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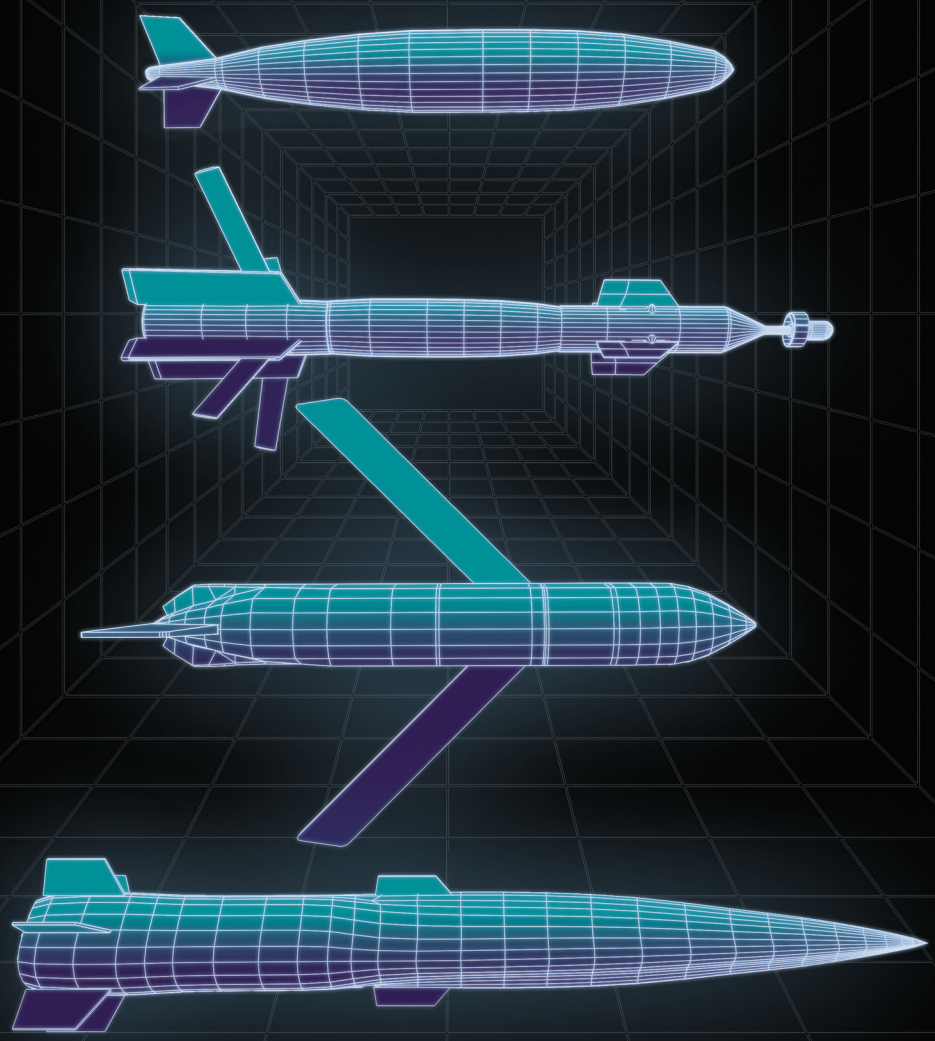
BEYOND PRECISION

MAINTAINING AMERICA'S STRIKE ADVANTAGE IN GREAT POWER CONFLICT



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Russia's ongoing war in Ukraine and the West's efforts to supply weapons to Ukraine have revealed the inadequacy of Western munition stocks and the weapon industrial base for the enormous demands of contemporary conflict. The provision and consumption of vast quantities of weapons have led to questions about the sufficiency of U.S. and allied inventories of more advanced weapons for a conflict with China. The events of the last year have focused a spotlight on a seldom prioritized and understudied topic in defense analysis: munitions, especially the precision-guided munitions (PGMs) essential to modern warfighting. Despite recent attention devoted to weapons and their industrial base, concerns about the inadequacy of U.S. PGM stocks are nothing new. In fact, the U.S. military has encountered difficulties meeting its PGM demands in nearly every campaign since their adoption.

Facing the potential of great power conflict in the Indo-Pacific, the United States is currently procuring increasing numbers of PGMs and seeking to bolster its munitions industrial base. These efforts, however, may not be enough to satisfy the demands of future campaigns, particularly protracted conflicts against a near-peer or peer opponent. Many assumptions about munitions consumption and the United States' ability to surge weapons production are no longer valid. Procuring greater quantities of PGMs and fortifying their industrial base is critical in the long-run, but realistic fiscal, industrial, and political constraints might prevent the United States from producing or purchasing weapons at a rate that meets the staggering requirements of a near-term conflict. Ultimately, these demands should force the U.S. military to think innovatively about precision-strike and seek improved ways of designing, producing, and employing the next generation of precision-guided munitions.

This monograph reaches these conclusions by following the evolution of precision-strike and exploring the U.S. military's most urgent munitions requirements for great power conflict. Most importantly, it highlights the ways in which the United States might harness innovative technologies and concepts to overcome the capacity and capability shortcomings of its current PGM portfolio and expand its munitions industrial base. Our analysis begins with an examination of historical strike campaigns and proceeds with a forward-looking assessment of potential conflict scenarios between the United States and China in the Indo-Pacific. Three decades of precision-strike operations since the Gulf War have shown that despite the

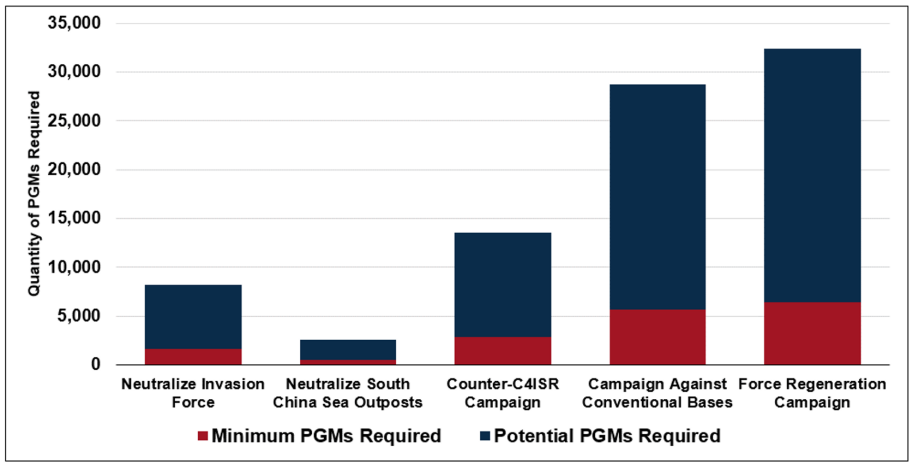
massive advantage in effectiveness gained with PGMs, the U.S. military has repeatedly run its inventories of these weapons alarmingly low in limited campaigns against regional and non-state opponents. Even with the current ubiquity of PGMs within the U.S. military, the vast geographies, numerous targets, and dense defenses of a great power adversary mean that a comprehensive strike campaign would today entail a massive expenditure of PGMs—one which the U.S. military may struggle to provide.

To determine the extent of these requirements and what sorts of PGMs would be in highest demand in such a campaign, this study examines the munitions requirements of five illustrative great power conflict scenarios in the Indo-Pacific between the U.S. military and the Chinese People's Liberation Army (PLA). These scenarios include:

1. A campaign to neutralize a PLA invasion force in the Taiwan Strait;
2. A campaign to neutralize PLA outposts in the South China Sea;
3. A counter-C4ISR campaign against PLA forces;
4. A campaign against PLA conventional bases;
5. And a campaign against PLA force regeneration assets.

Our analysis of these scenarios highlights the immense munition demands of great power conflict. Figure 1 summarizes the results of this analysis by showing the range of potential quantities of munitions required to strike these campaign target sets using varied assumptions about the effectiveness of Chinese defenses and the proportion of targets that must be struck to achieve operational objectives.

FIGURE 1: SUMMARY OF PGM REQUIREMENTS ACROSS FIVE INDO-PACIFIC CONFLICT SCENARIOS (INITIAL STRIKES ONLY)



Source: The full analysis leading to these figures can be found in Chapter Three. These figures include only initial strikes and do not account for additional strikes against recurring targets that are repaired or rebuilt during a campaign.

While each scenario favors a different mix of weapons, these figures highlight the existing capacity and capability gaps in the current U.S. PGM portfolio. Most notably, the United States suffers from a PGM capacity gap with two dimensions: insufficient on-hand inventories and inadequate production capacity.

The United States must have sufficient quantities of PGMs on-hand to support (or deter) a rapid, intense conflict or to sustain the opening acts of a prolonged conflict. The degree to which recent strike campaigns have stressed U.S. stocks gives reason to doubt the sufficiency of short-range PGM inventories. With long-range and more complex weapons such as the Joint Air-to-Surface Standoff Missile, or JASSM, procurement documents reveal the inadequacy of current American inventories. The U.S. military purchased only 3,243 missiles between fiscal years 2010 and 2021. Disregarding the number of JASSMs expended during operations in the Middle East, this quantity appears woefully insufficient against the requirements displayed in Figure 1. A campaign that strikes a modest portion of targets in the South China Sea, our least demanding scenario, could consume over half of these cruise missiles depending on stand-off requirements. Given the payload capacity and sortie rates of U.S. bombers, the entire inventory of JASSMs could be expended in less than a week of sustained long-range strike operations. On-hand inventories of other critical PGMs are similarly inadequate.

Beyond available stocks, the United States' weapons industrial base would be unable to refill PGM inventories at a pace sufficient for continued strike operations. For example, between fiscal years 2000 and 2021, the U.S. military procured an average of 209 *Tomahawk* cruise missiles per year. During Iraqi Freedom, however, it expended 802 *Tomahawks* in 30 days. At an average consumption rate of 27 missiles per day, a single year of *Tomahawk* production at existing levels would only supply enough cruise missiles for just over a week of sustained strike operations. And as recent demands for *Javelin* and *Stinger* missiles have revealed, these production rates cannot be quickly scaled in the event of a conflict.

Several constraints prevent the United States from quickly remedying these gaps, with the most urgent barriers being insufficient spending on munitions and a downsized weapons industrial base with limited surge capacity. CSBA estimated the Department of Defense's (DoD's) total request for PGM procurement funding at $5.6 billion in fiscal year 2023—just 0.72 percent of DoD's total requested funding and less than 4 percent of all requested procurement funding for the Department.

These developments leave the United States facing both a short- and long-run PGM problem. Given these requirements and constraints, the United States will struggle to produce and stock sufficient quantities of PGMs for a great power conflict occurring in the next five years. Maintaining the United States' near-term precision-strike advantage will require it to increase its funding and procurement of essential PGMs to maximize their production rates under current industrial limitations. As U.S. stocks of PGMs grow, DoD should also explore ways to expand the capabilities of current weapons, as well as innovative concepts to achieve campaign objectives using the current portfolio of precision weapons more effectively.

Continued spending on weapons and their industrial base over the long-term is essential, but a prolonged great power war involving the expenditure of tens or hundreds of thousands of munitions will exceed U.S. capacity to buy and produce weapons. Accordingly, the U.S. military should rethink how it develops, purchases, and expends PGMs to achieve its aims in future campaigns. One answer may be innovative technologies and concepts that advance beyond precision—weapons that leverage enhanced features to ease their manufacturing requirements, increase their effectiveness, and produce equivalent or greater effects using fewer munitions.

This monograph's analysis and exploration of these technologies and concepts lead to the summarized findings and recommendations below, which will begin readying America's PGM inventory for the challenges of future conflicts. Of course, the U.S. military will encounter technological, political, and cultural barriers as it attempts to develop and field innovative weapons. Nevertheless, precision munitions stand as a long-running advantage that the United States can no longer take for granted and shortchange in its preparation for the potential of great power conflict in coming years.

Findings

Previous assumptions about munitions production and consumption do not apply to contemporary great power conflict. Three key planning assumptions that informed the U.S. military's current PGM inventory no longer hold and must be reexamined:

1. *A conflict between the United States and a great power adversary would be rapid and short in duration, allowing the U.S. military to rely on small inventories of advanced stand-off munitions.* History and an examination of prospective Indo-Pacific conflict scenarios indicate that great power conflict is more likely to be protracted and could last months or years. Current fighting in the Russia-Ukraine war reinforces this view.

2. *PGM production and procurement are less important than platforms because munitions production can rapidly surge to meet the demands of a conflict.* The complexity of today's PGMs and the state of the munitions industrial base mean that the production of many PGMs essential to great power conflict cannot be quickly surged. On-hand quantities may be the only weapons available in the first months of a conflict, depending on the munition and the complexity of its supply chain and manufacturing process.

3. *The precision-strike advantage by itself will continue to enable the United States to dominate its adversaries in a contemporary great power conflict.* Although precision was sufficient in the regional and limited strike campaigns of the previous 30 years, today's adversaries have spent decades preparing to counter U.S. precision-strike operations. As a result, the munitions requirements for great power conflict are likely to exceed the quantities and capabilities of the current U.S. PGM inventory.

An examination of munitions requirements for great power conflict reveals that the United States has significant capacity and capability gaps in its current PGM portfolio. PGM procurement to date has mostly been driven by operational usage and unit cost rather than by long-term strategy or analysis. In addition to an overall PGM capacity gap that has reappeared throughout campaigns in the Middle East, the U.S. military lacks sufficient quantities of weapons with the range and features ideal for conflict in the Indo-Pacific. Current PGM stocks are insufficient to provide precision effects in volume during a protracted conflict.

Beyond capacity, our examination of potential great power conflict scenarios exposes several capability gaps in the U.S. military's current array of PGMs. Given the current U.S. military force structure, which consists of mostly non-penetrating bombers and short-range fighters, many existing PGMs suffer from insufficient range and survivability. Most current weapon programs are subsonic and rely on external guidance support that increases the demands on targeting processes and makes them unsuitable for time-sensitive and mobile targets. The U.S. PGM inventory also lacks non-kinetic options and weapons designed to attack hardened and deeply buried targets, wide area targets, and airfields.

Even with increased spending on and production of PGMs, the United States will likely struggle to maintain adequate quantities of PGMs to execute a comprehensive precision-strike campaign against a great power adversary. Unlike previous U.S. campaigns against regional opponents, the number of targets, extended distances, and density of defenses in a contemporary great power conflict create staggering munitions requirements for a comprehensive, protracted campaign. Conducting a campaign with a similar target set and depth as that of Desert Storm or Iraqi Freedom would involve tens of thousands of targets, many of them mobile, heavily defended, and/or spread throughout vast geographic areas. Short of total mobilization, realistic fiscal and industrial constraints mean the United States is likely incapable of maintaining PGM stocks adequate for such operations.

Simply put, DoD may not be able to quickly spend or produce its way out of its current PGM shortcomings in the near-term. Instead, the U.S. military may be forced to rethink how it intends to accomplish certain operational objectives in a great power conflict. In addition to maximizing the production of critical munitions, the U.S. military must develop new weapons and concepts suited for fighting today's great power adversaries.

Precision alone is necessary but insufficient for munitions in a modern great power conflict. Future wars will require PGMs with advanced features such as semi-autonomous and collaborative capabilities, integrated sensors, automatic target recognition, loitering capabilities, and heterogenous payloads that include both kinetic and non-kinetic effects. Many of these features are not wholly new but are becoming inexpensive and ubiquitous thanks to commercial and government advances in microelectronics and computing.

These features offer solutions to the capacity and capability gaps described above. Next-generation PGMs could reduce total munitions requirements to more feasible levels by multiplying the effects of each weapon. Rather than expending numerous PGMs on a single target, future technologies and concepts could allow each PGM to affect multiple targets.

Several variables have outsized effects on munitions requirements for great power conflict, including the operational objectives, the proportion of targets that must be attacked to achieve these objectives, and the effectiveness of enemy defenses. The five conflict scenarios explored in this monograph show how a precision-strike campaign's operational objectives (and, by corollary, the target set) influence the numbers and kinds of PGMs required. Planning assumptions—such as the ability to strike mainland targets or dual-use targets and the availability of long-range penetrating strike platforms—are particularly key to assessing a scenario's munitions requirements. These assumptions reveal the value of strategic and operational wargaming of munitions mixes in addition to more in-depth modeling and simulation.

In addition to objectives and targets, assumptions about the depth of the total target set that must be affected are also key determinants of munitions requirements. Sinking a quarter or even a half of a Taiwan invasion fleet is a much different munitions problem than attacking all three hundred or more vessels. Finally, the effectiveness of enemy defenses at keeping delivery platforms at stand-off ranges and intercepting PGMs greatly affects both the quantity of munitions required and the ideal characteristics of those weapons. More effective defenses necessitate PGMs and delivery platforms with longer ranges and more advanced survivability features, as well as more complex attack concepts.

Conflict duration is a major determinant of munitions requirements and, as a result, could influence campaign objectives. This study's scenario analysis shows how rapid and protracted conflicts have different operational objectives and target sets. If a conflict is expected to become prolonged, then a limited inventory of weapons may be better expended on force regeneration assets instead of more numerous and attritable forces or easily repairable basing and infrastructure. In a protracted conflict scenario, the United States must consider its long-term advantages and weaknesses relative to a great power adversary and utilize its PGMs to reduce that adversary's long-term comparative advantage. Against the People's Republic of China (PRC), this advantage may be their ability to rapidly manufacture and replace munitions and other defense materiel. For this reason, a protracted conflict may favor a campaign that targets defense production and sustainment infrastructure over one that over-emphasizes attrition of enemy forces.

Maintaining the United States' strike advantage requires more than munitions; it requires improvements along the entire kill chain. Many of the issues and constraints outlined in this monograph also apply to ISR assets, targeting processes, network infrastructure, and delivery platforms. As the final effector in a kill chain, however, munitions are of particular importance and require near-term attention due to long-term neglect. The use of large numbers of PGMs also creates unprecedented demands on sensors,

ISR platforms, and staff targeting processes, particularly if PGMs do not possess internal sensing and guidance capabilities. Persistent surveillance technologies, AI-assisted data processing, and in-depth intelligence preparation of the battlefield may help alleviate these demands. Large numbers of networked PGMs with internal sensors also increase demands for network bandwidth and robustness.

Recommendations

The United States must prepare its PGM inventories for the potential of protracted great power conflict. Given fiscal, industrial, and political constraints, the U.S. military should implement a time-phased set of recommendations to address both its near-term and long-run PGM and industrial base challenges. The following recommendations, phased by five-year Future Years Defense Programs (FYDPs), can help the U.S. military achieve these ends.

Near Term: Recommendations within the FYDP (2023 to 2027)

In the near term, the United States must rapidly increase PGM procurement to bolster its preparedness for a conflict in the coming years before it can amass large quantities of critical PGMs or significantly expand its munitions industrial base. The U.S. military must move quickly to maintain the precision-strike advantage of its current force structure in operations within the "Davidson window."

Immediately increase munitions funding and procurement to maximize the production of critical precision munitions. This monograph's examination of potential Indo-Pacific conflict scenarios highlights several essential categories of weapons, including anti-ship and anti-air munitions, stand-off munitions to equip non-penetrating bombers and tactical aircraft, and intelligent loitering munitions capable of striking moving targets. Given current manufacturing capacity, the military services should maximize purchases of these weapons within the FYDP to reinforce current stockpiles and prepare for a conflict in the near term. PGM procurement quantities should reflect the reality that today's munitions cannot be rapidly surged and must be stocked in quantities sufficient for potential conflict scenarios. As this study concludes, it appears that DoD is requesting funds for larger quantities of key PGMs, but it remains to be seen how these requests translate into increased appropriations, contracts, and deliveries.

Align PGM procurement spending with long-term strategy and analysis requirements rather than simply replacing weapons expended in recent operations. As increased procurement of essential PGMs begins reducing critical near-term capability and capacity gaps, the Department must ensure that munitions funding and requirements for the remainder of the FYDP are driven by thorough analysis with a long-term focus. Based on the 2018 and 2022 National Defense Strategies, these changes should manifest in more balanced spending between delivery platforms and munitions and between short- and long-range weapons.

Ultimately, DoD must avoid thinking of inexpensive munitions as replacements for exquisite weapons, or exquisite long-range PGMs as replacements for high-tech delivery platforms. Rather, these systems should complement each other's capabilities as components of a strike package. For instance, advanced aircraft will benefit from long-range munitions that reduce their attrition and short-range munitions that increase the volume of effects they can deliver. Exquisite munitions will benefit from simpler weapons carrying sensors and decoys to augment their effectiveness.[1]

Incentivize expansion of the weapons industrial base by committing to consistent munitions purchases through multi-year procurements, direct investments, and other policies that foster a steady demand signal for precision weapons. Beyond additional spending to maximize active production lines, near-term investments must support the expansion of the weapons industrial base beyond the current FYDP. Building additional manufacturing capacity will take years, so the United States must make adequate purchases and investments in the near term to create additional capacity over the next several years. The military services should continue using multi-year procurements and other measures taken in response to the Russia-Ukraine conflict to kick-start the industrial base and signal a commitment to sustained munitions spending. The Defense Department may also wish to explore direct investment in additional production capacity or the maintenance of surge capacity to ensure that weapons manufacturing can be scaled to support a prolonged conflict. Finally, DoD should explore other policies to incentivize the expansion of the munitions industrial base, such as streamlining foreign military sales and export requirements to support foreign buys of U.S. weapons, fostering joint development opportunities with allied nations, large lot purchases of common subcomponents, or offering tax credits and other incentives for the construction and maintenance of excess capacity.

Bolster the current PGM arsenal with rapidly producible modular kits and modifications to operational weapons. While increasing procurement of current PGM programs, DoD should expand the capabilities of these weapons using modular kits that draw on the success of the Joint Direct Attack Munition (JDAM) and *Paveway* guidance kits. Glide kits and add-on propulsion systems can be fielded within the FYDP to extend the range of many PGMs and better equip non-stealthy platforms for the contested environments of a Pacific conflict. These kits should rely on mature technologies and be prioritized to fill urgent capability and capacity gaps, such as maritime strike, emplacing naval mines, and attacking mobile targets. Modular kits can be expanded with inexpensive, proven sensors and datalinks to increase their effectiveness in great power conflict. When possible, the Department and industry should take advantage of advances in commercial technologies related to sensors, networking, and autonomy to augment these kits.

Beyond modular kits for existing payloads, DoD should deploy additional payloads in already-fielded munitions. These payloads could include more powerful energetics,

1 Exquisite munitions are further defined and explored on page 42.

non-kinetic effectors, persistent sensors, or policy-compliant area effects that provide multiple precision effects within a large target area. Both modular kits and new payloads can be fielded on expedited timelines that leverage existing weapon-platform integration. Together, they would allow more weapons within the United States' current precision arsenal to service a greater number of targets with increased lethality.

Consider campaigns, operational concepts, and target sets that enable the current portfolio of precision weapons to be most effective, particularly in a protracted conflict. Creative operational concepts can help reduce total munitions requirements in a great power conflict. In the near-term, the U.S. military can reduce the number of aimpoints in a strike campaign by targeting essential nodes, utilizing virtual attrition concepts, and attacking the fixed elements of mobile target kill chains. Focusing attacks on the key elements of adversary kill chains, command networks, and transportation and sustainment architectures may accomplish U.S. objectives using smaller quantities of munitions. Likewise, striking fixed pieces of mobile target support chains would allow U.S. forces to employ GPS-guided munitions, which make up a majority of its current PGM inventory. Until capability gaps can be filled by new munitions, planners must explore innovative methods of accomplishing campaign objectives using the current precision arsenal.

Medium-Term: Recommendations for the Next FYDP (2028 to 2032)

By the late 2020s and early 2030s, a steady demand signal driven by near-term investments in munitions and their industrial base will expand production capacity for the weapons essential to future great power conflict. At that point, the Department should continue to shape the growth of the industrial base through requirements for resilient supply chains and advanced manufacturing processes. These middle years are key to designing and experimenting with new munitions designs that operationalize advanced technologies as they mature.

Continue expanding the active and surge capacity of the munitions industrial base with a focus on resilient and redundant rather than lean supply chains. While maintaining a steady demand signal through continued procurement, the Department should implement policies, requirements, and incentives that push weapon manufacturers to shift from "just-in-time" to "just-in-case" supply chain models for select programs or components. Of course, this shift will reduce efficiency and increase costs, so analysis is key to prioritizing resiliency between weapon programs and determining which pieces or components of a munition are suited for just-in-case versus just-in-time methods. In determining these requirements, the Department should also study the most operational- and cost-effective balance between maintaining stockpiles and maintaining excess production capacity of different munitions. Increased costs will drive DoD to prioritize excess capacity and resiliency, making analysis key to ensuring that these expenditures match future requirements.

Implement open architectures and digital engineering into new munitions designs to take advantage of modularity and advanced manufacturing methods. Beyond spending more on current PGMs, in the medium term, the U.S. military must develop the next generation of weapons that fully utilize advanced technologies to enable their rapid development and large-scale production. These weapons should begin by leveraging digital engineering and modular architectures to ease their manufacturing requirements, expand their supply chains to more commercial producers, and increase their operational versatility. Automated production and additive manufacturing can alleviate workforce issues and allow future munitions to be affordably produced in large quantities. Modular and versatile designs fill capacity gaps by reducing procurement tradeoffs, increasing weapon upgradeability, and allowing weapons (or components of weapons) to be used in a greater number of scenarios. These advancements are already happening on a small scale and should be implemented across programs and producers by the late 2020s.

Continue experimenting with and fielding advanced munitions technologies to fill current capability gaps. By the mid-2020s, technologies developed in the current FYDP should be widely fielded throughout the force. These advancements include exquisite and low-cost sensors that free PGMs from reliance on external targeting support and enable them to better track and attack mobile targets, collaborative and loitering capabilities that allow weapons to work together to attack wide area and elusive targets effectively and efficiently, and area effect payloads that reduce the quantities of munitions required to attack large and complex targets. Additionally, hypersonic weapons should be fielded in greater numbers as current programs mature and costs are reduced.

In the medium-term, the services should continue experimentation with more advanced technologies, including interchangeable "mix-and-match" munitions, advanced propulsion, improved automatic target recognition and data collection, non-kinetic effects, and heterogenous payloads.

Pursue an affordable mix of exquisite and cheap PGMs to enable "affordable precision in mass." Modular designs, digital engineering, and advanced manufacturing techniques can open the door to inexpensive weapons producible at scale. The Department should experiment with and pursue PGMs that, in combination with delivery platforms, optimally balance features such as range, speed, and cost to ensure adequate quantities can be procured for great power conflict. This balance might include developing and procuring "second-tier" PGMs with minimum capabilities that are inexpensive enough to be stocked in high quantities. In tandem with unmanned munition carriers, these second-tier PGMs could enable tactical aircraft such as the F-35 or naval vessels to guide the delivery of an unprecedented volume of precision effects. As delivery platforms evolve and more long-range penetrating strike platforms are fielded, the Department should actively reassess the balance of capability between its platforms and weapons.

Develop new employment techniques and operational concepts that leverage the advanced features of next-generation PGMs. As technologies and weapons evolve, the U.S. military must implement innovative concepts that employ these weapons most effectively. U.S. forces should utilize heterogenous salvos and complex coordinated attacks from multiple domains to increase munition survivability and effectiveness. Underpinning these concepts is the idea that future munitions will be more than just effectors. As components in broader force packages of sensors and delivery platforms, DoD must optimize munition force packages to carry out specific missions in the most resource-efficient manner. To increase the options available and better examine tradeoffs when constructing force packages, the services should first develop concepts to address operational challenges, and then use these concepts to determine priority capabilities and requirements. The PGMs of tomorrow will provide their package with more capabilities than a short-lasted kinetic effect, and U.S. warfighting concepts must leverage these new capabilities accordingly.

Long-Term: Preparing for Beyond 2033

In the long run, the U.S. military must shape its PGM portfolio around its evolving force structure and the need to provide an immense volume of effects against an adversary striving to modernize its defenses at an equivalent or faster rate. Maintaining America's strike advantage will require new PGM designs that leverage technologies matured in the 2020s and are stocked in the quantities necessary for future great power conflict.

Procure a mix of PGMs that complement next-generation platforms as they are fielded in the 2030s. The U.S. military's current force structure, particularly in the air domain, is centered around legacy platforms that require stand-off munitions to confront the distances and defenses associated with the Indo-Pacific theater. By the 2030s, however, fielding significant numbers of long-range, penetrating B-21 bombers may shift the favored balance between stand-off and stand-in weapons and increase the volume of short-range munitions the U.S. military can deliver in contested environments at reduced costs. Similar force structure shifts may occur as the Navy fields unmanned surface and undersea vessels or the U.S. Marine Corps and U.S. Army deploy stand-in ground forces. Given the continued tradeoff between munition range and cost, each change in force structure and posture presents new opportunities to reexamine the alignment of range and capability between delivery platforms, munitions, and other intermediaries.

Concurrently, the Chinese military will continue to modernize and evolve its own force structure. The PLA will likely continue pushing its defensive perimeter outward from the mainland and may seek to bolster its own long-range strike capacity. The U.S. military must continually adjust its weapon-platform pairing and force packages to confront these developments.

Develop and field munitions that utilize advanced technologies to fill long-running capability gaps, reduce planning tradeoffs, and outpace adversary countermeasures. Some of the technologies highlighted throughout this study may not be sufficiently mature for operational use until the 2030s. Continued investment in artificial intelligence and computing underwrite future progress in stealth, speed, and autonomy that will increase PGM survivability and effectiveness. The Department of Defense must fund not only the research and development of weapons-related technologies, but also their operationalization in the next decade. DoD must avoid the development of advanced weapons that never become programs of record, such as the Low Cost Autonomous Attack System or the Tri-Service Standoff Attack Missile.

Refine employment techniques and operational concepts to utilize advanced munitions and future force packages to create the greatest advantage. The Department must constantly explore innovative concepts that most effectively employ the advanced capabilities of future weapons. As subsequent generations of PGMs are fielded, the U.S. military should continually redesign its force packages to create kill chains to address the evolving threat. These packages must include not only future delivery platforms and weapons, but also future unmanned ISR platforms and intermediaries such as attritable UAS and unmanned munitions trucks. Planners should use increasingly capable modeling, simulation, and integrated test beds to create force packages that deliver the greatest volume of effects on target sets while minimizing risk, attrition, and cost to levels appropriate for protracted great power conflict.

CHAPTER 1

Introduction

The ongoing conflict in Ukraine has led many Western nations, including the United States, to send significant quantities of munitions to support Ukraine's fight against the Russian Federation. Early in the war, the United States transferred up to one-third of its total stock of *Javelin* anti-tank guided missiles and a similarly significant quantity of *Stinger* missiles—both of which could take years to replenish.[2] American support continued to flow as the conflict progressed beyond its initial stages, with the U.S. Army sending over one million 155mm artillery shells, a move which has left some officials and analysts concerned about the sufficiency of U.S. stocks.[3] The Department of Defense (DoD) has remained tight-lipped about total transfers of more complex munitions such as the Guided Multiple Launch Rocket System (GMLRS). With the Army only purchasing between four and six thousand GMLRS per year and a maximum production rate of about 10,000 rockets annually, Ukrainian expenditure rates of precision munitions such as GMLRS call into question the adequacy of U.S. inventories.[4] The munitions stocks of U.S. allies appear to be equally diminished, with

2 Mark F. Cancian, "Will the United States Run Out of Javelins Before Russia Runs Out of Tanks?," *Center for Strategic and International Studies*, April 12, 2022, https://www.csis.org/analysis/will-united-states-run-out-javelins-russia-runs-out-tanks; Jen Judson and Joe Gould, "US Army signs deal to backfill Stingers sent to Ukraine," *Defense News*, May 27, 2022, https://www.defensenews.com/land/2022/05/27/us-army-signs-deal-to-backfill-stingers-sent-to-ukraine/.

3 Gordon Lubold, Nancy A. Youssef, and Brett Forrest, "U.S. Reaches Deep Into Its Global Ammunition Stockpiles to Help Ukraine," *Wall Street Journal*, March 16, 2022, https://www.wsj.com/articles/u-s-reaches-deep-into-its-global-ammunition-stockpiles-to-help-ukraine-8224d985; Mark F. Cancian, "Is the United States Running out of Weapons to Send to Ukraine?" *Center for Strategic and International Studies*, September 16, 2022, https://www.csis.org/analysis/united-states-running-out-weapons-send-ukraine#:~:text=While%20the%2026%20million%20rounds,no%20danger%20of%20running%20out.

4 Limited U.S. stocks have been cited as one reason for not providing the longer-range ATACMS (Army Tactical Missile System) to Ukraine. Department of Defense, "Fiscal Year (FY) 2023 Budget Estimates, Justification Book of Missile Procurement, Army," April 2022, p. 95, https://www.asafm.army.mil/Portals/72/Documents/BudgetMaterial/2023/Base%20Budget/Procurement/MSLS_ARMY.pdf; Howard Altman, "Are There Enough Guided Rockets For HIMARS To Keep Up With Ukraine War Demand?," *The Drive*, July 27, 2022, https://www.thedrive.com/the-war-zone/are-there-enough-guided-rockets-for-himars-to-keep-up-with-ukraine-war-demand; and Paul McLeary, Lara Seligman, and Alexander Ward, "U.S. Tells Ukraine It Won't Send Long-Range Missiles Because It Has Few To Spare," *Politico*, February 13, 2023, https://www.politico.com/news/2023/02/13/u-s-wont-send-long-range-missiles-ukraine-00082652.

some smaller nations left with "a bare minimum" of weapons in reserve.[5] These concerns led the *Financial Times* to declare that the "Ukraine war has exposed the skimpiness of western defense stockpiles."[6]

These anecdotes have brought the topic of munitions and the munitions industrial base to the forefront of the discussion, despite weapons procurement traditionally being overshadowed by debates over billion-dollar platforms and "transformational" operational concepts. Still, the conflict in Ukraine is limited in scale and intensity compared to previous wars of the 20th century. Moreover, the shortages caused by Ukraine are far from an isolated incident. Campaigns from the last three decades in Iraq, Kosovo, Libya, and Syria have repeatedly exposed Western munitions inventories as deficient, particularly in the precision-guide munitions (PGMs) so vital to modern warfighting concepts.[7]

Past experiences and the potential for great power conflict provoke hard questions about future requirements for precision munitions. If these regional and low-intensity conflicts stress Western munitions stocks to the extent reported, what would weapon expenditure rates and demands look like in a 21st-century great power war between the United States and China? As the U.S. military refocuses on the challenges presented by China and the features of the Indo-Pacific theater, how extensive are munitions requirements for potential great power conflict? Do previous assumptions about munitions consumption and production hold true? Will the long-standing U.S. precision-strike advantage hold in a great power war in the 2020s?

Defense analysts have widely noted that the United States and its allies need *more* munitions if they are to prepare for great power conflict.[8] In a world of limited resources, however, the key question remains: *more of what*? Moreover, what if *more* weapons alone are no longer sufficient to maintain the United States' precision-strike advantage in great power conflict?

5 Quote from Dovilė Šakalienė, a member of the Lithuanian Parliament. The German Ministry of Defense also recently described their munitions stocks as "limited." See Tara Copp, "Weapons Shortages Could Mean Hard Calls for Ukraine's Allies," *The Associated Press*, October 23, 2022, https://apnews.com/article/russia-ukraine-nato-united-states-business-government-and-politics-2cc634e38b50f43cfd1fb9a4e0412c4a.

6 John Paul Rathbone and Steff Chavez, "Military Briefing: Is the West Running Out of Ammunition to Supply Ukraine?," *Financial Times*, July 11, 2022, https://www.ft.com/content/d413576c-c4d5-4ca6-9050-58f3f8dc3c00.

7 These examples will be fully explored in Chapter Two.

8 For example: Elbridge A. Colby and Alexander B. Gray, "America's Industrial Base Isn't Ready for War With China," *Wall Street Journal*, August 18, 2022, https://www.wsj.com/articles/americas-industrial-base-isnt-ready-for-war-with-china-weapons-defense-funding-military-war-conflict-taiwan-supplier-11660833718; Jeff Schogol, "The US Military Needs a Lot More Artillery Shells, Rockets, and Missiles for the Next War," *Task & Purpose*, September 5, 2022, https://taskandpurpose.com/news/military-artillery-shells-rockets-missiles-war-russia-china/; Mackenzie Eaglen, "Earth to DoD: The Military Needs More Rockets, Missiles, and Bombs," *American Enterprise Institute*, September 12, 2022, https://www.aei.org/foreign-and-defense-policy/earth-to-dod-the-military-needs-more-rockets-missiles-and-bombs/; and Hal Brands, "Ukraine War Shows the US Military Isn't Ready for War With China," *Bloomberg*, September 18, 2022, https://www.bloomberg.com/opinion/articles/2022-09-18/ukraine-war-shows-the-us-military-isn-t-ready-for-war-with-china.

To explore these questions, this study traces the evolution of U.S. precision-strike through the campaigns of the previous three decades and then considers munitions requirements for potential Indo-Pacific conflict scenarios. These exercises reveal significant capacity and capability gaps in America's current inventory of PGMs. With munitions demands that far exceed the limited and regional wars of years past, precision alone may no longer be enough to sustain the U.S. military's strike advantage in the next conflict. The United States may need to harness innovative technologies and concepts to increase weapon effectiveness, optimize U.S. PGM stocks for future campaigns, and meet the staggering munitions demands of tomorrow's wars. This monograph aims to explore the magnitude of future munitions demands and provide a starting point for considering how next-generation weapons and concepts can help the U.S. military deter and, if necessary, win a great power conflict in the Indo-Pacific.

The Munitions Analysis Gap

Although the Russia-Ukraine conflict has recently highlighted the significance of massed precision fires, weapon requirements and stockpiles remain an understudied facet of modern warfare. There are several reasons for this gap, most of which stem from the preeminence of platforms over munitions in defense analysis. The U.S. DoD traditionally has an institutional bias toward large, expensive platforms. As far back as 1993, the Defense Science Board noted that DoD "heavily favors new systems with more emphasis on platforms than on architectures for information flow, sensor improvements and weapons programs."[9] This preference makes sense, considering the largest investments in the U.S. defense budget have historically tended to be exquisite platforms. Because of their implications for force structure and industry, it follows that these platforms naturally attract the most debate, analysis, and political attention.[10] In addition, military communities and culture typically center around these platforms. From submariners to tankers to fighter pilots, the tendency of these communities to focus on their platforms of choice leads to an "attitude [that] overlooks the fact that what counts is not what delivers the warhead but that the warhead destroys the target."[11]

Because of their relegation behind platforms, munitions funding is often sacrificed in the name of next-generation platforms. Former Air Force acquisition chief Dr. Will Roper explained in 2019 that "Munitions … often become a bill payer in program reviews.

9 Office of the Under Secretary of Defense for Acquisition & Technology, *Report of the Defense Science Board Task Force on Tactical Air Warfare* (Washington, DC: Department of Defense, November 1993), p. 7, https://apps.dtic.mil/dtic/tr/fulltext/u2/a275347.pdf.

10 Travis Sharp, Chris Bassler, and Tyler Hacker, "In a Connected Era, We Talk Too Much About Individual Weapons," *Defense One*, June 8, 2022, https://www.defenseone.com/ideas/2022/06/connected-era-we-talk-too-much-about-individual-weapons/367898/.

11 Kenneth P. Werrell, *Chasing the Silver Bullet: U.S. Air Force Weapons Development from Vietnam to Desert Storm* (Washington, DC: Smithsonian, 2003), p. 7.

Budgeters think 'you just buy fewer.'"[12] This reflex originates in part from the perception that unlike advanced platforms, munitions production can be easily surged during a conflict. As the Russia-Ukraine conflict has shown—and this monograph will more fully explore—this assumption is dated and inaccurate when discussing modern PGMs. It may take months to produce today's guided munitions and years to expand production lines.

Even so, the outcome of future great power conflict is likely to hinge on the expenditure of large quantities of these guided munitions. Policymakers, strategists, analysts, and military professionals accept that high-intensity conflict involves more targets, longer ranges, and effective adversary defenses and countermeasures. The 2018 National Defense Strategy Commission clearly stated these demands:

> Nearly any conflict between the United States and its most capable competitors would entail significant demand for long-range, high-precision munitions so that U.S. forces can remain outside the range of advanced air defenses systems and other anti-access/area-denial capabilities. (Large quantities of shorter-range high-precision munitions will be needed, as well.) … Current and planned DOD investments promise some gains in this area, but *more must be done to ensure a substantial, sustainable, and rapidly scalable supply of preferred weapons* [emphasis in original].[13]

CSBA has previously noted the importance of precision-guided munitions for high-intensity conflict in operational concepts and publications such as *AirSea Battle* and *Sustaining America's Precision Strike Advantage*.[14] Wargames, workshops, and exercises held by CSBA consistently reinforce the need for greater emphasis on munitions and their industrial base.[15]

Despite this growing demand signal, there has been little public analysis of munition needs for great power war that advances beyond the conclusion that the United States needs more weapons overall. Much munitions-related analysis remains classified and driven by tactical

12 Quoted in John A. Tirpak, "Climbing Out of the Munitions Hole," *Air & Space Forces Magazine*, March 22, 2019, https://www.airandspaceforces.com/article/climbing-out-of-the-munitions-hole/.

13 Commission on the National Defense Strategy for the United States, *Providing for the Common Defense: The Assessment and Recommendations of the National Defense Strategy Commission* (Washington, DC: United States Institute of Peace, 2018), p. 41, https://www.usip.org/sites/default/files/2018-11/providing-for-the-common-defense.pdf.

14 For example, in *AirSea Battle*: "Peacetime inventories of precision-guided munitions would be exhausted quickly in a high-intensity war against a powerful enemy. The ability to sustain such a war without a prolonged operational pause potentially lasting months would require considerable increases in global inventories." See Jan van Tol with Mark Gunzinger, Andrew Krepinevich, and Jim Thomas, *AirSea Battle: A Point-of-Departure Operational Concept* (Washington, DC, Center for Strategic and Budgetary Assessments, 2010), pp. 45, 46, 91, https://csbaonline.org/research/publications/airsea-battle-concept; Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015), https://csbaonline.org/research/publications/sustaining-americas-precision-strike-advantage.

15 Thomas G. Mahnken, "The US Needs a New Approach to Producing Weapons. Just Look at Ukraine.," *Defense News*, April 26, 2022, https://www.defensenews.com/opinion/2022/04/26/the-us-needs-a-new-approach-to-producing-weapons-just-look-at-ukraine/.

modeling and operational-level campaign analysis.[16] Although specific war plans and exact munitions inventory numbers are sensitive in nature, leaving munitions analysis confined to the realm of modeling, simulation, and operations research fails to consider the broader assumptions that drive these calculations and their implications. This monograph will examine modern weapons' role in strategic decision-making—a point that may be lost when munitions analysis is confined to rigid classified modeling for operational scenarios.

Open-source studies that do examine requirements are often limited in scope and focus on rapid campaigns and winning the initial "salvo competition" phase of a conflict.[17] Little analysis has been devoted to munitions requirements for a protracted great power conflict, which, as strategists like Joshua Rovner and Hal Brands have argued, is increasingly likely.[18] Brands sees prolonged conflict as a likely outcome of great power competition for four reasons.[19] First, history shows that most great power conflicts were not rapid but lasted numerous months or years. Second, attempts to achieve strategic objectives through rapid, decisive campaigns often fail, leaving conflicts in an open-ended, protracted state while both sides recover and decide how to proceed. In the words of Secretary of the Air Force Frank Kendall, "the short war you anticipate might not be the war you get."[20] Third, even if decisive operations defeat an adversary quickly, the high stakes of great power conflict make them unlikely to simply surrender their aims and terminate the conflict. Instead, great power adversaries are likely to continue the conflict via any means available. Finally, the presence of nuclear weapons may prolong conflict because they may limit escalation and encourage the expenditure of all conventional means to achieve victory. Military leaders have echoed

16 For an example of open-source modeling of the munitions mix problem, see Robert J. Lempert, Drake Warren, Ryan Henry, and Robert W. Button et al., *Defense Resource Planning Under Uncertainty: An Application of Robust Decision Making to Munitions Mix Planning* (Santa Monica, CA: RAND, 2016), https://www.rand.org/pubs/research_reports/RR1112.html.

17 Former Deputy Secretary of Defense Robert Work's third Offset Strategy emphasized winning the "guided munitions salvo competition." See Sydney J. Freedberg Jr., "Work Elevates Electronic Warfare, Eye On Missile Defense," *Breaking Defense*, March 17, 2015, https://breakingdefense.com/2015/03/raid-breaker-work-elevates-electronic-warfare-eye-on-missile-defense/; Mark Gunzinger and Bryan Clark, *Winning the Salvo Competition: Rebalancing America's Air and Missile Defenses* (Washington, DC: Center for Strategic and Budgetary Assessments, 2016), https://csbaonline.org/research/publications/winning-the-salvo-competition-rebalancing-americas-air-and-missile-defenses.

18 Joshua Rovner, "Two kinds of catastrophe: nuclear escalation and protracted war in Asia," *Journal of Strategic Studies* 40, no. 5, February 28, 2017, pp. 696–730.

19 Hal Brands, *Getting Ready for a Long War with China: Dynamics of Protracted Conflict in the Western Pacific* (Washington, DC: American Enterprise Institute, 2022), https://www.aei.org/research-products/report/getting-ready-for-a-long-war-with-china-dynamics-of-protracted-conflict-in-the-western-pacific/. Other analysts have echoed Brands' reasoning, see Zamone Perez, "Experts urge US logistics revamp in light of Ukraine war," *Defense News*, October 12, 2022, https://www.defensenews.com/home/2022/10/12/experts-urge-us-logistics-revamp-in-light-of-ukraine-war/.

20 Quoted in Lee Ferran, "Key lessons Air Force's Kendall would 'prefer' China learn from Russia's invasion of Ukraine," *Breaking Defense*, December 3, 2022, https://breakingdefense.com/2022/12/3-lessons-air-forces-kendall-would-prefer-china-learn-from-russias-invasion-of-ukraine/.

these concerns when discussing potential conflict scenarios in the Indo-Pacific.[21] Most concerningly, People's Liberation Army (PLA) doctrinal writings show that the Chinese military believes that protracted conflict under nuclear overhang is possible, even likely, and is preparing accordingly.[22]

For these reasons, it is imperative that the U.S. military consider conventional munitions requirements for prolonged conflicts rather than planning only for the rapid and limited campaigns of the last 30 years. These protracted scenarios challenge traditional planning assumptions, force a deeper prioritization of munitions expenditures, and demand a reconsideration of the role of PGMs in shaping the military's operational and strategic approach.

Report Purpose, Scope, and Outline

This monograph examines prospective PGM consumption in great power conflict scenarios to determine essential munitions capabilities for contemporary war and provide insights into how the United States can prepare its portfolio of precision weapons to meet these requirements. As an expansion of previous CSBA works on precision-strike, munitions, and great power conflict, this study:

- Examines PGM consumption in historical U.S. and allied strike campaigns;
- Explores munitions requirements in several illustrative great power conflict scenarios in the Indo-Pacific;
- Assesses the current U.S. PGM portfolio against great power conflict requirements; and
- Identifies technologies and concepts to help close munitions capacity and capability gaps.

To conduct a manageable analysis, this study focuses on conflict scenarios involving the People's Republic of China (PRC) in the Indo-Pacific theater. China remains the U.S. military's preeminent threat, particularly with Russia locked in an ongoing conflict in Ukraine. Focusing our assessment on a single adversary and theater allows for uniform analysis

21 For example, U.S. Army Pacific commander General Charles Flynn stated "Despite any wishful thinking, we can be sure that the next war will be very violent, it will be very human, it will be very unpredictable. And so our Pacific theatre army is preparing for long war because history has proven that wars are often longer than we expect." Admiral Charles A. Richard, commander of U.S. Strategic Command, recently expressed similar sentiments. Charles Flynn quoted in Brendan Nicholson, "U.S. Army Pacific Commander: Next War Will Be Violent, Very Human, Unpredictable and Long," *Real Clear Defense*, February 21, 2022, https://www.realcleardefense.com/articles/2022/02/21/us_army_pacific_commander_next_war_will_be_violent_very_human_unpredictable_and_long_817777.html?mc_cid=58d0f5dd0e&mc_eid=7cbf43077b; Oliver Parken and Tyler Rogoway, "Extremely Ominous Warning About China From US Strategic Command Chief," *The Drive*, November 6, 2022, https://www.thedrive.com/the-war-zone/extremely-ominous-warning-about-china-from-us-strategic-command-chief.

