effectiveness from the large-scale use of PGMs helped create opportunities to wring efficiencies from the Pentagon in the post-Cold War era. Conducted after Operation Desert Storm, DoD's 1993 Bottom-Up Review cited the fact that, "Advanced precision-guided munitions can dramatically increase the effectiveness of a fighting force," as part of the rationale for why it decided to cut U.S. fighter and bomber forces. Reductions to the U.S. military's strike forces have continued nearly unabated. Since 2000, the Air Force has retired nearly 25 percent of its fighter aircraft, 33 percent of its B-1s, and 20 percent of its B-52s.[26] DoD made similar reductions to its naval aviation forces.

**Advantages in time.** Precision guidance reduces the number of weapons, sorties, and time needed to attack large target sets. Further, attacking forces can synchronize the use of large numbers of standoff attack PGMs to saturate an enemy's defenses and enable strike aircraft to penetrate contested areas at a time of the attacker's choosing. Standoff attack PGMs also enable U.S. land, air, and sea-based power projection forces to simultaneously strike multiple aimpoints across a battlespace. Finally, PGMs with internal precision navigation systems, data links to receive target updates, and electromagnetic sensors that can "see" targets through clouds and obscurants have improved the U.S. military's ability to strike fixed and moving targets in all weather conditions and at night.

**Wider range of targets held at risk.** Owing to advances in sensors, data processing, and precision navigation systems, some PGMs launched from extended ranges have the ability to find and engage mobile and moving targets located on land and at sea. Precision-enabled weapons can strike specific points on targets, which can improve their lethality, especially against hard or deeply buried targets. And benefiting from progress in automated target recognition capabilities, PGMs can increasingly discriminate among targets in cluttered environments, which may reduce the need for strike aircraft to penetrate contested areas to find and strike moving and relocatable targets with direct attack weapons.

**Ability to defeat precision strikes.** Precision-guided weapons can also be used defensively, not only to defeat enemy aircraft and other PGM launch platforms, but to destroy incoming missiles and bombs as well. This drives the salvo competition by compelling attackers to use more weapons and sorties, or more sophisticated weapons that have higher PA values.

26 For a more comprehensive assessment of DoD's combat air force reductions, see Mark A. Gunzinger and David A. Deptula, *Toward A Balanced Combat Air Force* (Washington, DC: Center for Strategic and Budgetary Assessments, 2014).

## Summary

PGMs delivered by platforms that operate in the air, on the ground, and at sea have changed the way America prefers to conduct strike operations. Long-range, standoff attack munitions help create advantages in time by reducing the need to mass combat forces in close proximity to target areas that may be heavily defended. Precision guidance also reduces the need to use large numbers of missiles and aircraft sorties to ensure enough munitions hit their designated aimpoints.

The force multiplying benefit of PGMs has also helped justify a series of cuts to the U.S. military's strike forces since the end of the Cold War. Consequently, the size of the U.S. military's fighter and bomber force is now at a historic low. The assumption that these forces provide sufficient strike capacity has held up well during operations against opponents with fragile or nearly non-existent air and missile defenses. It may not remain true for future operations against enemies that have developed effective countermeasures against PGM strikes.

CHAPTER 2

# An Emerging Salvo Competition

The introduction of precision defenses in the military forces of America's potential adversaries is creating a far more challenging environment than the conditions experienced by U.S. power projection forces in recent decades. Advanced air and missile defenses, electronic warfare systems, cyber threats, and other active and passive countermeasures threaten to degrade U.S. strike operations at every step of the find, fix, track, target, engage, and assess "kill chain" (see Figure 2).[27] These countermeasures could force attackers to use more sorties and PGMs to service future target sets.

## FIGURE 2. COUNTERING THE U.S. MILITARY'S PRECISION STRIKE KILL CHAIN


27 DoD describes its find, fix, track, target, engage, and assess cycle as a kill chain that applies to "all targets whether developed during deliberate targeting or dynamic targeting" planning. DoD, *Joint Targeting*, Joint Publication 3-60 (Washington, DC: DoD, January 31, 2013), pp. II-1–II-36.

Russia, China, North Korea, and other potential aggressors have fielded "active" kinetic and non-kinetic precision strike defenses. These defenses are designed to degrade U.S. targeting networks, attack its theater airbases and aircraft carriers, intercept ships and strike aircraft, and destroy or divert individual PGMs before they can reach their targets.

Chinese self-propelled short-range air defense system

Kinetic defenses include "double-digit" mobile SAM systems such as the S-300 (also known as the SA-10) that was first fielded by the Soviet Union more than thirty years ago. Russia has since fielded a family of S-300 derivatives, including S-300 PMU-2 (NATO codename SA-20) and S-400 (NATO codename SA-21) systems that may be capable of intercepting aircraft and cruise missiles at ranges exceeding 100 nm. S-300 variants have been procured by Egypt, Armenia, Belarus, China, other Asian and Eastern European states, and will shortly be exported to Iran. China has also fielded its own S-300 variants. Other defenses include radar-directed, short-range missiles and Gatling gun-like weapons that fire thousands of rounds per minute for last resort point defense.

MOP test release

Non-kinetic active defenses include electronic warfare jammers and decoys. Leveraging commercially available technologies, potential adversaries have developed low power emitters to defeat PGM seekers or disrupt the GPS signals they use for guidance. Future non-kinetic defenses against U.S. precision strike capabilities may include high-power lasers and other directed energy weapons. All of these capabilities can be linked to coordinate their fires, increasing their effectiveness against aircraft and PGMs.

Passive countermeasures can similarly reduce the probability that PGMs will strike actual targets or create the level of damage desired by attackers. These measures include camouflage and deception, hardening and/or deeply burying vulnerable stationary facilities, and making at-risk weapon systems highly mobile. Decoys and concealment tactics complicate an attacker's intelligence, surveillance, and reconnaissance (ISR) operations and could cause it to waste PGMs against false targets. To strike very hard or deeply buried targets, attackers must use specialized penetrating conventional munitions that are large and expensive, such as the 30,000 pound Massive Ordnance Penetrator (MOP), or even nuclear weapons. America's potential enemies also understand that making their key military systems mobile or giving them the ability to quickly relocate degrades the U.S. military's "ability to detect, locate, identify, and take action"[28] against them and may require U.S. forces to conduct persistent strike operations over large areas.

## Illustrating the Challenge of Precision Defenses

Active and passive countermeasures degrade an attacker's ability to strike target sets, which can be measured by changes in the probability that an attacker's PGMs will reach their targets and generate the required amount of damage. The following examples assume an enemy's active and passive defenses are capable of reducing the PA values of DoD's PGMs. While other actions to degrade U.S. kill chain operations (such as cyber-attacks) can be measured by gauging their impact on PGM PAs, assessing all possible combinations of kill chain countermeasures is beyond the scope of this report.

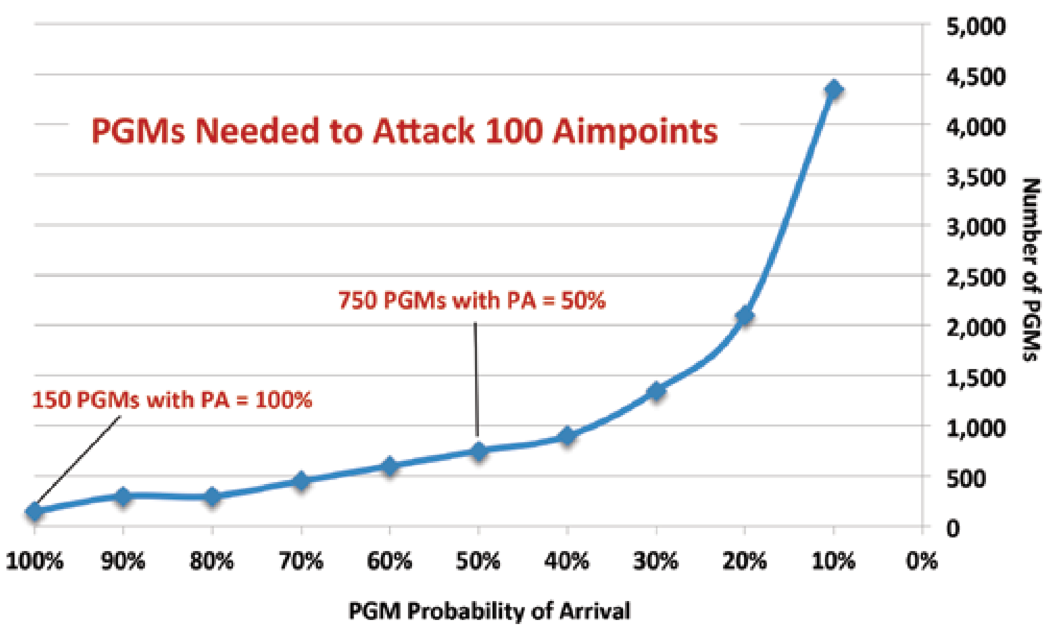
Figure 3 illustrates how degraded PGM PA values could increase the number of weapons needed to strike 100 separate aimpoints.[29] A total of 150 PGMs would be needed to attack 100 aimpoints assuming each PGM has a 100 percent PA and a PGM-to-aimpoint ratio of 1.5-to-1, similar to that of Operation Iraqi Freedom. Approximately 750 munitions would be needed to strike the same 100 aimpoints if enemy defenses reduce average PGM PA values to 50 percent.[30]

28 Department of Defense, *Joint Targeting,* p. II-10. In other words, mobility increases what DoD defines as target location errors: "the difference between the coordinates generated for a target and the actual location of the target. See DoD, *Department of Defense Dictionary of Military and Associated Terms*, p. 250.

29 A very large military airfield or industrial complex may have many aimpoints. "Aimpoint" is shorthand for a designated point of impact (DPI). A DPI is "a precise point, associated with a target, and assigned as the impact point for a single unitary weapon to create a desired effect." Department of Defense, *Joint Targeting*, p. GL-5.

30 This example assumes the objective is to ensure with a 95 percent confidence level that each aimpoint is hit by a PGM. It also assumes one PGM would be needed for each aimpoint under ideal conditions when PA values are 100 percent. During Operation Iraqi Freedom, an average of 1.5 PGMs were needed per target.

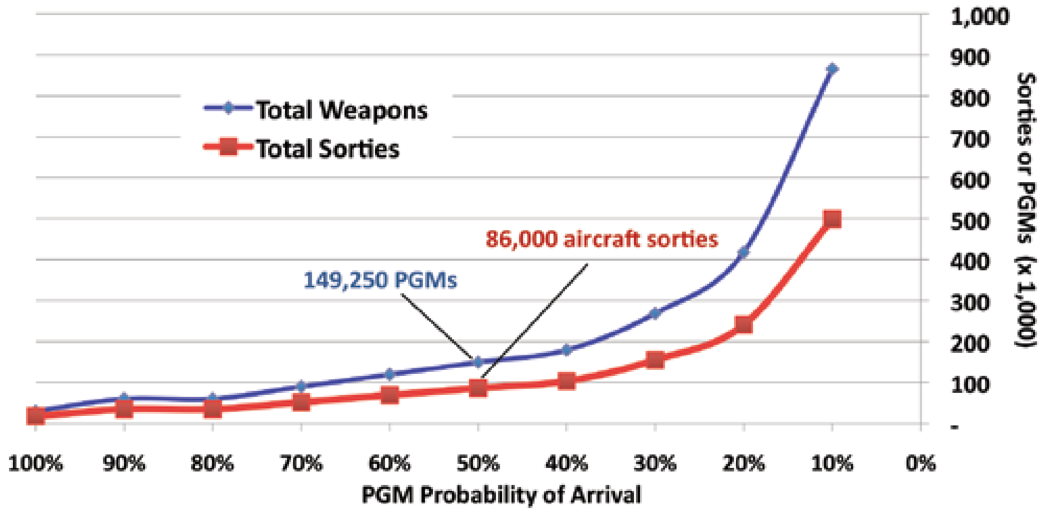
FIGURE 3. ILLUSTRATIVE DEGRADED PGM PROBABILITY OF ARRIVAL




Extending this argument to a larger target set representative of a major strike campaign brings the implications of a salvo competition into sharper relief. Coalition forces used slightly more than 18,700 PGMs and 9,100 unguided bombs to hit 19,900 targets during the 2003 Operation Iraqi Freedom air campaign. Striking the same 19,900 targets in contested conditions where PGMs have a degraded PA value of 50 percent would require about 149,250 munitions and approximately five times the number of strike sorties flown during the OIF air campaign (see Figure 4).[31] This example illustrates that while PGMs can be force multipliers, countermeasures that significantly degrade PGM probability of arrival values have the opposite effect.

31 Anthony H. Cordesman, *The Iraq War: Strategy, Tactics, and Military Lessons* (Washington, DC: Center for Strategic and International Studies, 2003), p. 143; Chuck Roberts, "War and Peace—A Look at Operation Iraqi Freedom," *Airman Magazine*, June 5, 2003, available at http://www.af.mil/News/ArticleDisplay/tabid/223/Article/139088/war-and-peace-a-look-at-operation-iraqi-freedom.aspx; and "Operation Iraqi Freedom Quick Facts," *The Information Warfare Site,* accessed on October 21, 2014 at http://www.iwar.org.uk/news-archive/iraq/quick-facts.htm.

FIGURE 4. WEAPONS AND SORTIES NEEDED FOR AN OIF-SIZED STRIKE CAMPAIGN WITH DEGRADED PGM PROBABILITY OF ARRIVAL[32]




**Considering future target sets.** While the example illustrated by Figure 4 uses the number of targets attacked during the Iraqi Freedom air campaign, DoD's PGM assessments should consider the need to prepare for campaigns against target sets that may be much larger as well as better defended. China and Iran are about twenty-two times and four times the size of Iraq, respectively. While the sizes of potential operational areas do not translate to an exact number of targets, it goes without saying that target sets during a conflict with China and Iran could be much larger than the number of targets attacked in Iraq. If this should be the case, the combination of degraded PGM PA values and larger target sets could increase DoD's future munitions requirements far beyond what it has become accustomed to funding.

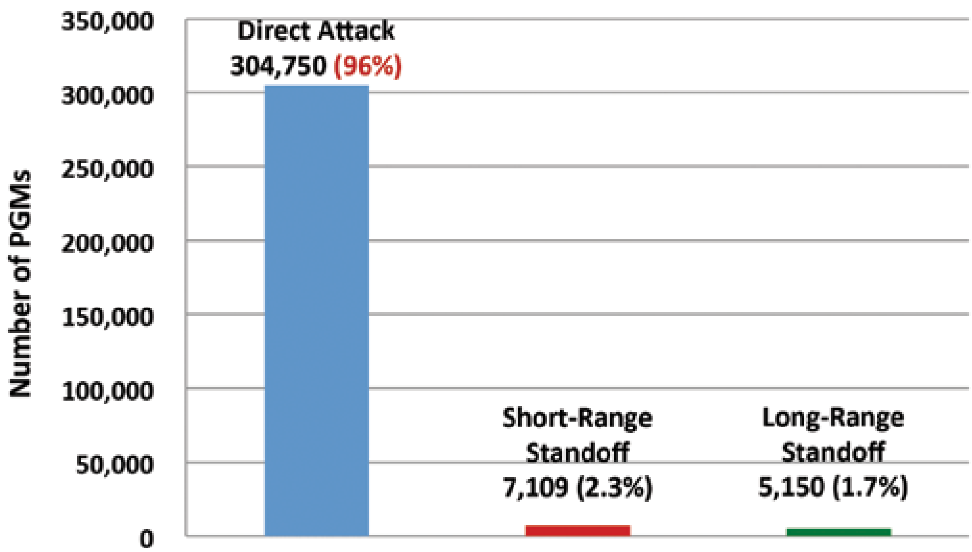
To illustrate this point, if enemy countermeasures reduce U.S. PGM PA values to 50 percent, nearly 298,500 PGMs (2 x 149,250) may be needed to attack a target set that is twice the number of targets struck during Operation Iraqi Freedom. This nearly equals the *total* number of PGMs (317,000) the Pentagon procured from 2001 through 2014, many of which have already been expended to support overseas contingency operations. The number of munitions DoD may need in future salvo competitions could be greater if it must conduct two or more strike campaigns in separate regions as required by its own strategic planning guidance.[33]

32 Figure 4 assumes a 1.5-to-1 PGM-to-aimpoint ratio as in the previous charts. It also assumes bombers perform all strikes, which is the most efficient approach in terms of number of sorties. If fighters or ships conduct the strikes, many more sorties or ship operations would be needed to attack the same number of aimpoints.

33 DoD's strategic guidance directs the Services to prepare to support future operations to "defeat a regional adversary in a large-scale multi-phased campaign, and deny the objectives of—or impose unacceptable costs on—another aggressor in another region." In other words, the Services must provide sufficient capabilities, including PGMs, to conduct two major combat operations. OSD, *Quadrennial Defense Review 2014,* p. 22.

Moreover, in future operations against capable militaries, it is probable that most targets worth attacking will be heavily defended. This could preclude the use of direct attack munitions by even the stealthiest strike aircraft. Nonetheless, DoD's munitions procurements indicate that it assumes its strike platforms will continue to be able to closely approach targets and strike them with direct attack weapons. Since 2001, DoD has procured far more direct attack PGMs than standoff weapons (see Figure 5).

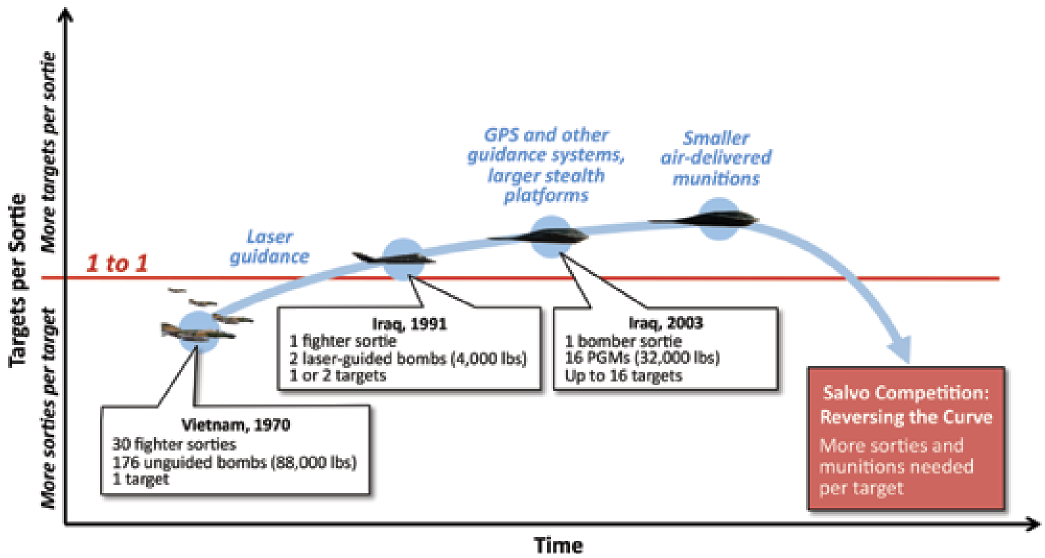
FIGURE 5. PGMS BY CATEGORY PROCURED BY DOD FROM 2001 THROUGH 2014[34]




If this assumption is no longer valid, the Pentagon faces a strategic choice: it could return to relying on mass (see Figure 6) to compensate for precision defenses, or it could choose to develop new operational concepts and take advantage of munitions technologies that help the U.S. military to maintain its precision strike advantage. Also, in order to maximize the number of weapons that can be delivered per sortie and reduce the overall cost of PGMs expended in a campaign, it would be advantageous to keep DoD's future PGM mix weighted toward smaller and lower cost munitions.

