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Key Points

The Air Force should pursue a new generation of mid-range stand-in PGMs to develop a munitions inventory with the capacity to strike 100,000 or more aimpoints in a major conflict with China or Russia.

Next-generation mid-range PGMs should be sized to be carried internally in large numbers by stealth fighters and bombers to reduce the time and cost to attack target sets that are highly dispersed and located deep in contested and highly contested environments.

These PGMs should also be designed with low observability and other features to penetrate advanced integrated air defense systems, reducing the number of USAF sorties and weapons needed in a peer conflict.

Penetrating stealth aircraft with next-generation stand-in PGMs will have the range, survivability, and ability to independently complete kill chains against target sets that are increasingly mobile and relocatable.

Affordable Mass: The Need for a Cost-Effective PGM Mix for Great Power Conflict

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Abstract

After decades of deferred and canceled modernization programs, the Air Force's lead over America's peer competitors is eroding, and its forces are undersized for the operational demands it is asked to meet. At the same time, the squeeze on defense spending threatens the Air Force's annual budget, which has long been less than the Army and Navy's individual budget shares. These challenges place the Air Force in a tenuous position, and missteps in its modernization investments could be disastrous. The Air Force must make smart choices if it is to maximize its combat power with the scant resources it will receive to do so. One critical choice will be the strategy it adopts for developing a precision-guided munitions (PGM) inventory that is sized for peer conflict. The Air Force must balance the range, size, speed, survivability, and capacity of munitions in its inventory if it is to maintain a precision strike advantage over China and Russia. This will require the Air Force to develop a family of affordable next-generation, mid-range (50 to 250 nautical miles) air-to-ground PGMs that can be carried in large numbers by its 5th generation fighters and stealth bombers. This family of weapons will go a long way toward maximizing the capacity and lowering the cost of U.S. strike operations in contested environments. The Air Force's future PGM inventory should:

1. Support future long-range penetrating strikes against targets that are highly dispersed and located deep in contested areas.
2. Consist of weapons that are designed to survive and reach their designated targets located in contested environments.
3. Be effective against challenging targets that are mobile, can quickly relocate, or are hardened or deeply buried.
4. Have the capacity to strike 100,000 or more target aimpoints in an extended operation against a peer adversary.
5. Include a mix of weapons that will maximize the cost-effectiveness of penetrating strike operations conducted at scale.

Rebalancing the Air Force's PGM mix to include a family of next-generation, mid-range PGMs for stand-in strikes will complement the capabilities of the USAF's 5th generation fighters and bombers, improve its ability to defeat challenging targets, and will be affordable enough to procure at the scale needed for a peer conflict.

Introduction

Most defense experts correctly point to the need for the Air Force to field new stealth aircraft to keep pace with China and Russia yet forget that the service's 5th generation F-35 fighters and B-2 and B-21 stealth bombers give America's warfighters another advantage—the ability to conduct "stand-in" strikes that penetrate contested areas to kill multiple targets per sortie. The ability to penetrate and release PGMs closer to targets allows stealth aircraft to carry larger payloads of smaller munitions—smaller because the PGMs may not need powerplants and other components such as sophisticated units to navigate over long flight paths to targets. Moreover, smaller mid-range PGMs that are designed with low observability and other characteristics needed to survive in high-threat areas will help **maximize the lethality and cost-effectiveness** of the Air Force's precision strikes.

For example, a B-2 stealth bomber could carry up to 48 notional stand-in weapons that are sized to have a range of 50 to 150 nm in its two internal weapons bays. In contrast, non-stealthy B-52s can carry up to 20 longer-range and therefore larger JASSM-ER cruise missiles internally and externally. That's up to 48 targets per penetrating B-2 sortie compared to 20 targets for a B-52 that must launch strikes from "stand-off" ranges, which can exceed 500 nm from Chinese or Russian air defenses.

Stand-off strike aircraft like 4th generation fighters and non-stealthy bombers must use weapons that are designed to fly very long distances to attack targets located in contested areas. Designing weapons to fly these long distances increases their cost as well as their sizes, since they must have an engine, fuel, multiple guidance systems, and possibly an advanced seeker to locate targets and precisely guide their warheads to designated aimpoints. Powered subsonic JASSM-ERs cost about $1.1 million each, which is about six times the average cost of a mid-range weapon like the Small Diameter Bomb II (SDB II), which is a 250-pound class unpowered bomb equipped with wings that allow it to glide to a target.

The ability to fly at very high speeds also adds cost. The procurement unit cost of some air-launched hypersonic (Mach 5-plus) weapons now in development, like the Hypersonic Air-breathing Weapon Concept (HAWC), may be in the range of $3 million to $4 million. Cost is a critical factor since DOD must buy enough PGMs to strike 100,000 or more aimpoints during a major campaign against China or Russia. This is not an unreasonable projection, given U.S. air forces attacked approximately 40,000 Iraqi aimpoints during Operation Desert Storm in 1991.[1]

In short, the Air Force should adopt a munitions development strategy that balances the range, speed, survivability, and cost-effectiveness of its PGM inventory so it will have the capacity needed for high-intensity peer conflict. This argues for fielding a new family of stand-in munitions

Maximizing cost-effectiveness

To determine the most cost-effective mix of capabilities, DOD should assess the effects that each capability can create and compare their overall costs to achieve desired operational outcomes. This will help planners maximize the value of their force mix given limited resources. For airstrikes, these comparisons should include the number and cost of PGMs as well as the aircraft needed to execute missions and direct support assets such as aerial refueling tankers, electromagnetic jamming platforms, and SAM suppression efforts. They could also include aircrews and infrastructure like basing and maintenance support.

that have a range between 50 nm and 250 nm and are designed to survive to reach their targets in contested environments. PGMs at the lower end of this range band—less than 100 nm—will give stealth aircraft the ability to strike while remaining outside the most lethal radius of short-range "point" air defenses surrounding high-value targets. These reduced ranges will also permit the Air Force to design PGMs with shorter lengths, which would increase the number of weapons that stealth aircraft can carry internally. This, in turn, would help maximize weapons per sortie. PGMs at the upper end of this range band will increase target areas that penetrating aircraft can hold at risk without inordinately increasing the size and cost of the weapons.

Munitions that are vulnerable to enemy defenses, ineffective against high-value targets, or simply number too few are not a prescription for victory in a peer conflict.

Overall, procuring lower-cost, mid-range stand-in weapons at scale would increase the Air Force's strike capacity and help reduce stress on a budget that is severely pressed to meet its other modernization requirements. In other words, these weapons will help the Air Force provide the precision strike affordable mass that America's warfighters will need to defeat great power aggression.

What Is the Need?

A corollary to the maxim that "you go to war with the forces you have" is that you also go to war with the munitions you have. Munitions that are vulnerable to enemy defenses, ineffective against high-value targets, or simply number too few are not a prescription for victory in a peer conflict. All these shortcomings are now true for a significant portion of the U.S. military's PGM inventory. Moreover, these shortcomings cannot be addressed during a crisis given both the time needed to develop new, technologically advanced PGMs and the U.S. defense industry's inability to quickly surge PGM production.[2] Most air-to-surface munitions in DOD's inventory were designed for campaigns of the past 30 years where U.S. forces confronted lesser regional militaries that operated weak air defenses. DOD is now planning for conflicts with peer and near-peer adversaries equipped with integrated air defense systems (IADS) that are highly capable against non-stealthy aircraft and their legacy weapons. This is why the Air Force is acquiring 5th generation F-35 fighters and B-21 stealth bombers that can penetrate advanced IADS and launch strikes close to defended targets. However, new stealth aircraft alone will not be enough—General Mark Kelly, who leads the Air Force's Air Combat Command, has said his service will not have a true 5th generation force until its "fifth-gen fighters have fifth-gen weapons and fifth-gen sensing."[3] From an operational perspective, putting 3rd generation weapons on the Air Force's stealth F-35s, F-22s, B-2s, and future B-21s will greatly limit their combat effectiveness.[4]

The good news is DOD is developing multiple new PGMs suitable for strikes in contested environments. The not-so-good news is many of these efforts are intended to field very-long-range weapons that will permit its non-stealthy aircraft to launch stand-off attacks against targets while remaining outside the reach of an enemy's air and missile defenses. These long-range stand-off PGMs can cost millions of dollars each, and, because of their extended flight times and small warheads, they may not be effective against highly mobile targets or targets that are sheltered in hardened facilities. At the same time, the Air Force and other services continue to acquire large quantities of non-stealthy, short-range

Munitions Ranges and Uses

Very-Long-Range "Stand-off" Munitions

- Ranges greater than 750 nm, can fly at subsonic (Tomahawk cruise missile) or hypersonic (Air-Launched Rapid Response Weapon) speeds
- Enable non-stealthy aircraft to launch long-range strikes while remaining outside contested areas

Long-Range "Stand-off" Munitions

- Ranges 250 nm to 750 nm, typically winged and powered to achieve range (JASSM-ER)
- May have sufficient range to allow non-stealthy aircraft to launch strikes without penetrating contested areas

Mid-Range "Stand-in" Munitions

- Ranges from 50 nm up to 250 nm, may have wings allowing them to glide after release and powered to extend their range
- Enable penetrating aircraft to strike while remaining outside the lethal range of "point" defenses surrounding many high-value targets

Short-Range "Direct Attack" Munitions

- Ranges of low tens of nm or less, typically unpowered such as JDAMs, Quickstrike mines, etc.
- Must be released close to targets

"direct attack" weapons that would require strike aircraft to fly too close to lethal air defenses surrounding high-value targets in a peer conflict.

In other words, there is a gap between the Air Force's very-long-range and very-short-range munition types that will reduce the number of targets U.S. airmen will be able to strike effectively in contested and highly contested areas. This gap will increase the cost of its future strike operations for two reasons. First, both its stealth and non-stealthy aircraft will have to use greater numbers of costly stand-off weapons if they are to remain out of reach of the enemy's most lethal IADS capabilities. Second, arming stealth aircraft with direct attack weapons for large-scale strikes in highly contested environments would greatly increase risk and reduce options for them to avoid air defenses. Plus, the force "packages" needed to suppress threats enough to allow stealth aircraft to use direct attack weapons against defended targets would require multiple supporting aircraft and an excessive amount of resources. Using stealth aircraft for these risky missions should be reserved for cases where large, penetrating direct attack weapons are required to kill high-value hardened targets.

Background: The Continuous Offensive-Defensive Competition and How It Changes DOD's Munitions Requirements

Thirty years ago, U.S. air forces equipped with a new generation of guided weapons inflicted a stunning defeat on Iraqi forces that had invaded Kuwait. No other military could match the strike capabilities the Air Force brought to the fight during Operation Desert Storm. Today, the Air Force and other services have inventories of air-to-surface PGMs that are increasingly unsuitable for a conflict with a peer military and more advanced regional adversaries. Why is this so? One way to frame the answer is to think of the evolution of precision strike capabilities and their countermeasures as a competition. In fact, the history of air warfare—like warfare in other domains—has been a continuous competition between new offensive and defensive capabilities.

For example, the advantage between Allied and German air forces repeatedly swung back and forth during World War II as technologies, such as more accurate bombsights, radars controlling air defense operations, and early generation guided weapons, were fielded.[5] During the Vietnam conflict, U.S. air forces sought to develop new tactics and capabilities to overcome North

Figure 1: B-47, B-52, B-58 bombers Credit: U.S. Air Force Photos [B-47 | B-52 | B-58]

Vietnamese air defenses, which included a large number of Soviet-made SA-2 surface-to-air missiles (SAM).[6] During the 1967 Six-Day War between Israel and its Arab neighbors, the Israeli Air Force (IAF) quickly gained air superiority by launching preemptive strikes on enemy airfields. A short six years later during the Yom Kippur War, the IAF suffered heavy losses inflicted by the SA-3, SA-6, and SA-7 SAMs and other air defenses the Soviet Union had exported to Egypt, Syria, and their partners.[7] In the 1970s and 1980s, the U.S. Air Force developed aircraft like the F-4G and EF-111, munitions including the High-speed Anti-Radiation Missile (HARM), and new electronic countermeasures (ECM) and tactics to suppress increasingly capable Soviet air defenses. These and other capabilities were key to defeating Soviet and other foreign-supplied air defenses with minor losses during Operation Desert Storm and in later campaigns against Serbia and Iraq. The ability to suppress air defenses allowed U.S. non-stealthy aircraft to strike targets with precision and conduct operations in support of friendly ground troops. In short, the offense was dominant in these post-Cold War conflicts against lesser militaries who were often poorly trained and used dated tactics.