22 In its war with Ukraine, Russia has also shown its willingness to engage in protracted conflict. Brands, *Getting Ready for a Long War with China*, p. 9; and Stephen Blank, "Russia Acknowledges a Prolonged War: What Does That Mean?," *Real Clear Defense*, December 21, 2022, https://www.realcleardefense.com/articles/2022/12/21/russia_acknowledges_a_prolonged_war_what_does_that_mean_871367.html?mc_cid=041335c00d&mc_eid=7cbf43077b.

across a broad set of Indo-Pacific scenarios. Our analysis focuses on PGMs because guided weapons are central to the American way of war and are likely to comprise the majority of weapons expended in any future conflict. This assumption also differentiates future scenarios from great power wars of the past, which relied on massive numbers of unguided munitions.

This monograph is not intended to produce exact munitions requirements or quantities. Instead, it is meant to use historical cases and illustrative vignettes to generate broad insights into the types of munitions ideal for future campaigns, the depth of stocks needed, and the sensitivity of munitions requirements to variables such as campaign objectives, conflict duration, and the effectiveness of enemy defenses.

To reach these insights, Chapter Two examines previous U.S. strike campaigns to identify munitions trends and lessons that may carry over to great power conflict in the 2020s. Chapter Three outlines five potential Indo-Pacific conflict scenarios and their munitions demands to find common requirements, major variables, and key assumptions from across the cases. Chapter Four assesses the current U.S. PGM portfolio against the requirements identified in Chapter Three to highlight capacity and capability gaps. It also describes the constraints on weapon development, production, and procurement that may prevent the U.S. military from spending or producing its way out of its PGM shortcomings. Chapter Five then explores technologies, platforms, employment techniques, and operational concepts that could help close these capability and capacity gaps. Finally, the monograph concludes with key findings and recommendations to improve the readiness of the U.S. PGM portfolio for the challenges of future great power conflict.

Our analysis finds that the munitions demands of a war in the Indo-Pacific are likely to outpace the United States' current capacity to produce and procure sufficient numbers of PGMs. In the near-term, the United States must increase its focus on munitions procurement and expanding its weapon industrial base. Concurrently, the U.S. military must move beyond current approaches to achieving precision and invest in technologies, platforms, and concepts that prepare its PGM portfolio and munitions industry for the immense requirements of modern warfare. Military planners can reduce these requirements and achieve precision in mass by decreasing a campaign's quantity of aimpoints, increasing the chances that weapons reach their targets and have the desired effects, and increasing the number of aimpoints each munition can affect. Together, the innovative technologies and concepts explored in this monograph provide a range of ways for the U.S. military to affect these variables and maintain its precision-strike advantage in the wars of the future.

CHAPTER 2

Previous Trends in Munitions Consumption

Munitions consumption in wars-to-come is often foreshadowed by expenditures in wars of the past. A classic example of this notion is the foretelling of World War One artillery shell requirements in the Balkan Wars of 1912 to 1913.[23] Although artillery shell expenditure rates remained relatively consistent through the Franco-Prussian (1870–1871) and Russo-Japanese (1904–1905) wars, Bulgaria's average monthly consumption from 1912 to 1913 was nearly triple that of previous conflicts. The great powers, however, failed to notice this change. When the First World War began the following year, France expended more than two-thirds of its pre-war stock of artillery shells within the first month of combat. By the end of 1914, the French were consuming munitions at more than ten times the rate of previous conflicts and three and half times that of Bulgaria during the Balkan Wars. By the end of the war, Germany was firing an average of eight million shells per month—more than the entire stock of seven million shells France held in inventory at the start of the conflict.[24]

These exponential increases in munitions expenditures by the belligerents of World War One had significant consequences on the battlefield and in politics more broadly, with the infamous "Shell Crisis of 1915" leading to the resignation of British Prime Minister H.H. Asquith.[25] In the years preceding the war, the leading powers of the time overlooked a significant indicator of evolving trends in warfare. With this warning in mind, this chapter examines munitions trends in recent strike campaigns in order to glean lessons for future

23 This anecdote is drawn from David T. Zabecki, "The Dress Rehearsal: Lost Artillery Lessons of the 1912-1913 Balkan Wars," *Field Artillery*, February 1988, https://books.google.co.uk/books?id=Z6UrAAAAYAAJ&pg=RA2-PA22&dq=ammunition+consumption+russo+japanese+war&hl=en&newbks=1&newbks_redir=0&sa=X&redir_esc=y#v=onepage&q&f=false.

24 Ibid., pp. 22-23.

25 David French, "The Military Background to the 'Shell' Crisis of May 1915," *Journal of Strategic Studies* 2:2, pp. 192–205, https://www.tandfonline.com/doi/abs/10.1080/01402397908437021.

great power war. Although the world has not seen widespread conflict between major powers since the Second World War, the development, evolution, and ubiquitous usage of precision-guided munitions (PGMs) since the 1960s offers a prescient look at potential munitions requirements for 21st-century great power conflict.

The Evolution of Precision-Strike

Before exploring recent campaigns, two interrelated trends concerning modern munitions expenditures must be highlighted. Since the Second World War, the introduction and widespread use of guided munitions has altered the fundamental tradeoffs associated with munitions employment. U.S. bombing operations and strike campaigns over the previous 50 years have seen the maturation of the precision-strike complex, a process thoroughly documented in previous CSBA studies.[26] This development has led to two significant trends: weapon accuracy becoming independent of engagement range, and tactical effectiveness achieved with fewer weapons.

Accuracy Independent of Range, But Not Without Costs

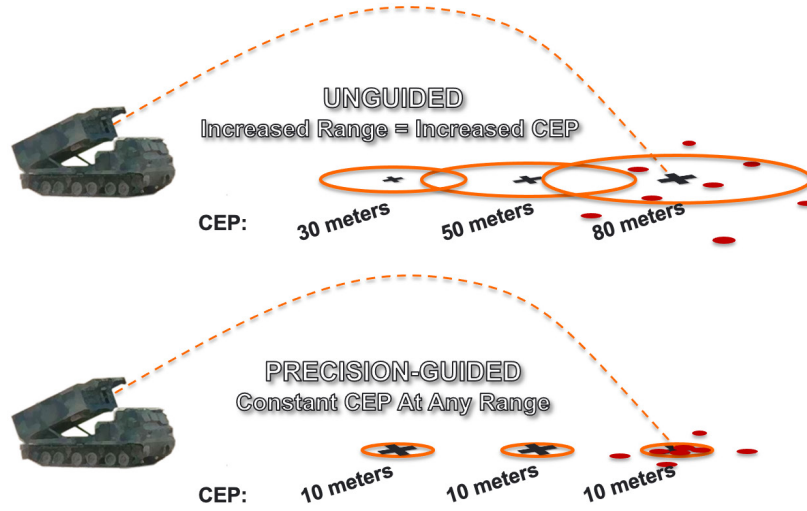
Prior to the advent of guided munitions, an inverse relationship existed between weapon employment range and accuracy.[27] Due to firing errors and environmental factors affecting ballistic flight, accuracy decreased as the range to the target increased. This principle is illustrated by traditional artillery munitions (Figure 2), which have a larger circular error probable (CEP) as the engagement range increases.[28] A longer range entails a longer flight time, which adds to the amount of time the projectile is exposed to environmental forces that affect its trajectory, such as gravity, weather, air drag, and the rotation of the earth.

26 See, for example: Barry D. Watts, *Long-Range Strike: Imperatives, Urgency and Options* (Washington, DC: Center for Strategic and Budgetary Assessments, 2005), https://csbaonline.org/uploads/documents/2005.04.06-Long-Range-Strike.pdf; Barry D. Watts, *Six Decades of Guided Munitions and Battle Networks: Progress and Prospects* (Washington, DC: Center for Strategic and Budgetary Assessments, 2007), https://csbaonline.org/uploads/documents/2007.03.01-Six-Decades-Of-Guided-Weapons.pdf; Barry D. Watts, *The Case for Long-Range Strike: 21st Century Scenarios* (Washington, DC: Center for Strategic and Budgetary Assessments, 2008), https://csbaonline.org/uploads/documents/2008.12.31-The-Case-for-Long-Range-Strike.pdf; Mark Gunzinger, *Sustaining America's Strategic Advantage in Long-Range Strike* (Washington, DC: Center for Strategic and Budgetary Assessments, 2010), https://csbaonline.org/research/publications/americas-strategic-advantage-long-range-strike; Barry D. Watts, *The Evolution of Precision Strike* (Washington, DC: Center for Strategic and Budgetary Assessments, 2013), https://csbaonline.org/uploads/documents/Evolution-of-Precision-Strike-final-v15.pdf; and Mark Gunzinger and Bryan Clark, *Sustaining America's Precision Strike Advantage* (Washington, DC: Center for Strategic and Budgetary Assessments, 2015), https://csbaonline.org/uploads/documents/Sustaining-Americas-Precision-Strike-Advantage.pdf.

27 This monograph uses the terms accuracy and precision interchangeably.

28 CEP is a measure of a weapon's precision. CEP is the radius of a circle, centered on the mean point of impact, within which 50 percent of a given salvo is expected to land.

FIGURE 2: ACCURACY OF UNGUIDED VERSUS GUIDED MUNITIONS



Source: Created by CSBA.

Guidance systems begin to ameliorate this problem by correcting deviations from the projectile's intended flight path. Precision-guidance essentially negates this tradeoff by correcting for errors and meteorological effects throughout the munition's flight to ensure the projectile hits its specified aimpoint.[29]

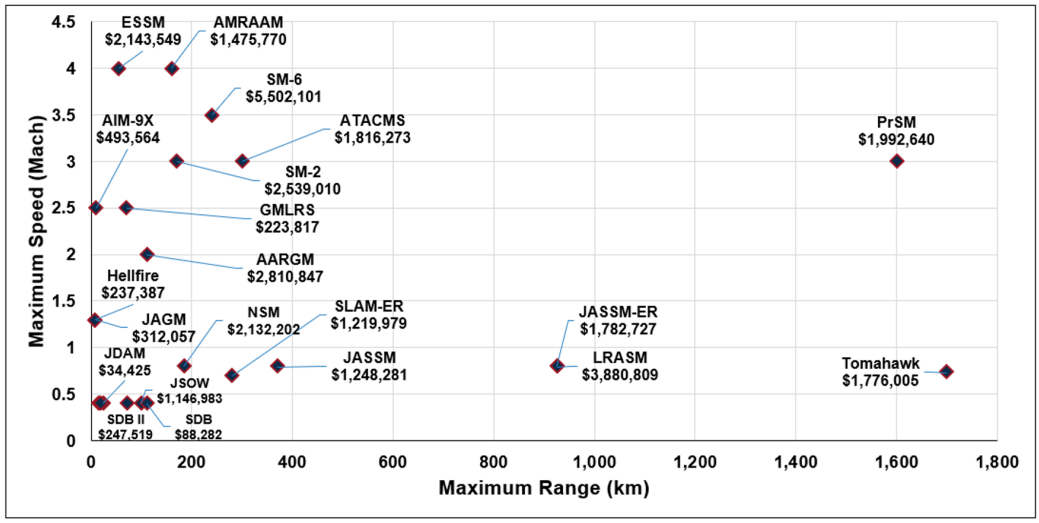
The ability to strike accurately, regardless of range, has revolutionized warfare—with one crucial caveat. Although guided munitions eliminate the tradeoff between range and accuracy, their range is still very much related to their procurement cost. Put simply, the longer the munition's range, the more it typically costs. The employment of precision versus unguided munitions thus still entails tradeoffs, but these compromises are now mainly associated with cost (resource constraints) rather than operational effectiveness.

The higher cost of long-range guided munitions has several causes. Increased range often requires expensive propulsion systems and increased fuel capacity, making these munitions comparable to small aircraft and increasing their price accordingly. Munition speed, also tied to propulsion, also drives cost. The relationship between range, speed, and procurement cost for a handful of modern PGMs is displayed in Figure 3. Additionally, guidance capability itself creates additional costs for sensors and seekers, electronics, and control surfaces. All in all, despite accuracy now being independent of range, a munition's cost remains directly related to range and speed, with guidance systems putting the "icing on the cake" of total weapon cost. These factors can be observed in the Gulf War, where although guided

29 This monograph uses the DoD definition of precision-guided munition: "A guided weapon intended to destroy a point target and minimize collateral damage." See Department of Defense, *Joint Publication 3-03: Joint Interdiction*, September 9, 2016, p. GL-4, https://www.jcs.mil/Portals/36/Documents/Doctrine/pubs/jp3_03.pdf.

munitions were only 7.6% of total munitions expended, they accounted for 84% of total munitions' costs.[30]

FIGURE 3: GUIDED MUNITIONS RANGE, SPEED, AND UNIT COST TRENDS



Source: Created by CSBA using data from DoD budget documents from FY1998 to FY2023 and *Jane's* database. Unit costs are averages based upon FY1998 to FY2023 procurement costs.

Effectiveness Without Mass

Prior to the widespread use of guided munitions, inaccuracy was compensated for with volume—firing large numbers of projectiles to increase the likelihood that at least some hit the desired aimpoint. Because precision-guidance now removes the error from a weapon's trajectory, however, fewer munitions are needed to attain the same effects. First seen in the Vietnam War, this revolution in weapon capability led to, in the words of the Gulf War Air Power Survey, a "fundamental rethinking of the means of achieving the destruction goal."[31]

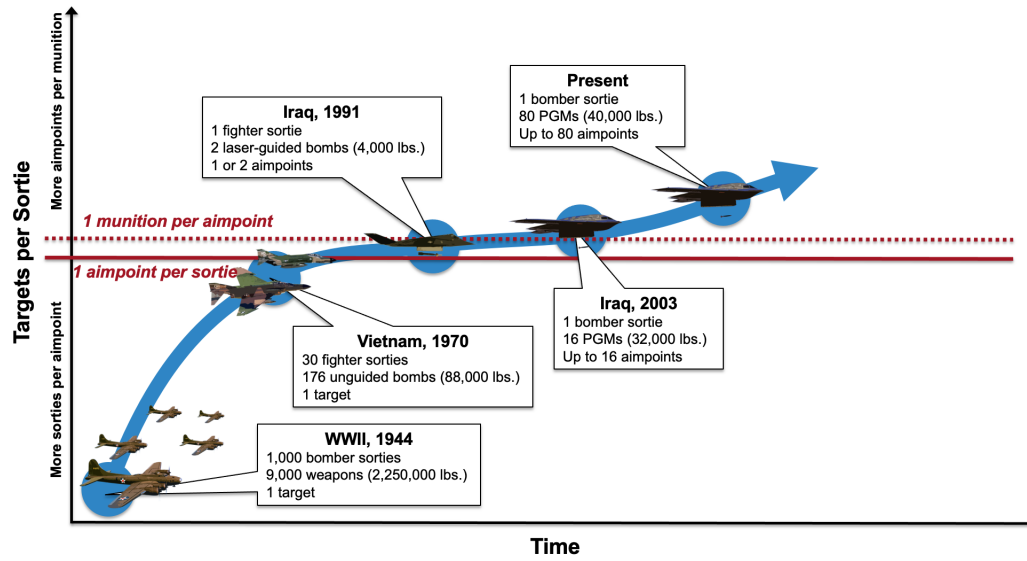
PGMs have significantly reduced the number of munitions required to achieve the same effects. The extreme degree of this reduction was also first seen in the Gulf War, where one ton of PGMs replaced an estimated 12 to 20 tons of unguided munitions on a tonnage per

30 GAO/NSIAD-97-134, *Operation Desert Storm: Evaluation of the Air Campaign* (Washington, DC: Government Accountability Office, June 1997), p. 178, https://www.gao.gov/assets/nsiad-97-134.pdf.

31 *Gulf War Air Power Survey, Volume IV: Weapons, Tactics, and Training and Space Operations* (Washington, DC: Department of Defense, 1993), p. 252, https://media.defense.gov/2010/Sep/27/2001329817/-1/-1/0/AFD-100927-066.pdf.

target kill basis.[32] By utilizing PGMs, a military is able to greatly reduce its total munitions requirement for the same target set.

FIGURE 4: EFFECTS OF PGMS ON MUNITIONS EXPENDITURES



Source: Created by CSBA with inspiration from Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*.

In short, the post-WWII era has witnessed a shift in focus from massing large quantities of unguided weapons to long-range precision-strike, albeit with significant increases in the cost of individual munitions. These two trends have several follow-on implications for weapon, platform, and basing requirements. The reduction in munitions needed per aimpoint translates to fewer sorties required to strike a greater number of targets. Fewer sorties per target could potentially reduce the total number of platforms required to attack the same target set. Moreover, delivery platforms can often attack certain targets from further distances with the same level of effectiveness, allowing platforms to remain further from enemy defenses. All of these factors have significant effects on theater logistics and sustainment requirements. Of course, these trends have become apparent during limited conflicts rather than large industrial wars of attrition. It remains to be seen how they apply to modern great power conflicts.

32 The Defense Science Board also estimated that one ton of PGMs saved as much as 35 to 40 tons of aviation fuel. Office of the Under Secretary of Defense for Acquisition & Technology, *Report of the Defense Science Board Task Force on Tactical Air Warfare* (Washington, DC: Department of Defense, November 1993), p. 17, https://apps.dtic.mil/dtic/tr/fulltext/u2/a275347.pdf.

The Enduring Munitions Problem

Ideally, the United States would take advantage of these trends and prepare for future high-intensity conflict by maintaining a nearly unlimited inventory of varied types of precision munitions. However, fiscal, industrial, and logistical constraints force the U.S. military to make tradeoffs when considering which PGMs to produce, stock, and maintain. Before examining munitions requirements in future scenarios, we must briefly explore how the United States currently navigates these weapon tradeoffs and some of the recurring issues with this process.

How the U.S. Military Determines Munitions Requirements

The DoD determines the type and quantity of its munitions purchases through the Munitions Requirements Process (MRP).[33] The Department utilizes illustrative planning scenarios identified by the Office of the Under Secretary of Defense for Policy (USD(P)) in conjunction with the Chairman of the Joint Chiefs of Staff and DoD component heads. With these scenarios and threat analysis provided by the Defense Intelligence Agency (DIA), the military services work with the combatant commanders to develop their munitions requirements. The services create two sets of requirements, one *unconstrained* and another *constrained*. The *unconstrained* requirements are not limited by projected inventory numbers or funding, but may be limited by production capacity or external caps on procurement. The *constrained* requirement, on the other hand, is limited by projected inventory. In other words, the services first create an ideal mix before subjecting it to the realistic constraints of budgeting and procurement. This process underscores the enduring challenge of determining munitions mixes: reconciling ideal requirements with the constraints of reality.

The military services, as the leaders of budgeting and programming, are ultimately responsible for squeezing munitions requirements into their Program Objective Memorandums (POMs). Although the MRP is intended to ensure the services acquire the *optimal* mix of weapons according to their analysis of the planning scenarios, previous studies have shown that the quantity of a munition procured is mostly driven by cost.[34] Regardless of scenario or strategy, higher-cost munitions are typically purchased in much smaller quantities than inexpensive weapons.[35]

In determining the unconstrained and constrained requirements, the services depend on modeling, simulation, and other analyses of illustrative planning scenarios and operational plans. As a result, their outputs rely on certain assumptions about the scenarios, the overall

33 The MRP is outlined in DoD Instruction (DoDI) 3000.04. Department of Defense, "DoDI 3000.04: DoD Munitions Requirements Process," August 31, 2018, https://www.esd.whs.mil/Portals/54/Documents/DD/issuances/dodi/300004p.pdf?ver=2019-02-25-133944-863.

34 DODI 3000.04 defines *optimal* as the "most favorable or desirable solution depending on factors involved."

35 Watts, *Evolution of Precision Strike*, pp. 20–21.

national objectives and strategy, and preconceived munitions employment concepts. As we look to future great power competition, we must contemplate how many of these previous assumptions might be challenged or no longer applicable.

The Persistent Shortage of PGMs

One consistent failure of the current process, perhaps due to faulty assumptions or inadequate funding, is chronically insufficient inventories of PGMs. Despite their effectiveness and extensive operational use, the United States and its allies are perennially running their PGM stocks low. This trend goes all the way back to the widespread fielding of PGMs in the early 1990s, with one post-Gulf War study noting that "The greatest current imbalances in capability are in inadequate numbers of precision-guided weapons and associated target engagement systems."[36]

Despite these warnings, each major strike campaign since has suffered from a dearth of precision munitions. During Operation Allied Force in 1997, the Joint Direct Attack Munition (JDAM) was still in early production and testing. Insufficient stocks of these weapons and other guided munitions such as the Conventional Air-Launched Cruise Missile (CALCM) led to increased use of unguided bombs once precision stocks were depleted.[37] In Operation Enduring Freedom, high consumption and low inventories of JDAMs pushed the Pentagon to hurriedly fund the opening of a second JDAM production line.[38] Operation Inherent Resolve again saw shortages of specific types of PGMs, leading RAND to call existing stockpiles "insufficient" in their official assessment of the air war over Iraq and Syria.[39] PGM expenditure rates during this campaign led then-Air Force Chief of Staff General Mark Welsh to admit "We're expending munitions faster than we can replenish them. … This is a critical need."[40]

The munitions stockpiles of many U.S. allies may be in even worse condition. The 2011 bombing campaign in Libya quickly exposed the inadequacy of European inventories of PGMs, with Britain, France, and others unable to independently sustain continuous strike

36 Even after early PGMs proved effective during the Vietnam War, the U.S. military did not fully embrace their potential until years later. Office of the Under Secretary of Defense for Acquisition & Technology, *Report of the Defense Science Board Task Force on Tactical Air Warfare* (Washington, DC: Department of Defense, November 1993), introductory memorandum, https://apps.dtic.mil/dtic/tr/fulltext/u2/a275347.pdf.

37 Benjamin S. Lambeth, *NATO's Air War for Kosovo: A Strategic and Operational Assessment* (Santa Monica, CA: RAND, 2001), pp. 170-171, https://www.rand.org/content/dam/rand/pubs/monograph_reports/MR1365/RAND_MR1365.pdf.

38 Watts, *Six Decades of Guided Munitions and Battle Networks*, p. 220.

39 Becca Wasser, Stacie L. Pettyjohn, Jeffrey Martini, Alexandra T. Evans et al., *The Air War Against the Islamic State: The Role of Airpower in Operation Inherent Resolve* (Santa Monica, CA: RAND, 2021), pp. 305-306, https://www.rand.org/pubs/research_reports/RRA388-1.html.

40 Quoted in Tom Vanden Brook, "Air Force Burning through Bomb Stockpiles Striking ISIL," *USA Today*, December 3, 2015, https://www.usatoday.com/story/news/world/2015/12/03/isil-iraq-syria-hellfire-missiles-drones/76741954/.

operations due to shortages of laser-guided bombs and other weapons.[41] The current conflict in Ukraine has further shown the shallowness of NATO munitions stocks. By mid-March 2022, Canadian Defense Minister Anita Anand admitted that Canadian weapon inventories were "exhausted," with little more available for transfer to Ukraine.[42] Around the same time, Germany made a similar announcement and delayed its donation of *Gepard* anti-aircraft vehicles due to shortages of medium-caliber ammunition.[43] U.K. Defense Minister Ben Wallace called the weapons stocks of Western nations "inadequate for the threats we face," and cited a war game in which British forces ran out of munitions in eight days.[44]

Munitions Trends in Modern Strike Campaigns

Beyond shortages of PGMs, what other munitions trends have characterized U.S. strike campaigns since the maturation of precision-strike operations? How will these trends translate to great power conflict in the 2020s? To answer these questions, CSBA compiled available munitions data from several post-Cold War U.S. military operations. Displayed in Table 1, these figures allow us to compare total munitions expenditures, the proportion of guided and unguided weapons, the share of long-range munitions, and the types of targets these campaigns prosecuted.

41 Karen DeYoung and Greg Jaffe, "Nato Runs Short on Some Munitions in Libya," *Washington Post*, April 15, 2011, https://www.washingtonpost.com/world/nato-runs-short-on-some-munitions-in-libya/2011/04/15/AF3O7ElD_story.html.

42 Nick Taylor-Vaisey, "Sorry Ukraine, We Ran Out of Guns," *Politico*, March 17, 2022, https://www.politico.com/newsletters/ottawa-playbook/2022/03/17/sorry-ukraine-we-ran-out-of-guns-00018052.

43 *Ntv.de*, "Lambrecht: Lieferungen von Bundeswehr-Waffen 'erschöpft'," March 18, 2022, https://www.n-tv.de/politik/Lambrecht-Lieferungen-von-Bundeswehr-Waffen-erschoepft-article23207612.html; and Sabine Siebold and Sarah Marsh, "Tanks, but No Ammo – Germany's Ukraine Pledges Show Military Muddle," *Reuters*, May 25, 2022, https://www.reuters.com/world/us/tanks-no-ammo-germanys-ukraine-pledges-show-military-muddle-2022-05-25/.

44 Rathbone and Chavez, "Military Briefings: Is The West Running Out of Ammunition to Supply Ukraine?"

TABLE 1: COMPARISON OF POST-COLD WAR U.S. STRIKE CAMPAIGNS

	Desert Storm 1990 – 1991	Allied Force 1999	Enduring Freedom 2001	Iraqi Freedom 2003	Odyssey Dawn Unified Protector (NATO combined) 2011	Inherent Resolve 2014 – 2019
Length (days)	43	78	176	30	234	~1,700
Total Sorties	116,000	38,004	~25,000	47,600	26,500+	234,000
Average Sorties/ Day	2,500	200 – 1,000	~100	~1,600	~113	~143
Aimpoints	~40,000	7,600 fixed 3,400 mobile 11,000 total	120 fixed 400+ mobile 520+ total	30,542 19,898 struck	-	-
Total Munitions	277,165	23,614	17,472	29,199	7,642	115,983
Guided Munitions	17,161 (7.6%)	6,728 (29%)	12,001 (69%)	19,948 (68%)	7,642 (100%)	Largely PGMs
Average Guided Munitions/Day	399	86	68	665	33	~68
TLAMs/ CALCMSExpended	332	270	74	955	110	172
SEAD Sorties	4,326	4,538	-	-	1,500+	-
HARMs Expended	1,961	1,000+	-	408	-	-
Radars Destroyed	~250 / 500	10 / 41	-	-	-	-
SAMs Destroyed	35 / 120 fixed batteries	3 / 25 SA-6 batteries	-	-	Presumed by DoD: 11 SA-5 batteries 4 SA-2 batteries 16 SA-3 batteries Mobile uknown	-
Combat Losses (# of aircraft)	38 total coalition	2	0	1	1 mechanical	2 mechanical 5 UAS

Sources: See full table in **Appendix A** for a complete list of sources and notes.

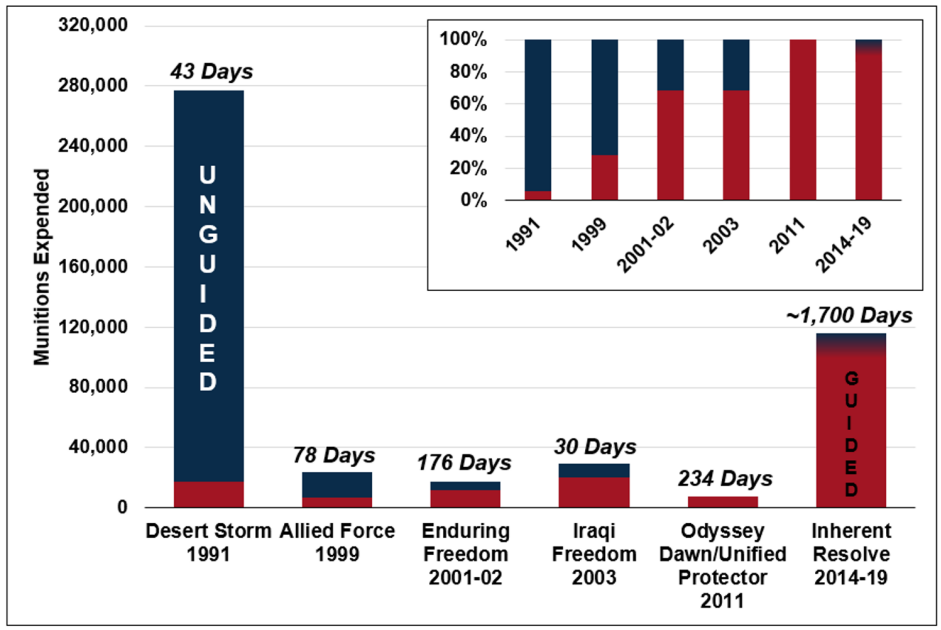
The campaigns in Table 1 vary significantly in their duration, size, and target set. The air war conducted during Operation Desert Storm was a comprehensive strike campaign carried out over several weeks that attacked Iraqi command and control (C2), integrated air defense systems (IADS), and military, communications, and transportation infrastructure. The end of the air war saw attacks shift to Iraqi ground forces. In Operation Allied Force, most targets were ground force facilities, C2 facilities, and lines of communication (namely bridges, rail, and roadways).[45] Other key targets in Allied Force included "counter-regime" targets and Serb air defenses, many of which were mobile SA-3s and SA-6s. The 2001 air war over Afghanistan lasted significantly longer than either Desert Storm or Allied Force, but struck fewer targets at a slower rate, many of which were ground forces. Two years later,

45 Lambeth, *NATO's Air War for Kosovo*, pp. 62–63.

Iraqi Freedom was comparatively short and intense, with the majority of sorties apportioned to strike Iraqi forces, maintain air supremacy, and suppress Iraqi ballistic missile systems.[46] Finally, NATO's campaign in Libya and the fight against ISIS in Iraq and Syria consisted of protracted air operations with periods of higher intensity. From these strike campaigns, several trends can be identified.

First, each campaign saw the increasing prevalence of guided munitions, with more recent campaigns relying almost exclusively on PGMs. Over time, PGMs have gone from exquisite munitions utilized for specific targets or situations to the standard strike munitions of the U.S. military. This trend has, in turn, had second- and third-order effects on U.S. force structure, doctrine, training, and logistics. As PGMs have become ubiquitous, the majority of platforms are now capable of employing them. Pilots and operators are not only trained in their use, but also have years of operational experience doing so. U.S. operational concepts and plans—the modern American way of war—now rely on precision-strike capabilities. Precision has become the standard, and current and future weapons inventories should reflect this fact.

FIGURE 5: INCREASING PGM USAGE SINCE 1990

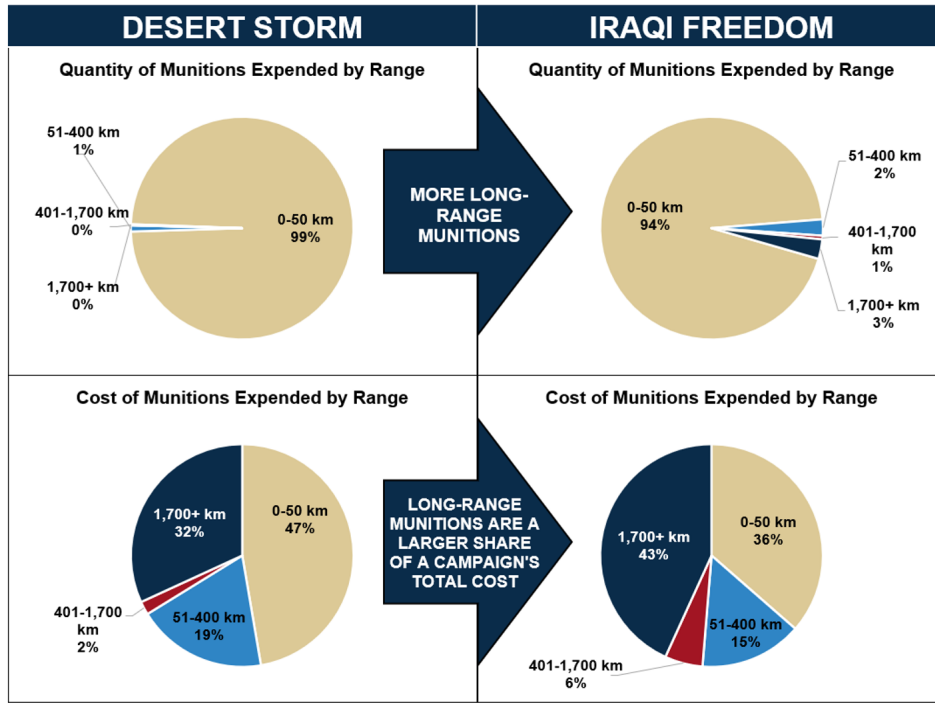


Source: Created by CSBA using data from Table 1. See Appendix A.

46 U.S. Central Command Air Forces, Assessment and Analysis Division, "Operation IRAQI FREEDOM – By The Numbers," April 30, 2003, p. 5, https://www.globalsecurity.org/military/library/report/2003/uscentaf_oif_report_30apr2003.pdf.

Second, long-range and stand-off munitions have made up an increasingly large portion of the total munitions expended. Operations Desert Storm and Iraqi Freedom best exemplify this trend because both campaigns occurred in the same geography and were short, intense, and comprehensive in scope. Although long-range munitions still make up a relatively small share of total munitions consumption, they are increasing in proportion. This trend is significant because of the previously identified relationship between increased range and increased cost. Figure 6 shows the growing usage of long-range munitions and how munitions' costs in Iraqi Freedom were driven by stand-off weapons like the Tomahawk Land Attack Missile (TLAM) and CALCM. Short-range munitions are a shrinking slice of the total munitions pie—in both quantity expended and cost. As more long-range munitions are needed, fiscal tradeoffs between quantities of long- and short-range weapons become more pressing.[47]

FIGURE 6: AIR- AND SEA-DELIVERED MUNITIONS EXPENDED IN DESERT STORM VERSUS IRAQI FREEDOM BY RANGE AND COST



Source: Created by CSBA using data from DoD budget documents; GAO/NSIAD-97-134, *Operation Desert Storm: Evaluation of the Air Campaign*; and U.S. Central Command Air Forces, Assessment and Analysis Division, "Operation IRAQI FREEDOM – By The Numbers."

47 For an exploration of the cost tradeoff between standoff munitions and penetrating bombers carrying short-range munitions, see Thomas Hamilton, *Comparing the Cost of Penetrating Bombers to Expendable Missiles Over Thirty Years: An Initial Look* (Santa Monica, CA: RAND, 2011), https://www.rand.org/pubs/working_papers/WR778.html.

Finally, many of these campaigns featured large munitions expenditures on mobile and elusive targets, often without achieving the desired effects. This trend can be seen in the varied success of suppression and destruction of enemy air defense (SEAD/DEAD) missions between Desert Storm and Allied Force. These operations included a similar number of SEAD/DEAD sorties with large numbers of anti-radiation missiles expended. In Desert Storm, coalition forces quickly incapacitated Iraq IADS, which consisted mostly of fixed radars and missiles controlled by centralized C2 centers. Serb air defenses, on the other hand, relied on mobile missile launchers and radars that remained concealed and emitted intermittently, making them difficult for allied air forces to target and destroy.[48] Iraqi SCUD launchers during Desert Storm presented a similar problem, despite being in the same flat and uniform terrain as fixed IADS sites. Because of their mobility, coalition air strikes were unable to destroy a single launcher, despite SCUD hunting consuming "as much as 25 percent of F-15E and LANTIRN equipped F-16 sorties in the war."[49] These mobile and elusive targets consumed valuable munitions and resources that could have been devoted to other vital missions.

U.S. Adversaries Adapt to These Trends

These munitions trends have not only been noticed by the U.S. military, but have also been studied extensively by U.S. adversaries, who have attempted to adapt their forces to defeat U.S. operations asymmetrically and capitalize on perceived weaknesses in the precision-strike complex. These adaptations began after Desert Storm in the Soviet military, which worried in the conflict's aftermath that widespread use of PGMs might "negate the traditional measures of military power and have a revolutionary impact on future combined-arms concepts."[50]

The Chinese military drew similar lessons about future warfare from the U.S. campaigns of the 1990s and 2000s. PLA scholars credit the Gulf War with spurring a "wholesale reconsideration of future warfare" within the Chinese military that ultimately shifted the PLA's focus from mechanized warfare to information warfare.[51] Rather than simply imitating the

48 Eric Heginbotham, Michael Nixon, Forrest E. Morgan, and Jacob L. Heim et al., *The U.S.-China Military Scorecard: Forces, Geography, and the Evolving Balance of Power, 1996-2017* (Santa Monica, CA: RAND, 2015), p. 128, https://www.rand.org/pubs/research_reports/RR392.html.

49 Although no SCUD launchers were destroyed, analysts estimate that these sorties had a *virtual attrition* effect by discouraging road movement and reducing the number of SCUDs launched by half. Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, *Report of the Defense Science Board Task Force on Future Strategic Strike Forces* (Washington, DC: Department of Defense, February 2004), p. 6–4, https://dsb.cto.mil/reports/2000s/ADA421606.pdf; and Gregory Wilson, *A Time-Critical Targeting Roadmap* (Maxwell Air Force Base, AL: Air Command and Staff College, Air University, 2002), pp. 4–5, https://apps.dtic.mil/sti/pdfs/ADA420658.pdf.

50 David M. Glantz in Gilberto Villahermosa, "DESERT STORM: The Soviet View," Foreign Military Studies Office, Fort Leavenworth, KS, May 25, 2005, p. 22, https://community.apan.org/cfs-file/__key/docpreview-s/00-00-00-96-94/2005_2D00_05_2D00_25-Desert-Storm_2D00_The-Soviet-View-_2800_Villahermosa-and-Glantz_2900_.pdf.

51 M. Taylor Fravel, *Active Defense: China's Military Strategy since 1949* (Princeton, NJ: Princeton University Press, 2019), pp. 182, 187, 190.

precision-strike complex of the United States, the PLA aimed to counter U.S. offensive operations with weapons and concepts that exploited U.S. weaknesses and dependencies in an asymmetric manner. The resulting strategy has become known as anti-access/area denial (A2/AD), which seeks to keep U.S. maritime and airborne strike assets as far from Chinese territory as possible. Central to A2/AD is a robust air and missile defense network intended to deny the United States the ability to conduct strike campaigns such as those in Table 1. The PLA recognized the need for such a system after the Gulf War, with U.S. operations in Kosovo and Iraq further reinforcing the PLA's fears.[52]

Beyond denying U.S. delivery platforms the ability to operate within weapons range of the mainland, the PLA has sought to mitigate the U.S. precision-strike advantage by vastly increasing the number of potential aimpoints confronting U.S. forces and decreasing the probability that American munitions reach and have effects on these aimpoints. The PLA aims to achieve this through both active and passive defenses, including extensive dispersion, redundancy, and camouflage, concealment, and deception (CC&D).[53]

Active defenses are mainly China's IADS, which it has rapidly modernized since the 1990s.[54] Comprised of early warning sensors, airborne interceptors, surface-to-air missiles (SAMs), and point defenses, China's IADS is capable of neutralizing PGMs before they reach their targets. At long ranges, airborne interceptors and advanced SAM systems such as the S-300 and HQ-9 can shoot down cruise missiles and contest U.S. strike aircraft. At shorter ranges, point defenses such as close-in weapon systems or non-kinetic weapons can destroy, jam, or spoof incoming PGMs.[55] With an estimated probability of kill between 40 and 85 percent for cruise missiles, systems like the S-300 vastly increase the number of munitions required to ensure effects on a given target.[56] Learning from NATO difficulties with SEAD in Kosovo, the PLA has focused its modernization efforts on mobile and rapidly employable air defense systems of all types.[57] While the United States expended over 1,000 HARM anti-radiation

52 A study conducted by the PLA's National Defense University in the wake of the Operation Allied Force "focused on the lethality of air strikes in modern warfare and the need for China to develop appropriate countermeasures. … the NDU study highlighted the use of short-range and long-range airstrikes, precision strikes, and stealth aircraft." Fravel, *Active Defense*, p. 224–228; and Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.-China Military Scorecard*, p. 97.

53 Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, pp. 13–15.

54 Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.-China Military Scorecard*, p. 98.

55 Close-in weapon systems include gatling gun-type systems, short-range SAMs, and self-propelled anti-aircraft guns. The PLA possesses all three types of systems, including platforms that combine two or more of these weapons. Non-kinetic defenses include electronic warfare jammers and decoys, and may include high-power lasers or microwaves in the near future.

56 Ryan Fedasiuk, "S-300P Air and Missile Defense System," *Missile Defense Advocacy Alliance*, December 2017, https://missiledefenseadvocacy.org/missile-threat-and-proliferation/todays-missile-threat/russia/russia-anti-access-area-denial/s-300p-air-and-missile-defense-system/.

57 Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.-China Military Scorecard*, p. 129.

missiles at approximately 40 Serb mobile SAM launchers in 1999, China is currently estimated to field over 600 mobile long-range SAM launchers.[58]

Munitions that survive China's active defenses will then contend with the PLA's many forms of passive defense, with the most visible measure being the thorough hardening of PLA basing and infrastructure. Airbases in China's depths have long included underground hangars built into mountainsides, but the PLA also increased its number of hardened aircraft shelters (HAS) by around 240 percent between 2000 and 2014, mainly in the coastal areas opposite Taiwan.[59] These shelters not only protect Chinese aircraft from many PGMs, but also increase munitions consumption through dispersion and deception:

> Chinese construction efforts have increased the number of aimpoints by nearly 130 percent from 2002 to 2014. In particular, the number of aimpoints that must be struck to disrupt Chinese combat operations near Taiwan has significantly increased. … The additional HAS also adds a layer of deception, making US and allied planning and targeting more difficult. With roughly 200 additional HAS spread over 15 air bases, the PLA can now disperse its squadrons more effectively to confuse targeting efforts.[60]

Other passive defenses include extensive use of concealment, camouflage, and decoys to further expand the number of aimpoints for the PLA's adversaries.[61] These measures may even be employed around non-military facilities and infrastructure.[62]

All of these measures combine to exponentially increase U.S. munitions requirements for any strike campaign against the Chinese military. Dispersion and CC&D increase the total number of targets. Active defenses further increase munitions requirements by reducing the probability that munitions survive the flight to their intended targets. Passive defenses increase the number of munitions required by decreasing the likelihood that a weapon has the desired effects on the target. Figure 7 shows how these factors combine to drive U.S. PGM requirements against a great power adversary such as China.

58 U.S. forces only destroyed three Serb TELs. Serb TEL quantities taken from Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.–China Military Scorecard*, p. 128; Chinese TEL quantities taken from *The Military Balance: Chapter Six: Asia* (London, UK: International Institute for Strategic Studies, 2022), p. 261.

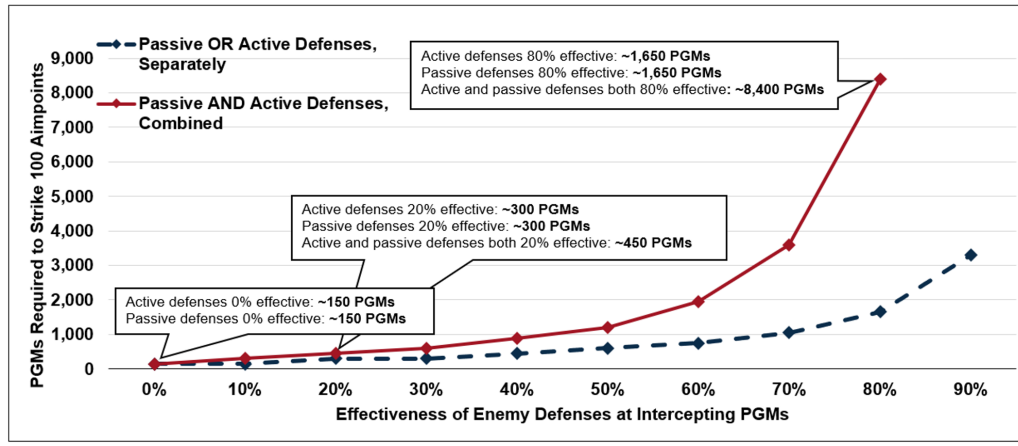
59 David Lewton, "The Dragon Pours Concrete," *Air & Space Forces Magazine*, November 26, 2014, https://www.airandspaceforces.com/article/the-dragon-pours-concrete/.

60 Ibid.

61 *China Military Power: Modernizing a Force to Fight and Win* (Washington, DC: Defense Intelligence Agency, 2019), p. 47, https://www.dia.mil/Portals/110/Images/News/Military_Powers_Publications/China_Military_Power_FINAL_5MB_20190103.pdf.

62 For example, the PLA has held drills involving balloons carrying radar reflectors around critical infrastructure. Emma Helfrich and Tyler Rogoway, "China Is Using Radar Reflector Balloons To Defend Critical Targets From Aerial Attack," *The Drive*, December 5, 2022, https://www.thedrive.com/the-war-zone/china-seen-using-radar-reflector-balloons-to-defend-key-targets.

FIGURE 7: EFFECTS OF ACTIVE AND PASSIVE DEFENSES ON MUNITIONS REQUIREMENTS FOR A FIXED NUMBER OF AIMPOINTS



Source: Created by CSBA. Calculations assume a desired probability of kill of 90% or greater.

Lessons for Great Power Conflict

The capabilities and adaptations of near-peer adversaries like the Chinese PLA differentiate potential great power conflict campaigns from previous U.S. operations analyzed in this chapter. Recent campaigns have been mostly limited in nature and were conducted against regional powers or non-state actors with limited defenses. Additionally, most munitions data centered on weapons delivered by aircraft, with a much smaller number of PGMs delivered by maritime or ground forces. Nevertheless, our examination of previous munitions trends and adversary reactions leads to several broad insights for contemporary great power conflict.

First, PGMs will continue to be the preferred munitions for many types of targets so long as inventories last. Guided munitions will continue to be the "go-to" weapon of the U.S. military and a centerpiece of the American way of war. These weapons offer unprecedented improvements in effectiveness and operational efficiency. The U.S. military's force structure is shaped to fight a war of precision strike, and it tailors its training, doctrine, and procurement around these concepts. What remains unclear is whether U.S. PGM stocks are sufficient to support this kind of war against a peer competitor. Given limited stocks of long-range PGMs, it is likely that any comprehensive or protracted strike campaign will also require a large quantity of shorter-range munitions as well. This is particularly true for certain wide-area targets and situations where air defenses have been temporarily or permanently mitigated. DoD's report to Congress on the 1999 Kosovo campaign summarized this requirement:

> The requirement to maintain a mix of weapon capabilities and platforms was highlighted by Operation Allied Force. In the final stages of the campaign when the weather had improved and the air defense system had been degraded, the availability of a complete mix of weapons

maximized the flexibility of strike options against the remaining priority targets. Because pilots could now employ direct attack weapons at less risk, less costly legacy weapons were, in many cases, as effective (and sometimes more) as more costly preferred weapons against such targets as fielded forces, large military storage complexes, and airfields.[63]

Second, the potential quantity of complex targets and their geographic spread in a great power war is staggering. Air campaigns in Desert Storm and Iraqi Freedom incorporated thousands of aimpoints for C2, IADS, basing, ground forces, and military infrastructure targets. An equally comprehensive campaign with similar objectives against a great power adversary would entail an even more overwhelming number of aimpoints. Moreover, many of these targets are mobile, requiring additional resources to find, track, and attack. Beyond the sheer quantity of targets, the vast geographies of China and Russia complicate any potential strike operations and range requirements for weapon-platform pairs.[64] As Figure 8 shows, China is more than 22 times the size of Iraq, with the PLA's Eastern Theater Command alone occupying nearly 1.5 times the area of Iraq.[65] Potential targets are spread over a greater area and have more places to hide, requiring additional sensor capacity to meet targeting requirements. Targets in the depths of China's interior could require munitions with increased range and penetration capability should delivery platforms be unable to operate in contested Chinese airspace.

FIGURE 8: COMPARISON OF IRAQ AND CHINA BY GEOGRAPHIC AREA

Source: Created by CSBA using map data courtesy of naturalearthdata.com.

