



CSBA

Center for Strategic and Budgetary Assessments

CHOOSING LESS BANG FOR BUCK

THE UNDERUTILIZATION OF
ADVANCED ENERGETICS

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Cover graphic: U.S. Airmen prepare to load GBU-31 munition systems onto F-15E Strike Eagles within the U.S. Central Command area of responsibility, December 18, 2025, in support of Operation Hawkeye Strike. Photo by U.S. Central Command Public Affairs.

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Executive Summary

With the United States rushing to refill its stocks of critical munitions, expand its munitions industrial base, and field large volumes of new weapons, the energetic materials contained within these munitions are an increasingly crucial part of alleviating one of the nation's most serious defense shortfalls. By providing greater explosive effects or powering weapons that fly farther or faster, novel explosives and propellants promise to increase the lethality of U.S. munitions and, potentially, reduce the number of weapons required to conduct offensive and defensive military operations. Constructing additional facilities to produce these new compounds would also expand a critical bottleneck within the U.S. munitions industrial base.

Despite these potential gains, most American weapons remain reliant on energetics developed decades ago. Newer formulas with improved performance characteristics, such as CL-20, were created by American researchers during the Cold War, but failed to make their way into large-scale production for the warheads and motors of U.S. munitions. By contrast, the U.S. military's precision-guided munitions feature cutting-edge sensor, networking, and signature-reduction technologies to deliver extreme accuracy against the world's most challenging targets.

Why has there been comparatively little improvement in the realm of explosives, and how could advances in this area provide the U.S. military tactical, operational, or even strategic advantages in future conflict? Most importantly, what must be done to turn the promises of new energetic materials like CL-20 into military reality?

This report explores these questions in four parts. First, it recounts the history of RDX during World War II to draw several enduring lessons for overcoming barriers that, as early as the 1920s, inhibited the adoption of novel energetics by the U.S. military. RDX played a vital role in maximizing U.S. and allied combat power during the war, and the story of its fielding shows that not only has the U.S. military resisted new energetics in the past, but that persistent advocacy, new manufacturing methods, and the compound's operational use in special-purpose munitions were all key to encouraging its eventual widespread use.

Second, it identifies the numerous structural, political, strategic, bureaucratic, and cultural barriers that have limited energetics innovation and fielding since the end of the Cold War. Some barriers were consequences of a particular era, such as the political and strategic environment of the 1990s and 2000s, while others are byproducts of the nature of munitions and the structure of the energetics industrial base itself. This survey shows how overcoming these long-standing obstacles hinges on fielding novel energetics in ways that mitigate their potential risks and costs while maximizing the advantages they deliver.

To highlight exactly what these advantages may be, the third part illustrates the potential military value of improved energetics by exploring the tactical, operational, and strategic value of munitions with increased range and explosive power in the Indo-Pacific theater. Because munitions constitute the final link in the complex kill chains of modern military operations, improving the performance of individual weapons may have cascading effects that influence broader operations and strategy, such as reducing total munition expenditures, decreasing sortie and attrition rates, and easing logistical burdens.

Finally, the report concludes with recommendations for overcoming the three primary obstacles to employing novel energetics: the lack of requirements for the performance improvements offered by new materials, the added costs of new energetics and their production infrastructure, and the bureaucratic and safety risks inherent in the adoption of new explosives and propellants. Transcending these barriers favors utilizing novel energetics in munitions for specific military applications that best leverage their advantages while mitigating their potential risks. These applications include:

1. Reduced-size weapons and payloads, specifically to equip unmanned systems or weapons containing submunitions;
2. Ground-launched weapons, including both long-range and short-range, shoulder-launched systems;
3. Hypersonic weapons;
4. Torpedoes and unmanned undersea vessels; and
5. Special-purpose weapons, such as munitions for hardened and deeply buried targets.

New energetic materials such as CL-20 will not resolve all the U.S. military's challenges in the Indo-Pacific, and a weapon's range and power are determined by more than just its propellant or explosive compound. A weapon's energetic materials, however, affect all military operations from the smallest tactical engagement to the broader operational and strategic balance. By continuing to ignore the potential benefits of improved energetics, the Department of Defense may be actively choosing less bang for its buck.

CHAPTER 1

Introduction

The U.S. military has a severe munitions problem. Recent conflicts in Europe and the Middle East have shown that modern warfare requires military forces to expend immense quantities of weapons. Yet America's attempts to rebuild its munition stocks and supply allies and partners have come up short, from simple artillery shells to exquisite surface-to-air missiles. As the United States looks to compete with and deter China in the Indo-Pacific region, munitions and the capacity to produce them are among the nation's most serious defense shortfalls.¹

A technology that may help alleviate these challenges is energetic materials, the explosives and propellants filling the U.S. military's arsenal of missiles, rockets, and bombs. By providing greater explosive effects or powering weapons that fly farther or faster, novel energetics promise to increase the lethality of U.S. munitions and, potentially, reduce the number of weapons required to conduct offensive and defensive military operations.² Constructing additional facilities to produce these new compounds would also expand a small but crucial portion of the U.S. munitions industrial base. If history is a guide, the United States may need these advanced materials to compete with rising adversaries who, keenly aware of the tactical and operational advantages of improved weapons, appear to be using the latest energetics in their own munitions.

If fielding new energetics offers numerous military and industrial benefits, why are most American weapons still reliant on RDX and HMX, energetic materials derived from

1 Independent committees, congressional testimony, and think tank analyses continually point to increasing munition stockpiles and investing in the munitions industrial base as key components of preparing the United States for future great power conflict. See RAND, *Commission on the National Defense Strategy* (Santa Monica, CA: RAND, 2024), p. vii, <https://www.rand.org/nsrd/projects/NDS-commission.html>.

2 This report is focused on how improved energetics may impact the U.S. military's conventional weapons. Novel explosives and propellants may also have significant implications for other areas, such as space launch and nuclear weapons.

compounds developed during World War II?³ Newer formulas with improved performance characteristics, such as CL-20, were created by American researchers during the Cold War, but they failed to make their way into large-scale production for the warheads and motors of U.S. munitions. By contrast, the U.S. military's precision-guided munitions (PGMs) feature cutting-edge sensor, networking, and signature-reduction technologies that allow them to deliver extreme accuracy against the world's most challenging targets. Why has there been comparatively little improvement in the realm of explosives, and how could advances in this area provide the U.S. military with tactical, operational, or even strategic advantages in future conflict? Most importantly, what must be done to turn the promises of new energetic materials like CL-20 into military reality?

This report addresses these questions by examining the barriers that have historically impeded energetics innovation and assessing the potential military, economic, and industrial advantages of improved materials in future great power conflict. It begins at the creation of the modern American energetics enterprise—the Second World War. The war's demands led to the construction of a munitions industry that remains the basis of today's industrial base. It also saw the fielding and expanded production of new energetic compounds that proved essential for allied military operations. Thus, World War II's history contains not only the origins of today's munitions industrial base but also lessons for fielding improved energetics in the U.S. military bureaucracy.

The report then examines how the nature of munitions, munitions procurement, and the resulting structure of their industrial base create enduring barriers to fielding new energetics today. Its second section examines how these attributes have combined with strategic, bureaucratic, and cultural factors in recent decades to create an environment hostile to energetics experimentation and fielding. Given these barriers, a true appreciation for the potential advantages of improved energetics is key to securing their adoption.

The third section of this report identifies these advantages in a variety of military applications and assesses their potential tactical, operational, and strategic impacts. It highlights key mission areas where improved energetics could make the greatest contributions, give U.S. forces the supreme advantage, or be the deciding factor in an engagement or operation.

The report concludes with a series of recommendations for overcoming existing barriers and integrating the next generation of energetics into the U.S. military's current and future weapons.

3 Some U.S. weapons also use IMX-based explosives, which were developed and adopted more recently to reduce the sensitivity of munitions filled with older TNT or RDX mixes.

CHAPTER 2

Lessons from the Past: Fielding RDX During World War II

Eight decades have passed since the early 1940s, but the history of the U.S. energetics industrial base has many parallels to today's challenges. As this section shows, the history of military energetics production in the United States and the adoption of RDX during World War II sheds light on both the enduring challenges associated with munitions production and those accompanying the adoption of new and improved energetic compounds. An appreciation of the nation's past experiences with energetics research and production is key to understanding today's challenges.

Since the nation's founding, the United States enjoyed a robust energetics industry in the form of private sector gunpowder and then explosives manufacturers. Despite the strength of this industry before and during WWI, when firms like DuPont made military explosives, the lack of demand for munitions after the war and the isolationist sentiments of the interwar period combined to hollow out much of this capacity for producing energetics.⁴ Many arms producers and their suppliers were branded "merchants of death," accused of war profiteering, and associated with the root causes of World War I. As a result, on the eve of World War II the United States was left with little in the way of a domestic munitions industry.⁵ These attitudes extended into research and academia. George Kistiakowsky, who

4 DuPont's grasp on the energetics market was so strong that it was sued for antitrust violations and split into three firms in 1912. Mark Swanson, *The World War II Ordnance Department's Government-Owned Contractor-Operated (GOCO) Industrial Facilities: Holston Ordnance Works Historic Investigation* (Fort Worth, TX: U.S. Army Corps of Engineers, August 1996), p. 18, <https://apps.dtic.mil/sti/pdfs/ADA315291.pdf>.

5 Tyler Hacker, *Arsenal of Democracy: Myth or Model? Lessons for 21st-Century Industrial Mobilization Planning* (Washington, DC: Center for Strategic and Budgetary Assessments, 2025), chap. 2, <https://csbaonline.org/research/publications/arsenal-of-democracy-myth-or-model-lessons-for-21st-century-industrial-mobilization-planning>.

led the development of the high-explosive elements of the first atomic bomb, summed up the antebellum attitude: “Prior to this war the subject of explosives attracted very little scientific interest, these materials being looked upon as blind destructive agents rather than precision instruments.”⁶

Although the United States largely exited the munitions market during the interwar period, energetics research continued elsewhere in the world. A new, more powerful explosive compound, dubbed hexogen or cyclonite, was formulated by German chemists around the turn of the 20th century. In their search for an improved explosive for underwater applications, British scientists at Woolwich Arsenal began experimenting with this compound in the 1920s, calling it RDX or “Research Department Explosive.” Despite early tests showing more explosive power, RDX remained expensive and difficult to produce using the small-quantity, batch-focused processes used by scientific labs during the interwar period. High costs, production challenges, bureaucratic inertia, and fears of the compound’s sensitivity led the U.S. Army’s Ordnance Department to dismiss the new compound as impractical for military applications in the 1920s. Accordingly, the Ordnance Department and U.S. munitions remained reliant on TNT—proven during World War I—as the primary high explosive going into the 1940s. Even so, as late as July 1940, the entire nation’s production of TNT amounted to only 12 tons per day.⁷

War in Europe brought the United States back into the business of munitions and energetics production. In May 1940, the fall of France gave President Franklin Roosevelt the political support to begin mobilizing the U.S. armed forces. To supply ammunition to these forces, the Army set out to rapidly expand the nation’s withered munitions industrial base, with energetics production a foundational element of mobilization. Based on its experience with expanding munitions production during World War I, the Army understood that munitions and their energetic components required specialized factories and that little commercial or peacetime demand existed for these materials.⁸ The military therefore pursued a hybrid approach to investing in munitions production, one in which the government constructed and owned the plants but arranged for commercial firms to oversee their daily operation. This arrangement, which became known as government-owned, contractor-operated (GOCO), proved to be an innovative way to construct a network of munition plants and leverage commercial manufacturing expertise. GOCO also shifted to the government the financial risk—namely concerns about the large capital investments necessary to construct

6 Colin F. Baxter, *The Secret History of RDX: The Super-Explosive That Helped Win World War II* (Lexington: The University Press of Kentucky, 2018), p. 33.

7 Harry C. Thomson and Lida Mayo, *The Ordnance Department: Procurement and Supply* (Washington, DC: U.S. Army Center of Military History, 1991), p. 32.

8 The history of the Army’s Ordnance Department states: “Because powder and ammunition plants offered none of the usual attractions for private capital, it was recognized that they would have to be built at government expense if they were to be built at all.” Military planners came to this conclusion years before the war, so they had drawn up “plans and specifications” for the sorts of factories that would need to be constructed and prepurchased some of the specialized tooling necessary for energetics production. Thomson and Mayo, *Ordnance Department*, p. 12.

these facilities and their postwar fate when munitions were no longer needed in large quantities. The GOCO arrangement recognized that as specialized products with little peacetime demand but massive wartime demand, munitions and their energetic components required unique approaches to procurement and production.