The evolution of the U.S. bomber force and its weapons after World War II is another example of the continuous offensive-defensive strike competition. The U.S. bomber force emerged from World War II well experienced in conducting massive strikes from high altitudes. In the late 1940s and early 1950s, the Air Force procured new jet engine bombers like the B-47, B-52, and B-58. Their on-board defenses and ability to fly at high altitudes and high speeds were considered sufficient to counter nascent Soviet air defenses. The Soviet Union's deployment of the SA-2 SAM in the late 1950s was game-changing—its speed and ability to reach high altitudes made it a serious threat to the Air Force's ISR and strike aircraft. In May 1960, an SA-2 shot down a high-flying U-2 reconnaissance aircraft piloted by USAF Major Francis Gary Powers, and in October 1962 an SA-2 deployed to Cuba intercepted a U-2, killing its Air Force pilot. In response to this growing threat, the USAF's Strategic Air Command trained its B-52 force to fly at low altitudes to evade Soviet air defenses and developed the turbojet-powered AGM-28 Hound Dog missile, which B-52 crews could launch to suppress threats.

In the 1960s, the Air Force began to develop the solid-fuel AGM-69 Short-Range Attack Missile (SRAM) so that its penetrating bombers could launch stand-in nuclear strikes on air defenses and relocatable targets. SRAMs had a range of up to 100 nm, could fly at subsonic and supersonic speeds, had some low observability to improve their survivability in contested areas, and were small and light enough so Air Force B-52s and FB-111s could carry them in significant numbers.[8] In the 1970s, the Air Force began developing the much-longer-range AGM-86B Air Launched Cruise Missile (ALCM) to give its increasingly vulnerable non-stealthy B-52s the ability to launch stand-off nuclear strikes, and it developed a new B-1 bomber capable of high-speed, low altitude flight.

These moves generated countermoves. In the late 1970s, the Soviet Union began deploying a new generation of air defenses, including its SA-10 series of SAMs capable of long-range, high-speed intercepts of multiple airborne targets. The SA-10 also improved the Soviet Union's ability to intercept low-flying aircraft, as did new fighters like the Mikoyan MiG-31 that had look-down/shoot-down radars capable of finding and tracking bombers flying at low altitudes. The Soviet Union also fielded the Mainstay A-50 airborne early warning and control aircraft in 1984 that could, in theory, enable its interceptor aircraft to attack B-52s before they could launch their cruise missiles.[9]

To counter these new defenses, the Air Force modified the B-1's design to further reduce its radar cross section and upgraded both the B-1 and B-52's ECM systems.[10] The Air Force also began to develop the stealth B-2 bomber, Advanced Cruise Missile (ACM), SRAM II missile, and Tri-Service Standoff Attack Missile (TSSAM). These weapon systems were designed with special shapes, radar absorbing materials, and other "low observable" features to avoid detection by enemy air defense sensors.[11] The Air Force decided to acquire the ACM after studies indicated that emerging Soviet air defenses could too easily detect its ALCMs despite their ability to fly at low altitudes.[12] The TSSAM, a cruise missile with a conventional warhead, was the progenitor of DOD's Joint Air-to-Surface Standoff Missile (JASSM) low observable cruise missile.

By 1990, investments in stealth aircraft, more survivable weapons, and other advanced capabilities had swung the offensive-defensive advantage back in favor of U.S. strike forces. Regaining the offensive advantage required the Air Force to develop next-generation aircraft *and next-generation munitions* that, in combination, gave it the range, speed, survivability, and lethality to overcome air defenses and attack targets with precision. Following the end of the Cold War, however, DOD made a series of decisions that now threaten to reverse this dynamic in favor of the increasingly capable IADS of China, Russia, and other adversaries who have acquired advanced air defenses.

A One-Sided U.S. Pause in the Competition

Following the Soviet Union's collapse, the Department of Defense shifted its focus toward preparing for regional contingency operations instead of global conflict with a peer military. In 1993, DOD's Bottom-Up Review determined aggression by lesser adversaries like Iraq and North Korea were the new primary threat to U.S. global security interests. To a large extent, these regional adversaries were equipped with antiquated air defenses and lacked the training needed to operate them effectively. Because of the permissive operating environments of the day and a desire to cut defense spending, DOD curtailed or outright ended multiple programs to acquire new stealth aircraft and munitions designed to operate in contested environments. Over the next fifteen years, DOD decided to buy only 21 of the Air Force's required 132 B-2 stealth bombers, 187 of the Air Force's required 750 F-22 stealth fighters, 460 of the originally planned 1,460 ACMs, and canceled SRAM II and TSSAM procurement. This created a significant gap—which persists today—in the Air Force's ability to conduct precision strikes and other combat operations in contested environments.[13]

The shift toward guided direct attack munitions

DOD's 1993 Bottom-Up Review also called for developing new "smart" precision-guided anti-armor munitions to defeat the mechanized forces of North Korea and Iraq. Developing "all-weather" PGMs like JDAMs became another pressing requirement after Operation Desert Storm had shown that poor weather, dust, or smoke obscuring targets could degrade the effectiveness of laser-guided weapons.[14] JDAMs, which joined DOD's inventory in 1997 and remain in production today, are ideal weapons for precision strikes in permissive operational environments. Non-stealthy JDAMs use positioning, navigation, and timing information provided by DOD's constellation of Global Positioning System (GPS) satellites to accurately strike targets in all weather conditions. Unpowered JDAMs can reach targets up to 15 nm from their release points, depending on the releasing aircraft's altitude and speed. They are precise enough to reduce unwanted collateral damage and cost between $25,000 and $45,000 each depending on the variant. It is not surprising that JDAMs became the signature air-to-surface PGM of the post-Cold War era.[15] The Air Force also acquired small quantities of much larger GPS-guided direct attack 5,000-pound and 30,000-pound bombs to penetrate and kill hardened targets.[16]

Mid-range stand-in weapons for regional conflicts

DOD began to develop several new mid-range all-weather strike weapons in the 1990s and 2000s, including the Air Force and Navy's Joint Standoff Weapon (JSOW) and Small Diameter Bomb. Like JDAMs, both JSOWs and SDBs are non-stealthy weapons that are best suited for strikes in permissive environments. JSOWs have a GPS/inertial navigation guidance system (GPS/INS) and wings that extend after release that allow them to glide up to 70 nm.

The Small Diameter Bomb II

An upgraded SDB variant called the SDB II has a "tri-mode" seeker that consists of a millimeter wave radar to locate and track targets in all weather conditions, an imaging infrared (IIR) sensor to improve target discrimination, and a semi-active laser that can track a laser spot placed on a target by the releasing aircraft or another source. The SDB II also has a datalink to receive updated information inflight and can glide for more than 40 miles.

Courtesy photo/Raytheon Missiles and Defense, released by USAF

The Air Force canceled its procurement of the JSOW in 2005.[17] In 1997, the Air Force identified a need for a smaller glide weapon, which culminated in the SDB program. The reduced size of the 250-pound class SDB increases the number of weapons that can be carried by fighters and bombers in a single sortie. The initial SDB variant was equipped with a GPS/INS guidance system which allowed the Air Force to attack suitable fixed targets day and night in all weather conditions.[18]

Anti-radiation weapons

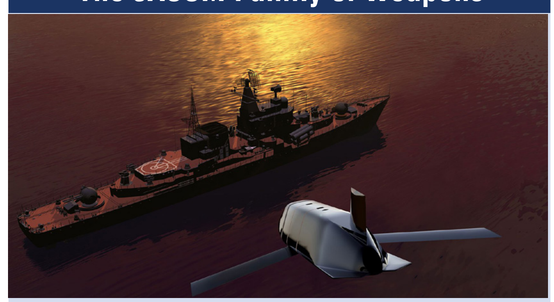
DOD has also fielded PGMs capable of homing in on active emitters such as air defense radars. Air-launched High-speed Anti-Radiation Missiles (HARM), which entered service in the 1980s and had a range of 26 nm and a top speed of Mach 1.8, were extensively employed against enemy radars during Operation Desert Storm, Operation Allied Freedom, and Operation Iraqi Freedom.[19] An upgraded HARM variant called the Advanced Anti-Radiation Guided Missile (AARGM) has a new guidance system and seeker allowing it to attack non-emitting targets and provide battle damage assessments. The AARGM-Extended Range (AARGM-ER) now in development has a new motor, is faster (Mach 2-plus), and has twice the range of the AARGM.[20]

The Air Force is also developing a new Stand-in Attack Weapon (SiAW) similar to the AARGM-ER to attack time-urgent targets like mobile missile launchers, air defense systems, and anti-satellite systems. AARGM-ER and SiAW will give stealth fighters and bombers the ability to conduct penetrating SEAD operations against peer adversaries by the early 2020s. As one defense writer has noted, "A bomber loaded with a mix of AARGM-ERs and SiAWs would be a particularly capable tool for destroying both air defenses and targets of opportunity along a certain route, helping clear a path for following-on forces both in the air and down below."[21]

Post-Cold War cruise missile development

DOD's post-Cold War priorities included improving its ability to launch limited numbers of long-range stand-off weapons against high-value targets without penetrating politically denied or hostile airspace. In the late 1990s, the Air Force began developing the JASSM, the technological successor to TSSAM, which has a 1,000-pound class conventional warhead and an announced range of over 200 nautical miles.[22] It is now buying AGM-158B JASSM-Extended Range (JASSM-ER) missiles with a declared range that exceeds 500 nm, and the Air Force and Navy are acquiring an anti-ship JASSM-ER derivative called the Long Range Anti-Ship Missile (LRASM).

The JASSM Family of Weapons



JASSM, JASSM-ER, and LRASM are low observable, highly survivable munitions equipped with GPS-aided INS for guidance, IIR seekers, and a pattern-matching autonomous target recognition capability designed to strike high-value, heavily defended fixed and relocatable targets. The JASSM has 3-meter accuracy, which reduces the number of JASSMs that must be used on targets.

LRASM image courtesy of Lockheed Martin

An enduring bias toward lower-cost direct attack munitions

DOD's PGM procurements over most of the last 30 years were strongly biased toward direct attack munitions needed for operations against less capable theater adversaries and counterterror/counterinsurgency strikes. According to FY 2021 defense budget documents, DOD acquired 331,673 JDAM kits, over 41,099 SDBs, and 1,685 SDB IIs through FY 2020 and may buy 29,800 more JDAMs, 9,670 SDBs, and 9,039 SDB IIs through FY 2025.[23] By contrast, the Air Force has procured about 3,600 of the 7,200 JASSM/JASSM-ER stand-off missiles that it intends to buy and will acquire about 410 LRASM through FY 2025.[24] The Navy procured 5,168 JSOW through FY 2015, and has decided to forego plans buy JSOW-Extended Range missiles in favor of acquiring a variant of the low observable JASSM-ER.[25] About 700 AARGM kits were produced for DOD through 2018 out of a total of 2,575 planned, and DOD intends to acquire at least 2,097 ARRGM-ER.[26]

It is not a surprise that these quantities correlate with the cost of these PGMs. As shown by the two shaded columns in Table 1, the number of each type that DOD has procured and plans to acquire in the next few years decrease as their unit costs increase.[27]

The same bias is evident for air-to-surface munitions that were expended during major U.S.-led air campaigns in the late 1990s and 2000s. During Operation Allied Force in 1999, coalition forces launched 28,018 direct attack munitions, 743 HARMs, and 278 cruise missiles against targets.[28] This was repeated during the Operation Enduring Freedom and Operation Iraqi Freedom air campaigns when coalition forces expended a combined total of 50,213 direct attack munitions, 1,012 cruise missiles, and 408 HARMs.[29] **Overall, 97 percent of the air-to-ground munitions used in these air campaigns were direct attack munitions.** From 2004 through 2019, U.S. and coalition partner aircraft delivered about 176,000 munitions on counterterror and counterinsurgency targets during operations in Iraq, Afghanistan, and Syria, almost all of which were JDAMs and direct attack Hellfire missiles.[30]

DOD's use of large numbers of direct attack munitions in operations over the last 30 years is not a surprise given their lower unit

	Range (nautical miles)	Length (inches)	Weight (pounds)	Average procurement unit cost ($)	Number procured plus plan to acquire
JDAM variants	up to 15	92 to 152	559 to 2,040	25,000+	375,403
SDB I	up to 60	70.8	285	36,000	50,769
SDB II	more than 40	69	204	186,000	10,724
JSOW	up to 70	161	1,067	357,000	5,168
JASSM	more than 200	168	2,250	698,150	2,034
AARGM	more than 60	164	795	970,000	2,475
JASSM-ER	more than 500	168	2,645	1,048,000	5,166
AARGM-ER	120	< 144	Unknown	1,578,000	2,097
LRASM	more than 200	168	2,755	3,162,000	410

Credit: Mitchell Institute

Table 1: Comparing the ranges, sizes, unit costs, and quantity of direct attack, mid-range stand-in, and long-range stand-off PGMs procured by the Air Force and Navy

costs compared to long-range stand-off PGMs and relatively permissive environments that allowed non-stealthy fighters and bombers to strike targets across battlespaces. In short, the munitions that DOD developed and procured in the first two decades after the Cold War proved extremely effective in lower-end conflicts against regional aggressors and during counterterror and counterinsurgency campaigns. However, the precision strike offensive-defensive balance has once again changed, and munitions that were optimal for low-end operations are no longer suitable in an era of renewed great power conflict.