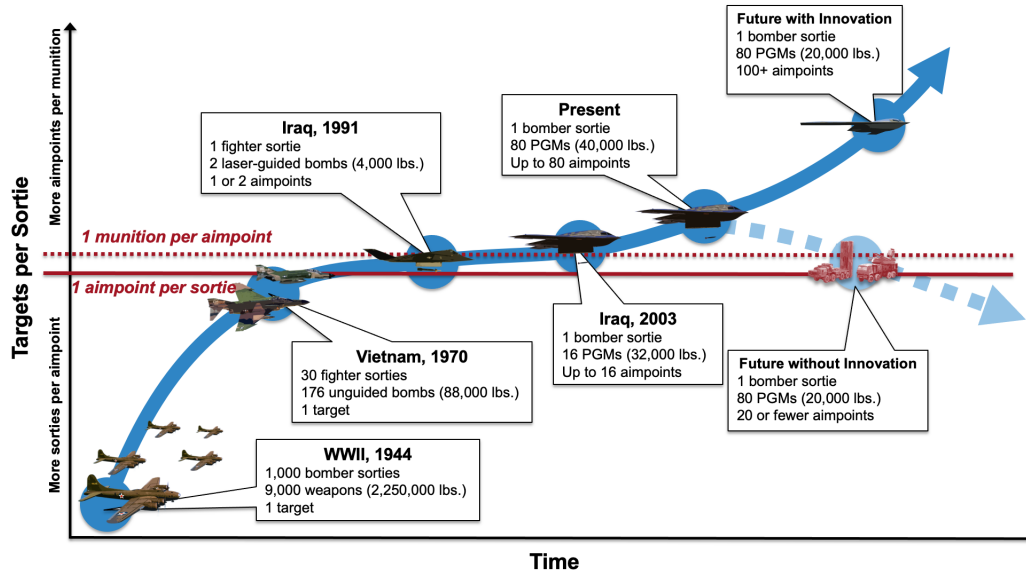
63 Department of Defense, "Report to Congress: Kosovo/Operation Allied Force After-Action Report," January 31, 2000, p. 90, https://www.airandspaceforces.com/PDF/DocumentFile/Documents/2005/Kosovo_013100.pdf.

64 Not all of China and Russia's expanses are equally populated with military targets. Nevertheless, the scenarios examined in Chapter Three will show how targets in the depths of these vast states complicate strike operations and munitions requirements.

65 China occupies around 9.6 million square kilometers versus Iraq's 435,000.

Third, the defenses of great power adversaries will further increase munitions requirements. Figure 7 illustrates how both active and passive defenses will multiply the number of aimpoints and expand the number of munitions required for every aimpoint. Regardless of the exact effectiveness of enemy defenses, they will certainly add to the quantity of munitions required for great power conflict.[66] Of course, the presence of these defenses puts U.S. strategy and munitions design—the U.S. precision-strike advantage itself—at an inflection point. As shown in Figure 9, the U.S. military can innovate to sustain and increase its existing advantage or languish and find its advantage reduced by adversary advancements in coming years. Future innovation could take many forms. The United States can reduce munitions requirements by eliminating or mitigating adversary defenses. These measures might include first-wave strikes that "kick in the door" by targeting active defenses. The United States might also develop countermeasures against adversary defenses or build special munitions designed to defeat certain passive defenses and hardening. U.S. forces may also be able to drive up adversary costs by using low-cost munitions to absorb expensive interceptors. These possibilities will be fully explored in Chapter Five.

FIGURE 9: PRECISION-STRIKE AT AN INFLECTION POINT



Source: Created by CSBA.

Fourth, the intelligence and targeting requirements for great power conflict will be unprecedented in both volume and depth. In addition to munitions and delivery platforms, intelligence collection and processing are vital to a mature

66 Even if China's defenses are ultimately found to be ineffective during a conflict, their presence and the uncertainty they create is likely to affect the U.S. military's actions and munitions employment doctrine in the initial phases of conflict.

precision-strike regime. Beyond simply finding, identifying, and tracking suspected targets, most currently fielded PGMs require exact intelligence about target location, type, and disposition in order to be employed effectively. Large-scale use of PGMs will drive the need for additional intelligence, surveillance, and reconnaissance (ISR) assets, as well as the capacity to process, analyze, and disseminate this information to strike forces.[67] The DoD's current Joint All-Domain Command and Control (JADC2) efforts seek to create these linkages and networks, and the introduction of artificial intelligence (AI) assisted analysis may increase future intelligence processing throughput. These functions are outside the scope of this study, but we must recognize that munitions are only one link in precision-strike kill chains.[68]

Given these trends and lessons, it is possible that the United States will never have enough munitions, sorties, or intelligence to conduct this style of all-encompassing precision-strike campaign against a great power adversary such as China. The U.S. military may struggle to produce the immense volume of precision effects required against such a large, dispersed, and heavily defended target set. Sufficient massing of PGMs may be impossible due to budgetary and industrial constraints. Even if an enormous quantity of PGMs are procured, moving them into theater without creating the vulnerable "iron mountain" of previous campaigns would present a massive logistical challenge, especially in the Indo-Pacific.

...

If the nature of today's threats leaves the U.S. military challenged to conduct a comprehensive strike campaign in the style of the last three decades, how should the United States maintain its precision-strike advantage in contemporary great power conflict? Like the Balkan Wars prior to WWI, past strike campaigns serve as a warning that munitions, specifically PGMs, will be a central determinant of future great power conflict. If simply producing and buying *more* PGMs is necessary, but not sufficient to meet demands, then the U.S. military must target its investments to capitalize on weapons and concepts tailored to the specific demands of great power conflict. The next chapter examines potential war scenarios in the Indo-Pacific to identify these demands and explore the optimal array of PGMs for great power conflict.

67 Kenneth Werrell notes the paradox that as intelligence-collection capabilities improve, parallel improvements in PGMs drive increased intelligence requirements—making targeting efforts seem perpetually inadequate. See Werrell, *Chasing the Silver Bullet*, pp. 277–278.

68 A point made by Barry Watts in *The Evolution of Precision Strike*, p. 12.

CHAPTER 3

Munitions Requirements for Five Great Power Conflict Scenarios

With previous limited and regional wars pointing toward unprecedented munitions requirements for great power conflict, this chapter explores the kinds of PGMs best suited for contemporary war scenarios. To determine these requirements, we outline five potential conflict scenarios which vary from short to protracted, limited to comprehensive, with differing operational objectives. An examination of each scenario and its target set reveals insights into the types and quantities of munitions needed to execute these campaigns.

This chapter does not generate specific requirements by weapon type or the exact quantity of munitions. Rather, the intent is to use simplified scenarios to highlight the categories of munitions and potential volume of weapons required. Most importantly, this chapter shows how several key variables and assumptions—including conflict duration, target set, and the effectiveness of adversary defenses—greatly affect munitions requirements in contemporary great power conflict. In addition to tradeoffs, the chapter closes by highlighting common weapon requirements across the five scenarios.

Envisioning Contemporary Great Power Conflict

Basic Assumptions

Our analysis focused on conflict scenarios between American and Chinese forces in the 2023 to 2025 time period in the Indo-Pacific theater. We examined the near future in order to assess munition requirements against current munition procurement and production rates. Focusing on a near-term conflict also allowed us to build our potential target lists using current government documents and satellite imagery rather than speculative figures.

We concentrate on conflict with China in the U.S. Indo-Pacific Command (USINDOPACOM) area of responsibility for several reasons. First, conflicts involving the PLA would likely be the most munitions-intensive campaigns, making them a challenging case for examination. Second, focusing on a single great power adversary allows the scenarios to complement each other and be layered or combined. Moreover, Russia, the United States' other great power competitor, is currently embroiled in a conflict in Ukraine, making its current and future military potential more difficult to accurately assess at this time. Finally, the vast geography of the Indo-Pacific presents unique challenges to the U.S. military, whose force structure and munitions inventory was largely shaped by Cold War scenarios in central Europe.[69]

We excluded the munitions stockpiles of U.S. allies and partners. Although these weapons may be invaluable during a conflict, foreign munitions inventories are more difficult to assess using open sources. Furthermore, there is inconsistent publicly available data about the compatibility of allied weapons with U.S. platforms. Lastly and most importantly, it is unclear which allies might join the fight or make their munitions available to U.S. forces in the event of a conflict in the Indo-Pacific. In addition, the United States' industrial base manufactures and supplies munitions (or their components) to many of its allies and partners. Though some allies, such as Australia and Japan, have committed to expanding their munitions production capacity, they may still rely on the United States for weapons during a war.[70] Thus, the requirements derived from this analysis, if anything, understate the requirements for conflict scenarios in the Indo-Pacific theater.

This chapter does not offer a deep examination of the political causes ("road to war") or broader strategic aims of the conflict scenarios. Rather, the scenarios are driven by more concrete operational objectives. At times, political or strategic assumptions and decisions do influence munitions requirements, and these factors are stated in the affected scenarios.

Scenario Selection

In order to assess and compare varying munitions requirements, we chose a wide-ranging mix of plausible Indo-Pacific conflict scenarios. Each scenario was chosen based not only on its plausibility but also on its analytical value. Several other scenarios were considered but not included because their requirements were similar to those of another case.[71] In choosing

69 Eric Edelman, Christopher Bassler, Toshi Yoshihara, and Tyler Hacker, *Rings of Fire: A Conventional Missile Strategy for a Post-INF Treaty World* (Washington, DC: Center for Strategic and Budgetary Assessments, 2022), p. 5, https://csbaonline.org/research/publications/rings-of-fire-a-conventional-missile-strategy-for-a-post-inf-treaty-world.

70 For Australia, see Australian Government, "Australia accelerates Sovereign Guided Weapons manufacturing," accessed February 28, 2023, https://www.globalaustralia.gov.au/news-and-resources/news-items/australia-accelerates-sovereign-guided-weapons-manufacturing; for Japan, see Jeffrey W. Hornung, "Japan's Upcoming Defense Efforts," *The RAND Blog*, December 13, 2022, https://www.rand.org/blog/2022/12/japans-upcoming-defense-efforts.html.

71 For example, a scenario involving the PLAN in the Indian Ocean might have similar requirements to a Taiwan contingency (scenario 1), and a confrontation in the East China Sea might have similar requirements to a conflict in the South China Sea (scenario 2).

scenarios, CSBA is not judging the likelihood of conflict or advocating particular strategies, objectives, or targets. Instead, we aim to simply envision the *kinds* of campaigns and targets that U.S. military planners might execute in order to draw conclusions about munitions usage in contemporary great power conflict. By choosing campaigns with varied durations, geographic breadths, and target types, we can identify broad munition requirements in each scenario.

The first three cases are intended to be short campaigns that seek to achieve decisive operational objectives, with the latter two cases exploring the realm of protracted conflict. The first two short conflict scenarios cover the most commonly considered U.S.-China contingencies: countering a Chinese amphibious invasion of Taiwan and a fight for control of the South China Sea. These scenarios are often used in studies and wargames intended to shape the U.S. military's future force structure and weapons inventory.[72]

Indo-Pacific Great Power Conflict Scenarios

1. Neutralize Invasion Force in Taiwan Strait
2. Neutralize South China Sea Outposts
3. Counter-C4ISR Campaign
4. Strike Campaign Against Enemy Conventional Bases
5. Force Regeneration Campaign

Although we considered only conventional munitions, our selection of scenarios and their operational objectives, particularly protracted scenarios, drew heavily on the literature surrounding Cold War nuclear targeting. As outlined in Chapter Two, many recent U.S. strike campaigns have been comprehensive, with thousands of targets of all kinds, but against regional adversaries with smaller militaries. Nuclear strategy literature, on the other hand, explores the merits and risks of attacking great power adversaries through different sets of targets with a limited number of weapons.[73] Accordingly, the third through fifth cases assess scenarios reflective of this literature: conventional counter-command, control, communications, computers, intelligence, surveillance, and reconnaissance (C4ISR), a campaign against conventional bases, and a campaign that targets force regeneration assets.[74]

These five scenarios are not meant to be strictly independent of one another. Rather, they could be layered or combined in different variations. For example, a counter-C4ISR

72 These scenarios will likely continue to drive defense analysis, in part because the 2022 National Defense Strategy highlights Taiwan and the South China Sea as key elements of strategic competition with the PRC. U.S. Department of Defense, "2022 National Defense Strategy of the United States of America," October 27, 2022, p. 4, https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF.

73 See, for example, Lawrence Freedman and Jeffrey Michaels, *The Evolution of Nuclear Strategy: New, Updated and Completely Revised* (London, UK: Palgrave Macmillan, 2019).

74 We describe our fourth scenario as a "strike campaign against conventional bases" to avoid confusing it with a "conventional counterforce" campaign, which is used by scholars like Caitlin Talmadge to describe a conventional attack on Chinese nuclear forces.

campaign could be combined with strikes to neutralize a PLA invasion force in the Taiwan Strait. Similarly, one of the protracted campaigns could be pursued if a rapid campaign does not lead to conflict termination. To keep the scenarios independent and complementary, they are constructed as vignettes of campaign *types* rather than fully detailed scenarios.

Methodology

For each chosen scenario, CSBA assembled lists of hypothetical targets that could be attacked to achieve the case's operational objective.[75] Data was collected using open sources and includes information such as target location and characteristics. These lists are meant to include a broad range of targets the U.S. military might consider in a U.S.-China conflict. They are not comprehensive but are intended to illustrate the range of target types and locations essential to their given scenario.

From these target lists, we estimated the total number of aimpoints for different target types, such as airfields, ships, harbor facilities, and other military installations and infrastructure.[76] We then calculated the quantity of conventional precision munitions required to attack these aimpoints with a 90 percent or higher probability of kill, given varying probabilities that a munition is intercepted during its flight.[77] This probability of intercept, or P(*i*), is a single probability figure meant to account for several statistical variations that could result in a munition failing to reach its target or failing to achieve the desired effect: the probability of accurate targeting data, the reliability of the munition, the probability a munition is intercepted by enemy defenses, the probability of hit (accuracy), and the probability that the munition has the desired effects. We assume each of these factors to be irrelevant except for the probability a munition is intercepted by enemy defenses, which constitutes the P(*i*) value in our calculations. Any of these additional factors, however, would further reduce the chance a munition achieves its desired effect and increase this P(*i*) value. As such, our munitions calculations, even at the greatest probability of intercept, are likely conservative. We calculated munitions requirements at a P(*i*) of 10, 25, and 50 percent. The result is a rough quantity of munitions required to attack each scenario's target list at varying probabilities of intercept.

Lastly, we charted these quantities at 100, 75, 50, and 25 percent to show the range in quantity of munitions required to attack varying portions of the total target set. We calculated these portions because it is unclear how much of each target set the U.S. military would need to strike to accomplish its operational objectives. The munitions requirements for varying portions of the total target set allow us to examine requirements using differing assumptions

75 Complete scenario details, target lists, munitions quantities, and target maps can be found in Appendix B. This chapter contains summarized findings and conclusions based on the data and analysis in Appendix B.

76 This monograph uses the term aimpoints to describe desired points of impact (DPIs). Along with scenario details, a detailed explanation of aimpoint calculations by target type can be found in Appendix B.

77 The methodology for these calculations was drawn from Morris R. Driels, *Weaponeering for the Warfighter* (Reston, VA: American Institute of Aeronautics and Astronautics, 2021).

about how thorough U.S. strikes would need to be to achieve the stated operational objectives. We used these quantity ranges, along with scenario details and the geographic location of targets, to draw conclusions about the types and quantities of munitions necessary for each great power conflict scenario.

Five Great Power Conflict Scenarios in the Indo-Pacific

Based on these assumptions and CSBA's analysis, this section provides a summary of the major munitions requirements and findings for each scenario. Further scenario data, including target lists, aimpoint calculations, and geographic analysis, can be found in Appendix B. Appendix B also contains information on the selection and sourcing of targets in each case.

Neutralize Invasion Force in Taiwan Strait

Scenario 1 focuses on neutralizing a PLA invasion force during an attempted assault on Taiwan. This scenario is similar to former Undersecretary of Defense for Policy Michele Flournoy's testimony about the U.S. military's need to "sink 300 military vessels, submarines, and merchant ships within 72 hours" and is the focus of much recent defense analysis.[78] Former commander of USINDOPACOM Admiral Philip Davidson testified in 2021 that China could move to invade Taiwan before 2027. The "Davidson window" was further shortened by Chief of Naval Operations Michael Gilday, who urged that the U.S. military needs to be ready for a Taiwan contingency before 2024.[79]

A Chinese attempt to invade Taiwan could follow several triggers, including a declaration of Taiwanese independence, disputes over island territories, or a military accident in the Strait.[80] The massing of invasion forces in Chinese ports opposite Taiwan would be detectable by U.S. and Taiwanese intelligence.[81] The PLA Navy (PLAN) would surge into the waters

78 Michele A. Flournoy, "Testimony before the House Armed Services Committee Future of Defense Task Force," October 29, 2019, p. 4, https://www.congress.gov/116/meeting/house/110154/witnesses/HHRG-116-AS00-Wstate-FlournoyM-20191029.pdf; This scenario has been modeled in Mark F. Cancian, Matthew Cancian, and Eric Heginbotham, *The First Battle of the Next War: Wargaming a Chinese Invasion of Taiwan* (Washington, DC: Center for Strategic and International Studies, 2023), https://www.csis.org/analysis/first-battle-next-war-wargaming-chinese-invasion-taiwan; and Jordan Rosza, *Improving Standoff Bombing Capacity in the Face of Anti-Access Area Denial Threats* (Santa Monica, CA: RAND, 2015), pp. 32–42, https://www.rand.org/pubs/rgs_dissertations/RGSD363.html; A Taiwan invasion scenario is also used to assess U.S. PGM stocks in Stacie Pettyjohn and Hannah Dennis, *Precision and Posture: Defense Spending and the FY23 Budget Request* (Washington, DC: Center for New American Security, November 2022), https://www.cnas.org/publications/reports/precision-and-posture-defense-spending-tre.

79 Demetri Sevastopulo, "US Navy Chief Warns China Could Invade Taiwan before 2024," *Financial Times*, October 20, 2022, https://www.ft.com/content/1740a320-5dcb-4424-bfea-c1f22ecb87f7.

80 David Lague and Maryanne Murray, "T-DAY: The Battle for Taiwan," *Reuters*, November 5, 2021, https://www.reuters.com/investigates/special-report/taiwan-china-wargames/.

81 Much of the narrative and many assumptions in scenario 1 are drawn in part from Ian Easton's *The Chinese Invasion Threat*. See Ian Easton, *The Chinese Invasion Threat: Taiwan's Defense and America's Strategy in Asia* (Manchester: Eastbridge Books, 2019).

surrounding Taiwan, possibly to enact a blockade or soften Republic of China (ROC) forces with air and missile strikes. Should the United States choose to intervene, it would have a narrow window to attack massed invasion forces, potentially as little as one to three days.[82]

Scenario 1 – Neutralize Invasion Force in Taiwan Strait

- **Operational Objective:** Rapidly neutralize PLA invasion force in the Taiwan Strait to prevent large-scale amphibious landings on Taiwan.
- **Target Set:**
  - Eastern, Southern, and Northern Theater Navies (invasion escort and screening forces)
    - 247 surface combatants and attack submarines
  - 63 commercial transport ships and ferries
  - Eastern and Southern Theater Command aviation forces
    - Up to 750 fighter aircraft, 250 bombers/attack aircraft, 100+ special-purpose aircraft
- **Total Aimpoints:** 590+ maritime, 1,050+ aircraft
- **PGMs Required to Attack Complete Target Set:**
  - 600 – 2,400+ anti-ship munitions
  - 1,000 – 4,200+ anti-air or air-to-air munitions

The essential munitions in this scenario are anti-ship and anti-air missiles. The mobility of the vessels and aircraft in this target set necessitates munitions capable of tracking moving targets and/or receiving targeting updates in flight. Accurate and timely intelligence is necessary to feed these munitions and complete maritime kill chains. Moving ships also put a premium on weapon speed in this case, because slower munitions increase the time available for a target to move during the munition's flight. U.S. forces could wait for the invasion armada to anchor in preparation for disembarking forces and then attack using munitions designed for fixed targets, but doing so would shorten the time available for massing munitions in the target area and increase the risk that PLA forces successfully disembark and reach their landing areas.

Long-range weapons launched from outside the Strait would require some form of target identification and discrimination capability such as command guidance or automatic target recognition. The PLAN would likely attempt to protect invasion forces using a large number of decoys and countermeasures to distract and absorb U.S. anti-ship weapons. Even without dedicated decoys, hundreds of smaller support and landing vessels from the PLA Ground Force, Chinese Coast Guard, maritime militia, and civilian merchant fleet would crowd the Strait and act as clutter for incoming munitions to distinguish from targets.[83] These factors could push the P(i) for certain munitions in this case well above our 50 percent maximum. Even with advanced weapons, some U.S. platforms will likely need to approach PLA forces

82 Easton, *The Chinese Invasion Threat*, p. 112.

83 Conor M. Kennedy, "Getting There: Chinese Military and Civilian Sealift in a Cross-Strait Invasion," in *Crossing the Strait: China's Military Prepares for War with Taiwan*, ed. Joel Wuthnow, Derek Grossman, Phillip C. Saunders, Andrew Scobell, and Andrew N.D. Yang (Washington, DC: National Defense University Press, 2022), p. 224–243.

at much closer ranges to effectively employ their weapons.[84] U.S. forces could reduce total anti-ship missile requirements by attacking Chinese vessels with torpedoes from attack submarines, but these undersea forces carry a limited inventory of torpedoes to split between undersea and surface targets, would need to be supplemented by attacks from other domains, and would suffer attrition over the course of the campaign.[85]

A fundamental assumption of this scenario is that strikes on mainland China are prohibited because of the risk of further escalation. This restriction could come from U.S. political leadership or could be a condition from coalition partners such as Japan.[86] Although the United States may conduct a counter-invasion campaign with or without this restriction, CSBA included this assumption to create a point of comparison between this scenario and others that emphasize mainland targets. Because U.S. forces are unable to attack PLA A2/AD forces on the mainland in this scenario, U.S. delivery platforms would be forced to operate within range of many Chinese threats. This restriction would increase the need for penetrating delivery platforms or long-range munitions. Given the predominance of legacy, non-stealthy platforms in the current U.S. force structure, executing this campaign in the near future would favor the use of long-range munitions. In addition to being more costly, these munitions are typically larger and may have to be carried externally on strike aircraft. Externally carried munitions limit the ability of low observable aircraft to penetrate and operate in contested environments. Stealthy bombers, however, could carry such weapons internally.

Our analysis of Scenario 1 leads to two primary conclusions. First, because of the presence of Chinese A2/AD assets on the mainland, either U.S. delivery platforms, munitions, or both must be capable of penetrating layered enemy defenses. Furthermore, the possibility of encountering PLA combat air patrols (CAPs) and naval forces will require U.S. maritime and air forces to balance their offensive payloads with munitions for self-defense. ASCMs will compete for space on aircraft pylons, and strike munitions must be balanced with surface-to-air missiles in ships' vertical launch system (VLS) tubes. These constraints will further limit the number of munitions the United States can mass in the target area at any given time. As a result, a key variable is *how close* U.S. delivery platforms can operate to the Taiwan Strait—a variable that determines the necessary range of munitions and the rate at which delivery platforms can sortie, reach weapon launch points, and return and rearm.

Second, this scenario favors a large inventory of high-cost munitions due to target type, mobility, and the near-term need for weapons with stand-off ranges to equip non-stealthy

84 For example, U.S. attack submarines firing torpedoes. See Eric Heginbotham, Michael Nixon, Forrest E. Morgan, and Jacob L. Heim et al., *The U.S.–China Military Scorecard: Forces, Geography, and the Evolving Balance of Power, 1996–2017* (Santa Monica, CA: RAND, 2015), pp. 207-208, https://www.rand.org/pubs/research_reports/RR392.html.

85 Ibid., 206–214.

86 For an in-depth examination of the mainland strike issue, see John Speed Meyers, *Mainland Strikes and the U.S. Military Strategy Towards China: Historical Cases, Interviews, and Scenario-Based Survey of American National Security Elites* (Santa Monica, CA: RAND, 2019), https://www.rand.org/pubs/rgs_dissertations/RGSD430.html.

aircraft. This assessment is consistent with other wargames and studies.[87] Attacking PLA maritime and aviation forces in the Strait requires a very different set of munitions than attacking these forces on the ground or in port. Adequate stocks of exquisite and tailored weapons like stand-off penetrating ASCMs, however, could crowd out investments in munitions for other contingencies. For this reason, the U.S. military should continue exploring more cost-effective ways of conducting the maritime strike mission.[88]

Neutralize South China Sea Outposts

Scenario 2 features another rapid and limited campaign but in a different geographic area and with different types of targets. In the past decade, China has steadily improved and expanded its presence in the Paracel and Spratly Islands of the South China Sea through dredging and the construction of manmade islands.[89] In the event of a conflict, the United States might attack these outposts for several reasons. The facilities and weapons deployed on these manmade features allow the PLA to contest maritime and air traffic in the greater South China Sea, making the neutralization of these outposts essential for free navigation throughout the region. The bases and their airfields and harbors also serve as points from which the PLA can project power into the South China Sea and vital maritime chokepoints like the Strait of Malacca. Although this scenario would involve the Southern and Eastern

Scenario 2 – Neutralize South China Sea Outposts

- **Operational Objective:** Rapidly neutralize PLA outposts in the Paracel and Spratly islands to deny the PLA the ability to use these bases and features to project power or challenge freedom of navigation.
- **Target Set:**
  - Paracel Islands: major outpost and airfield on Woody Island; 7 smaller outposts
  - Spratly Islands: major outposts with airfields on Fiery Cross Reef, Mischief Reef, and Subi Reef; 4 smaller outposts
- **Total Aimpoints:** 530+, mostly fixed infrastructure
- **PGMs Required to Attack Complete Target Set:** 500 – 2,100+

87 For example, a wargame at the Center for Strategic and International Studies estimated that the U.S. military would need between 800 and 1,200 Long Range Anti-Ship Missiles (LRASMs) to blunt an invasion of Taiwan. More recent wargames found that "In the three to four weeks of [a Taiwan] conflict, U.S. forces usually expended about 5,000 long-range precision missiles, primarily JASSMs and LRASMs." Patrick Tucker and Jacqueline Feldscher, "As China, Taiwan Tensions Flare, US Faces Shrinking Window to Deter Conflict," *Defense One*, August 8, 2022, https://www.defenseone.com/threats/2022/08/china-taiwan-tensions-flare-us-faces-shrinking-window-deter-conflict/375514/; and Cancian, Cancian, and Heginbotham, *The First Battle of the Next War*, p. 136.

88 For instance, through programs such as the High Altitude Anti-Submarine Warfare Weapon Capability (HAAWC). See Joseph Trevithick, "Navy P-8 Poseidon Can Now Drop Winged Torpedoes In Combat (Updated)," *The Drive*, November 22, 2022, https://www.thedrive.com/the-war-zone/navy-p-8-poseidon-can-now-drop-winged-torpedos-in-combat.

89 For a detailed analysis of China's progress, see Asia Maritime Transparency Initiative, "China Island Tracker," Center for Strategic and International Studies, https://amti.csis.org/island-tracker/china/.

fleets of the PLAN, Chinese surface combatants and aviation forces are not included in this scenario because their munitions requirements would be largely similar to those in scenario 1. Some or all of the targets described in the previous scenario should be added to this case to form a realistic assessment.

The munitions required to neutralize these outposts are minimal compared to other scenarios because the targets are fixed, close to one other, and are some distance from the Chinese mainland. The airfields, harbors, radars, and other military infrastructure on these island outposts are fixed targets that can easily be attacked with more common GPS-guided munitions. Air defense TELs, radars, and coastal missile units on these features may be mobile, but the small size of the islands limits their ability to move and hide. The number of munitions required to neutralize these outposts depend largely on how thoroughly the U.S. military strikes large area targets like airfields and harbors and if these targets require periodic reattack. Given the limited resources on these artificial islands, it may be more difficult for the PLA to quickly repair these bases compared to those on the mainland.

The close proximity of these outposts to one another and the proximity of targets on each feature favor the use of weapons capable of providing effects over a large area. For example, munitions that can neutralize several sensors or destroy a large number of parked aircraft could reduce the total number of weapons required to attack this clustered target set. Closely situated targets on these islands are ideal for attack by collaborative munitions.

Although the types of weapons needed to attack PLAN and PLAAF forces in the vicinity of these outposts are similar to scenario 1, the increased distance of these island groups from mainland China reduces the need for anti-ship and anti-air weapons with the same stand-off range. The South China Sea would allow U.S. delivery platforms to operate closer to their targets, particularly after the limited defenses on the artificial islands are neutralized. At that point, the need for stand-off weapons or penetrating platforms would be determined by the presence of PLAN and PLAAF assets in the area.

Overall, attacking PLA outposts in the South China Sea presents a less difficult munitions problem than other scenarios. This case is more akin to previous regional and limited strike campaigns than other great power conflict scenarios, albeit with a strong maritime flavor. Of course, this contingency is unlikely to be executed alone and might be combined with one or more of the other four campaigns, particularly attacking a portion of the naval and air forces described in scenario 1. Even so, this case shows how the location of the target set in the Indo-Pacific matters for munitions planners. Campaigns away from the mainland and the Taiwan Strait—even only as far as the Paracel Islands—reduce the need for penetrating and long-range munitions. The location of these features also increases the number of potential basing and deployment locations for sea- and ground-based weapons in the theater.

Counter-C4ISR Campaign

Shifting to cases with mainland targets, Scenario 3 involves a campaign in which the United States might try to narrow its focus to a specific type of target. Rather than attempting to destroy PLA forces or basing, the U.S. military could aim to "blind" the PLA by attacking its C4ISR infrastructure.[90] A counter-C4ISR campaign could be a response to Chinese attacks on U.S. forces in the Indo-Pacific. The United States would attempt to degrade the battle networks necessary for PLA A2/AD assets in order to protect U.S. forces in the region from further attacks and enable offensive strikes. Reducing the PLA's ISR capabilities could also force it to hold its rocket and missile inventories until they regain connectivity or expend these limited weapons on "shots in the dark" without adequate targeting intelligence. Additionally, attacking the sensing, communications, and C2 infrastructure of a centralized military such as the PLA could induce some level of "force paralysis" as PLA leaders attempt to regain connectivity, reestablish situational awareness, and make informed decisions about their next moves. In this way, a counter-C4ISR campaign could buy additional time for decisionmakers, demonstrate U.S. capabilities, and enable the United States to regain the initiative after a Chinese attack.

Of course, attacking certain C4ISR targets carries a risk of escalation, particularly if these C4ISR nodes are intertwined with China's nuclear command, control, and communications (NC3) architecture. At worst, Beijing might interpret a counter-C4ISR campaign as an attempt to decapitate the regime or destroy China's nuclear deterrence, although recent analysis suggests that as China builds its nuclear forces and gains a secure strategic deterrent, U.S. leaders could be less inhibited from targeting dual-use platforms and infrastructure.[91] Should the United States want to limit this risk, certain targets in the Beijing region or Central Theater Command could be excluded. This change would slightly modify the geography of the target set, but the munitions requirements in this scenario remain largely unchanged.

Scenario 3 – Counter-C4ISR Campaign

- **Operational Objective:** Rapidly degrade PLA sensing, communications, and C2 capabilities to cause "force paralysis" among units in the Eastern and Southern Theater Commands.
- **Target Set:**
  - Select Central Military Commission (CMC), Theater Command, and Joint headquarters
  - Counter-space, satellite monitoring, and communications facilities
  - Over-the-horizon (OTH) radar sites and submarine communication stations
  - C2 infrastructure at select airfields and naval bases
  - Communications, radar, and other sensor sites in Eastern and Southern theater commands
- **Total Aimpoints:** 2,800+
- **PGMs Required to Attack Complete Target Set:** 2,800 – 10,700+ for initial strikes

90 Many aspects of this scenario are drawn from the blinding campaign detailed in *AirSea Battle*. See van Tol with Gunzinger, Krepinevich, and Thomas, *AirSea Battle*, pp. 56–64.

91 Evan Braden Montgomery and Toshi Yoshihara, "The Real Challenge of China's Nuclear Modernization," *The Washington Quarterly* 45, no. 4, pp. 45–60, https://bpb-us-e1.wpmucdn.com/blogs.gwu.edu/dist/1/2181/files/2022/12/MontgomeryYoshihara_TWQ_45-4.pdf.

A counter-C4ISR campaign would emphasize munitions or platforms capable of deeply penetrating enemy territory to destroy vital C4ISR nodes. Many headquarters, space, long-range sensor, and communication nodes are located in areas with dense, layered defenses. Even if early warning sensors along coastal areas or en route to these deep targets are disabled, air and missile defenses may still independently target delivery platforms and incoming PGMs. With a limited number of penetrating long-range strike platforms in the near-term, this scenario favors exquisite long-range weapons, which we refer to as "silver bullets." These silver bullets will need some combination of stealth, speed, or other survivability features to reach these high-value nodes. Some munitions may also need to be capable of destroying hardened or deeply buried targets (HDBTs) such as underground command posts or hardened communications facilities, but the demands of these targets may require penetrating delivery platforms carrying specialized munitions with short ranges. These targets will require a significant intelligence effort before and during the conflict to identify, probe, and confirm the locations and significance of specific elements of the PLA's C4ISR architecture.

Still, the sheer number of radar and other early warning sensors in coastal areas necessitates a volume of less sophisticated and potentially shorter-range munitions. Depending on the quantity of exquisite and stand-off munitions available, some suppression of enemy defenses may be required to enable low observable (LO) aircraft to penetrate contested airspace and deliver shorter-range munitions. These suppression efforts might not entail the destruction of large quantities of missile launchers themselves but could instead focus on keeping TELs mobile or hidden and sensors from emitting.[92]

A counter-C4ISR campaign would also benefit from non-kinetic weapons with area effects. Many sensors and nodes are located in coastal areas and clustered around key installations. U.S. strike forces could blind certain sensors with non-kinetic payloads in order to attack vital headquarters and facilities with kinetic munitions. Non-kinetic weapons with area effects would reduce the number of aimpoints, particularly in areas with dense clusters of radars and communications arrays. This campaign could also be paired with offensive cyber capabilities. If the effects of these weapons are temporary or of limited duration, however, then these targets would require reattack and consume additional munitions.

Strike Campaign Against Conventional Bases

Moving beyond C4ISR nodes, Scenario 4 involves attacking PLA air and maritime forces and bases in eastern and southern China. Unlike Scenario 1, in which restrictions against striking the Chinese mainland necessitate targeting PLA forces in the air and underway at sea, this case focuses on destroying PLA forces on the ground and in port. Neutralizing air

92 Much like in Operation Allied Force, the threat of attack by U.S. SEAD efforts could prevent PLA air defense systems from operating effectively. This is an example of *virtual attrition*, a concept that will be further examined in Chapter Five.

and naval bases in these regions would seriously degrade the PLA's ability to contest U.S. forces operating in the Taiwan Strait, South China Sea, and East China Sea. This contingency more closely reflects a traditional comprehensive strike campaign such as the Desert Storm air war, although on a much larger scale.

This scenario focuses on fixed basing, headquarters, and known logistics and air defense sites. Attacking the mobile radars and TELs of air defense batteries and ballistic and cruise missile forces would greatly increase munitions requirements beyond our estimate. Depending on the PLA's posture at the time of the conflict, these forces could include over 270 SAM launchers, up to 700 theater-range ballistic missile TELs, and over 120 ground-launched cruise missile launchers.[93] This case also excludes the basing and units of the PLA Ground Force (PLAGF) because we do not anticipate a major ground engagement on the Chinese mainland. However, these forces could also be added to this scenario to prevent their use in an invasion of Taiwan.[94]

Scenario 4 – Strike Campaign Against Conventional Bases

- **Operational Objective:** Neutralize PLA air and maritime bases and A2/AD forces in eastern and southern China to enable follow-on operations in vicinity of the Taiwan Strait.
- **Target Set:**
  - Major Theater Command headquarters of the PLAN, PLAAF, PLARF
  - Airfields, naval bases, and rocket brigade bases in eastern and southern China
  - Long-range air defense sites in eastern and southern China
  - Key logistics nodes in eastern and southern China
- **Total Aimpoints:** 5,700+, many recurring targets
- **PGMs Required to Attack Complete Target Set:** 5,700 – 23,000+ for initial strikes only

A strike campaign against enemy basing, even limited to air and maritime forces in these regions, would require a significant volume of weapons. Desert Storm and Iraqi Freedom targeted around 40,000 and 20,000 aimpoints, respectively, in a target area smaller than a single Chinese theater command. The munitions required in this case are highly sensitive to several variables. First, the effectiveness of PLA air and missile defenses would determine the quantity of munitions required to attack each aimpoint and could double, triple, or even quadruple the total quantity of PGMs required.[95] These defenses would also affect

93 *Military and Security Developments Involving the People's Republic of China 2022: Annual Report to Congress* (Washington, DC: Department of Defense, 2022), p. 167, https://media.defense.gov/2022/Nov/29/2003122279/-1/-1/1/2022-MILITARY-AND-SECURITY-DEVELOPMENTS-INVOLVING-THE-PEOPLES-REPUBLIC-OF-CHINA.PDF; and Andrew S. Erickson, Ryan D. Martinson, and Peter A. Dutton, *China's Near Seas Combat Capabilities* (Newport, RI: Naval War College Press, February 2014), p. 5, https://digital-commons.usnwc.edu/cgi/viewcontent.cgi?article=1010&context=cmsi-red-books.

94 The PLAGF and PLAN Marine Corps have over 50 brigades spread throughout bases in the Eastern and Southern Theater Commands. These targets would be unique as mobile maneuver forces and would add thousands of additional aimpoints to this scenario. *Military and Security Developments Involving the People's Republic of China 2022*, p. 165.

95 Assuming a probability of intercept between ten and 50 percent. See Figure 36 in Appendix B.

the distance at which U.S. strike platforms would be able to launch their munitions and, as a result, the stand-off requirements for PGMs.

Second, munitions quantities are dependent on the depth of the target set that must be attacked to achieve the case's operational objective. Our estimate accounts for over 20 naval bases and 50 airbases of varying sizes. If the United States can determine which bases are crucial to PLA operations in the region, however, it could reduce the number of aimpoints by limiting its attacks to these key installations. Conversely, we ignored non-military airports in our target set, but PLA dispersal to civil airports would increase the demands of this case. This case also assumes that neutralizing these bases involves a combination of cutting runways, disabling docks and berths, and striking hangars and aircraft shelters. Focusing on just one of these methods could reduce munitions requirements, while seeking more comprehensive destruction would increase quantities beyond our estimates.[96]

Third, the duration of the conflict plays heavily in this scenario because many of the targets would be repaired and require reattack to prevent their use. This variable depends on the efficiency of PLA ordnance disposal and engineering assets and the degree of destruction wrought by initial U.S. strikes. Keeping these airfields and naval bases disabled could require reattacks in intervals as short as four to eight hours.[97] In any case, the sheer quantity of targets in this scenario requires munitions that can be massed on complex targets. The targets consuming the most munitions in this case are airfields and naval bases, so efficiently disabling these installations is key to determining munitions requirements.

Finally, if finding and destroying ground forces such as air defense TELs and PLARF launchers is included in this scenario, munitions requirements quickly balloon and shift the focus from fixed to mobile targets. Speed, specialized sensors, and datalinks become essential munition attributes. Current stand-off weapons would be less useful against these targets because of their mobility. In this case, a campaign against these forces would require the addition of many munitions similar to those demanded by scenario 1, albeit with land attack weapons with potentially smaller payloads than large anti-ship cruise missiles.

Force Regeneration Campaign

With a campaign targeting conventional forces and bases requiring an immense quantity of munitions, particularly in a protracted conflict, how could the United States avoid the operational problem of keeping PLA airfields and naval bases shut down for days or weeks? One solution could be a campaign that focuses on force regeneration assets and the PLA's ability to sustain its forces.

96 For example, attacking aircraft parked on large aprons or infrastructure distributed in the vicinity of the bases like fuel and munitions storage facilities would increase munitions quantities beyond our estimates.

97 This estimate is based off RAND's modeling of U.S. attacks on Chinese air bases using cruise missiles and freefall bombs. See Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.-China Military Scorecard*, p. 143.

Scenario 5 is a campaign focused on degrading the PLA's military capabilities in the long-term. This campaign could be pursued if a conflict becomes prolonged or devolves into a war of attrition. Rather than attacking repairable and recurring targets, this case focuses on neutralizing military production and industrial facilities that would be more difficult to repair.[98] For this reason, such a campaign could lead to a sustained operational pause, negotiation, or conflict termination.

Scenario 5 – Force Regeneration Campaign

- **Operational Objective:** Degrade the PLA's ability to sustain and regenerate the forces required for a protracted conflict with the United States.
- **Target Set:**
  - Defense production facilities such as aerospace factories and shipyards
  - Defense research and space facilities
  - Petroleum, oil, and lubricant (POL) infrastructure such as crude oil terminals and refineries
- **Total Aimpoints:** 6,400+
- **PGMs Required to Attack Complete Target Set:** 6,400 – 26,000+

Much like a counter-C4ISR campaign, this case requires munitions or platforms that can deeply penetrate heavily defended Chinese territory. The key difference, however, is that many weapons in a force regeneration campaign must be capable of destroying large, complex targets spread over a wide area, such as factories and shipyards. While a counter-C4ISR campaign necessitates "silver bullet" PGMs, a force regeneration campaign would benefit from stand-off weapons with area effects or penetrating aircraft carrying large volumes of shorter-range munitions.

Force regeneration targets are more geographically dispersed throughout China than the bases examined in the previous scenario, which were primarily limited to eastern and southern China. Unlike military installations, defense production facilities and POL infrastructure are less likely to be protected by a multitude of point air defenses, reducing the need for survivable munitions.

Finally, unlike a campaign that targets military bases, many of these industrial targets are unlikely to require reattacks at short intervals. Production facilities and petroleum infrastructure could be difficult to repair and may interrupt supplies to PLA forces, particularly if kinetic conflict is combined with trade sanctions.[99] A well-executed force regeneration campaign could cripple the PLA's ability to engage in a protracted conflict and could lead to negotiations or conflict termination.

98 The military nature of the targets considered in this scenario differentiate it from a campaign that counter-value campaign that targets civilian infrastructure, such as that being carried out by Russia in Ukraine. The United States has targeted petroleum infrastructure in previous operations. See Mark Thompson, "U.S. Bombing of ISIS Oil Facilities Showing Progress," *Time*, December 13, 2015, https://time.com/4145903/islamic-state-oil-syria/.

99 The limited attack on Saudi oil facilities by drones in 2019 caused fires that interrupted the supply of an estimated 5.7 million barrels of oil. *BBC*, "Saudi Oil Attacks: Images Show Detail of Damage," September 16, 2019, https://www.bbc.com/news/world-middle-east-49718975.

Key Tradeoffs and Common Requirements

These five notional campaigns reveal some key differences and similarities in the munitions required for each case. These differences and similarities are notable as either strategic choices or low-hanging fruit for munitions planners.

Key Tradeoffs Between Scenarios

The varying target sets and their geographic locations and attributes highlight the need for a specific category or type of munition in each case.

Summary of Munitions Focuses in Each Scenario

1. **Neutralize Invasion Force in Taiwan Strait:** Long-range ASCMs and anti-air missiles
2. **Neutralize South China Sea Outposts:** Short-range munitions with area effects
3. **Counter-C4ISR Campaign:** "Silver bullets," specialized, and non-kinetic munitions
4. **Campaign Against Conventional Basing:** Large volumes of varied munitions for fixed/mobile targets
5. **Force Regeneration Campaign:** Munitions for large, complex targets

These varied focuses are the results of several major variables. **Most obviously, the geographic location and dispersion of the targets determine the range and survivability requirements for platforms and munitions in each case.** Targets on China's periphery do not require the same stand-off range and/or survivability as targets deep within the layered defenses of the mainland. This difference is particularly relevant in the Indo-Pacific, where the theater's vast maritime character also limits basing options and increases the distance that delivery platforms must travel before releasing their weapons. Deeper targets that require munitions to fly through multiple layers of PLA defenses increase the chances that a weapon is successfully intercepted and expand the demands placed on munitions and platforms.

Accordingly, the target's location is also a key determinant of the degree to which PLA A2/AD systems must be suppressed. **Deep targets increase the number of mobile A2/AD platforms that must be targeted in some form, which affects the second key variable: the proportion of mobile versus fixed targets.** Mobile targets in these cases are often elusive and require specialized munitions and intensive ISR efforts to destroy. The sensors and intelligent munitions needed for these targets go well beyond the precision provided by many of today's common GPS-guided PGMs. Thus, the degree to which U.S. forces hunt and attack highly-mobile targets to enable a strike campaign is one key operational decision for planners concerned with the adequacy of munitions stocks.

A third variable driving munition demands is the proportion of recurring targets versus targets requiring a single attack. While maneuver targets like naval vessels or vulnerable targets like SATCOM facilities may only require a single salvo

to permanently destroy, recurring targets are either easily repairable, such as cratered runways, or require persistent effects, such as sensors affected by temporary non-kinetic effects. Using these examples, the need to re-crater runways or continuously blind sensors can rapidly multiply the quantity of munitions expended in prolonged scenarios. For this reason, pursuing objectives that necessitate the prosecution of a large quantity of recurring targets is a second key operational decision for military staffs, particularly when protracted conflict is likely.

These variables combine to illustrate the major tradeoff between the five scenarios: the quantity of *exquisite* munitions required versus the need for a large volume of simpler munitions. We use the term *exquisite* to refer to weapons with long-range, penetration and survivability features, and advanced sensors and payloads. Rapid contingencies like those imagined in scenarios 1 and 3 favor larger stocks of exquisite munitions. Protracted conflicts like scenarios 4 and 5 require exquisite munitions but also demand an immense volume of effects over a prolonged duration. The range, speed, and cost tradeoffs identified in Chapter Two still apply to future great power conflict. Campaign and munitions inventory planners must balance these competing demands for survivable platforms and weapons with the ability to mass less complex weapons in volume.

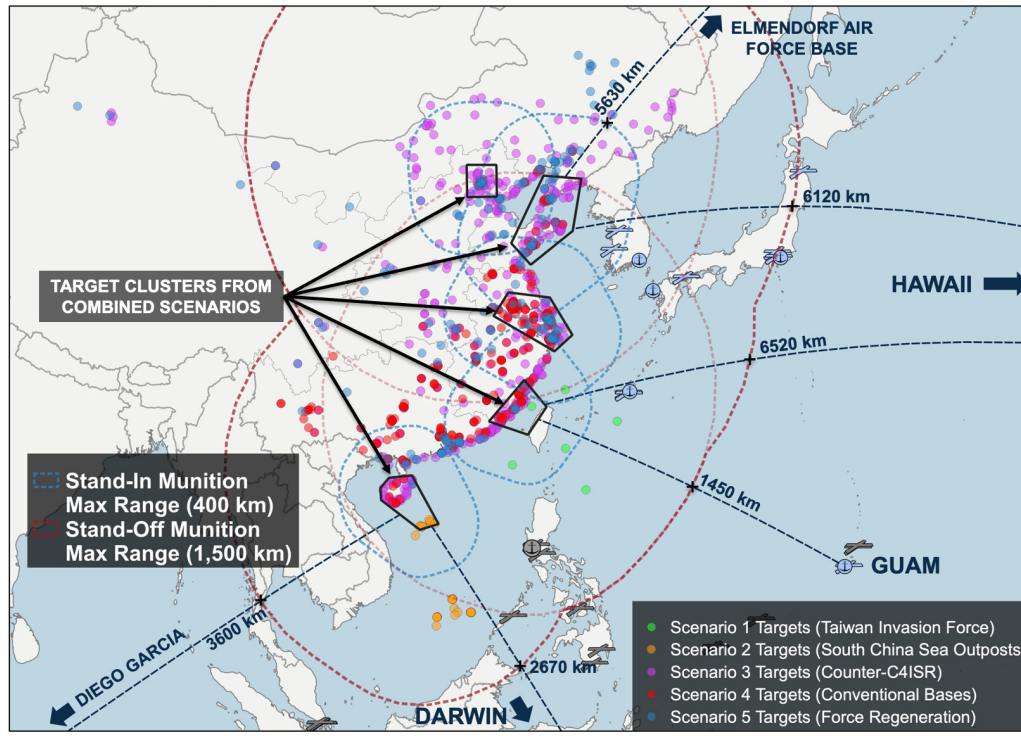
Common Requirements Across Scenarios

Despite the large differences between each case, several commonalities are also apparent and could be capitalized on by decision makers seeking to prepare U.S. munitions stocks for great power conflict. **First, almost every scenario requires a significant quantity of munitions with some degree of stand-off range to avoid putting delivery platforms at high risk from A2/AD threats.** Direct attack munitions have limited uses in the opening stages of a great power conflict. For weapons fired from naval vessels, ranges beyond 400 km allow ships to strike coastal targets while remaining outside the range of many Chinese land-based ASCMs.[100] Chinese air and missile defense systems put a premium on air-delivered munitions with ranges greater than 200 km, while those with ranges around 1,000 km allow tactical aircraft to deliver them from a variety of basing and aircraft carrier locations in the Indo-Pacific. In addition to these long-range munitions, many of the scenarios require a large quantity of munitions with ranges around or above 50 km, just adequate to keep delivery platforms from being targeted by point defenses. While penetrating aircraft and SEAD efforts may allow delivery platforms to operate in airspace contested by long-range SAM systems, avoiding the point defenses of heavily defended targets like airfields and headquarters will require these shorter-range "stand-in" munitions in large volumes. Therefore, a key tradeoff for campaign planners is the decision to attack targets using legacy platforms carrying survivable stand-off munitions or penetrating platforms carrying shorter-range, less complex weapons.