34 Figure 5 includes all air-launched direct attack munitions such as JDAMs and Hellfire missiles as well as short-range and long-range standoff PGMs that are listed in Appendix 1. It excludes short-range, ground-launched weapons like Javelin or TOW missiles. All PGM procurement quantities and funding in this report were compiled from the Procurement Programs (P-1) Amendment from DoD's budget requests from FY2001 through FY2014.

FIGURE 6. USING PRECISION PLUS MASS TO COMPENSATE FOR ENEMY DEFENSES




## Summary

The U.S. military has become accustomed to fighting militarily weak opponents that lack effective countermeasures against precision strikes. Benign threat environments have allowed U.S. strike aircraft to stage their operations close to an enemy and strike targets with direct attack PGMs without significant challenge. This is unlikely to be the case for all future operations. China, Russia, Iran, North Korea, and other potential adversaries are developing active and passive capabilities to disrupt the U.S. military's precision strike kill chain.

In the context of a salvo competition, new operational concepts and weapons that cost less and are smaller than very long-range standoff weapons could enable future strike forces to deliver more weapons per sortie. While this report focuses primarily on the PGMs themselves, it is imperative to note that taking advantage of shorter range weapons will require survivable delivery platforms such as the Long Range Strike Bomber (LRS-B), submarines, land- and carrier-based unmanned combat air systems (UCAS), and unmanned undersea vehicles (UUVs).

The next chapter assesses the feasibility of taking a brute force, "precision plus mass" approach to compensate for the precision strike defenses of an enemy. The last two chapters of this report assess alternative operational concepts and new PGMs that promise to create advantages for the U.S. military in a salvo competition.

CHAPTER 3

# Challenges of Precision Plus Mass

This chapter assesses the feasibility of simply using more strike sorties and current-generation PGMs to attack defended target sets. There are two basic "precision plus mass" approaches to overcome precision defenses. DoD could plan to employ more direct attack munitions delivered by strike platforms with sufficient range to reach enemy targets and survivability to operate in the face of enemy defenses. Or, DoD could plan to use more standoff attack PGMs that can be launched by aircraft, ships, and submarines located in low-threat safe areas. In both cases, relatively small decreases in PGM PA values could drive disproportionately large increases in the number of munitions and sorties needed for strike operations. Further, attempting to compensate for a salvo competition by taking a precision plus mass approach is likely to impose significant if not prohibitive costs on the United States rather than on its adversaries.

## More Direct Attack Munitions?

The U.S. military could plan to operate in the future much as it has over the last twenty-five years and rely on its ability to use direct attack PGMs—albeit in much larger numbers—to compensate for enemy countermeasures in a salvo competition. This brute force, precision plus mass approach raises a number of issues.

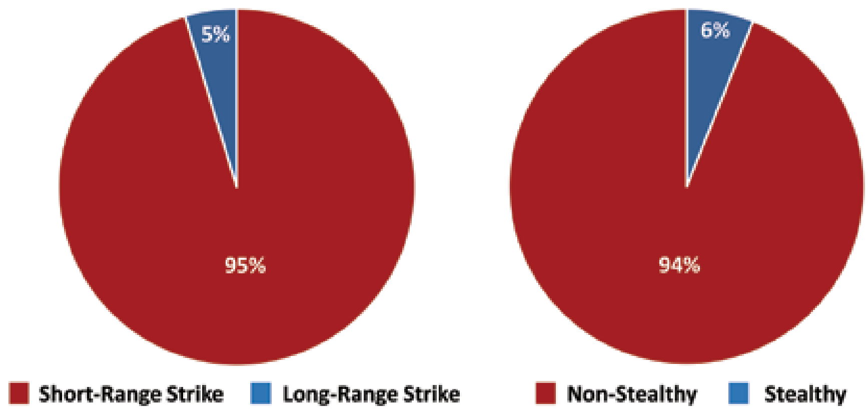
First, the U.S. military does not have enough strike platforms that are capable of penetrating contested areas to deliver much larger quantities of direct attack PGMs. The result of a near-continuous series of force cuts since 1991 is a joint combat air force that is the smallest and oldest DoD has ever operated.[35] Moreover, by 2024 the "penetrating" portion of DoD's aviation portfolio will consist of 20 B-2 bombers that have an average age of just over thirty

35 The number of submarines capable of launching standoff attack PGMs is also decreasing, and undersea strike capacity will drop by more than 60 percent between now and 2030 largely due to the decommissioning of all four of the Navy's nuclear-powered guided missile submarines.

years, 177 F-22 fighters with an average age of seventeen years, and about 460 more recently acquired F-35s.[36] Only the B-2s will have the range and degree of all-aspect, broadband low observability needed to penetrate and persist in high threat environments.[37]

Second, DoD is reducing the range over which it can conduct strike operations. Today's combat air force consists predominantly of short-range fighters (see Figure 7) that cannot easily conduct strikes with direct attack PGMs without access to bases and orbiting aerial refueling aircraft located in close proximity to target areas.[38] The need to dedicate some fighters to protect close-in bases and refueling aircraft from air and missile attacks would reduce the U.S. military's offensive strike capacity.

### FIGURE 7. COMPOSITION OF THE DEPARTMENT OF DEFENSE'S CURRENT COMBAT AIRCRAFT




Third, the U.S. military's fighters typically carry a dozen or fewer PGMs internally. DoD's fleet of about 140 surface combatants and submarines are similarly limited. They can launch Tomahawk strike missiles from standoff ranges of 800 nm to 1,000 nm, but can only expend 12 to 154 large standoff weapons before they need to return to port to reload.

Given the survivability, range, and payload constraints of DoD's current air and naval combat forces, it would be difficult for them to support large-scale precision plus mass strike operations penetrating deep into contested areas. This situation will not soon improve, given that DoD does not plan to significantly increase its strike capacity. Although DoD intends to replace most of its current fighters with F-35s, its future force will remain heavily weighted toward combat aircraft with an unrefueled combat radius of 600 nm to 800 nm.

36 DoD, *Annual Aviation Inventory and Funding Plan Fiscal Years (FY) 2015–2044* (Washington, DC: DoD, April 2014), p. 9.

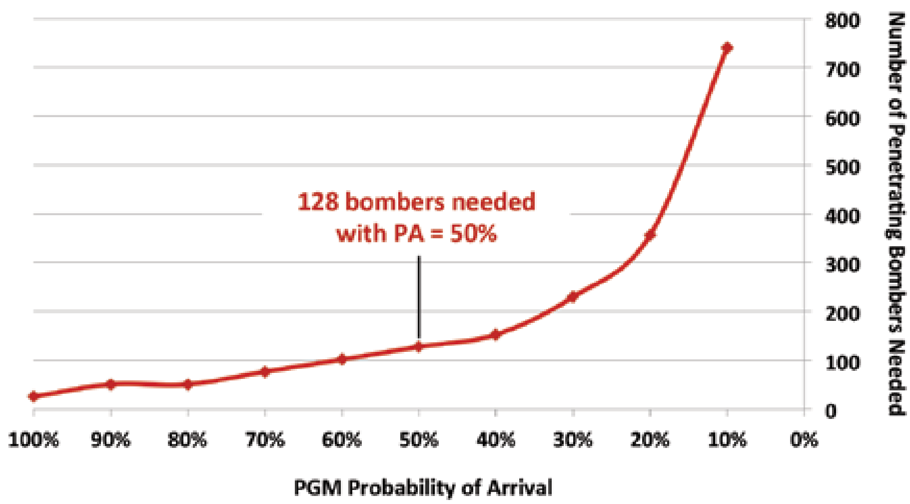
37 To a large extent, these reductions will be the result of defense budgets that are likely to remain close to levels required by the Budget Control Act of 2011 and Bipartisan Budget Act of 2013.

38 Figure 7 does not include stealthy F-35s that are in DoD's FY2015 inventory since they are not operationally capable. Data was compiled from DoD, *Annual Aviation Inventory and Funding Plan: Fiscal Years (FY) 2015–2044,* p. 9, and other sources.

Procuring new long-range, penetrating aircraft that are able to operate from aircraft carriers and airbases located outside the effective range of cruise and ballistic missile threats could create a more secure force posture and increase U.S. capacity for precision strike in contested environments. DoD has not started a program to develop a long-range, carrier-based strike aircraft. It does intend to procure up to 100 new land-based LRS-Bs that will be capable of operating from more secure bases and penetrating deep into high threat areas. Unfortunately, the combined payload capacity of DoD's planned penetrating bomber force—100 LRS-Bs and 20 B-2s (assuming all B-2s remain in the active inventory)—may still be insufficient to compensate for degraded PGM probability of arrival values.

To illustrate this point, the following example assesses the number of bombers needed for a notional strike campaign. When the final LRS-B is delivered sometime in the 2030s, DoD's combat-coded long-range penetrating strike force will consist of 105 stealthy bombers capable of flying operational missions.[39] This does not translate directly to 105 sorties per day if the bombers must fly 2,500 nm from the Western Pacific island of Guam to attack targets on continental Asia, or 2,700 nm from Diego Garcia in the Indian Ocean to strike deep into Iran. Based on data from previous air campaigns, 105 bombers operating from distant bases could generate 65 or fewer sorties per day.[40] While this may provide sufficient strike capacity for a single campaign against an Iraqi Freedom-sized target set assuming PGM PA values are 50 percent or higher, it would fall short of what is needed to attack a much larger target set or support two separate strike campaigns (see Figure 8).

### FIGURE 8. PENETRATING BOMBERS NEEDED TO SUPPORT A 30-DAY STRIKE CAMPAIGN[41]




39 This assumes approximately 15 percent of the future LRS-B force will be coded for training, testing, attrition reserve, and backup inventory, which is consistent with today's B-1 fleet.

40 The GAO reported B-52s flew an average of 0.6 sorties per day during Operation Desert Storm primarily because they operated from "far more distant bases" than fighters. GAO, *Operation Desert Storm Evaluation of the Air Campaign*, p. 170.

41 This chart assumes a 3-to-2 PGM-to-aimpoint ratio similar to that in Operation Iraqi Freedom and a 95 percent confidence level that each aimpoint is struck by a PGM.

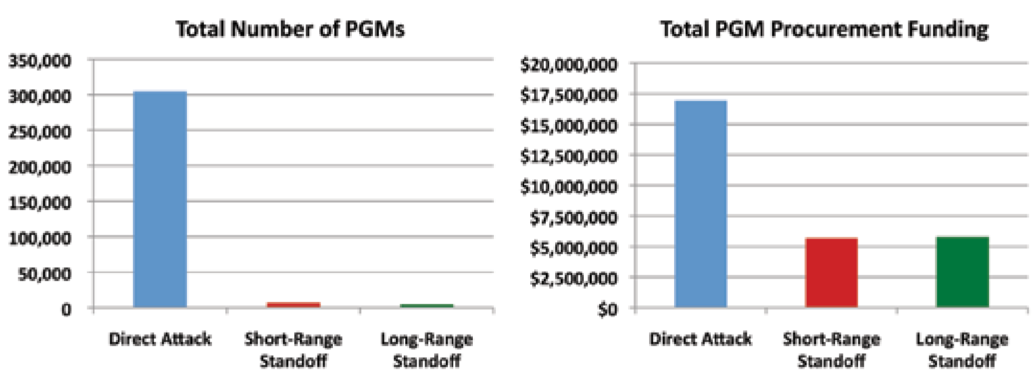
Bombers are used in this example because they can carry more weapons per sortie than smaller aircraft, and they can conduct more strikes over time compared to ships. If tactical aircraft or ships were included in this analysis, many more platforms would be needed. Further, bombers with longer ranges will have more basing options compared to short-range aircraft or ships that must stage their strikes from bases and littoral waters located close to an enemy.

## More Very Long-Range Standoff Attack PGMs?

It is important to note that Figure 8 assumes bombers will carry payloads of direct attack PGMs. Stealth aircraft rely on designs, materials, and tactics that reduce the probability that air defenses will track them with enough accuracy to cue intercepts by aircraft or surface-to-air weapons. Requiring stealth bombers to fly close (less than 50 miles) to point defenses surrounding targets could greatly increase the risk that they will be detected, tracked, and attacked by enemy defenses. This could make strikes using direct attack PGMs infeasible. Some have suggested that DoD could address this growing challenge by shifting the weight of its PGM investments toward buying long-range, standoff attack PGMs. While this shift would enable DoD to use its non-stealthy and short-range strike platforms in future strike operations, it would also be costly and create new operational challenges.

**Range can be costly.** Cruise missiles designed for very long-range standoff attacks are comparable to small, unmanned aircraft that have wings, engines, navigation systems, datalinks, and possibly one or more terminal seekers—all of which are sacrificed to deliver a warhead to a target. Similar to aircraft, long-range standoff missiles must use a combination of reduced radar cross-section (i.e., stealth), onboard decoys and electronic attack, and higher speeds in some cases in order to penetrate enemy air defenses. Together, these characteristics drive up the unit cost of standoff weapons. The average price of long-range standoff attack PGMs bought by DoD since 2001 was nearly $1.1 million, far more than the $55,500 average procurement unit cost of a direct attack weapon (see Figure 9).

### FIGURE 9. TOTAL DOD PGM PROCUREMENT SINCE 2001



Considering their high unit costs, using large numbers of current-generation standoff PGMs against large target sets is prohibitively expensive. Even assuming a PGM probability of arrival of 100 percent, which is probably unachievable, attacking an Operation Iraqi Freedom-sized target set of 19,900 aimpoints using only long-range standoff PGMs would cost $22 billion for the PGMs alone.[42] This $22 billion roughly equals the amount DoD has spent over the last ten years to procure PGMs of all classes. The total cost for long-range PGMs would quickly escalate for large operations against enemies with effective precision strike countermeasures.

**Operational limitations.** It is also important to consider operational factors that can reduce the utility of standoff weapons.

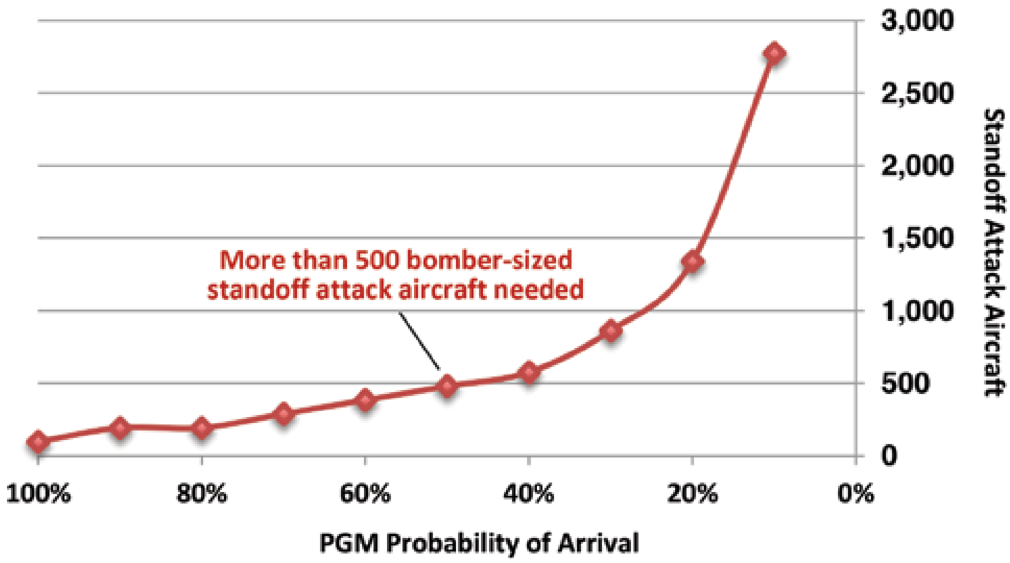
- Although non-stealthy cruise missiles are smaller than manned aircraft, and some are capable of maneuvering and low altitude flight to evade defenses, they could still be detected, tracked, and attacked by advanced air and missile defenses. Modern SAMs such as variants of Russia's S-300 and China's Hongqi-9 (HQ-9) are assessed to be capable of intercepting cruise missiles.
- Location errors induced by targets that are moving or have moved after a PGM is launched have the effect of reducing PGM PA values. Cruise missiles that fly at subsonic or supersonic speeds over long distances may not arrive in time to find and kill missile transporter erector launchers (TELs) and other targets that can quickly relocate. Provisioning long-range standoff weapons with datalinks so they can receive updates and terminal guidance commands while inflight could reduce target location errors.[43] However, long-range communications to munitions that penetrate contested areas may be susceptible to enemy jamming, and maintaining connectivity with a large number of PGMs over long distances could further strain the U.S. military's command and control networks.
- It is cost prohibitive to develop cruise missiles that carry conventional warheads large enough to penetrate very hard or very deeply buried targets. While it may be possible to develop enhanced penetrating warheads for cruise missiles that are suitable for these targets, these weapons are not yet in DoD's inventory.

**Salvo size.** The size of long-range standoff PGMs is another factor that calls into question the feasibility of using them on a much larger scale. Aircraft can carry fewer long-range standoff PGMs per sortie than most direct attack munitions that are smaller in size. As a result, the number of aircraft needed to deliver larger numbers of long-range, standoff PGMs would likely be much greater than the size of DoD's planned bomber inventory (see Figure 10).

42 This example assumes a 3-to-2 PGM-to-aimpoint ratio similar to that in Operation Iraqi Freedom.

43 DoD defines target location error as, "The difference between the coordinates generated for a target and the actual location of the target. Target location error is expressed primarily in terms of circular and vertical errors or infrequently, as spherical error." DoD, *Department of Defense Dictionary of Military and Associated Terms*, p. 250.