The Need for a Different Mix of Air-to-Surface PGMs

Strike aircraft and guided munitions developed by DOD during and immediately after the Cold War excelled in regional conflicts because they were used in highly favorable operational conditions. Regional adversaries had few air defenses that were effective against non-stealthy aircraft, lacked the advantage of great geographic depth, and were unable to launch large-scale air and missile strikes against U.S. and allied theater bases. Consequently, U.S. and allied non-stealthy combat aircraft based close to adversaries could fly multiple sorties per day to deliver large numbers of direct attack munitions on targets across battlespaces nearly unopposed.

These favorable conditions will not be available in a conflict with a peer or near-peer adversary. As described by DOD's *National Defense Strategy*, China and Russia's modernized militaries are unlike the regional forces, terrorists, and insurgents the United States has confronted since 1991. China and Russia's militaries are far larger, more technologically capable, and can challenge DOD's access to the South China Sea, the Baltics, and other areas critical to U.S. national security. Both have fielded advanced weapons systems to deny U.S. forces freedom of action in the air, sea, space, cyberspace, and electromagnetic spectrum (EMS). Like other modern militaries, U.S. forces are highly dependent on sensors that operate in all these domains to find targets, track them, and then strike them with PGMs—the precision strike "kill chain." Numerous studies have warned that DOD has fallen behind China and Russia in fielding new electromagnetic warfare systems that will be critical to conducting precision strikes and other operations.[31]

Great geographic distances and highly capable air defenses will also affect the U.S. military's ability to sustain large-scale strike operations against a peer adversary. U.S. commanders will need the capability and capacity to attack large numbers of Chinese or Russian targets, including asymmetric threats like anti-satellite weapons and ballistic missile launchers that are located hundreds of miles in their interiors. These targets will be defended by advanced IADs that are capable against U.S. non-stealthy aircraft and their 3rd generation PGMs. China and Russia have also deployed passive defenses such as hardened shelters, decoys, camouflage, and other forms of concealment to reduce the effectiveness of U.S. precision strikes. Moreover, both will exploit their geographic depth and breadth by frequently moving their high-value relocatable systems to complicate the Air Force's ability to find, track, and target them, and they will use their long-range missiles to strike U.S. and allied airbases across a theater of conflict.[32]

Overcoming these challenges will require combat aircraft that have enough range to attack targets located anywhere in China and Russia, 5th generation stealth to survive in contested environments, and the capacity to carry large payloads of munitions, sensors, and other mission systems needed to find and attack mobile/

relocatable targets independently. It is for these reasons the Air Force decided to procure F-35As and B-21 stealth bombers. Maximizing the combat effectiveness of these next-generation platforms will also require a different mix of air-to-surface weapons—a PGM inventory that meets the following essential design objectives. Failing to do so will increase the risk that the service will fall short of maintaining its precision strike advantage over peer and more sophisticated near-peer adversaries. Overall, the Air Force's future PGM inventory should:

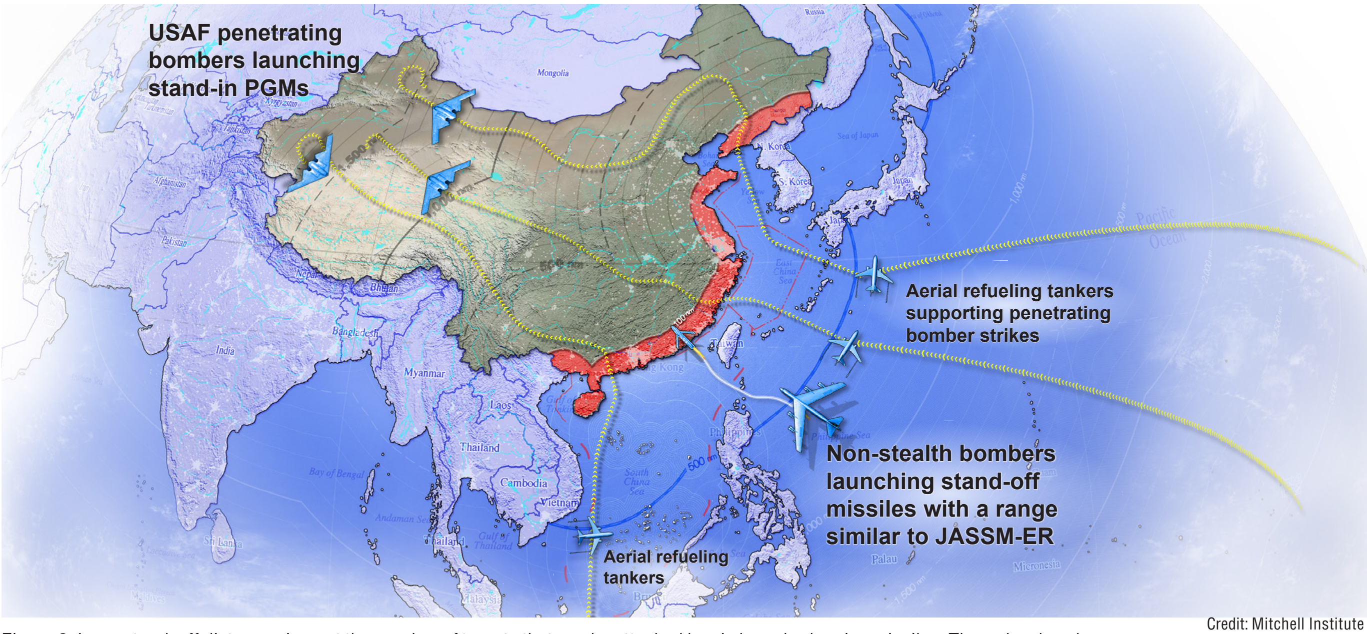
1. Support future long-range penetrating strike operations against targets that are highly dispersed and located deep in contested areas.
2. Consist of weapons that are designed to penetrate enemy defenses and reach targets located in contested operational environments.
3. Be effective against targets that are mobile, can quickly relocate, or are hardened.
4. Have the capacity to strike tens of thousands of targets in an extended operation against a peer adversary.
5. Include a mix of weapons that will maximize the cost-effectiveness of penetrating precision strike operations conducted at scale.

Fielding a family of next-generation, mid-range PGMs for stand-in strikes will help the Air Force achieve all of these objectives. These PGMs will complement the capabilities of its stealth fighters and bombers, improve its ability to defeat mobile, hardened, deeply buried, and other challenging targets, and will be affordable enough to procure at the scale needed for a peer conflict.

1. The Air Force's PGM inventory must support long-range strike operations against targets that are highly dispersed and located deep in contested areas.

U.S. theater commanders must have the capacity to strike a very large number—tens of thousands—of targets such as a peer adversary's bomber airfields, naval ports, command and control complexes, ballistic missile fields, and key military industrial facilities. These targets may be located along the peripheries of China and Russia or deep in their vast interiors. The depth and dispersed nature of potential target sets create significant challenges for the USAF's fighter force which now largely consists of non-stealthy aircraft that cannot survive in contested areas or air refuel close enough to Chinese or Russian defenses to allow then to penetrate deep. Moreover, the Air Force's current bomber force consists of 76 non-stealthy B-52s, 45 non-stealthy B-1s, and only 20 penetrating stealth B-2s. Due to then-Secretary of Defense William Cohen's 1997 decision to truncate B-2 procurement, all but the USAF's B-2s must now use long-range stand-off PGMs to launch strikes and remain outside the reach of Chinese or Russian air defenses. This imposes significant operational limitations on a U.S. theater commander's ability to strike critical targets in a peer conflict.

For instance, cruise missiles launched by non-stealthy bombers and fighters that must stand-off 500 nm to 800 nm from a land-based IADS will only be able to reach a small fraction of targets that are dispersed across land masses as large as China. This means that targets such as anti-satellite weapons, ballistic missile units, and command and control facilities located deep inside China cannot be reached by most cruise missiles launched by non-stealthy aircraft. However, as Figure 2 shows, stealth bombers armed with mid-range, stand-in



Credit: Mitchell Institute

Figure 2: Long stand-off distances impact the number of targets that can be attacked by air-launched cruise missiles. The red-colored area shows potential target areas that could be reached by non-stealthy aircraft launching cruise missiles from stand-off distances of 500 nm from China's coastline. In contrast, stealth bombers with stand-in munitions and supported by aerial refueling have the range to penetrate and reach targets located anywhere in China and do so from multiple directions. Stealth bombers will need to use mid-range PGMs for most strikes in contested areas, since the very short ranges of direct attack weapons would require them to nearly overfly lethal point defenses surrounding high-value targets.

weapons can penetrate defenses to attack targets anywhere in China, and their ability to attack from unexpected directions can greatly complicate an enemy's air defense challenge.

2. PGMs must also survive to reach targets located in contested and highly contested areas.

With the shift in focus toward deterring and defeating great power aggression, the U.S. military once again must prepare to conduct precision strikes and other missions against adversaries that have cutting-edge air defenses. Unlike defenses U.S. air forces faced during campaigns in the 1990s and 2000s, Russian and Chinese IADS can deny access to 4th generation non-stealthy aircraft which still comprise most of the USAF's combat air forces. Even as DOD decided to take a multi-decade pause in fielding stealth aircraft and weapons in the aftermath of the Cold War, Russia and China improved their ability to counter U.S. strikes. This one-sided halt in the precision strike competition created a situation where the U.S. military is now at risk of losing its advantage.

Russia and China's air defenses are increasingly mobile, long-range, and fully integrated. Russia began to field its S-300 (NATO designation SA-10) family of SAM systems in the late 1970s. S-300s were initially mounted on towed trailers and could take 30 to 120 minutes to deploy their radar and other systems in preparation to launch or stow in order to relocate.[33] Later systems like the S-300V (SA-12), S-300PMU-1/2 (SA-20A/B) and S-400 (SA-21) used self-propelled vehicles for all of its components, which allow them to deploy or stow within minutes.[34] Russia has introduced phased array radars into its SAM systems, which are jam-resistant and increasingly powerful. Its latest SAMs include active electronically steered array (AESA) radars that have increased range, improved resolution, and the ability to track multiple targets simultaneously. Several

Figure 3: Russian S-400 (top) and a Chinese HQ-9 (bottom), a derivative of Russia's S-300

Credit: RIA Novosti | Chinese media

variants of advanced SAMs have radars that operate in lower frequency bands to improve their capability against stealth aircraft that were designed to avoid detection in higher EMS bands.[35] Russia has increased the range of some of its SAMs to 400 kilometers or more—quadruple the range of its 1980s-era SAMs—and its most modern missiles have active seekers capable of locating and guiding themselves to airborne targets.[36] In addition to producing its own derivative systems like the long-range HQ-9, China has also fielded Russian-made S-300 and S-400s.

The issue is not simply that modern IADS have increased mobility and engagement ranges; they are also networked in a way that amplifies their individual capabilities. Networking allows radars to work collaboratively across a range of spectrums and enables long-range and short-range SAMs to receive target data from multiple sensors operating in all domains.[37] Modernized airborne early warning aircraft like Russia's A-100 and China's KJ-2000 and KJ-500 employ AESA radars that extend the range of their air defense networks and support fighter and SAM engagements against airborne targets. China is investing in "low band" Ultra High Frequency (UHF) and Very High Frequency (VHF) ground radars like the JY-26 to improve its ability to detect and track aircraft over long ranges. Modern IADS also include fighters like Russia's Su-35, Su-57, and MiG-35, as well as China's 5th generation J-20 and FC-31, which have AESA radars, infrared sensors, and carry very-long-range air-to-air missiles. Some of these missiles, like Russia's R-37 and China's PL-XX are designed to kill U.S. high-value airborne assets like AWACS, aerial refueling tankers, and non-stealthy bombers.