Beyond standard industrial considerations such as the availability of labor, transportation, and electricity, GOCO energetics plants also required a large supply of fresh water and huge tracts of land to ensure that various production and storage facilities could be safely spread out over large distances. Combined with the War Department's recommendation that defense production facilities be located between the Appalachian and Rocky Mountains and more than 200 miles from the Canadian and Mexican borders, these specifications led to most GOCO plants being constructed in the upper South and the Midwest.⁹

Because TNT remained the most common high explosive in prewar American weapons and was favored by the Ordnance Department, initial GOCO investments in the summer of 1940 supported the construction of a TNT plant in Kankakee, Illinois. The Kankakee Ordnance Works (later known as the Joliet Army Ammunition Plant) was one of over 70 GOCO plants constructed by the War Department, of which at least nine produced TNT and many more produced energetic inputs such as ammonia, ammonium picrate, and toluene.¹⁰ The government relied on established explosives manufacturers such as DuPont, Atlas, Hercules, and Trojan to manage TNT and smokeless powder production, while a variety of commercial chemical and petroleum firms administered the plants producing the chemical inputs for energetics production.¹¹ Alongside massive increases in explosives production came improvements in manufacturing efficiency and a 50 percent reduction in the cost of TNT.¹²

Despite explosives production expanding rapidly, the first two years of the war saw TNT shortages that impacted munitions production. Admiral William H.P. Blandy, chief of the Navy's Bureau of Ordnance, said he was forced to dole out TNT to the Navy "with a teaspoon."¹³ Explosives were in such high demand that Ordnance officials were stretching TNT supplies by filling weapons with amatol, a mixture of TNT and ammonium nitrate.¹⁴ Adopting improved TNT production processes, namely reverse nitration, increased output

9 As with most American defense procurement, political factors in Congress and the White House also heavily impacted GOCO site selection. Scott C. Shaffer and Deborah L. Crown, *The World War II Ordnance Department's Government-Owned Contractor-Operated (GOCO) Industrial Facilities: Badger Ordnance Works Historic Investigation* (Fort Worth, TX: U.S. Army Corps of Engineers, February 1996), pp. 13–19, <https://apps.dtic.mil/sti/pdfs/ADA315696.pdf>.

10 Thomson and Mayo, *Ordnance Department*, p. 111.

11 *Ibid.*, p. 112.

12 *Ibid.*, p. 128.

13 Quoted in *Ibid.*, p. 134.

14 *Ibid.*, *Ordnance Department*, p. 134.

and reduced prices, but high explosives remained a critical shortage for weapons from air-delivered bombs to artillery shells, depth charges, torpedoes, and demolition charges.¹⁵

In this context—a rush to increase production of TNT and its precursors in order to eliminate shortages that were affecting ongoing military operations—the British government began lobbying the U.S. government to produce the experimental RDX at scale. With the United Kingdom declaring war on Germany in September 1939, British officials were forced to confront questions about improved energetics years before the United States. Early on, Lord Beaverbrook, the British minister of aircraft production, complained to the chief of the Royal Air Force’s (RAF) Bomber Command that he was “alarmed that we have no real brains working on the question of improved explosives.” After visiting Woolwich Arsenal, Britain’s primary explosives factory, he was concerned that “except for the costumes, we had stepped back into the Crimean [War] period.”¹⁶ Given British experiments with RDX in the interwar period, Beaverbrook went on to call Britain’s failure to construct a plant to produce the superior compound at scale a “serious failure.”¹⁷ Numerous British military and civilian officials agreed that, in many applications, RDX promised a 30 percent increase in explosive power over TNT mixtures.¹⁸

The British began using RDX produced in small quantities at Woolwich Arsenal for specialized munitions filled with Torpex, a mixture of RDX, TNT, and aluminum powder concocted for underwater munitions. When their improved effects became clear, pressure mounted to increase RDX production and convince the United States to begin producing the explosive at a scale sufficient to supply both countries’ forces. With RAF bombing picking up in 1941, Prime Minister Winston Churchill wrote to Sir Archibald Sinclair, the secretary of state for air, that he was “disappointed that such a large proportion of our efforts should still be applied to carrying bombs with only half the blasting power they might have.”¹⁹ Moreover, it became increasingly clear to the Allies that Germany, Japan, and Italy were employing RDX or other improved energetics to maximize the power of their munitions.²⁰

Based on limited interwar experiments, however, the U.S. Army showed little interest in RDX. Despite British claims, Ordnance Department leaders still considered RDX to be highly experimental and too shock sensitive. They believed it presented no “unqualified advantages over Pentolite” or TNT, which remained the focus of their efforts to increase production and eliminate shortages.²¹ U.S. military requests for improved explo-

15 Ibid., pp. 134–135.

16 Baxter, *Secret History of RDX*, pp. 9–10.

17 Ibid., p. 11.

18 Ibid., pp. 22–23.

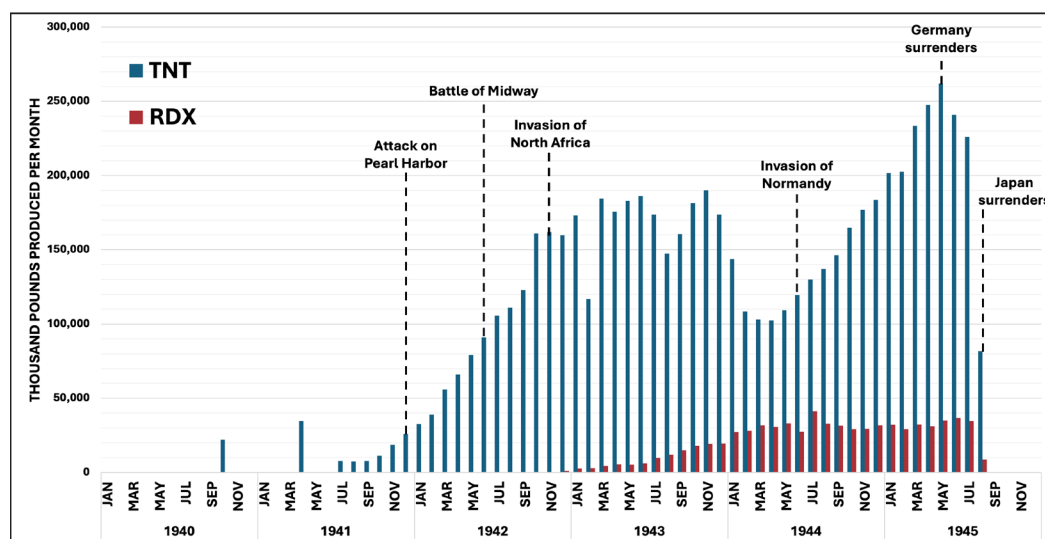
19 Ibid., p. 26.

20 From 1940 to 1942, Allied militaries discovered RDX in Japanese torpedoes, Italian naval shells, and German bombs. Ibid., pp. 40, 56, 70, 72.

21 Ibid., p. 38.

sives skyrocketed after the attack on Pearl Harbor and the U.S. entrance into the war, and American officials agreed to construct a pilot plant for RDX in Indiana beginning in January 1942. With the war effort and industrial mobilization in full swing, continued pressure from the highest levels of the Roosevelt administration finally pushed the Ordnance Department to explore a significant expansion of RDX production. These efforts led to the Tennessee Eastman Corporation inventing a refined process to produce RDX at scale, which paved the way for the construction of Holston Ordnance Works in Kingsport, Tennessee, beginning in June 1942. Holston began operation in May 1943, doubled its output in January 1944, and ultimately became the world's largest producer of RDX and its derivatives such as Composition B.²²

FIGURE 1: MONTHLY U.S. PRODUCTION OF TNT AND RDX DURING WORLD WAR II



Note: Created by CSBA using data from Civilian Production Administration, *Official Munitions Production of the United States: By Months, July 1, 1940-August 31, 1945* (Washington, DC: Civilian Production Administration, May 1, 1947), p. 208.

The superior effects of weapons filled with RDX, Torpex, and Composition B were apparent across the war's campaigns. Three munition types were significantly affected by the introduction of improved energetics: torpedoes, depth charges, and aerial bombs. Early in the war, American officials were concerned about the greater explosive power of Japanese versus American torpedoes.²³ Blandy, chief of the U.S. Navy's Bureau of Ordnance, was an early proponent of RDX and Torpex, which he argued produced 50 percent more damage than TNT in underwater engagements.²⁴ Blandy advocated funding an RDX plant before the House Naval Affairs Committee. Beginning in November 1942, Torpex-filled torpedoes

22 Ibid., pp. 44, 61.

23 Ibid., p. 40.

24 Ibid., p. 38.

would go on to play a key role in U.S. submarine operations in the Pacific, where “ship sinkings increased” and submariners claimed “Torpedex warheads were able to break vessels in two.”²⁵ For similar reasons, RDX was widely adopted in British and American depth charges and “hedgehog” anti-submarine missiles. Torpedex’s increased explosive power allowed smaller British Coastal Command aircraft to carry lighter 250-pound depth charges that remained capable of damaging German U-boats, unlike charges of similar weight filled with TNT.²⁶ For British and American pilots hunting U-boats with larger depth charges, the power of Torpedex was key to ensuring that any engagement with these elusive, difficult-to-hit targets resulted in a sinking.²⁷ By war’s end, the U.S. Navy also introduced an RDX mixture into small- and medium-caliber ammunition to make each round 60 to 100 percent more powerful, an improvement paired with the advent of the new variable time or proximity fuze, which was fielded just in time to confront the kamikaze attacks prevalent late in the conflict.²⁸

RDX was also crucial to improving the effectiveness of air-delivered bombs, particularly those designed for special targets. British aircraft employed 4,000-pound Blockbuster, 12,000-pound Tallboy, and 22,000-pound Grand Slam bombs filled with RDX mixtures against transportation infrastructure (e.g., tunnels, bridges, canals, and viaducts), U-boat pens, dams, and military-industrial sites.²⁹ Because of production constraints, Composition B did not become the standard filling for U.S. Army Air Corps bombs until late in the war, but it nevertheless proved instrumental in attacks against Axis war industries.³⁰ Composition B also played a key role in the war’s final actions, where it formed a large part of the explosive lens used to trigger the Fat Man atomic bomb in August 1945.³¹ Robert O. Bengis, an integral member of the American RDX program, wrote after the war that “Without question, it would have been most advantageous to the War Effort if it had been possible to meet all the requirements where RDX showed its superiority.”³²

Scaling Innovation and the Enduring Lessons of the RDX Story

The story of RDX’s introduction, fielding, and production during World War II has many parallels to today’s energetics challenges. Like today’s armed forces, the U.S. Army of 1940

25 Ibid., p. 39; and Buford Rowland and William B. Boyd, *U.S. Navy Bureau of Ordnance in World War II* (Washington, DC: U.S. Government Printing Office, 1954), p. 206.

26 Baxter, *Secret History of RDX*, pp. 115–128.

27 Ibid., p. 119.

28 Rowland and Boyd, *U.S. Navy Bureau of Ordnance*, pp. 209–210.

29 Tallboy bombs were also crucial in RAF raids against the German battleship *Tirpitz*. See Baxter, *Secret History of RDX*, pp. 28–29.

30 Baxter, *Secret History of RDX*, pp. 49–50.

31 Robert S. Norris, *Racing for the Bomb: General Leslie R. Groves, the Manhattan Project’s Indispensable Man* (Lebanon, NH: Steerforth Press, 2003), pp. 199–200.

32 Baxter, *Secret History of RDX*, p. 61.

relied on older energetic materials despite the discovery of more effective compounds several decades earlier. Introducing improved energetics into U.S. military munitions in World War II was met with skepticism and uncertainty and resisted by bureaucratic and industrial inertia that proved very challenging to overcome. The story of RDX's fielding is less about scientific discovery and more about implementing, fielding, and producing innovation at scale within a constraining bureaucracy. Given these similarities, it offers several enduring lessons as the United States again confronts the challenge of introducing energetic materials with known advantages into the U.S. military's current and future arsenal of munitions.

The bureaucratic resistance to RDX was immense, but it was overcome by advocacy and intervention at the highest levels of government. Bengis wrote after the war that RDX's introduction was only successful "due to the untiring efforts and aggressiveness of all concerned."³³ The primary source of resistance was the U.S. Army, specifically the Ordnance Department, which clung to its two-decades-old tests to argue that the compound was not significantly better than TNT and was "too sensitive and too costly for military purposes."³⁴ Even when British officials confirmed RDX's superiority in actual use against Germany, the Army continued to reject RDX as too expensive. The compound's cost would make it at most a "luxury" explosive confined to, in the words of Army Air Corps Chief General Henry "Hap" Arnold, "very special projects;" thus, it did not require investments in large-scale production.³⁵ At that point, RDX still suffered from the chicken-and-egg problem associated with investing in production and reducing costs via economies of scale. Brigadier General R.H. Somers, chief of the Ordnance Department's Technical Division, stated that "Cyclonite [RDX] can be used by the Army when its production is sufficiently large to justify its adoption as an alternative explosive."³⁶ This suggestion ignored the fact that RDX's production would only increase—and its cost decrease—with investment and demand from the armed services themselves.