100 Even at 400 km from the Chinese mainland, naval vessels would still be subject to a variety of threats ranging from anti-ship ballistic missiles to PLA combat air patrols carrying ASCMs.

Figure 10 overlays each scenario's targets along with the maximum range launch points for stand-in (400 km) and stand-off (1,500 km) weapons. Also shown are the distances from these maximum range launch points to U.S. and allied basing in Alaska, Hawaii, Guam, Darwin, and Diego Garcia.

FIGURE 10: MUNITIONS RANGE REQUIREMENTS ACROSS FIVE INDO-PACIFIC CONFLICT SCENARIOS



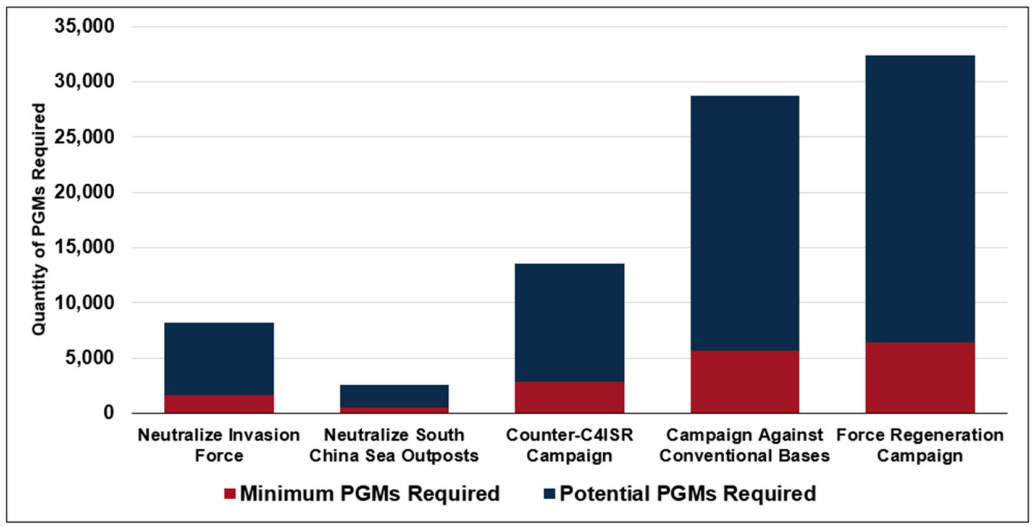
Source: Created by CSBA. See Appendix B for target maps and analysis of each scenario.

Each scenario, including those in the Taiwan Strait and South China Sea, involves striking targets protected by several layers of air and missile defense. Particularly in cases that attack targets on mainland China, the sheer number of mobile area and point defenses makes destroying significant numbers of these assets a munitions-intensive objective. **With at least some of these defenses likely to survive, PGMs in these cases must be capable of penetrating PLA air and missile defenses.** Longer-range munitions that will spend more time in contested airspace must be more survivable than shorter-range weapons with shorter and simpler flight paths. Survivability could come in many forms, including speed, stealth, hardening, or other countermeasures, and should be tailored to each weapon's range, flight profile, and intended role.

Third, all scenarios require some degree of capability to attack significant quantities of mobile targets, whether they be PLA air and maritime forces or mobile air defense and rocket TELs. Contesting PLA forces away from their fixed bases requires munitions with the sensors and data links required to locate, track, and defeat moving targets. Even in scenarios with entirely fixed target sets, such as a force regeneration campaign, U.S. platforms may have to defend themselves against mobile PLA forces. This requirement goes beyond the capabilities of many GPS-guided PGMs and will require munitions capable of more than just precision. Additionally, this requirement puts a premium on weapons with onboard sensors that can semi-autonomously complete their own kill chains with limited external targeting and intelligence support.

Finally, most of the campaigns feature complex area targets such as airfields, naval bases, production facilities, and refineries. These targets have many aimpoints and thus require a volume of PGMs to strike specific vulnerabilities or destroy key infrastructure. Efficiently targeting and attacking these facilities is essential to controlling munitions requirements. Striking these targets requires exact intelligence about vulnerabilities and single points of failure, such as control rooms or power supplies.[101] Alternatively, future munitions could be tailored to attack these targets using more efficient methods or area effects.

FIGURE 11: SUMMARY OF PGM REQUIREMENTS ACROSS FIVE INDO-PACIFIC CONFLICT SCENARIOS (INITIAL STRIKES ONLY)



Source: These figures include only initial strikes and do not account for additional strikes against recurring targets that are repaired or rebuilt during a campaign.

101 Such as the target elements identified in Rosza, *Improving Standoff Bombing Capacity in the Face of Anti-Access Area Denial Threats*, p. 42.

...

Clearly, no single "ideal mix" exists across these five scenarios. Each case's unique objective and targets lead to a different munitions focus. This exercise shows how determining and prioritizing likely scenarios and their parameters in advance is essential to developing and procuring the right mix of weapons. Still, the analysis in this chapter further reinforces the conclusions of Chapter Two: to succeed in a contemporary great power conflict, the United States needs immense quantities of munitions, including both exquisite and intelligent weapons. But procuring large numbers of fast, penetrating stand-off weapons leads to a high cost per effect and risks putting the United States on the wrong side of the cost imposition ratio *vis-à-vis* China. Preparing for great power conflict might ultimately force the U.S. military to find ways to turn the tables by pursuing weapons that flip this ratio. With these insights in mind, the following chapter will assess the current U.S. munitions portfolio and industrial base against the demands identified in this chapter.

CHAPTER 4

Assessing Current Munitions Gaps and Constraints

The historical and illustrative analyses of Chapters Two and Three highlighted a range of critical munitions requirements for contemporary great power conflict. But how does the current U.S. PGM portfolio stack up to these demands? Will stocks of current weapons and those fielded in the near future be sufficient for the kinds of scenarios explored in the previous chapter?

This chapter seeks to answer these questions by assessing current and developmental American PGMs against these requirements. Our evaluation reveals several major capacity and capability gaps in the U.S. precision-strike arsenal, along with the most pressing constraints on munitions development and production that prevent the United States from quickly correcting these gaps.

The Current U.S. Precision-Guided Munition Portfolio

Examining U.S. munitions inventories involves two preliminary steps: selecting the munitions relevant to our analysis and determining how to organize and categorize these weapons for comparison. Beginning with selecting relevant munitions, we excluded PGMs with limited applicability to our great power conflict scenarios. These programs included weapons confined to close ground engagements, such as short-range anti-tank guided missiles or artillery shells, and specialty munitions stocked in small quantities or out of production.[102] Due to the offensive and maritime nature of our scenarios, we also did not consider exclusively ground-based SAMs such as the Patriot and Terminal High Altitude Area Defense (THAAD) missiles and ballistic missile defense (BMD) weapons such as the

102 Some examples of munitions excluded for these purposes include: GBU-43/B Massive Ordnance Air Blast (MOAB, produced in small quantities), M982 *Excalibur*, FGM-148 *Javelin*, and various small loitering munitions utilized by ground forces and Special Operations Command (SOCOM).

SM-3 missile. We also excluded undersea weapons such as torpedoes and mines, which are more difficult to fit into the categories of analysis used below. These munitions would be vital in several of our scenarios, however, and represent an opportunity for further study.[103] Finally, we excluded munitions developed or currently procured only by U.S. allies, such as the Joint Strike Missile (JSM).[104] Although these weapons may be future purchases or play a role in future conflicts, they are not currently programs of the U.S. DoD. These criteria left a portfolio of 36 PGMs for examination.

Next, we classified or "bucketed" these munitions into categories for comparison. Traditional methods of categorizing and describing weapons, or munitions taxonomies, include range, flight profile, target type, or launch platform. As Chapter Three's analysis illustrated, today's conflict scenarios demand munitions with a multitude of specific attributes beyond "long-range," "short-range," "air-delivered," or "anti-ship" weapons. These requirements render the simplistic single-category taxonomies used in most munitions analyses insufficient.[105]

Accordingly, this chapter assesses munitions according to several characteristics. We primarily organize munitions by range, because range is a key factor in pairing weapons with delivery platforms and assigning these pairs to targets. As Chapter Three showed, Indo-Pacific geography and PLA defenses put a premium on long-range, survivable weapon-platform pairs. We use range descriptors relative to the Chinese threat (shown in Figure 12) because the reach of PLA air and missile defenses plays an important role in determining viable weapon launch points for U.S. delivery platforms and, in turn, necessary stand-off and stand-in munition ranges.[106] These range categories are less applicable to air-to-air missiles and defensive weapons like SAMs, but help compare the various strike weapons vital in our scenarios.

Much of the current U.S. military force structure, which is comprised of legacy, non-penetrating platforms, require survivable stand-off munitions to strike targets while remaining outside the reach of adversary A2/AD systems. Penetrating platforms, on the other hand, can advance further into contested territory to deliver shorter-range, less complex

103 For a brief discussion of undersea weapons, see Bryan Clark, Peter Haynes, Bryan McGrath, and Craig Hooper et al., *Restoring American Seapower: A New Fleet Architecture for the United States Navy* (Washington, DC: Center for Strategic and Budgetary Assessments, 2017), pp. 89–90, https://csbaonline.org/research/publications/restoring-american-seapower-a-new-fleet-architecture-for-the-united-states-.

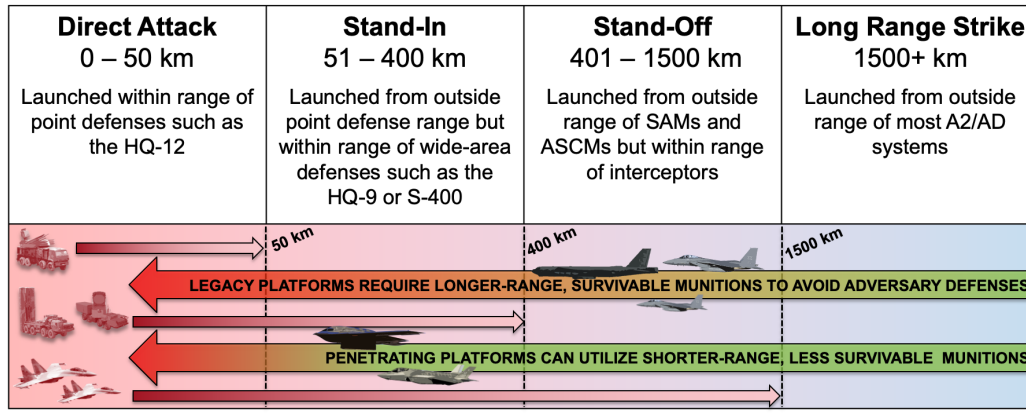
104 This study considers weapons through the fiscal year 2023 DoD budget. The U.S. Air Force has since requested procurement funding for the Joint Strike Missile in its fiscal year 2024 budget request.

105 For a thorough exploration of the inadequacy of current munitions taxonomies and an example new taxonomy, see Tyler Hacker and Christopher Bassler, "A New Munitions Taxonomy: Categorizing Advanced Weapons for Robust Analysis and Artificial Intelligence Assisted Applications" (paper presented at the 16th NATO Operations Research and Analysis Conference, Copenhagen, Denmark, 18 October 2022).

106 Many other analyses utilize the same or similar terms and range buckets. For other examples, see Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, pp. 6-7; Mark A. Gunzinger, "Affordable Mass: The Need for a Cost-Effective PGM Mix for Great Power Conflict," *Mitchell Institute for Aerospace Studies*, November 2021, p. 4, https://mitchellaerospacepower.org/wp-content/uploads/2021/11/Affordable_Mass_Policy_Paper_31-FINAL.pdf; and Pettyjohn and Dennis, *Precision and Posture*, p. 6.

munitions. This relationship is illustrated in Figure 12. Given the tradeoff between range and cost, this allows penetrating platforms to economically deliver larger payloads of short-range munitions—a key capability when massing a large quantity of effects is essential. This trade between platform and munition range will be further explored below, but is particularly important to consider as the United States fields significant numbers of long-range, penetrating strike platforms in the 2030s.

FIGURE 12: MUNITION RANGE CATEGORIES FOR THE CURRENT THREAT ENVIRONMENT



Source: Created by CSBA.

These range categories are likely to be relevant to the Indo-Pacific theater for the foreseeable future, although the PLA will undoubtedly continue to push the range of their A2/AD systems as far out from the mainland as possible. Major advancements in PLA capability will require an adjustment of these range categories. Beyond range, we examined munitions using the previously identified attributes essential for great power conflict: speed and survivability, guidance system, payload, and advanced features like networking, datalinks, and autonomous capabilities. We sought to compare weapons across a broad range of characteristics that affect their suitability and employment for contemporary great power conflict.

Combining our selection criteria and categorization yields Table 2, which contains the 36 current and developmental U.S. PGMs applicable to our analysis, organized by range. Weapons still in development are shaded in grey. Appendix C contains a table of all characteristics used to inform this chapter's analysis. The following assessment of U.S. PGM capacity and capability gaps is based on this set of munition programs.

TABLE 2: CURRENT AND DEVELOPMENTAL U.S. PGM PORTFOLIO BY RANGE

Direct Attack > 50 km	**Stand-In** 51 – 400 km	**Stand-Off** 401 – 1,500 km	**Long-Range Strike** 1,500+ km
Laser-guided bombs (LGB)	**RIM-162 ESSM** (Evolved Sea Sparrow Missile)	**HACM** (Hypersonic Attack Cruise Missile)	**BGM-109 *Tomahawk*** (all variants)
JDAM (Joint Direct Attack Munition)	**GMLRS** (Guided Multiple Launch Rocket System)	**AGM-183 ARRW** (Air-Launched Rapid Response Weapon)	**AGM-158D JASSM-XR** (Extreme Range)
CBU-105 Sensor Fuzed Weapon (SFW)	**GBU-53/B *StormBreaker***	**HALO** (Hypersonic Air-Launch Offensive anti-surface warfare)	**Long-Range Hypersonic Weapon** (LRHW)
GBU-57A/B Massive Ordnance Penetrator (MOP)	**AGM-154 JSOW** (Joint Standoff Weapon)	**Precision Strike Missile** (PrSM)	**Conventional Prompt Strike** (CPS)
AGM-114 *Hellfire*	**GBU-39/B SDB** (Small Diameter Bomb)	**AGM-158C LRASM** (Long Range Anti-Ship Missile)	
JAGM (Joint Air-to-Ground Missile)	**AGM-88E AARGM** (Advanced Anti-Radiation Guided Missile)	**ADM-160 MALD** (Miniature Air-Launched Decoy)	
AIM-9X *Sidewinder*	**GMLRS-ER** (Extended Range)	**AGM-158B JASSM-ER** (Extended Range)	
	SiAW (Stand-in Attack Weapon)		
	AGM-88G AARGM-ER (Extended Range)		
	AIM-120D AMRAAM (Advanced Medium-Range Air-to-Air Missile)		
	AIM-260 JATM (Joint Advanced Tactical Missile)		
	NSM (Naval Strike Missile)		
	RGM/AGM/UGM-84 *Harpoon*		
	SM-6		
	AGM-84H/K SLAM-ER (Standoff Land Attack Missile Expanded Response)		
	MGM-140 ATACMS (Army Tactical Missile System)		
	AGM-158A JASSM (Joint Air-to-Surface Standoff Missile)		
	SM-2		

Source: See Appendix C.

Major Munitions Gaps

An assessment of the munitions listed in Table 2 against the requirements outlined in Chapter Three exposes several key capacity and capability gaps in the American arsenal.

Overall Capacity

The most apparent inadequacy revealed by U.S. munitions expenditures over the past three decades and our analysis of potential conflict in the Indo-Pacific is that the United States does not currently maintain stocks of PGMs sufficient to sustain a protracted great power conflict (see figures 13 and 16 in the proceeding pages). How long U.S. PGM stocks would last in an Indo-Pacific contingency is dependent on the variables identified in Chapter Three, namely conflict objectives, intensity, and the effectiveness of Chinese defenses. Although exact munitions inventory quantities are classified, it is clear that if the U.S. military endangered its PGM stocks during low-intensity campaigns like those in Iraq and Syria, it would struggle to sustain a prolonged precision-strike campaign against a great power. Scenarios that target enemy bases could demand tens of thousands of PGMs for an initial salvo of strikes alone. These expenditures would compound rapidly as the conflict continues and adversary basing and infrastructure is repaired or replaced. Expanding the conflict beyond eastern and southern China or the widespread targeting of mobile forces would only further increase the need for immense quantities of PGMs.

Even if the United States procures sufficient weapons to sustain a rapid high-intensity conflict in the Indo-Pacific, it must ensure it has the capacity to maintain reserves of PGMs for other contingencies that may arise simultaneously. This requirement is set in the 2022 *National Defense Strategy*, which states, "In a potential conflict with a competitor, the United States would need to be able to deter opportunistic aggression by another competitor."[107] Expending conventional munition reserves in one theater risks leaving nuclear weapons as the only remaining deterrent against other adversaries. Moreover, munitions stocks and the U.S. industrial base must also sustain the needs of many allies and partners that are likely to participate in these conflicts. Therefore, the U.S. weapons industrial base must be robust enough to support U.S. needs in multiple theaters as well as the needs of U.S. allies and partners in these theaters.

This PGM capacity gap has two dimensions. First, the United States must have sufficient inventories on-hand to support (or deter) a rapid, intense conflict or to sustain the opening acts of a prolonged conflict. Of course, should a rapid contingency not lead to conflict termination, American stocks must support the transition to a prolonged conflict, whether that be a matter of weeks or, more likely, months. Weapons must not only be bought, maintained,

107 *2022 National Defense Strategy of the United States* (Washington, DC: Department of Defense, 2022), p. 12, https://media.defense.gov/2022/Oct/27/2003103845/-1/-1/1/2022-NATIONAL-DEFENSE-STRATEGY-NPR-MDR.PDF.

and upgraded, but must also be stored or prepositioned in locations that enable their rapid employment.

The degree to which recent strike campaigns have stressed U.S. stocks gives reason to doubt the sufficiency of short-range PGM inventories. With more complex weapons such as the JASSM, procurement documents reveal the inadequacy of American inventories. Despite the JASSM being the U.S. military's premier air-launched stand-off cruise missile, it purchased only 3,243 missiles between FY2010 and FY2021.[108] Disregarding the number of JASSMs expended during operations in the Middle East, this quantity appears inadequate when compared to the requirements identified in the previous chapter. A campaign that strikes a modest portion of targets in the South China Sea, our least demanding scenario, could consume over half of these cruise missiles depending on stand-off requirements. Should conflict continue or escalate, the U.S. military might find itself running dangerously low on these crucial weapons in a matter of days. In terms of bomber sorties, 3,243 JASSMs would only fill bomb bays for 135 B-1 or 162 B-52 sorties.[109] With other analysis suggesting that the U.S. Air Force could realistically generate 30 or fewer bomber sorties per day, this inventory of JASSMs could be expended in less than a week of sustained long-range strike operations.[110] Bringing tactical aircraft into the mix, U.S. fighters conducted an average of 674 strike sorties per day during Operation Iraqi Freedom.[111] At this rate, even if each fighter carried only a single missile per sortie, fighter aircraft could expend all 3,243 JASSMs in under five days. An examination of U.S. budget documents paints a similar picture of on-hand inventories for other U.S. PGMs as well.

The second component of total munition capacity is production capacity. The United States must have the ability to expand its munitions production rates rapidly in the event of a protracted great power conflict. Even if enormous munitions stocks were fiscally viable, a high-intensity conflict with a duration measured in months is likely to consume hundreds of thousands of weapons. For the United States and its adversaries, the conflict will eventually shift to a war of production.

The constraints posed by today's munitions industrial base and its capacity will be further discussed below, but again, historical production rates tell a concerning story. Between FY2000 and FY2021, the United States procured an average of 209 *Tomahawk* cruise

108 Data gathered from U.S. Air Force budget documents and John R. Hoehn, *Precision-Guided Munitions: Background and Issues for Congress* (Washington, DC: Congressional Research Service, June 11, 2021), https://sgp.fas.org/crs/weapons/R45996.pdf.

109 The B-1B can carry 24 JASSMs and the B-52H can carry 20 JASSMs per sortie. The B-2 can carry 16 JASSMs per sortie.

110 This sortie rate considers total bomber inventory as well as typical mission-capable rates. It excludes the need to keep some nuclear-capable bombers supporting nuclear deterrence missions. See Mark Gunzinger, *Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces* (Arlington, VA: Mitchell Institute for Aerospace Studies, 2020), p. 17, https://mitchellaerospacepower.org/long-range-strike-resetting-the-balance-of-stand-in-and-stand-off-forces/.

111 U.S. fighter aircraft executed 20,228 strike sorties over a 30 day period. Robert S. Dudney, "The Gulf War II Air Campaign, by the Numbers," *Air Force Magazine*, July 2003, p. 37, https://www.airandspaceforces.com/PDF/MagazineArchive/Magazine%20Documents/2003/July%202003/0703Numbers.pdf.

missiles per year.[112] In Iraqi Freedom, the U.S. military expended 802 *Tomahawks* in 30 days.[113] At an average consumption rate of 27 missiles per day, a single year of *Tomahawk* production at previous levels would only supply enough cruise missiles for just over a week of sustained strike operations. Although it is unlikely that operations would continue at this intensity for multiple months, repeated Russian missile barrages in Ukraine have highlighted the need for numerous periods of high-volume strikes in a single year of protracted war.[114] As we will explore in the next section and recent demands for *Javelin* and *Stinger* missiles have revealed, these production rates cannot be quickly scaled in the event of a conflict. PGM inventories and surge production capacity must be maintained at the level required for great power conflict if the U.S. military is to be prepared for a war in the Indo-Pacific.

These inventory and industrial capacity increases will come at a cost. With limited resources, long-term strategy and analysis are key to buying the right weapons as the United States moves to remedy these gaps. Because capacity will always be limited, the United States must also seek new methods of maximizing the effectiveness of its munitions and enabling the rapid manufacturing of large quantities of weapons. The U.S. military must buy weapons and employ them in ways that allow it to achieve its objectives in an efficient manner—ultimately more efficiently than the PLA can defend against these munitions.

Range

Beyond total capacity, the United States' current portfolio of PGMs and delivery platforms lacks the range ideal for the Indo-Pacific theater. The geography of the scenarios examined in Chapter Three revealed a need for weapons and platforms with ranges adequate to transit the vast distances between theater basing and potential weapon launch points. Because of the predominance of non-stealthy, legacy delivery platforms in today's forces, a campaign in the Indo-Pacific demands weapons with ranges well beyond the reaches of Chinese combat air patrols and other A2/AD systems, as well as PGMs capable of striking targets deep in Chinese territory. In the words of the Defense Science Board, "If the U.S. wishes to be able to dissuade, deter, or if necessary, deny such actions [as a blockade of Taiwan or navigation restrictions in the South China Sea] using military force, it will need the ability to

112 Based on data in Hoehn, *Precision-Guided Munitions: Background and Issues for Congress*.

113 See Table 2 or Appendix A.

114 U.S. defense officials estimated that Russia fired over 2,100 missiles as of May 10, 2022. Russian forces fired additional salvos of up to 75 missiles at a time in October, November, and December 2022. Tara Copp, "Russia has Fired Between '10 and 12' Hypersonics into Ukraine, Pentagon Says," *Defense One*, May 10, 2022, https://www.defenseone.com/threats/2022/05/russia-has-fired-between-10-and-12-hypersonics-ukraine-pentagon-says/366748/; and Andrew E. Kramer, "Russian Missile Barrage Staggers Ukraine's Air Defenses," *New York Times*, December 29, 2022, https://www.nytimes.com/2022/12/29/world/europe/russia-strikes-ukraine.html.

achieve decisive military [victory] from a range outside of the adversary A2/AD reach."[115] The requirement for survivable combinations of stand-off munitions and penetrating delivery platforms will only increase as the PLA fields more advanced SAMs, ASCMs, and anti-ship ballistic missiles (ASBMs) and expands further into the Indo-Pacific.[116] Every base and outpost outside the mainland that hosts A2/AD systems expands the Chinese threat bubble and increases the need for long-range munitions and penetrating delivery platforms.[117]

Currently, however, the majority of U.S. PGMs in service have ranges well below 400 km, with only the *Tomahawk* reaching beyond 1,500 km. For naval platforms like attack submarines and destroyers, the TLAM has sufficient range and will see its versatility expand further with the introduction of a maritime strike capability in future Block V missiles.[118] Below the TLAM, however, there is a gap in offensive naval weapons with ranges between the *Tomahawk* and the 250 km *Harpoon*.[119] The *Harpoon*'s short range impedes the Navy's ability to conduct distributed maritime operations by forcing naval commanders to concentrate ships to mass fires.[120]

The ranges of U.S. air-delivered munitions present more distinct limitations. Although long-range bombers have the endurance to fly from distant bases to weapon launch points near mainland China, the majority of the U.S. Air Force's bomber fleet consists of non-stealthy B-52s and B-1s.[121] The threat presented by PLA air defenses means these non-stealthy bombers still require munitions with stand-off ranges to be effective. As the United States fields the B-21, a long-range penetrating bomber, the need for large quantities of stand-off

115 Office of the Under Secretary of Defense for Acquisition, Technology, and Logistics, *Report of the Defense Science Board: Study on Countering Anti-access Systems with Longer Range Standoff Capabilities: Assault Breaker II* (Washington, DC: Department of Defense, June 2018), p. 10, https://dsb.cto.mil/reports/2010s/LRE%20Executive%20Summary__Final.pdf.

116 For example, the eventual Chinese procurement of systems like the Russian S-500 could increase the threat to U.S. delivery platforms by a few hundred kilometers. See *Missile Threat*, "S-500 Prometheus," Center for Strategic and International Studies, July 1, 2021, https://missilethreat.csis.org/defsys/s-500-prometheus/.

117 For a look at China's overseas ambitions, see Toshi Yoshihara and Jack Bianchi, *Seizing on Weakness: Allied Strategy for Competing with China's Globalizing Military* (Washington, DC: Center for Strategic and Budgetary Assessments, 2021), ch. 4–6, https://csbaonline.org/research/publications/seizing-on-weakness-allied-strategy-for-competing-with-chinas-globalizing-military.

118 Mallory Shelbourne, "Raytheon Awarded $217M Tomahawk Missiles Contract for Navy, Marines, Army," *USNI News*, May 25, 2022, https://news.usni.org/2022/05/25/raytheon-awarded-217m-tomahawk-missiles-contract-for-navy-marines-army.

119 See Figure 26 in Appendix B for an illustration of this gap in a Taiwan invasion scenario.

120 Dmitry Filipoff, "Fighting DMO: Pt. 2: Anti-Ship Firepower and the Major Limits of the American Naval Arsenal," *Center for International Maritime Security*, February 27, 2023, https://cimsec.org/fighting-dmo-pt-2-anti-ship-firepower-and-the-major-limits-of-the-american-naval-arsenal/.

121 As of 2020, the U.S. Air Force operated 138 B-52s and B-1s and only 20 penetrating B-2 bombers. Gunzinger, *Long-Range Strike: Resetting the Balance of Stand-in and Stand-off*, p. 3.

munitions will be reduced.[122] Long-range penetrating strike platforms like the B-21 will grow the need for large volumes of stand-in munitions. Operating from distant bases increases sortie transit time and decreases the mass that U.S. strike forces can achieve at any given time, which could inherently prolong campaigns intended to be rapid such as countering a Taiwan invasion.[123] Fighter aircraft require munitions with extended ranges just to reach weapon release points from air bases in the Indo-Pacific theater, which are sparse and distant in many scenarios.[124] Like its bomber fleet, the U.S. military's fighter inventory is still predominately non-stealthy, further increasing the need for stand-off and long-range munitions in the near term.

Even with the fielding of larger numbers of penetrating aircraft, such as the F-35 and B-21 bomber, stand-in and stand-off weapons help planners maximize the capability of low-observable aircraft. Commander of Air Combat Command (ACC) General Mark Kelly explained, "We [take] a lot of bang out of our low-observable force because we push them into ranges where everyone [including stealth aircraft] is observable."[125] Tactical stealth aircraft require munitions that fit in their internal weapons bays to maintain their penetrating capability, which currently limits them to smaller glide munitions like the Small Diameter Bomb series and the JSOW. The fielding of the SiAW and AARGM-ER will help remedy this gap, but both possess stand-in ranges.

Ground-based strike munitions are currently the most range deficient. The GMLRS and ATACMS are wholly inadequate for remote island launch locations in the Indo-Pacific theater.[126] The Army's introduction of the Precision Strike Missile, Mid-Range Capability (consisting of the SM-6 and *Tomahawk*), and the Long-Range Hypersonic Weapon will start to close this gap but will be limited in quantity for some years to come.

Beyond the variety of long-range PGMs, the total quantity of long-range munitions available is also lacking. Figure 13 displays the historic imbalance between the procurement of short versus long-range weapons over the previous two decades. Spending on stand-in and stand-off munitions has been increasing in recent defense budgets, but at an insufficient

122 For a deeper exploration of how the B-21's fielding will affect Air Force capabilities, see Christopher J. Bowie, *Air Power Metamorphosis: Rethinking Air Force Combat Force Modernization* (Washington, DC: Center for Strategic and Budgetary Assessments, 2023), https://csbaonline.org/research/publications/air-power-metamorphosis-rethinking-air-force-combat-force-modernization.

123 For a visual depiction of how the Air Force's capability to provide a volume of effects decreases with the range aircraft must fly, see Figure 1-1 in *Alternatives for Long-Range Ground-Attack Systems* (Washington, DC: Congressional Budget Office, 2006), p. 6, https://www.cbo.gov/sites/default/files/109th-congress-2005-2006/reports/03-31-strikeforce.pdf.

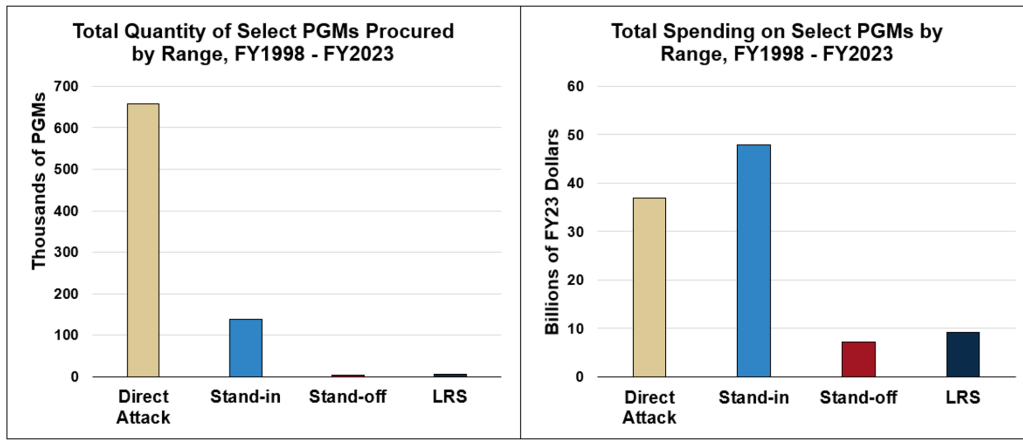
124 Figures 26, 29, 32, 35, and 38 in Appendix B illustrate these distances for each great power conflict scenario.

125 Quoted in John A. Tirpak, "New Longer-Range Missiles Needed to Preserve Stealth Advantages," *Air & Space Forces Magazine*, September 23, 2021, https://www.airandspaceforces.com/new-longer-range-missiles-needed-to-preserve-stealth-advantages/.

126 For a comparison of U.S., Chinese, and Russian ground-based missile ranges and an analysis of potential launch locations for ground-based missiles in the Indo-Pacific, see Edelman, Bassler, Yoshihara, and Hacker, *Rings of Fire,* p. 11-23.

rate. The U.S. military simply needs more munitions with ranges beyond those of existing direct attack weapons. Many great power conflict scenarios demand not only long-range munitions, but also those with stand-in ranges to equip penetrating aircraft. Procurement of these stand-in weapons has increased significantly in recent years, but the United States requires large quantities of these weapons in order to provide a sufficient volume of effects in a modern strike campaign.[127]

FIGURE 13: SELECT PGM PROCUREMENT QUANTITIES AND COSTS, FY1998 TO FY2021



Source: Created by CSBA using data from DoD budget documents and Selected Acquisition Reports (SARs) from FY1998 to FY2023.

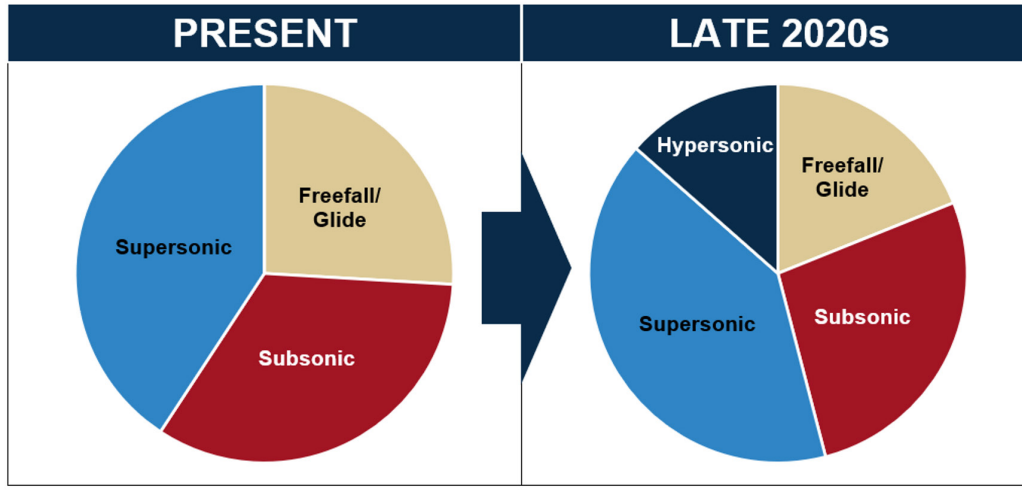
Survivability

Not only do many current U.S. PGMs lack adequate range for the Indo-Pacific, but they also are not survivable against the defenses of a great power adversary. The previous chapter illustrated the outsized effect of the probability of intercept on munitions requirements for a given target set. Still, a large portion of current U.S. PGMs are freefall, glide, and subsonic cruise weapons that can be intercepted by low-cost air defense systems.[128] Many long-range American cruise missiles incorporate stealth characteristics, but stealth and speed are only two facets of survivability. PGMs must also be hardened against specific capabilities of great power adversaries such as electronic warfare and future directed energy (DE) weapons. The classification of survivability features and countermeasures prevents us from assessing the true survivability of many American weapons, but these features are vital for future PGMs.

127 A variety of studies and officials support a robust mix of stand-in and stand-off weapons, including former Air Force Chief of Staff General David Goldfein. See Mark Gunzinger, "Stand In, Standoff," *Air & Space Forces Magazine*, July 1, 2020, https://www.airandspaceforces.com/article/stand-in-standoff/.

128 For example, gun- and cannon-based air defense vehicles such as the Type 95 and Type 09 self-propelled anti-aircraft vehicles. Ukraine has reportedly used similar German *Gepard* vehicles to intercept Russian cruise missiles and drones. Dan Parsons, "Ukraine Situation Report: More German Gepard Air Defense Gun Systems On The Way," *The Drive*, December 2, 2022, https://www.thedrive.com/the-war-zone/ukraine-situation-report-more-german-gepard-air-defense-gun-systems-on-the-way.

FIGURE 14: QUANTITY OF U.S. PGM PROGRAMS BY SPEED



Source: Created by CSBA.

Guidance Without External Support

Despite the need to operate in highly contested environments, many of America's PGMs, particularly those with ranges below 400 km, are reliant on some form of external guidance to hit their targets accurately. External support includes GPS signals and other space-based communications support or laser designation by aircraft or ground forces. These outside guidance enablers are vulnerable to interference, particularly in the heavily defended environments of modern high-intensity conflict. Moreover, these requirements can place delivery platforms at risk as they "paint" targets with laser energy or find targets with their sensor pods before utilizing GPS-guided munitions. Even if GPS-guided munitions are launched from a distance at pre-assigned coordinates, they still require a significant third-party targeting effort to determine and refine these aimpoints. The planning efforts needed to support such large target sets may overwhelm the U.S. military's current targeting cycle, which struggled to keep up with the demands of limited campaigns like Inherent Resolve.[129]

The U.S. military possesses a limited number of munitions capable of completing their own kill chains and providing precision effects without outside support. Although many stand-off and long-range strike weapons carry onboard sensors, most stand-in and direct attack PGMs do not. Stand-in munitions with multi-mode sensors and automatic target recognition, such as the GBU-53/B *StormBreaker,* are a step in the right direction. Still, much of the U.S. arsenal remains incapable of self-guidance, increasing the risk to munitions and their

129 Stacie L. Pettyjohn and Becca Wasser, "From Forever Wars to Great-Power Wars: Lessons Learned From Operation Inherent Resolve," *War on the Rocks*, August 20, 2021, https://warontherocks.com/2021/08/from-forever-wars-to-great-power-wars-lessons-learned-from-operation-inherent-resolve/.

delivery platforms, generating enormous targeting support requirements, and limiting the use of these weapons against targets of opportunity.

Munitions for Time Sensitive and Mobile A2/AD Targets

Self-guidance is also an important piece of another existing capability gap: munitions that find, track, and attack mobile and elusive A2/AD targets such as air defenses, ASCM launchers, and PLA Rocket Force TELs. Despite the difficulties encountered by U.S. forces in the Gulf War and Kosovo, the United States' selection of munitions suitable for this task has not changed significantly, and weapons like the AGM-88E AARGM cannot be internally carried by penetrating aircraft like the F-35.[130] The number of potential mobile targets in a conflict, however, has steadily risen.

Although mobile and elusive targets are one of the most challenging munitions tasks, attacking these targets is ultimately a layered problem, with munitions constituting one crucial piece of the kill chain. Mobile targets first require some form of persistent ISR to find and track them as they expose themselves. Once detected, a delivery platform must be within striking range at the time of target detection. Given the speed with which modern mobile targets can tear down and displace, the proximity of the delivery platform is particularly vital. This requirement lends advantages to penetrating aircraft and persistent platforms such as attack submarines and ground-launched fires. The final link in the mobile target kill chain is typically the munition, which must deliver its payload before the target moves or be capable of tracking the target and striking it on the move. For this reason, these munitions benefit from features like high speeds, which reduce flight time, and loitering, which allow the weapon to search for and track moving targets. They also require onboard sensors to provide this tracking and terminal guidance or features such as datalinks to receive targeting updates from external sources. Mobile targets may demand certain kinds of sensors, such as active radar seeking or anti-radiation homing. Ultimately, multiple types of munitions are capable of performing this mission, but they must be matched and integrated with other ISR and delivery elements to create a kill chain (or *force packages*) optimized for mobile and elusive targets.

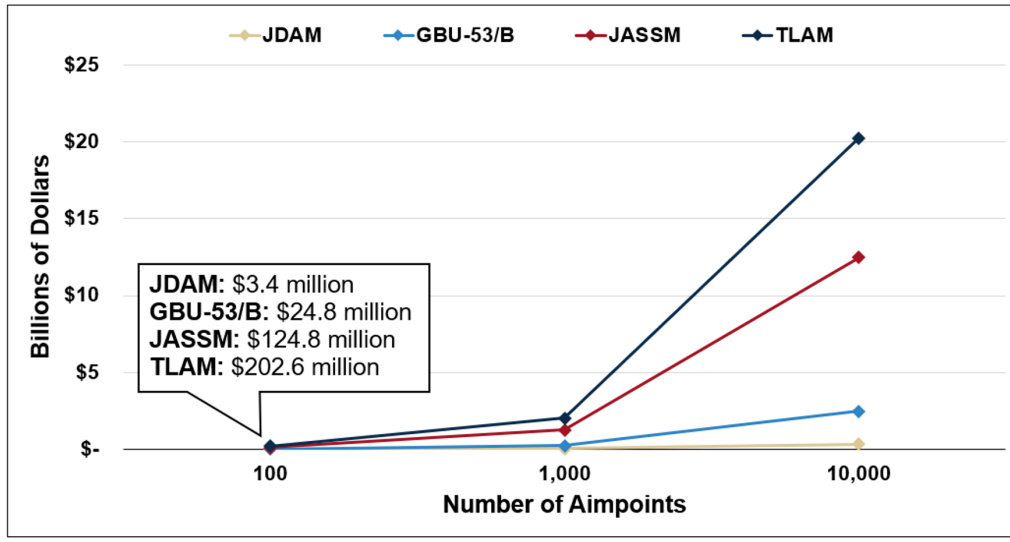
Ideally, the U.S. PGM arsenal would contain two primary groups of counter-A2/AD munitions: long-range varieties able to "kick in the door" during the opening stages of a conflict, and shorter-range weapons that fit into the bays of penetrating aircraft like the F-35. These shorter-range PGMs should be inexpensive enough to be employed in volume without imposing unaffordable costs.

130 For internal carry, this leaves the F-35 reliant on subsonic glide weapons for attacking these targets. The AARGM-ER and SiAW will alleviate this issue, but have not yet been fielded. Joseph Trevithick and Tyler Rogoway, "Navy Orders Development of New Air Defense Blasting Missile That Will Fit Inside F-35," *The Drive*, June 30, 2019, https://www.thedrive.com/the-war-zone/17947/navy-orders-development-of-new-air-defense-blasting-missile-that-will-fit-inside-f-35; and Joseph Trevithick, "Navy To Test Ground-Launched Version Of New Radar-Busting Missile," *The Drive*, February 17, 2023, https://www.thedrive.com/the-war-zone/navy-to-test-ground-launched-version-of-new-radar-busting-missile.

Affordable Mass

PGMs that allow the United States to mass effects while maintaining an acceptable cost imposition ratio are another key capability gap in the current U.S. PGM portfolio. Great power conflict could require the U.S. military to strike tens of thousands of aimpoints, particularly in dense target areas and around complex targets such as airfields, shipyards, and production facilities. As shown in Figure 15, many current PGMs are simply too costly and exquisite to be employed in volume, particularly in a prolonged conflict. Some direct attack weapons, such as the JDAM, are less expensive but lack the range and other features ideal for a contingency in the Indo-Pacific. Moreover, the inventories of even simple PGMs like the JDAM have been exposed as insufficient by recent operations in the Middle East.

FIGURE 15: COST OF STRIKING A FIXED QUANTITY OF AIMPOINTS USING THE JDAM, GBU-53/B, JASSM, AND TLAM



Source: Created by CSBA. Unit costs are averages based on FY1998 to FY2023 procurement costs.

The U.S. military could pursue affordable precision in mass through several means, some of which will be discussed in the next chapter. The fielding of greater numbers of penetrating platforms will help enable the affordable massing of PGMs by allowing the use of less expensive, shorter-range munitions. The design of future weapons can also help U.S. forces achieve precision in mass. The majority of current PGMs are unitary weapons able to provide effects on only a single aimpoint. Future PGMs could fill this gap by providing precision effects on multiple aimpoints, which would decrease munitions requirements and the cost per aimpoint. These weapons must balance the advanced features ideal for great power conflict (range, speed, survivability, etc.) with the affordability and producibility that allows for production, procurement, and expenditure in large volumes.

Low Versatility

The current U.S. PGM inventory lacks flexibility in two important facets: launch platform versatility and weapon-target pairing. Many of the weapons in Table 2 can only be delivered by platforms in a single domain. The current situation is the natural result of each military service developing and buying munitions for its own air, sea, and ground platforms. Some joint programs, such as the Common Hypersonic Glide Body, aim to improve the versatility of U.S. munitions and their components, but the U.S. military largely lacks munitions employable from a wide variety of launch platforms. Other nations, such as Sweden, stock weapons like the RBS-15 ASCM that can be launched from naval ships, aircraft, and ground-based coastal defense systems. Russia utilizes the 3M-54 *Kalibr* cruise missile, which includes variants fired by submarines, ships, aircraft, and container-based launchers. Certain restrictions like the dimensions of weapons bays and launchers naturally limit weapon versatility, but the United States should move toward munitions capable of being carried by a wider range of launch platforms. Current efforts to field ground-based launchers for the NSM, *Tomahawk*, and SM-6 are steps in the right direction. It appears that further experimentation in this realm is ongoing, with the Navy set to demonstrate a ground-launched AARGM-ER and the U.S. government providing Ukraine with ground-launched Small Diameter Bombs.[131]

The second area in which U.S. PGMs lack versatility is in weapon-target pairing. Many PGMs are designed with a specific mission or target in mind. For example, the *Harpoon* and NSM are optimized for attacking ships, and the AGM-88 HARM was developed to hunt enemy radars. These munitions have been modified over decades to increase their versatility, but these new variants are typically separate munitions and not interchangeable with their parents.[132] The United States lacks stand-off PGMs capable of attacking a wide range of targets.[133] Like launch platforms, encouraging progress in weapon-target versatility is being made with weapons such as the SM-6, an anti-air missile now tested as an anti-ballistic missile, anti-ship, and land attack weapon.[134]

Increasing the versatility of the U.S. munitions portfolio would go a long way toward easing the munitions problem. If a weapon can attack more than one kind of target or be carried by a variety of platforms, then it can fulfill multiple requirements and decrease the number of tradeoffs and choices that planners must address. Versatility reduces the optimization

131 Of course, joint programs run the risk of being slowed by the multitude of different service requirements. These delays were evident in the development and subsequent cancellation of the AGM-137 Tri-Service Standoff Attack Missile (TSSAM). Joseph Trevithick, "Navy To Test Ground-Launched Version Of New Radar-Busting Missile;" and Joe Gould, "US pledges longer-range 'small-diameter bomb' for Ukraine," *Defense News*, February 3, 2023, https://www.defensenews.com/pentagon/2023/02/03/us-pledges-longer-range-small-diameter-bomb-for-ukraine/.

132 For example, the *Harpoon* was used a base for the SLAM, and the HARM has evolved into the AARGM.

133 The fielding of the Block V *Tomahawk* and maritime-strike variants of the PrSM will eventually reduce this gap.

134 David Axe, "The U.S. Navy Finally Has A Universal Missile—And That Means More Firepower For War With China," *Forbes*, April 29, 2021, https://www.forbes.com/sites/davidaxe/2021/04/29/the-us-navy-finally-has-a-universal-missile-and-that-means-more-firepower-for-war-with-china/?sh=725444ac1830.

problem and allows policymakers to assume less risk in preparing for a broad range of conflict scenarios. More flexible weapons could also decrease the costs of developing separate programs and building and maintaining independent production lines, as well as decrease the costs of maintaining separate fleets of specialized munitions that may only be employed in particular scenarios.