Advanced IADS are also increasingly effective against legacy munitions. Russia and China's advanced IADS are eroding the effectiveness of the U.S. military's legacy strike systems. A major difference between air defenses of the 1990s and IADS of today is the proliferation of systems capable of engaging incoming cruise missiles and other guided munitions. These defenses include Russia's SA-15 (Tor), SA-19 (Tunguska) and SA-22 (Pantsir) mobile SAMs that can target low-flying aircraft, cruise missiles, anti-radiation missiles, and bombs.[38] China has developed its own variant of the Tor, known as the HQ-17, and an FK-1000 short-range "point defense" system that resembles the Pantsir. These short-range weapons are fully integrated with electronic warfare systems and longer-range SAMs. China, Russia, Iran, North Korea, and others also employ decoys, camouflage, concealment, deception, and hardening that further reduce the effectiveness of an adversary's precision strikes.

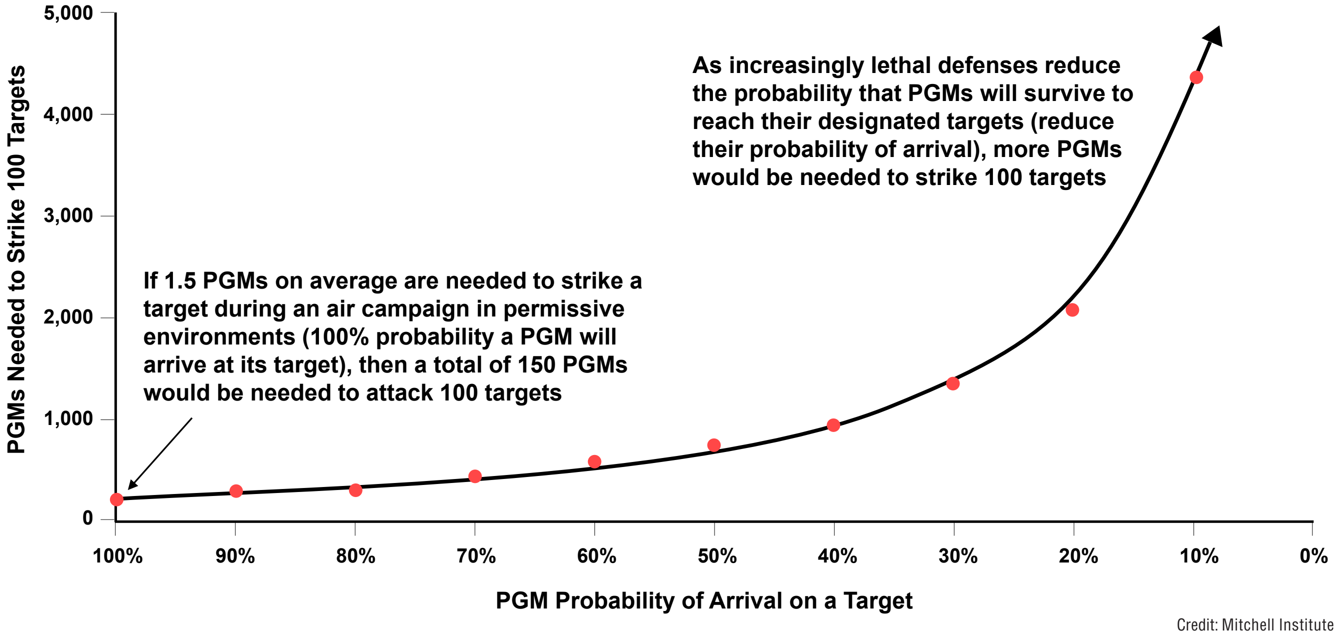


Figure 4: The number of munitions needed to attack targets increases as the probability they will survive to reach their targets decreases. A PGM's "probability of arrival" on a target depends on factors such as the PGM's low observability, ability to maneuver to avoid defenses, and time of flight which can increase an enemy's ability to detect and counter an attack.

In combination, these active and passive defenses significantly alter the calculus of U.S. forces looking to deter aggression or counter threats in a conflict. For starters, they will greatly increase the number of legacy PGMs U.S. forces would have to use to ensure at least one weapon survives to reach the designated target. As Figure 4 illustrates, 150 non-stealthy cruise missiles or bombs may be needed to attack 100 notional targets located in permissive environments. This is based on the average number of PGMs—about 1.5—that were used to strike individual targets during Operation Iraqi Freedom in 2003. Notably, this is a weapon-to-target ratio that USAF airmen who flew in the Korean War and Vietnam conflict could only have imagined.[39] In other words, the probability that a munition will arrive at its designated target in highly permissive environments is nearly 100 percent, excluding factors such as a failure of the PGM's hardware or software. Figure 4 also shows the number of PGMs needed to strike 100 notional targets steadily increases as the operational environment becomes contested and more PGMs are attrited by enemy defenses. At some point, the number of PGMs—and aircraft sorties—needed to ensure successful strikes in contested environments becomes prohibitive. At an extreme, attacking the same 100 targets using munitions that have a very low probability of survival may require hundreds of aircraft sorties.

A new generation of survivable mid-range PGMs is needed. Given the USAF's bomber and fighter inventories are the smallest in its history, it would be impossible for it to greatly increase the number of sorties it can generate to compensate for legacy PGMs that are attrited at a high rate. Plus, significant force growth is not in the cards: it is likely the USAF's budget will continue to flatten or decline, despite recommendations of multiple government and independent studies to increase the size of its combat air forces.

Fielding a new generation of mid-range, stand-in weapons that are capable of penetrating Chinese and Russian IADS is another means to increasing the USAF's lethality and reducing the total number of sorties and weapons needed to kill targets in contested environments. In other words, these weapons would be an operationally effective *and* cost-effective means to maintain the USAF's precision strike advantage. Although it is certainly feasible to develop next-generation direct attack munitions with the survivability needed in contested environments, their very short ranges would still require stealth aircraft to nearly overfly lethal point defenses surrounding high-value targets. At the other extreme, new very-long-range stand-off cruise missiles may be able to penetrate defenses and allow strike aircraft to launch attacks while remaining in more permissive environments. Yet as Table 1 indicates, increasing PGM range increases their cost, and buying many tens of thousands of stand-off missiles for millions of dollars each is not cost-effective. The happy median would be to invest in mid-range, stand-in munitions that can be launched by penetrating manned and unmanned aircraft and are affordable enough to procure at scale

Moreover, the shorter flight times of stand-in PGMs will reduce the time available for an enemy to detect incoming weapons and then complete a kill chain to intercept them. Conversely, a subsonic (Mach 0.8) cruise missile launched 500 nm from a target would need about an hour to reach it, which could give an enemy the time it needs to detect the weapon and intercept it or move a mobile or relocatable target. In this case, while the attacking cruise missile may strike its preprogrammed target coordinates with great accuracy, the missile would be a net loss if its target is no longer there. While some advanced cruise missiles can receive updated target information after launch, enemy jamming could degrade the ability to communicate with them in a real-time, on-demand fashion. Even weapons capable of flying at hypersonic speeds may not be fast enough to engage highly mobile targets—depending on the distance the weapons must travel after launch and the time needed for their designated targets to relocate. A better alternative would be to rely on stand-in weapons that have flight times measured in single-digit minutes. Plus, launching larger salvos of less expensive stand-in munitions are a more affordable way to overwhelm the intercept capacity of an enemy's defenses.

More survivable hypersonic weapons are also needed, but they will not be a panacea. Hypersonic weapons will give U.S. forces additional options to strike targets in contested and highly contested environments. Hypersonic weapons combine the very high speeds of ballistic missiles with the agility of cruise missiles to evade enemy defenses.[40] "Boost-glide" hypersonic weapons like the Air Force's Air-Launched Rapid Response Weapon (ARRW), the Navy's ship-launched Conventional Prompt Strike munition, and the Army's ground-launched Long-Range Hypersonic Weapon (LRHW) will all use a rocket to boost a maneuverable glide vehicle carrying a warhead to high altitudes and airspeeds that allow it to glide to a distant target.[41] The LRHW, which pairs a rocket booster with the Common Hypersonic Glide Body (C-HGB) developed by the Army and Navy, will have a range of at least 2,250 kilometers and could cost $40 million or more each.[42] The Air Force is also developing air-launched hypersonic cruise missiles powered by "air-breathing" scramjet engines. Crucially, air-launched hypersonic boost-glide weapons will be a fraction of the LRHW's cost, as they do not require the use of large, expensive rockets to boost them to high altitudes and speeds.

Both boost-glide and air-breathing hypersonic weapons will improve the Air Force's ability to launch long-range strikes against time-sensitive targets such as mobile and relocatable missile launchers that operate from contested environments. That said, the basic limitations regarding subsonic and supersonic stand-off munitions also apply to very-long-range hypersonic weapons. Complex kill chains consisting of multiple sensors and C2 capabilities are needed to provide initial targeting information and target updates to stand-off strike platforms over long ranges even if they are carrying hypersonic weapons. A basic rule of thumb is that the complexity and cost of kill chains grow as the distance between strike aircraft and their intended targets increases. Long stand-off ranges also increase the size of hypersonic weapons, which reduces the number of weapons that fighters and bombers can carry. Some long-range hypersonic weapons may be so large that they can only be carried externally by bomber aircraft. This would preclude them from being carried by stealth aircraft into contested areas, since they would greatly increase the aircraft's radar signature. Furthermore, very-long range hypersonic weapons would still need to fly tens of minutes to reach their targets, which can give an enemy more time to detect and counter them, and hypersonic weapons that cost millions of dollars each will constrain the number the Air Force can afford to buy.

3. The Air Force's future munitions mix must also be effective against mobile, relocatable, hardened, or deeply buried targets.

China, Russia, and other adversaries have increased the mobility of their high-value weapon systems to complicate the U.S. military's ability to find, fix, track, target, and attack them over long ranges. Defeating large numbers of these challenging targets effectively will require penetrating strike aircraft that can independently locate and attack them with payloads of mid-range, stand-in weapons. The unsustainable alternative would be to use very-long-range stand-off weapons with extended flight times that give an enemy more time to counter attacks or short-range direct attack weapons that significantly increase risk to aircraft that deliver them.

Target mobility reduces the effectiveness of long-range stand-off strikes. Like Russia's modern SAMs, advanced Chinese air defenses like the HQ-9 have mobile launchers, radars, and command vehicles that enable them to launch a missile at an airborne target and then begin to relocate within minutes. These shoot-and-scoot operations complicate the ability of U.S. forces to detect a SAM launch, locate the launcher, and then complete the rest of a kill chain before the launcher and other SAM components relocate.[43] Other potential targets such as ground maneuver forces, missile transporter-erector-launchers (TELs), and naval forces use their mobility to degrade U.S. precision strike kill chain operations. This is a key reason for why long-range stand-off munitions are best suited for strikes against fixed targets that cannot quickly relocate.

Countermeasures that degrade the U.S. military's ability to provide target cues to its stand-off air forces is another reason why they may be less effective against mobile and relocatable targets compared to penetrating aircraft that can independently find and attack them. Stand-off aircraft and other launch platforms are dependent on external ISR assets to find and track mobile targets. The usual practice is to program a stand-off weapon with the coordinates of a mobile or relocatable target just before the weapon is launched. If the target changes its location after a weapon is launched, then the weapon may miss its target even though it hits its preprogrammed coordinates with great precision. To compensate for a target's movement, one or more external sensors must track it, and then updated target information must be relayed to the weapon while it is inflight. If a target cannot be tracked or updated data cannot be passed to a weapon after launch, then the weapon is wasted. The external sensors, networks, and datalinks needed to provide target information to stand-off aircraft and weapons may be vulnerable to enemy jamming and other countermeasures. Tracking a highly mobile target becomes even more challenging as the flight time of a stand-off weapon increases, as it also increases an enemy's opportunity to detect the incoming strike, move the potential target, and take other actions to defeat the strike.

Affordability is another factor to consider, since the advanced engines and other capabilities needed to achieve and sustain very high speeds significantly increase weapon unit costs. In most cases, a better, more cost-effective choice is to employ penetrating strike aircraft that have on-board sensors capable of detecting and tracking mobile/relocatable targets instead of relying on targeting information provided by external ISR systems. Plus, their ability to launch mid-range, stand-in weapons that cost $300,000 or less each against challenging mobile and relocatable targets would improve the USAF's ability to impose costs on a peer aggressor.