This bureaucratic stonewalling was eventually overcome by the continued advocacy of civilian scientists and officials over the heads of uniformed personnel to very high levels of the Roosevelt administration. The British realized this first, with Beaverbrook suggesting that the RAF should appeal directly to the president and civilian mobilization officials, who could overrule "the inevitably professional view of the [American] Service chiefs."³⁷ By November 1941, Secretary of War Henry Stimson was driving the Ordnance Department to push forward with RDX production and fielding.³⁸ When shortages of stainless steel threatened to halt the construction of Holston Ordnance Works, RDX advocates appealed directly

33 Ibid., p. 25.

34 Ibid., p. 36.

35 Quoted in Ibid., p. 19.

36 Quoted in Ibid., p. 18.

37 Quoted in Ibid., p. 13.

38 Ibid., pp. 41–42.

to Roosevelt to continue the project.³⁹ The Ordnance Department would later write that its “distrust of the NDRC [National Defense Research Committee] lay in the century-old conflict of military versus civilian.”⁴⁰ With some exceptions (such as Blandy), the RDX story pit uniformed members of the military bureaucracy against civilian scientists, academics, and engineers.

In appealing to political leaders, these civilians went far beyond touting RDX’s impressive gains in explosive power (often described by military officials as a 20 to 30 percent increase) to focus on the larger second- and third-order strategic and economic benefits of substituting RDX for TNT. Lord Cherwell, a scientific advisor to Churchill, advocated RDX’s use in aerial bombs, saying: “Something like a million men are engaged in building and maintaining bombers in order to drop bombs on Germany, so that any increase in the efficiency of these bombs, even if only by a small percentage, is worth a very large number of man-hours.”⁴¹ J.R. Donald, a Canadian scientist and member of the Canadian–American RDX Committee, expanded on this line of reasoning:

The number of planes over enemy territory is obviously not the objective but the explosive force which can be delivered by the planes.... The more powerful the explosive permits the use of fewer planes. It is a reasonable assumption that the capital cost of doubling RDX production in the United States would be a great deal less than the capital cost of creating plants to increase bomber production by 40%.⁴²

Donald continued in a 1943 memo:

In round figures, 70 bombers carrying bombs loaded with RDX/TNT mixture [Composition B] carry the same explosive force as 100 utilizing TNT loaded bombs. By spending a comparatively small sum of money on RDX expansion, the equivalent of a good many million dollars in bomber production and operation can be obtained. It also seems possible that the limiting factor in bombing will be the heavy demands for high octane gasoline, trained air and ground crews and, if this proves to be the case, the use of a super explosive becomes increasingly important.⁴³

A 1943 memorandum to Roosevelt to secure stainless steel for the construction of Holston Ordnance Works argued along similar lines: “A swing-over from TNT to RDX would be similar in its effect to an increase in plane and pilot output, and would mean saving in material and gasoline.”⁴⁴ These arguments are quoted at length because they show how the adoption of improved energetics creates advantages well beyond military effectiveness at

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39 Ibid., p. 57.

40 Quoted in Ibid., p. 39.

41 Ibid., p. 26.

42 Ibid., p. 55.

43 Ibid., p. 72.

44 Ibid., p. 57.

the tactical or even operational level. These advantages resonated with civilian and military decision makers whose concerns included not just individual weapon technologies, engagements, or campaigns but the strategic and economic conduct of the entire war. Emphasizing these benefits rather than simple percentage increases in explosive power proved instrumental to overcoming institutional resistance to RDX and may be crucial to encouraging the adoption of advanced energetics today.

Improved manufacturing methods were key to encouraging the scaled production and adoption of RDX, and civilian researchers and commercial producers were essential to developing these improvements.

In addition to the Army's concerns about RDX's sensitivity, British methods for producing the compound early in the war were inefficient and ill-suited to mass production. This made RDX expensive and resulted in more material waste than TNT production.⁴⁵ Researchers at McGill University improved the process to allow production of larger batches, and University of Michigan chemist Werner Bachmann then invented a more refined process in December 1941 that doubled the yield of RDX while reducing the quantity of nitric acid needed by 85 percent.⁴⁶ Although these processes enabled reduced-cost production of larger batches of RDX, only manufacturing equipment developed by the Tennessee Eastman Corporation allowed the explosive to be produced at Holston in a continuous manner in the quantities desired.⁴⁷ These process improvements were also necessary to reduce RDX's cost to a level competitive with TNT. With the GOCO plants in operation, TNT cost between six and 15 cents per pound.⁴⁸ In smaller-scale production, before the invention of refined manufacturing processes, RDX cost between \$1 and \$2 per pound.⁴⁹ Even RDX's strongest advocates estimated that mass production might only bring the cost down to around 50 cents per pound.⁵⁰ Thanks to the developments of the Tennessee Eastman Corporation, however, Holston Ordnance Works began producing Composition B for 30.5 cents per pound in May 1943 and reduced this to 10.5 cents per pound by war's end.⁵¹ Without the process improvements and manufacturing expertise of academic researchers and commercial chemical companies, the U.S. military would have been incapable of producing RDX in the quantities and at the costs required by World War II. Given the enduring structural barriers that will be explored in the next section, commercial companies and their manufacturing expertise may again be essential for enabling the production of advanced energetics in larger quantities and at reduced costs.

45 British production of RDX utilized the Woolwich method, named after the arsenal where it was developed. This process was described as "a nitric-acid-plant dog with a RDX-plant tail." *Ibid.*, p. 36.

46 *Ibid.*, p. 69.

47 *Ibid.*, pp. 76–82.

48 Thomson and Mayo, *Ordnance Department*, p. 135; and *Ibid.*, p. 6.

49 Baxter, *Secret History of RDX*, p. 38.

50 *Ibid.*, p. 39.

51 Swanson, *Holston Ordnance Works*, p. 39.

More efficient production methods helped overcome another barrier to producing RDX at scale: the need to maintain maximum TNT production under wartime resource constraints.

After industrial mobilization and the construction of GOCO TNT plants began, inertia became a key argument against expanding RDX production and use. Even if RDX promised greater explosive power, American industry was already struggling to keep up with demand for TNT-filled munitions. Any realignment of resources toward increasing production of the still experimental RDX might disrupt TNT production and intensify munition shortages on the front line.⁵² The chief of the Ordnance Department's Ammunition Branch, Brigadier General Roswell E. Hardy, said the need to maximize TNT production became a "severe handicap in expediting the RDX expansion."⁵³ In the end, the authority of Roosevelt himself was necessary to ensure that sufficient critical materials were prioritized toward the construction of Holston Ordnance Works. At present, similar arguments can be made against integrating experimental energetics into munitions already in short supply or expanding production of new compounds within an already strained energetics industrial base. Like any military technology, new energetics offer improved military effectiveness but also carry significant risks should they prove less advantageous or less suitable for military applications than expected. In the case of RDX, British employment early in the war proved to decision makers that the explosive could be used in weapons to great effect. Similar pilot programs or field tests, potentially by U.S. allies or partners, may again be useful for proving the advantages of and limiting the risks associated with improved energetics.

Even after RDX's adoption, concerns about the compound's sensitivity and suitability for operational use hampered its fielding and took time to overcome.

Thanks to several tests conducted in the 1920s, many officials within the U.S. military were concerned about RDX's stability, even after later mixtures were retested and successfully employed.⁵⁴ Several incidents involving improper munition handling further concerned Ordnance Department officers as well as bomber crews who were issued bombs filled with Composition B.⁵⁵ Although the new bombs had a sensitivity comparable to TNT- or Amatol-filled bombs, rumors spread through aircrews that hindered usage of RDX-filled bombs well into the American strategic bombing campaign in Europe. Only time and repeated use mitigated the stigma attached to RDX and Composition B bombs.

RDX use was encouraged by early experiments employing the compound in specialized munitions and specific military applications that harnessed its advantages and mitigated its risks. Perhaps the most convincing arguments for increasing production of RDX were the positive reports flowing back from the successful

52 Baxter, *Secret History of RDX*, p. 42.

53 Quoted in *Ibid.*, p. 53.

54 *Ibid.*, p. 6.

55 *Ibid.*, pp. 44–47.

use of specialized, experimental, RDX-filled weapons. Rather than immediately fielding RDX to standard, general-purpose munitions, production constraints meant that the material was first employed by the British for special missions where its added power was most needed. These missions included attacking transportation infrastructure, dams, and U-boat pens with large bombs made for those purposes. RDX's power also allowed smaller aircraft to attack some of these special targets using lighter bombs.⁵⁶ In the U.S. military, stability concerns encouraged the material's use in applications where its sensitivity posed less risk, such as torpedoes or aerial depth charges.⁵⁷ When these munitions proved more effective, the Navy then refined the mixture of RDX to further reduce its sensitivity and employ it in a greater range of applications. These anecdotes illustrate the value of identifying specific missions where improved energetics might have the most significant contributions, as well as applications in which a new material's disadvantages—sensitivity, cost, or limited availability—are irrelevant or justified by potential gains.

56 Ibid., p. 26.

57 Because Navy leaders worried about the potential for RDX-filled depth charges to explode if struck by enemy fire, they initially prohibited its use in torpedoes and depth charges used to arm surface combatants. Given the already high casualty rate of torpedo planes, they viewed the additional risk of RDX to be justified by the material's added power. Rowland and Boyd, *U.S. Navy Bureau of Ordnance*, pp. 205–206.

CHAPTER 3

Enduring Barriers to Adopting Improved Energetics

The history of energetics production in 20th-century America highlights some of the most significant barriers to adopting new compounds and scaling their manufacture, including the unique nature of munitions, munitions procurement cycles, and their effect on the structure of the munitions industrial base. These structural barriers have combined with the political and strategic environment of the post–Cold War era to create more obstacles to the widespread adoption of new energetics in U.S. military munitions. Drawing on the preceding historical narrative, this section highlights the numerous barriers that have inhibited the U.S. military from expanding the production and employment of improved energetics since World War II.

Structural Barriers

The munitions industrial base is subject to many of the same peculiarities as the wider defense industry of which it is a subset.⁵⁸ The nature of weapons and their energetic components, however, makes the munitions industrial base unique and presents a distinctive set of barriers to innovation. Because these factors result from the character of weapons themselves and their purpose in warfare, they are enduring and, to some extent, immutable.

Most obviously, munitions and energetics are explosive, so their manufacturing and handling is dangerous and must be subject to specialized rules, processes, and equipment. Producing energetics has long been risky, with numerous accidents killing workers and destroying infrastructure. During World War II, accidents in munition plants contributed to

58 Jacques S. Gansler noted that the U.S. defense industrial base is a “uniquely structured market” that has “essentially a single buyer (the Department of Defense), has a small group of major suppliers (essentially an oligopoly in each sector), and is controlled by government laws and regulations.” Jacques S. Gansler, *Democracy’s Arsenal: Creating a Twenty-First-Century Defense Industry* (Cambridge, MA: The MIT Press, 2013), p. 9.

the tally of civilian industrial deaths, which in 1941 and 1942 exceeded U.S. service members killed in action.⁵⁹ Even in the 21st century, Holston Army Ammunition Plant suffered an explosion in 2019; Radford Army Ammunition Plant experienced a fire in early 2025;⁶⁰ and an explosion killed 16 workers at Accurate Energetic Systems, a military energetics supplier in Tennessee in October 2025.⁶¹ The long history of accidental explosions at ordnance factories underscores the safety concerns that drive specialized facilities, firms, and workers, all of which set energetics and munition manufacturing facilities apart from other elements of the defense industrial base.

Explosives manufacturing can also be an environmentally hazardous undertaking. World War II-era plants polluted the air, soil, and water, with the U.S. Forest Service recalling that “water in Grant Creek ran red” when the Joliet Army Ammunition Plant was producing TNT.⁶² Several current and former ordnance sites can be found on the Environmental Protection Agency’s National Priorities List, a collection of “the nation’s most contaminated land.”⁶³ The hazardous nature of producing and handling energetic materials means that plants are large in order to maintain safe distances between operations.⁶⁴ Such large

59 An explosion at the Elwood Ordnance Plant in June 1942 killed 48 workers and caused almost half a million dollars in property damage. Although not inside a munitions plant, an explosion caused by munitions loading at the Port Chicago Pier in California killed over 250 and injured more than 1,000 people in 1944. Andrew E. Kersten, *Labor’s Home Front: The American Federation of Labor During World War II* (New York: New York University Press, 2006), p. 168; and Thomson and Mayo, *Ordnance Department*, p. 131.