## FIGURE 10. AIRCRAFT NEEDED TO SUPPORT A 30-DAY STANDOFF STRIKE CAMPAIGN[44]




DoD now operates 96 combat-coded B-2s, B-52s, and B-1s. This small force would struggle to support the all-standoff strike campaign example illustrated in Figure 10, even in benign threat conditions where PGM PA values approach 95 percent. From a logistics perspective, providing sufficient aerial refueling and overseas basing for a much larger force of standoff strike aircraft and ships could outstrip what is available today.

As in Figure 9, this analysis is based on bombers conducting a notional strike campaign. Incorporating into this assessment fighter-sized aircraft that carry far fewer standoff weapons or ships and submarines that need days or weeks to reload after they expend their weapons, depending on the location of their reloading facilities, would further increase the number of strike platforms needed.[45]

## Summary

Allocating one or two PGMs per target may become the exception rather than the rule for future operations against enemies that have effective precision strike countermeasures. Attempting to compensate for reduced PGM probability of arrival and probability of damage by expanding the U.S. military's strike forces to deliver more current-generation PGMs could

44 This chart assumes a 3-to-2 PGM-to-aimpoint ratio and a 95 percent confidence that each aimpoint is hit by a sufficient number of PGMs.

45 Submarines and ships such as destroyers can carry long-range standoff weapons but must return to port to reload their magazines.

be a choice that imposes unsustainable costs on the United States. "More of the same" precision strike approaches could also prove ineffective, especially for campaigns against target sets that are more mobile, hardened, or deeply buried compared to target sets of the recent past.

There are alternatives. In lieu of assuming "one PGM, one target" will continue to be a rule of thumb for precision strikes, the U.S. military could develop new operational concepts and take advantage of munitions technologies that offset enemy active and passive defenses. DoD should also assess if its overall level of PGM investment, which has averaged roughly $2 billion a year, will be sufficient to prepare for future strike operations in environments that will be increasingly contested. While major programs to develop next-generation strike platforms have garnered a great deal of the Defense Department's attention and resources, it is time to acknowledge that these platforms will only be as effective as the PGMs they deliver.

CHAPTER 4

# New Operational Concepts for Larger PGM Salvos

This chapter proposes five new approaches for improving the size and survivability of strike salvos. These concepts address two major considerations that impact the U.S. military's ability to conduct effective precision strike operations:

- Range. The size of precision strike salvos fundamentally derives from the range over which they are launched. Airbases or aircraft carriers located close to target areas could increase U.S. military sortie rates and thus increase salvo sizes. However, operating from close-in bases could make U.S. forces more susceptible to enemy air and missile strikes that suppress U.S. sortie generation. While using more distant bases could reduce the threat or size of enemy precision attacks, the need to fly longer distances would reduce the total number of aircraft strike sorties U.S. power projection forces could generate each day.

- Platform-weapons pairing. New operational concepts for precision strike should seek to pair PGMs with launch platforms to achieve the greatest effect, rather than consider each in isolation. More specifically, concepts should strike a balance between launch platform survivability, platform PGM capacity, PGM cost, and PGM standoff range. Non-stealthy strike platforms that cannot penetrate contested areas may need to use very long-range PGMs against enemies with advanced air and missile defenses. Since the sizes of standoff PGMs increase with their range, long-range weapons are large and could weigh thousands of pounds.[46] Increased PGM size and weight reduces the number of weapons that ships and aircraft can deliver in a single sortie. Conversely, penetrating platforms that can approach more closely to defended targets can carry larger numbers of smaller,

46 For example, Conventional Air Launched Cruise Missiles (CALCMs) are about 20 feet long, weigh about 3,250 pounds, and have a range of more than 600 nm. The size and weight of a standoff attack PGM is also dependent on the size and weight of its warhead.

less expensive weapons. However, to defend themselves from enemy defensive combat air patrols (CAPs) protecting target areas, strike aircraft may have to devote payload capacity to self-defense weapons. This would reduce payload capacity available for offensive strike weapons.

## Leveraging America's Range Advantage

**Long-range strike operations**. Air forces can increase their salvo sizes by operating from bases located far enough away from an enemy to reduce the risk that air and missile attacks will suppress their ability to generate sorties. This would play to an advantage of the U.S. military, which has a fleet of bombers with unrefueled ranges of more than 4,000 nm and the capacity to carry up to 80 PGMs (depending on weapon size) each per sortie. U.S. long-range strike and ISR forces are also more fuel-efficient than forces operated by China, Russia, and other potential enemies, and are supported by the world's largest and most capable aerial refueling fleet.

These capability attributes could give U.S. forces a significant long-range strike "throw-weight" advantage in future wars. For instance, at strike distances greater than 2,500 nm, U.S. combat aircraft would be able to deliver more weapons for a given amount of fuel compared to the People's Liberation Army (PLA), which has less fuel efficient aircraft and fewer tankers. This advantage, combined with the reduced risk of PLA air and missile attacks against U.S bomber bases, would translate into larger U.S. PGM salvos compared to the PLA. The opposite may be true for U.S. forces that operate from bases that are located within 2,500 nm of China's mainland. At strike distances less than 2,500 nm, the PLA's much larger fighter and bomber force would be able to launch more PGMs for a given amount of fuel, primarily because they would not need a great deal of aerial refueling support.

Given the benefits of operating from longer ranges, DoD should plan to operate a larger percentage of its strike forces from bases that are beyond the reach of most cruise and medium-range ballistic missiles launched from mainland China, Iran, North Korea, and other potential enemies (see Figure 11).

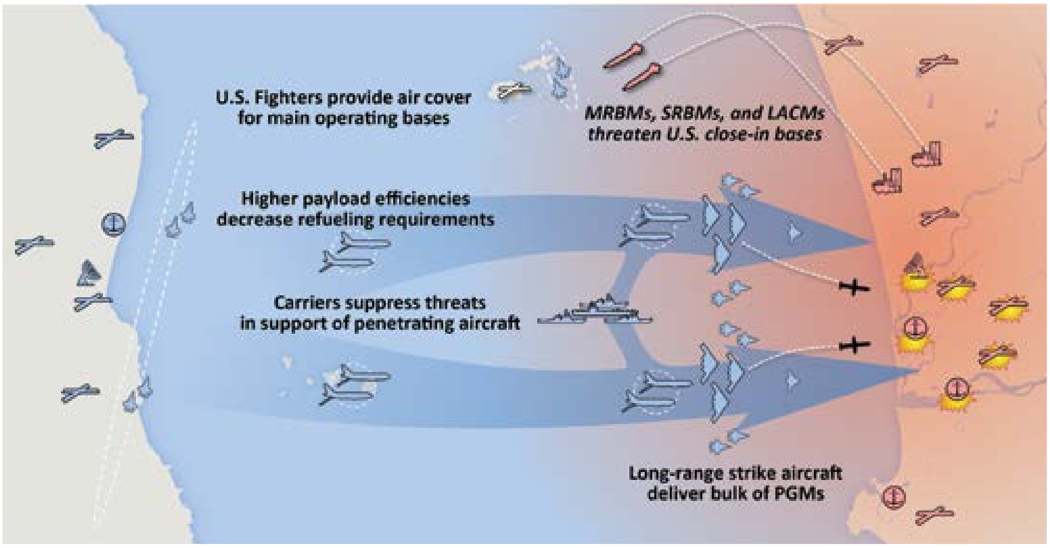
A shift toward longer-range strike operations has obvious implications for DoD's future bomber, tanker and ISR force structure, and future fighter operations.

Today, DoD's manned bombers are capable of sustaining operations over very long ranges. In the future, unmanned long-range strike aircraft such as carrier-based and land-based unmanned combat air vehicles (UCAVs) may be more efficient at delivering these strikes for a given amount of fuel. Similar to manned penetrating aircraft, these UCAVs would need broadband, all-aspect stealth to evade advanced integrated air defense systems.[47] A

47 For more information on desirable capability attributes for future UCAVs, see Robert Martinage, *Toward a New Offset Strategy* (Washington, DC: Center for Strategic and Budgetary Assessments, 2014), p. 87.

shift toward long-range strike operations would also require more surveillance and targeting support from space-based sensors that cover targets deep in contested areas, as well as submarines that can be positioned close to target areas. In the future, precision targeting information could be provided by unmanned undersea vehicles (UUVs); penetrating UAVs that have long-range sensors; and high altitude, long endurance aircraft such as the MQ-4 Global Hawk, Broad Area Maritime Surveillance (BAMS) unmanned aerial vehicle (UAV).

FIGURE 11. OPERATING CONCEPT FOR LONG-RANGE STRIKE




## Dispersing Fighter Bases

DoD's fighter aircraft will not contribute significantly to the salvo capacity of future U.S. power projection forces if they must operate over very long ranges. Compared to a bomber, a fighter has about one-fifth the unrefueled range and can carry one-tenth the payload. Because of their short unrefueled ranges, most fighters may need to operate from bases that are located inside contested areas.

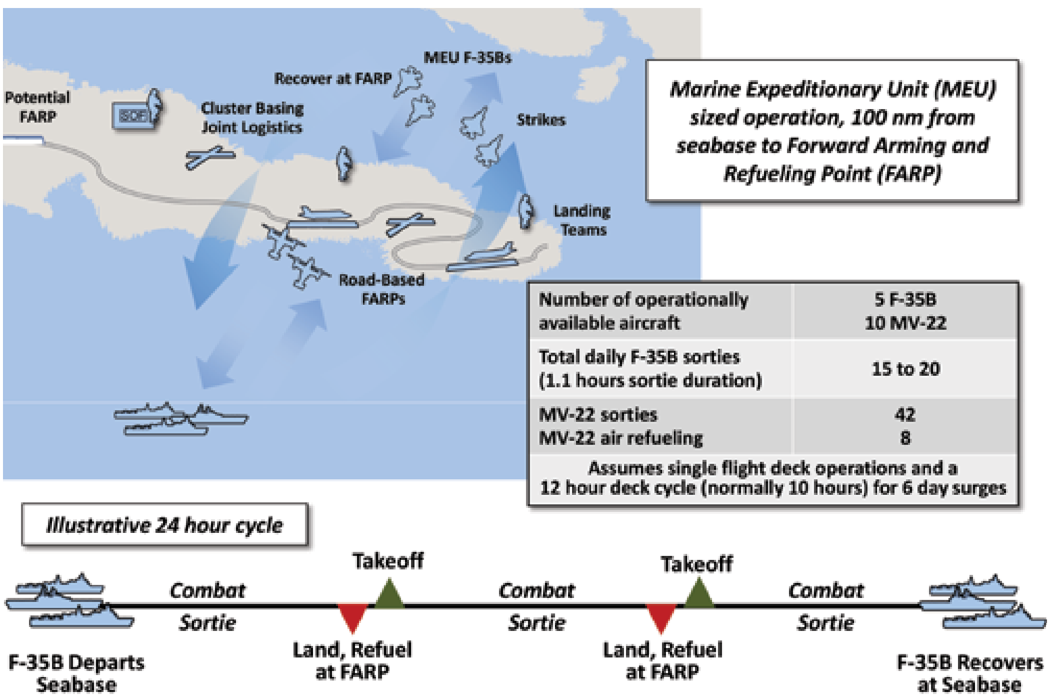
Considering their range and payload limitations, DoD should consider using its fighters to attack lightly defended targets that require smaller PGM salvos during future operations. Fighter aircraft could also contribute indirectly to future strike campaigns by suppressing threats to bomber aircraft, allowing the bombers to more closely approach targets and deliver their large payloads of PGMs.

DoD fighters include short takeoff and vertical landing (STOVL) aircraft such as Harrier "jump jets" and F-35Bs operated by the U.S. Marine Corps, conventional takeoff and landing (CTOL) aircraft, and aircraft carrier-based aircraft. Different operational concepts for each type of aircraft could increase their sortie generation potential during operations in contested areas.

**Distributed STOVL Operations.**[48] Operating from bases located close to target areas would enable deployed U.S. forces to generate more fighter strike and defense suppression sorties per day. Of course, this would also increase the risk that enemy air and missile attacks on forward bases will degrade U.S. fighter sortie generation. To decrease this risk, U.S. forces could stage some of its fighter operations from small, expeditionary airfields, and relocate its fighter forces to new expeditionary airfields every few days. Using temporary, relocatable expeditionary airfields instead of fixed main operating bases that are at well known locations could greatly complicate an enemy's ability to target U.S. fighter forces.

One approach would be to conduct dispersed operations from multiple, small forward air refueling points (FARPs) ashore using Marine Corps STOVL fighters that are designed to fly from large-deck amphibious ships and improvised austere airstrips. Nearby amphibious ships would provide maintenance and support facilities for these small airfields and provide lift to periodically redeploy fighter forces to new expeditionary airfields (see Figure 12).

## FIGURE 12. EMERGING CONCEPT FOR DISTRIBUTED STOVL OPERATIONS

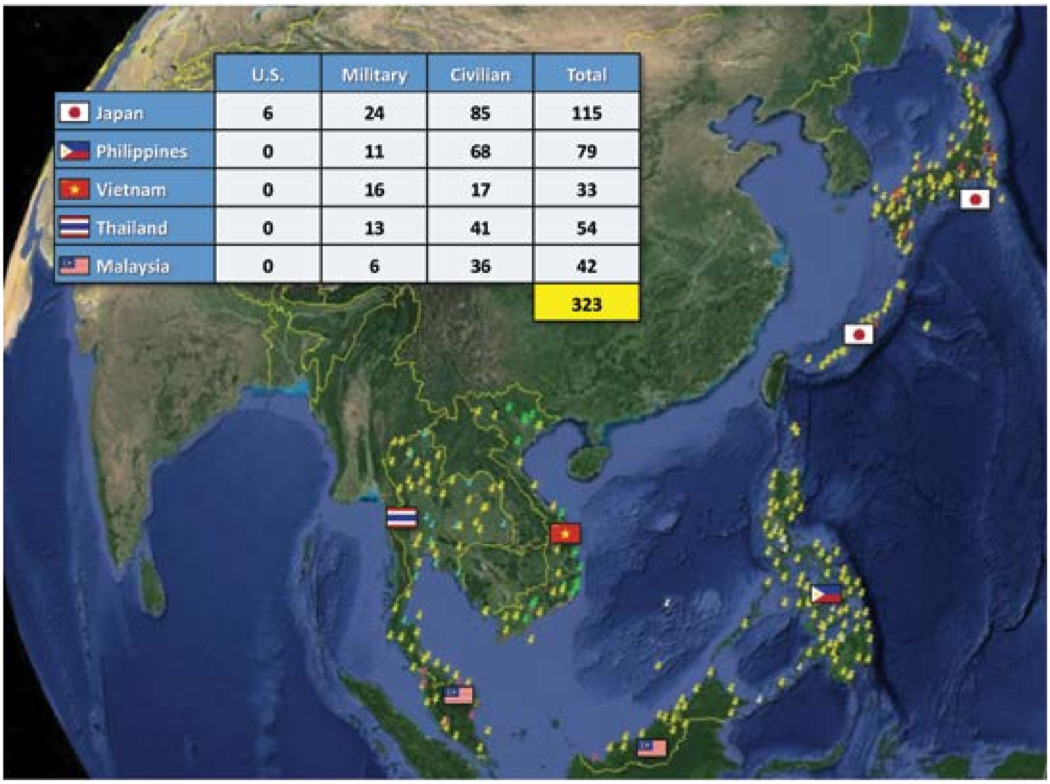



| | |
|---|---|
| Number of operationally available aircraft | 5 F-35B<br>10 MV-22 |
| Total daily F-35B sorties (1.1 hours sortie duration) | 15 to 20 |
| MV-22 sorties<br>MV-22 air refueling | 42<br>8 |
| Assumes single flight deck operations and a 12 hour deck cycle (normally 10 hours) for 6 day surges | |

48 The distributed STOVL operations (DSO) concept is being developed within the Marine Corps Concept Development Command (MCCDC).

Hundreds of airstrips on the periphery of the South and East China Seas may be capable of supporting DSO in the future (see Figure 13). Some of these airstrips may need improvements such as expeditionary runway matting in order to support STOVL aircraft.[49]

### FIGURE 13. POTENTIAL WESTERN PACIFIC AIRFIELDS FOR STOVL AIRCRAFT[50]



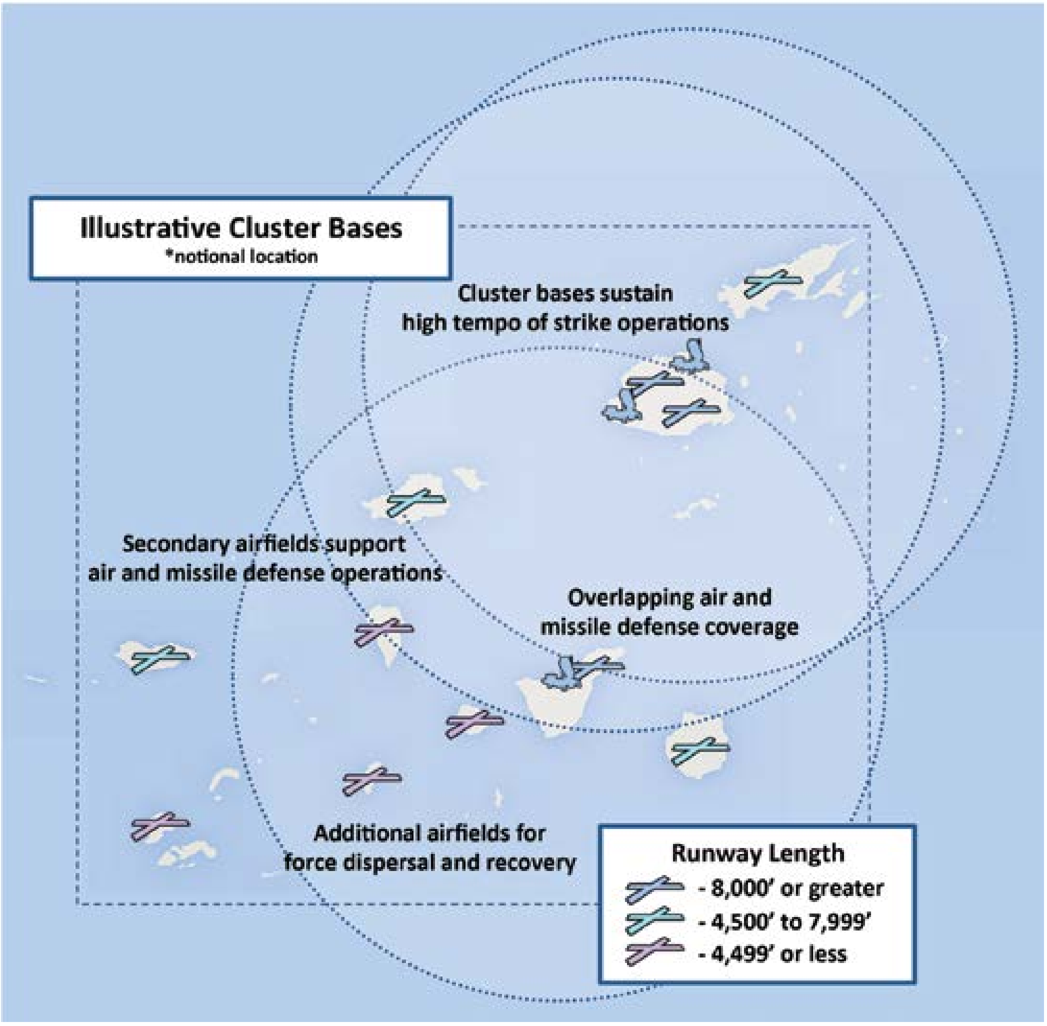
| | U.S. | Military | Civilian | Total |
|---|---|---|---|---|
| Japan | 6 | 24 | 85 | 115 |
| Philippines | 0 | 11 | 68 | 79 |
| Vietnam | 0 | 16 | 17 | 33 |
| Thailand | 0 | 13 | 41 | 54 |
| Malaysia | 0 | 6 | 36 | 42 |
| | | | | 323 |

**Cluster Basing.** Compared to STOVL aircraft, CTOL fighters need longer runways and will be less able to use improvised or austere airfields. They will need to use operational concepts that improve the ability of traditional bases to generate sustained strike and escort fighter sorties. "Cluster basing" is one such approach that consists of airfields located close enough together for their air and missile defenses to be mutually supporting, as represented by the blue circles in Figure 14. A base cluster may include large and small airfields, not all of which would be in operation at any particular time.