Munitions for Specialized Targets

Although versatility is key to solving the current capacity gap, the U.S. inventory lacks some specific capabilities demanded by great power conflict. Maintaining small quantities of these specialized weapons would lower the risk presented by certain scenarios. Many of these specialty munitions could also provide particular effects more efficiently than more general PGMs. By stocking a limited number of these weapons, the U.S. military could avoid expending large quantities of more generic munitions.

One such group of weapons are those designed for attacking hardened and deeply buried targets (HDBTs) such as command posts, headquarters facilities, and communications nodes. Current long-range strike munitions struggle to penetrate and destroy these targets efficiently.[135] "Bunker busting" weapons such as the GBU-57B MOP are heavy direct attack weapons that put the limited number of penetrating bombers at risk. The United States requires better munitions for attacking these targets, particularly weapons able to be carried by a wider range of platforms and, ideally, employed from standoff ranges.[136]

Weapons ideal for destroying wide area targets like maneuver forces, production facilities, or aircraft parked on runway aprons constitute another capability gap. Unitary precision weapons like the JDAM are inadequate for these large targets and certain pinpoint targets.[137] Relying on large numbers of unitary munitions also increases the demand for delivery platforms with large payloads, which could further stress the limited fleet of U.S. bombers. Legacy cluster munitions, traditionally used on many of these targets, are being phased out of U.S. inventories.[138] Efforts such as the GMLRS Alternative Warhead and the Next Generation Area Attack Weapon could fill some of the gap left by older cluster munitions,

135 This shortfall has long been noted by defense analysts. See, for example, Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, "Report of the Defense Science Board Task Force on Future Strategic Strike Forces," February 2004, p. 6-3, https://dsb.cto.mil/reports/2000s/ADA421606.pdf; and Russell J. Hart, Jr., "Defeating Hard and Deeply Buried Targets in 2035," Air University, Air War College, February 15, 2012, https://apps.dtic.mil/sti/pdfs/AD1018630.pdf.

136 The need for heavy munitions with large explosive payloads makes attacking these targets difficult with stand-off weapons. The next chapter will explore technologies that may reduce the physical challenges of this problem.

137 Very small targets or moving targets may be unaffected by a JDAM which "hits" within its CEP. Wilson, *A Time-Critical Targeting Roadmap* pp. 23–24.

138 As of 2017, DoD policy directs the military services to "program for capabilities to replace cluster munitions currently in active inventories" and "only procure cluster munitions containing submunitions or submunition warheads that do not result in more than one percent unexploded ordnance." Deputy Secretary of Defense, "DoD Policy on Cluster Munitions," November 30, 2017, p. 2, https://man.fas.org/eprint/cluster.pdf.

but the U.S. military lacks a replacement for aging weapons like the CBU-105 that are optimized for destroying dispersed armored formations and air defense batteries.[139] As the next chapter will explore, technology is quickly making the tradeoff between precision and area effects a false choice. The U.S. military should capitalize on new technology to field PGMs suitable for defeating area targets.

Finally, the United States lacks weapons dedicated to neutralizing airfields. Though there are many ways to disable airbases, the U.S. military has previously "cut" runways using a series of craters produced by unitary PGMs. The United States does not currently field a dedicated precision-guided anti-runway munition, and instead relies on direct attack PGMs or cruise missiles with delay fuzes to produce craters.[140] Neutralizing runways requires significant quantities of these weapons, particularly if these targets require periodic reattack to keep disabled. The United States should consider various weapons and concepts that could accomplish this task more efficiently from ranges that do not require the delivery platform to fly directly over the target. The U.S. military should also consider the value of time-delayed weapons to disrupt adversary ordnance removal and repair processes.

Non-Kinetic Options

The only publicly revealed PGMs dedicated to delivering offensive non-kinetic effects are the MALD and minimal numbers of the Counter-Electronics High Power Microwave Advanced Missile Project (CHAMP).[141] It remains unclear what non-kinetic effects other cruise missiles and advanced PGMs can produce in addition to their kinetic payloads. Due to their cost and power requirements, electronic warfare and other non-kinetic effects have traditionally been mostly limited to being employed by delivery platforms like the EA-18G *Growler*. However, many targets in our great power conflict scenarios could be attacked more efficiently (or less provocatively) through non-kinetic effects. For example, a blinding campaign that requires neutralizing many sensors and networks would benefit from U.S. PGMs that could employ non-kinetic effects over a wide area or an extended period.

139 While the CBU-105 disperses BLU-108 submunitions that utilize sensors to seek and attack vehicles using explosively formed penetrators, many efforts to replace cluster munitions attempt to provide effects through blast and fragmentation. Ryan Pickrell, "The Air Force is testing a new fragmenting alternative to cluster bombs," *Task & Purpose*, September 3, 2020, https://taskandpurpose.com/news/air-force-blu-136-next-generation-area-attack-weapon-cluster-bomb-testing/.

140 The U.S. Air Force has utilized the BLU-107/B *Durandal* anti-runway bomb in previous conflicts, but this weapon is unguided and must be released at low altitudes.

141 The U.S. military is currently testing a potential successor to the CHAMP program called the High-Powered Joint Electromagnetic Non-Kinetic Strike (HiJENKS). John Keller, "Air Force deploys B-52 missiles that could disable enemy military electronics with high-power microwaves," *Military & Aerospace Electronics*, May 17, 2019, https://www.militaryaerospace.com/rf-analog/article/14033453/air-force-deploys-b52-missiles-that-could-disable-enemy-military-electronics-with-highpower-microwaves; and Inder Singh Bisht, "USAF, Navy Concluding Five-Year Microwave Weapon Test," *The Defense Post*, July 12, 2022, https://www.thedefensepost.com/2022/07/12/usaf-navy-microwave-weapon-test/.

Constraints on PGM Development, Production, and Procurement

If the current U.S. arsenal suffers from these capacity and capability gaps, then what are the primary barriers to closing these gaps? This section outlines a few of the major constraints that future munitions programs must confront.

Budget

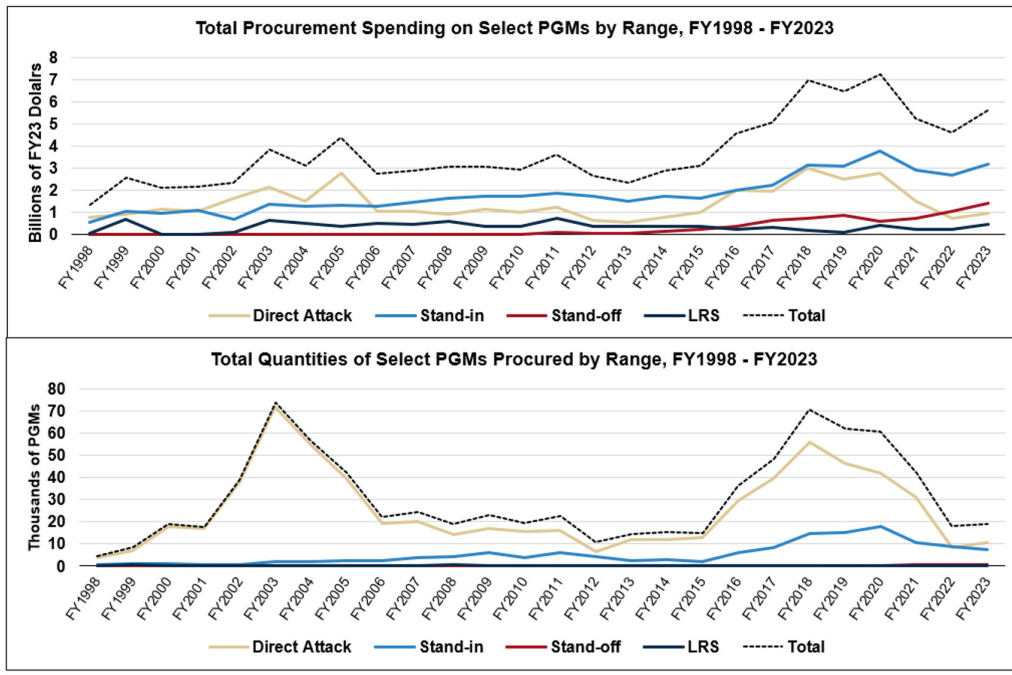
The primary constraint limiting the procurement of PGMs for great power conflict is budgetary. Estimates of DoD's total spending on munitions and PGMs vary based on the programs and accounts considered.[142] CSBA estimated total DoD spending on PGMs by totaling the procurement funding allotted for the programs included in Table 2. The Department requested a sum of $5.6 billion across these 36 PGM programs in fiscal year 2023, down from the $6.5 to $7.2 billion highs of FY2018 to FY2020. DoD's FY2023 request for these PGMs represents just 0.72 percent of DoD's total requested funding and less than 4 percent of requested procurement funding.[143]

Regardless of exactly how much the U.S. military is spending to buy PGMs, one limitation is clear from DoD's annual budget requests: munitions spending remains directly tied to operational usage rather than long-term strategy or analysis. When the United States expends large quantities of PGMs, DoD buys more in the following years to replenish stocks. Irrespective of its expectations of future contingencies, however, DoD spending on PGMs drops in subsequent years, presumably as stocks are replenished. This trend is illustrated in Figure 16, which shows how munitions spending increases in the wake of each conflict before falling again. This trend is especially displayed by increased spending on direct attack and stand-in munitions from FY2016 to FY2020 to replenish weapons expended during Operation Inherent Resolve.

142 For example, DoD's FY2023 budget request includes $24.7 billion for "missiles & munitions," which includes procurement and research, development, test, and evaluation (RDT&E) funding for small-arms ammunition and strategic weapons. The Center for New American Security assessed DoD's FY2023 request for "key conventional PGMs" as $5.7 billion. Office of the Under Secretary of Defense (Comptroller)/Chief Financial Officer, "Program Acquisition Cost by Weapon System, United States Department of Defense Fiscal Year 2023 Budget Request," April 2022, p. ix, https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2023/FY2023_weapons.pdf; and Pettyjohn and Dennis, *Precision and Posture*, p. 5.

143 DoD's FY2023 budget request totaled $773 billion, with just under $146 billion requested for procurement. Figures drawn from Table 1-2 in Office of the Under Secretary of Defense (Comptroller), "National Defense Budget Estimates for FY 2023," Department of Defense, July 2022, p. 7, https://comptroller.defense.gov/Portals/45/Documents/defbudget/FY2023/FY23_Green_Book.pdf.

FIGURE 16: SELECT PGM PROCUREMENT SPENDING AND QUANTITY BY RANGE, FY1998 TO FY2021



Source: Created by CSBA using data from DoD budget documents and SARs from FY1998 to FY2023.

Beyond the cycle of total spending, Figure 16 also highlights the consistent lack of spending on stand-off and long-range strike munitions. Instead, operational use has driven spending on large quantities of short-range munitions. Maintaining these stocks of direct attack and stand-in weapons is important, but procuring a munitions portfolio suited for great power conflict will necessitate balancing near-term demands with long-term imperatives for PGMs with extended reach.

On top of lacking strategic guidance, munitions funding has historically been a "bill payer" that is often sacrificed in the name of other budgetary priorities, especially advanced platforms.[144] Neglecting stand-in and stand-off munitions, however, could force America's next-generation aircraft and ships to operate dangerously close to Chinese threats. At worst, inadequate weapons stocks could leave even the most advanced platforms stranded without PGMs to execute their missions. Rather than viewing them purely as competing fiscal priorities, policymakers must start considering platforms and munitions symbiotically—part of a broader force package that is required to accomplish a particular mission.[145] Preparing America's arsenal for great power conflict is not just a matter of increasing spending on

144 For an example of DoD's failure to "follow-through" and procure the quantities of munitions it projects purchasing in years prior, see Pettyjohn and Dennis, *Precision and Posture*, p. 13.

145 For a deeper discussion of networked force package analysis and its potential for DoD budgeting, see Sharp, Bassler, and Hacker, "In a Connected Era, We Talk Too Much About Individual Weapons."

munitions relative to platforms, but ensuring that spending on platforms is proportional to spending on a balanced portfolio of weapons to enable their missions.[146]

Like many other acquisition programs, the use of continuing resolutions (CRs) by Congress is detrimental to procuring sufficient stocks of weapons and their supporting systems. A 2021 CR put funding for hypersonic weapons and critical programs like the GBU-53/B *StormBreaker* on hold.[147] Continuing resolutions have a long history of negative impacts on munitions programs and the defense industrial base and are likely to negatively affect future weapons initiatives.[148]

Industrial Base

Funding that cycles with munitions expenditures amplifies the challenge of maintaining America's munitions industrial base—another major constraint on producing adequate numbers of weapons for future conflict. Traditionally, defense planners and budgeters assumed that munitions production, unlike platforms, could be surged in the event of a major conflict. During the Cold War, DoD sometimes funded the maintenance of multiple production lines for munitions to ensure surge capacity.[149] Under this assumption, cutting procurement funding for munitions in favor of platforms was a more reasonable tradeoff.

This assumption is no longer valid. Modern weapons such as long-range cruise missiles are essentially small unpiloted aircraft and are equally complex to produce. Today's advanced munitions are manufactured from thousands of subcomponents with multi-tiered supply chains. Nevertheless, assumptions about conflict remaining limited and rapid in the wake of the Cold War led to the consolidation of many weapons manufacturers.[150] As defense priorities shifted from resiliency to efficiency, overreliance on just-in-time manufacturing has added to the fragility of munitions supply chains. The inability to quickly surge the production of modern weapons has been seen in the U.S. response to the Russia-Ukraine conflict. Industry is predicting that it may take over a year to increase the production of weapons like

146 Proportional spending can also be thought of as balancing near- and long-term priorities. See David Alman, "Don't Buy Warships (Yet)," *Proceedings*, U.S. Naval Institute, June 2022, https://www.usni.org/magazines/proceedings/2022/june/dont-buy-warships-yet.

147 Joe Gould, Megan Eckstein, and Jen Judson, "Here's how the new continuing resolution will frustrate the Pentagon," *Defense News*, October 1, 2021, https://www.defensenews.com/congress/2021/10/01/heres-how-the-new-continuing-resolution-will-frustrate-the-pentagon/?mc_cid=f5e1af0dd9&mc_eid=7cbf43077b.

148 For a brief overview of the effects of continuing resolutions on national defense, see Mackenzie Eaglen and Rick Berger, "1,000 Days of Continuing Resolutions in 10 Years," *American Enterprise Institute*, June 10, 2019, https://www.aei.org/articles/1000-days-continuing-resolutions-10-years/.

149 Tirpak, "Climbing Out of the Munitions Hole."

150 Mick Ryan, "The West needs to boost its industrial capacity fast," *Engelsberg Ideas*, November 24, 2022, https://engelsbergideas.com/notebook/the-west-needs-to-boost-its-industrial-capacity-fast/; and John C. Johnson, "Military Must Factor in Industry's Surge Capacity," *National Defense Magazine*, September 2, 2021, https://www.nationaldefensemagazine.org/articles/2021/9/2/military-must-factor-in-industrys-surge-capacity.

the *Stinger* anti-aircraft missile and *Javelin* anti-tank missile—weapons that are smaller and simpler than critical munitions like the JASSM or LRASM.[151]

Moreover, the downsizing and consolidation of the industrial base have left a limited number of weapons producers. Unlike other aerospace products, the lack of a commercial market for munitions creates higher barriers to entry for many high-technology manufacturers.[152] The inconsistent and conflict-driven demand signal further limits firms from committing to weapon development and production because there is no guarantee of continued, steady government funding. The remaining munitions manufacturers are limited by a reliance on a dwindling number of specialized subcontractors and component suppliers. This reliance leads to multiple munitions sharing subcontractors and components. Some component industries, such as energetics, are particularly burdened by aging infrastructure, outdated business models, and difficulties maintaining a trained workforce.[153]

A thorough exploration of the challenges facing the munitions industrial base is worthy of its own monograph.[154] For the purposes of this study, it stands as major constraint to producing a sufficient inventory of PGMs for great power conflict. Even with vast increases in funding, the speed at which weapons could be acquired (and the speed at which production capacity could be expanded) would be limited by the current munitions industrial base.[155] Most importantly, the Pentagon can no longer assume that surge production will fill existing capacity gaps or sustain the U.S. military in the event of a prolonged conflict. The munitions the United States has on hand at the onset of a conflict are the munitions it will have available for some time.

Technology

In addition to creating opportunities, technology can at times remain a barrier to munitions development. Chapter Two explored the enduring tradeoffs between range, speed, and cost. New propulsion systems, materials, and energetics may ease the degree of these

151 Ethan Sterenfeld, "Raytheon CEO: Stinger production surge not coming this year," *Inside Defense*, April 26, 2022, https://insidedefense.com/insider/raytheon-ceo-stinger-production-surge-not-coming-year.

152 Office of the Under Secretary of Defense for Acquisition and Sustainment, "State of Competition within the Defense Industrial Base," February 2022, p. 19, https://media.defense.gov/2022/Feb/15/2002939087/-1/-1/1/STATE-OF-COMPETITION-WITHIN-THE-DEFENSE-INDUSTRIAL-BASE.PDF.

153 For a deeper look at the energetics industrial base and these issues, see Nadia Schadlow, Brady Helwig, Bryan Clark, and Timothy A. Walton, *Rocket's Red Glare: Modernizing America's Energetics Enterprise* (Washington, DC: Hudson Institute, 2022), https://www.hudson.org/supply-chains/rockets-red-glare-modernizing-americas-energetics-enterprise.

154 For a brief assessment of the munitions industrial base, see Office of the Under Secretary of Defense for Acquisition and Sustainment, "Fiscal Year 2020 Industrial Capabilities Report," January 2021, pp. 85–87, https://media.defense.gov/2021/Jan/14/2002565311/-1/-1/0/FY20-INDUSTRIAL-CAPABILITIES-REPORT.PDF.

155 Marcus Weisgerber, "'Can We Actually Build It?' Defense Industry Leaders Look Ahead to Uncertain 2023," *Defense One*, https://www.defenseone.com/business/2022/12/can-we-actually-build-it-defense-industry-leaders-look-ahead-uncertain-2023/380725/.

tradeoffs and increase total capability, but there will always be a limit to what technology can accomplish.

Munitions may also be limited by adjacent technologies vital to different elements of the kill chain, such as battle networks and communications. Taking advantage of the speed and capabilities of advanced munitions will require C2 systems that provide commanders sufficient situational awareness to quickly integrate and deconflict the delivery of multiple munitions across different domains.[156]

In the words of military historian Kenneth Werrell, "War is a major stimulus for military technology. In contrast, the path for new technology in peacetime is long, convoluted, and littered with many obstacles that require time, skill, and money to be negotiated successfully."[157] In order to prepare for the possibility of great power conflict, DoD must strive to advance weapons technology during the present peace.

Policy and Ethics

At times, the advancement of weapons technology can be inhibited by ethical and political concerns that limit the development and implementation of certain capabilities. One such concern relates to the use of submunitions, which are traditionally associated with indiscriminate cluster munitions. Although modern technology allows for intelligent, discriminating submunitions with dud rates below DoD's 1% threshold, the controversy surrounding cluster munitions has created a culture focused on prioritizing precision over all other attributes. Despite many nations moving away from traditional cluster munitions, China and Russia continue to develop and field cluster munitions for the roles they are best suited to perform, such as attacking grounded aircraft.[158]

A second area of ethical concern surrounds the use of autonomy in munitions. Features like automatic target recognition (ATR) conjure fears of "killer robots" and other potentially dangerous or unethical uses of artificial intelligence. In previous years, these issues have contributed to the cancellation of advanced munitions programs such as the Low Cost Autonomous Attack System (LOCAAS).[159] These concerns, however, often suffer from a lack of nuanced understanding of technologies like ATR. Several current U.S. weapon systems already make their own final engagement decisions without a human in or on the decision-

156 Operation Inherent Resolve revealed the continuing difficulties of managing battlespace and coordinating fires with modern long-range systems. Stacie L. Pettyjohn and Becca Wasser, "From Forever Wars to Great-Power Wars: Lessons Learned From Operation Inherent Resolve," *War on the Rocks*, August 20, 2021, https://warontherocks.com/2021/08/from-forever-wars-to-great-power-wars-lessons-learned-from-operation-inherent-resolve/.

157 Werrell, *Chasing the Silver Bullet*, p. 276.

158 China Aerospace Studies Institute, "Uncovering the Truth Behind the PLA Rocket Force's August 2021 Missile Launch," p. 4, https://www.airuniversity.af.edu/Portals/10/CASI/documents/Research/CASI%20Articles/2021-08-30%20PLARF%20missile%20test%20Aug%202021.pdf?ver=MfVUtaBGoQb25e0_dH3ZwQ%3D%3D.

159 Robert O. Work, "A Short History of Weapon Systems with Autonomous Functionalities," Center for a New American Security, 2021, https://www.jstor.org/stable/pdf/resrep32146.4.pdf.

making loop.[160] Policymakers must consider the various types of autonomous munitions and how each fit within DoD's autonomous weapons policy.[161] It is possible that many thresholds surrounding the use of autonomous weapons in combat have already been surpassed by other nations, and DoD must consider the implications of potential adversaries embracing these technologies.[162]

Myriad political constraints have also affected the operational use of PGMs. History shows that restrictions such as specific rules of engagement (ROE) or limitations posed by alliance and coalition members often interfere with the use of certain U.S. weapons. Features like advanced sensors are of no benefit if ROE or risk-averse leaders do not allow for their usage. For instance, requirements that aircrews visually identify artillery targets during Operation Allied Force prevented the effective use of AN/TPW-37 *Firefinder* radars to identify counter-battery targets.[163] In contemporary great power conflicts, leaders will have to make quick decisions in fluid and potentially disconnected environments. A munition's speed or precision is moot if leaders are not empowered to make rapid engagement decisions. Even with political constraints removed, this shift may require a change in U.S. military culture, which has operated for two decades in a risk-averse counterinsurgency environment that emphasized high-level authorizations.[164] Leaders will have to become increasingly comfortable and willing to make decisions at lower echelons, delegate authority, and rely on the sophisticated capabilities of next-generation munitions.

Organizational and Bureaucratic Interests

The adoption and popularization of advanced munitions can also be held back by the cultures of the armed services themselves. Perhaps the best example of this cultural intransigence is the Air Force's initial aversion to early PGMs.[165] Despite the success of the laser-guided bomb in Vietnam, post-war Air Force analysis focused on the effects of B-52 bombing over newly introduced precision capabilities. Rather than embracing the potential of PGMs, the service pursued a "smart-jet, dumb-bomb" strategy centered on the accu-

160 For instance, the Family of Scatterable Mines (FASCAM), BLU-108 submunitions, and the *Phalanx* close-in weapon system (CIWS).

161 The Department's autonomous weapons policy is described in DoD Directive 3000.09. The Department recently updated DOD Directive 3000.09 for the first time since 2012. For an analysis of the update, see Paul Scharre, "NOTEWORTHY: DoD Autonomous Weapons Policy," *Center for a New American Security*, February 6, 2023, https://www.cnas.org/press/press-note/noteworthy-dod-autonomous-weapons-policy.

162 Joe Hernandez, "A Military Drone With A Mind Of Its Own Was Used In Combat, U.N. Says," *NPR*, June 1, 2021, https://www.npr.org/2021/06/01/1002196245/a-u-n-report-suggests-libya-saw-the-first-battlefield-killing-by-an-autonomous-d.

163 Alan J. Vick, Richard M. Moore, Bruce R. Pirnie, and John Stillion, *Aerospace Operations Against Elusive Ground Targets* (Santa Monica, CA: RAND, 2001), p. 23, https://www.rand.org/pubs/monograph_reports/MR1398.html.

164 For example, U.S. pilots were hesitant to engage enemy combatants in self-defense without approval from higher authority. Pettyjohn and Wasser, "From Forever Wars to Great-Power Wars."

165 Watts, *Six Decades of Guided Munitions and Battle Networks*, pp. 190–198.

racy of the F-16's bombing computer. Precision munitions ran counter to Air Force culture, where PGMs devalued the traditional focus on a pilot's bombing skills demonstrated on the gunnery range. The TLAM faced similar opposition in the Navy, where it overlapped the mission of naval aviation and threatened to distract submarines and surface combatants from their primary missions.[166] The Army has also struggled to popularize guided munitions, with artillery shells like the laser-guided *Copperhead* running counter to the field artillery's traditional culture of massed fires.[167] Even with the widespread acceptance of precision munitions, the services still bicker and compete over the introduction of new strike capabilities. This strife was most recently displayed in the back-and-forth between Air Force and Army officials concerning the Army's pursuit of long-range precision fires systems with ranges that, in the view of the Air Force, encroach on the roles and missions of the other services.[168]

...

Clearly, many gaps exist in the U.S. military's current portfolio of PGMs as it prepares for the possibility of great power conflict. In addition to capacity and capability gaps, there are several long-running constraints that prevent the Pentagon from quickly and easily spending or producing its way out of its current predicament in the near future. Creating a steady demand for critical PGMs and reinforcing their industrial base is critical, but DoD must also reexamine its view of munitions and explore new solutions for filling existing PGM gaps. Each of these gaps represents an opportunity for new technologies and innovative concepts to improve America's current and future PGM arsenal. The next chapter will explore these opportunities in depth.

166 John F. Lehman, *Command of the Seas* (Annapolis, MD: Naval Institute Press, 2001), p. 169.

167 Watts, *Six Decades of Guided Munitions and Battle Networks*, pp. 204–213.

168 Theresa Hitchens, "Long-Range All-Domain Prompts Roles & Missions Debate," *Breaking Defense*, July 9, 2020, https://breakingdefense.com/2020/07/long-range-all-domain-prompts-roles-missions-debate/.

CHAPTER 5

Future Weapon Technologies and Concepts

The precision-strike revolution altered the fundamental tradeoffs in warfare and drastically reduced the number of munitions required to destroy a target. Looking toward contemporary great power conflict, however, our analysis to this point has revealed that precision alone may not be enough to maintain the U.S. military's strike advantage. The immense munitions demands of war with a peer or near-peer adversary could run U.S. PGM stocks dangerously low, with the industrial base unable to quickly supply the volume of weapons needed.

In these scenarios, how can the U.S. military maintain its precision-strike advantage? With precision being necessary but insufficient, the answer lies in munitions that advance beyond precision: smart weapons that provide enhanced effects, reduce total munitions expenditures, and balance the cost per effect. This chapter outlines technologies and concepts to achieve this vision and fill the previously identified capacity and capability gaps in America's PGM arsenal.

Military planners have several means of affecting munitions requirements and easing munitions demands, including:

- Reducing the total number of targets or aimpoints;
- Increasing the chance that weapons reach their targets and have the desired effect;
- And increasing the number of targets and aimpoints each munition can affect.

By embracing weapon technologies and concepts that influence each of these variables, the U.S. military can better prepare its PGM arsenal for the next conflict.

Technological Innovations

Technology remains America's competitive advantage and offers a variety of opportunities to improve modern PGMs and reduce munitions requirements. This section explores technologies the United States could exploit to solve the munitions problem, beginning with a weapon's design and continuing through its production, maintenance, and employment.

Design and Producibility

Meeting the demands of great power conflict begins with ensuring American PGMs are designed and produced using 21st-century approaches that allow for rapid testing, iteration, and affordable production by a wide sector of the technology and industrial base.

Digital engineering. The use of digital engineering techniques allows for rapid design, prototyping, and testing of future PGMs. Digital engineering starts with the use of modular open architectures in munitions design. Open architectures are one way munitions manufacturers can capture and leverage private sector research and development. The Pentagon noted in its most recent assessment of American industrial capabilities that the precision-guided munition market expanded by over 50 percent between 2014 and 2020.[169] By utilizing open architectures, DoD can encourage commercial firms to take advantage of this growing market and the opportunities presented by the next-generation munitions industrial base. Future PGMs must utilize technology advancements made in the commercial sector for small drones, self-driving cars, and the plethora of other experimental technologies making their way into the consumer market.[170] Open system architectures could help close the gap between commercial and military production lines and expand the munitions industrial base, particularly for weapon components. Initial efforts such as the Air Force's Weapons Open System Architecture (WOSA) have laid the groundwork for open architectures to be a part of future munitions acquisition programs and increase competition at the subcomponent level.[171] To effectively implement digital engineering in its weapons programs, DoD must work with defense manufacturers to overcome the challenges associated with proprietary designs, intellectual property, and systems integration.[172]

169 Office of the Under Secretary of Defense for Acquisition and Sustainment, "Fiscal Year 2020 Industrial Capabilities Report," p. 87.

170 Bryan Clark and Dan Patt, "Exploit Commercial Electronics To Deter Beijing Before It's Too Late," *Real Clear Defense*, December 15, 2022, https://www.realcleardefense.com/articles/2022/12/15/exploit_commercial_electronics_to_deter_beijing_before_its_too_late_870352.html?mc_cid=9f2cccb8c7&mc_eid=7cbf43077b.

171 For more on WOSA, see Jonathan Shaver and Leo Rose, "Open System Architecture as Applied to Air-Launched Weapons," Air Force Research Laboratory, October 2019, https://ndiastorage.blob.core.usgovcloudapi.net/ndia/2019/systems/Wed_22468_Rose.pdf; and Estella Holmes, "New technical standard refines open solution," Air Force Materiel Command Public Affairs," January 26, 2022, https://www.afrl.af.mil/News/Article/2928547/new-technical-standard-refines-open-solution/.

172 Tirpak, "Climbing Out of the Munitions Hole."

Advanced manufacturing techniques. Digital engineering also supports additive manufacturing and other methods of mass-producing complex systems for missiles and munitions. Defense manufacturers, including facilities owned by the U.S. government, must move from handcrafting weapons to automated production lines that increase efficiency and help mitigate recurring workforce issues.[173] Advances in additive manufacturing allow for its use to rapidly create components with applications in weapon production, including propulsion components and rocket engines.[174] The rapid iteration of designs and prototypes enabled by digital engineering and additive manufacturing is key to quickly adapting munitions to adversary countermeasures (CMs) and developing counter-countermeasures (CCMs). Staying ahead in the back-and-forth game between CMs and CCMs is vital for increasing the survivability of PGMs and controlling munitions requirements.

Multi-role munitions. Digital engineering and open system architectures are key to promoting a second essential design aspect of future munitions—modularity. Defense officials have praised current efforts to increase the versatility of the SM-6 and *Tomahawk* as positive steps, but future PGMs must be designed from the start with multiple roles and domains in mind.[175] Multi-role weapons are critical to ensuring the payloads of delivery platforms are balanced between offensive and defensive weaponry. Munitions that can perform both functions reduce the mission planning tradeoffs that would otherwise constrain the quantity of offensive munitions carried by U.S. air and naval forces.

Modular munition designs with interchangeable components. Beyond multi-role weapons, the U.S. military should develop munitions with increasingly modular features that can be swapped in a "mix-and-match" fashion. The success of attachable guidance kits such as the *Paveway* and JDAM series, which augment existing dumb bombs with precision capability, is a foundation that could be further expanded. Already, efforts exist to increase the capability of these bombs with propulsion kits like the Powered JDAM, which adds propulsion to a 500 lb. bomb, or the Air Force Research Laboratory's (AFRL) *Quicksink* project, which modifies JDAMs to attack maritime targets.[176] These efforts are inexpensive ways to significantly increase the range, capability, and versatility of existing

173 For example, much of the U.S. military's organic industrial base related to munitions production still lacks automation, especially in areas that present significant production bottlenecks such as energetics. See Joe Gould, "After munition worker deaths, Army floats $16 billion plan to modernize production," *Defense News*, September 22, 2020, https://www.defensenews.com/congress/2020/09/22/after-munition-worker-deaths-army-floats-16-billion-plan-to-modernize-production/.

174 See, for example, "Ursa Major delivers its first additively manufactured rocket engine components," *Metal AM*, July 18, 2022, https://www.metal-am.com/ursa-major-delivers-its-first-additively-manufactured-rocket-engine-components/.

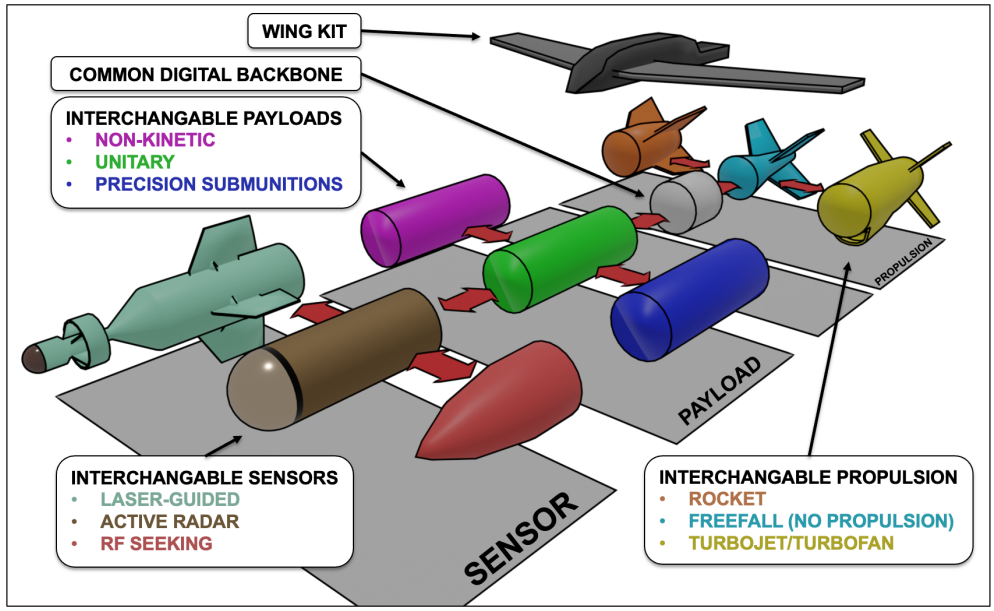
175 John Grady, "William Roper: Pentagon Needs to Look Toward Repurposing Technology," *USNI News*, October 28, 2021, https://news.usni.org/2021/10/28/william-roper-pentagon-needs-to-look-toward-repurposing-technology?mc_cid=71efadcbbb&mc_eid=7cbf43077b.

176 Tobias Naegele, "Powered JDAM: Boeing's New Alternative to Cruise Missiles," *Air & Space Forces Magazine*, February 28, 2020, https://www.airandspaceforces.com/power-jdam-boeings-new-alternative-to-cruise-missiles/; and Whitney Wetsig, "AFRL technology makes new weapon for sinking ships a reality," Air Force Research Laboratory Public Affairs, April 28, 2022, https://www.afrl.af.mil/News/Article/3014096/afrl-technology-makes-new-weapon-for-sinking-ships-a-reality/.

general-purpose bombs. One benefit of improving existing families of modular kits such as JDAM is their pre-integration with most U.S. delivery platforms and many allied and partner platforms.

The next step in modularity is standardized weapon bodies, or "trucks," that can deliver a variety of interchangeable payloads using the same propulsion system and container. The ultimate goal is munitions designed to be entirely modular with components and subcomponents that can be traded based on the mission at hand, such as the Army's Modular Missile Technologies (MMT) demonstrator.[177]

FIGURE 17: EXAMPLE MODULAR "MIX-AND-MATCH" MUNITION WITH INTERCHANGEABLE COMPONENTS



Source: Created by CSBA with inspiration from Christopher S. Lofts, "Modular Missile Technologies (MMT): A Modular Open Architecture Approach for Guided Missiles," U.S. Army Aviation and Missile Research, Development, and Engineering Center, April 2015, p. 4, https://apps.dtic.mil/sti/pdfs/ADA622336.pdf.

Modular weapons are valuable from both an industrial base and an operational standpoint. These weapons facilitate munitions production by allowing changes and updates to be made to components independently of each other before being integrated with a larger system at minimal cost. Combined with open architectures, modular munitions would allow for increased competition around subcomponents and an expansion of the munitions industrial base. Non-defense firms could match their technologies and talents to designing certain

177 The Navy has also sought to begin work on a Navy Modular Missile (NMM) program. See *GovTribe*, "Model Based Systems Engineering (MBSE) for Navy Modular Missile (NMM) Program, June 4, 2021, https://govtribe.com/opportunity/federal-contract-opportunity/model-based-systems-engineering-mbse-for-navy-modular-missile-nmm-program-n0002421r5424.

pieces of a weapon without delving into the munition-specific components and overall integration that require traditional weapon manufacturers to have specialized facilities and workforces.[178] This shift is essential to harnessing the capabilities of commercial firms advancing technologies related to unmanned and autonomous systems. If a modular component is usable by more than one weapon program (for instance, a multi-mode seeker that could be paired with a ground-launched or air-launched weapon body), then paying to maintain surge capacity for that component is increasingly justifiable. Moreover, interchangeable components would allow munitions to be maintained, upgraded, and adapted to current threats without replacing the entire weapon.

In addition to diversifying the munitions industrial base, modularity and interchangeable components could increase the operational versatility of future PGMs. Before a mission, units could assemble weapons to attack the targets at hand most effectively. Rather than stocking weapons for a specific scenario or attempting to stock a mix adequate for multiple contingencies, planners could forgo many of these tradeoffs and stock a variety of modular components that could be assembled to suit whichever situation arises.

Beyond increasing overall versatility, modularity could also help the U.S. military balance versatility with specialization. Modular munitions could fill multiple specific capability gaps without purchasing and maintaining separate inventories of weapons over-specialized for specific uses. For instance, rather than stocking distinct inventories of weapons designed for C4ISR targets and others intended to attack runways and air bases, the U.S. military could procure only the specialized payloads for these targets, which could be fitted to a single set of modular weapon bodies. This versatility will be especially important as the United States fields exquisite and expensive systems like hypersonic munitions.[179] Modularity would allow these high-impact but low-density weapons to be effective in a wider range of applications.[180]

The United States could also pursue "modularity for export," with munition pieces interchangeable for components that comply with export restrictions and allow for rapid transfer to a wider range of allies and partners.[181] These designs could increase international demand for U.S. weapons and could also allow foreign firms to design and produce their own subcomponents, further increasing competition and diversity in the industrial

178 John A. Tirpak, "Modular Weapons Could Improve Surge Capacity, Bunch Says in Exit Interview," *Air & Space Forces Magazine*, June 9, 2022, https://www.airandspaceforces.com/modular-weapons-could-improve-surge-capacity-bunch-says-in-farewell-interview/.

179 As part of its Vintage Racer program, DoD has tested a hypersonic munition with modular features and some degree of loitering capability. Joseph Trevithick, "Pentagon Has Tested Suicide A Suicide Drone That Gets To Its Target Area At Hypersonic Speed," *The Drive*, June 8, 2020, https://www.thedrive.com/the-war-zone/33934/pentagon-has-tested-a-suicide-drone-that-gets-to-its-target-area-at-hypersonic-speed.

180 Already, efforts such as AFRL's Mayhem program seek to develop hypersonic weapons with modular weapons bays. See Briana Reilly, "AFRL indicates intentions to select SDA for 'Mayhem' air-breathing hypersonics program," *Inside Defense*, July 21, 2021, https://insidedefense.com/insider/afrl-indicates-intentions-select-sda-mayhem-air-breathing-hypersonics-program%C2%A0.

181 The author would like to thank former CSBA colleague Chris Bassler for his ideas on modularity for export.

base.[182] Increasing the versatility, producibility, and affordability of munitions through digital engineering and modularity can help fill capacity and capability gaps and enable affordable mass.

Launchers and Delivery Methods

In addition to modular munitions, the United States could also increase the versatility of its delivery platforms and their weapon interfaces.

Delivery platform versatility. Weapons that can be launched from multiple platforms across several domains are key to reducing the tradeoffs munitions planners must confront. Expanding the launch options for the SM-6 and *Tomahawk* missiles is set to increase the flexibility of forces in the Indo-Pacific. Near-term efforts such as the container-launched AARGM-ER or ground-launched Small Diameter Bomb could further increase the usability of standard munitions by multiple delivery platforms.[183] Rather than the military services buying separate munitions designed only for their platforms, munitions shareable by multiple platforms across the services could decrease munitions costs and simplify theater logistics. Modularity is key to ensuring weapons are compatible with a variety of delivery platforms and satisfy the demands of multiple services.

Standardized launchers, mounts, and interfaces. As a stepping stone to general modularity, standardized launchers and weapon mounts could enable platforms in multiple domains to deliver the same munition. On the software side, universal interfaces like the Air Force's Universal Armaments Interface (UAI) speed weapon and aircraft software integration.[184] These efforts could be expanded across services, platforms, weapons, and with key allies and partners.[185] Like software interfaces, standardized launchers and mounts can also increase weapon compatibility with a variety of platforms. Current programs like the Common Launch Tube (CLT) and JAGM Quad Launcher (JQL) illustrate how standard mounts can enable platforms in multiple domains to seamlessly employ the same

182 Of course, such modularity might also reduce the control the United States has over the capability it transfers to its allies and partners. Modularity for export may be better suited for certain close allies such as the United Kingdom, Australia, and Japan.

183 See Joseph Trevithick, "Land-Based Strike Version of Navy's Long-Range Air Defense Blasting Missile Breaks Cover," *The Drive*, May 21, 2021, https://www.thedrive.com/the-war-zone/40733/land-based-strike-version-of-navys-long-range-air-defense-blasting-missile-breaks-cover; and Saab, "Flexible, Precise and Reliable – The Versatile Long Range Solution That Has It All," September 22, 2022, https://www.saab.com/newsroom/stories/2019/march/flexible-precise-and-reliable--the-versatile-long-range-solution-that-has-it-all.

184 For more information on UAI, see Jim Byrd and Oren Edwards, "Standard Weapon Interfaces: The Path to a Universal Armament Interface," *Defense Standardization Program Journal*, July/September, 2005, pp. 21–27, https://www.dsp.dla.mil/Portals/26/Documents/Publications/Journal/050701-DSPJ.pdf.

185 Such as NATO's UAI program. See Julan Hale, "NATO Project May Provide Allied Air Forces with 'Plug and Play' Precision Munitions," *Atlantic Council*, January 22, 2014, https://www.atlanticcouncil.org/blogs/natosource/nato-project-may-provide-allied-air-forces-with-plug-and-play-precision-munitions/.

munitions.[186] Utilizing standardized mounts and software interfaces further increases mission versatility and ensures that future platforms, such as attritable UAS, will be capable of delivering a range of PGMs without extensive modification of the weapon or the platform.

Propulsion

Although the tradeoff between range, speed, and cost remains, advances in propulsion can reduce the degree of this tradeoff, fill range capability gaps, and increase the survivability of munitions in contested environments.

Advanced propulsion technologies. Innovative designs such as rotating detonation engines offer increased range and speed in smaller, more efficient packages that could extend the reach of existing munitions and lead to smaller weapons.[187] DARPA is currently experimenting with integrating these propulsion systems on missiles.[188] New energetic materials, which are discussed further below, are another vital aspect of advancing weapon propulsion. Integral to both propulsion and weapon payloads, modern energetics offer increased efficiency and range for future munitions. The energetics industrial base, which is partially government-owned, will play a vital role in preserving the U.S. military's strike advantage.[189]

Modular propulsion kits and additions. In addition to improving propulsion systems, existing weapons could be augmented with glide wings or low-cost engine kits. Glide kits like the JDAM-ER or add-on engine kits like the Powered JDAM and JSOW-ER could extend the ranges of proven PGMs with little additional cost or integration effort.[190] Add-on kits could be one way the U.S. military provides a large volume of effects from stand-in range and could even be used as low-cost decoys to absorb enemy missile defenses. These kits can

186 The CLT has been integrated on the Air Force's AC-130 aircraft and the Marine Corps' KC-130J. The JQL seeks to rapidly integrate the air-launched JAGM into maritime and ground-based platforms. Michael Peck, "Special Operations Command Wants Tiny Cruise Missiles with Hundreds of Miles Range," *The Drive*, September 7, 2021, https://www.thedrive.com/the-war-zone/42280/special-operations-command-wants-tiny-cruise-missiles-with-hundreds-of-miles-range; and Peter Ong, "JQL Could Be The "Game Changing Force Multiplier" For Small Naval Boats And Littoral Warfare Ships," *Naval News*, December 17, 2020, https://www.navalnews.com/naval-news/2020/12/jql-could-be-the-game-changing-force-multiplier-for-small-naval-boats-and-littoral-warfare-ships/.

187 Alex Hollings, "What Is a Rotating Detonation Engine and What Could It Mean for Aviation?," *Sandboxx*, October 24, 2022, https://www.sandboxx.us/blog/what-is-a-rotating-detonation-engine-and-what-could-it-mean-for-aviation/.

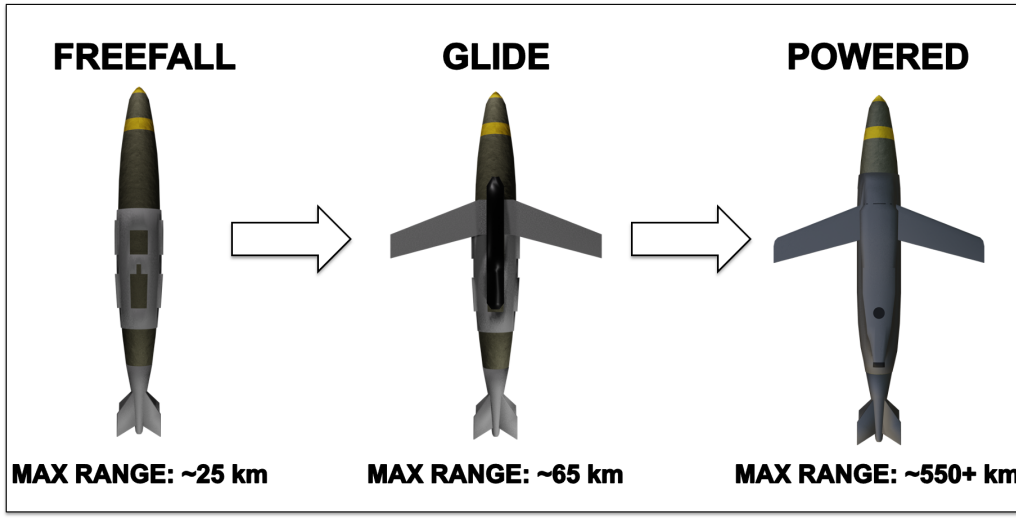
188 Stew Magnuson, "Air Force Labs Pursue More Powerful, Efficient Engines," *National Defense* Magazine, January 5, 2023, https://www.nationaldefensemagazine.org/articles/2023/1/5/air-force-labs-pursue-more-powerful-efficient-engines?mc_cid=8bc52b1cf4&mc_eid=7cbf43077b; and Alex Hollings, "DARPA's New Missile Hints at Truly Game-Changing Technology," *Sandboxx*, July 26, 2022, https://www.sandboxx.us/blog/darpas-new-missile-hints-at-truly-game-changing-technology/.

189 Ashley D. Johnson, "The Dangerous Depletion of U.S. Weapon Arsenals," *Proceedings*, U.S. Naval Institute, August 2022, https://www.usni.org/magazines/proceedings/2022/august/dangerous-depletion-us-weapon-arsenals.

190 *Airforce Technology*, "Boeing and RAAF evaluate JDAM ER weapon system," February 24, 2015, https://www.airforce-technology.com/news/newsboeing-and-raaf-evaluate-jdam-er-weapon-system-4519524/; Naegele, "Powered JDAM;" and Joseph Trevithick, "Cruise Missile Variant Of Navy's JSOW Glide Bomb Is On The Chopping Block," *The Drive*, June 2, 2021, https://www.thedrive.com/the-war-zone/40886/cruise-missile-variant-of-jsow-glide-bomb-on-the-chopping-block-in-new-navy-budget-request.

also extend the range of other essential weapons, such as torpedoes and undersea mines.[191] For other missiles, additional range could be added with multi-stage propulsion systems.[192] Ultimately, DoD should utilize advanced propulsion technologies to increase the number of munitions with an optimal balance of range and cost and enable the affordable massing of large numbers of weapons.

FIGURE 18: MODULAR PROPULSION KITS AND ADDITIONS



Source: Created by CSBA. Boeing, "Joint Direct Attack Munition: Historical Snapshot," accessed February 9, 2023, https://www.boeing.com/history/products/joint-direct-attack-munition.page; Boeing, "Powered Joint Direct Attack Munition: Affordable Standoff," accessed February 9, 2023, https://www.boeing.com/resources/boeingdotcom/defense/weapons-weapons/images/powered_JDAM_product_card.pdf.