60 Caleb Perhne, “Still No Answers One Year After Holston Army Ammunition Plant Explosion,” *WCYB5 News*, updated December 30, 2019, <https://wcyb.com/news/local/still-no-answers-one-year-after-holston-army-ammunition-plant-explosion>; and Associated Press, “No Injuries Reported in Virginia Army Ammunition Plant Explosion,” *Defense News*, February 28, 2025, <https://www.defensenews.com/industry/2025/02/28/no-injuries-reported-in-virginia-army-ammunition-plant-explosion/>.

61 Hannah Park, Isabel Rosales, Maxime Tamsett, and Ray Sanchez, “Massive Blast That Destroyed a Tennessee Explosive Plant Leaves 16 Dead, Officials Say,” *CNN*, updated October 11, 2025, <https://www.cnn.com/2025/10/11/us/tennessee-explosion-military-accurate-energetic-systems-wwk-hnk>.

62 U.S. Forest Service, “The Joliet Army Ammunition Plant,” accessed December 29, 2025, <https://www.fs.usda.gov/r09/midewin/recreation/discover-history/joliet-army-ammunition-plant>.

63 U.S. Environmental Protection Agency, “Superfund,” accessed December 29, 2025, <https://www.epa.gov/superfund>.

64 For example, Holston Army Ammunition Plant consists of nearly 500 buildings (not including 129 buried storage magazines) spread over 5,980 acres. Radford Army Ammunition plant consists of 1,038 individual buildings and 214 storage igloos on 6,901 acres. The Allegany Ballistics Laboratory occupies roughly 1,627 acres. U.S. Army, “Holston Army Ammunition Plant: Government-Owned, Contractor-Operated (GOCO),” accessed December 30, 2025, https://www.jmc.army.mil/thumbnails/pdfs/HSAAP_Brochure.pdf; U.S. Army, “Radford Army Ammunition Plant: Government-Owned, Contractor-Operated (GOCO),” accessed December 30, 2025, https://www.jmc.army.mil/Radford/docs/RFAAP_Brochure.pdf; and U.S. Environmental Protection Agency, “Superfund Site: Allegany Ballistics Laboratory (U.S. Navy), Mineral County, WV: Cleanup Activities,” accessed December 30, 2025, <https://cumulis.epa.gov/supercpad/SiteProfiles/index.cfm?fuseaction=second.Cleanup&id=0303171#bkgground>.

facilities also make better use of economies of scale to help defray the significant capital investments necessary to manufacture, test, store, and ship explosive materials.⁶⁵

The munitions industrial base, and by extension the energetics industrial base, is further affected by the lack of commercial applications for munitions and their components. Producers of military aircraft, ships, or ground vehicles can draw on more general aerospace, maritime, and automotive subcontractors in their supply chains, and these subcontractors often sell components to both commercial and defense manufacturers. Many firms that produce defense platforms, such as Boeing or Airbus, also have large commercial businesses and do not depend on military sales. No equivalent commercial market exists for munitions and their energetic components, whose only large-volume customers are militaries.⁶⁶

Finally, munitions are expendable, which sets them apart from reusable defense systems. Despite expending large quantities of munitions in wartime, militaries use fewer weapons during peacetime for testing and training. This varied usage creates an erratic demand signal that discourages private sector investment in munition and energetics production. There is no steady, consistent demand to offset the risks associated with the large, long-term capital investments necessary to construct energetics plants and munition assembly factories. Expendability and the cyclical demand signal it creates compelled the U.S. government to finance and build its own munition plants using the GOCO model during World War II.⁶⁷ Whereas a commercial firm might have shut down and sold some or all of its energetics production capacity at the end of the war when demand ceased, the GOCO model enabled the U.S. government to maintain ownership of the plants, put them into a reserve status, and reopen them to support the conflicts in Korea and Vietnam.⁶⁸ Although this approach provided the U.S. military a ready supply of explosives during wartime, the predominance of government-owned energetics plants has stifled competition and innovation in the military

65 Holston Ordnance Works was one of the most expensive GOCO facilities constructed during World War II. DoD's 2023 National Energetics Plan stated that building energetics production facilities "requires time and substantial financial investment, a major challenge in a limited and relatively unprofitable market." Swanson, *Holston Ordnance Works*, p. 36; and Office of the Under Secretary of Defense for Research and Engineering, *National Energetics Plan* (Washington, DC: U.S. Department of Defense, May 2023), p. 12, https://www.nacconsortium.org/wp-content/uploads/2023/08/National_Energetics-Plan_DRAFT_DISTRO_A.pdf.

66 There are numerous uses for energetic materials in the commercial sector (e.g., in the mining, construction, and oil and gas industries), but none of them demand explosives in the same volume as military applications. Many of these applications favor different energetics with attributes distinct from military explosives or propellants.

67 A key lesson of World War I for the U.S. Army Ordnance Department was that munitions and explosive materials would require direct government investment in production capacity. Thomson and Mayo, *Ordnance Department*, pp. 11, 33.

68 As an example: Badger Ordnance Works was put into a reserve status from 1945 to 1950, reopened in 1951 to support the Korean War, inactivated from 1958 to 1966, reopened to support the war in Vietnam, put into stand-by in 1975, and ultimately closed after being declared excess in 1997. Shaffer and Crown, *Badger Ordnance Works*, pp. 100–104.

energetics market by reducing the need for commercial producers, particularly during peacetime and periods of reduced munitions procurement.⁶⁹

Political and Strategic Barriers

Over the last several decades, the political and strategic environment has combined with these structural factors to further inhibit energetics production and innovation. The end of the Cold War brought reductions in defense spending that led to consolidation in the munitions industrial base, an emphasis on efficiency, and the closure of excess facilities. The lack of a peer competitor and the military's focus on the Middle East directed munition innovation in areas other than more powerful energetics, such as increased precision and insensitivity. With little demand for energetics that offer more power or range, the energetics space remained stagnant.

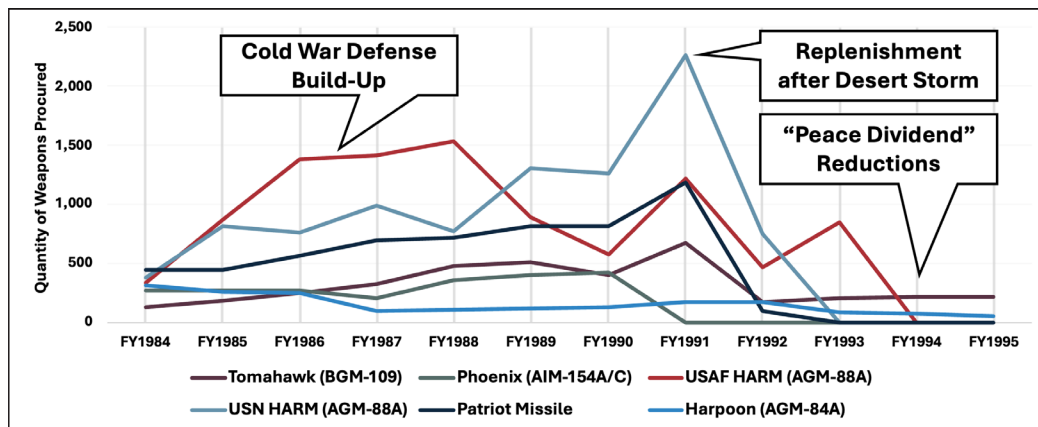
The end of the Cold War in the early 1990s drastically altered the munitions and energetics industrial base, just as it did the rest of the American defense industry. With the dissolution of America's primary adversary, existing stockpiles of munitions were deemed sufficient and procurement of many weapons dropped dramatically (Figure 2). Defense spending fell by over \$100 billion, with more than 60 percent of those reductions coming in procurement spending.⁷⁰ To make matters worse, munitions have long been sacrificed as "bill payers" within the Department of Defense's (DoD's) procurement portfolio. Unlike large, exquisite platforms, weapons have lower unit costs and are typically purchased in higher quantities. Budgeters looking to trim spending cannot purchase half a bomber or destroyer, but shaving off percentages of a weapons buy is a straightforward way to trim spending without creating controversy.⁷¹ Whereas cuts to platform procurement are often associated with broader, more impactful cuts to force structure and the personnel associated with those platforms, the operational and industrial risks of fractional cuts to munition procurement are more challenging to articulate.

69 More recently, the Pentagon has used a mixed approach (dubbed the direct-to-supplier model) to expand production of certain munition components such as solid rocket motors. For example, DoD recently invested \$1 billion in the motor manufacturer Missile Solutions to "increase its solid rocket motor production, modernize its facilities and improve industrial resilience," under the Industrial Base Analysis and Sustainment initiative. With DoD as the "anchor investor," Missile Solutions is planning an initial public offering in 2026. See Stephen Losey, "Pentagon to Invest \$1B in L3Harris Spinoff Rocket Motor Firm," *Defense News*, January 13, 2026, <https://www.defensenews.com/pentagon/2026/01/13/pentagon-to-invest-1b-in-l3harris-spinoff-rocket-motor-firm/>.

70 Gansler, *Democracy's Arsenal*, p. 11.

71 Former Air Force acquisition chief Will Roper summarized this tendency, saying: "Munitions...often become a bill payer in program reviews. Budgeters think 'you just buy fewer.'" 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/>.

FIGURE 2: SELECTED MUNITIONS PROCUREMENT QUANTITIES IN THE WAKE OF THE COLD WAR



Note: Quantities displayed are the quantities funded from Fiscal Year (FY) 1984 through FY 1994 and requested for FY 1995. "Total Quantities and Unit Procurement Cost Tables, 1974 – 1995," Congressional Budget Office, April 13, 1994, <https://www.cbo.gov/sites/default/files/cbofiles/ftpdocs/75xx/doc7535/94doco2b.pdf>.

Reductions in weapon procurement resulted in the consolidation of private munition producers and closure of many government-owned munition and energetics production facilities. As early as 1992, the Congressional Budget Office predicted that ordnance, explosive, and missile manufacturers would suffer from reduced defense spending because they remained reliant on defense sales and lacked commercial alternatives or analogues.⁷² Accordingly, the number of contractors involved in tactical missile production fell from 13 to three.⁷³ This consolidation extended to the network of GOCO explosives factories built for World War II, with only 27 of the 77 original GOCO facilities remaining by the 1990s.⁷⁴ The military's identification of some facilities as excess capacity combined with closures from Base Realignment and Closure Act (BRAC) deliberations to further winnow and consolidate the military's energetics and munition industrial base.⁷⁵ Holston was left as the sole producer of RDX- and HMX-based explosives, Radford the sole producer of some propellants, and domestic TNT production ceased.⁷⁶

72 Congressional Budget Office, *The Economic Effects of Reduced Defense Spending* (Washington, DC: Congressional Budget Office, February 1992), pp. 23, 52, https://www.cbo.gov/sites/default/files/102nd-congress-1991-1992/reports/1992_02_theeconomiceffectsofreduceddefence.pdf.

73 DoD, *State of Competition Within the Defense Industrial Base* (Washington, DC: DoD, February 2022), p. 5, <https://media.defense.gov/2022/feb/15/2002939087/-1/-1/1/state-of-competition-within-the-defense-industrial-base.pdf>.

74 Swanson, *Holston Ordnance Works*, p. 92.

75 Five rounds of BRAC were conducted from 1988 to 2005.

76 Swanson, *Holston Ordnance Works*, p. 92; and Derek Operle, "First TNT Manufacturer to Operate on American Soil Since 1980s to Be Built in Kentucky," *WKMS*, November 8, 2024, <https://www.wkms.org/military/2024-11-08/first-tnt-manufacturer-to-operate-on-american-soil-since-1980s-to-be-built-in-kentucky>.

At the same time, the defense industry was following the broader business world by increasing its emphasis on efficiency, cost savings, and the elimination of excess capacity.⁷⁷ Tighter budgets left little money for experimentation with improved energetics, which may have increased costs and stretched development timelines. Just as early batches of RDX were extremely expensive compared to TNT, new energetic compounds such as CL-20 remained pricey due to small-scale production using complex, experimental methods. Furthermore, there was insufficient demand for the integration of more powerful energetics into munitions. The U.S. military's weapons technology far exceeded that of the new Russian Federation, the People's Republic of China, or other lesser adversaries. With the Cold War against the Soviet Union replaced by smaller, regional threats and nonstate actors, there was little reason to expend time, money, or bureaucratic energy on integrating experimental energetic compounds into America's already impressive arsenal. Absent an operational or strategic problem to break bureaucratic preferences and foster urgency, military innovation is challenging. The threat environment of the 1990s and early 2000s produced little need for the advantages offered by new energetics.⁷⁸ With negligible investment in improved production methods or larger-scale manufacturing, the cost of producing compounds like CL-20 remained high.