Hardening and deeply burying fixed targets also reduce the effectiveness of stand-off strikes. China, Russia, and other adversaries now routinely harden or deeply bury potential fixed targets such as large command and control installations and weapon storage facilities to protect them. These methods are particularly effective against smaller warheads like those typically carried by very long-range stand-off weapons. The weight of warheads carried by air-launched missiles tends to diminish as missile ranges increase. Cruise missiles with conventional warheads that weigh about 1,000 pounds have historically been limited to ranges of 1,000 miles or less.

Much larger conventional warheads may be required to attack underground

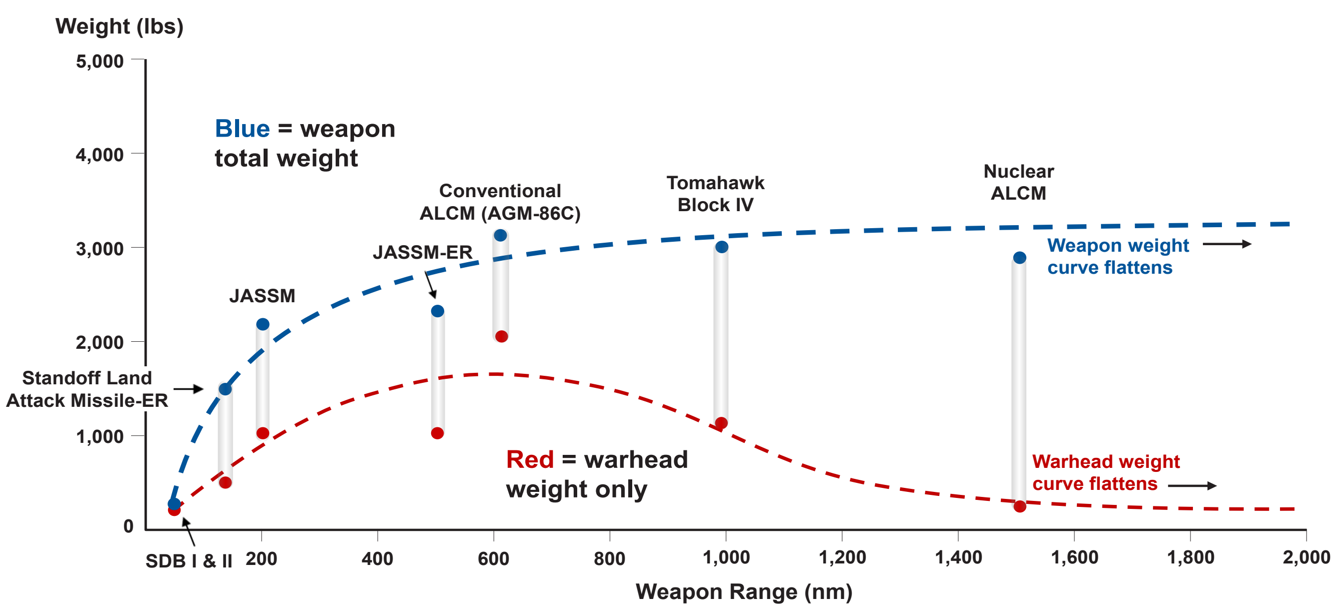


Figure 5: As PGM ranges increase so do their total weight, since they need a powerplant, fuel, and other features to extend flight. The reverse is true for PGM warhead weights, which are often decreased in order to increase a weapon's potential range. Both weights eventually "flatten" as it becomes impractical to further grow the size and weight of stand-off PGMs that can be carried by aircraft.

Credit: Mitchell Institute

facilities such as leadership bunkers, hardened shelters protecting weapons of mass destruction, and certain types of reinforced infrastructure such as bridges.[44] Only stealth bombers have the ability to both carry very large "bunker buster" direct attack weapons, such as the 5,000-pound GBU-28 and the 30,000-pound GBU-57 Massive Ordnance Penetrator, and achieve the ranges necessary to use them to strike hardened targets deep in a peer adversary's interior. It may be feasible to design mid-range PGMs with enhanced warheads that are capable against many hardened and deeply buried targets. However, designing weapons with very long ranges and conventional warheads that have the mass and explosive power to penetrate very hard or deeply buried targets would require significant technological advances.

4. The Air Force's PGM inventory should have the capacity to strike tens of thousands of targets in a major campaign against a peer adversary

The size of a potential target set in a fight with China or Russia and the probability that their defenses will attrit the Air Force's legacy PGMs drive the service's need to procure new, more survivable weapons in quantities that are significantly larger than what it has historically acquired. This should be an immediate Air Force priority, given its chronic PGM shortfall and the need to prepare for a high intensity peer conflict that could occur with little warning and last longer than the air campaigns it has led against regional aggressors since the Cold War.

Theater commanders will need a PGM inventory that won't run out in a week. The Air Force now lacks enough PGMs to engage in an extended duration campaign against China or Russia plus meet other operational needs in other theaters as required by the *National Defense Strategy*.[45] To an extent, this shortfall is an artifact of post-Cold War planning policies that sized DOD's forces—including its PGM inventory—for relatively short campaigns against lesser regional militaries and counterterror operations. DOD planners in the 1990s estimated that a conflict with a regional opponent such as Iraq would be a "short" war that would not require it to maintain very large stockpiles of PGMs in peacetime.[46] This assumption was reinforced by real-world operations. The Operation Desert Storm and Operation Iraqi Freedom air campaigns were intense, but only lasted 42 and 43 days, respectively. Operation Allied Force was somewhat protracted at 78 days, but not very intense.[47] Similarly, airstrikes against terrorists and insurgents since 2001 were protracted, but not intense. The nature of these post-Cold War air campaigns allowed DOD to draw down its PGM stockpiles during crises and then slowly replenish them over a matter of years. A notable exception occurred in 2015, when strikes against ISIS in Syria and Iraq—despite their low intensity—threatened to excessively deplete DOD's PGM stockpiles.[48] While DOD reacted by surging the production of JDAMs, SDBs, Hellfire missiles, and other munitions, it required five years for its stockpiles to recover. This is not surprising, given the U.S. industrial base's inability to quickly surge PGM production.[49]

The stark reality is an operation to defeat Chinese or Russian aggression would be far more intense and could last significantly longer than DOD's other post-Cold War campaigns. Precision strikes against either adversary would involve hundreds of sorties per day and last for many weeks—or at least until U.S. forces exhausted their PGMs. Absent sufficient munitions, the Air Force will not be able to sustain high-tempo strike operations regardless of how many combat aircraft it brings to the fight.

Figure 6 shows how JASSM, JASSM-ER, and LRASM inventories the Air Force is procuring could be quickly depleted in a fight against a peer aggressor. This example assumes only half of the Air Force's non-stealthy B-52s and B-1s—41 aircraft—are tasked to launch JASSM and LRASM.[50] Even at this modest tempo, the USAF's entire inventory of these PGMs could be depleted in about a week.

The ability to quickly surge PGM production to meet operational requirements during a war with China or Russia could be decisive and should be part of the Air Force's plans to prepare for high-end peer conflict.[51] As the noted defense strategist Hal Brands recently observed, "The outcome of a great power war may be determined by what happens after the first campaign—who can ramp up production of missiles and other munitions, who can quickly replace lost ships and aircraft, who has the stronger, more adaptive industrial base and can better withstand the economic damage a conflict will inflict."[52] Creating a more resilient PGM industrial base could entail creating new capacity in existing facilities to surge wartime production, possibly by maintaining some munitions facilities in "layaway" status during peacetime despite the additional cost of doing so.

Acquiring mid-range PGMs that take maximum advantage of lighter, stronger, and more adaptable materials would be another step toward developing a munitions inventory suitable for peer conflict. Current stand-in weapons are mostly made of metal, are easy for advanced air defenses to detect, and use 50-year-old warhead technology. New mid-range PGMs could be hybrids constructed of metal and lightweight composite materials, have miniaturized electronics, and carry larger payloads per weapon size than current munitions. JASSM cruise missiles are one example of a hybrid munition with a metal

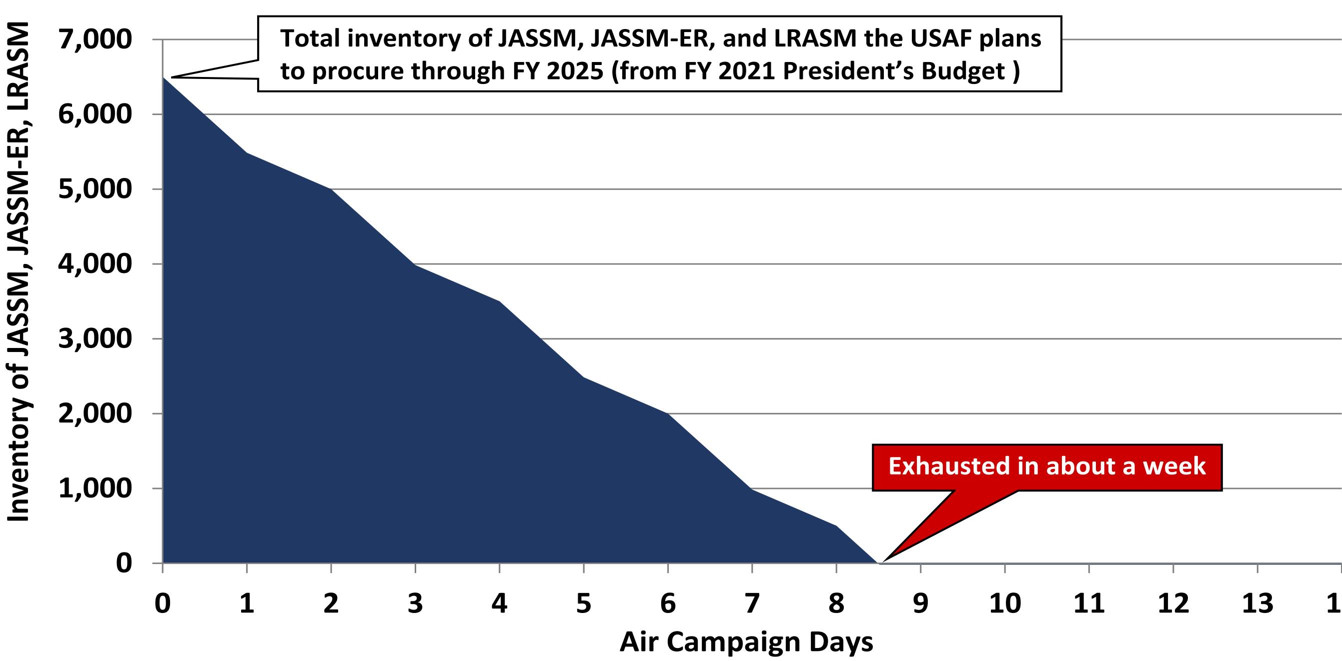


Figure 6: Notional depletion of the Air Force's JASSM family of PGMs assuming plausible utilization rates in a conflict with a peer aggressor. This burn-down rate is optimistic since the USAF's other bombers and fighters would also employ JASSM-ERs and LRASMs, which could easily exhaust their inventories in just a few days. The consequences of a lack of JASSM and other advanced PGMs would be immediate and severe, since no other U.S. service or NATO force can provide the precision strike capacity needed to defeat Chinese or Russian aggression.

Credit: Mitchell Institute
See Endote 51

and composite airframe. Plus, in many cases, the logistics footprints of DOD's legacy weapons are large, cumbersome, and require many personnel to support. All of these can be significant limiting factors given the U.S. military must be ready to conduct logistics operations while under attack. New hybrid mid-range weapons—and hybrid weapons of all range classes—could help reduce time and resources needed to ensure the Air Force's fighters and bombers have the weapon loads they need when and where they are needed in a peer conflict.

Finally, an inadequate PGM stockpile combined with an inability to surge production has implications for conventional deterrence and alliance management. Some may argue that munitions stockpiles do not have as visible a presence as aircraft or ships in a forward theater, and thus do not contribute to deterrence. However, potential adversaries might decide that a nation that lacked the capacity to sustain protracted offensive operations also lacked political resolve. Plus, strategic competitors certainly track America's readiness for war, to include its PGM stockpiles and surge production capacity.[53] The lack of PGMs—and the combat aircraft that deliver them—could convince China or Russia that it could continue to fight and achieve victory after the U.S. forces exhausted their best strike weapons, aircraft, and aircrews.