49 Airfields not constructed with high-strength, thermally resistant concrete may require substantial amounts of runway matting to support F-35B STOVL aircraft operations.

50 Figure 13 illustrates airfields that are at least 2,000 feet long. It excludes highways, taxiways, and other locations that may be able to support STOVL operations.

FIGURE 14. EMERGING CONCEPT FOR CLUSTER BASING



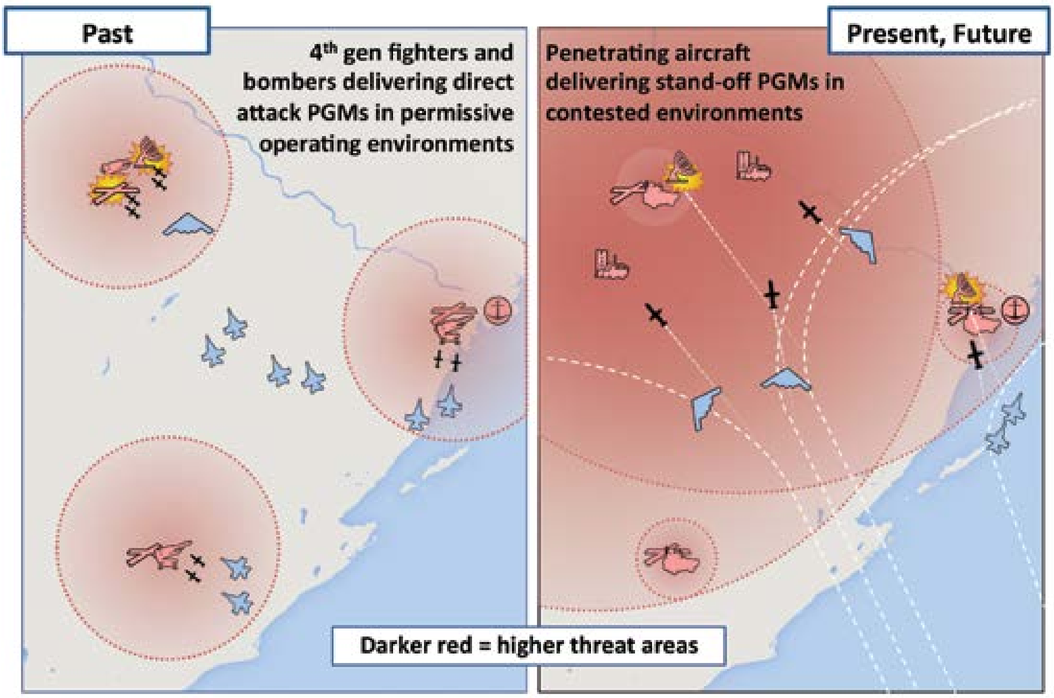

Cluster basing would increase the area over which adversaries have to conduct strikes to suppress U.S. sortie generation while increasing the defensive capacity that could be brought to bear in protection of any particular base in the cluster. CTOL and STOVL fighters operating from clustered airfields could conduct CAP operations to augment the cluster's defenses. In the future, base clusters could be protected by high-capacity air and missile defense systems such as electromagnetic rail guns, artillery firing high-velocity guided projectiles (also known as "powder" guns), and directed energy weapons.

Large airfields in clusters may also be able to act as temporary rearming and refueling points for long-range aircraft that are stationed at more distant main operating bases. These benefits, along with improving the operational tempo of fighter aircraft in close-in contested areas, could increase the overall strike capacity of U.S. forces.

## Shifting to Short-Range Standoff Strike

As described above, over the past twenty-five years U.S. forces have been able to conduct the vast majority of their strikes using short-range, direct attack weapons delivered by non-stealthy platforms. As enemy point defenses improve, U.S. strike aircraft—even stealthy ones—will need to operate at higher risk to deliver direct attack PGMs and possibly devote some of their payload to defensive weapons. The effect of these measures would be smaller strike salvos. Penetrating aircraft could improve their survivability against point defenses by delivering PGMs from standoff distances that reduce the probability that they will be detected and attacked (see Figure 15).

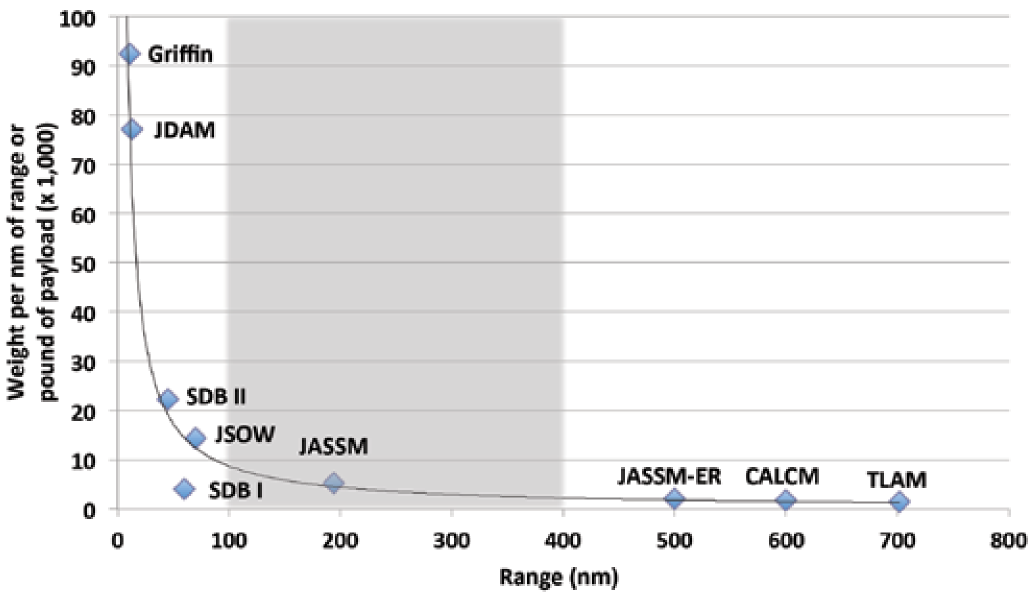
FIGURE 15. SHIFT TOWARD STANDOFF ATTACK IN CONTESTED ENVIRONMENTS




Longer standoff distances, however, will require aircraft to use larger, standoff attack PGMs that will reduce the total number of weapons they can carry per sortie. Achieving the right balance between standoff range and weapon size would help optimize the size and effectiveness of the U.S. military's PGM salvos.

Figure 16 suggests how DoD could achieve this balance. The figure shows how many pounds a weapon weighs for each pound of warhead explosive or nautical mile worth of PGM fuel.[51] At short ranges, PGMs are generally designed to maximize their destructive potential instead of aerodynamic efficiency. As PGM ranges increase from 0 to 100 nm, each additional pound of warhead or nautical mile worth of PGM fuel increases weapon size less than the preceding pound or mile, because the weapons are generally designed to be more aerodynamically efficient. At ranges greater than 400 nm the curve becomes nearly linear, showing that each pound of warhead or nautical mile worth of fuel adds the same weight as the preceding one because PGMs with those ranges are essentially designed to be small, aerodynamically efficient unmanned aircraft.

## FIGURE 16. WEIGHT VS. RANGE, OR WEIGHT VS. PAYLOAD FOR DOD STRIKE WEAPONS




The grey area in Figure 16 between 100 nm and 400 nm illustrates there may be a "sweet spot" for standoff range that reduces the risk to strike aircraft while not increasing the size of weapons to the point where PGM salvos are greatly reduced. Standoff strike ranges of 100 nm or more would be sufficient for penetrating stealth aircraft to avoid most enemy point defenses. Non-stealth aircraft engaging weakly or modestly defended target areas could employ PGMs with ranges between 100 and 400 nm. PGMs with ranges greater than 400 nm would still be needed by non-stealth aircraft attacking targets in contested operational environments (i.e., defended by air interceptors), by surface combatants that are likely to be tracked and targeted

51 Figure 16 assumes a standoff weapon system's payload consists of fuel and warhead explosives. Therefore, the chart shows how much the weapon weighs for each pound of warhead explosive or nautical mile of range provided by fuel. Seekers and guidance systems are assumed to not be significant contributors to weight; they are also assumed to be nearly constant in size regardless of the weapon, so should not significantly affect the relationship between overall PGM size and range.

in close-in littoral waters, or when time constraints preclude strike platforms from travelling longer distances to target areas. In these cases, operational concepts should compensate for the resulting reduction in salvo sizes by using PGMs with capabilities that increase their PA values against enemy defenses.

Figure 16 also shows that DoD's current PGMs, with the exception of JASSMs, have a range of less than 100 nm or are very long-range standoff (greater than 400 nm range) weapons. This PGM mix requires strike planners to either place aircraft at risk by tasking them to deliver direct attack weapons or to accept much smaller salvos by using long-range standoff weapons against target sets. Shifting toward standoff strike operations that use PGMs with ranges between 100 nm and 400 nm could create a better balance between standoff attack ranges, aircraft survivability, and PGM salvo sizes.

## Increasing PGM Salvo Survivability

In addition to weapon features such as stealthy shapes and electronic countermeasures that improve the survivability of individual weapons, new operational concepts could improve the overall PA of PGM salvos. Smaller salvos with higher overall PAs could place the same number of weapons on targets as larger salvos delivered using traditional operational concepts. The following two approaches would help achieve this objective.

**Tunneling.** U.S. forces could increase the PA of their PGM salvos by leading them with a wave of decoys and small, cheap munitions. An enemy may deplete its ready-to-launch defensive interceptor missiles, loaded gun rounds, and directed energy batteries on this initial "tunneling" wave, opening a window in which it has less defensive capacity until these systems can be reloaded or rearmed. During this time, which can be seconds to minutes, subsequent waves of more capable PGMs could penetrate to strike targets.

SDB IIs on an aircraft

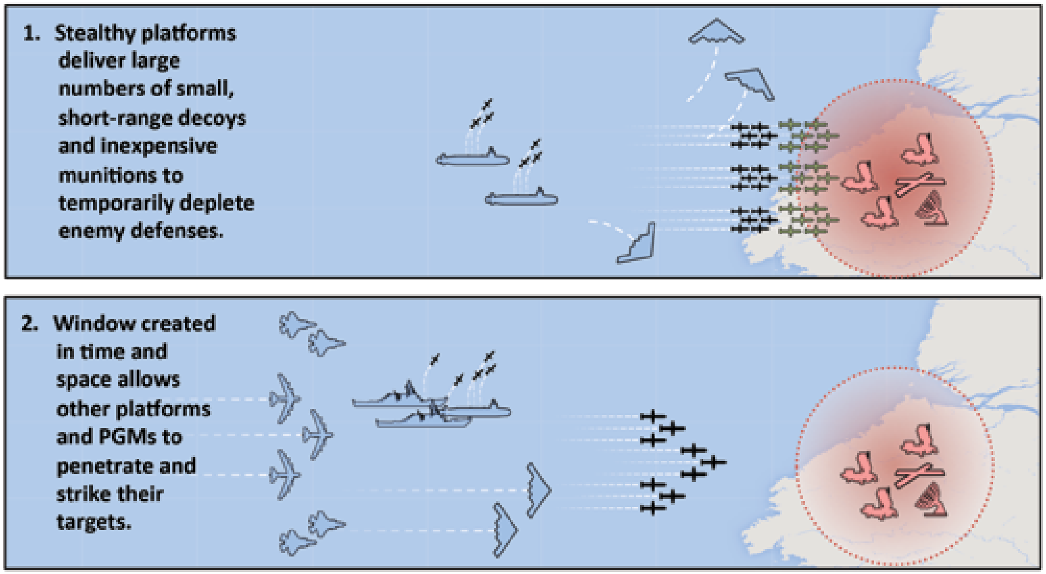
MALD-J in flight

DoD now has some capabilities to conduct tunneling operations. Strike salvos could be preceded with decoys such as the Miniaturized Air Launched Decoy-Jammer (MALD-J) that draw defensive weapons away from PGMs and reduce the effectiveness of air defense radars. Small, inexpensive PGMs such as SDBs could be used at the beginning of salvos to deplete enemy defenses and improve the survivability of follow-on waves (see Figure 17).[52] New

52 Chapter 5 describes additional capabilities for tunneling operations.

weapons and decoy technologies described in Chapter 5 could enable more effective or less expensive tunneling operations.

## FIGURE 17. OPERATIONAL CONCEPT FOR "TUNNELING"

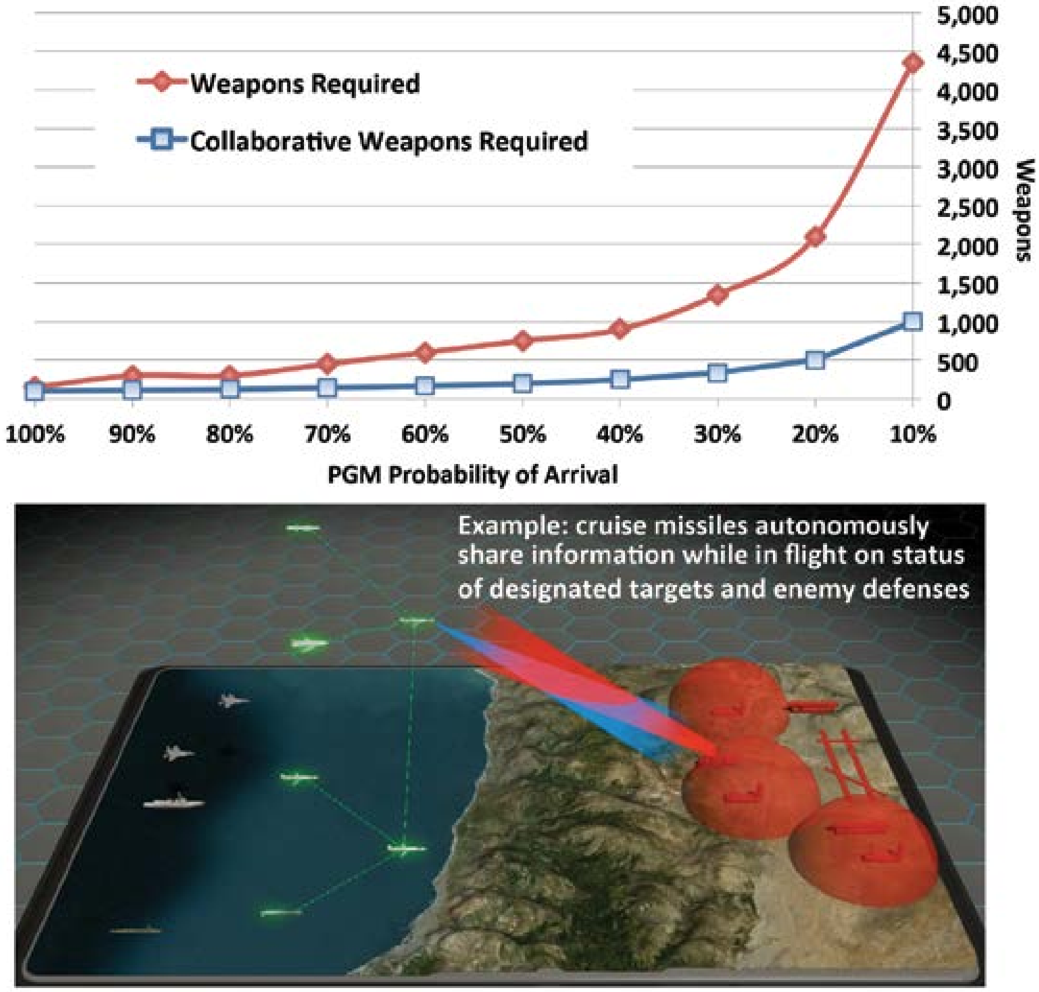



**Collaborative weapons operations.** As discussed in Chapter 3, attackers may need to assign multiple PGMs to each aimpoint to compensate for uncertainty over which weapons will be intercepted by precision defenses. For example, if PGMs in a salvo have individual PA values of 50 percent, an attacker would need to use five PGMs against every aimpoint.[53] This number could be reduced, as shown in Figure 18, if a salvo of PGMs could be retargeted in flight either through command direction or as a result of autonomous collaboration between PGMs. This would help ensure that all aimpoints are struck by a PGM salvo, even if a portion of the PGMs originally designated for a particular aimpoint are defeated by enemy defenses.

DoD has some capabilities to conduct collaborative strikes by using surveillance systems and datalinks to determine which PGMs have been intercepted and redirecting surviving PGMs inflight to strike remaining targets. JASSM and Tomahawk missiles already have datalinks for near-real-time feedback and remote command and control. Because these functions require "man in the loop" controllers, however, enemy jamming that degrades their datalinks and increases the time needed to retarget could limit the scale of JASSM or Tomahawk collaborative strikes. Chapter 5 describes new weapons technologies that promise to automate PGM collaboration and enable it to occur within large salvos.