With engineers under pressure to meet performance requirements at minimum costs, the expense of novel energetics discouraged their use in new and developmental weapon programs. DoD's National Energetics Plan summarized the problem concisely:

As a result of rising costs per [energetic materials systems] unit, new and modernizing (via spiral development) weapon systems programs do not often consider the increased performance afforded by new [energetic materials systems] technologies.... Without performance-based (lethality, propulsion) requirements, [program managers] view integration of new [energetic materials] chiefly as a significant source of risk and increased cost, and cost has been the chief consideration of the acquisition community over recent decades, with other parameters (schedule, risk) lagging not far behind. Moreover, the Government typically solicits system designs from industry, where competition and the drive for profit margin work against investment in new [energetic materials].⁷⁹

Instead, the U.S. military's involvement in the Global War on Terror and the wars in Iraq and Afghanistan focused munition and energetic development on a different set of attributes: increased precision, reduced collateral damage, and improved insensitivity. Precision guidance again proved its worth during the opening phases of the invasions of Afghanistan and

77 Barry D. Watts, *The U.S. Defense Industrial Base: Past, Present and Future* (Washington, DC: Center for Strategic and Budgetary Assessments, October 2008), pp. 2–3, <https://csbaonline.org/research/publications/the-us-defense-industrial-base-past-present-and-future>.

78 For more on the elements of successful military innovation, see Thomas G. Mahnken, Evan B. Montgomery, and Tyler Hacker, *Innovating for Great Power Competition: An Examination of Service and Joint Efforts* (Washington, DC: Center for Strategic and Budgetary Assessments, 2023), <https://csbaonline.org/research/publications/innovating-for-great-power-competition-an-examination-of-service-and-joint-innovation-efforts>.

79 Office of the Under Secretary of Defense for Research and Engineering, *National Energetics Plan*, pp. 12–13.

Iraq, when PGMs constituted the majority of weapons employed and helped minimize the total number of munitions expended.⁸⁰ A desire to avoid collateral damage favored weapons with smaller energetic payloads, with some specialized Hellfire missiles eventually forgoing explosive warheads altogether in favor of a series of blades.⁸¹ Rather than improved power, energetics research and experimentation was mostly centered on reducing the sensitivity of American weapons to shock, heat, and accidental detonations. Numerous accidents caused or exacerbated by exploding munitions led to the creation of the U.S. Navy's insensitive munitions program in 1984 and a joint memorandum between the Services in 1987, with insensitive munition requirements written into U.S. law in 1996.⁸² The path to integrating insensitive energetics into American weapons was littered with many of the same obstacles described in this report (technical roadblocks, high costs, and bureaucratic resistance), but it eventually succeeded because the costs of munition accidents (loss of military personnel and platforms, including extensive damage to several aircraft carriers) clearly justified the added costs of the insensitive munitions program.

Cultural Barriers

Adding to these structural and strategic barriers are cultural factors that disadvantage energetics and munitions innovation: institutional biases against weapons and a risk-averse organizational culture that often avoids near-term bureaucratic and political risk while accruing long-term operational and industrial risk. First, DoD culture favors large, expensive platforms over smaller weapons programs. Most budgetary resources are devoted to large programs, which attract more attention from Congress and lobbying organizations. In this game, munitions lack a dedicated military or bureaucratic community to promote their procurement. Fighter pilots advocate for more fighters and surface warfare officers advocate for more ships, but no single military community or culture centers on munitions. These factors add to the tendency for weapons to become bill payers during the budget process and may help explain DoD's poor track record of following through with the munitions purchases projected in future years defense programs (FYDPs).⁸³ Failure to purchase weapons in the quantities predicted in previous years furthers industry doubts about the certainty and

80 See Tyler Hacker, *Beyond Precision: Maintaining America's Strike Advantage in Great Power Conflict* (Washington, DC: Center for Strategic and Budgetary Assessments, 2023), chap. 2, <https://csbaonline.org/research/publications/beyond-precision-maintaining-americas-strike-advantage-in-great-power-conflict>.

81 Tyler Rogoway, "Bladed 'Ginsu' Hellfire Missile Seen in Action for First Time," *The War Zone*, March 1, 2025, <https://www.twz.com/air/bladed-hellfire-missile-seen-in-action-for-the-first-time>.

82 For an overview of the U.S. military's insensitive munition efforts, see Kenneth J. Graham, "Insensitive Munitions: U.S. Problems and Solutions," *NATO Science & Technology Organization*, June 26, 2023, <https://publications.sto.nato.int/publications/STO%20Educational%20Notes/STO-EN-AVT-214/EN-AVT-214-05.pdf>.

83 For a detailed examination of how DoD spending on critical munitions has followed its own FYDP projections, see Stacie Pettyjohn and Hannah Dennis, *Precision and Posture: Defense Spending Trends and the FY23 Budget Request* (Washington, DC: Center for a New American Security, November 2022), https://s3.us-east-1.amazonaws.com/files.cnas.org/documents/Budget2022_Final.pdf.

longevity of demand, which in turn discourages investments in munitions and energetics development and production.

Second, the DoD bureaucracy has, according to some senior officials, preferred to eschew risk in favor of the status quo.⁸⁴ Recent military innovation efforts have benefited from a host of initiatives meant to overcome this inertia, but the explosive nature of weapons and energetics creates inherent safety concerns that complicate efforts to adopt innovative business practices and “move fast and break things.” After working for several decades to reduce the sensitivity of energetics and avoid repeating accidents responsible for the deaths of scores of servicemembers, DoD is understandably hesitant to experiment with or adopt explosive compounds that may trade away insensitivity for power. These concerns have helped foster a byzantine, years-long testing and certification process for new energetic materials that creates a bottleneck for all new explosives. This process contributes to the extremely wide “valley of death” between energetics research and development and the adoption and integration of new compounds into U.S. munition programs.

Third, the potential advantages of new energetics are often difficult to compare to the very real risks and costs of adopting them. From safety risks to the financial risks of investing in the development of improved compounds and production methods, the hazards of adopting new energetic compounds are abundantly clear, as are the currently higher costs of munitions containing them. Furthermore, describing the potential advantages of improved energetics requires assumptions and the use of hypotheticals. Estimates of percentage increases in explosive power mean little when compared to a safety concern that might endanger service members. Moreover, these technical estimates do not provide immediate insight into the tactical advantages that compounds might give U.S. forces or the follow-on operational and strategic benefits of these improvements.

Together, these factors have resulted in compounds like CL-20 being trapped in the same chicken-and-egg problem experienced during RDX’s adoption: All parties (industry, the Services, DoD) stand to benefit from the production of improved energetics and their integration into munitions, but no party appears willing to risk the resources necessary to develop, test, integrate, and produce new energetics at scale. The path to the widespread utilization of improved energetics hinges on these risks and their mitigation or acceptance.

84 To some extent, bureaucracies are intended to routinize operations and are naturally resistant to innovation and change. Jackson Barnett, “Esper Takes Aim at DOD ‘Culture,’ Risk Aversion,” *FedScoop*, January 27, 2020, <https://fedscoop.com/esper-emerging-technology-governance/>; and Meghann Myers, “Risk Aversion and Secrecy Are Costing U.S. Its Military Advantage, No. 2 General Says,” *Military Times*, October 28, 2021, <https://www.militarytimes.com/news/pentagon-congress/2021/10/28/risk-aversion-and-secrecy-are-costing-us-its-military-advantage-no-2-general-says/>.

CHAPTER 4

The Contemporary Case for Improved Energetics

Many factors have hindered innovation and contributed to the U.S. military's continued reliance on decades-old energetics technology. Some innovation barriers are consequences of a particular era, such as the political and strategic environment of the 1990s and 2000s. Others are byproducts of the nature of munitions and the structure of the energetics industrial base. Many of these barriers appear, for now, to endure. The examination of historic and current barriers highlighted that the successful adoption of new energetics often required advocates to build their case around not just potential performance improvements but also the broader operational, strategic, and economic advantages of improving the effectiveness or safety of munitions. RDX advocates appealed to the explosive's potential to reduce the number of bombers to be built and to decisively impact anti-submarine operations in the Atlantic. Similarly, the prospective advantages of insensitive munitions were clear after several major accidents killed servicemembers, destroyed or damaged the military's most expensive assets, and interrupted training and combat operations.

Just as improved energetics were key to winning the wars of the past, new compounds promise to deliver advantages in future military operations. In tests, novel mixtures that harness compounds such as CL-20 demonstrate higher energy density and explosive power than RDX- and HMX-based materials.⁸⁵ Depending on warhead and munition design, some officials expect CL-20 to offer weapons as much as “a 40 percent increase in penetration depth” and substantially increased range.⁸⁶ These data points sound promising, but they may

85 CL-20 has a higher density, specific energy, and shock velocity than RDX or HMX. John Fischer and Robert Wardle, *CL-20 in the Beginning: Perspectives from Eyewitnesses to the Early Days*, Energetics Technology Center, May 14, 2024, slide 7, https://imemg.org/wp-content/uploads/2024/05/24112_presentation-CL-20-from-beginning-May-2024-Wardle-vo.pdf.

86 Frank Wolfe, “Lawmakers Look Into Advanced Energetics for Munitions,” *Defense Daily*, March 24, 2023, <https://www.defensedaily.com/lawmakers-look-into-advanced-energetics-for-munitions/advanced-transformational-technology/>.

not resonate with policymakers, military leaders, and program managers concerned with balancing operational challenges in the Indo-Pacific, budgetary constraints in Washington, and the safety and programmatic concerns associated with unfamiliar explosives. How could new energetic materials really affect the military balance between the United States and its adversaries?

If the past tells us anything, it is that we must illustrate the benefits of novel energetics in ways that resonate with these audiences and enable comparison of safety, fiscal, and operational risk factors. This chapter explores the potential impacts of improved energetics using the tactical, operational, and strategic terms key to assessing their true military value.

Propulsion: Increased Range

Physics meets geography to make munition and platform range fundamental constraints and key planning variables in military operations. Given the importance of the maximum distance at which a weapon can be employed, additional range is almost always beneficial, particularly if it can be achieved while keeping design characteristics such as size and weight constant. This maxim is particularly true in the Indo-Pacific region, where the vast distances between land masses have always been a defining feature of military operations.⁸⁷ A weapon's maximum range, however, has far-ranging impacts beyond simply determining the depth of targets that could be attacked or the necessary range of delivery platforms. Increased munition range affects various weapon systems and mission areas in dissimilar ways, and the often unexamined second- and third-order effects of additional munition range may have significant impacts on the operational and strategic balance.

This section analyzes the effects of increasing munition ranges by 10 to 30 percent. These gains represent the low- and high-end estimates of range improvements that might be gained by harnessing novel energetic compounds in weapon propellants. Of course, propellant choice is only one aspect of designing weapons that fly farther. To achieve large improvements in range, advanced energetics may need to be combined with other elements of weapon design and employment such as modified weapon bodies or more efficient motors. Nevertheless, the energetic material used in munition propulsion is the foundation for determining a weapon's maximum effective range.

Long-Range Strike

The obvious benefit of increased munition range is a broader, more flexible assortment of offensive strike options. Power projection in the Indo-Pacific region is especially challenging

87 For assessments of the Indo-Pacific's geography and its impact on ideal munition platform ranges, see 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), chap. 2, <https://csbaonline.org/research/publications/rings-of-fire-a-conventional-missile-strategy-for-a-post-inf-treaty-world>; and Hacker, *Beyond Precision*, pp. 42–43, 53–56.