5. The Air Force needs a new generation of mid-range stand-in munitions that maximize its ability to conduct cost-effective precision strikes at scale

Leaving aside the operational limitations of long-range stand-off weapons against mobile, relocatable, hardened, and deeply buried targets, it is simply not feasible to procure tens of thousands of them if they are too expensive. A better, more cost-effective

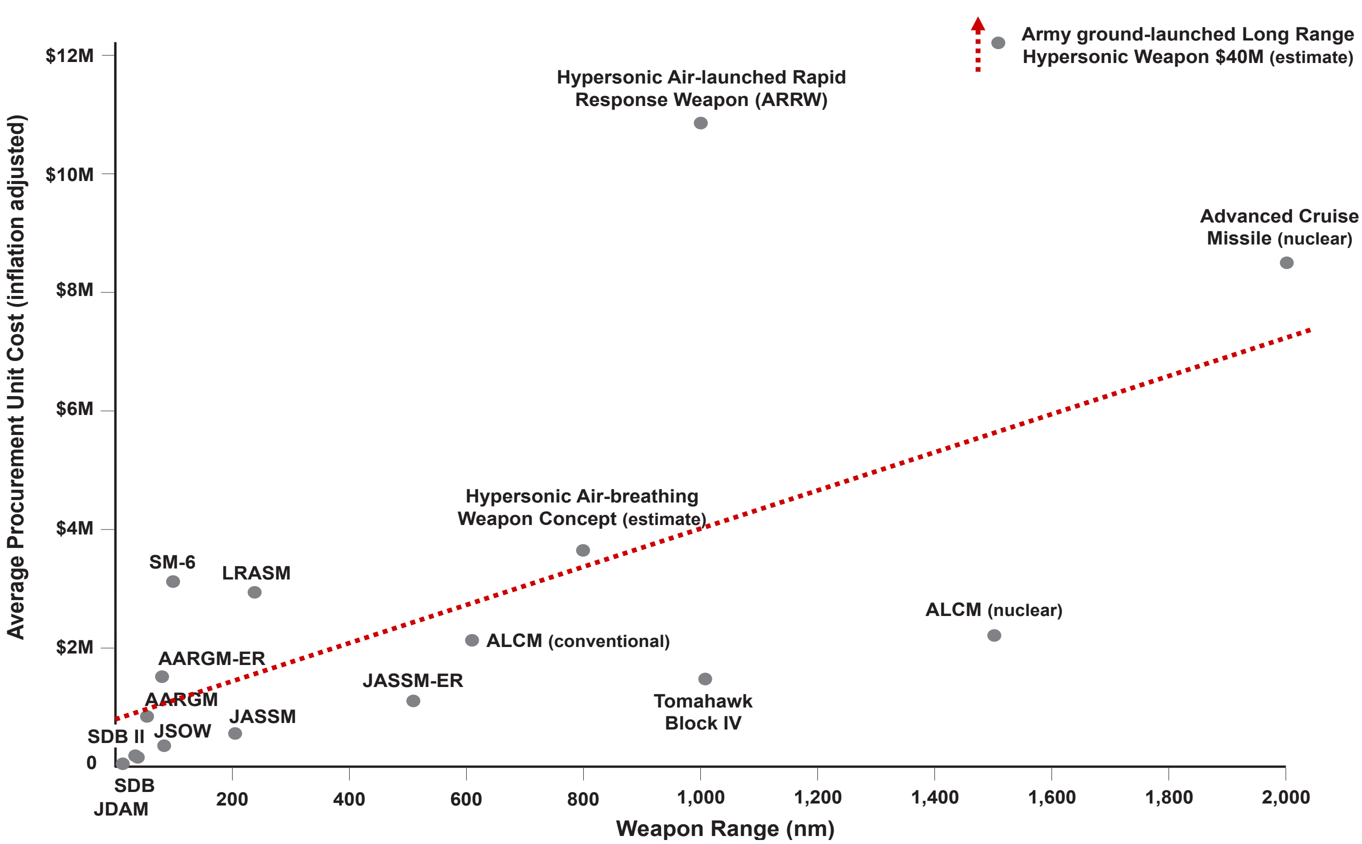


Figure 7: The unit costs of weapons increase with their range

Credit: Mitchell Institute

PGM	Unit cost	Historical maximum single year procurement rate	Total acquired by DOD
SDB I	$36,000	6,878	50,769
Hellfire II	$73,000	10,462	101,477
SDB II	$186,000	2,910	10,724
JASSM	$698,150	288	2,034
AARGM	$970,000	261	2,435
JASSM-ER	$1,048,000	360	5,166
Tomahawk	$1,358,787	678	8,874
SM-6	$3,300,000	125	2,631

Credit: Mitchell Institute

Table 2: DOD procurement of selected air-to-surface PGMs correlate with their unit costs

choice would be to invest in next-generation mid-range PGMs that cost $300,000 or less each and can be carried in significant numbers by stealth aircraft.

Thinking about the cost-effectiveness of next-generation PGMs. Increasing the cost-effectiveness of precision strikes and other operations will be critical to creating a future Air Force that is sized and shaped for major conflicts with peer adversaries. This includes the cost-effectiveness of its expendable PGMs as well as its strike aircraft, supporting ISR capabilities, and other weapons systems. As shown by Figure 7, a weapon's costs increase with its range and sophistication. Figure 7 also illustrates that, when it comes to hypersonic weapons, it is fair to say that speed is an advantage that can be very costly. In the case of some hypersonic weapons, like the Army's ground-launched LRHW, their high cost may limit their procurement to a few dozen missiles or less.

Cost has certainly been a factor in DOD's total procurement and maximum buy rates of different PGMs. As Table 2 shows, DOD has generally acquired a few hundred high-cost, very-long-range weapons like the Navy's Tomahawk cruise missile and SM-6 per year, and the total acquired over the life of their programs averages well under 10,000 weapons.[54]

Table 2 also suggests that next-generation PGMs should cost considerably less than $1 million each, and $300,000 is an even better target if they are to be procured in the quantities needed for high-intensity peer conflict. PGMs with average procurement unit costs of $300,000 or less would likely have ranges up to about 100 nm. The challenge is to achieve these lower costs for weapons that are designed to survive in contested environments and strike mobile/relocatable and other challenging targets. Greater weapons affordability may result from reducing their range, which would also reduce their size, time of flight, and possibly their need for more sophisticated navigation systems and seekers. Developing new mid-range weapons suitable for stand-in strikes by penetrating aircraft would help achieve these "affordable mass" objectives and create a PGM inventory that has the capacity needed to defeat peer aggression.

Maximizing weapons per sortie is a must. New stand-in PGMs should also be designed to fit efficiently in the weapons bays of current and future stealth aircraft to maximize targets attacked per sortie. Today, all Air Force strike aircraft can carry missiles that are up to 168 inches long, 20 inches in diameter, and weigh 2,250 pounds.[55] The larger weapons bays of the B-2 allow it to carry munitions that are up to 250 inches long, including the 5,000-pound GBU-28 at 225 inches and the 30,000-pound GBU-57 at 246 inches. However, some stand-off PGMs like the JASSM, at 14 feet long, and the AARGM, at 13 feet long, would leave seven or eight feet of empty space in the B-2's bomb bay, plus JASSM and JASSM-ER are too large to be carried internally by F-35 fighters.[56] On the other hand, a B-2 equipped with a modular rotary launcher could efficiently carry about 32 stand-in munitions internally that are about 10 feet long and weigh 1,000 pounds—which is comparable to the size and weight of the GBU-32 JDAM. It could alternatively carry about 48 stand-in weapons that are 80 inches long and weigh 500 pounds each. Both the F-22 and F-35 could have the space to carry four of these 80-inch weapons internally. This would help the Air Force to meet its objective of increasing the lethality and survivability of its combat forces for peer conflict.

PGM procurement rates are another important consideration. Over most of the post-Cold War era, DOD was able to slowly rebuild its stocks of PGMs after a regional conflict. Stretching out procurement allowed it to reduce year-by-year PGM expenditures in favor of investing in other capabilities. This is not an optimum PGM acquisition approach in an era of renewed great power competition where PGM deficits that last for years would translate directly to a reduced ability to deter and respond to aggression that can occur with little prior warning.

The average production rates of long-range PGMs in recent decades highlight this challenge.[57] Continuing to acquire long-range missiles like the JASSM-ER at a rate of a few hundred per year will not create a significantly larger stockpile of PGMs for a large-scale peer conflict. Even manufacturing JASSM-ER at the program's historical peak rate of 525 missiles in FY 2022—which is double the average annual rate over the life of the program—would not significantly reduce the time needed to build-up the Air Force's precision strike staying power. Plus, acquiring a much larger inventory of very long-range stand-off weapons would be inordinately expensive due to their high costs. 10,000 additional JASSM-ERs would cost about $10 billion at current prices and 10,000 SM-6 missiles would cost $33 billion. By contrast, acquiring 10,000 new mid-range PGMs could cost $3 billion spread over several years depending on their production rate.

Weapon	Average annual production rate	Highest one-year production rate	Cost to acquire 10,000 weapons	Time to acquire 10,000 weapons at highest one-year production rate
SM-6	115	125	$33 billion	80 years
JASSM-ER	257	525	$10 billion	19 years
Notional new	2,500	2,500	$3 billion	4 years
stand-in weapon	5,000	5,000	$3 billion	2 years
SDB II	1,716	2,910	$1.86 billion	3 years
SDB	2,500	6,878	$0.40 billion	1.5 years
JDAM	16,780	43,594	$0.30 billion	0.2 year

Credit: Mitchell Institute

Table 3: The "average annual production rates" in Table 3 are based on DOD production rates averaged over the course of each program. The "best case production rates" are the highest rate achieved by each munitions program in a single year—a rate that was rarely sustained for more than a year. The SM-6, which is a Navy surface-to-surface missile, is included for purposes of comparison.

Another example: What could a $5 billion PGM procurement plus-up buy? Based on historical data, it is entirely plausible that acquiring significant numbers of a new PGM could cost $5 billion over a few years.[58] This $5 billion could buy well over 10,000 next-generation mid-range PGMs that cost $300,000 each. This inventory could support over a month—33 days—of precision strikes assuming they are delivered on targets at a modest rate of 500 per day. By comparison, Table 4 shows how buying $5 billion more expensive stand-off weapons would create an inventory that could be expended in just a couple of days. **This is a better way to think about the Air Force's PGM priorities**—not strictly in terms of dollars and cents, but the potential to maximize its strike capacity, the cost-effectiveness of its strike operations, and the resiliency of its PGM inventory in a conflict with China or Russia.

Some could suggest that an even more cost-effective approach would be to continue to rely on less expensive direct attack weapons like JDAMs and SDBs. However, the Air Force must also consider the high cost of aircraft—and aircrews—that could be lost because they had to employ very short-range direct attack weapons in contested areas. If the employment of a short-range PGM like a JDAM contributed to the loss of a single $80 million F-35 or a $550 million B-21 bomber, then the potential savings of buying less expensive JDAMs would be nil.[59] Plus, enemy defenses would attrit non-stealthy PGMs like JDAMs and SDBs at increased rates compared to next-generation PGMs that are designed for use in contested operational environments. As the probability of arrival of direct attack munitions on targets declines, their cost advantage over slightly more expensive mid-range stand-in PGMs also decreases.

Finally, the Air Force must be cautious about shifting its strike forces toward more non-stealthy aircraft that must launch weapons from long stand-off ranges. In a major conflict with China or Russia, non-stealthy bombers and fighters would quickly run out of JASSM-ERs and other stand-off weapons, which could effectively take them out of the fight.[60] Take, for example, the total number of JASSM-ERs the Air Force will procure through FY 2025—4,467 weapons.[61] There are currently 44 combat-coded B-52 bombers and 26 combat-coded B-1 bombers in the force. B-52s can carry 20 JASSM-ERs each, and B-1s can carry 24 JASSM-ERs each.[62] So, these 4,467 JASSM-ERs would equate to slightly less than three sorties for each combat-coded B-52 and B-1 in the force. A munitions mix that includes much larger numbers of more affordable mid-range stand-in munitions would create a deeper magazine for the Air Force's warfighters.