53 This assumes the attacker's objective is to strike each aimpoint with a confidence level of 95 percent.

FIGURE 18. COLLABORATIVE PRECISION-GUIDED MUNITIONS TO HIT 100 AIMPOINTS




## Increasing Maritime Strike Capacity

Ships and submarines carry a relatively small number (12 to 154) of strike weapons and require days or weeks to return to port and reload. As a result, they may have little impact on future large-scale strike operations against enemies with effective precision defenses. The strike capacity of naval platforms could be improved through new operating concepts that focus on maximizing the offensive capacity of their vertical launch system (VLS) magazines.[54]

54 Bryan Clark, *Commanding the Seas: A Plan to Reinvigorate U.S. Navy Surface Warfare* (Washington, DC: Center for Strategic and Budgetary Assessments, 2014), p. 17.

**A new concept for defensive anti-air warfare.** The U.S. Navy uses a layered air defense concept that attempts to defeat incoming weapons as far as possible from surface ships. This concept creates disadvantageous cost and missile exchanges, because it preferentially uses the largest and most expensive air defense interceptors to destroy air and missile threats as far as possible from the defended ship at ranges of up to 100 nm or more. The Navy only employs smaller, less expensive interceptors and electronic warfare (EW) systems after long-range interceptors have failed to hit their targets.

This air defense approach could use the entire VLS magazine of a destroyer to defeat adversary ASCMs that cost less than 2 percent of the cost of the destroyer. It would also leave the destroyer with no VLS capacity for offensive weapons to attack enemy ships and aircraft or conduct strikes ashore. If the Navy adopted a shorter-range air defense concept for its surface fleet, it could load its VLS cells with a larger number of small SAMs and free up VLS capacity for strike missiles. A short-range air defense operational concept would also enable the Navy to use electronic warfare systems and, when they mature, defensive laser weapons and electromagnetic rail guns instead of SAMs against some air and missile threats. These weapons could be effective at ranges of 10 to 30 nm and would protect ships from attack without crowding out VLS capacity for offensive missiles.

**At-sea VLS reloading.** Today, U.S. ship and submarine VLS cells carry weapons that are generally dedicated to single missions such as anti-air, anti-ship, and strike, and they can only be reloaded when in port. As a result, ships and submarines have a fixed capacity for each particular mission once they are underway. When the mission priorities of a ship change, it is unable to increase its capacity for the new mission unless it returns to port to reload its VLS magazine. For example, a ship could deploy with a VLS load-out weighted toward air defense, but be redirected to conduct strike missions. The ship would have a small capacity for strike that would be quickly exhausted. Similarly, a ship cannot replenish its magazine at sea.

The Navy could reduce this operational limitation and increase its strike capacity by providing its ships with the ability to reload VLS cells at sea. However, even with such an improvement, ships and submarines would still have limited magazine capacity relative to air-delivered strikes. This suggests that ships and submarines should primarily be used for small long-range standoff strikes using PGMs with very high PAs, rather than large-scale attacks.

## Summary

U.S. forces could address salvo competition challenges by operating in ways that improve their ability to generate sorties and increase the survivability and size of their precision strike salvos. In particular, U.S. strike forces could gain an advantage by leveraging their greater range, fuel efficiency, and ability to sustain operations from distant bases that enemy forces can only reach with large, expensive missiles. Short-range combat aircraft could complement this operational approach by shifting from being the U.S. military's predominant strike force to a force that is more focused on counterair and supplementary small-scale attacks.

New operational concepts could also help maximize the salvo capacity of U.S. penetrating aircraft in future conflicts. As air defenses improve, even stealthy strike platforms will need to operate from standoff ranges to avoid point defenses around enemy targets. Too great a standoff range, however, will require strike aircraft to use large PGMs that reduce the number of weapons they carry. PGMs with a "sweet spot" range of 100 nm to 400 nm could provide strike platforms with sufficient standoff and maintain their salvo potential.

New operating concepts for ships could make more of their VLS capacity available for offensive PGMs and increase their strike capacity by reloading at sea. Salvo sizes could be further increased by structuring them in ways that would improve the survivability of individual PGMs. Some of the operational concepts suggested in this chapter, such as tunneling and collaboration, could be done on a limited scale with today's weapons. New technologies for high-speed flight and electromagnetic warfare would improve their effectiveness and ability to ensure designated aimpoints are struck even when some PGMs are lost in flight. These and other new PGM capabilities are addressed in Chapter 5.

CHAPTER 5

# Creating New Precision Strike Advantages

New operational concepts for precision strike should be complemented by PGMs that are more survivable and effective against challenging target sets. This chapter assesses four broad munitions initiatives that could support operational concepts summarized in Chapter 4 and help reduce the impact of an enemy's precision strike countermeasures.

First, the Pentagon could leverage existing technologies to improve the capabilities of its contemporary PGMs. For instance, it may be feasible to extend the range of some direct attack PGMs to allow the launching penetrating aircraft to avoid point defenses and strike targets. Modifying some PGMs by provisioning them with small, inexpensive rockets or motors to increase their standoff ranges could be far less expensive than buying more long-range cruise missiles that cost more than $1 million each on average. Existing technologies could also enable PGMs to perform multiple missions, increasing the effective strike capacity of ships and aircraft.

Second, it may be possible to improve PGM survivability by taking advantage of stealth technologies, hypersonic engine and airframe designs, and electronic warfare capabilities. All three would complicate an enemy's defensive operations and impose costs by partially negating their investments in precision strike countermeasures.

Third, DoD could take greater advantage of advances in miniaturization and smart submunitions, increasing the number of targets that aircraft, surface combatants and submarines, and even individual PGMs can strike.

Fourth, DoD could invest in options to increase PGM lethality against hardened targets. Powered, earth-penetrating warheads could, for example, provide MOP-like effects with smaller weapons that could be delivered by aircraft other than bombers. HPM warheads could also neutralize physically hardened targets by attacking their "soft" command, control, and communications systems.

It is also important to ensure DoD's future penetrating strike platforms will be able to carry new and modified PGMs in their internal weapon bays. PGMs carried externally increase the signature of stealth aircraft and the probability they will be detected and tracked by air defense systems. Moreover, designing PGMs so they can be launched by multiple platforms including submarines, surface ships, and ground-based launchers may help the Pentagon to take advantage of economies of scale, rather than fund separate programs for PGM designs that are unique to particular strike platforms.

## Improving the Capabilities of PGMs

**Creating multi-mission functionality.** DoD could take advantage of existing technologies to upgrade today's PGMs and develop new PGMs to achieve greater mission flexibility. This would increase the effective capacity of its strike platforms and help achieve economies of scale in weapons procurement.


SM-6 launch from a U.S. Navy destroyer

For instance, ship VLS magazines have a relatively small capacity and are difficult to reload at sea. Multi-mission weapons would enable a ship or submarine to have more capacity for any specific mission and possibly reduce the need to change its weapon load-out when, for example, its operations change from strike to counter-shipping warfare. The Navy is working on modifications to its Tomahawk Land Attack Missiles that would enable them to also attack surface ships.[55] The Navy's older Standard Missile-2 (SM-2) air defense interceptors can strike targets on land and at sea, although they may lack the range to do so without exposing the launching ship to counterattacks. The Navy is developing an SM-6 variant with GPS guidance that could, with modifications to the Aegis fire control system, enable it to also strike surface and land-based targets at OTH ranges.

Similarly, the Joint Air-to-Surface Standoff Missile and its derivatives could become another family of multi-mission PGMs. Designed to penetrate contested areas, JASSMs have GPS-aided INS for inflight guidance, imaging infrared seekers, and pattern matching autonomous target recognition capability for attacking fixed and relocatable targets. An upgraded variant, JASSM-Extended Range (JASSM-ER), has a range that exceeds 500 nm, more than double the original JASSM's range.[56] DoD has chosen JASSM-ER as the baseline weapon

55 The Navy originally fielded a long-range anti-ship variant of the Tomahawk, the RGM-109B Tomahawk Anti-Ship Missile (TASM), in the 1980s, but then-extant targeting capabilities were inadequate to enable its long range to be exploited. The missiles were withdrawn from the fleet by 1994, and remanufactured into land-attack missiles.

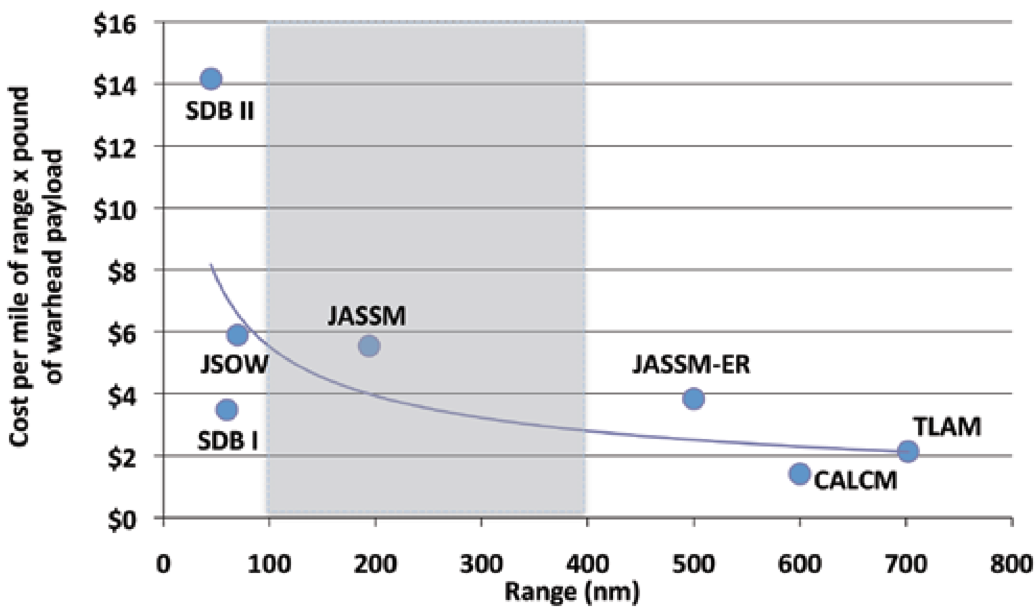
56 "AGM-158A JASSM (Joint Air-to-Surface Standoff Missile), AGM-158B JASSM-ER and LRASM," in Hewson, *Jane's Weapons: Air-Launched 2014–2015*.

for developing a stealthy air-launched and surface-launched Long Range Anti-Ship Missile (LRASM). Designing LRASMs so they are also capable of striking land-based targets would help increase the Navy's offensive punch and reduce the need to develop a new surface-to-surface weapon.

**Increasing PGM range at reasonable cost.** Chapter 4 describes how the proliferation of advanced point defense weapons will increasingly necessitate penetrating stealth aircraft to launch attacks from standoff distances. Future strike operations against well-defended targets could require large numbers of standoff attack weapons. Procuring these weapons would be a significant challenge under the defense budget caps of the 2011 Budget Control Act and subsequent laws. Therefore, DoD should balance PGM unit costs with the need for standoff range.

The 100 to 400 nm range sweet spot suggested in Chapter 4 may also apply to PGM unit costs. The cost of a PGM rises with the distance that it must fly after launch. As range requirements increase, powered PGMs will need to carry more fuel for their engines and larger or more efficient components such as batteries to power their systems until they reach their targets. Figure 19 compares the ranges, payloads, and costs of current U.S. standoff attack PGMs. From 0 to 200 nm the curve is particularly steep, indicating a weapon could increase its standoff range for a small increase in cost; these PGMs could be winged bombs that have small, short-endurance engines. Beyond about 400 nm, more range increases the weight, size, and cost of cruise missiles nearly linearly. Shifting investments toward PGMs in the 100 to 400 nm range band would increase the U.S. military's capacity to strike defended targets and avoid the high cost of buying large numbers of PGMs that have much longer ranges.

## FIGURE 19. COST VS. RANGE, OR COST VS. PAYLOAD FOR DOD STANDOFF PGMS



Booster engine on a JSOW

**Enabling PGM internal carriage.** DoD should ensure its future standoff attack PGMs are sized to fit in the internal weapons bays of aircraft that must remain stealthy. According to the Air Force, all of its combat aircraft have weapons bays that can carry munitions that are up to 168 inches long and 20 inches in diameter.[57] The unpowered JSOW, which can glide for about 65 nm,[58] is 160 inches long, 13 inches in diameter, and can be carried internally by the F-35 and other fighters. JASSM-ERs, which have a range of more than 500 nm, are 168 inches long but have a width that exceeds the capacity of F-22 and F-35 weapon bays. Bombers with larger weapon bays can carry PGMs that are up to 250 inches long. The Conventional Air-Launched Cruise Missile (CALCM), which has a range of 600 nm or more, is 249 inches in length and has a diameter of 24.5 inches.[59] As a result, CALCMs must be carried in bomber-sized weapons bays or on aircraft external pylons.

There are several options for fielding PGMs that are affordable, have ranges in the 100 to 400 nm sweet spot, and can be carried internally by penetrating aircraft.

First, it is feasible to modify some less expensive, direct attack PGMs to increase their ranges. For instance, adding wings to the JDAM that deploy after the weapon's release from an aircraft can nearly triple its glide range to 45 nm.[60] It is also feasible to add small powerpacks to direct attack weapons to extend their range. A terminated DoD program added a small turbojet engine to the JSOW to quadruple its range to 250 nm.[61] Powered JSOWs conformed to the size and shape of unmodified JSOWs that can be carried by F-35s internally. The same would likely be true for the Small Diameter Bomb Increment II (SDB II), one of DoD's newest PGMs.

57 U.S. Air Force, Scientific Advisory Board, *Report on Why and Whither Hypersonics Research in the US Air Force* (Washington, DC: DoD, 2000), p. 47.

58 Unpowered JSOWs can glide as far as 65 nm if they are dropped by aircraft flying at high altitudes.

59 U.S. Air Force, "AGM-86B/C/D Missiles," Fact Sheets, May 24, 2010, available at http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104612/agm-86bcd-missiles.aspx.

60 "Australia To Receive JDAM-ER Wing Kits As Boeing Pursues U.S. Sales," *InsideDefense*, April 28, 2015, available at http://insidedefense.com/defensealert/australia-receive-jdam-er-wing-kits-boeing-pursues-us-sales.

61 The extended range JSOW was created by adding a TJ-150 turbojet engine to the JSOW C-1 variant. JSOW C-1 has a two-way Link 16 jam-resistant datalink and an infrared seeker to detect and guide the weapon to targets with better than 10 meter accuracy. Raytheon, "Raytheon Demonstrates New Joint Standoff Weapon Extended Range Integrated Fuel System: Powered weapon provides greater capability to warfighter," news release, April 9, 2013, available at http://investor.raytheon.com/phoenix.zhtml?c=84193&p=irol-newsArticle&ID=1804499.


Illustration of a Joint Strike Missile

The SDB II has wings that deploy after release to give it a glide range of more than 40 nm.[62] Small engines could give SDB IIs enough range to be launched at targets from outside the lethal radius of point defenses.

Second, the Pentagon could modify or procure existing standoff attack PGMs that already have ranges in the 100 to 400 nm sweet spot and have reasonable unit costs. For example, the JASSM is about four times as large as a SDB and cannot fit in F-35 weapon bays. Decreasing the size of the JASSM's 800-pound warhead could allow production of a variant that is small enough to be carried internally by F-35s. The foreign-produced Joint Strike Missile (JSM) that is "designed to be carried and launched internally from the F-35 Lightning II fighter's two internal bays" may be another option.[63] The JSM can also be launched from VLS against ships and land-based targets. Both the JASSM and JSM are designed to penetrate high threat areas. The large-scale use of these and other PGMs that have a high PA values could reduce the total number of sorties needed to attack targets sets in contested environments.

**Attacking moving and relocatable targets.** The ability to strike moving and relocatable targets is another factor that should influence the design of new standoff attack PGMs. A target set that is highly mobile complicates an attacker's precision targeting operations and could require an attacker to use more weapons to achieve a desired probability of damage compared to strikes against fixed targets with known locations. Many modern weapon systems such as radar systems, missile launchers, and mobile command centers can relocate in ten minutes or less. Cruise missiles that fly at 500 nm per hour must fly for about 18 minutes to reach targets located 150 nm from their launch points. Long flight times can reduce the probability that standoff attack PGMs will hit mobile or relocatable targets that have changed their locations after the PGMs are launched. Target location errors caused by targets that have moved can force attackers to fly additional strike sorties and expend more PGMs.

Target location errors can be reduced by providing standoff attack PGMs with inflight target updates over Link 16 or other jam-resistant datalinks. Some contemporary U.S. standoff attack PGMs have one-way or two-way links. Tomahawk Block IV, the latest addition to the Navy's Tomahawk family of cruise missiles, has a satellite datalink that can be used to retarget it inflight. As with datalinks for penetrating aircraft, however, connectivity with PGMs could be degraded or temporarily denied by enemy countermeasures.

62 SDB IIs are 69 inches long and 6 to 7 inches in diameter.

63 "Kongsberg's NSM/JSM Anti-Ship & Strike Missile Attempts to Fit in Small F-35 Stealth Bay," *Defense Industry Daily,* February 26, 2015, available at http://www.defenseindustrydaily.com/norwegian-contract-launches-nsm-missile-03417/.

Giving PGMs multi-mode seekers that can find and classify targets nearly autonomously are a second means to reducing target location errors. The SDB II has a tri-mode millimeter wave (MMW), imaging infrared (IIR), and semi-active laser seeker that can find, track, and hit moving targets.[64] DoD could upgrade Tomahawk Block IV cruise missiles with multi-mode seekers that enable them to "hit moving targets at sea or on land in darkness and all kinds of weather.[65] While multi-mode seekers are expensive, their added cost must be compared to using larger numbers of less-capable PGMs against moving and relocatable targets.

DoD could also modify current PGMs or develop new PGMs capable of loitering and attacking targets with near autonomy. A powered SDB II with 250 nm range could loiter for up to 30 minutes in a target area. Reducing the size of its warhead could give it even longer loiter times. A discontinued DoD program developed a prototype for a Low Cost Autonomous Attack System (LOCAAS) that was intended to become a "miniature, autonomous powered munition capable of broad area search, identification, and destruction of a range of mobile ground targets."[66] The powered LOCAAS was envisaged as a weapon with a laser-radar (LADAR) imaging sensors that would loiter for up to thirty minutes to find and categorize target.

A third approach to reducing target location errors would be to use standoff attack PGMs capable of flying at supersonic or hypersonic (Mach 5 and above) speeds after launch. A Mach 8 missile could fly 400 miles in less than 5 minutes to strike mobile weapon systems that have broken concealment, compared to 48 minutes for subsonic missiles. Increasing the speed of standoff attack PGMs would also improve the probability they will arrive at their designated targets, a consideration that is addressed in the next section.