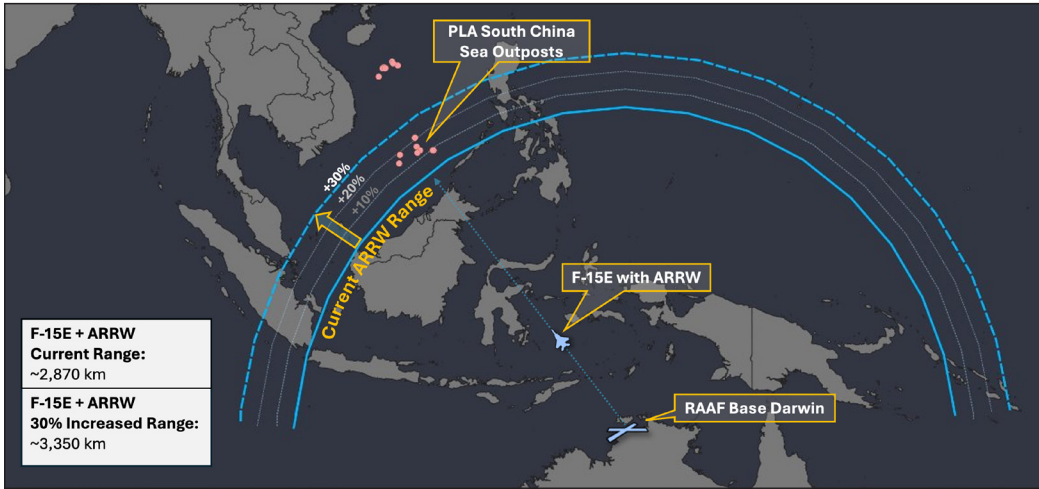
due to the limited number of basing locations and the enormous distances between those bases and potential target areas. Attack weapons that already have substantial ranges stand to gain the most reach in absolute terms. Although many of the U.S. military's cruise missiles are powered by turbojet and turbofan engines that consume liquid fuels, a growing number of strike weapons are powered by rocket motors that could harness the power of improved energetics.⁸⁸ These weapons include the SM-6, AGM-183 Air-Launched Rapid Response Weapon (ARRW), AGM-88G Advanced Antiradiation Guided Missile-Extended Range (AARGM-ER), Stand-in Attack Weapon (SiAW), Precision Strike Missile (PrSM), Guided Multiple Launch Rocket System-Extended Range (GMLRS-ER), and a number of shorter-range missiles. Additional range could advantage U.S. forces in at least three ways: striking deeper, engaging from farther away, and adding flexibility to flight path choice and maneuvering options.

First, longer-range weapons would allow U.S. forces to strike targets deeper in adversary territory while using current delivery platforms and basing locations. For some target sets, this additional range might allow the United States to attack a larger portion of a total target set without advancing farther into the adversary's defensive networks. For example, U.S. ships carrying an extended-range SM-6 would be able to strike more of China's oil refineries from the seas around the mainland. The ability to strike larger portions of industrial and economic targets like refineries with numerous types of weapons could be crucial if the United States pursues a counter-industrial strategy during a protracted conflict.⁸⁹ Longer-range weapons might also allow U.S. platforms to strike targets deeper within the Chinese mainland than they otherwise could. Additional range may enable strikes from certain Indo-Pacific bases. For example, Figure 3 illustrates how additional range would allow F-15s operating from Darwin, Australia, to employ hypersonic weapons against China's South China Sea bases and outposts.

88 The BGM-109 Tomahawk, AGM-158 Joint Air-to-Surface Standoff Missile (JASSM), AGM-84 Harpoon, and RGM-184A Naval Strike Missile are powered by turbojet or turbofan engines. Some of these munitions use solid rocket motors as initial boosters.

89 Both Ukraine and Russia are currently conducting protracted strike campaigns against industrial, economic, and critical infrastructure in the other nation. Ukraine has focused on striking oil and natural gas infrastructure deep in Russian territory. See Tyler Hacker, Greg Malandrino, and Evan Braden Montgomery, "The Arsenal as the Battlefield: The War on Iran and the Return of Counter-Industrial Targeting," *War on the Rocks*, April 1, 2026, <https://warontherocks.com/2026/04/the-arsenal-as-the-battlefield-the-war-on-iran-and-the-return-of-counter-industrial-targeting/>.

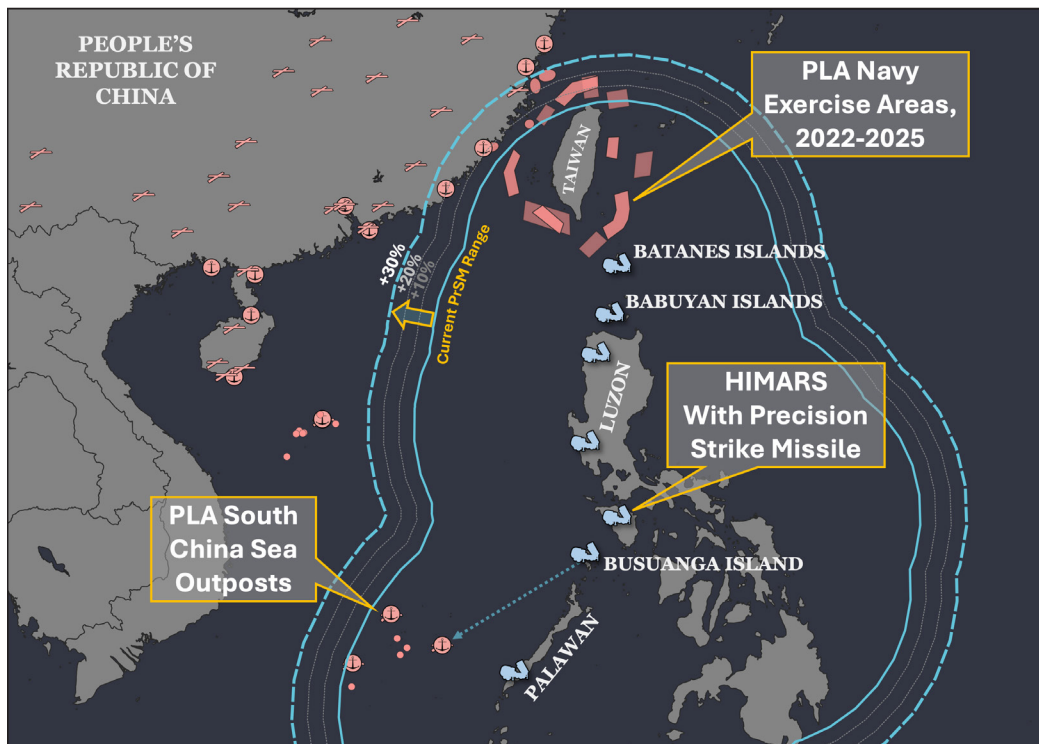
FIGURE 3: ADVANTAGE OF EXTENDED RANGE ARRW EMPLOYED BY F-15 FROM RAAF DARWIN



Note: F-15E range drawn from Janes database. ARRW range taken from “AGM-183 ARRW,” *Air & Space Forces Magazine*, <https://www.airand-spaceforces.com/weapons/agm-183-arrw/>.

The ability to reach a greater variety of targets is advantageous for all weapons, but it especially benefits ground-launched missiles. Whereas aircraft may be able to ingress closer to targets with added risk or refueling, ground-based launchers are constrained by geography. Giving weapons like the Army’s Long Range Hypersonic Weapon (LRHW or Dark Eagle) and PrSM additional range would allow them to threaten more targets and alleviate the operational tradeoffs between land-based, airborne, and naval strike assets. Figure 4 illustrates how extended range PrSMs would allow U.S. Army and Marine Corps High Mobility Artillery Rocket System (HIMARS) to engage farther into the Taiwan Strait and Chinese coastal areas from Philippine territory. Extended-range anti-ship PrSMs could be key for engaging PLA Navy ships attempting to blockade the port of Taipei or Chinese troop transports in the Strait. In the South China Sea, PrSMs with 20–30 percent more range would allow U.S. forces to strike PLA airfields and harbors at Mischief Reef from as far as Busuanga Island.

FIGURE 4: ADVANTAGE OF EXTENDED RANGE PRSM FIRED FROM THE PHILIPPINES



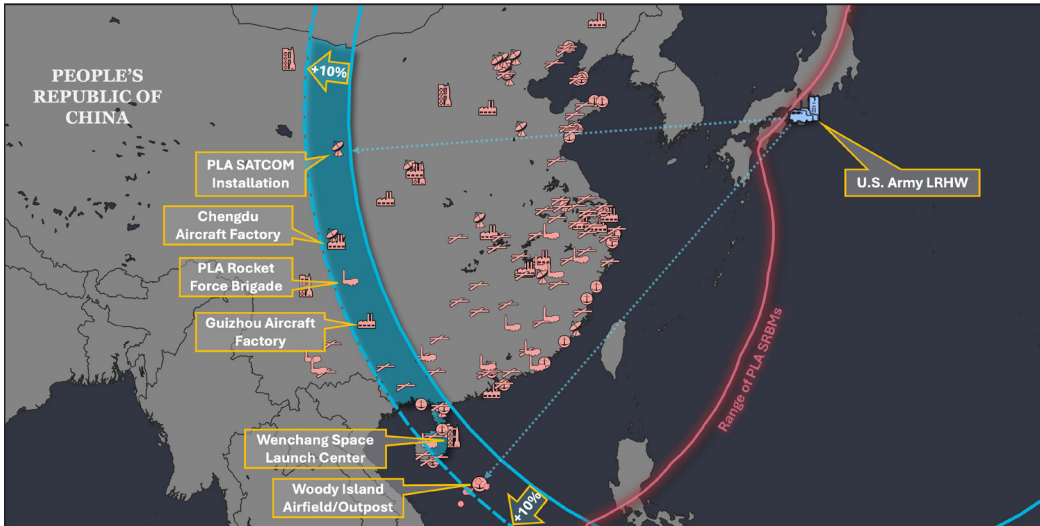
Note: PrSM range drawn from “Precision Strike Missile (PrSM),” Lockheed Martin, <https://www.lockheedmartin.com/en-us/products/precision-strike-missile.html>.

Extending the range of strike munitions may produce virtual attrition in addition to kinetic effects.⁹⁰ Even if these weapons are not used at their maximum ranges, their ability to hold a wider spread of targets at risk would force PLA planners to consider moving assets farther away or defend a larger area. For example, Figure 5 shows how extending the Army LRHW’s range by just 10 percent would allow it to reach targets spread over an additional 266,380 square miles of Chinese territory from outside the range of PLA short-range ballistic missiles. This additional territory—roughly the size of Texas—contains several strategic targets including the Chengdu aircraft factory that produces the JL-20 stealth fighter, the Guizhou aircraft factory, a DF-21 medium-range missile base, the Wenchang Spaceport in Hainan, and the PLA’s airfield on Woody Island in the South China Sea. Extending the range of the LRHW would enable it to threaten these targets from outside short-range ballistic missile range in Japan and increase the defensive burden on the PLA, which may consider adding air and missile defenses to these sites or distributing or relocating them. Similar virtual attrition effects can be plainly seen in U.S. reactions to China’s DF-21D and DF-26B

⁹⁰ Virtual attrition “entails the threat or use of violence to cause inefficient changes in enemy force generation or force employment.” See Evan Montgomery, Travis Sharp, and Tyler Hacker, “Quality Has a Quality All Its Own: The Virtual Attrition Value of Superior-Performance Weapons,” *War on the Rocks*, June 19, 2024, <https://warontherocks.com/2024/06/quality-has-a-quality-all-its-own-the-virtual-attrition-value-of-superior-performance-weapons/>.

anti-ship ballistic missiles. As the PLA fields missiles capable of reaching the Second Island Chain, U.S. analysts increasingly question the viability of operating the U.S. Navy’s aircraft carrier strike groups in large sections of the Indo-Pacific and call for expanded air and missile defenses for Guam and the Mariana Islands.⁹¹

FIGURE 5: ADDITIONAL CHINESE TERRITORY THREATENED BY EXTENDING LRHW RANGE BY 10 PERCENT



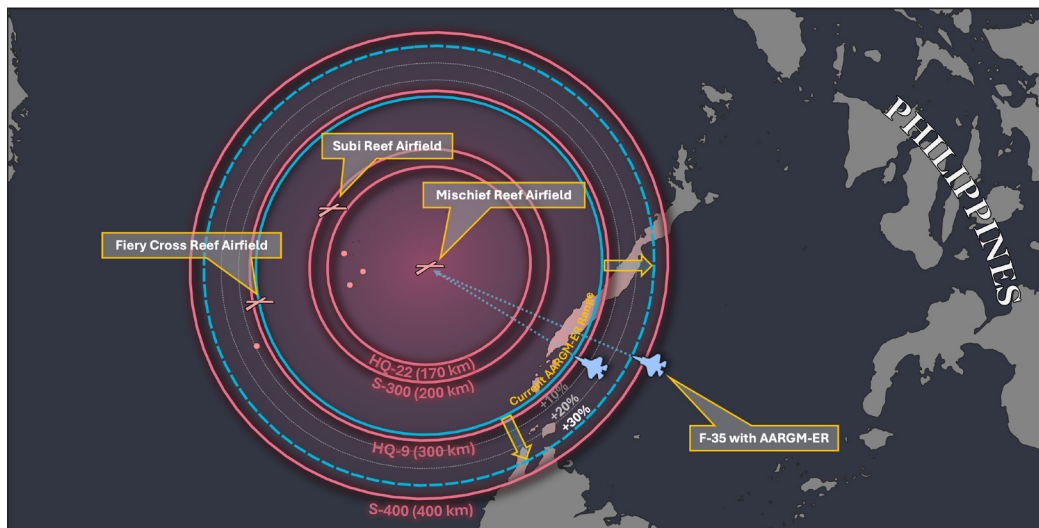
Note: LRHW range drawn from Andrew Feickert, *The U.S. Army’s Long-Range Hypersonic Weapon (LRHW): Dark Eagle* (Washington, DC: Congressional Research Service, 2025), <https://www.congress.gov/crs-product/IF11991>.