Weapon	Unit cost	Number of weapons $5 billion could potentially buy	Days of combat this number of weapons would support assuming a launch rate of 500 per day
Notional new air-breathing hypersonic cruise missile	$3,500,000	1,428	2.9
JASSM-ER	$1,048,000	4,771	9.5
Notional new mid-range stand-in weapon	$300,000 (illustrative)	16,667	33.3
SDB II	$186,000	26,882	54
SDB I	$36,000	138,889	278
JDAM	$25,000	200,000	400

Credit: Mitchell Institute

Table 4: Acquiring new mid-range stand-in PGMs could help the Air Force maximize its precision strike capacity and cost-effectiveness

Conclusion and Recommendations for an "Affordable Mass" PGM Inventory

The Air Force's procurement and employment of PGMs since 1990 has overwhelmingly consisted of direct attack weapons like the JDAM. Although these weapons were suitable for the low-threat environments that U.S. air forces have operated in over the past thirty years, they are unsuitable for strikes in contested and highly contested environments. Because of the very short range of direct attack weapons, fighters and bombers that employ them—including stealth aircraft—would have to approach too close to point defenses surrounding targets to release them. Plus, most of the Air Force's legacy PGMs like JDAM are non-stealthy weapons that are increasingly at risk of being intercepted or otherwise rendered ineffective by advanced air and missile defenses.

The Air Force has also procured much smaller numbers of long-range and very-long-range stand-off weapons. Unlike 5th generation aircraft, non-stealthy fighters and bombers must use these long-range weapons to attack targets located in contested areas. The drawbacks of long-range weapons include higher unit costs, larger sizes that reduce the number of weapons aircraft can carry per sortie, longer flight times which can decrease their effectiveness against mobile targets, and small warhead weights which reduce their ability to kill hardened targets.

As the Air Force develops a future PGM inventory suitable for a large-scale campaign against a peer adversary, it should seek the right balance between PGM ranges, sizes, survivability, and cost-effectiveness. Desirable attributes for new stand-in PGMs include a range between 50 and 250 nm, a degree of low observability, possibly increased speed to further improve survivability, and smaller sizes that increase the number of targets stealth fighters and bombers can strike per sortie. This range band would allow stealth aircraft to avoid most point defenses surrounding high-value targets without incurring the operational and cost limitations associated with very-long-range stand-off weapons. Additionally, sizing mid-range PGMs at natural divisions of one-half and one-third the size of current and future stealth bomber weapons bays could double or even triple the number of weapons they can carry per sortie.

The Air Force's future PGMs will also need sufficient low observability and other design features that reduce an enemy's ability to find, fix, track, and intercept or otherwise counter them. Although low observable munitions are more costly than comparable non-low observable PGMs, the more important metric is the cost to kill a target. Using a single low observable PGM that costs $300,000 or less to kill a defended target is far more cost-effective than employing several hundred non-stealthy $50,000 legacy weapons—and multiple sorties—to ensure at least one weapon survives to reach the target. The exact degree of low observability will require careful study of the trade-offs between weapons speed, low observability, and cost. The goal is to achieve the right threshold of survivability while maximizing the cost-effectiveness of the Air Force's precision strikes.

In conclusion, the Air Force should adopt the following five objectives as part of a strategy that transforms its obsolescing PGM stockpile to a balanced mix that maximizes its capacity to create effects on targets in a peer conflict:

1. The Air Force should prioritize fielding "5th generation weapons" to take full advantage of the range, survivability, and capability of its stealth aircraft to

complete kill chains independently in contested environments.

2. The Air Force's future munitions inventory should include a family of mid-range (50 nm to 250 nm) PGMs that can be delivered by penetrating aircraft on target sets that could number 100,000 or more discrete aimpoints. The size of these weapons and their corresponding ranges should be designed to maximize the number that can be carried in the internal weapons bays of stealth aircraft.
3. The Air Force's new mid-range, stand-in PGMs should have a unit cost objective of $300,000 or less. This would help maximize the service's "bang for the buck" with a limited budget that must also support other modernization priorities.
4. The Air Force's new mid-range, stand-in PGMs should have sufficient low observability and other capabilities needed to penetrate advanced IADS and survive to reach their designated targets. Increased weapons survivability will reduce the total number of strike sorties required for a major peer conflict.
5. The Air Force's next-generation PGM mix should be capable against target sets that are increasingly mobile, relocatable, hardened, or deeply buried.

The Air Force has said its highest priority is to size and shape its forces to deter and defeat Chinese or Russian aggression. As it does so, it must pay particular attention to its ultimate "point of the spear"—the munitions it employs against America's enemies. A munitions inventory that lacks the capacity, survivability, and ability to strike challenging targets will create opportunities for adversaries to further erode our nation's ability to project decisive military power. As the Air Force creates a future PGM mix that is suitable for great power conflict, it must not forget it has an advantage that is unmatched by any other U.S. or allied service: a growing force of advanced 5th generation fighters and stealth bombers. Developing multiple variants of mid-range, stand-in PGMs suitable for operations in contested environments would help the Air Force take maximum advantage of its stealth forces and create effects in the battlespace that theater commanders depend on. This is a "must do" for the Air Force—the best, most advanced combat aircraft in the world will be ineffective if they lack a PGM inventory that has the capacity, survivability, and effectiveness needed to win America's wars. ✪

Endnotes

1 David A. Deptula and Douglas A. Birkey, *Building The Future Bomber Force America Needs: The Bomber Re-Vector* (Arlington, VA: Mitchell Institute for Aerospace Studies, September 2018), p. 26.

2 The U.S. industrial base's ability to quickly surge production of air-to-air, surface-to-air, and air-to-surface munitions during a crisis is almost non-existent, especially at the sub-contractor level where many weapon components are manufactured. See Department of Defense, *Fiscal Year 2020 Industrial Capabilities Report to Congress* (Washington, DC: DOD, January 2021), pp. 85–87.

3 Valerie Insinna, "Four questions with the head of Air Combat Command," *Defense News*, September 6, 2021.

4 "Aerospace Nation: Lt Gen David Nahom, Air Force Deputy Chief of Staff for Plans and Programs," Mitchell Institute Aerospace Nation, July 14, 2021.

5 See Alfred Price, *Instruments of Darkness* (London, UK: Charles Scribner's Sons, 1978).

6 See Lon O. Nordeen Jr., *Air Warfare in the Missile Age* (Washington, DC: Smithsonian Institution, 1985), pp. 9–78; Bernard C. Nalty, *Tactics and Techniques of Electronic Warfare* (Washington, DC: Office of Air Force History, 1980); and Marshal L. Michel III, *Clashes* (Annapolis, MD: Naval Institute Press, 1997).

7 By 1982 Israel had developed new technologies and offensive tactics that enabled it to defeat Syria's SAM network in Lebanon's Beqaa Valley without friendly losses. Nordeen, *Air Warfare in the Missile Age*, pp. 111–185. Also see Anthony M. Thornborough and Frank B. Mormillo, *Iron Hand* (Yeovil, UK: Patrick Stephens, Limited, 2002), pp. 151–161 and 190–191.

8 SRAM replaced the much larger Hound Dog missile. Each B-52 could carry two Hound Dogs or up to 20 SRAM. Eventually the Air Force's B-1 bombers also carried SRAMs.

9 Central Intelligence Agency, "Air Defense of the USSR," NI IIM 85-10008, December 1985.

10 Peter E. Davis and Tony Thornborough, *Boeing B-52 Stratofortress* (Ramsbury, UK: Crowood Press, 1998), pp. 103–105. For background on the challenges of developing new ECM capabilities in the 1980s, see James W. Canan, "How Electronic Countermeasures Went Wrong," *Air Force Magazine*, August 1989, pp. 36–41.

11 The SRAM II was somewhat smaller and lighter than the SRAM, had a newer warhead with improved safety features, and had greater range, speed, survivability, and accuracy. President George H. W. Bush canceled the SRAM II in 1991. The Air Force retired its SRAMs in 1993 due to concerns over their aging propellant and reduced need for them after the Cold War.

12 "AGM-129A Advanced Cruise Missile," U.S. Air Force fact sheet, May 24, 2010. Also see Tyler Rogoway, "The Saga of the AGM-129 Cruise Missile," *The Drive*, December 4, 2019.

13 In the late 1990s, Air Force F-16CJs and Navy and Marine Corps EA-6Bs conducted SEAD operations. In 2008 the Navy began replacing its EA-6Bs with the EA-18G, a non-stealthy 4th generation aircraft.

14 DOD, *Report on the Bottom-Up Review* (Washington, DC: DOD, October 1993), p. 38. The objective of minimizing both friendly and enemy casualties and unintended collateral damage was a notable characteristic of DOD's strike planning operations.

15 Peter Grier, "The JDAM Revolution," *Air Force Magazine*, September 1, 2006.

16 The Air Force developed the 5,000-pound GBU-37 for the B-2 bomber. GBU-27s were later replaced by the 5,000-pound laser-guided "bunker buster" GBU-28. B-2 bombers can also carry the 30,000-pound GBU-57 Massive Ordnance Penetrator.

17 A glide weapon's range is based on the altitude and speed of its launching aircraft, its aerodynamic performance, and flight profile. Low-altitude aircraft can increase a glide munition's range by executing a "toss" maneuver that gives the munition an upward vector at release. Other factors can reduce a glide munition's range, such as diving at a steep angle to penetrate a hardened target. See "JSOW Family of Precision Strike Weapons," Raytheon factsheet.

18 "Low-Cost, Precision-Strike Weapon System," Boeing SDB fact sheet, 2015; and "Small Diameter Bomb II approved for operational use," Eglin Air Force Base news release, October 13, 2020.

19 "AGM-88 HARM," U.S. Air Force fact sheet, August 18, 2003. U.S. aircraft launched 1,961 HARMs during Operation Desert Storm, 743 HARMs during Operation Allied Force, and 408 HARMs during the Operation Iraqi Freedom air campaign.

20 "AGM-88E Advanced Anti-Radiation Missile," Jane's Air-Launched Weapons, October 21, 2020.

21 Joseph Trevithick and Tyler Rogoway, "Air Force to Turn Navy Air Defense Busting Missile into High-Speed Critical Strike Weapon," *The Drive*, March 18, 2019.

22 Before JASSM entered service, the Air Force employed a small number of GPS-guided, Conventional Air Launched Cruise Missiles (CALCMs) that it had converted from its excess nuclear-armed AGM-86B ALCMs.

23 SDB I and SDB II numbers from U.S. Air Force, *Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Air Force Justification Book,* Volume 1, *Missile Procurement, Air Force* (Washington, DC: U.S. Air Force, February 2020), pp. 72 and 83. JDAM numbers are from U.S. Air Force, *Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Air Force Justification Book*, Volume 1, *Procurement of Ammunition, Air Force* (Washington, DC: U.S. Air Force, February 2020), p. 43.

24 JASSM numbers from U.S. Air Force, *Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Air Force Justification Book*, Volume 1, *Missile Procurement, Air Force*, p. 17. The LRASM number is from Sara Sirota, "Air Force reveals plans to grow stockpile of JASSM, LRASM missiles," *Inside Defense*, September 27, 2019.

25 JSOW numbers from U.S. Navy, *Department of*

Defense Fiscal Year (FY) 2021 Budget Estimates, Navy Justification Book, Volume 1, *Weapons Procurement, Navy* (Washington, DC: U.S. Navy, February 2020), p. 88. Also see Richard Scott, "USN axes JSOW-ER in favour of JASSM-ER buy," *Janes*, June 9, 2021.

26 DOD, "AGM-88E Advanced Anti-Radiation Guided Missile," Selected Acquisition Report, December 2018, p. 8; and DOD, "Comprehensive Selected Acquisition Reports for the Annual 2019 Reporting Requirement as Updated by the President's Fiscal Year 2021 Budget," December 2019, p. 5.

27 The JDAM unit cost listed in Table 1 is based on prior year buys. JDAM strap-on guidance kits are attached to 500, 1,000, or 2,000-pound general purpose bombs that cost, respectively, $3,700, $7,000, and $12,000 each. New JDAM kits that include Strategic Anti-Jam Beamforming Receiver (*SABR-Y*) anti-GPS jamming capability cost about $35,000. The SDB I unit cost calculated over the life of the program is $47,245, but from FY 2017 through FY 2021 their unit cost was $36,000. The SDB-II unit cost calculated over the life of the program is $218,968, but the unit cost for FY 2021 was $186,000. The JSOW's average procurement unit cost converted to FY 2021 dollars is $357,000. See DOD, "Joint Standoff Weapon Selected Acquisition Report," March 2015, p. 40. JASSM and JASSM-ER costs are from U.S. Air Force, Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Air Force Justification Book, Volume 1, Missile Procurement, Air Force, pp. 19 and 22. For AARGM costs, see DOD, "AGM-88E Advanced Anti-Radiation Guided Missile," p. 26; and for the ARRGM-ER cost, see DOD, "Advanced Anti-Radiation Guided Missile–Extended Range Selected Acquisition Report," Selected Acquisition Report, April 2019, p. 29. The LRASM's cost was derived from DOD, "Long-Range Anti-Ship Missile," Selected Acquisition Report, April 2019, p. 30.