Reduced cost hypersonics. For hypersonics, achieving some degree of affordability is essential to fielding a sufficient quantity of weapons for great power conflict. As propulsion systems and weapon bodies are improved, procuring hypersonics in greater numbers is expected to drive down their cost.[193] In addition to balancing range and cost, the DoD must balance speed and cost to ensure that a significant portion of its PGMs are survivable and capable of striking mobile targets in contested environments. Should the cost of hypersonic

191 The Navy is currently using add-on kits to extend the range of its air-delivered mines and torpedoes. See Richard R. Burgess, "Navy Orders Quickstrike-Extended Range Glide Kits for Sea Mines," *Seapower*, July 23, 2021, https://seapowermagazine.org/navy-orders-quickstrike-extended-range-glide-kits-for-sea-mines/; and Joseph Trevithick, "Navy P-8 Poseidon Can Now Drop Winged Torpedoes In Combat (Updated)," *The Drive*, November 22, 2022, https://www.thedrive.com/the-war-zone/navy-p-8-poseidon-can-now-drop-winged-torpedos-in-combat.

192 For example, Boeing's Long-Range Air-to-Air Missile (LRAAM). See Joseph Trevithick, "Boeing Unveils New Two-Stage Long-Range Air-to-Air Missile Concept," *The Drive*, September 21, 2021, https://www.thedrive.com/the-war-zone/42454/boeing-unveils-new-two-stage-long-range-air-to-air-missile-concept.

193 Mike Stone, "Pentagon Says Hypersonic Weapons Are Too Expensive," *Reuters*, October 12, 2021, https://www.reuters.com/business/aerospace-defense/pentagon-says-hypersonic-weapons-are-too-expensive-2021-10-12/.

weapons prevent them from being procured in substantial quantities, the Pentagon could consider pursuing mid-range supersonic weapons that can be employed in higher volumes.[194]

Sensors, Networking, and Autonomy

Perhaps the most significant opportunities for technology to advance munitions capabilities are those related to improved sensors, networking, and autonomy, which could reduce munitions requirements by attacking target sets more efficiently and achieving a higher rate of good effects. Advancements in these areas apply to both exquisite weapons and less costly, more numerous munitions.

Multi-mode sensors. For high-end munitions, advanced sensors will guide the next generation of PGMs. Multi-mode sensors utilize a variety of phenomenologies, from electro-optical to radio frequency to laser radar, to make up for the inadequacies of any single phenomenology and provide accurate target detection in all environments.[195] Initially fielded on ISR platforms, these multi-spectral sensors' miniaturization and decreasing costs will ensure that exquisite munitions accurately reach their intended targets—even those camouflaged, hidden in challenging terrain, or obscured by decoys and non-combatants.[196] In addition to multi-mode seekers, quantum navigation sensors may eventually be compact and affordable enough to provide hyper-accurate guidance for specialty weapons without assistance from external inputs like GPS.[197]

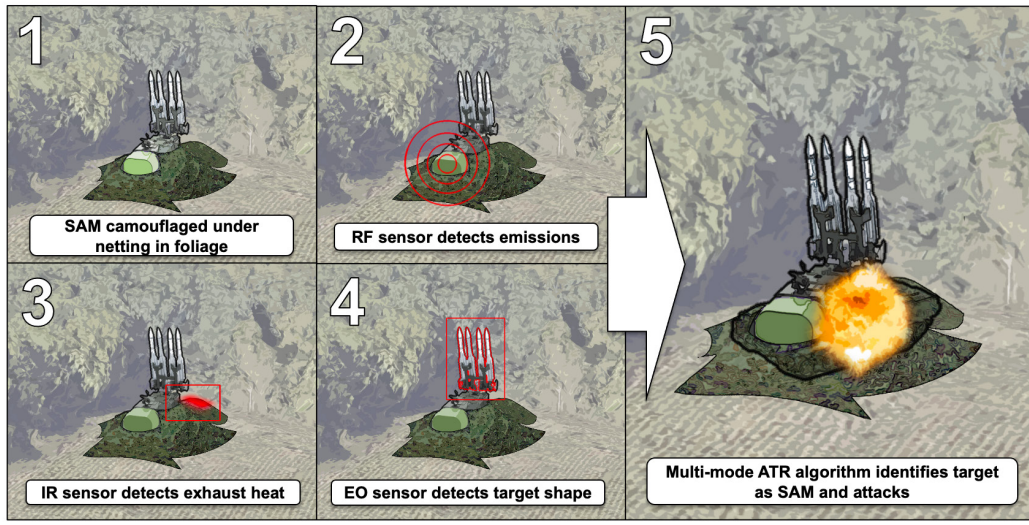
194 Such a weapon would move toward a "high, mid, low," mix of weapons instead of the mostly "high and low" mix the Pentagon is currently pursuing. See David N. Zikusoka, "How Fast Is Fast Enough? A Role For Supersonic Munitions In Standoff Strike," *War on the Rocks*, November 9, 2020, https://warontherocks.com/2020/11/how-fast-is-fast-enough-a-role-for-supersonic-munitions-in-standoff-strike/.

195 For example, see Air Force Research Laboratory, "AFRL/RYM – Multispectral Sensing & Detection Division, https://www.afrl.af.mil/About-Us/Fact-Sheets/Fact-Sheet-Display/Article/2332214/afrlrym-multispectral-sensing-detection-division/; BAE Systems, "EO/IR Sensor R&D," https://www.baesystems.com/en/product/eo-ir-sensor-r-d; and Lockheed Martin, "Missiles and Fire Control," https://www.lockheedmartin.com/en-us/who-we-are/business-areas/missiles-and-fire-control.html.

196 DARPA has long experimented with these kinds of sensors in programs such as Jigsaw. See Richard M. Marino and William R. Davis, Jr., "Jigsaw: A Foliage-Penetrating 3D Imaging Laser Radar System," *Lincoln Laboratory Journal* 15, no. 1, 2005, pp. 23-26, https://www.ll.mit.edu/sites/default/files/page/doc/2019-01/15_1jigsaw.pdf.

197 Patrick Tucker, "Quantum Sensor Breakthrough Paves Way For GPS-Free Navigation," *Defense One*, November 2, 2021, https://www.defenseone.com/technology/2021/11/quantum-sensor-breakthrough-paves-way-gps-free-navigation/186578/.

FIGURE 19: MULTI-MODE SEEKER FINDING A HIDDEN TARGET



Source: Created by CSBA.

Improved automatic target recognition. Paired with advanced sensors on exquisite munitions, improvements in automatic target recognition could reduce the need for detailed targeting and mission planning. This capability is key to defeating mobile and elusive targets as they are detected because the large numbers of these targets will overwhelm existing targeting processes in a great power war. Although concerns remain about autonomous weapons, artificial intelligence is already assisting with target identification in live operational kill chains.[198] Continued improvements will enable this capability to be integrated into munitions themselves and allow exquisite weapons to find, track, and engage the enemy semi-autonomously using a pre-loaded set of engagement criteria and rules.[199]

Ubiquitous affordable sensors. With next-generation sensors guiding "silver bullets" to high-value targets, affordable sensors that can be placed on inexpensive weapons are equally valuable. Increasingly capable and abundant sensors must cut the umbilical between weapon and delivery platform and guide munitions with less external support or vulnerability to adversary interference. Various technology demonstrators have illustrated improvements in affordable sensing, from the JDAM Direct Attack Munition Affordable Seeker to the light detection and ranging (LADAR) sensor developed for the LOCAAS.[200] More recent examples include the multi-mode seeker of the GBU-53/B *StormBreaker* and the ubiquity of TV and

198 Amanda Miller, "AI Algorithms Deployed in Kill Chain Target Recognition," *Air & Space Forces Magazine*, September 21, 2021, https://www.airandspaceforces.com/ai-algorithms-deployed-in-kill-chain-target-recognition/?mc_cid=524fe86410&mc_eid=7cbf43077b.

199 Even if human operators remain "on-the-loop" of future semi-autonomous weapons, they still offer increased speed and capability over existing precision targeting processes.

200 Both programs were cancelled. As of 2002, the DAMASK costed $12,700 per seeker, while the entire LOCAAS system was projected to cost $30,000. See Wilson, *A Time-Critical Targeting Roadmap*, pp. 31-33.

IR sensors on drones and loitering munitions such as UVision's *Hero* series.[201] Continued improvements will make these sensors more capable while also reducing their cost and allowing their integration with a variety of commonplace munitions. In many great power conflict scenarios, even weapons with simplistic seekers and targeting algorithms offer vast advantages over weapons requiring extensive operator input or external guidance support.

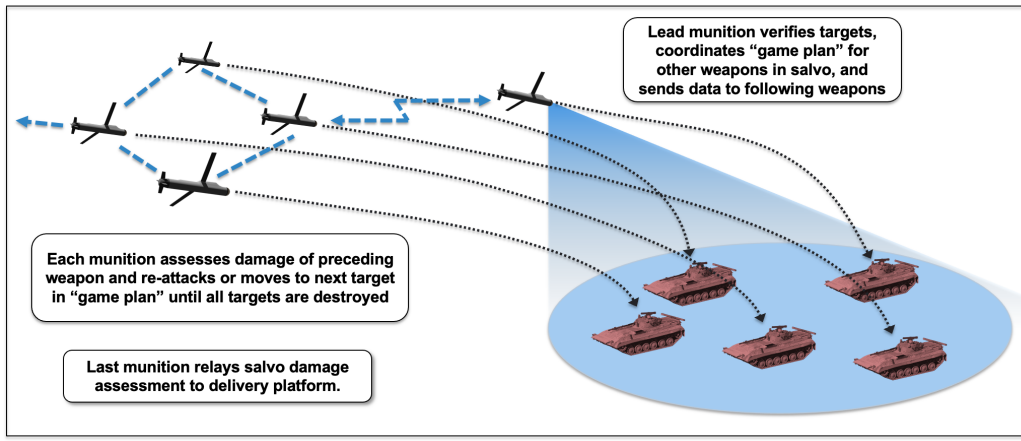
Collaborative capabilities. To truly enable weapons with these sensors, future munitions should be networked together and capable of semi-autonomous collaboration. These weapons communicate with each other and take advantage of loitering and sensor capabilities to coordinate target detection, self-deconflict, and cooperatively engage a target set. Rather than launching multiple munitions at a single aimpoint to increase the likelihood of good effects, collaborative munitions can assess each other's effects, reattack if necessary, or decide to move on to another aimpoint. Collaborative technologies were tested nearly two decades ago during the development of LOCAAS, and the Air Force has recently proven the collaborative weapon concept with Small Diameter Bombs as part of its Golden Horde program.[202] Integrating this technology into longer-range munitions increases the time weapons have to collect information, coordinate engagements, and relay valuable information back to the delivery platform.[203] Modular architectures are necessary to enable various munitions to "plug in" to weapon networks and communicate with each other.

201 See Raytheon, "GBU-53/B SDB II: Small Diameter Bomb Increment II," https://www.airandspaceforces.com/PDF/SiteCollectionDocuments/Reports/2010/August%202010/Day25/SDBII_factsheet_0810.pdf; and Joseph Trevithick, "This Is Our First Look at The Marines' Loitering Munition-Armed Light Armored Vehicle," *The Drive*, October 11, 2021, https://www.thedrive.com/the-war-zone/42707/this-is-our-first-look-at-the-marines-loitering-munition-armed-light-armored-vehicle?mc_cid=19c78693bd&mc_eid=7cbf43077b.

202 Mike Hanlon, "Low-Cost Autonomous Attack System (LOCAAS) Successfully Flight Tested," *New Atlas*, November 4, 2005, https://newatlas.com/low-cost-autonomous-attack-system-locass-successfully-flight-tested/4812/; and Valerie Insinna, "US Air Force Completes Tests of Swarming Munitions, But Will They Ever See Battle?," *Defense News*, June 7, 2021, https://www.defensenews.com/air/2021/06/07/us-air-force-successfully-completes-tests-of-swarming-munitions-but-their-future-is-unclear/.

203 For example, Israeli defense manufacturer Rafael claims its *Sea Breaker* missile combines collaborative capabilities with longer-range, an advanced seeker, and automatic target recognition. Seth J. Frantzman, "Rafael Combines AI and Automatic Target Recognition in New Sea Breaker Missile," *C4ISRNet*, July 2, 2021, https://www.c4isrnet.com/industry/2021/07/02/rafael-combines-ai-and-automatic-target-recognition-in-new-sea-breaker-missile/.

FIGURE 20: COLLABORATIVE MUNITIONS ATTACKING MULTIPLE AIMPOINTS



Source: Created by CSBA.

Improved data collection and processing. As sensors and networking increase the amount of data collected by munitions, it is imperative that this information be utilized to better battle damage assessments (BDA) and target databases. Weapon packages that collect and transmit their own BDA information can improve the accuracy of assessments and reduce the need for reattacks and expending additional munitions. Affordable sensors enable this by providing additional feedback to delivery platforms.[204] In addition, weapons that relay sensor data could update automatic target recognition databases and algorithms in order to improve the effectiveness of further engagements. Over time, these munitions could learn enemy camouflage and movement practices and reduce the number of munitions expended in subsequent missions.

Even with these improvements in networking and data sharing, the contested electromagnetic spectrum of great power conflict makes it essential that weapons remain network-*enabled*, but not network-*dependent*. Where possible, munitions must function using "smaller, semi-autonomous networks with their own organic data collection and processing capabilities."[205]

Payloads and Effects

Technology can also reduce munitions requirements through innovative payloads that improve the likelihood a weapon produces the desired effect.

204 Even basic electro-optical sensors provide a delivery platform (or potentially another munition) with better engagement feedback than a GPS-guided munition. Wilson, *A Time-Critical Targeting Roadmap*, pp. 14-15.

205 Jacquelyn Schneider and Julia MacDonald, "The Information Technology Counter-Revolution: Cheap, Disposable, and Decentralized," *War on the Rocks*, July 19, 2021, https://warontherocks.com/2021/07/the-information-technology-counter-revolution-cheap-disposable-and-decentralized/?mc_cid=86e7535659&mc_eid=7cbf43077b.

Advanced energetics. For kinetic munitions, advancements in energetics can reduce warhead size and allow designers to pack more lethality into smaller packages.[206] Small-form munitions like the Small Diameter Bomb series are already taking advantage of improved warheads that equal the effects of older, larger weapons. Industry continues to improve warhead designs and has tested modern weapons weighing as little as six pounds which pack 45 to 80 percent of the lethality of a 500-pound general-purpose bomb against light-skinned vehicles and radar.[207] Multi-effect warheads and conventional payloads with adjustable yields would increase the versatility of a weapon by allowing the user to select the optimal effects for a given target while reducing the chances of unintended or collateral damage.[208] In all, kinetic payloads using modern energetics and multi-effect warheads can give each munition a more lethal punch and help fill existing capability gaps such as attacking HDBTs. Already, China is experimenting with munitions that utilize more powerful materials.[209]

Modernized area effect weapons. In addition to more deadly unitary payloads, a plethora of technologies can help the U.S. military fill its requirement for area effects. Unlike the indiscriminate cluster munitions of the past, the miniaturization of electronics and sensors allows today's munitions to deliver numerous precision effects over a wide area. In this way, modern area-effect weapons will complement unitary precision munitions rather than replace them. One way of providing area effects is through innovative submunitions. Smart, penetrating submunitions or "skeets" have proven effective against armored vehicles in past campaigns and could be updated with better sensors and payloads.[210] Modern iterations of these submunitions could resemble small commercial quadcopters that collaborate to carry numerous explosively formed penetrators to spread out targets.[211] DoD has already tested small, independently targetable weapons that could augment existing PGMs and be deployed from a variety of platforms.[212] Submunitions are also key to efficiently attacking airfields. Modeling by RAND found that a 75 lb. payload of submunitions is three times more effective than a unitary warhead of equivalent weight for attacking parked aircraft in

206 Nadia Schadlow, "DoD Needs More 'Kaboom' for the Buck," *Proceedings*, U.S. Naval Institute, December 2022, https://www.usni.org/magazines/proceedings/2022/december/dod-needs-more-kaboom-buck.

207 Northrop Grumman, "Ready Now: Hatchet Completes Live Drop Testing," accessed March 30, 2023, https://www.northropgrumman.com/what-we-do/advanced-weapons/hatchet-completes-live-drop-testing/.

208 Wilson, *A Time-Critical Targeting Roadmap*, p. 36.

209 Sean Carberry, "Energetics: Community Warns of China's Edge Developing Explosive Materials," *National Defense*, June 27, 2022, https://www.nationaldefensemagazine.org/articles/2022/6/27/community-warns-of-chinas-edge-developing-explosive-materials?mc_cid=13a02fead4&mc_eid=7cbf43077b.

210 Such as the BLU-108/B submunition in the CBU-105. During Operation Iraqi Freedom, BLU-108/B submunitions stopped a large Iraqi tank column by "killing the whole first one-third to half of it." Seeing the devastating effects of the CBU-105, the remainder of the tank column surrendered to U.S. Marines. Ryan Hansen, "Capturing enemy forces," *Eglin Eagle*, August 15, 2003, available at the Air Force Armament Museum.

211 Chris Martin, "The US Army Wants a Missile Filled With Drones," *Defense News*, January 19, 2017, https://www.defensenews.com/industry/techwatch/2017/01/19/the-us-army-wants-a-missile-filled-with-drones/.

212 Such as *Hatchet*. See Northrop Grumman, "Ready Now: Hatchet Completes Live Drop Testing," accessed March 30, 2023, https://www.northropgrumman.com/what-we-do/advanced-weapons/hatchet-completes-live-drop-testing/.

the open.[213] Submunitions designed to crater and cut runways could also be used to attack airfields more effectively with fewer PGMs.[214] Should the United States field long-range ballistic missiles or hypersonic weapons, conventional multiple independent reentry vehicles (MIRVs) could enable these exquisite weapons to have outsized effects on high-value targets.[215] The use of advanced submunitions would go a long way toward enabling each PGM to precisely attack multiple aimpoints.

Loitering and persistent payloads. Next-generation munitions should also take advantage of technologies that decouple their time of effect from their time of launch, which increases their flexibility and utility for mobile targets. Loitering capability is one way to increase the time and space a weapon has to find its target. Small loitering munitions that blur the line between UAS and munitions have proven their worth in Ukraine, and future designs could increase their lethality when combined with swarming concepts and improved automatic target recognition.[216] Already, the Marine Corps is looking to integrate these capabilities into its Organic Precision Fires program.[217] In addition to providing persistent physical effects, loitering munitions can also cause virtual attrition of enemy forces.[218] Improved propulsion systems and designs will boost the endurance of future loitering weapons, increasing their effectiveness and utility for a wide variety of missions.[219] Like loitering munitions, weapons with persistent or "stay behind" payloads could also be used

213 According to RAND, this advantage "increases with increasing payload. An 1,100-pound M-9 ballistic-missile warhead covers almost eight times the area when using a submunition warhead than when using a unitary warhead." John Stillion and David T. Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks* (Santa Monica, CA: RAND, 1999), p. xiii, https://www.rand.org/pubs/monograph_reports/MR1028.html.

214 Jordan Rosza, *Improving Standoff Bombing Capacity in the Face of Anti-Access Area Denial Threats* (Santa Monica, CA: RAND, 2015), p. 48, https://www.rand.org/pubs/rgs_dissertations/RGSD363.html.

215 For illustrations of how conventional MIRVs might be utilized in great power conflict, see Edelman, Bassler, Yoshihara, and Hacker, *Rings of Fire*, pp. 57-61.

216 Loitering munitions and "kamikaze" drones have been utilized by both Ukrainian and Russian forces. See Brennan Deveraux, "Loitering Munitions In Ukraine And Beyond," *War on the Rocks*, April 22, 2022, https://warontherocks.com/2022/04/loitering-munitions-in-ukraine-and-beyond/; and Kyle Mizokami, "Self-Destructing 'Kamikaze Drones' Are Hunting Down Targets in Ukraine," *Popular Mechanics*, March 28, 2022, https://www.popularmechanics.com/military/weapons/a39517660/kamikaze-drones-in-ukraine/.

217 Audrey Decker, "Marine Corps Searching for More Autonomy out of its Organic Fires Capability," *Inside Defense*, September 17, 2021, https://insidedefense.com/daily-news/marine-corps-searching-more-autonomy-out-its-organic-fires-capability.

218 For example, the canceled AGM-136 *Tacit Rainbow* was designed to loiter over a target area for as much as 80 minutes looking for air defense radars to attack. Even if the anti-radiation missile did not find and strike an adversary's radar, it was intended to keep the radars from emitting, which would give friendly aircraft an opportunity to conduct strike missions unopposed. Alex Hollings, "America's Loitering Radar-Hunting Missile Is Due For A Comeback," *Sandboxx*, December 14, 2021, https://www.sandboxx.us/blog/americas-loitering-radar-hunting-missile-is-due-for-a-comeback/?mc_cid=db58d717e8&mc_eid=7cbf43077b.

219 Anduril Industries recently unveiled loitering munitions with "twice the range and endurance of what's currently best of breed." Chris Brose quoted in Andrew Eversden, "Meet Anduril's New Loitering Munitions, the Firm's First (But Not Last) Weapons Program," *Breaking Defense*, October 6, 2022, https://breakingdefense.com/2022/10/meet-andurils-new-loitering-munitions-the-firms-first-but-not-last-weapons-program/?mc_cid=8ac2397126&mc_eid=7cbf43077b.

to increase the amount of time available for a munition to deliver its effects.[220] Similar to mines, these weapons could be delivered to a target area (on land, sea, or undersea) from a variety of platforms, where they would wait to produce their effects until internal or external sensors detect a target.[221] These weapons could utilize organic sensors to identify their targets or could be networked to any number of external sensors and triggers.[222] Loitering and persistent weapons could enable U.S. forces to find and attack mobile targets without relying on exquisite, high-speed munitions and penetrating aircraft.

Non-kinetic payloads. Non-kinetic payloads are another opportunity for future munitions to affect multiple targets simultaneously. The U.S. military has already tested cruise missiles that use high-power microwaves (HPM) and electronic warfare to disable enemy electronics.[223] Although many non-kinetic technologies remain classified, electronic warfare packages can be included in increasingly small payloads.[224] Beyond electronic warfare, future munitions could deliver communications nodes and relays as their primary payload or in addition to other kinetic and non-kinetic packages. Munition-delivered networking nodes could play an important role in enabling other weapons or reinforcing communications between units in an A2/AD environment.[225] Other non-kinetic payloads might include sensors that increase the effectiveness of follow-on munitions. For instance, "interrogation munitions" packed with sensors could penetrate the ground to map and relay the precise location of hardened underground facilities to ensure subsequent bunker-busting weapons are maximally effective.[226] Auditory, seismic, or visual sensor payloads could lie in waiting in target areas, collecting information to update target databases and refine detection algorithms for subsequent platforms and weapons.[227] All of these non-kinetic payloads offer an opportunity to expand the munitions industrial base beyond traditional kinetic weapons

220 Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, *Report of the Defense Science Board Task Force on Future Strategic Strike Forces* (Washington, DC: Department of Defense, February 2004), pp. 6-6 – 6-7, https://dsb.cto.mil/reports/2000s/ADA421606.pdf.

221 Proven examples of these types of munitions include the Family of Scatterable Mines (FASCAM) on land and the *Quickstrike* series of naval mines. Even these legacy systems are capable of autonomous operation and self-destruction.

222 Persistent munitions could use any combination of imaging, acoustic, seismic, or other internal sensors. They could also be linked to external sensors placed nearby or triggered from afar if equipped with datalinks. The "force package" of networks, sensors, and payloads for persistent munitions must be tailored to their intended mission.

223 Such as the Counter-electronics High-powered Mircorwave Advanced Missile Project (CHAMP). See Boeing, "CHAMP – Lights Out," October 12, 2012, https://www.boeing.com/features/2012/10/bds-champ-10-22-12.page.

224 For example, the *Silent Impact* munition is a 155mm shell that contains a non-kinetic electronic warfare payload. Syracuse Research Corporation, "*Silent Impact* Munition Launched EW System," https://www.srcinc.com/products/ew-spectrum-operations/silent-impact-munition-launched-ew-system.html.

225 Alexander Bordetsky, Stephen Benson, and Wayne Hughes, "Mesh Networks in Littoral Operations," *U.S. Naval Institute Blog*, May 12, 2016, https://blog.usni.org/posts/2016/05/12/mesh-networks-in-littoral-operations.

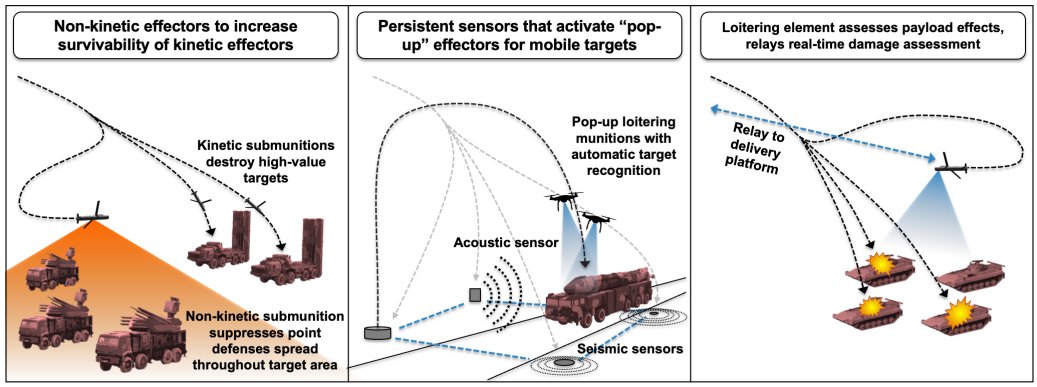
226 Office of the Under Secretary of Defense For Acquisition, Technology, and Logistics, *Report of the Defense Science Board Task Force on Future Strategic Strike Forces*, p. 6-6.

227 As part of its Advanced Remote Ground Unattended Sensor (ARGUS) program, the Air Force previously experimented with sensors capable of updating target databases and improving detection algorithms. See Vick, Moore, Pirnie, and Stillion, *Aerospace Operations Against Elusive Ground Targets*, pp. 98-100.

manufacturers.[228] For the highly-contested battlespaces of contemporary great power conflict, the U.S. military must think of munitions as more than just kinetic devices. Future weapons can enable other munitions and operations by delivering non-kinetic, communications, and sensor payloads in A2/AD environments.

Heterogenous payloads that combine complementary capabilities. Ultimately, many of these payload options should be included in modular, heterogenous mixes tailored to specific missions and targets. Modular munitions could contain mixed payloads that are mutually supportive and include sensors, network nodes, and kinetic and non-kinetic effects in a single weapon.[229] Instead of considering only delivery platform and munition pairing, weapons planners must begin to think in terms of force packages that efficiently arrange the combination of components required for particular missions.

FIGURE 21: EXAMPLE HETEROGENOUS PAYLOADS FOR VARIOUS MISSIONS



Source: Created by CSBA.

Training and Sustainment

Finally, certain innovations are essential for keeping high-tech munitions stocks ready for war.

Integrated test beds. Integrated test beds (ITBs) and virtual labs are crucial for testing munitions with extended ranges that cannot be easily live-fired. These systems are also important for evaluating collaborative weapons because repeated live testing of

228 DoD's FY2020 report on the defense industrial base noted that "the missiles and munitions sector definition could broaden through the 2020s due to changing technologies. Directed energy and cyber could enhance this sector by substituting non-kinetic weapons and effects for traditional missiles and munitions." Office of the Under Secretary of Defense for Acquisition and Sustainment, "Fiscal Year 2020 Industrial Capabilities Report," p. 85.

229 DARPA's LongShot program is already seeking to develop an unmanned aircraft with a weapons bay capable of carrying a variety of munitions. Large platforms like LongShot blur the line between UAS and modular munitions. Thomas Newdick, "General Atomics Unveils New 'LongShot' Aircraft-Launched Air-to-Air Combat Drone Rendering," *The Drive*, July 27, 2021, https://www.thedrive.com/the-war-zone/41719/general-atomics-unveils-new-longshot-aircraft-launched-air-to-air-combat-drone-rendering.

different collaborative tactics entails expending multiple munitions in each test. Virtual labs will allow planners to test millions of combinations of weapon and force packages on different targets without expending live munitions. As such, they are key to refining attack methods and developing future employment concepts. Virtual evaluation and testing will also assist the United States in keeping certain capabilities or concepts concealed from potential adversaries.

Predictive maintenance. Future PGMs will also benefit from predictive maintenance, where the use of "digital twins" and improved data collection will reduce the need for time-consuming and invasive maintenance checks.[230] These sustainment technologies are key to maintaining a large inventory of affordable PGMs that can be expended in significant volume. All smart weapons will require more intensive upkeep, so the U.S. military must pursue technologies that allow smaller troop formations to more easily and affordably maintain PGM inventories.

Conceptual Innovations

Technology is just one element of innovation key to meeting the munitions challenges of great power conflict. The United States must also think creatively about novel ways of executing traditional missions and how to best employ munitions that utilize these new technologies. New concepts should maximize the effects of legacy and future PGMs to cause the greatest dilemmas for great power adversaries. The following section highlights a range of employment and operational concepts that could reduce munitions requirements by decreasing the total number of aimpoints, increasing the chances that weapons survive to strike their targets, and attacking efficiently in volume.

Munitions as More Than Effectors

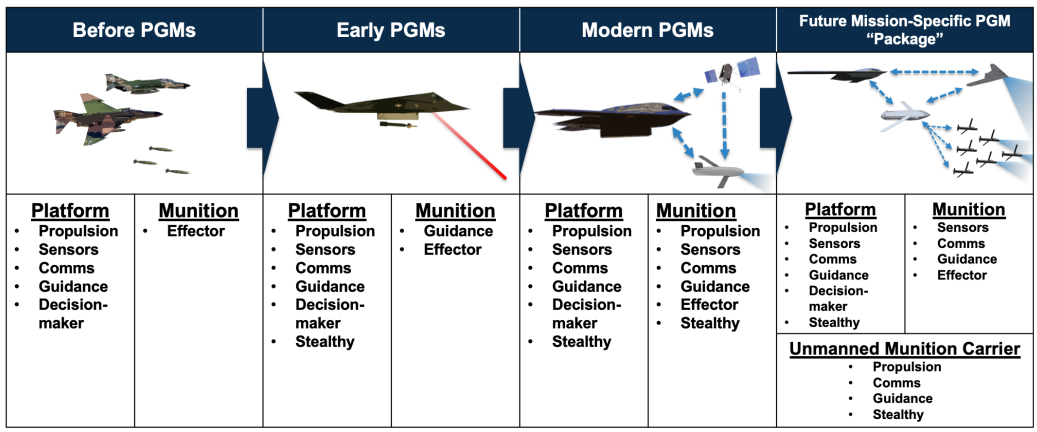
To develop and implement innovative munitions concepts, military planners must approach munitions as not just effectors, but rather as components in force packages assembled to accomplish specific missions. The munitions problem is, at its core, a resource (or component) optimization problem. The objective is to have some form of effects on a target. Given unlimited resources, every munition could resemble an unmanned aircraft with a long-distance propulsion system, advanced sensors and communications hardware, stealth characteristics, and the autonomous capability to make engagement decisions. With the previously identified fiscal and industrial base constraints, however, militaries cannot afford to expend all of these resources with every munition they launch—particularly if conflicts demand thousands or tens of thousands of weapons.

230 Frank Wolfe, "Digital Twins To Be New Hallmark for US Air Force Weapons Systems," *Aviation Today*, May 3, 2021, https://www.aviationtoday.com/2021/05/03/digital-twins-new-hallmark-us-air-force-weapons-systems/.

When components like propulsion systems, sensors, communications equipment, and other hardware are expensive, heavy, or large, it makes more sense to place them on non-attritable assets, typically delivery platforms. This arrangement is reminiscent of the pre-precision era, when munitions were little more than explosives in a steel casing. The delivery platform assumed all other functions, including carrying engagement authority in the form of pilots or weapons operators.

As the previous section illustrated, many munition components and systems are now smaller, lighter, cheaper, and more capable and reliable than ever before. Developments in commercial and military UAS and loitering munitions are actively blurring the lines between traditional PGMs and new forms of attritable and non-attritable weaponry. With these technological advancements come fresh opportunities to re-optimize the munitions arrangement and realign the placement of components between sensor platforms, delivery platforms, weapons, and other intermediaries. The first step to developing innovative munitions employment concepts is considering future munitions as not only effectors, but as pieces of broader force packages that include ISR, C2, and delivery platforms—attritable and non-attritable, manned and unmanned. Components must be arrayed between systems in a force package to efficiently accomplish the mission at hand.

FIGURE 22: OPTIMIZING MUNITION FORCE PACKAGES



Source: Created by CSBA.

Reducing the Total Number of Aimpoints

The U.S. military could reduce the number of aimpoints it must strike to achieve its objectives by reconsidering how it targets enemy forces, particularly in protracted conflict.

Targeting essential nodes. The strike campaigns examined in Chapter Two demonstrate the U.S. military's historic success in executing various forms of nodal warfare to quickly destroy an adversary's military capability. From the counter-IADS campaign of Desert Storm to strikes on transportation infrastructure in the Balkans, the targeted destruction

of nodes, chokepoints, and other single points of failure is essential to limiting munitions expenditures in great power conflict. Although this concept is not new, the technologies outlined in the previous section offer enhanced opportunities to identify, find, and disable these key assets. Persistent sensors and collaborative weapons with improved seekers can observe and refine their attacks to ensure these high-value targets are neutralized. Advances in target detection and recognition algorithms will increase the chances of future PGMs having the desired effects on vulnerable points, such as striking an enemy ship's bridge or C2 center. Modular weapons with specialized payloads could allow strikes against previously unreachable or hard-to-kill nodes. Rather than attacking entire airfields or port facilities, future PGM employment concepts can use enhanced precision and other effects to target and destroy the single points of failure inherent in these targets. Military planners must ensure that exquisite and "silver bullet" weapons are employed to strike these essential nodes and take full advantage of their advanced capabilities, which will reduce the quantity of munitions needed to subdue adversary basing, infrastructure, and C4ISR systems.

Virtual attrition concepts. Another existing concept that can be enhanced by improvements in weapon technology is virtual attrition. For some targets and objectives, physical destruction may not be necessary in every scenario. Rather than physically destroying a large target set by striking an equal or larger number of aimpoints, virtual attrition focuses on reducing the adversary's operational effectiveness to a level sufficient to achieve operational objectives. For example, rather than attempting to find and destroy mobile SAM launchers through targeted strikes, the steady presence of TEL-hunting forces could ensure that air defense forces remain hidden, stay mobile, avoid emplacing for significant periods of time, or keep their emitters switched off in fear of being detected.[231] Similar virtual attrition concepts could center around hypersonic munitions, area effect and area denial weapons, munitions with persistent sensors and effects, and non-kinetic weapons. All of these technologies present opportunities to produce virtual attrition while consuming fewer resources than a campaign focused on physical attrition. Virtual attrition, like deterrence, relies on affecting the adversary's thinking and planning. As such, it still requires U.S. forces to possess and use a number of weapons to demonstrate capability and influence adversary behavior. Even so, virtual attrition concepts require further examination and could be exploited to reduce total munitions expenditure by striking fewer aimpoints but accomplishing the same objectives as physical attrition.

Attacking fixed elements of mobile target kill chains. Finally, U.S. forces could reduce the number of aimpoints associated with mobile and elusive targets by focusing attacks on the fixed and unhardened elements of these forces' kill chains and support infrastructure. Most mobile targets will remain stationary during tasks such as refueling,

231 As was the case against Serbia in 1999. Although U.S. efforts in Operation Allied Force did not result in the destruction of Serbian air defense systems (as covered in Chapter Two), the SEAD campaign forced Serbian SAMs to remain mobile and emit intermittently. U.S. air forces suffered low casualties, making these efforts a success by some measures. See Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.–China Military Scorecard*, p. 128.

rearming, or embarking cargo. Nearly all mobile targets are reliant on some form of fixed or vulnerable infrastructure, such as hides or shelters, port facilities, ammunition dumps, POL points, or even planned assembly areas. By identifying and focusing strikes on these assets, the U.S. military can reduce the number of PGMs expended on hard-to-kill mobile targets. Stopping a PLA invasion force is less ISR and munitions intensive if the campaign is focused on disabling loading and port facilities rather than sinking every transport during transit. Likewise, mobile SAM launchers require missile and fuel resupplies. Even if they are resupplied in the field using tailgate sustainment methods, their munitions and fuel trains draw from fixed dumps, depots, and storage sites. Moreover, disabling key bridges and other road and rail chokepoints may hinder the mobility of launchers and their sustainment trains. Even PLA Rocket Force TELs using impenetrable mountainside shelters and tunnels could be targeted by destroying the openings of these shelters and the connecting road networks. Although targeting these assets may not prevent PLA forces from firing their initial salvo of missiles or opposing U.S. forces altogether, doing so could accomplish some U.S. objectives at a reduced munitions consumption rate over an extended period.

Increasing Munition Survivability and Effectiveness

Other concepts can improve the chances that a munition successfully reaches its target by increasing attack complexity and degrading the effectiveness of adversary defenses.

Heterogenous salvos. At the tactical level, heterogenous salvos of munitions and submunitions can be utilized to create multiple dilemmas for the enemy and increase weapon effectiveness. For example, employing a salvo (or force package) that includes a mix of PGMs with different sensor phenomenologies and varied payloads could increase the chances that some of the weapons evade defenses, find their targets, and produce the desired effects. The goal of these concepts is to create salvos and attacks where one defensive system, posture, countermeasure, or tactic will not defeat a strike or render it ineffective. By utilizing strikes with mixes of inexpensive PGMs, the U.S. military can create uncertainty and impose costs on the defender by forcing them to defend against multiple types of threats.

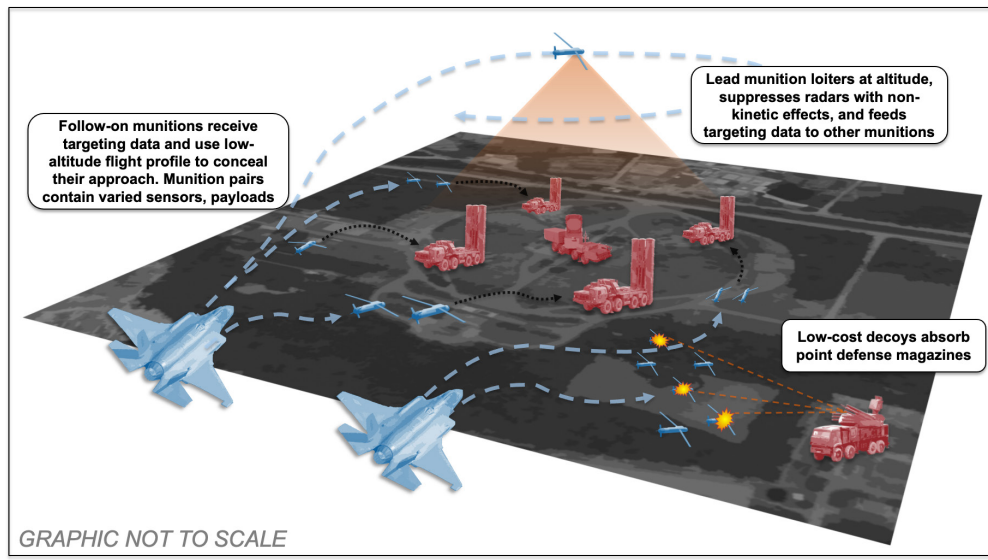
Complex coordinated attacks. At the operational level, heterogenous salvos can be scaled up to create coordinated attacks by multiple weapon types across numerous domains. Varied mixes of stand-in and stand-off weapons with different flight profiles, speeds, payloads, and effects can be combined in one strike operation to create simultaneous or sequenced attacks from multiple directions that disrupt enemy defensive systems and procedures. Joint warfighting concepts are key to integrating multi-domain strike capabilities from across the military services and making these complex attacks a reality. Organizations such as the Army's Fires Center of Excellence, the Air Force's Standoff Munitions Application Center, the Naval Air Warfare Center Weapons Division, or the Naval Surface

Warfare Centers are vital for synthesizing technical capabilities and employment techniques into broader multi-domain concepts tailored to solve specific operational challenges.[232]

DoD should assess the operational and cost-effectiveness of these concepts, as well as the degree to which they limit the risk assumed by various U.S. forces. "Silver bullet" hypersonics and long-range ground-launched weapons may be expensive, but if they are used as part of a complex attack to neutralize defensive systems that might otherwise down a $700 million B-21 bomber, even a unit cost of $5 to $15 million becomes more acceptable. Scenarios like this speak to the need for DoD to first consider various operational challenges, potential concepts to address them, the broad spectrum of capabilities available, and their various tradeoffs—rather than looking at an operational challenge and asking how a specific capability solves that problem.

One mission that illustrates the potential of heterogenous salvos and complex attack concepts is the suppression and destruction of enemy air defenses, or SEAD/DEAD. At the tactical echelon, future PGMs can be employed in salvos that contain mixes of sensors and payloads to confuse defenses and increase the weapons' survivability. These packages can be tested and modified using virtual labs to create the most efficient package for the targeted SAM systems and their kill chains.

FIGURE 23: COMPLEX SEAD/DEAD TACTICS TO INCREASE MUNITION SURVIVABILITY AND EFFECTIVENESS



Source: Created by CSBA.

232 See U.S. Army Fires Center of Excellence, "CDID Capabilities Development and Integration Directorate," https://sill-www.army.mil/cdid/; 8th Air Force, "Standoff Munitions Application Center," https://www.8af.af.mil/Units/Standoff-Munitions-Application-Center/; Naval Sea Systems Command, "Warfare Centers," https://www.navsea.navy.mil/Home/Warfare-Centers/; and Naval Air Warfare Center, "NAWCWD," https://www.navair.navy.mil/nawcwd/.

At higher echelons, various weapon packages could be coordinated at the operational level to temporarily degrade enemy air and missile defenses in a region and enable follow-on strikes with decreased probabilities of intercept. Previous studies have referred to these as "tunneling" operations.[233] These attacks could be modern versions of Cold War Soviet SEAD plans, which envisioned "sanitized" attack corridors kept free of NATO defenses through jamming, chaff, and potentially nuclear weapons.[234] Even modern air defense systems are limited by the number of targets their sensors can track simultaneously, their firing rate, and their magazine size and reload times. Rather than aircraft jamming enemy sensors or dropping chaff, initial waves of inexpensive munitions or purpose-built decoys could overwhelm enemy defenses and force them to expend their magazines before subsequent waves of more advanced munitions strike targets in these now undefended sectors.[235] Munitions with non-kinetic effects could also be used to temporarily disable defenses for follow-on strikes.

Generating Precision Effects in Volume

Most importantly, the U.S. military needs concepts to enable the precision effects it has come to rely on in the volumes necessary for great power conflict. The preceding section identified modernized area-effect weapons as a technological innovation that could increase the number of aimpoints each PGM could attack. These weapons could be combined with the following procurement concepts to generate precision effects in greater volume.

Procurement of range and cost-balanced PGMs. DoD could pursue munitions that optimally balance range, speed, size, and cost to enable large-quantity procurement and delivery. Figure 24 shows the relationships between range, speed, and cost to illustrate the increasing cost-effectiveness of additional range and speed. This type of cost analysis should be paired with scenario analysis (similar to Chapter Three) and an assessment of weapon size and weight to determine the optimum range for future weapons ideal for the Indo-Pacific theater.[236] Cost must be considered in order to procure large quantities of these PGMs. Size and weight must be considered to allow delivery platforms to carry large quantities of these same PGMs. Finally, range and speed must be balanced with these competing characteristics to ensure PGMs have maximum utility in potential conflict scenarios. The fielding of greater numbers of penetrating aircraft like the F-35 and B-21 will enable these weapons by allowing delivery platforms to get closer to their targets and reducing the minimum range requirements for munitions.

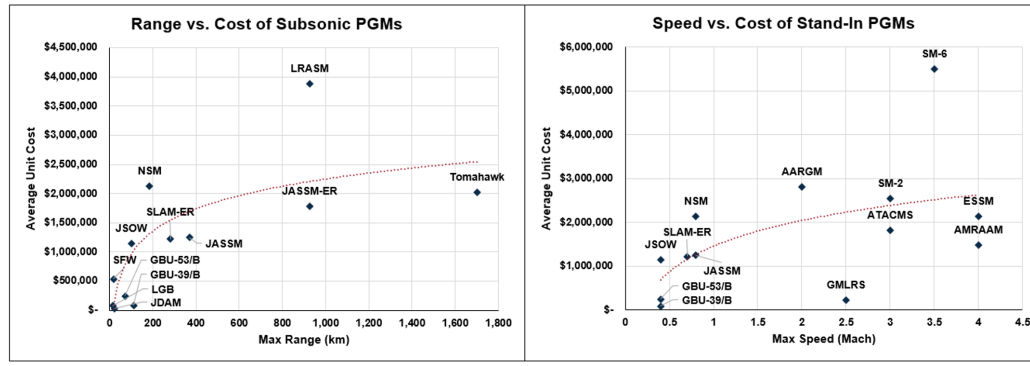
233 Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, pp. 37–38.

234 J.P. Santiago, "Soviet Wild Weasels: Part One (Doctrine/Tactics)," *Tails Through Time*, December 16, 2010, http://aviationtrivia.blogspot.com/2010/12/soviet-wild-weasels-part-one.html.

235 Ukraine has accused Russia of utilizing decoys to attempt to overwhelm Ukrainian air defenses and increase the survivability of Russian missiles. John Leicester and Hanna Arhirova, "Ukraine Says Russia Turns to Decoy Missiles, Intel Balloons," *AP News*, February 16, 2023, https://apnews.com/article/russia-ukraine-81de149dcbd4eaf8830879decc5614a4.

236 An example of size and weight analysis can be found Gunzinger and Clark, *Sustaining America's Precision Strike Advantage*, pp. 35–37.

FIGURE 24: RELATIONSHIPS BETWEEN PGM RANGE, SPEED, AND COST



Source: Created by CSBA using data from DoD budget documents from FY1998 to FY2023 and *Jane's* database. Unit costs are averages based upon FY1998 to FY2023 procurement.

Revised requirements for "second-tier" PGMs. To this point, PGM development has mainly focused on implementing new technologies and providing each weapon with the greatest number of advanced capabilities. The result is the current portfolio of exquisite PGMs that are produced and procured in numbers insufficient for great power conflict. To strike the volume of targets required in future campaigns, DoD may consider revising munitions requirements to develop and stock high quantities of simpler PGMs with the minimum capability required for their intended mission. If needed, some capabilities could be shifted to a reusable launch platform. By examining future target sets and potential campaigns, the U.S. military could estimate the number of targets that do not require capabilities such as a CEP of less than 3 meters, advanced sensors and target recognition, or low observable characteristics. DoD could create requirements for munitions "just good enough" to strike these targets at reduced costs. Although not individually survivable in many Indo-Pacific scenarios, Iranian, Russian, and Israeli loitering munitions show that long-range can be achieved at a reduced cost.[237]

Ideally, a future PGM portfolio would include second-tier PGMs in each range category to maximize the number of targets that could be attacked with simpler weapons. This idea draws on previous U.S. weapons, such as the M3 submachine gun, designed during WWII to supplement and replace the M1A1 *Thompson*, which was complex and expensive to produce. Realizing that many personnel who were issued the *Thompson*, such as vehicle crewmembers, did not require its ergonomics, the Army issued new requirements for a simpler, less expensive submachine gun. The resulting M3 consisted almost entirely of

237 Chris Gordon, "Cheap UAVs Exact High Costs," *Air & Space Forces Magazine*, January 20, 2023, https://www.airandspaceforces.com/article/cheap-uavs-exact-high-costs/; and David Axe, "Take a Look at Russia's New 'Suicide Drones'," *National Interest*, November 9, 2021, https://nationalinterest.org/blog/reboot/take-look-russias-new-suicide-drones-195929.

spot-welded stamped or pressed steel and was cheaply manufactured to equip large numbers of personnel for the duration of the war.[238]

Second-tier weapons would also allow capabilities to be disaggregated and distributed across salvos and force packages. Large quantities of simpler PGMs could be enhanced by utilizing them in packages that contain smaller quantities of other enabling weapons. In this manner, a group of second-tier munitions could be escorted into a target area by a more exquisite weapon with non-kinetic effects to suppress enemy defenses or advanced sensors to feed targeting data to second-tier weapons that lack their own sensors.