Second, in addition to striking deeper, munitions with improved ranges would allow the U.S. military to attack the PLA from farther away. Launching strikes from greater distances is advantageous for several reasons. Perhaps most importantly, launching weapons from longer range keeps the delivery platform farther from Chinese defenses, which could reduce attrition and save not only the lives of highly skilled personnel but also exquisite delivery platforms. Reducing potential attrition is especially important over the next decade while U.S. fleets of next-generation platforms like the B-21 Raider bomber, F-47 fighter, and *Virginia*-class attack submarine grow and production rates of existing platforms like the F-35 remain static. If delivery platforms can operate farther from enemy threats, then the aerial refueling tankers and other more vulnerable support aircraft necessary for strike

91 For example, Editorial Board, “Overmatched: Why the U.S. Military Needs to Reinvent Itself,” *New York Times*, December 8, 2025, <https://www.nytimes.com/interactive/2025/12/08/opinion/us-china-taiwan-military.html>; Timothy Noah, “Why on Earth Are We Still Building Aircraft Carriers?,” *New Republic*, May 31, 2023, <https://newrepublic.com/article/172482/why-america-still-building-aircraft-carriers>; and Justin Bachman, “How America’s Aircraft Carriers Could Become Obsolete,” *Bloomberg*, June 28, 2017, <https://www.bloomberg.com/news/articles/2017-06-28/how-america-s-aircraft-carriers-could-become-obsolete>.

operations can also remain farther from PLA engagement zones.⁹² Figure 6 illustrates how an extended range AARMG-ER anti-radiation missile might allow American F-35s to attack PLA airfields and air defenses in the South China Sea from safer distances farther outside the engagement ranges of Chinese air defense systems like the HQ-9.

FIGURE 6: F-35 WITH EXTENDED RANGE STAND-IN ATTACK WEAPON



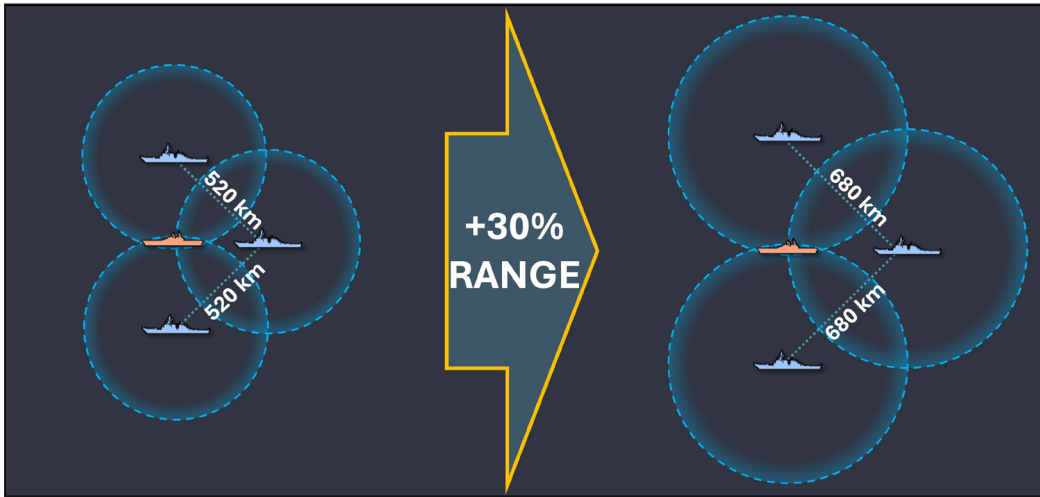
Note: All data drawn from Janes database.

Increased range may also allow groups of platforms to operate at greater distances from each other while remaining capable of massing their weapons on a single target or location. For example, expanding the range of the SM-6 would allow U.S. Navy surface combatants to operate in more distributed formations while supporting each other with massed anti-ship missile fires (Figure 7). Shooting first and massing fires is critical in fleet missile warfare, just as operating in a distributed manner is increasingly important to countering the PLA's numerous anti-ship missile systems.⁹³

⁹² Keeping high-value airborne assets at a distance from Chinese defenses is increasingly important as the PLA fields weapons designed to engage these aircraft at extended ranges.

⁹³ See Jeffrey R. Cares and Anthony Cowden, *Fighting the Fleet: Operational Art and Modern Fleet Combat* (Annapolis, MD: Naval Institute Press, 2021), chap. 1; and Wayne P. Hughes, Jr., and Robert P. Girrier, *Fleet Tactics and Naval Operations*, 3rd ed. (Annapolis, MD: Naval Institute Press, 2025).

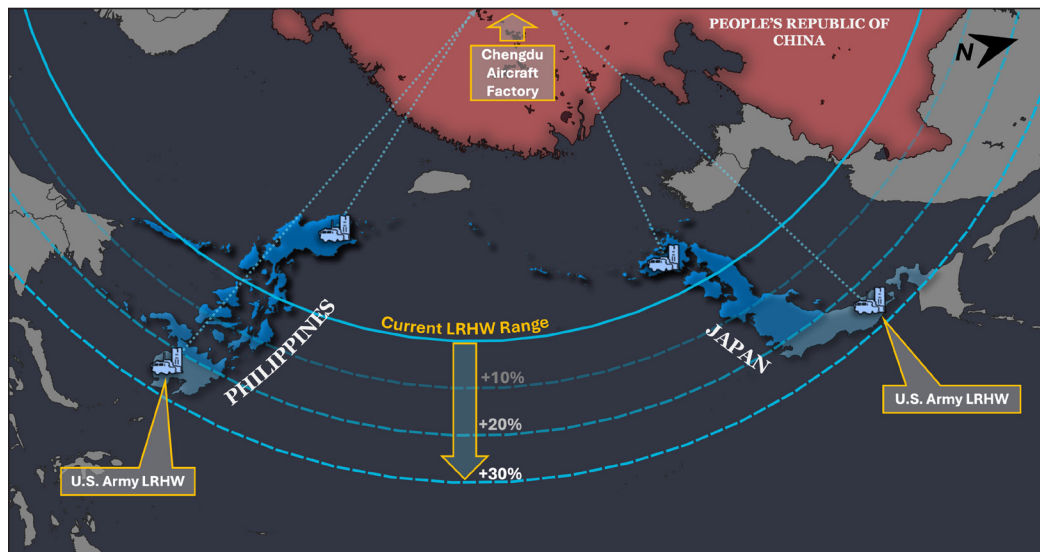
FIGURE 7: DESTROYERS MASSING FIRES USING EXTENDED RANGE SM-6 MISSILES



Note: This illustration is not intended to display the formation that U.S. Navy surface combatants would employ. Rather, it is meant to show how increased munition range translates into increased flexibility for commanders attempting to mass fires from distributed formations. SM-6 range drawn from Missile Defense Project, “Standard Missile-6 (SM-6),” Center for Strategic and International Studies, updated March 7, 2023, <https://missilethreat.csis.org/defsys/sm-6/>.

Range is especially important for ground-launched missiles because their maximum range determines the maneuver area and potential launch locations for missile batteries. In a theater dominated by water like the Indo-Pacific, increasing the range of ground-launched weapons adds to the number of nations and landmasses that could host American strike forces. Given the political sensitivity of deploying these missiles to allied and partner territory, additional operating locations would greatly increase the flexibility of these units. Moreover, additional weapon range increases the area in which ground-based missiles can maneuver and hide while threatening the same targets. Figure 8 illustrates how extending the range of the Army’s LRHW would allow it to strike the Chengdu aircraft factory from more locations in Japan and the Philippines. Additional mobility increases the survivability of these forces and expands the area that the PLA must search to locate, track, and attempt to destroy them.

FIGURE 8: EXPANDED MANEUVER AND FIRING AREAS FOR EXTENDED RANGE LRHW UNITS IN JAPAN AND THE PHILIPPINES



Note: LRHW range drawn from Feickert, *The U.S. Army's Long-Range Hypersonic Weapon (LRHW)*.

Third, improved propellants and increased range may offer more options for complex flight paths, nonballistic trajectories, and terminal maneuvering, all of which increase the survivability and lethality of offensive weapons. Modern munitions must be capable of penetrating a vast array of defensive systems, and additional range may be used to help them avoid enemy defenses by traversing around them, changing their altitude, or otherwise altering their trajectory. Better propellants may also leave munitions with more energy as they near their targets, which could be expended to increase the weapon's speed or to conduct evasive terminal maneuvers to defeat adversary defenses. Increased terminal speed may also be useful for increasing weapon penetration and attacking hardened or buried targets.

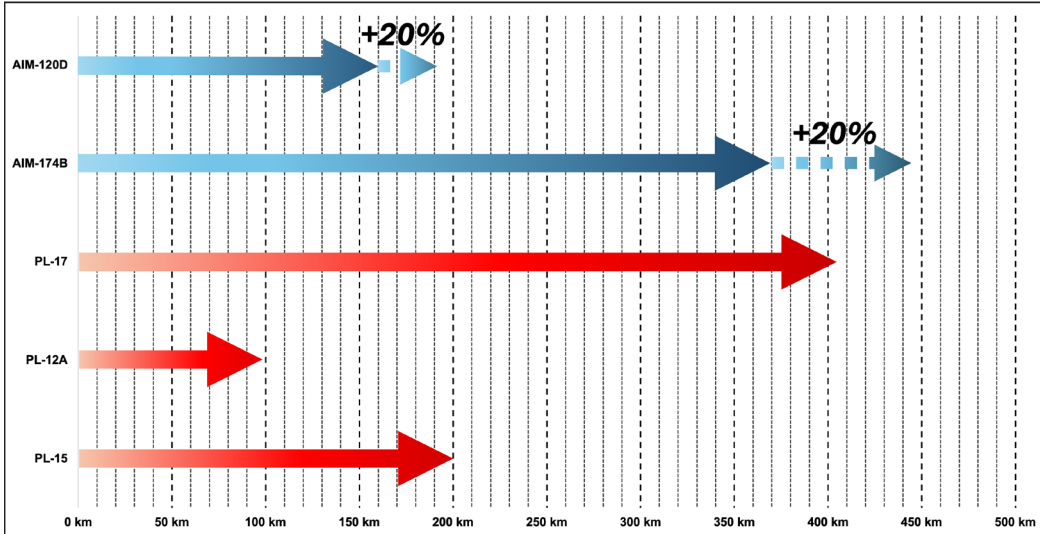
Air-to-Air

Modern air combat is dominated by beyond visual range (BVR) engagements in which the side that detects and engages first has a distinct advantage.⁹⁴ Air-to-air missiles like the AIM-120 Advanced Medium-Range Air-to-Air Missile (AMRAAM) and AIM-9X Sidewinder use solid rocket motors that may benefit from advancements in energetic materials. More efficient propellants give air-to-air missiles more potential energy, which allows aircraft to engage at longer ranges or lower altitudes. As shown in Figure 9, improved propellants that extend the range of current and future air-to-air missiles may give American pilots an

94 Detection and missile range appear to have played a key role in the recent BVR engagement between Indian and Pakistani air forces. Saeed Shah and Shivam Patel, "How Pakistan Shot Down India's Cutting-Edge Fighter Using Chinese Gear," *Reuters*, August 2, 2025, <https://www.reuters.com/business/aerospace-defense/how-pakistan-shot-down-indias-cutting-edge-fighter-using-chinese-gear-2025-08-02/>.

advantage over their Chinese counterparts. More energy may also increase the effectiveness of U.S. air-to-air missiles by making them harder for enemy aircraft to outrun.⁹⁵ Finally, improved propellants could be channeled into a missile speed advantage, which is increasingly important in BVR fighter engagements.

FIGURE 9: COMPARISON OF U.S. AND CHINESE AIR-TO-AIR MISSILE RANGES



Note: All data drawn from Janes database.

Air defense interceptors would also benefit from improved propellants that increase their maximum ranges and engagement altitudes. More range would increase the area that an individual air and missile defense unit can protect, which may allow launchers and units to be distributed more widely around defended areas. Additional range may also improve the effectiveness of interceptors by allowing air defense assets to engage at extended ranges, which increases the total time available for a shooter to defeat an incoming threat. For example, adding 10 to 30 percent to the range of an interceptor could expand the window to engage an incoming subsonic cruise missile by between 44 seconds and two minutes.⁹⁶ Large increases in engagement time could also allow air defense units more time to re-engage targets that are not intercepted or to reduce munition expenditures by changing their engagement doctrine.⁹⁷

95 Missiles with more efficient propellants may have larger kinematic no-escape zones (NEZ), which is the area in which a missile has sufficient energy to intercept a target even if it performs evasive maneuvers. Even within the NEZ, adversary aircraft may defeat the missile via other nonkinetic means, such as defeating the weapon’s guidance system.