28 Benjamin S. Lambeth, *NATO's Air War for Kosovo: A Strategic and Operational Assessment* (Santa Monica, CA: RAND Corporation, 2001), pp. 64, 94, 109, and 170.

29 See Lt Gen T. Michael Moseley, *Operation Iraqi Freedom—By the Numbers* (Shaw Air Force Base, SC: U.S. Air Force, April 30, 2003), p. 11. The total munitions cited for Operation Enduring Freedom were launched by U.S. combat aircraft only from October to December 2001. See Benjamin S. Lambeth, *Air Power Against Terror* (Santa Monica, CA: RAND Corporation, 2005), pp. 247–253.

30 See U.S. Air Forces Central Command, "Airpower Summaries." The rare exceptions were the small-scale cruise missile attacks against targets in Syria using TLAM in April 2017 and JASSM in April 2018 and October 2019.

31 See Bryan Clark, Whitney M. McNamara, and Timothy A. Walton, *Winning the Invisible War: Gaining an Enduring U.S. Advantage in the Electromagnetic Spectrum* (Washington, DC: Center for Strategic and Budgetary Assessments, November 20, 2019), pp. 1–2. Also see Mike Pietrucha, "Low-Altitude Penetration and Electronic Warfare: Stuck on Denial, Part III," *War on the Rocks*, April 25, 2016. The Air Force also reduced the size of its EC-130H dedicated communications jammer force.

32 China has a large arsenal of ballistic missiles, land-attack cruise missiles, anti-ship cruise missiles, anti-ship ballistic missiles, and increasingly capable combat aircraft. See Office of the Secretary of Defense (OSD), *Military and Security Developments Involving the People's Republic of China 2019*, annual report to Congress (Washington, DC: OSD, May 2, 2019), pp. 45–48. Russia also has a significant conventional long-range strike capability. See Robert Dalsjo, Christofer Berglund, and Michael Jonsson, *Bursting the Bubble: Russian A2/AD in the Baltic Sea Region: Capabilities, Countermeasures, and Implications* (Stockholm: Swedish Defense Research Agency, March 2019), pp. 36–43.

33 The SA-10B (S-300PS) and SA-10C (S-300PMU) had short-range threat engagement radars that could deploy or stow in about five minutes and were mounted on wheeled vehicles, but still used trailer-mounted long-range acquisition radars.

34 Carlo Kopp, "SAM System Mobility," *Air Power Australia*, June 2008. Use of the 40V6M mast to elevate radar antennas increases the range at which low-flying targets can be detected, but also increases the time needed to deploy or stow the radar. See Carlo Kopp, "NKMZ 40V6M/40V6MD/40V6MT Universal Mobile Mast," *Air Power Australia*, April 2012. Modern SAM systems also incorporate wireless datalinks that permit them to operate effectively while dispersed.

35 Carlo Kopp, "Advances in Russian and Chinese Active Electronically Scanned Arrays (AESAs)," IEEE International Symposium on Phased Array Systems and Technology, 2013, pp. 29–42.

36 The 5V55 and 9M83 missiles of the 1980s had maximum engagement ranges of 75 km; the 5V55U and 48N6 missiles of the 1990s had a range of 150 km; the 48N6E2 and 48N6E3 missiles of the 2000s had estimated maximum ranges of 200 km and 250 km respectively; and Russia's latest 40N6E missile may be able to reach airborne targets up to 250 km from their launchers. These maximum ranges are usually for targets at medium to high altitudes. See Carlo Kopp, "Surface to Air Missile Systems and Integrated Air Defense Systems," *Air Power Australia*, 2014. With command guidance, a ground radar tracks the target and guides the missile to it. For missiles with semi-active homing, a ground radar illuminates a target and the missile "homes in" on the reflected energy. A missile with an active seeker is first cued by an off-board radar and has its own radar that "goes active" in the endgame and guides itself to the target.

37 For an overview of modern Chinese and Russian IADS, see Mark Gunzinger, Carl Rehberg, Timothy A. Walton, and Lukas Autenried, *An Air Force for an Era of Great Power Competition* (Washington, DC:

Center for Strategic and Budgetary Assessments, 2019), pp. 42–46.

38 See Carlo Kopp, "KBP 2K22/2K22M/M1 Tunguska SA-19 Grison / 96K6 Pantsir S1 / SA-22 Greyhound," *Air Power Australia*, 2012. Analysts have noted SA-22s operated by Libyan and Syrian forces performed poorly. However, Russian defense experts have pointed out that Libyan and Syrian Pantsir operators were inexperienced and poorly trained, and their SA-22s were not part of an overall integrated defense system that included electronic warfare and long-range SAMs. See Altan A. Ozler, "Libya: A Catastrophe for Russia's Pantsir S1 Air Defense System," *Real Clear Defense*, June 19, 2020; and "Russian Pantsir Air Defense System – Sitting Duck or Top Dog?" *Defense World*, June 19, 2020.

39 See Moseley, Operation Iraqi Freedom, p. 11. For an expanded discussion on post-Cold War U.S. air campaign PGM-to-target ratios, see Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015), pp. 8–11.

40 Although DOD has invested in high-speed weapon technologies for decades, its requests for hypersonic weapons research and development funding increased significantly after 2016. DOD's hypersonic weapons research projects will cost almost $15 billion from FY2015 to FY 2024. General Accounting Office (GAO), *Hypersonic Weapons: DOD Should Clarify Roles and Responsibilities to Ensure Coordination across Development Efforts* (Washington, DC: GAO, March 22, 2021).

41 The Air Force canceled another program, the Hypersonic Conventional Strike Weapon, in early 2020 due to budget constraints. Kelley M. Sayler, *Hypersonic Weapons: Background and Issues for Congress* (Washington, DC: Congressional Research Service, December 1, 2020), pp. 4–8. The Conventional Prompt Strike and Long-Range Hypersonic Weapon have a common booster and glide body, with the former adapted for ship or submarine launch and the latter for ground launch.

42 Sayler, *Hypersonic Weapons*, p. 5. The C-HGB will separate from its booster after reaching high altitudes and hypersonic speeds and then glide to its target using a dynamic, non-ballistic flight path.

43 Carlo Kopp, "CPMIEC HQ-9 / HHQ-9 / FD-2000 / FT-2000 Self-Propelled Air Defence System," *Air Power Australia*, April 2012.

44 The Air Force developed the 30,000-pound Massive Ordnance Penetrator because certain hardened or very deeply buried targets could not be successfully attacked with 2,000-pound and 5,000-pound penetrating weapons.

45 For a summary of these requirements, see Mark Gunzinger and Lukas Autenried, *Building a Force That Wins: Recommendations for the 2022 National Defense Strategy* (Arlington, VA: Mitchell Institute for Aerospace Studies, June 15, 2021).

46 GAO, *Ammunition Industrial Base: Information on DOD's Assessment of Requirements* (Washington, DC: GAO, May 1996), p. 3.

47 Allied Force strike sorties gradually increased over time, with generally under 200 strikes per day in March and April and an average of 359 strikes per day overall. The number of munitions dropped each day then greatly increased in the final weeks when Air Force bombers delivered a large number of unguided bombs. Benjamin S. Lambeth, *NATO's Air War for Kosovo* (Santa Monica, CA: RAND Corporation, 2001), p. 64.

48 John A. Tirpak, "Empty Racks," *Air Force Magazine*, October 28, 2016; and John A. Tirpak, "Munitions Production Surge Planned for At Least Five Years," *Air Force Magazine*, February 22, 2018. Operation Inherent Resolve averaged about 90 weapons releases per day from 2015 to 2017. The manufacturer was making 110 JDAM tail kits per day, but increased production to 150 per day to replenish DOD's stockpiles.

49 John A. Tirpak, "Climbing Out of the Munitions Hole," *Air Force Magazine*, March 22, 2019.

50 Figure 7 assumes that ten B-52s and six B-1s are forward deployed and each fly a single sortie in a 24-hour period. The remaining bombers each fly a sortie every 48 hours from their mainland U.S. bases. The example also assumes the bombers carry full loads of weapon.

51 Since 2018, Congress has required DOD to prepare annual reports on defense industrial capabilities which include information on the defense industrial base's weaknesses. The reports comment on the lack of munitions production redundant capacity, lack of surge capacity, munitions production obsolescence, and an aging industrial base workforce.

52 Hal Brands, "Win or Lose, U.S. War Against China or Russia Won't Be Short," *Bloomberg*, June 14, 2021.

53 For more on this issue see Gunzinger and Autenried, *Building a Force That Wins*.

54 For sources on SDB I, SDB II, JASSM, JASSM-ER, and AARGM costs and procurement rate, see endnote 27. The SM-6 is included as an example of a surface-to-surface supersonic missile with a range of 130 to 250 nm. Gross unit cost over the entire program is $4,476,818, but the unit cost of SM-6 Block I/IA All Up Round Missiles from FY 2018 to FY 2021 was just under $3.3 million. See U.S. Navy, Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Navy Justification Book, Volume 1, Weapons Procurement, Navy, pp. 91 and 95. Tomahawk cruise missiles have been procured for a much longer time than Standard SM-6 or JASSM-ER, and thus the higher total procurement of Tomahawk is somewhat misleading. The maximum Tomahawk production rate of 678 was in FY 1991. See Congressional Budget Office (CBO), "Total Quantities and Unit Cost Tables, 1974-1995," April 1994, p. A-15. Recent Tomahawk procurement has been about 100 to 150 missiles per year. Tomahawk gross unit cost prior to FY 2020 was $1,597,852, and from FY 2020 to FY 2022, gross unit cost averaged $2.7 million. Tomahawk gross unit cost prior to FY 2020 was $1,597,852, and from FY 2020 to FY 2022, gross unit cost averaged $2.7 million.

See U.S. Navy, Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Navy Justification Book, Volume 1, Weapons Procurement, Navy, pp. 39, 41, and 44. Hellfire II unit cost is an average of "all up round" unit costs for FY 2017 to FY 2022. From U.S. Army, *Department of Defense Fiscal Year (FY) 2022 Budget Estimates, Army Justification Book, Missile Procurement, Army* (Washington, DC, U.S. Army, May 2021), p. 37. The Hellfire is a missile with a very short range. It is included for the purpose of comparison.

55 U.S. Air Force Scientific Advisory Board, *Why and Whither Hypersonics Research in the U.S. Air Force* (Washington, DC: Air Force, December 2000), p. 47.

56 Carrying JASSM or JASSM-ER externally would compromise the F-35's stealth signature. Xavier Vavasseur, "Lockheed Martin Progressing Towards LRASM Integration On F-35," *Naval News*, January 18, 2021.

57 The U.S. military launched 17,162 PGMs on targets during Operation Desert Storm out of 230,000-plus total munitions expended and 19,269 PGMs during Operation Iraqi Freedom.

58 Historically, a new munitions acquisition program that costs on the order of $5 billion per year is entirely plausible. From 1980 to 1992 DOD spent about $2 billion to procure ACM, $7 billion to procure ALCM, $7.5 billion to procure Maverick air-to-surface missiles, and $15 billion to buy Tomahawk cruise missiles. Costs are from CBO, "Total Quantities and Unit Cost Tables, 1974-1995," pp. A-11 to A-15, converted into FY 2021 dollars. As a further point of comparison, the Air Force spent a total of about $11.5 billion on conventional missiles and JDAM from 2016 to 2020. From FY 2019 to FY 2025, the Air Force plans to spend $4.6 billion for JASSM, $853 million for SDB, $1.7 billion for SDB II, and $3.1 billion for JDAM. See U.S. Air Force, Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Air Force Justification Book, Volume 1, Missile Procurement, Air Force, pp. 17, 73, and 83; and U.S. Air Force, Department of Defense Fiscal Year (FY) 2021 Budget Estimates, Air Force Justification Book, Volume 1, Procurement of Ammunition, Air Force, p. 43.

59 In addition, the loss of an aircraft may require assigning additional sorties and munitions to destroy the target, further increasing the "cost per kill" of that target.

60 Valerie Insinna, "Lockheed is developing a system to turn airlift planes into weapons trucks," *Defense News*, October 29, 2020.

61 The Air Force has procured some 2,444 JASSM-ERs through FY 2021, intends to procure another 2,057 from FY 2022 to FY 2025, and wants to buy another 699 missiles beyond FY 2025 for a total of 5,200.

62 This does not count the capability of the B-1 and B-52 to drop JDAM, since they would not be able to penetrate contested areas in a fight with a peer adversary to do so.

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