Unmanned munition carriers. To increase payload capacity and mass effects, "Loyal Wingman" type UAS could be utilized as munitions trucks to carry additional munitions in strike packages. Through manned-unmanned teaming (MUM-T), munitions-carrying UAS would not require advanced autonomous decision-making or sensors, only the capability to take off, land, and take commands from a manned "mothership" aircraft. The services are already experimenting with MUM-T concepts pairing the AH-64 *Apache* attack helicopter with the MQ-1C *Gray Eagle* and the F-35 and F-15EX with the XQ-58 *Valkyrie*.[239] These systems could not only reduce the risk for manned aircraft but could also greatly expand the strike capacity of platforms like the F-35 by allowing a single aircraft to coordinate the massing of a larger quantity of PGMs from multiple unmanned wingmen. In addition to unmanned aircraft, unmanned surface and undersea vessels could provide similar capabilities to U.S. maritime strike platforms. Unmanned munitions trucks would also be key to creating the capacity to execute many of the other concepts outlined in this monograph, such as heterogenous salvos and complex attacks.

...

New weapons technologies and the concepts to employ these advancements are essential for preparing the U.S. PGM arsenal for great power conflict. The innovations highlighted in this chapter represent opportunities to rethink the U.S. approach to munitions, reduce PGM requirements, and rebalance the cost ratio between attacker and defender. Just as U.S. adversaries have adapted to the precision-strike complex, the U.S. military must now move beyond precision to maintain its strike advantage in future conflicts.

238 Patrick J. Chaisson, "The Controversial M3 Grease Gun," *WWII History* 20, no. 2, April 2021, https://warfarehistorynetwork.com/article/the-controversial-m3-grease-gun/.

239 Becki Bryant, "Aerial MUM-T Reaches New Heights at DPG," *Army.mil*, October 27, 2020, https://www.army.mil/article/240283/aerial_mum_t_reaches_new_heights_at_dpg; and Valerie Insinna, "Under Skyborg Program, F-35 And F-15EX Jets Could Control Drone Sidekicks," *Defense News*, May 22, 2019, https://www.defensenews.com/air/2019/05/22/under-skyborg-program-f-35-and-f-15ex-jets-could-control-drone-sidekicks/.

CHAPTER 6

Findings and Recommendations

This study has revealed the inadequacies of the U.S. PGM portfolio for the demands of 21st-century great power conflict. Based on the historical evolution of precision-strike and CSBA's evaluation of potential conflict scenarios in the Indo-Pacific, the U.S. military should consider the following key findings and recommendations to fill critical PGM capacity and capability gaps.

Key Findings

Previous assumptions about munitions production and consumption do not apply to contemporary great power conflict. Three key planning assumptions that informed the U.S. military's current PGM inventory no longer hold and must be reexamined:

1. *A conflict between the United States and a great power adversary would be rapid and short in duration, allowing the U.S. military to rely on small inventories of advanced stand-off munitions.* History and our examination of prospective Indo-Pacific conflict scenarios indicate that great power conflict is more likely to be protracted and could last months or years. The current fighting in the Russia-Ukraine war reinforces this view.

2. *PGM production and procurement are of less importance than that of platforms because munitions production can be rapidly surged to meet the demands of a conflict.* The complexity of today's PGMs and the state of the munitions industrial base mean that production of many PGMs essential to great power conflict cannot be quickly surged. On-hand quantities may be the only weapons available in the first months of a conflict, depending on the munition and the complexity of its supply chain and manufacturing process.

3. *The precision-strike advantage by itself will continue to enable the United States to dominate its adversaries in contemporary great power conflict.* Although precision was sufficient in the regional and limited strike campaigns of the previous 30 years, today's adversaries have spent decades preparing to counter U.S. precision-strike operations. As a result, the munitions requirements for great power conflict are likely to exceed the quantities and capabilities of the current U.S. PGM inventory.

An examination of munitions requirements for great power conflict reveals that the United States has significant capacity and capability gaps in its current PGM portfolio. PGM procurement to date has mostly been driven by operational usage and unit cost rather than by long-term strategy or analysis. In addition to an overall PGM capacity gap that has reappeared throughout campaigns in the Middle East, the U.S. military lacks sufficient quantities of weapons with the range and features ideal for conflict in the Indo-Pacific. Current PGM stocks are insufficient to provide precision effects in volume during a protracted conflict.

Beyond capacity, our examination of potential great power conflict scenarios exposes several capability gaps in the U.S. military's current array of PGMs. Given the existing U.S. military force structure, which consists of mostly non-penetrating bombers and short-range fighters, many fielded PGMs suffer from insufficient range and survivability. A majority of current weapon programs are subsonic and rely on external guidance support that increases the demands on targeting processes and makes them unsuitable for time-sensitive and mobile targets. The U.S. PGM inventory also lacks non-kinetic options and weapons designed to attack hardened and deeply buried targets, wide area targets, and airfields.

Even with increased spending on and production of PGMs, the United States will likely struggle to maintain adequate quantities of PGMs to execute a comprehensive precision-strike campaign against a great power adversary. Unlike previous U.S. campaigns against regional opponents, the number of targets, extended distances, and density of defenses in a contemporary great power conflict create staggering munitions requirements for a comprehensive, protracted campaign. Conducting a campaign with a similar target set and depth as that of Desert Storm or Iraqi Freedom would involve tens of thousands of targets, many of them mobile, heavily defended, and/or spread throughout vast geographic areas. Short of total mobilization, realistic fiscal and industrial constraints mean the United States is likely incapable of maintaining PGM stocks adequate for such operations.

Simply put, DoD may not be able to quickly spend or produce its way out of its current PGM shortcomings in the near term. Instead, the U.S. military may be forced to rethink how it intends to accomplish certain operational objectives in a great power conflict. In addition to maximizing the production of critical munitions, the U.S. military must develop new weapons and concepts suited for fighting today's great power adversaries.

Precision alone is necessary but insufficient for munitions in modern great power conflict. Future wars will require PGMs with advanced features such as semi-autonomous and collaborative capabilities, integrated sensors, automatic target recognition, loitering capabilities, and heterogenous payloads that include both kinetic and non-kinetic effects. Many of these features are not wholly new but are becoming inexpensive and ubiquitous thanks to commercial and government advances in microelectronics and computing.

These features offer solutions to the capacity and capability gaps described above. Next-generation PGMs could reduce total munitions requirements to more feasible levels by multiplying the effects of each weapon. Rather than expending numerous PGMs on a single target, future technologies and concepts could allow each PGM to affect multiple targets.

Several variables have outsized effects on munitions requirements for great power conflict, including the operational objectives, the proportion of targets that must be attacked to achieve these objectives, and the effectiveness of enemy defenses. The scenarios outlined in Chapter Three show how the operational objectives (and, by corollary, the target set) of a precision-strike campaign influence the numbers and kinds of PGMs required. Planning assumptions, such as the ability to strike mainland targets or dual-use targets and the availability of long-range penetrating strike platforms, are particularly key to assessing a scenario's munitions requirements. These assumptions reveal the value of strategic and operational wargaming of munitions mixes in addition to more in-depth (and myopic) modeling and simulation.

In addition to objectives and targets, assumptions about the depth of the total target set that must be affected are also key determinants of munitions requirements. Sinking a quarter or even a half of a Taiwan invasion fleet is a much different munitions problem than attacking all three hundred or more vessels. Finally, the effectiveness of enemy defenses at keeping delivery platforms at stand-off ranges and intercepting PGMs greatly affects both the quantity of munitions required and the ideal characteristics of those weapons. More effective defenses necessitate PGMs and delivery platforms with longer ranges and more advanced survivability features, as well as more complex attack concepts.

Conflict duration is a major determinant of munitions requirements and, as a result, could influence campaign objectives. Chapter Three's scenarios show how rapid and protracted conflicts have different operational objectives and target sets. If a conflict is expected to become prolonged, then a limited inventory of weapons may be better expended on force regeneration assets instead of more numerous and attritable forces or easily repairable basing and infrastructure. In a protracted conflict scenario, the United States must consider its long-term advantages and weaknesses relative to a great power adversary and utilize its PGMs to reduce that adversary's long-term comparative advantage. Against the PRC, this advantage may be their ability to rapidly manufacture and replace munitions and other defense materiel. For this reason, a protracted conflict may favor a campaign that targets defense production and sustainment infrastructure, such as scenario

five in this study. Further research is needed to assess how the PRC's munitions stocks and industrial base compare to that of the United States.

Maintaining the United States' strike advantage requires more than munitions; it requires improvements along the entire kill chain. Many of the issues and constraints outlined in this monograph also apply to ISR assets, targeting processes, network infrastructure, and delivery platforms. As the final effector in a kill chain, however, munitions are of particular importance and require near-term attention due to long-term neglect. The use of large numbers of PGMs also creates unprecedented demands on sensors, ISR platforms, and staff targeting processes, particularly if PGMs do not possess internal sensing and guidance capabilities. Persistent surveillance technologies, AI-assisted data processing, and in-depth intelligence preparation of the battlefield may help alleviate these demands. Large numbers of networked PGMs with internal sensors also increase demands for network bandwidth and robustness. DoD's current JADC2 efforts seek to fill these requirements, but it remains to be seen how these networking and C2 programs materialize in scale.

Recommendations

The United States must prepare its PGM inventories for the potential of protracted great power conflict. Given fiscal, industrial, and political constraints, the U.S. military should implement a time-phased set of recommendations to address both its near-term and long-run PGM and industrial base challenges. The following recommendations, phased by five-year Future Years Defense Programs (FYDPs), can help the U.S. military achieve these ends.

Near-Term: Recommendations within the FYDP (2023 to 2027)

In the near term, the United States must rapidly increase PGM procurement to bolster its preparedness for a conflict in the coming years, before it can amass large quantities of critical PGMs or significantly expand its munitions industrial base. The U.S. military must move quickly to maintain the precision-strike advantage of its current force structure in operations within the "Davidson window."

Immediately increase munitions funding and procurement to maximize the production of critical precision munitions. The scenarios explored in Chapter Three highlight several essential categories of weapons for a conflict in the Indo-Pacific theater, including anti-ship and anti-air munitions, stand-off munitions to equip non-penetrating bombers and tactical aircraft, and intelligent loitering munitions capable of striking moving targets. Given current manufacturing capacity, the military services should maximize purchases of these weapons within the FYDP in order to reinforce current stockpiles and prepare for a conflict in the near term. PGM procurement quantities should reflect the reality that today's munitions cannot be rapidly surged and must be stocked in quantities

sufficient for potential conflict scenarios. As this study concludes, it appears that DoD is requesting funds for larger quantities of key PGMs, but it remains to be seen how these requests translate into increased appropriations, contracts, and deliveries.[240]

Align PGM procurement spending with the requirements of long-term strategy and analysis rather than simply replacing weapons expended in recent operations. As increased procurement of essential PGMs begins reducing critical near-term capability and capacity gaps, the Department must ensure that munitions funding and requirements for the remainder of the FYDP are driven by thorough analysis with a long-term focus. The scenarios presented in this monograph show the value that wargaming and campaign analysis bring to determining the munitions requirements for future conflicts. Based on the 2018 and 2022 National Defense Strategies, these changes should manifest in more balanced spending between delivery platforms and munitions and between short- and long-range weapons.

Ultimately, DoD must avoid thinking of inexpensive munitions as replacements for exquisite weapons, or exquisite long-range PGMs as replacements for high-tech delivery platforms. Rather, these systems should complement each other's capabilities as components of a strike package. For instance, advanced aircraft will benefit from long-range munitions that reduce their attrition and short-range munitions that increase the volume of effects they can deliver. Exquisite munitions will benefit from simpler weapons carrying sensors and decoys to augment their effectiveness.

Incentivize expansion of the weapons industrial base by committing to consistent munitions purchases through multi-year procurement, direct investments, and other policies that foster a steady demand signal for precision weapons. Beyond additional spending to maximize active production lines, near-term investments must support the expansion of the weapons industrial base beyond the current FYDP. Building additional manufacturing capacity will take years, so the United States must make adequate purchases and investments in the near term to create additional capacity over the next several years. The military services should continue using multi-year procurements and other measures taken in response to the Russia-Ukraine conflict to kick-start the industrial base and signal a commitment to sustained munitions spending. The Defense Department may also wish to explore direct investment in additional production capacity or the maintenance of surge capacity to ensure that weapons manufacturing can be scaled to support a prolonged conflict. Finally, DoD should explore other policies to incentivize the expansion of the munitions industrial base, such as streamlining foreign military sales and export requirements to support foreign buys of U.S. weapons, fostering joint development

240 For example, see Anthony Capaccio, "Pentagon Puts Priority on Replacing Munitions in 2024 Budget," *Bloomberg*, March 10, 2023, https://www.bloomberg.com/news/articles/2023-03-11/pentagon-puts-priority-on-replacing-munitions-in-2024-budget?srnd=premium&sref=IYQ5mP1s&mc_cid=ba555218d5&mc_eid=7cbf43077b&leadSource=uverify%20wall#xj4y7vzkg.

opportunities with allied nations, large lot purchases of common subcomponents, or offering tax credits and other incentives for the construction and maintenance of excess capacity.

Bolster the current PGM arsenal with rapidly producible modular kits and modifications to operational weapons. While increasing procurement of current PGM programs, DoD should expand the capabilities of these weapons using the modular kits explored in the previous chapter. These modifications should rely on mature technologies to fill key capability and capacity gaps. Glide kits and add-on propulsion systems can be fielded within the FYDP to extend the range of many PGMs and equip non-stealthy platforms. These kits should be prioritized to fill urgent capability and capacity gaps, such as maritime strike, emplacing naval mines, and attacking mobile targets. Modular kits can be expanded with inexpensive, proven sensors and datalinks to increase their effectiveness in great power conflict. When possible, the Department and industry should take advantage of advances in commercial technologies related to sensors, networking, and autonomy to augment these kits.

Beyond modular kits for existing payloads, DoD should field additional payloads in already-fielded munitions. These payloads could include more powerful energetics, non-kinetic effectors, persistent sensors, or policy-compliant area effects that provide multiple precision effects within a large target area. Both modular kits and new payloads can be fielded on expedited timelines that leverage existing weapon-platform integration. Together, they would allow more weapons within the United States' current precision arsenal to service a greater number of targets with increased lethality.

Consider campaigns, operational concepts, and target sets that enable the current portfolio of precision weapons to be most effective, particularly in a protracted conflict. Creative operational concepts can help reduce total munitions requirements in a great power conflict. In the near term, the U.S. military can reduce the number of aimpoints in a strike campaign by targeting essential nodes, utilizing virtual attrition concepts, and attacking the fixed elements of mobile target kill chains. Focusing attacks on the key elements of adversary kill chains, command networks, and transportation and sustainment architectures may accomplish U.S. objectives using smaller quantities of munitions. Likewise, striking fixed pieces of mobile target support chains would allow U.S. forces to employ GPS-guided munitions, which make up a majority of its current PGM inventory. Until new munitions with additional capability can fill the capability gaps explored in Chapter Three, planners must explore innovative methods of accomplishing campaign objectives using the current precision arsenal.

Medium-Term: Recommendations for the Next FYDP (2028 to 2032)

By the late 2020s and early 2030s, a steady demand signal driven by near-term investments in munitions and their industrial base will expand production capacity for the weapons essential to future great power conflict. At that point, the Department should continue to shape the growth of the industrial base through requirements for resilient supply chains

and advanced manufacturing processes. These middle years are key to designing and experimenting with new munitions designs that operationalize advanced technologies as they mature.

Continue expanding the active and surge capacity of the munitions industrial base with a focus on resilient and redundant rather than lean supply chains. While maintaining a steady demand signal through continued procurement, the Department should implement policies, requirements, and incentives that push weapon manufacturers to shift from a reliance on "just-in-time" to "just-in-case" supply chain models for select programs or components. Of course, this shift will reduce efficiency and increase costs, so analysis is key to prioritizing resiliency between weapon programs and determining which pieces or components of a munition are suited for just-in-case versus just-in-time methods. In determining these requirements, the Department should also study the most operational- and cost-effective balance between maintaining stockpiles and maintaining excess production capacity of different munitions. Increased costs will drive DoD to prioritize excess capacity and resiliency, making analysis key to ensuring that these expenditures match future requirements.

Implement open architectures and digital engineering into new munitions designs to take advantage of modularity and advanced manufacturing methods. Beyond spending more on current PGMs, in the medium term, the U.S. military must develop the next generation of weapons that fully utilize the technologies outlined in this study to enable their rapid development and large-scale production. These weapons should begin by leveraging digital engineering and modular architectures to ease their manufacturing requirements, expand their supply chains to more commercial producers, and increase their operational versatility. Automated production and additive manufacturing can alleviate workforce issues and allow future munitions to be affordably produced in large quantities. Modular and versatile designs fill capacity gaps by reducing procurement tradeoffs and allowing weapons (or components of weapons) to be used in a greater number of scenarios. These advancements are already happening on a small scale and should be implemented across programs and producers by the late 2020s.

Continue experimenting with and fielding advanced munitions technologies to fill current capability gaps. By the middle 2020s, technologies developed in the current FYDP should be widely fielded throughout the force. These advancements include exquisite and low-cost sensors that free PGMs from reliance on external targeting support and enable them to better track and attack mobile targets, collaborative and loitering capabilities that allow weapons to work together to attack wide area and elusive targets effectively and efficiently, and area effect payloads that reduce the quantity of munitions required to attack large and complex targets. Additionally, hypersonic weapons should be fielded in greater numbers as current programs mature and costs are reduced.

In the medium-term, the services should continue experimentation with the more advanced technologies highlighted in this study, including interchangeable "mix-and-match"

munitions, advanced propulsion, improved automatic target recognition and data collection, non-kinetic effects, and heterogenous payloads.

Pursue an affordable mix of exquisite and cheap PGMs to enable "affordable precision in mass". Modular designs, digital engineering, and advanced manufacturing techniques can open the door to inexpensive weapons producible at scale. The Department should experiment with and pursue PGMs that, in combination with delivery platforms, optimally balance features such as range, speed, and cost to ensure adequate quantities can be procured for great power conflict. This balance might include developing and procuring "second-tier" PGMs with minimum capabilities that are inexpensive enough to be stocked in high quantities. In tandem with unmanned munition carriers, these second-tier PGMs could enable tactical aircraft such as the F-35 or naval vessels to guide the delivery of an unprecedented volume of precision effects. As delivery platforms evolve and more long-range penetrating strike platforms are fielded, the Department should actively reassess the balance of capability between its platforms and weapons.

Develop new employment techniques and operational concepts that leverage the advanced features of next-generation PGMs. As technologies and weapons evolve, the U.S. military must implement innovative concepts that employ these weapons in the most effective manner. U.S. forces should utilize heterogenous salvos and complex coordinated attacks from multiple domains to increase munition survivability and effectiveness. Underpinning these concepts is the idea that future munitions will be more than just effectors. As components in broader force packages of sensors and delivery platforms, DoD must optimize munition force packages to carry out specific missions in the most resource-efficient manner. To increase the options available and better examine tradeoffs when constructing force packages, the services should first develop concepts to address operational challenges, and then use these concepts to determine priority capabilities and requirements. The PGMs of tomorrow will provide their package with more capability than a short-lasted kinetic effect, and U.S. warfighting concepts must leverage these new capabilities accordingly.

Long-Term: Preparing for Beyond 2033

In the long run, the U.S. military must shape its PGM portfolio around its evolving force structure and the need to provide an immense volume of effects against an adversary striving to modernize its defenses at an equivalent rate. Maintaining America's strike advantage will require new PGM designs that leverage technologies matured in the 2020s and are stocked in quantities adequate for future great power conflict.

Procure a mix of PGMs that complement next-generation platforms as they are fielded in the 2030s. The U.S. military's current force structure, particularly in the air domain, is centered around legacy platforms that require stand-off munitions to confront the distances and defenses associated with the Indo-Pacific theater. By the 2030s, however, the fielding of significant numbers of long-range, penetrating B-21 bombers will shift the

favored balance between stand-off and stand-in weapons and increase the volume of short-range munitions the U.S. military can deliver in contested environments at reduced costs. Similar force structure shifts may occur as stand-in ground forces are deployed and the Navy fields unmanned surface and undersea vessels. Given the continued tradeoff between munition range and cost, each of these changes in force structure and posture presents new opportunities to reexamine the alignment of range and capability between delivery platforms, munitions, and other intermediaries.

Concurrently, the Chinese military will continue to modernize and evolve its own force structure. The PLA will likely continue to push its defensive perimeter outward from the mainland and may seek to bolster its own long-range strike capacity. The U.S. military must continually adjust its weapon-platform pairing and force packages to confront these developments.

Develop and field munitions that utilize advanced technologies to fill long-running capability gaps, reduce planning tradeoffs, and outpace adversary countermeasures. Some of the technologies highlighted in this monograph may not be sufficiently mature for operational use until the 2030s. Continued investment in artificial intelligence and computing underwrite future progress in stealth, speed, and autonomy that will increase PGM survivability and effectiveness. The Department of Defense must fund not only the research and development of the weapons-related technologies explored in the previous chapter, but also their operationalization in the next decade. DoD must avoid the development of advanced weapons that never become programs of record, such as LOCAAS or the Tri-Service Standoff Attack Missile (TSSAM).

Refine employment techniques and operational concepts to utilize advanced munitions and future force packages to create the greatest advantage. The Department must constantly explore innovative concepts that most effectively employ the advanced capabilities of future weapons. As further generations of PGMs are fielded, the U.S. military should continually redesign its force packages to create kill chains to address the evolving threat. These packages must include not only future delivery platforms and weapons, but also future unmanned ISR platforms and intermediaries such as attritable UAS and unmanned munitions trucks. Planners should use increasingly capable modeling, simulation, and integrated test beds to create force packages that deliver the greatest volume of effects on target sets while minimizing risk, attrition, and cost to levels appropriate for protracted great power conflict.

Final Thoughts

Just as early PGMs and precision-strike concepts faced criticism, so too will the weapons and ideas presented in this monograph. Former Secretary of Defense Bill Perry noted the resistance encountered while implementing the second offset strategy:

> ...there was no shortage of critics in those days who questioned whether we could depend on technology. They argued that, when this modern technology was put into combat, the fog of war would make it ineffective. They also argued that this technology would be too sophisticated, too complex for our military personnel to operate and maintain.[241]

Ultimately, operations in Desert Storm vindicated supporters of precision strike. Of course, the Defense Department should not trick itself into believing that technology alone can solve the challenges of preparing its PGM inventories for great power conflict. In many cases of protracted war, there is no substitute for maintaining large quantities of "dumb" weapons and the industrial base capacity to rapidly produce more. Quantity is a quality of its own, and no technology will ever fully replace it, particularly with expendable weaponry. But refusing to utilize the United States' enduring technological advantage to its fullest potential risks the effectiveness of future military operations where PGM demands will inevitably exceed supplies.

As this study concludes, it appears the U.S. government is moving to greatly increase munitions funding, including funding for some types of weapons recommended by this monograph. The FY2023 NDAA authorizes multi-year procurements of large numbers of JAGMs, *Harpoons*, NSMs, GMLRS, AMRAAMs, LRASMs, JASSMs, and SM-6 missiles.[242] These actions are positive signs of the U.S. Congress and military accepting the inadequacy of current U.S. stocks. Still, these procurements appear to be mostly driven by operational usage in Ukraine and ensuing panic about the state of U.S. inventories. Long-term strategy, analysis, and creative thought remain lacking. These purchases are a positive step, but the potential for prolonged great power conflict requires a deeper look and innovative thinking about the U.S. precision-strike portfolio. This monograph has attempted to provide a step toward looking beyond precision at the munitions requirements of tomorrow's conflicts.

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APPENDIX A

Appendix A: Historical Strike Campaign Munitions Data

This appendix contains Table 1, annotated with a full list of sources and notes.

	Desert Storm 1990 – 1991	Allied Force 1999	Enduring Freedom 2001	Iraqi Freedom 2003	Odyssey Dawn Unified Protector (NATO combined) 2011	Inherent Resolve 2014 – 2019
Length (days)	43	78	176	30	234[1]	~1,700
Total Sorties	116,000[2]	38,004[3]	~25,000[4]	47,600[5]	26,500+[6]	234,000[7]
Average Sorties/ Day	2,500[8]	200 – 1,000[9]	~100[10]	~1,600[11]	~113[12]	~143[13]
Aimpoints	~40,000[14]	7,600 fixed 3,400 mobile 11,000 total[15]	120 fixed 400+ mobile 520+ total[16]	30,542 19,898 struck[17]	-	-
Total Munitions	277,165[18]	23,614[19]	17,472[20]	29,199[21]	7,642[22]	115,983[23]
Guided Munitions	17,161[24] (7.6%)	6,728[25] (29%)	12,001[26] (69%)	19,948[27] (68%)	7,642[28] (100%)	Largely PGMs[29]
Average Guided Munitions/Day[30]	399	86	68	665	33	~68
TLAMs/CALCMs Expended	332[31]	270[32]	74[33]	955[34]	110[35]	172[36]
SEAD Sorties	4,326[37]	4,538[38]	-	-	1,500+[39]	-
HARMs Expended	1,961[40]	1,000+[41]	-	408[42]	-	-
Radars Destroyed	~250 / 500[43]	10 / 41[44]	-	-	-	-
SAMs Destroyed	35 / 120 fixed batteries[45]	3 / 25 SA-6 batteries[46]	-	-	Presumed by DoD: 11 SA-5 batteries 4 SA-2 batteries 16 SA-3 batteries Mobile uknown[47]	-
Combat Losses (# of aircraft)	38 total coalition[48]	2[49]	0	1[50]	1 mechanical[51]	2 mechanical 5 UAS[52]

1 Operation Odyssey Dawn took place between March 19th and 31st of 2011, while Unified Protector lasted from March 24th to October 31st.

2 Charles Pope, "30 Years Later, Desert Storm Remains a Powerful Influence on Air, Space Forces," Secretary of the Air Force Public Affairs, February 23, 2021, https://www.af.mil/News/Article-Display/Article/2512938/30-years-later-desert-storm-remains-a-powerful-influence-on-air-space-forces/#:~:text=is%20well%20known.-,The%20U.S.%20and%20its%20allies%20flew%20more%20than%20116%2C000%20combat,used%20in%20a%20major%20way.

3 Benjamin S. Lambeth, *NATO's Air War for Kosovo: A Strategic and Operational Assessment* (Santa Monica, CA: RAND, 2001), p. 61, https://www.rand.org/content/dam/rand/pubs/monograph_reports/MR1365/RAND_MR1365.pdf.

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5 Chuck Roberts, "War and Peace – a Look at Operation Iraqi Freedom," *Airman Magazine*, June 5, 2003, https://www.af.mil/News/Article/139088/war-and-peace-a-look-at-operation-iraqi-freedom/.

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8 Youtube.com, "Desert Storm – The Air War, Day 1 – Animated," The Operations Room, August 8, 2020, https://www.youtube.com/watch?v=zxRgfBXn6Mg&list=PLErys4h2oiuyKCuzZhpHhCeRwSoQVEazb&index=3.

9 Lambeth, *NATO's Air War for Kosovo*, p. 62.

10 O'Hanlon, "A Flawed Masterpiece," p. 50.

11 Estimated by dividing total sorties by campaign length.

12 Estimated by dividing total sorties by campaign length.

13 Estimated by dividing total sorties by campaign length.

14 Mark Gunzinger, "Stand In, Standoff," *Air & Space Forces Magazine*, July 1, 2020, https://www.airandspaceforces.com/article/stand-in-standoff/.

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30 Calculated by dividing the total number of guided munitions expended in each campaign by the campaign's duration.

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APPENDIX B

Appendix B: Great Power Conflict Scenario Data

This appendix contains additional information about the methodology and data supporting the scenario analysis in Chapter Three.

Scenario Data

This section contains the complete great power conflict scenario analyses used to inform Chapter Three's conclusions. Targets were drawn from and verified using a variety of sources, including publicly available DoD documents, third-party studies, and open-source online databases such as *Janes*. Where possible, all target data was verified using a second open source or publicly available satellite imagery. CSBA then estimated the quantity of aimpoints for each target using 1,000 lb. warhead equivalents. Finally, the munitions requirements for each scenario were calculated to achieve a 90 percent or greater probability of hit for each aimpoint.

Neutralize Invasion Force in Taiwan Strait

Scenario 1 focuses on the naval and air forces of the PLA and civilian ships that would be used by the PLA to transport men and materiel across the Taiwan Strait. The operational objective in this scenario is the rapid neutralization of the Chinese invasion force, with the ultimate strategic objective of preventing large-scale amphibious landings on Taiwan. To accomplish this objective, U.S. forces would attack the invasion force itself as well as screening forces.

The primary targets in this scenario are PLA maritime and aviation forces. The Eastern and Southern fleets would likely support the invasion itself in the vicinity of the Taiwan Strait. The Northern Theater Navy would screen the invasion from the eastern side of Taiwan and possibly enforce a maritime blockade. PLAN attack submarines would patrol to defend surface forces and engage U.S. forces attempting to intervene. Together, these forces comprise around 250 surface combatants and submarines.

The invasion force itself would be supplemented by commercial transport ships and ferries, along with an unknown number of decoys and support vessels. PLA experts estimate that "63 civilian RO-RO ships are currently suitable for use by military units, totaling 140,000 deadweight tons."[243] Combining these 63 RO-RO vessels with the previously

243 Kennedy, "Getting There," p. 234.

described PLA naval combatants brings the total number of vessels to 310, on par with former Undersecretary of Defense for Policy Michele Flournoy's testimony concerning the need to sink 300 Chinese vessels. Excluded from this target set are potentially hundreds of smaller landing and support vessels of the PLA Ground Force, civilian merchant fleet, Chinese Coast Guard, and maritime militia.[244] These vessels could be used for a variety of functions, including transporting PLA forces. Should U.S. munitions be unable to effectively discriminate between these vessels and surface combatants and large RO-ROs, these ships could serve as decoys that absorb exquisite weapons like anti-ship cruise missiles. For these reasons, CSBA's estimate of 310 vessels to sink in a Taiwan invasion scenario is likely conservative.

In addition to maritime targets, the invasion would be supported by PLAN and PLA Air Force (PLAAF) aircraft from the Eastern and Southern theater commands. These forces include around 700 fighter aircraft, 250 bombers, and over 100 special-purpose aircraft. Table 3 contains a list of the targets included in scenario 1. Figure 25 shows how this target list translates into munition aimpoints.

244 Ibid., pp. 224–243.

TABLE 3: SCENARIO 1 TARGET LIST

Category	Subcategory	Target Type	Quantity
PLAN Surface Vessels[245]	**Northern Theater Navy**	Aircraft carrier	1
		Cruisers	2
		Destroyers	11
		Frigates	12
		Corvettes	12
		Tank landing ships	2
		Medium landing ships	3
	Eastern Theater Navy	Destroyers	13
		Frigates	23
		Corvettes	24
		Amphibious transport docks	3
		Tank landing ships	16
		Medium landing ships	5
	Southern Theater Navy	Aircraft carrier	1
		Destroyers	10
		Frigates	14
		Corvettes	20
		Amphibious transport docks	5
		Tank landing ships	10
		Medium landing ships	8
Auxiliaries[246]	**Commercial Transports**	RO-RO ships	63
PLAN Submarines[247]	**Northern, Eastern, and Southern Theater Navies**	Nuclear-powered attack subs	6
		Diesel-powered attack subs	46
Eastern/Southern TC PLAAF[248]	**Special Mission Aircraft**	Special mission aircraft	100
	Bomber/Attack Aircraft	Bombers/Attack aircraft	250
	Fighter Aircraft	Fighter aircraft	700

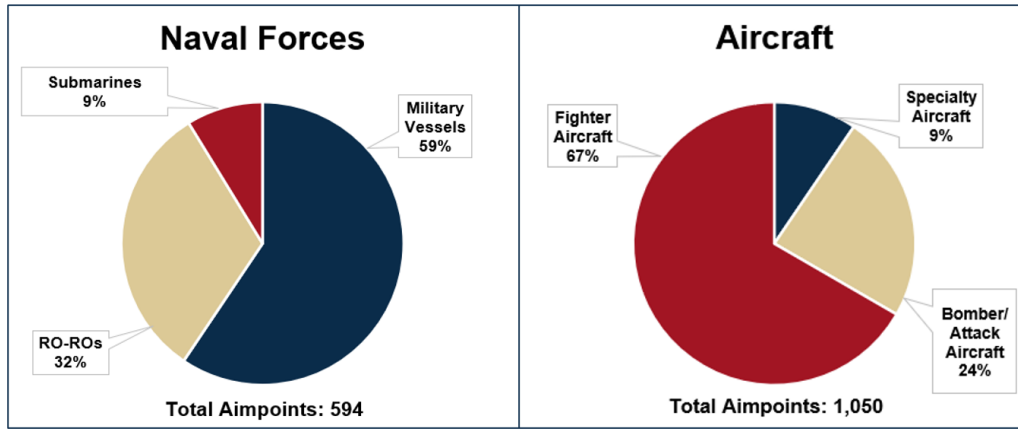
245 Theater surface vessel force laydowns taken from Office of the Secretary of Defense, *Military and Security Developments Involving the People's Republic of China 2021: Annual Report to Congress* (Washington, DC: Department of Defense, 2021), p. 54, https://media.defense.gov/2021/Nov/03/2002885874/-1/-1/0/2021-CMPR-FINAL.PDF.

246 Kennedy, "Getting There," pp. 233–241.

247 Submarine force numbers taken from Office of the Secretary of Defense, *Military and Security Developments Involving the People's Republic of China 2021*, p. 54.

248 Ibid., p. 162.

FIGURE 25: SCENARIO 1 AIMPOINTS



Given this target set, Figure 26 displays the approximate locations of PLA forces, along with the maximum engagement range of different munition types and the distances between these potential engagement ranges and U.S. bases in the Indo-Pacific. Figure 27 displays an estimate of munitions required by target type and the proportion of targets attacked.

FIGURE 26: SCENARIO 1 TARGET MAP

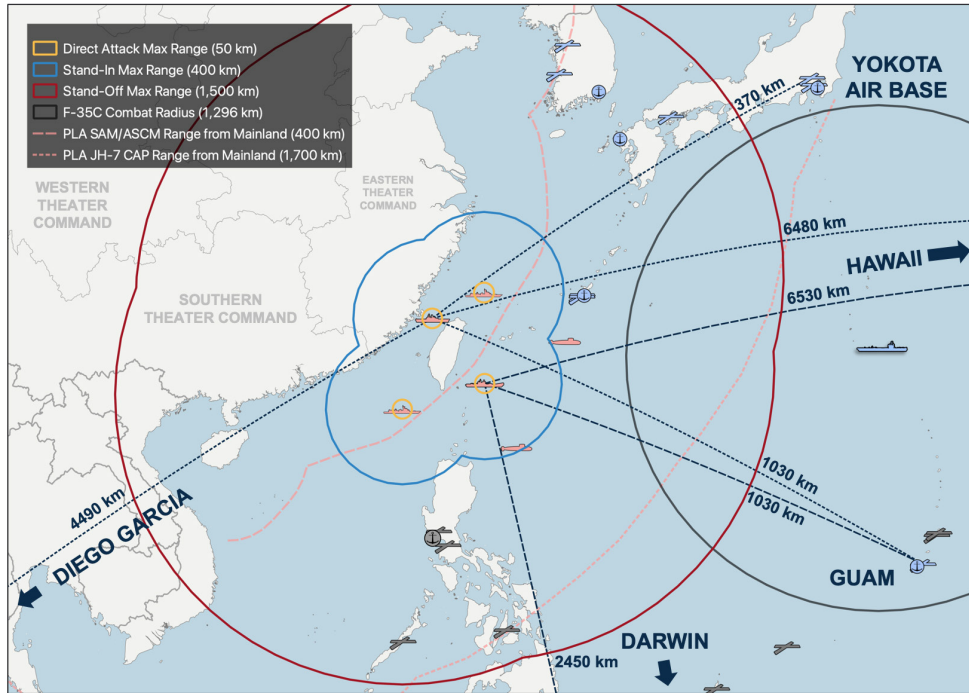
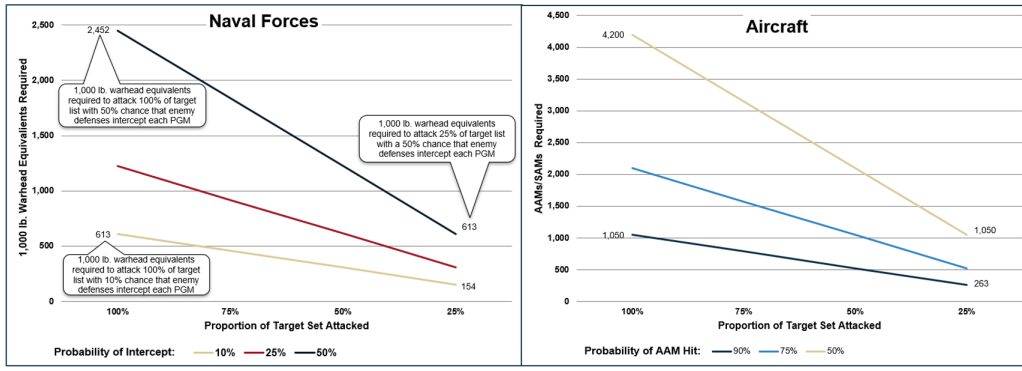


FIGURE 27: SCENARIO 1 MUNITIONS REQUIREMENTS



Neutralize South China Sea Outposts

Scenario 2 encompasses China's manmade island features in the Paracel and Spratly Islands of the South China Sea. Unless otherwise noted, all data surrounding South China Sea targets was sourced from satellite imagery and analysis from the Asia Maritime Transparency Initiative at the Center for Strategic and International Studies.[249] The operational objective of scenario 2 is the neutralization of these outposts through the destruction of key infrastructure on each feature. Accomplishing this objective would prevent the PLA from using these outposts as bases to project power into the South China Sea and beyond, as well as remove A2/AD threats, such as air defenses and anti-ship cruise missiles, from the area.

China's South China Sea outposts include four major bases with large airfields and harbors and a host of smaller features that vary in size. CSBA estimated the number of aimpoints of each feature based on its size and the facilities identifiable in satellite imagery.

PLA air and naval forces are not included in this target list because they are considered separately in Scenario 1. The following targets comprise Scenario 2:

249 See Asia Maritime Transparency Initiative, "China Island Tracker," Center for Strategic and International Studies, https://amti.csis.org/island-tracker/china/.

TABLE 4: SCENARIO 2 TARGET LIST

Category	Subcategory	Target Type
Paracel Islands[250]	**Woody Island**	Airfield
		Harbors
		Communications arrays
		Radars
		Fuel/water storage
		Munitions storage
		SAM sites
		Short-range air defenses
	Tree Island	Outpost (harbor, helipads, radar)
	Lincoln Island	Outpost (harbor)
	Drummond Island	Outpost (harbor, helipads, radar)
	Pattle Island	Outpost (harbor, helipads, radar)
	Money Island	Outpost (harbor, helipads, radar)
	Duncan Islands	Outpost (harbor, helipads, hangars, radar)
	Triton Island	Outpost (harbor, helipads, radar)
Spratly Islands[251]	**Fiery Cross Reef**	Airfield
		Harbor
		Communications arrays
		Radars
		Fuel/water storage
		Munitions storage
		SAM sites
		Short-range air defenses
	Mischief Reef	Airfield
		Harbor
		Communications arrays
		Radars
		Fuel/water storage
		Munitions storage
		SAM sites
		Short-range air defenses
	Subi Reef	Airfield
		Harbor
		Communications arrays
		Radars
		Fuel/water storage
		Munitions storage
		SAM sites
		Short-range air defenses
	Gaven Reef	Outpost (harbor, radars, communications, helipad, air defenses)
	Hughes Reef	Outpost (harbor, radars, communications, helipad, air defenses)
	Johnson Reef	Outpost (harbor, radars, communications, helipad, air defenses)
	Cuarteron Reef	Outpost (harbor, radars, communications, helipad, air defenses)

250 Asia Maritime Transparency Initiative, "Update: China's Continuing Reclamation in the Paracels," Center for Strategic and International Studies, August 9, 2017, https://amti.csis.org/paracels-beijings-other-buildup/.

251 Asia Maritime Transparency Initiative, "Comparing Aerial and Satellite Images of China's Spratly Outposts," Center for Strategic and International Studies, February 16, 2018, https://amti.csis.org/comparing-aerial-satellite-images-chinas-spratly-outposts/; Asia Maritime Transparency Initiative, "China's New Spratly Island Defenses," Center for Strategic and International Studies, December 13, 2016, https://amti.csis.org/chinas-new-spratly-island-defenses/.

FIGURE 28: SCENARIO 2 AIMPOINTS

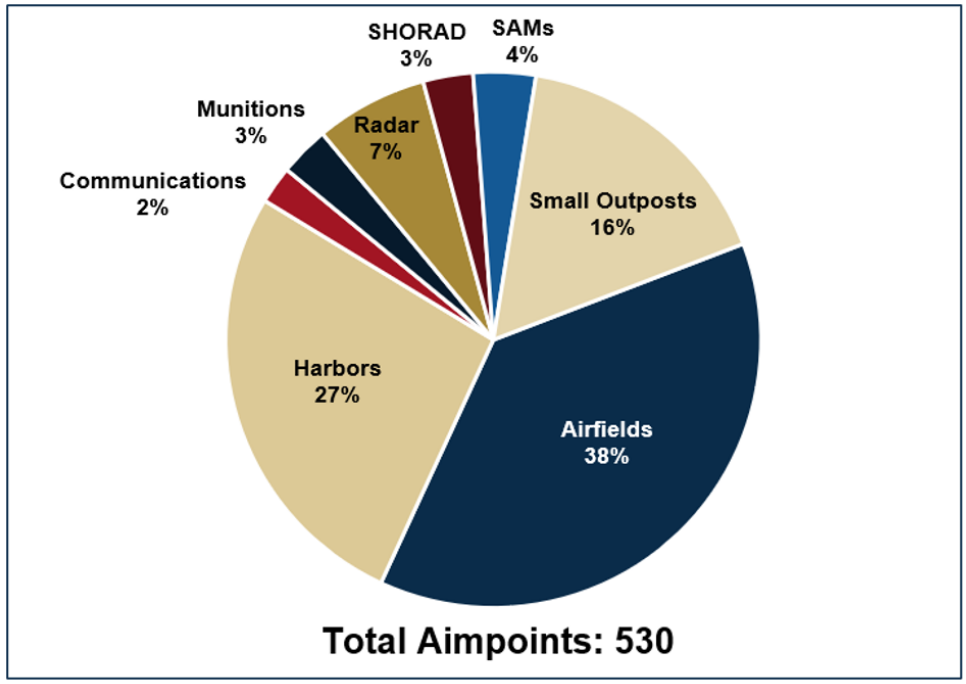


FIGURE 29: SCENARIO 2 TARGET MAP

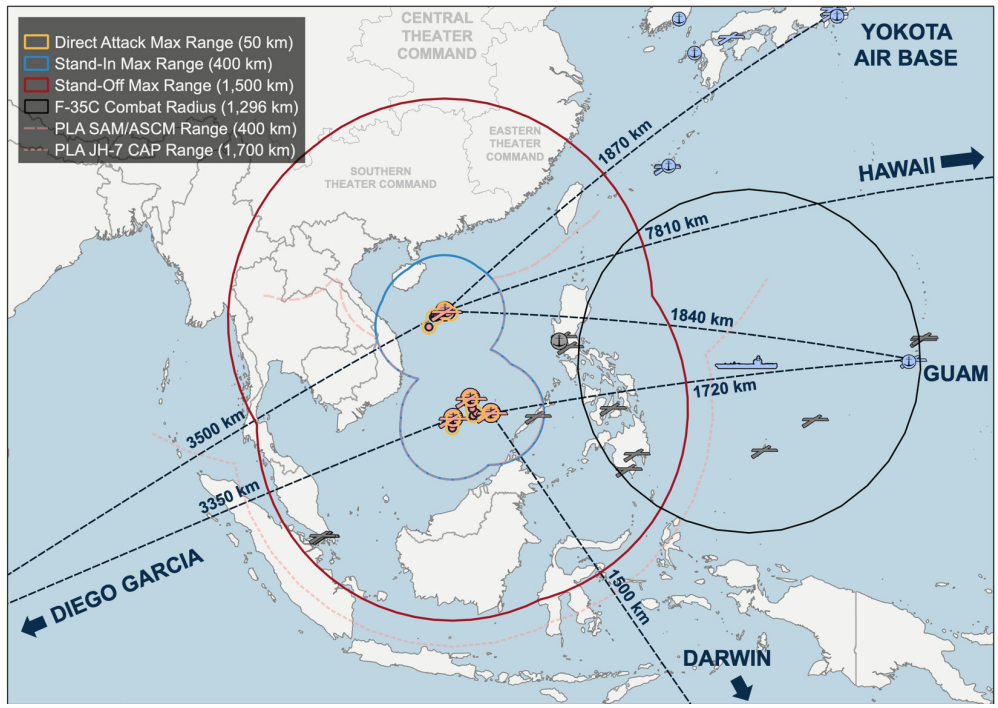
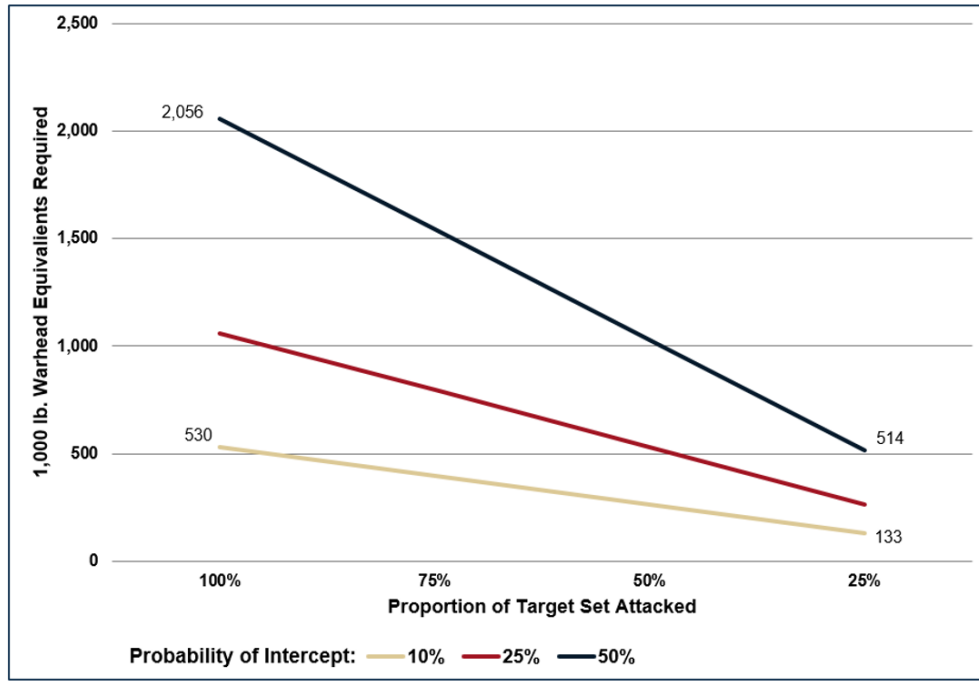


FIGURE 30: SCENARIO 2 MUNITIONS REQUIREMENTS



Counter-C4ISR Campaign

Scenario 3 expands the target list to C4ISR targets on the Chinese mainland, including early warning sensors, communications nodes, IADS elements, and command and control elements. CSBA selected these targets to represent the key C4ISR nodes essential to executing a "blinding" campaign against the PLA.