## Improving PGM Probability of Arrival

DoD could increase its effective strike capacity by developing PGMs that have higher PA values in contested operational environments. Stealth technologies, integrated electronic warfare countermeasures, and faster speeds after launch could increase PGM survivability. These capabilities could be complemented by the use of expendable decoys and jammers. The combination of stealth, higher speeds, and the use of electronic warfare capabilities could significantly decrease the number of sorties and PGMs needed in future salvo competitions.

**PGM electronic warfare capabilities and stealth.** Integrating electronic warfare jammers in PGMs could increase their survivability in contested areas. To avoid operational penalties associated with increasing PGM size and weight, these jammers should be small and not

64 MMW radars can penetrate weather to find and classify targets. Imaging infrared seekers can increase the accuracy of a PGM. Advanced IIR seekers such as the seeker on the SDB II are uncooled, which reduces their size and weight.

65 Raytheon, "Tomahawk Cruise Missile," accessed on November 2, 2014 at http://www.raytheon.com/capabilities/products/tomahawk.

66 DoD, "Contracts," *Defense.gov*, December 17, 1998, available at http://www.defense.gov/Contracts/Contract.aspx?ContractID=1423.

require large batteries. As a result, they would emit at low power levels across a small range of azimuths and be most effective when close to threat systems.

Reducing the signatures of PGMs in the electromagnetic spectrum would complement low-power jamming. Similar to aircraft, cruise missiles and other PGMs can be detected by modern radars and other radio frequency sensors. Stealth treatments such as energy absorbing coatings and body shapes that do not reflect energy back to threat receivers could reduce the probability that PGMs will be detected and tracked in time for defenses to react. Some contemporary U.S. PGMs are known to have low observable characteristics, including the JASSM, JASSM-ER, and future LRASM that is based on the JASSM.[67]

**PGM speed of flight.** Increasing the speed of PGMs after launch would also improve their ability to penetrate defended areas and to strike time-sensitive targets.

Most contemporary cruise missiles fly at subsonic speeds to avoid range penalties that result from flying long distances at high speeds. Adding a small booster rocket to accelerate cruise missiles to supersonic speeds when they are approaching their targets could improve their survivability without reducing their range significantly. DoD could also leverage maturing technologies to develop glide or powered weapons that fly at hypersonic velocities—between five to ten times the speed of sound (Mach 5 to Mach 10)—over most of their flight profiles.

DoD has experimented with using surface-launched ballistic missiles or rockets to propel glide vehicles to very high altitudes, at which time the vehicles separate and glide at hypersonic speeds. The ballistic missile-launched Falcon Hypersonic Test Vehicle-2 (HTV-2) was developed by a research program that has the long-term objective of designing hypersonic weapons capable of striking targets at global ranges within 60 minutes. The Pentagon is also experimenting with air-launched glide vehicles that are boosted to high altitudes and hypersonic speeds by rockets.

Illustration of HTV-2 separating from booster

A third hypersonic weapon concept pairs a missile body with an air-breathing ramjet or scramjet engine capable of sustaining flight at speeds above Mach 5. Ramjet engines compress high-speed air entering their inlets and combine it with fuel-enriched air in a combustion chamber to create thrust. Supersonic combusting ramjets (scramjets) use compressed air that enters the combustion stage at supersonic speeds.[68] Future ramjet or scramjet powered

67 Marina Malenic, "USAF Approves JASSM-ER FRP," *IHS Jane's Defence Weekly*, December 15, 2014, available at http://www.janes.com/article/47000/usaf-approves-jassm-er-frp.

68 Scramjets need to accelerate to about Mach 4.5 before their engines can ignite.

weapons launched by aircraft or vertical launch systems will need boosters that carry them to approximately 70,000 feet in altitude before their engines can ignite and accelerate them to hypersonic speed.

Weapons that fly at hypersonic speeds would greatly reduce time available for enemy defenses to complete their find, fix, track, target, and engage kill cycle. Enemy defenses that detect hypersonic weapons flying at Mach 6 toward a target 150 nm away would have little time—about 2 minutes—to establish a reliable track and launch an interceptor.[69] Using hypersonic weapons to suppress enemy air and missile defenses would also improve the PA for other PGMs and reduce threats to penetrating aircraft.

Similar to conventional standoff PGMs, DoD will need to determine appropriate tradeoffs between the cost, size, and range of its future hypersonic weapons.

It is difficult to predict unit costs for PGMs that are still in the concept or technology demonstration phase of development. This said, global-range weapons that depend on one-time-use ballistic missiles to boost them to high altitudes and hypersonic speeds would likely cost tens of millions of dollars each.[70] By comparison, hypersonic missiles that are carried to 45,000 feet or more by reusable aircraft before they are launched to higher altitudes suitable for hypersonic flight could be far smaller and less expensive. Given space and weight limitations, however, air-launched hypersonic weapons could also have less range than surface-launched missiles.

Hypersonic weapons designed to be carried internally by aircraft will be subject to the same physical constraints as other PGMs. DoD is funding a High Speed Strike Weapon technology initiative for an air-breathing hypersonic weapon that is compatible with "5th generation stealth platforms to include geometric and weight limits for internal B-2 Spirit bomber carriage and external F-35 Lightning II fighter carriage."[71] To fit inside B-2s, it is likely that an air-breathing hypersonic missile would have a size and possibly a range similar to that of JASSM-ERs.[72] Hypersonic weapons designed to be carried by aircraft externally could be larger and have longer ranges. Compared to hypersonic missiles sized to fit inside weapons bays, they would also be more expensive, reduce the total number of PGMs that can be carried per sortie, and increase the probability that penetrating aircraft will be detected.

69 Mach 6 is roughly 66 miles per minute.

70 For a cost assessment of a ballistic missile boosted hypersonic glide vehicle, see Mark A. Gunzinger, *Sustaining America's Advantage in Long-Range Strike* (Washington, DC: Center for Strategic and Budgetary Assessments, 2010), pp. 71–72.

71 Dr. David E. Walker, Deputy Assistant Secretary of the Air Force for Science, Technology, and Engineering, "Presentation to the Senate Armed Service Committee, Subcommittee on Emerging Threats and Capabilities," April 18, 2013, pp 9–10, available at http://www.armed-services.senate.gov/imo/media/doc/Walker_04-18-13.pdf.

72 The range of future hypersonic weapons could be extended by reducing the size of their warheads in favor of more fuel capacity. JASSMs and JASSM-ERs share a common framework. A B-2 can carry sixteen JASSMs in its weapons bays. "AGM-158A/-B (JASSM/JASSM-ER)," *Missile Threat*, updated April 9, 2013, available at http://missilethreat.com/missiles/agm-158a-b-jassmjassm-er/.

Ramjet-equipped weapons using hydrocarbon fuels may also be limited to speeds of Mach 6 or less if their combustion chambers and other internal components are uncooled.[73] While internal cooling or different fuels could increase this top-end speed, they would also add weight and increase the complexity and cost of hypersonic missiles.[74] Fortunately, Mach 6 speeds may be sufficient for short-range standoff attacks with hypersonic weapons. Mach 6 missiles would be able to fly 400 nm in about six minutes to strike relocatable targets. This could eliminate the need to provision the missiles with expensive terminal seekers and make them more affordable compared to subsonic or much longer range PGMs that require seekers to compensate for target location errors caused by their long flight times.

While very long range (greater than 500 nm) hypersonic weapons may prove too large or costly to use in large numbers, at too short a range they may not reach a high enough speed to increase their survivability. It may require 100 nm or more after launch for a ramjet-powered hypersonic weapon to reach hypersonic speeds.

Given these cost, size, and performance considerations, future air-launched hypersonic cruise missiles may have a range sweet spot that is close to the sweet spot for conventionally powered standoff PGMs assessed earlier in this chapter. Surface-launched hypersonic weapons with much greater ranges could provide the U.S. military with the ability to attack very high value, time-critical targets such as enemy command and control centers from distant theater bases or even from the U.S. mainland. However, the size and cost of these weapons may make them niche capabilities that are best used against only the most critical targets.

**Expendable decoys and jammers.** The use of expendable decoys and jammers would also increase the probability that PGMs will arrive at their targets in contested operational environments. Expendable decoys use electromagnetic signals or energy-reflecting "chaff" materials to attract surface-to-air and air-to-air missiles to false targets, as described in Chapter 4's discussion of tunneling operations. DoD's MALD-J is a combined decoy and jammer that degrades or denies the ability of enemy sensors to detect "friendly aircraft or munitions."[75]

MALD-Js on a B-52

Future expendable jammers could use high-power electromagnetic energy to jam multiple frequency bands used by enemy air and missile defense sensors or use low-power energy to target specific frequencies where SAMs and other guided weapons are particularly susceptible. DoD could also develop standoff attack PGMs that disperse small repeating jammers around enemy

73 See U.S. Air Force, Scientific Advisory Board, *Report on Why and Whither Hypersonics Research*, p. 48.

74 Another option might be to throttle down the weapon's engine during hypersonic flight to reduce its fuel burn rate and extend the weapon's range. Ibid., p. 48.

75 DOT&E, *Director, Operational Test and Evaluation FY2013 Annual Report* (Washington, DC: DoD, January 2014), p. 287.

defenses. These repeaters could boost jamming signals from other PGMs and penetrating electronic warfare platforms.

While expendable decoys and jammers may not prevent future defenders from detecting attacks, they would improve the PA of associated PGMs if launched as a vanguard to or embedded in PGM salvos. In combination, the use of decoys, jammers, and low observable PGMs with integrated electronic warfare capabilities could significantly reduce the numbers of sorties and munitions needed to strike defended target sets.

## More Targets per Salvo

Miniaturized PGMs and area weapons that carry multiple small, smart submunitions could become future force multipliers to help maintain the U.S. military's advantage in a salvo competition.

**Miniaturization.** Small Diameter Bombs are a prime example of the force-multiplying potential of miniaturized weapons. When they become operational, F-35s will be able to carry two JDAMs and two air-to-air-missiles internally. Replacing the two JDAMs with eight 250-pound class SDBs would quadruple the number of aimpoints an F-35 can strike in a single sortie.[76] Combat aircraft with larger weapons bays such as the B-2 bomber will be able to carry eight to ten times as many SDBs internally as fighters. Using smaller PGMs that have highly accurate guidance systems could also decrease the potential that air and missile strikes will result in undesired collateral damage. This is a significant factor for operations against targets that are located in urban terrain or in close proximity to sensitive areas.

**Collaborative weapons technologies.** The Defense Advanced Research Projects Agency (DARPA) is pursuing communication, networking, and guidance technologies needed for unmanned systems to collaborate in contested areas. When mature, these technologies could give cruise missiles as well as unmanned aircraft the ability to collaboratively find targets, share information, and defend "each other by quantitatively overwhelming defenses."[77] Autonomous information sharing could also allow PGMs to rapidly retarget themselves to ensure all required aimpoints in a target set are struck when some or even all PGMs originally designated for particular aimpoints are intercepted. When they reach maturity, future collaborative weapons promise to reduce the total number of PGMs needed to attack defended target sets, as illustrated by the blue line in Figure 18.

**Targets per munition, not munitions per target.** A new generation of PGMs that are *each* capable of striking multiple aimpoints would also help compensate for precision strike countermeasures and create new advantages for the U.S. military in future salvo competitions.

76 This comparison does not include weapons F-35s will be able to carry externally.

77 Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office, "Collaborative Operations in Denied Environment (CODE)," *FedBizOpps.gov*, Special Notice DARPA-SN-15-20, January 21, 2015, p. 3, available at https://www.fbo.gov/index?s=opportunity&mode=form&id=0db5a2ebace9cdac0c6c12d56dab686d&tab=core&_cview=0.

In the mid-1980s, DoD fielded the direct attack cluster bomb unit-87 (CBU-87) Combined Effects Munition to partially replace its Vietnam War-era cluster munitions. Used extensively in Operation Desert Storm, the CBU-87 carried 202 unguided Combined Effects Bombs that were effective against light armored vehicles and other soft area targets. Bomblets from a single CBU-87 could cover a target area that was larger than a football field, depending on the weapon's altitude at release.

DoD developed the CBU-97 Sensor Fuzed Weapon (SFW) in the 1990s to precisely attack targets over large areas. First used during Operation Iraqi Freedom, each CBU-97 SFW dispenses ten BLU-108 submunitions. Each BLU-108 in turn deploys four precision-guided warheads called "skeet" that are effective against soft targets such as SAMs, radars, artillery, parked aircraft, and all types of armored vehicles including main battle tanks.[78] Skeet from one CBU-97 can attack multiple targets over an area the size of twelve American football fields.

In contrast with unguided Combined Effects Bomblets, skeet have active laser and passive infrared sensors to detect and autonomously classify targets using onboard stored information. After identifying appropriate targets, skeet fire an explosive charge, forming into a projectile capable of penetrating armor. Each of the SFW's 40 skeet is capable of striking a fixed or mobile target.[79]

Submunitions deployed by standoff attack weapons could support tunneling or swarm attacks designed to exhaust an enemy's defenses. A JSOW variant already carries BLU-108 submunitions with skeet. Another application of this approach is the Air Force's now discarded concept of placing a single powered LOCAAS in a JASSM. Future cruise missiles carrying skeet or miniaturized LOCAAS-like submunitions capable of loitering in target areas and autonomously coordinating their attacks would be force multipliers that reduce U.S. sortie and weapons requirements.


Cutaway of LOCAAS with engine

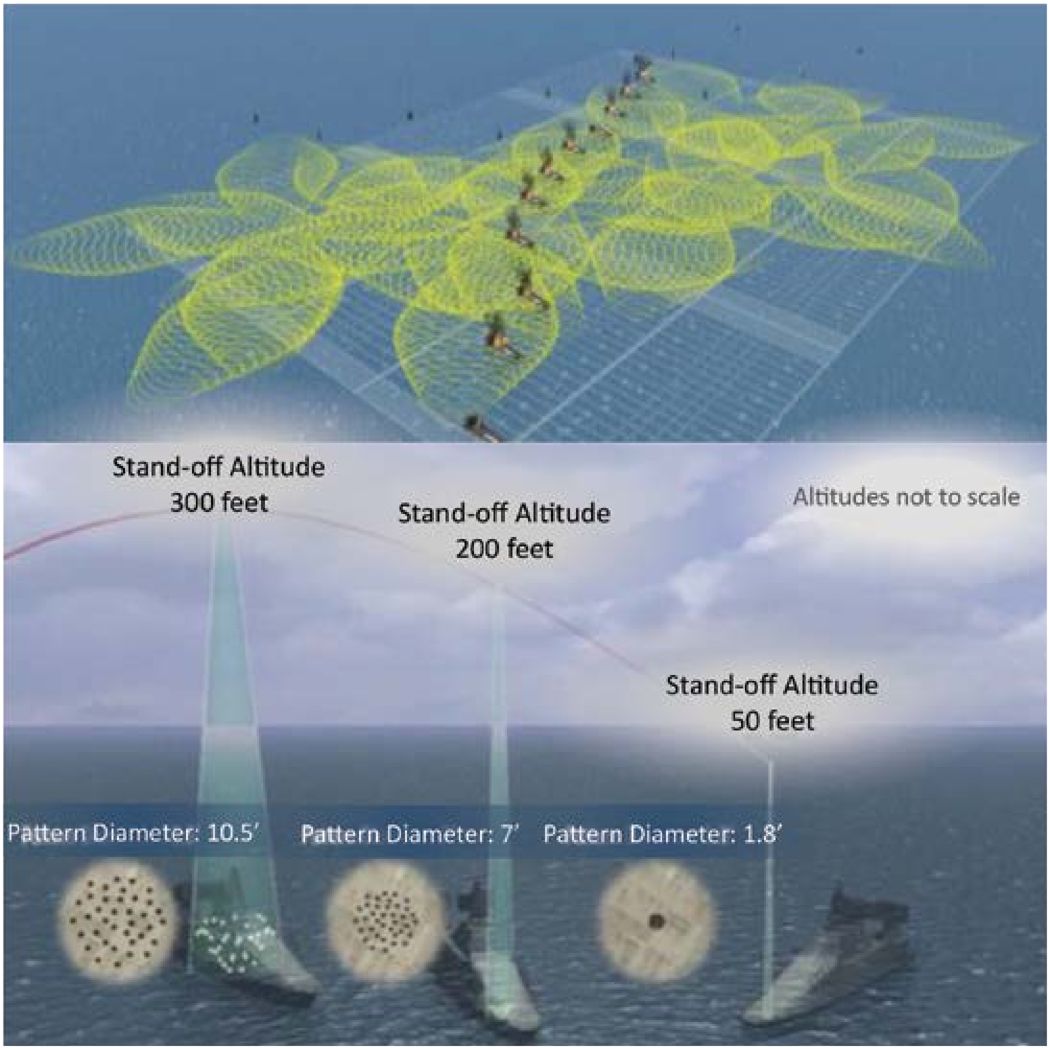
Smart submunitions could also improve the U.S. military's ability to *defeat* swarming attacks. For instance, future ship-launched missiles with BLU-108 submunitions could counter small boat swarm attacks. It may be possible to procure these weapons for $60,000 each, which is less than the cost of expending a separate PGM against each boat. CBU-97 PGMs or their close

78 After deploying from CBU-97 canisters, BLU-108s sling their four skeet in different directions. Skeet spin and activate their infrared and laser sensors to find and characterize ground targets.

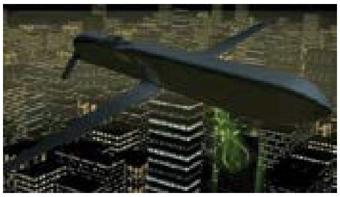
79 DoD procured an inexpensive guidance tail kit that could be attached to area weapons such as the CBU-87 and CBU-97. The tail kits steer the weapons to a precise point after release from an aircraft, correcting for winds aloft and other environmental factors that can affect the weapons flight path. These modified weapons are called Wind Corrected Munitions Dispensers (WCMDs).

cousin, the CBU-105 Wind Corrected Munitions Dispenser, dropped by ship-based helicopters and fixed-wing aircraft could attack up to forty hostile boats over large areas (see Figure 20). Counter-swarm PGMs that free up space in ship magazines for other weapons would also be force multipliers.

### FIGURE 20. POTENTIAL AREA COVERED BY FUTURE COUNTER-SWARM WEAPONS




In addition to procuring new PGMs with smart submunitions, the Pentagon could exploit directed energy technologies to increase its strike capacity. It is possible within five years to field cruise missiles with HPM emitters capable of damaging or destroying electronic components in weapons systems. HPM weapons generate very short pulses of microwave radiation to attack targets in specific locations or over wide areas. At high enough power levels, microwave pulses can disrupt or burn out unshielded electronic components that are critical to the operation of weapons systems such as computers, target acquisition radars, and SAMs. Unlike high-energy laser beams, pulses emitted by HPM warheads would not be affected by weather or the presence of particulates in the atmosphere.