Many of the counter-space, long-range sensor, and communications targets in this case were drawn from *AirSea Battle*. For some targets, CSBA utilized maps created by Taiwanese student Joseph Wen as an initial reference before verifying locations using satellite imagery.[252]

In this scenario, CSBA considered the number of munitions required to attack only the sensing and communications infrastructure of airfields and naval bases, not the weapons required to completely disable the bases through the destruction of runways or docks.

252 For an explanation of Wen's efforts and methodology, see Keoni Everington, "Taiwanese Student Creates Map of China's PLA Bases," *Taiwan News*, June 21, 2022, https://www.taiwannews.com.tw/en/news/4576244.

TABLE 5: SCENARIO 3 TARGET LIST

Category	Target Type	Quantity
Headquarters[253]	CMC and Joint Headquarters	4
	Theater Command Headquarters	12
	Space Headquarters and Satellite Monitoring Facilities	2
	PLA Rocket Force Headquarters[254]	2
Airfields[255]	Large PLAAF Air Bases	12
	Medium PLAAF Air Bases	23
	Small PLAAF Air Bases	3
	Large PLAN Air Bases	6
	Medium PLAN Air Bases	13
	Small PLAN Air Bases	2
Naval Bases[256]	Surface Combatant Bases	21
	Submarine Bases	4
Space Facilities[257]	Launch Centers	4
	ASAT Facilities	2
Communications	SATCOM Facilities[258]	29
Radar and IADS	OTH Radar Sites and Submarine Communication Stations[259]	6
	Sensor and Radar Sites[260]	443

253 Easton, *The Chinese Invasion Threat*; and Joseph Wen, "中國人民解放軍基地及設施（持續更新）[Chinese People's Liberation Army Bases and Facilities (Continuously Updated)]," Google Maps, accessed April 10, 2023, https://www.google.com/maps/d/u/0/viewer?hl=zh-TW&mid=19Q8BraU1Nmnk23TzMb5rhXFuIAnOpTTq&ll=26.552553613860333%2C117.87935509962861&z=6.

254 Hans M. Kristensen and Matt Korda, "Nuclear Notebook: Chinese Nuclear Forces, 2020," *Bulletin of the Atomic Scientists*, December 7, 2020, Table 2, https://thebulletin.org/premium/2020-12/nuclear-notebook-chinese-nuclear-forces-2020/#post-heading.

255 Airfield locations sourced from *Janes* database and verified using satellite imagery.

256 Naval base locations sourced from *Janes* database and verified using satellite imagery.

257 Jan van Tol with Mark Gunzinger, Andrew Krepinevich, and Jim Thomas, *AirSea Battle: A Point-of-Departure Operational Concept* (Washington, DC: Center for Strategic and Budgetary Assessments, 2010), p. 59, https://csbaonline.org/research/publications/airsea-battle-concept.

258 SATCOM facilities were found using Joseph Wen's maps as an initial reference and verified using satellite imagery.

259 OTH radar and submarine communication installations were found using Joseph Wen's maps as an initial reference and verified using satellite imagery.

260 Radar sites sourced from *Janes* database and verified using satellite imagery.

FIGURE 31: SCENARIO 3 AIMPOINTS

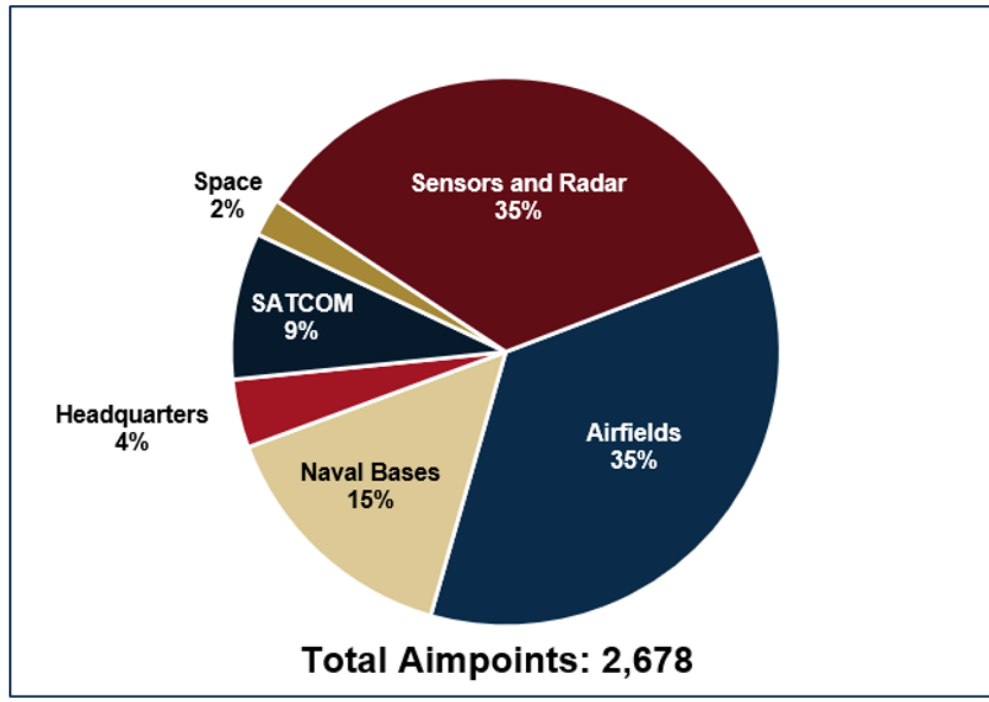


FIGURE 32: SCENARIO 3 TARGET MAP

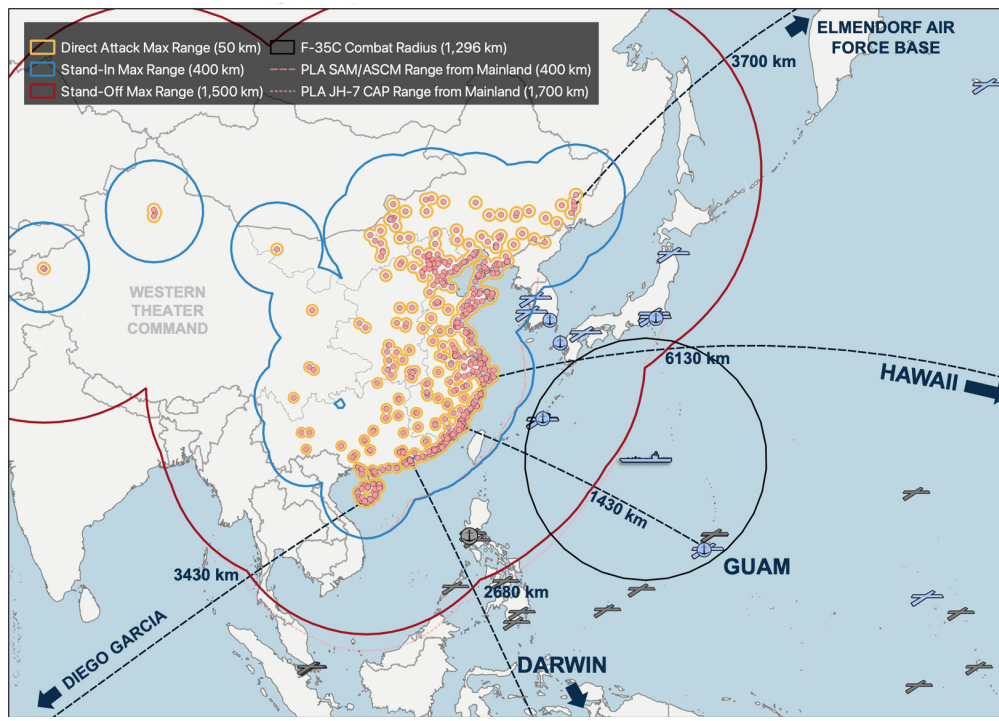
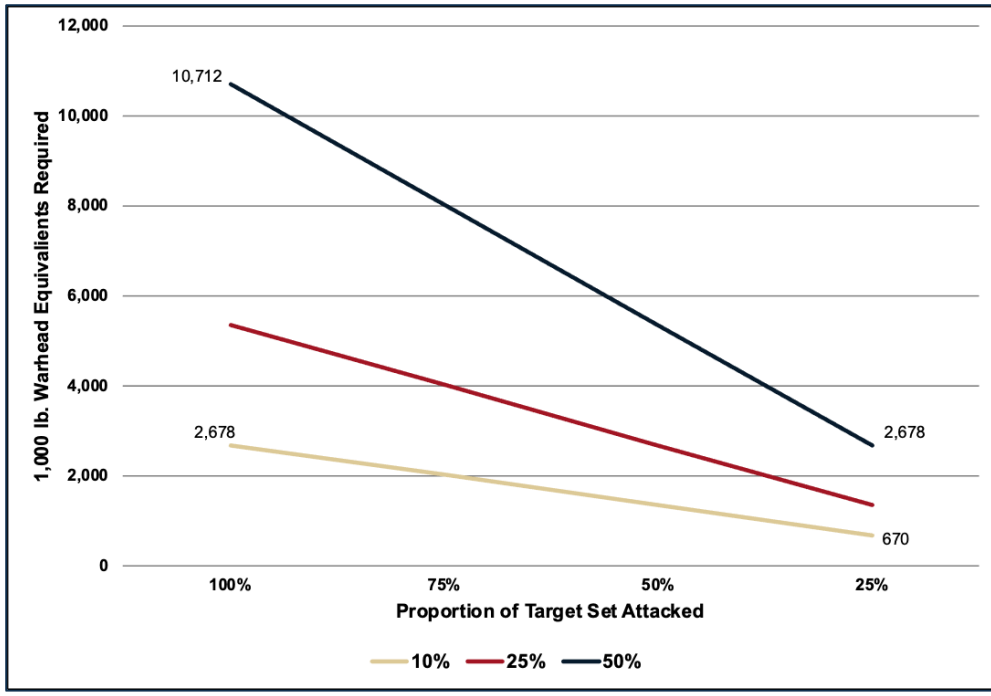


FIGURE 33: SCENARIO 3 MUNITIONS REQUIREMENTS



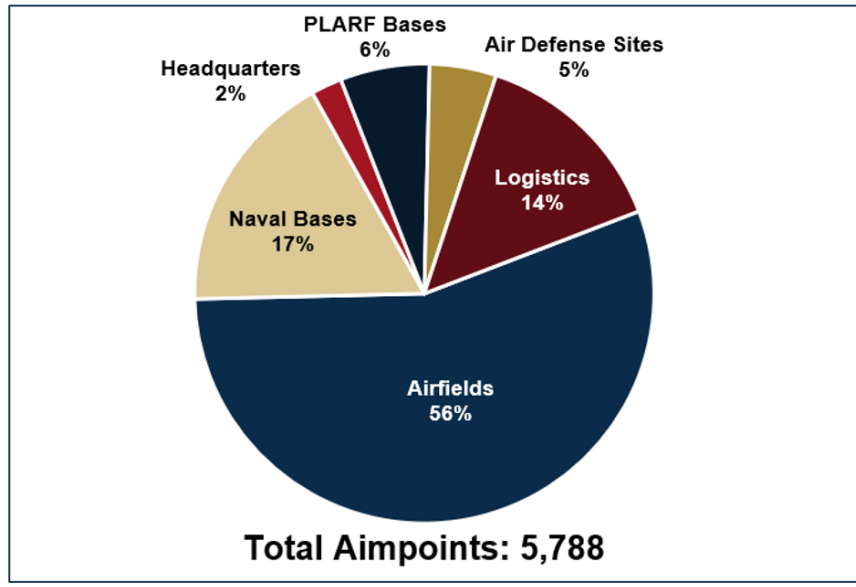
Strike Campaign Against Conventional Bases

Scenario 4 examines a strike campaign against PLA air, maritime, and rocket force basing in eastern and southern China. CSBA scoped this campaign to these regions to show the immense requirements for such a campaign against even a portion of the PLA's total force. The northern and central regions of China are similarly dense with PLA bases and supporting infrastructure.

TABLE 6: SCENARIO 4 TARGET LIST

Category	Target Type	Quantity
Headquarters	PLAN Theater Headquarters/Fleet Commands	3
	PLAAF Theater Headquarters	3
	PLARF Headquarters	2
Naval Bases	Surface Combatant Bases	21
	Submarine Bases	4
Airfields	Large PLAN Air Bases	6
	Medium PLAN Air Bases	13
	Small PLAN Air Bases	2
	Large PLAAF Air Bases	12
	Medium PLAAF Air Bases	23
	Small PLAAF Air Bases	3
Rocket Forces[261]	PLARF Brigade Bases	14
Air Defense Forces[262]	Long-Range Air Defense Sites	34
Logistics[263]	Depots, POL Storage, and Railheads	102

FIGURE 34: SCENARIO 4 AIMPOINTS



261 Hans M. Kristensen and Matt Korda, "Nuclear Notebook: Chinese Nuclear Forces, 2020," *Bulletin of the Atomic Scientists*, December 7, 2020, Table 2, https://thebulletin.org/premium/2020-12/nuclear-notebook-chinese-nuclear-forces-2020/#post-heading.

262 Long-range air defense sites sourced from *Janes* database and verified using satellite imagery.

263 Logistics facilities in the Eastern and Southern Theater Commands were found using Joseph Wen's maps as an initial reference and verified using satellite imagery.

FIGURE 35: SCENARIO 4 TARGET MAP

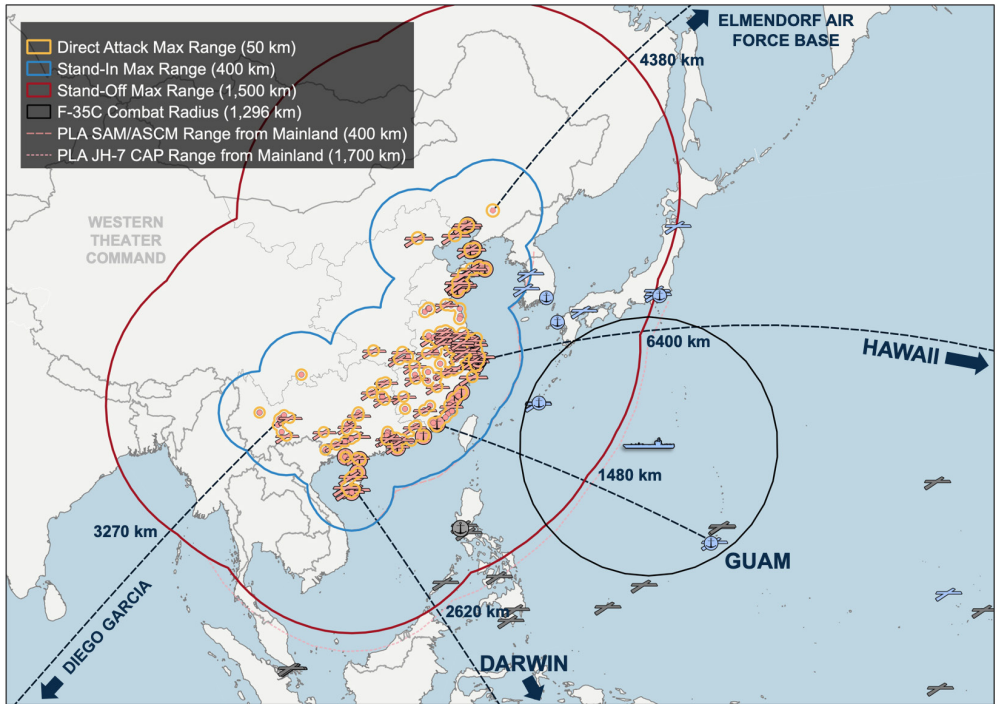
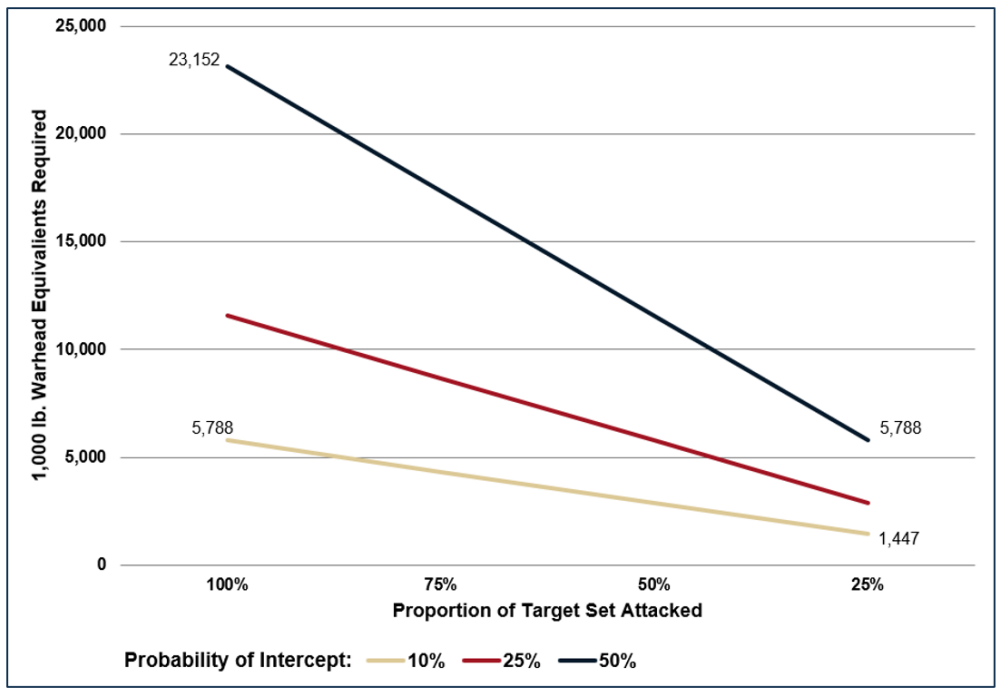


FIGURE 36: SCENARIO 4 MUNITIONS REQUIREMENTS



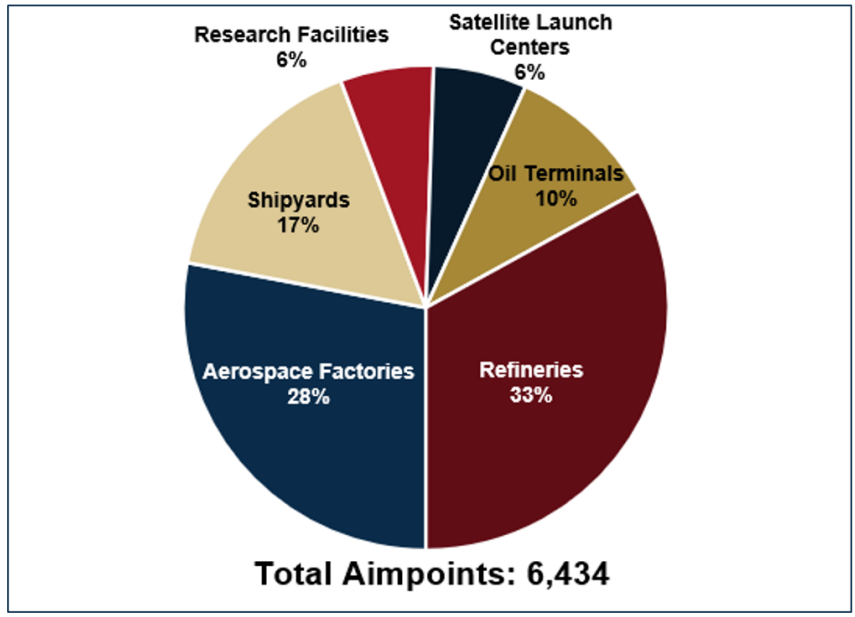
Force Regeneration Campaign

Scenario 5's targets were chosen to represent industrial facilities that would support the PLA in a protracted war of attrition. CSBA focused on the production and research facilities themselves rather than supporting dual-use infrastructure such as power plants and energy distribution. The facilities included in this target set are in no way comprehensive, but represent a selection of major identifiable Chinese facilities.

TABLE 7: SCENARIO 5 TARGET LIST

Production Facilities[264]	Aerospace Factories	15
	Military Shipyards	15
Research Facilities[265]	Aerospace, Maritime, Electronics, and Munitions Research Facilities	25
Space Facilities	Satellite Launch Centers	4
POL Infrastructure[266]	Crude Oil Terminals	55
	Oil Refineries	59

FIGURE 37: SCENARIO 5 AIMPOINTS



264 Chinese military production facilities were found using Joseph Wen's maps as an initial reference and verified using satellite imagery.

265 Chinese military research facilities were found using Joseph Wen's maps as an initial reference and verified using satellite imagery.

266 Chinese oil terminals and refineries were found using the open source World Oil Map 2021 and the China Energy Map from Rice University's Baker Institute for Public Policy. See Roque Leal, "World Oil Map 2021," https://www.oilmap.xyz/; Center for Energy Studies, "China Energy Map," Baker Institute for Public Policy, Rice University, https://www.bakerinstitute.org/chinas-energy-infrastructure.

FIGURE 38: SCENARIO 5 TARGET MAP

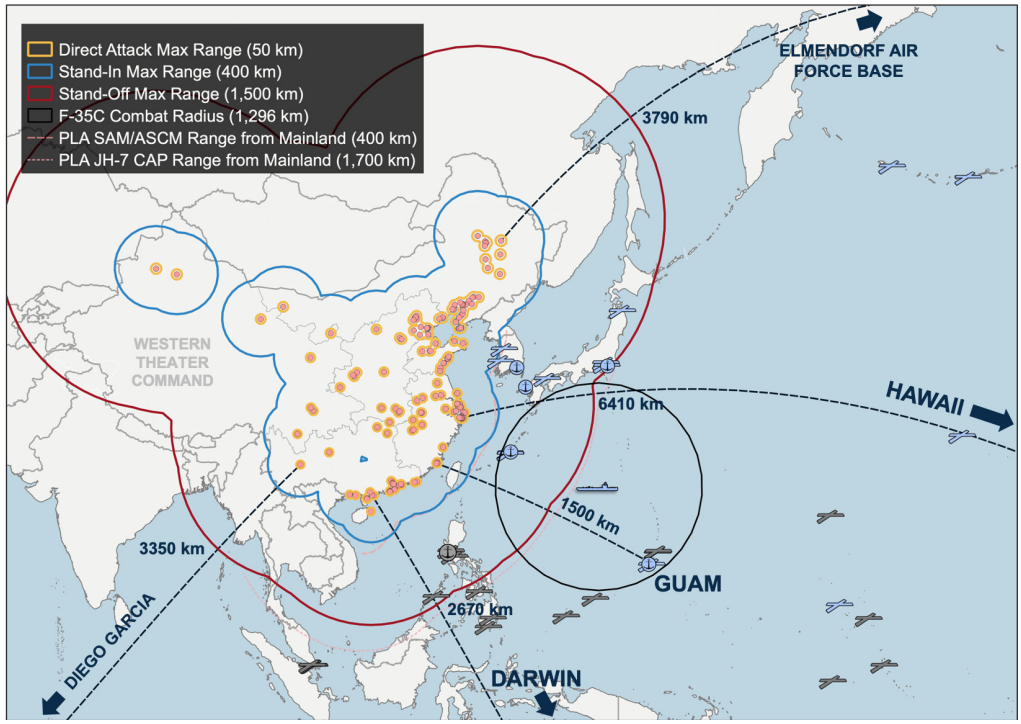
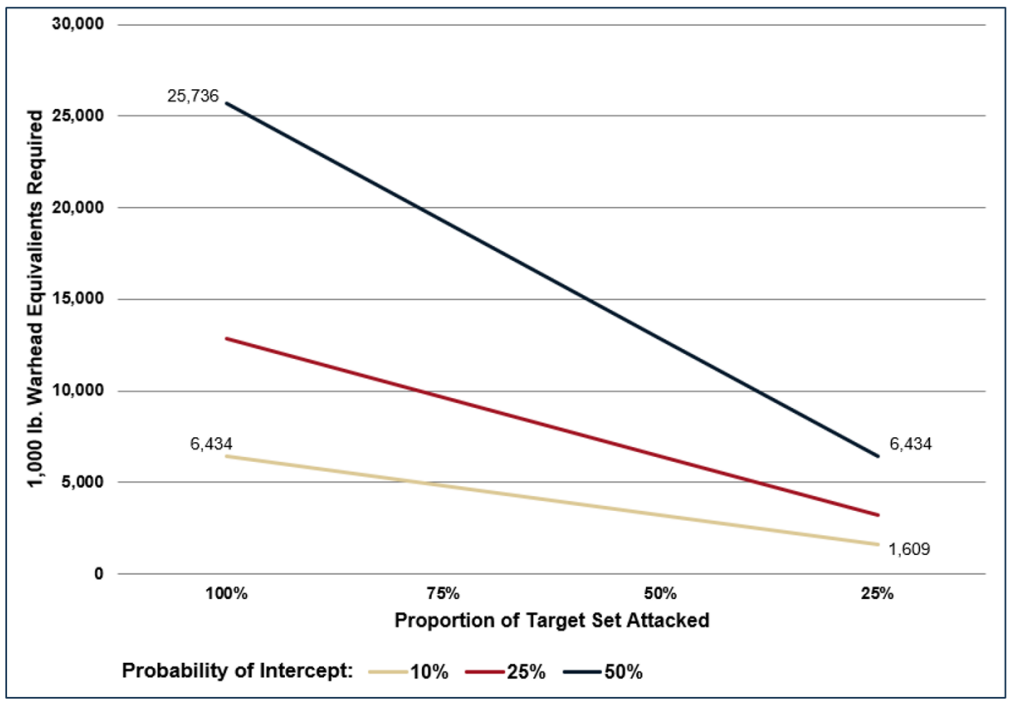


FIGURE 39: SCENARIO 5 MUNITIONS REQUIREMENTS



Aimpoint Methodology and Assumptions

CSBA utilized several methods to determine the quantity of aimpoints and estimate munitions requirements based on target type. This section outlines the methodologies used for several major categories of targets found in each of the great power conflict scenarios. Where possible, CSBA used 1,000 lb. warhead equivalents as a standard measure of munition explosive power to estimate the number of aimpoints for each target. This measure equates to the Mark 83 general-purpose bomb, which weighs about 1,000 lbs.—halfway between the 500 lb. Mark 82 and 2,000 lb. Mark 84.[267] This increment allows us to easily extrapolate munitions requirements for weapons of different sizes. In addition, many stand-off PGMs and cruise missiles carry 1,000 lb.-class warheads.

Naval Forces

Munitions requirements for ship targets were determined by vessel tonnage. CSBA utilized the average displacement of various PLA vessels by class and calculated the number of 1,000 lb. warhead equivalents required to neutralize the vessel according to the formula below, where T is the vessel's displacement tonnage.[268] CSBA rounded to the nearest whole number of warheads.

$$\#\text{ of 1,000 lb.warhead equivalents required} = \sqrt[3]{T * 0.001}$$

CSBA assumed that a single heavyweight torpedo (such as the Mark 48) will sink a nuclear or diesel attack submarine if it hits its target.

Aircraft

To simplify the analysis, CSBA assumed all air-to-air missiles and surface-to-air missiles have the same probability of hit and probability of kill. Our analysis also assumed that a single missile hit is sufficient to destroy an aircraft, regardless of type. Accordingly, each aircraft is considered a single aimpoint in our estimates.

Airbases

PLAAF and PLAN airbases were coded by size based on runway length and the number of aircraft parking spaces, hangars, and shelters.[269] Figure 40 shows aimpoint calculations for

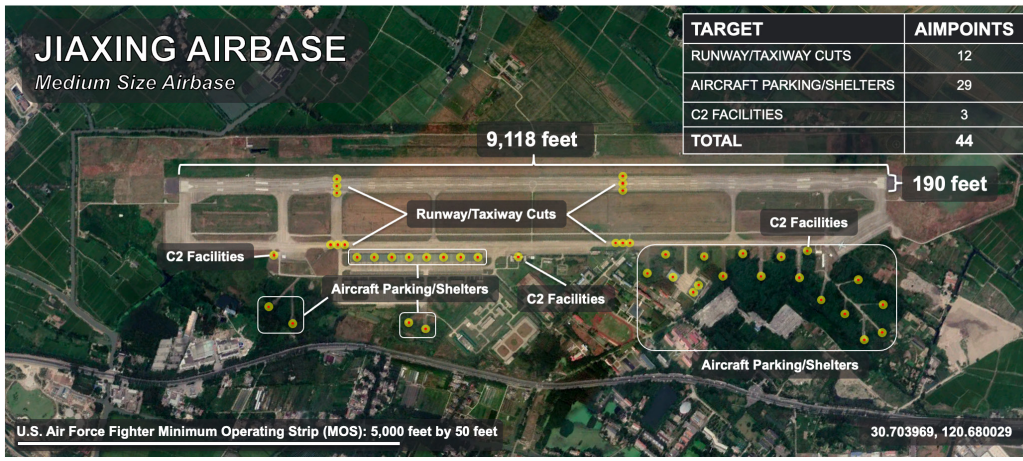
267 These direct attack general-purpose bombs can each be augmented with laser- or GPS-guided precision-guidance kits.

268 This formula is derived from Alan D. Zimm, "Antiship Missile Lessons from Sinking of the Moskva," *Proceedings* 148/5/1,431, May 2022, https://www.usni.org/magazines/proceedings/2022/may/antiship-missile-lessons-sinking-moskva.

269 Airbase target attack methodology was informed by John Stillion and David T. Orletsky, *Airbase Vulnerability to Conventional Cruise-Missile and Ballistic-Missile Attacks* (Santa Monica, CA: RAND, 1999), https://www.rand.org/pubs/monograph_reports/MR1028.html; and Sal Sidoti, *Airbase Operability: A Study in Airbase Survivability and Post-Attack Recovery* (RAAF Base Fairbairn: Aerospace Centre, 2001), https://airpower.airforce.gov.au/sites/default/files/2021-03/FELL20-Airbase-Operability-A-Study-in-Airbase-Survivalability-and-Post-Attack-Recovery.pdf.

neutralizing medium-sized airbases using Jiaxing Airbase as a typical example.[270] CSBA used satellite imagery to estimate the number of aimpoints required to cut runways and taxiways, destroy parked aircraft, and neutralize base C2 facilities. Depending on base size, additional aimpoints were added to consider camouflaged, hidden, and underground storage facilities not visible in satellite photographs. Runways and taxiways were cut so that no usable stretch exceeded 5,000 feet by 50 feet—the U.S. DoD's minimum operating strip (MOS) for fighter aircraft.[271]

FIGURE 40: EXAMPLE AIRBASE AIMPOINT ESTIMATE



Source: Created by CSBA using satellite imagery from Google Earth.

Naval Bases and Harbors

Aimpoints for harbor and port facilities were estimated by the size of available berthing space, measured from open-source satellite imagery. Two aimpoints were allotted for every 100 meters of berthing space. CSBA assumed that these aimpoints would be focused on infrastructure and cargo-handling equipment such as cranes, shiploaders, docks, and piers. Figure 41 displays an example of CSBA's methodology using harbor facilities at Subi Reef in the Spratly Islands.

270 CSBA's aimpoint estimates for Chinese airbases is similar to that of several RAND models. See Heginbotham, Nixon, Morgan, and Heim et al., *The U.S.–China Military Scorecard*, Chapter 6; Jordan Rozsa, *Improving Standoff Bombing Capacity in the Face of Anti-Access Area Denial Threats* (Santa Monica, CA: RAND, 2015), p. 48, https://www.rand.org/pubs/rgs_dissertations/RGSD363.html.

271 U.S. Department of Defense, *O&M: Airfield Damage Repair*, Tri-Service Pavement Working Group (TSPWG) Manual, May 21, 2020, p. 36, https://www.wbdg.org/FFC/DOD/STC/TSPWG_M_3_270_01_3_270_07.pdf.

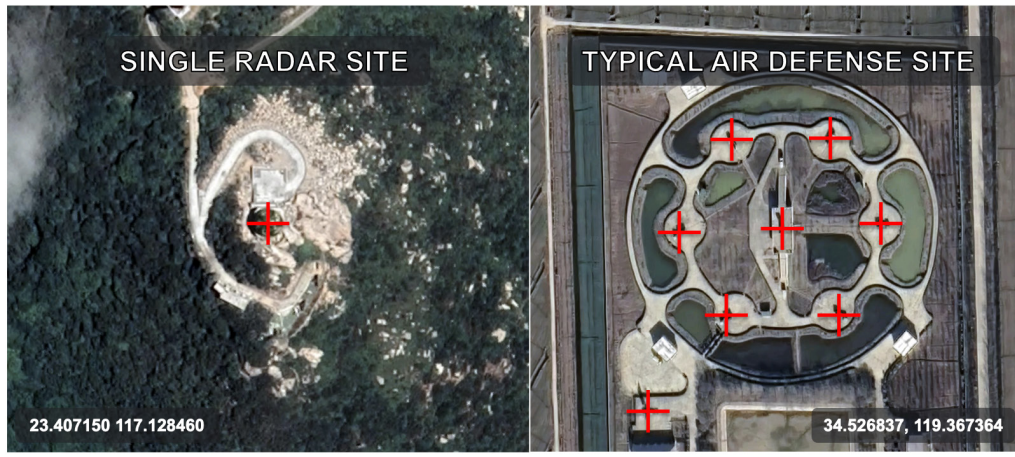
FIGURE 41: EXAMPLE HARBOR AIMPOINT ESTIMATE

Source: Created by CSBA using satellite imagery from Google Earth.

Fixed Point Targets: Air Defenses, Outposts, Radars, and Communications Nodes

Point targets throughout the scenarios include SAM sites, radar and communications sites, small outposts, and other targets of limited area or with small targetable elements. CSBA estimated the number of aimpoints based upon the size and nature of each target type.[272] For example, single radar sites (Figure 42) were considered one aimpoint. Air defense sites with multiple, separated elements were allotted a single aimpoint for each major element (radar, C2, TELs, etc.).

FIGURE 42: EXAMPLE FIXED POINT TARGET AIMPOINT ESTIMATE



Source: Created by CSBA using satellite imagery from Google Earth.

272 This point target methodology makes similar assumptions to cruise missile modeling in Rosza, *Improving Standoff Bombing Capacity in the Face of Anti-Access Area Denial Threats*, pp. 42–47.

Area Targets: Military Facilities, Logistics Targets, Industrial Targets

CSBA considered large targets that required effects spread over a wide area as area targets. Military facility targets included headquarters, basing, various space facilities, and large SATCOM installations. Logistics targets included munitions and POL storage facilities and railheads. Industrial targets included production and research facilities as well as oil terminals and refineries.

CSBA estimated the quantity of aimpoints for these targets based on the average size of targets of similar type (e.g., command posts, railheads, aerospace production facilities). For some complex targets, CSBA assumed that striking key elements (such as the process towers or control rooms of oil refineries) could effectively shut down larger facilities. The large size and distance between these numerous elements, however, differentiated these targets from point targets with multiple closely situated aimpoints.

APPENDIX C

Appendix C: Attributes of Selected Current and Developmental PGMs

This appendix contains the full list of current and developmental PGMs, along with selected attributes, used to support the analysis in Chapter Four. Grey highlights denote programs that are currently developmental and have not reached IOC. CSBA drew munitions data from *Janes* database, with additional sources included in the footnotes. Blank boxes represent data that may not be publicly available at this time.

Munition	Range	Speed	Target Type	Delivery	Guidance	Notes
Laser-guided bombs (LGB)	Direct Attack	Freefall	Land Attack	Air	Laser seeking	Guidance kit for 500, 1,000, 2,000, and 5,000 lb. bombs.
JDAM (Joint Direct Attack Munition)		Freefall	Land Attack	Air	GPS, INS	Guidance kit for 500, 1,000, and 2,000 lb. bombs.
CBU-105 Sensor Fuzed Weapon (SFW)		Freefall	Land Attack	Air	GPS, INS	Releases 10 BLU-108 smart submunitions.
GBU-57A/B Massive Ordnance Penetrator (MOP)		Freefall	Land Attack	Air	GPS, INS	30,000 lb. "bunker buster."
AGM-114 *Hellfire*		Supersonic	Land Attack	Air	Laser seeking or MMW radar	Various payloads up to 100 lbs.
JAGM (Joint Air-to-Ground Missile)		Supersonic	Land Attack	Air	Laser seeking, MMW radar	Approved for full-rate production in August, 2022.[273]
AIM-9X *Sidewinder*		Supersonic	Air-to-Air	Air	IR seeking	
RIM-162 ESSM (Evolved Sea Sparrow Missile)	Stand-in	Supersonic	Anti-Air	Sea	Active/semi-active radar	Datalink.
GMLRS (Guided Multiple Launch Rocket System)		Supersonic	Land Attack	Ground	GPS, INS	Unitary and alternative warhead (fragmentation) variants.
GBU-53/B *StormBreaker*		Glide	Land Attack	Air	GPS, INS, IR seeking, laser seeking, active radar	250 lb. bomb with datalink.

273 Lockheed Martin, "Lockheed Martin's Joint-Air-To-Ground Missile (JAGM) Cleared for Full Rate Production, August 2022, https://www.lockheedmartin.com/en-us/news/features/2022/lockheed-martins-joint-air-to-ground-missile-jagm-cleared-for-full-rate-production.html.

Munition	Range	Speed	Target Type	Delivery	Guidance	Notes
AGM-154 JSOW (Joint Standoff Weapon)	Stand-in	Glide	Land Attack	Air	GPS, INS or IIR seeker	Variants carry 500 lb. unitary warhead, cluster munitions, or smart submunitions. Can be internally carried by F-35.
GBU-39/B SDB (Small Diameter Bomb)		Glide	Land Attack	Air	GPS, INS	250 lb. bomb.
AGM-88E AARGM (Advanced Anti-Radiation Guided Missile)		Supersonic	Land Attack	Air	Anti-radiation homing, MMW radar seeker, GPS, INS	Datalink.
GMLRS-ER (Extended Range)		Supersonic	Land Attack	Ground	GPS, INS	
SiAW (Stand-in Attack Weapon)		Supersonic	Land Attack	Air	-	Intended to fit in F-35 internal bay and "to operate in [A2/AD] environments to strike mobile targets."[274]
AGM-88G AARGM-ER (Extended Range)		Supersonic	Land Attack	Air	Anti-radiation homing, MMW radar seeker, GPS, INS	Intended for internal carry by F-35, "incorporates hardware and software modifications to include extended range, survivability, and effectiveness against future threats."[275]
AIM-120D AMRAAM (Advanced Medium-Range Air-to-Air Missile)		Supersonic	Air-to-Air	Air, Ground	Active radar, INS	Datalink for mid-course updates.
AIM-260 JATM (Joint Advanced Tactical Missile)		Supersonic	Air-to-Air	Air		
NSM (Naval Strike Missile)		Subsonic	Anti-Ship	Sea, Ground	IIR seeker, GPS, TERCOM, INS	275 lb. warhead.
RGM/AGM/UGM-84 ***Harpoon***		Subsonic	Anti-Ship	Air, Sea	Active radar, GPS, INS	Datalink for mid-course updates, 500 lb. warhead.
SM-6		Supersonic	Anti-Air, Anti-Ship, BMD	Sea, Ground	Active or semi-active radar, GPS, INS	Datalink, 150 lb. warhead. Ground-based SM-6s are part of the Army's Mid-Range Capability (MRC) program.
AGM-84H/K SLAM-ER (Standoff Land Attack Missile Expanded Response)		Subsonic	Land Attack	Air	IIR seeker, GPS, INS	Derivative of Harpoon with automatic target recognition and two-way datalink for man-in-the-loop control.

274 Frank Wolfe, "USAF Awards Contracts for Next Phase of Stand-in Attack Weapon to Lockheed Martin, Northrop Grumman and L3Harris," *Defense Daily*, August 26, 2022, https://www.defensedaily.com/usaf-awards-contracts-for-next-phase-of-stand-in-attack-weapon-to-lockheed-martin-nothrop-grumman-and-l3harris/air-force/.

275 Naval Air Systems Command, "AARGM," https://www.navair.navy.mil/product/AARGM.

Munition	Range	Speed	Target Type	Delivery	Guidance	Notes
MGM-140 ATACMS (Army Tactical Missile System)	Stand-in	Supersonic	Land Attack	Ground	GPS, INS	Variants with unitary and submunition payloads.
AGM-158A JASSM (Joint Air-to-Surface Standoff Missile)		Subsonic	Land Attack	Air	IIR seeker, GPS, INS	Datalink, 1,000 lb. warhead.
SM-2		Supersonic	Anti-Air	Sea	Semi-active radar, IR seeker, INS	Datalink.
HACM (Hypersonic Attack Cruise Missile)	Stand-off	Hypersonic	Land Attack	Air	Unknown	Fighter-sized "scramjet-powered hypersonic weapon designed to hold high-value targets at risk in contested environments from standoff distances."[276]
AGM-183 ARRW (Air-Launched Rapid Response Weapon)		Hypersonic	Land Attack	Air	Unknown, intended for fixed targets	Tested from B-52.
HALO (Hypersonic Air-Launch Offensive anti-surface warfare)		Hypersonic	Anti-ship	Air	Unknown	"envisioned to be a long-range, aircraft carrier-based, strike fighter aircraft-launched weapon system providing [anti-surface warfare] capabilities."[277]
Precision Strike Missile (PrSM)		Supersonic	Land Attack	Ground	GPS, INS	Potential for future variants to include multi-mode seekers for moving targets and extended range.[278]
AGM-158C LRASM (Long Range Anti-Ship Missile)		Subsonic	Anti-Ship	Air, Sea	IIR seeker, passive radar homing, GPS, INS	Derivative of JASSM, 1,000 lb. payload, datalink, automatic target recognition and discrimination.
ADM-160 MALD (Miniature Air-Launched Decoy)		Subsonic	Decoy, Non-Kinetic	Air	GPS, INS	Low-cost expendable decoy. Jammer and electronic warfare variants in service.
AGM-158B JASSM-ER (Extended Range)		Subsonic	Land Attack	Air	IIR seeker, GPS, INS	

276 Secretary of the Air Force Public Affairs, "Air Force Announces Hypersonic Missile Contract Award," September 22, 2022, https://www.af.mil/News/Article-Display/Article/3167976/air-force-announces-hypersonic-missile-contract-award/.

277 Lee Willett, "HALO Programme Accelerates US Navy Hypersonic Capability Drive," *Naval News*, September 5, 2022, https://www.navalnews.com/naval-news/2022/09/halo-us-navy-hypersonic-capability/.

278 Peter Ong, "Precision Strike Missile (PrSM) Information Update," *Naval News*, August 5, 2022, https://www.navalnews.com/naval-news/2022/08/precision-strike-missile-prsm-information-update/.

Munition	Range	Speed	Target Type	Delivery	Guidance	Notes
BGM-109 *Tomahawk* (all variants)	Long-Range Strike	Subsonic	Land Attack, Anti-Ship in development	Sea, Ground	TERCOM, DSMAC, GPS, INS	Datalink and loitering capabilities. Future Block V variants will be capable of striking moving targets at sea. Ground-based Tomahawks are part of the Army's MRC program and are being experimented with by the USMC.
AGM-158D JASSM-XR (Extreme Range)		Subsonic	Land Attack	Air	IIR seeker, GPS, INS	Also designated AGM-158B-2.
Long-Range Hypersonic Weapon (LRHW)		Hypersonic	Land Attack	Ground	Unknown	Utilizes Common Hypersonic Glide Body (CHGB).
Conventional Prompt Strike (CPS)		Hypersonic	Land Attack	Sea	Unknown	Utilizes Common Hypersonic Glide Body (CHGB).

LIST OF ACRONYMS

A2/AD	Anti-access/area denial
AARGM	Advanced Anti-Radiation Guided Missile
AARGM-ER	Advanced Anti-Radiation Guided Missile – Extended Range
ACC	Air Combat Command
AFB	Air Force Base
AFRL	Air Force Research Laboratory
AI	Artificial intelligence
AMRAAM	Advanced Medium-Range Air-to-Air Missile
ARGUS	Advanced Remote Ground Unattended Sensor
ARRW	Air-Launched Rapid Response Weapon
ASAT	Anti-satellite
ASCM	anti-ship cruise missile
ATACMS	Army Tactical Missile System
ATR	Automatic target recognition
BDA	Battle damage assessment
BMD	Ballistic missile defense
C4ISR	Command, control, communications, computers, intelligence, surveillance, and reconnaissance
CALCM	Conventional Air-Launched Cruise Missile
CC&D	Camouflage, concealment, and deception
CCP	Chinese Communist Party
CEP	Circular error probable
CG	guided missile cruiser
CHAMP	Counter-Electronics High Power Microwave Advanced Missile Project
CHGB	Common Hypersonic Glide Body
CLT	Common Launch Tube
CMC	Central Military Commission
CPS	Conventional Prompt Strike
CR	Continuing resolution
CSBA	Center for Strategic and Budgetary Assessments
DAMASK	Direct Attack Munition Affordable Seeker
DARPA	Defense Advanced Research Projects Agency
DE	Directed energy
DEAD	Destruction of enemy air defenses
DIA	Defense Intelligence Agency

DoD	U.S. Department of Defense
DoDI	Department of Defense Instruction
DSMAC	Digital Scene Matching Area Correlator
ESSM	Evolved Sea Sparrow Missile
FASCAM	Family of Scatterable Mines
FY	Fiscal year
FYDP	Future Years Defense Program
GMLRS	Guided Multiple Launch Rocket System
GPS	Global Positioning System
HAAWC	High Altitude Anti-Submarine Warfare Weapon Capability
HACM	Hypersonic Attack Cruise Missile
HALO	Hypersonic Air-Launch Offensive anti-surface warfare
HAS	Hardened aircraft shelters
HPM	High-power microwave
IAD	Integrated air defense system
IIR	Imaging infrared
INS	Inertial navigation system
IOC	Initial operational capacity
IR	infrared
ISR	Intelligence, surveillance, and reconnaissance
JAGM	Joint Air-to-Ground Missile
JASSM	Joint Air-to-Surface Standoff Missile
JASSM-ER	Joint Air-to-Surface Standoff Missile – Extended Range
JASSM-XR	Joint Air-to-Surface Standoff Missile – Extreme Range
JATM	Joint Advanced Tactical Missile
JDAM	Joint Direct Attack Munition
JQL	JAGM Quad Launcher
JSM	Joint Strike Missile
JSOW	Joint Standoff Weapon
LADAR	Light detection and ranging
LGB	Laser-guided bomb
LO	Low observable
LOCAAS	Low Cost Autonomous Attack System
LRAAM	Long-Range Air-to-Air Missile
LRASM	Long Range Anti-Ship Missile
LRHW	Long-Range Hypersonic Weapon

MALD	Miniature Air-Launched Decoy
MMT	Modular Missile Technologies
MMW	Millimeter wave
MOAB	Massive Ordnance Air Blast
MOP	Massive Ordnance Penetrator
MOS	Minimum operating strip
MRC	Mid-Range Capability
MRP	Munitions Requirements Process
MUM-T	Manned-unmanned teaming
NATO	North Atlantic Treaty Organization
NMM	Navy Modular Missile
NSM	Naval Strike Missile
OTH	Over-the-horizon
PGM	Precision-guided munition
PLA	People's Liberation Army
PLAAF	People's Liberation Army Air Force
PLAGF	People's Liberation Army Ground Force
PLAN	People's Liberation Army Navy
PLARF	People's Liberation Army Rocket Force
POL	Petroleum, oil, and lubricant
PRC	People's Republic of China
PrSM	Precision Strike Missile
RDT&E	Research, development, testing, and evaluation
ROC	Republic of China
ROE	Rules of engagement
RO-RO	Roll-on roll-off
SAM	surface-to-air missile
SATCOM	Satellite communications
SDB	Small Diameter Bomb
SEAD	Suppression of enemy air defenses
SiAW	Stand-in Attack Weapon
SLAM-ER	Standoff Land Attack Missile Expanded Response
SOCOM	U.S. Special Operations Command
TEL	Transporter, erector, launcher
TERCOM	Terrain contour matching
THAAD	Terminal High Altitude Area Defense

TLAM	Tomahawk Land Attack Missile
TSSAM	Tri-Service Standoff Attack Missile
UAI	Universal Armaments Interface
UAS	Unmanned aerial system
USAF	U.S. Air Force
USD(P)	Office of the Under Secretary of Defense for Policy
USINDOPACOM	U.S. Indo-Pacific Command
USN	U.S. Navy
VLS	Vertical launch system
WOSA	Weapons Open System Architecture

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