Notional HPM cruise missile

The Air Force completed a successful Counter-Electronics High Power Microwave Advanced Missile Project (CHAMP) demonstration that flew cruise missiles with HPM emitters. If funded, DoD could field an operational inventory of CHAMP-like missiles that could attack scores of targets at a cost that is far less than expending a PGM on each target.

## Increasing PGM Lethality Against Hardened or Deeply Buried Targets

A PGM's overall PD for a specific target is a combination of its PA and its ability to achieve a desired effect against the target. Passive defenses such as burying or building obstructions around targets and hardening them against shock can increase the number of weapons needed to damage targets or render them invulnerable to many PGMs. Weapons technologies such as energy-dense materials and enhanced penetration capabilities can improve PGM lethality against hardened or deeply buried targets (HDBTs), increasing the effectiveness of U.S. salvos and reducing the number of weapons needed.

**More bang for the buck.** The development of new energy-dense materials could increase the explosive potential of PGMs. Small PGMs that can create the effects of much larger weapons would reduce the total number of sorties needed in salvo competitions.

Energy-dense materials can be formed by mixing high explosives with powdered metal and metal oxides to increase their potential energy per unit volume. Newer weapons such as the JASSM and SDB use a mixture of the explosive RDX, aluminum powder, and aluminum perchlorate that is approximately 50 percent more powerful than TNT. DARPA's Energy-Dense Explosives initiative is experimenting with other mixes that "offer the potential of significantly increasing performance without increasing weight" of future weapons. If successful, DARPA may be able to develop PGMs with the size and weight of 250-pound class SDBs that can create the effects of 1,000- or 2,000-pound class weapons. Energy-dense materials could also reduce the size and weight of penetrating weapons. This would increase the number of weapons a strike platform could carry and increase salvo sizes.

**Boosted penetrating weapons.** Velocity, along with weight, density, and shape, is a key factor in a PGM's ability to penetrate a hardened or deeply buried target. Equipping penetrating PGMs with rocket motors that increase their velocity during their terminal phase of flight can improve their ability to destroy HDBTs. The first boosted penetrator was the rocket-assisted 4,500-pound "Disney Bomb" used by British forces during World War II to penetrate concrete fortifications. A more

Disney Bomb after release

recent example is the BLU-106/B Boosted Kinetic Energy Penetrator developed by DoD in the mid-1980s.[80]

The Air Force Research Laboratory (AFRL) is developing a 2,000-pound class rocket-boosted High Velocity Penetrating Weapon (HVPW) that could have the penetrating power of a 5,000-pound gravity bomb and is designed to fit in the internal weapons bay of an F-35.[81] Some of the challenges to fielding weapons of this type are creating fuzes and explosives that will survive a boosted impact, as well as terminal guidance systems that can accurately gauge a weapon's angle of attack at high speeds.[82] The AFRL also intends to develop a "Global Strike Penetrating Munition" with a warhead that travels at 4,000 feet per second to strike targets hardened to withstand forces greater than 15,000 pounds per square inch.[83] This boosted penetrator could be carried by a future Submarine-Launched Global Strike Missile (SLGSM), an Advanced Hypersonic Weapon, a Biconic/Conventional Strike Missile, or a long-range hypersonic weapon.[84]

## Summary

A salvo competition with capable enemies could compel U.S. power projection forces to use more strike sorties and weapons than has been the norm since the end of the Cold War. Alternatively, the Pentagon could offset precision strike countermeasures by modifying current weapons and developing new PGMs that are more versatile, survivable, and capable of creating effects against multiple target sets compared to today's munitions. In other words, the U.S. military has an opportunity to take the next step up the PGM force-multiplication curve (see Figure 21).

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80 Andreas Parsch, "Textron (Avco) BLU-106/B BKEP," *Directory of U.S. Military Rockets and Missiles*, May 16, 2006, available at http://www.designation-systems.net/dusrm/app4/blu-106.html.

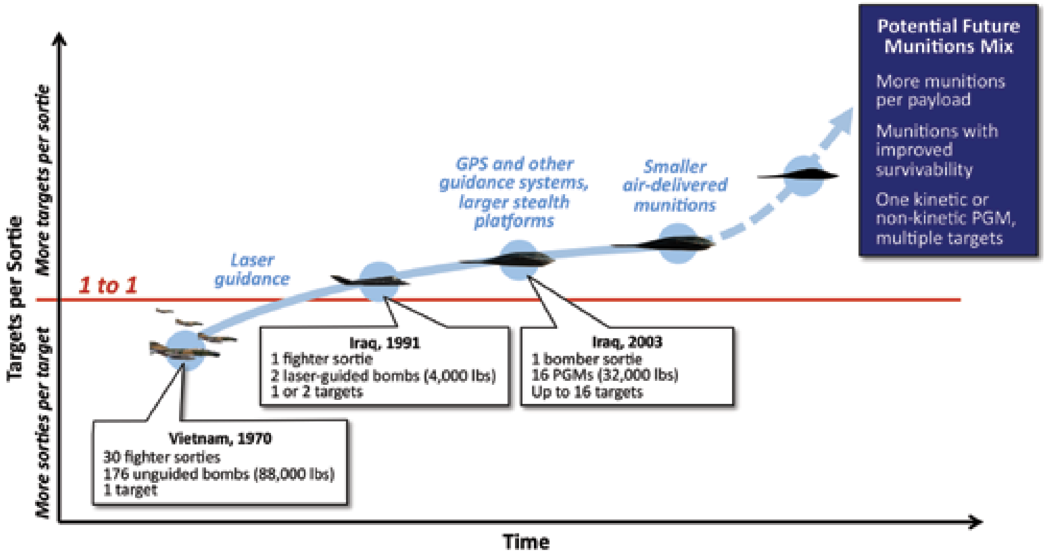
81 Air Force Material Command, "High Velocity Penetrating Weapon," *FedBizOpps.Gov,* Broad Agency Announcement BAA-RWK-12-0002, September 8, 2011, available at https://www.fbo.gov/index?s=opportunity&mode=form&id=e865d57a7d32f755e64e3a3433fea479&tab=core&_cview=0; and Air Force Research Laboratory Munitions Directorate, *High Velocity Penetrating Weapon Program Overview*, Power Point Presentation (Eglin AFB, FL: U.S. Air Force, April 13, 2011), available at http://www.dtic.mil/ndia/2011SET/Rose.pdf.

82 Impact speed for the HVPW will be around 2,500 feet per second, compared to a gravity bomb which falls at under 1,000 feet per second. "Mechanics of Bombing," *Flight and the Aircraft Engineer*, 38, No. 1658, October 3, 1940, available at http://www.flightglobal.com/pdfarchive/view/1940/1940%20-%202755.html. "A persistent problem experienced [...] in these weapons has been explosive rebounding in the weapon cavity wherein the explosive responds elastically creating internal wave fronts rebounding from impact stresses. This creates waves, eddies, cracks, and can cause premature or unreliable detonation." Small Business Innovation Research/Small Business Technology Transfer, "Reinforced Boosted Penetrator Formulations," *SBIR.gov*, award information, available at https://www.sbir.gov/sbirsearch/detail/336712; and Scott R. Gourley, "High Velocity Penetrating Weapon Addresses 'Hard Target' Challenges," *Defense Media Network*, September 13, 2011, available at http://www.defensemedianetwork.com/stories/high-velocity-penetrating-weapon-addresses-%E2%80%9Chard-target%E2%80%9D-challenges/.

83 J.R. Wilson, "Guidance and control for bunker-busting munitions," Military and Aerospace Electronics, August 15, 2013, available at http://www.militaryaerospace.com/articles/print/volume-24/issue-8/special-report/guidance-and-control-for-bunker-busting-munitions.html.

84 Russell J. Hart, *Defeating Hard and Deeply Buried Targets in 2035* (Maxwell AFB, AL: Air War College, 2012), pp. 13–14, available at http://www.au.af.mil/au/awc/awcgate/cst/bh_2012_hart.pdf.

FIGURE 21. SHIFTING THE PRECISION STRIKE EFFECTIVENESS CURVE



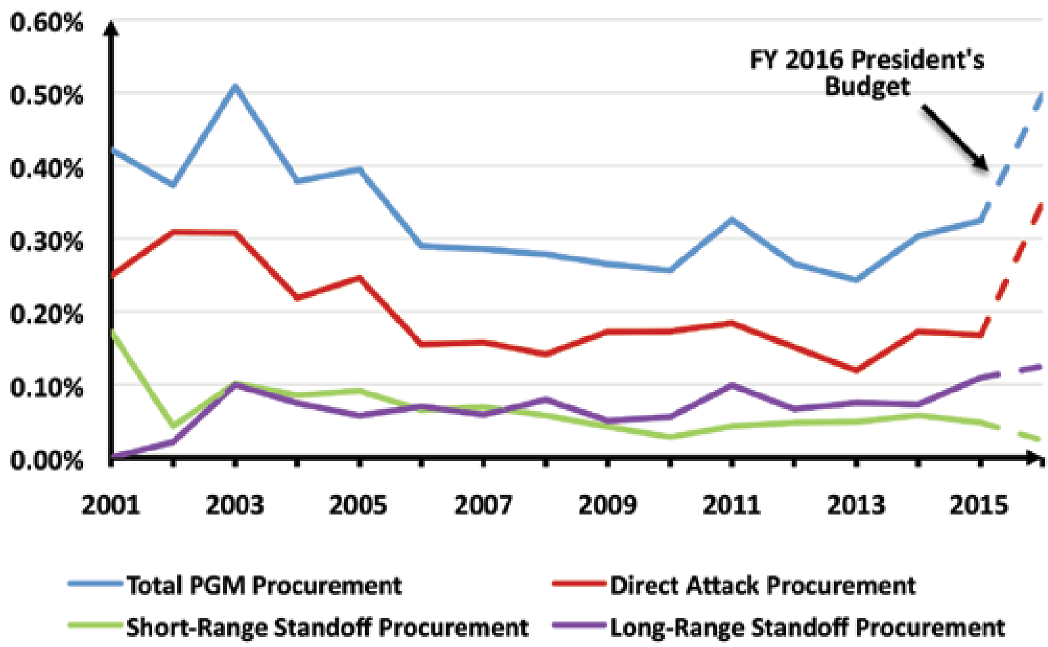

Combined with new operational concepts, existing and maturing munitions technologies could give U.S. power projection forces advantages that are unmatched by its future opponents.

CHAPTER 6

# Potential Barriers to Change

**Funding barriers.** New PGMs that help the U.S. military to retain its advantage in precision strike will not be cost-free and will compete for funding with other existing programs. This is a formidable barrier to overcome, especially if the Pentagon continues to fund PGM procurement at the levels illustrated by Figure 22.

FIGURE 22. PGM PROCUREMENT AS A PERCENTAGE OF THE DEPARTMENT OF DEFENSE'S TOTAL BUDGET



The FY2015 President's Budget requested $3.67 billion to buy PGMs. This is a fraction of the $26.62 billion for aircraft and $14.40 billion for ships requested in the same budget.[85] The President's Budget for FY2016 requested an increase in funding for PGMs. Figure 22 shows the vast majority of this increase is attributable to requests for additional direct attack munitions, especially Hellfire missiles and JDAMs that are needed for small-scale strike operations against radical Islamic terrorist groups in Iraq and Syria. It may be argued that the funding levels required by the Budget Control Act (BCA) of 2011 present another significant challenge to increasing DoD's PGM investments. Without a budget agreement that increases defense spending above the BCA's budget caps, DoD will need to reduce funding to existing programs to begin new programs that would deliver the new and modified PGMs recommended by this report.

**Industrial base barriers.** DoD's munitions investment history could be attributed in part to a belief that the U.S. defense industrial base has the capacity to quickly ramp-up its PGM production in the event of a crisis. There are at least three reasons why this may not be the case.

First, it requires days and possibly weeks, not hours, to manufacture technically complex PGMs. Cruise missiles with many subcomponents must go through multiple stages of manufacturing, assembly, and testing before they are certified ready for use. These stages cannot easily be truncated without sacrificing the overall reliability and safety of weapons.

Second, there are only a handful of U.S. prime contractors that produce PGMs. They rely on more than 100 specialized suppliers for components such as batteries, sensors, datalinks, guidance systems, and engines. These subcontractors have reduced their costs by specializing in specific components and "leaning" their production capacity. This enables subcontractors to efficiently supply components to multiple PGM programs but leaves them a very limited surge capacity. The resulting production chokepoints mean it may take many months for the munitions industrial base as a whole to increase production for even a small number of different PGMs.[86]

Third, the U.S. munitions industrial base does not have civilian counterparts that it can turn to in the event of an unforeseen production surge. Unlike the defense aerospace industrial base, there are no "commercial derivative" PGMs designed and manufactured by workforces that produce similar products for civilian use.

85 Todd Harrison and Jacob Cohn, *FY 2015 Weapon Systems Factbook* (Washington, DC: Center for Strategic and Budgetary Assessments, 2014).

86 One PGM prime contractor informed the authors of this report that it could quickly increase the production of a single major direct attack PGM by about 35 percent. Doubling the PGM's production rate from current levels would require at least ten months, since supporting subcontractors would need to expand their production lines. A second prime contractor indicated it had the organic capacity to double production of a standoff attack PGM within a month. Actually doing so, however, would require its subcontractors to substantially ramp-up their production, a process that could take up to eighteen months.

Beyond increasing DoD's overall investment in PGM programs, two factors could help compensate for the PGM industrial base's inability to quickly surge production. First, thought should be given to designing future PGMs that are less complex and share more components. This could reduce the time needed to assemble PGMs as well as reduce their average unit cost, for example by employing more additive manufacturing as opposed to complex machining. Creating larger stocks of PGMs prepositioned in overseas theaters could buy time for the U.S. munitions industrial base to increase their production in a crisis. It would have the added benefit of reducing strains on DoD's logistics infrastructure that deploys and sustains power-projection forces in time of war, and possibly help offset what may be an emerging shortfall in PGMs needed to support future contingency operations.

**Policy barriers.** Lastly, policy constraints could delay or prevent the development of new PGMs capable of swarming attacks or defeating large area targets.

In 2008, 107 states agreed to a convention that banned the production and use of certain kinds of cluster munitions. States that have signed or ratified the Convention on Cluster Munitions agree they will not "use cluster munitions" or "develop, produce or otherwise acquire, stockpile, retain or transfer to anyone, directly or indirectly, cluster munitions."[87]

Due to growing international concern over the use of cluster weapons that could create unexploded ordnance that could harm civilians, the Secretary of Defense established a new policy on U.S. military use of cluster munitions. The policy limits DoD's use of cluster munitions after 2018 to:

> …cluster munitions containing submunitions that, after arming, do not result in more than 1% unexploded ordnance (UXO) across the range of intended operational environments. The 1% UXO limit will not be waived. Although the use of self-deactivation devices or mechanisms can reduce the hazards to civilians, self-deactivated submunitions will still be considered UXO.[88]

This policy is consistent with some, but not all of the requirements in the Convention on Cluster Munitions. Should the United States join the Convention, it would have to forego the use of PGMs that carry more than ten submunitions as well as the use of submunitions that lack the ability to deactivate or self-destruct, so that they do not become hazardous unexploded ordnance. The Convention's stipulation that individual PGMs must carry less than ten submunitions could hinder DoD's future development of area munitions that could provide new advantages in salvo competitions. Its requirement for submunitions to autonomously deactivate or self-destruct would not be a technical challenge, as demonstrated by skeet

87 Convention on Cluster Munitions, May 30, 2008, p. 3, available at http://www.clusterconvention.org/files/2011/01/Convention-ENG.pdf.

88 Secretary of Defense, "DoD Policy on Cluster Munitions and Unintended Harm to Civilians," *Defense.gov News*, memorandum, June 19, 2008, p. 2, available at http://www.defense.gov/news/d20080709cmpolicy.pdf.

submunitions that have redundant means of deactivating or destroying themselves.[89] Further, CBU-105 area munitions have an unexploded ordnance rate of less than 1 percent as required by DoD's submunitions policy.

## Summary

DoD cannot ignore PGM funding, defense industry capacity, and policy challenges that affect its ability to maintain our Nation's precision strike advantage. If future adversaries have offensive and defenses capabilities that allow them to dominate in a salvo competition, U.S. security guarantees will suffer, and with them the alliances upon which much of the current global security order is based. The United States cannot afford to cede its leadership position by failing to create new operational concepts, ignoring new weapons technologies, and underfunding programs that promise to sustain its precision strike advantage well into the future.

89 According to the skeet's manufacturer, "If a skeet warhead does not detect a valid target over its lofted trajectory, one of its three safety modes will activate. The first two modes enable the skeet to self destruct after eight seconds from launch or within a 50-foot altitude above the ground. The skeet's third feature is a time-out device that will yield the warhead inert minutes after hitting the ground." Textron Defense Systems, *Delivering Confidence: BLU-108 Submunition*, datasheet (Wilmington, MA: Textron Defense Systems, 2010), p. 1, available at http://www.textronsystems.com/sites/default/files/pdfs/product-info/blu108_datasheet.pdf.

# Conclusion and Recommendations

> *The transition from gravity bombs to smart munitions was huge […] What's next?*
>
> *—General Larry O. Spencer, Air Force Vice Chief of Staff*[90]

The combination of highly accurate munitions, advanced sensors, and global C4ISR networks has given the U.S. military an unmatched advantage in precision strike since the end of the Cold War. This advantage is waning as potential enemies develop effective countermeasures against U.S. precision strikes as well as their own capabilities to strike with precision.

The dynamic between two militaries that each have PGMs and capabilities to counter one another's strikes can be called a salvo competition. In this competition, both combatants seek to gain advantages by improving their capabilities to attack and/or defend. Simply using more current-generation PGMs to offset an enemy's precision strike countermeasures could be a very costly proposition for the U.S. military. Conversely, DoD could create new operational concepts and exploit weapons technologies that would maintain the precision strike advantage upon which America has come to rely.

The U.S. military could leverage its long-range strike advantage by conducting precision strike operations from bases that are out of reach of most cruise and ballistic missile threats. These long-range land-based and (in the future) carrier-based strike aircraft could be protected by fighters operating from highly dispersed expeditionary airfields and cluster bases located closer to target areas. To address the growing threat of advanced point defenses, the U.S. military could shift toward conducting short-range, standoff attacks. And strikes from any distance could be more effective if U.S. power-projection forces exploit operational concepts such as tunneling and collaborative weapons employment that increase the probability PGMs will reach targets. Deploying small, expendable decoys with strike salvos could complicate an

90 James Drew, "Vice Chief Calls For Desert Storm-Like Technological Advancement," *James Drew Reporting*, January 29, 2015, available at http://jamesdrewjournalist.com/vice-chief-calls-for-desert-storm-like-technological-advancement/.

enemy's defensive operations, force it to waste resources on false PGM targets, and further improve the probability that U.S. precision strike salvos will arrive at their targets

Procuring new PGMs that are stealthy, have self-protection features, or are capable of hypersonic flight could provide new advantages against enemies with precision defenses. PGMs that are multi-mission capable or have the ability to strike multiple aimpoints per weapon would increase the U.S. military's strike capacity and possibly reduce the number of munitions needed in future conflicts. Attacking large numbers of mobile weapon systems and fixed targets that are hardened or deeply buried will require investments in PGMs with multi-mode sensors, improved autonomy, and enhanced penetration capabilities.

In summary, this report makes the following recommendations.

**Change operational concepts.** To sustain its precision strike advantage, DoD should change its operational concepts in the following ways:

- Place a greater emphasis on long-range strike operations. To sustain its offensive sortie capacity, the U.S. military should shift toward conducting more long-range strikes from operating locations that are out of range of most cruise and ballistic missile threats.
- Adopt new operational priorities for short-range aircraft. In future salvo competitions, short-range combat aircraft with small weapons payloads will be most useful performing counterair operations and launching small strikes and raids. Counterair operations will enable strike platforms to attack target sets from shorter ranges and allow them to employ a wider and cheaper range of weapons. Further, fighter CAPs that protect U.S. bases and aircraft carriers could compel enemies to use large and expensive long-range standoff weapons for their counterstrikes.
- Adopt new basing approaches. New concepts for dispersed operations inside contested areas could increase the sortie rates of fighters and enable refueling and rearming for long-range strike aircraft operating from more distant bases.
- Shift from direct attacks to short-range, standoff strikes. To counter increasingly capable point defenses, even stealthy strike aircraft will need to launch attacks from standoff ranges. With today's PGM portfolio, this would require strike aircraft to mostly use large, long-range standoff weapons that can be carried in much smaller numbers. To sustain salvo capacity, the U.S. should instead shift toward using more short-range, standoff attack PGMs.

**Free magazine capacity for offensive strike PGMs.** Increasing the offensive capacity of ship and shore-based weapon magazines in some cases now requires a reduction in their weapons capacity for defensive missions. The U.S. military's current long-range layered air defense approach preferentially uses large, expensive surface-to-air interceptors and only uses smaller, short-range interceptors or other air defense systems after long-range interceptors have failed. This dynamic is most pronounced on VLS-equipped ships that have finite magazine capacity and a significant air defense mission. A shorter-range air defense scheme would enable the use of smaller SAMs and non-VLS weapons such as electronic warfare, lasers, and electromagnetic railguns. This would free up magazine capacity for offensive weapons.

**Develop the ability to reload VLS at sea.** To get the most out of finite VLS magazines, U.S. ships should be equipped to conduct weapons reloading operations while underway. This would enable ships to replenish their strike weapons and allocate more VLS cells to other missions without first returning to port.

**PGM development and procurement priorities.** DoD should establish the following program and research and development priorities for PGMs:

- Multi-mission capability. DoD should leverage advances in precision guidance and warhead technologies to ensure its anti-air and anti-ship weapons are also capable of attacking targets on land.

- Short-range standoff. Short-range, direct attack weapons will be of decreasing value in all but the most permissive environments. DoD should modify existing direct attack PGMs such as SDB II, JDAM, and JSOW to give them more standoff range as well as develop new weapons with modest standoff ranges that do not unnecessarily decrease the size of strike salvos.

- Miniaturization. DoD should take advantage of advances in miniaturization of seekers and warheads to develop smaller weapons that take up less space in ship magazines and aircraft weapon bays. This would increase the salvo potential of current and future strike platforms.

- Improved survivability. In future salvo competitions, PGMs will need features that improve the probability they will arrive at defended targets. New weapons could incorporate either hypersonic speed or autonomous sense-and-avoid technology to enable them to outrun or circumvent enemy air defenses. Future weapons will also need shapes and treatments that reduce their radar and infrared signatures.

- Electronic warfare. Current and future munitions may need to rely on jammers and decoys to reduce their own susceptibility to detection or draw away enemy air defenses. Self-protection jammers should be integrated into suitable current-generation PGMs to reduce their effective signature while new, inexpensive decoys should be developed that have similar range and signatures in the electromagnetic spectrum as the weapons they will accompany.

- PGM networking. Current weapons should be modified and new weapons developed to incorporate the capability to be redirected in flight by a remote sensor, an operator, or another weapon. This would enable both collaborative operations that improve salvo efficiency and attacks against mobile and relocatable targets. With improvements in weapons autonomy, retargeting can be done without operator interaction and between weapons in a salvo.

- Greater number of aimpoints per PGM. DoD should procure more weapons that can each strike multiple targets. These weapons could have autonomous submunitions, electronic warfare systems, or high-power microwave warheads. These weapons would significantly increase the U.S. military's effective strike capacity.
- Smaller, more lethal warheads. DoD should procure PGMs that are smaller, rely less on mass to attack challenging targets, and exploit vulnerabilities in enemy weapon systems. For instance, DoD should develop warheads that use more energetic explosives or boosters that improve their ability to penetrate hard and deeply buried targets. Similarly, warheads with shaped charges to penetrate ship hulls and PGMs with high power microwave generators that can damage electronic components could create new advantages for future power projection forces.

Finally, DoD has heavily weighted its PGM procurement toward buying direct attack munitions that may not be well suited for a salvo competition as described by this report. In terms of quantity, DoD may not have enough PGMs to support more than a single large-scale operation against an enemy with effective PGM countermeasures. To address these capability shortfalls, DoD will need to spend more than its customary one-half of one percent of its budget on PGM procurement. Rebalancing DoD's weapons portfolio will take time and could be delayed by the budget levels mandated in the 2011 Budget Control Act. Provided with adequate resources, however, DoD has the opportunity to create a new generation of PGMs that could have as significant an impact on future operations as early PGMs did during the Vietnam War and Operation Desert Storm.

# APPENDIX 1: GROSS WEAPON SYSTEM UNIT COSTS FOR PGMS IN PRODUCTION FOR THE U.S. MILITARY

| Category | PGM | Target Capability | Warheads (includes variants) | Guidance | Procurement Unit Cost (FY16 $K) |
|---|---|---|---|---|---|
| Direct Attack (Short Range) | Guided Bomb Unit (GBU)-31, 32, 38B JDAM | fixed, moving | Unitary<br>GBU-31: 2,000 lbs<br>GBU-32: 1,000 lbs<br>GBU-38B: 500 lbs | GPS/INS fixed targets; laser sensor for JDAMs with moving target capability | $27 for fixed target variants<br>$42 for moving target variants |
| | GBU-15<br>Enhanced GBU-15 (EGBU-15) | fixed<br>fixed, buried, hardened | 2,000 lbs (Mk 84)<br>2,000 lbs hard target penetrator (BLU-109/B) | TV or IIR<br>INS, GPS | Not in production |
| | EGBU-28 LGB | fixed buried, hardened | 4,500 lbs penetrator (BLU-113) or 5,000 lbs penetrator (BLU-122) | INS, GPS, laser guided | Not in production |
| | CBU-103, CBU-104, CBU-107<br>WCMD | fixed | CBU-103: 202 BLU-97/B bomblets<br>CBU-104: 72 BLU-91B anti-tank mines; 22 BLU-92/B anti-personnel mines<br>CBU-107: 350 14” tungsten rods; 1,000 7” tungsten rods; 2,400 2” steel flechettes | INS wind corrected to enable delivery from higher altitude | Not in production |
| | CBU-105<br>SFW with WCMD | fixed, moving | BLU-108 submunitions with 40 explosively formed penetrators | infrared (IR), active laser sensors | Not in production |
| | GBU-43/B<br>Massive Ordnance Air Blast (MOAB) | fixed | 18,633 lbs high explosive tritonal<br>(BLU-120/B) | GPS | not available |
| | GBU-57A/B<br>MOP | fixed | 5,300 lbs penetrator (BLU-127) | GPS/INS | not available |
| | AGM-114<br>Hellfire variants | fixed, moving | 21 lbs HE, 27 lbs HE, blast/ fragmentation, or thermobaric | K, M, N variants: semi-active laser<br>R variant: adds INS | $170 Army variant<br>$126 Predator variant<br>Navy variant not in production |
| | Standoff Precision Guided Munitions (SOPGM) Viper Strike, Griffin, Archer variants | fixed, moving | Viper Strike: 6 lbs shaped charge<br>Griffin: 13 lbs high explosive<br>Archer: 9 lbs high explosive | Viper Strike, Archer: semi-active laser<br>Griffin: GPS, INS, semi-active laser | Viper Strike, Archer not in production<br>Griffin: $158 |
| | AGM-65 Maverick | fixed, moving | B, D, H variants: 125 lbs<br>E, E2, F, G, K variants: 299 lbs blast/frag, penetration | B, H, K variants: TV<br>D, F, G variants: imaging infrared<br>E, E2 variants: semi-active laser | Not in production, some variants are being upgraded to AGM-65E2 standard |

# APPENDIX 1: GROSS WEAPON SYSTEM UNIT COSTS FOR PGMS IN PRODUCTION FOR THE U.S. MILITARY

| Category | PGM | Target Capability | Warheads (includes variants) | Guidance | Procurement Unit Cost (FY16 $K) |
|---|---|---|---|---|---|
| Direct Attack (Short Range) | AGM-154A, B, C JSOW | fixed, moving | A: 145 combined effects submunitions<br>B: 6 BLU-108 SFW<br>C: BROACH warhead | A, B variants: GPS/INS<br>C variant: infrared terminal seeker | Not in production |
| | Guided Multiple Launch Rocket System | fixed | Unitary rocket, 196 lbs unitary high explosive | GPS/INS | $151 |
| | AGM-88B/C<br>High-Speed Anti-Radiation Missile;<br>AGM-88E Advanced Anti-Radiation Guided Missile | fixed, moving | 146 lbs blast/ fragmentation | AGM-88B/C: passive radar<br>AGM-88E: anti-radiation homing receiver, GPS, and terminal guidance radar | Not in production, upgrading existing AGM-88B/C to AGM-88E standard |
| | GBU-39<br>SDB I | fixed | 206 lbs blast/ fragmentation | GPS/INS | $50 |
| | GBU-53<br>SDB II | fixed, moving | 250 lbs blast/ fragmentation | GPS/INS, MMW radar, radar, IIR, and semi-active laser seeker | $185 |
| Short-Range Standoff | AGM-84K<br>Standoff Land Attack Missile-Expanded Response (SLAM-ER) | fixed, moving | 793 lbs penetration, blast/fragmentation | INS, GPS, imaging infrared | Not in production |
| | ATACMS | fixed, moving | WDU-18B or WDU-40/B | INS, GPS | Not in production |
| | AGM-158A<br>JASSM | fixed | 952 lbs HE penetration, blast fragmentation | INS, GPS, imaging infrared | $736 |
| Long-Range Standoff | TLAM-C/D | fixed | C variant: 1,000 lbs class unitary<br>D variant: 166 combined effects bomblets | INS, GPS, terrain contour matching (TERCOM), digital scene matching area correlation (DSMAC) | Not in production |
| | Tomahawk<br>Block IV (TLAM-E) | fixed, moving | 1,000 lbs class unitary | INS, GPS, TERCOM, DSMAC | $1,848 |
| | AGM-86<br>CALCM | fixed | AGM-86C Block I: 2,998 lbs high explosive<br>AGM-86D: 1,201 lbs high explosive penetrator | INS, GPS, TERCOM | not in production |
| | ADM-160 MALD and MALD-J | fixed, moving | - | INS, GPS | $379 |
| | AGM-158B<br>JASSM-ER | fixed | 952 lbs HE penetration, blast fragmentation | INS, GPS, imaging infrared | $1,412 |

## Table Notes

The President's Budget for FY2016 does not provide gross weapon system unit costs split between the fixed and moving target variants of JDAMs, nor does it provide those costs split between SDB I and SDB II. Costs for these variants were calculated by allocating support costs proportionately based on the number of each variant procured to recurring costs unique to each variant.

Numerous sources were used to compile the table in Appendix 1, including: *Jane's Air-Launched Weapons*, (London: IHS Jane's, 2012, 2013 and 2014); *Jane's Strategic Weapon Systems*, (London: Jane's Information Group, 2014); U.S. Air Force, "Joint Direct Attack Munition GBU- 31/32/38," Fact Sheets, June 18, 2003, available at http://www.af.mil/AboutUs/FactSheets/Display/tabid/224/Article/104572/joint-direct-attack-munition-gbu-313238.aspx; U.S. Navy, "AGM-154 Joint Standoff Weapon (JSOW)," Fact File, February 20, 2009, http://www.navy.mil/navydata/fact_display.asp?cid=2100&tid=300&ct=2; U.S Navy, "Tomahawk Cruise Missile," Fact File, August 14, 2014, available at http://www.navy.mil/navydata/fact_display.asp?cid=2200&tid=1300&ct=2; Joakim Kasper Oestergaard Balle, "GMLRS M270A1," *AeroWeb*, October 28, 2014, available at http://www.bga-aeroweb.com/Defense/GMLRS.html; Joakim Kasper Oestergaard Balle, "Small Diameter Bomb (SDB)," *AeroWeb*, November 10, 2014; "GBU-15," *Global Security*, July 7, 2011, available at http://www.globalsecurity.org/military/systems/munitions/gbu-15.htm; and "Delivering Confidence: Sensor Fuzed Weapon," Textron Defense Systems, 2010, available at http://www.textronsystems.com/sites/default/files/pdfs/product-info/sfw_datasheet.pdf.

## LIST OF ACRONYMS

| | |
|---|---|
| **AGM** | air-to-ground missile |
| **AFRL** | Air Force Research Laboratory |
| **ASCM** | anti-ship cruise missile |
| **ATACMS** | Army Tactical Missile Systems |
| **BAMS** | Broad Area Maritime Surveillance |
| **BLU** | bomb live unit |
| **C4ISR** | command, control, communications, computers, intelligence, surveillance, and reconnaissance |
| **CALCM** | Conventional Air-Launched Cruise Missile |
| **CAP** | combat air patrol |
| **CBU** | cluster bomb unit |
| **CHAMP** | Counter-Electronics High Power Microwave Advanced Missile Project |
| **CSBA** | Center for Strategic and Budgetary Assessments |
| **CTOL** | conventional takeoff and landing |
| **DARPA** | Defense Advanced Research Projects Agency |
| **DAWMS** | Deep Attack Weapons Mix Study |
| **DoD** | Department of Defense |
| **DPI** | designated point of impact |
| **DSMAC** | digital scene matching area correlation |
| **DSO** | Distributed STOVL Operations |
| **EGBU** | enhanced guided bomb unit |
| **EW** | electronic warfare |
| **FARP** | forward air refueling and rearming points |
| **FY** | fiscal year |
| **G-RAMM** | guided rockets, artillery, mortars, and missiles |
| **GAO** | Government Accountability Office |
| **GBU** | guided bomb unit |
| **GPO** | Government Printing Office |
| **GPS** | Global Positioning System |
| **HDBT** | hard and deeply buried targets |
| **HE** | high explosive |
| **HPM** | High-Power Microwave |
| **HQ-9** | Hongqi-9 |
| **HSSW** | high-speed strike weapon |

## LIST OF ACRONYMS

| | |
|---|---|
| **HTV-2** | Hypersonic Test Vehicle-2 |
| **HVPW** | High Velocity Penetrating Weapon |
| **IR** | infrared |
| **IIR** | imaging infrared |
| **INS** | inertial navigation system |
| **ISR** | Intelligence, surveillance, and reconnaissance |
| **JASSM** | Joint Air-to-Surface Standoff Missile |
| **JASSM-ER** | Joint Air-to-Surface Standoff Missile-Extended Range |
| **JDAM** | Joint Direct Attack Munition |
| **JSM** | Joint Strike Missile |
| **JSOW** | Joint Standoff Weapon |
| **JSOW-ER** | Joint Standoff Weapon Extended Range |
| **LADAR** | laser-radar |
| **LGB** | laser-guided bomb |
| **LOCAAS** | Low Cost Autonomous Attack System |
| **LRASM** | Long Range Anti-Ship Missile |
| **LRS-B** | Long Range Strike Bomber |
| **MALD** | Miniature Air Launched Decoy |
| **MALD**-J | Miniature Air Launched Decoy Jammer |
| **MCCDC** | Marine Corps Concept Development Command |
| **MMW** | millimeter wave |
| **MOAB** | Massive Ordnance Air Blast |
| **MOP** | Massive Ordnance Penetrator |
| **NATO** | North Atlantic Treaty Organization |
| **nm** | nautical mile |
| **OSD** | Office of the Secretary of Defense |
| **OTH** | over-the-horizon |
| **PA** | probability of arrival |
| **PD** | probability of damage |
| **PGM** | precision-guided munition |
| **Pk** | probability of kill |
| **PLA** | People’s Liberation Army |
| **QDR** | Quadrennial Defense Review |
| **RDX** | Research Department explosive (cyclotrimethylenetrinitramine) |

## LIST OF ACRONYMS

| | |
|---|---|
| **SAM** | surface-to-air missile |
| **Scramjet** | supersonic combusting ramjet |
| **SDB** | Small Diameter Bomb |
| **SDB II** | Small Diameter Bomb Increment II |
| **SFW** | Sensor Fuzed Weapon |
| **SLAM-ER** | Standoff Land Attack Missile-Expanded Response |
| **SLGSM** | Submarine-Launched Global Strike Missile |
| **SM** | Standard Missile |
| **SOPGM** | standoff precision-guided munition |
| **STOVL** | short takeoff and vertical landing |
| **TEL** | transporter erector launcher |
| **TERCOM** | terrain contour matching |
| **TLAM** | Tomahawk Land Attack Missile |
| **TLAM-E** | Tomahawk Land Attack Missile Block IV |
| **TNT** | trinitrotoluene (explosive) |
| **UAV** | unmanned aerial vehicle |
| **UCAS** | unmanned combat air system |
| **UCAV** | unmanned combat aerial vehicle |
| **USSBS** | United States Strategic Bombing Survey |
| **UUV** | unmanned underwater vehicle |
| **UXO** | unexploded ordnance |
| **VLS** | vertical launching system |
| **WCMD** | Wind Corrected Munitions Dispenser |

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