96 This simplified example assumes a cruise missile flying directly toward the air defense unit at Mach 0.8. It does not account for the flight time of the interceptor itself, which also varies based on the engagement range.

97 For example, an air defense unit with a shoot-shoot-look doctrine fires two missiles and then assesses the success of the intercept. Additional time might allow defenders to utilize a shoot-look-shoot doctrine in which a second missile is only fired if the first missile fails to intercept the target.

Ground Combat

Extended range is crucial for rocket and cannon artillery and anti-armor weapons. Outranging the adversary is a key advantage in artillery duels and counterbattery fires, areas in which Russian ground forces have long maintained a significant advantage over the U.S. military.⁹⁸ With the latest variants of American cannon artillery maintaining a 39-caliber gun, improved propellant and shell design are the primary options for increasing the range of U.S. artillery.⁹⁹ For rocket artillery such as the HIMARS, additional range would allow launcher trucks to attack the same targets from farther behind the forward line of troops, increasing their survivability. Like the naval vessels shown in Figure 7, it would also allow the individual launchers of a HIMARS unit to mass their missiles on a single target from more distributed positions, which would in turn make it harder for enemy forces to concentrate their counterbattery salvos on the HIMARS unit.

For smaller anti-tank weapons and shoulder-launched guided missiles, longer ranges would allow infantry to engage armored targets sooner and, like air defense interceptors, may allow ground forces to reattack enemy armor before it can effectively return fire. Increased range might also be turned into additional loiter time, a key advantage against modern camouflage and countermeasures. Some novel energetic materials might also lead to propellants that produce less smoke. For rocket artillery, the large smoke trails left by missile launches can visually expose their positions to enemy reconnaissance and surveillance assets.¹⁰⁰ Similarly, the smoke trails produced by anti-tank and surface-to-air missiles give away the firing unit's position and provide the adversary warning of the incoming munition. Energetic materials that reduce the smoke generated by a missile's rocket motor would benefit weapons in multiple roles.

Across Mission Areas

Rather than filling existing propellant stores with a more efficient compound that increases weapon range, more efficient propellants could be used to reduce the weight or space devoted to weapon propulsion. This space could be replaced with other features or removed altogether to produce a lighter or smaller weapon. For example, portions of a missile body previously filled by propellant could be replaced by larger payloads (e.g., more powerful warheads or greater quantities of submunitions), more effective sensors (e.g., multiple sensor types, more onboard computing, or battery power), or additional countermeasures (e. g.,

98 Michael Jacobson and Robert H. Scales, "The United States Needs to Get Serious About Artillery Again," *War on the Rocks*, October 6, 2016, <https://warontherocks.com/2016/10/the-united-states-needs-to-get-serious-about-artillery-again/>.

99 Many nations utilize artillery systems with a 52-caliber barrel, which allows shells to be fired farther (at greater muzzle velocities) using the same projectiles and propellants.

100 The large smoke trails produced by HIMARS launches can be seen at Maria Grazia Murru, "Ukrainian Authorities Report Attacks on Russian Ammunition Depot in Southern Ukraine," *PBS News*, July 12, 2022, <https://www.pbs.org/newshour/world/ukrainian-authorities-report-attack-on-russian-ammunition-depot-in-southern-ukraine>.

additional penetration aids or chaff). The advantages and applications of smaller munitions are discussed in the next section.

Payload: Increased Explosive Power

The second way novel energetics could improve U.S. munitions is by increasing their explosive power. New compounds such as CL-20 promise more bang in smaller, lighter packages. This additional power could be used in two ways: to maintain the size of current warhead designs while increasing their explosive effects or to reduce warhead size while maintaining the same explosive power with more efficient energetics.

Constant Payload Size, Increased Effects

Increasing the strength of a weapon's warhead while maintaining payload size and weight equates to more power in the same package. Weapons packing a greater punch may provide the same effects as multiple munitions, which would reduce the total number of munitions required to attack a target and help alleviate current munition capacity shortfalls. Beyond easing munition requirements, more power may be particularly beneficial for certain types of special-purpose munitions. Just as in World War II, munitions intended for hardened and deeply buried targets must be large to penetrate and destroy their targets, but they are limited by the size and weight their delivery platforms can carry. With weapons like the GBU-57 Massive Ordnance Penetrator (MOP) already pushing the limits of bomber payload capacity, better energetics could increase the effects of these bombs or reduce their size and weight to allow them to be carried by smaller aircraft.¹⁰¹ Similarly, equipping surface-to-air missiles with more powerful warheads that produce wider blast and fragmentation effects would increase the chances that the missiles damage their targets. A larger effects radius might also enable future interceptors to use less exquisite guidance systems and sensors that are cheaper and easier to produce at scale. In other words, enhanced effects increase the design trade space between performance and producibility in future weapons systems.

Another application of novel energetics is weapons with reduced size and weight requirements, such as small unmanned systems, shoulder-launched weapons, loitering drones, and submunitions. Small weapons have proven their capability in recent years, from the quadcopters and loitering munitions employed by the Ukrainian military against Russian

¹⁰¹ The MOP, used recently to strike Iranian nuclear sites, weighs around 30,000 pounds, contains 5,000 pounds of explosives, and can only be carried by the B-2 Spirit bomber. See Deni Ellis Bechard, "Why This Is the Only Bomb That Could Destroy Iran's Nuclear Bunker—Under 300 Feet of Rock," *Scientific American*, June 18, 2025, <https://www.scientificamerican.com/article/the-massive-ordnance-penetrator-bomb-israel-wants-to-destroy-irans-fordo/>.

vehicles to the Small Diameter Bomb series used by U.S. forces against Houthis in Yemen.¹⁰² The size and weight of these weapons' payloads are extremely limited, putting a premium on maximizing the power of their explosive fill.¹⁰³ Similarly, submunitions carried by larger weapons are limited by the need to carry tens or even dozens of small explosives. Improved energetics could increase the power of each submunition, multiplying the aggregate effects of the host munition.

The follow-on effects of filling existing payloads with more powerful explosives may be more significant than their increased effects in isolation. Additional power could reduce the complexity of matching munitions to targets and weaponeering the desired effects. Employment considerations such as the altitude at which the munition is released or the angle of attack may become less constraining. More effective payloads could reduce the quantity or quality of intelligence, surveillance, and reconnaissance (ISR) required to generate an effective strike against some targets, easing demands on overtasked ISR platforms and targeting staff. Perhaps most importantly, more powerful warheads might allow some weapons to have catastrophic effects on targets they are now only capable of damaging, impairing, or delaying. Enabling weapons to destroy targets they previously could only "mission kill" would greatly enhance the operational value of smaller, reduced-cost munitions, a change that could drastically affect munition requirements and procurement.¹⁰⁴

Constant Effects, Reduced Payload Size

Future munition designs could also leverage improved energetics to create smaller, lighter warheads that produce similar effects. Much like more efficient propellants, these smaller payloads would allow designers to pack more fuel, sensors, or countermeasures in the bodies of existing weapons to extend their range and enhance their lethality. Alternatively, manufacturers could use more powerful propellants and smaller warheads to reduce the total size and weight of future weapons. Small form factor munitions allow delivery platforms to carry more firepower and attack more targets in a single mission.¹⁰⁵ These improvements would

102 The Switchblade 300 "effectively utilizes a CL-20 explosive warhead" and has been employed by Ukrainian forces. The U.S. Navy has also recently employed the GBU-53/B StormBreaker in combat operations. *Department of Defense Authorization Request for Appropriations for Fiscal Year 2024 and the Future Years Defense Program: Hearing Before the Senate Committee on Armed Services on S. 2226*, 118th Cong., 1st sess. (2023), p. 44, <https://www.congress.gov/118/chr/CHRG-118shrg60098/CHRG-118shrg60098.pdf>; and Thomas Newdick, "StormBreaker Advanced Glide Bomb Lands in Yemen Largely Intact," *The War Zone*, April 25, 2025, <https://www.twz.com/air/stormbreaker-advanced-glide-bomb-lands-in-yemen-largely-intact>.

103 AFX-757, an improved explosive developed for the JASSM cruise missile, enabled the Small Diameter Bomb program. Kevin P. Sweeney, *Miniature Munitions: Is the U.S. Military Prepared to Support Major Combat Operations?* (Maxwell Air Force Base, AL: U.S. Air Force Air Command and Staff College, August 2016), p. 3, <https://apps.dtic.mil/sti/pdfs/AD1041216.pdf>.

104 For example, munitions employed for maritime strike are traditionally large, complex, and expensive. The utility of more producible low-cost cruise missiles for maritime strike hinges on their ability to deliver significant effects on enemy warships.

105 These improvements may be especially valuable for low-observable (stealth) aircraft whose total payload capacity is constrained by the size of their internal weapons bays.

enable platforms to attack the same number of targets in fewer sorties, which reduces the amount of time spent transiting and reloading. Most crucially, fewer sorties might reduce attrition because platforms would spend less time within range of enemy defenses.

Smaller weapons also increase the potential value of future unmanned platforms that are smaller than their manned counterparts. For example, the U.S. Air Force's Collaborative Combat Aircraft program would benefit from reduced-size air-to-air missiles that maximize the capacity of its limited weapons bay. The Air Force has already started exploring the potential for such missiles, and these weapons are prime candidates for integrating new energetics into their warheads.¹⁰⁶ Smaller munitions might be equally useful for equipping unmanned systems in other domains, including unmanned surface vessels and undersea vessels.

How Tactical Improvements Lead to Operational and Strategic Effects

Because munitions are the final link in the complex kill chains of modern military operations, improving the performance of individual weapons through improved energetics may have cascading effects that influence broader operations and strategy. To demonstrate using munition range and strike operations: Once weaponeers match a weapon to a target, the munition's range determines which platforms are capable of delivering it, which support assets (tankers, ISR, command and control) these platforms require, and the bases that each of these systems might operate from to conduct the strike. Similarly, the power of a munition's warhead determines how many weapons are required to destroy a target, the type and quantity of platforms necessary to deliver that quantity of weapons, the support platforms to enable the mission, and so on. In this way, munitions and their energetic components are the ultimate "nail" when the "for want of a nail" proverb is applied to military operations.¹⁰⁷ Munition characteristics affect much more than one-on-one engagements and tactics; improving their performance may have far-reaching consequences for operations, strategy, procurement, and budgeting. These follow-on effects were key to the adoption of RDX during World War II, and they can be plainly seen in the massive impact of PGMs on U.S. military operations, strategy, and force structure since their introduction in the 1970s.¹⁰⁸

Using novel energetics to improve weapon range and explosive power could produce greater effects in at least four ways. More effective weapons may reduce the total number of munitions required to attack a target or conduct offensive and defensive military campaigns. The previous section provided several scenarios in which increased explosive power or

106 Thomas Newdick, "Air Force Looking For Cheap Air-to-Air Missile Half the Size of AMRAAM," *The War Zone*, May 5, 2025, <https://www.twz.com/air/air-force-looking-for-cheap-air-to-air-missile-half-the-size-of-amraam>.

107 The "For want of a nail" proverb can be found in Benjamin Franklin, *The Way to Wealth or Poor Richard Improved* (1795), pp. 13–14, https://archive.org/details/bim_eighteenth-century_the-way-to-wealth-or-poo_franklin-benjamin_1795/.

108 See 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/research/publications/six-decades-of-guided-munitions-and-battle-networks-progress-and-prospects>.

additional range might reduce the quantity of weapons expended during strike operations or air defense engagements. Although improved energetics alone will not solve America's munitions shortfalls, even small reductions in munition expenditures would ease the dilemmas faced by military planners tasked with conducting a strike campaign in the Indo-Pacific region. If, for example, the advantages highlighted in the previous sections reduced Tomahawk and Standard Missile expenditures during recent operations in the Red Sea by even a small amount, then U.S. stockpiles might be in better condition for future contingencies.¹⁰⁹ Reducing munition expenditures by any degree is crucial because the United States currently struggles to procure and produce weapons in the quantities that may be required in a great power conflict.¹¹⁰ Because munitions are the final and irreplaceable link in all military kill chains, weapon shortfalls would severely inhibit the U.S. military's ability to conduct operations of almost any kind.

Besides the strategic advantages of alleviating stockpile shortfalls, reducing munition requirements may have fiscal benefits. With many modern PGMs having unit costs over \$1 million (and others, such as hypersonics, costing more than \$5 million per weapon), reducing expenditures and stockpile requirements has implications for weapons procurement. Adopting novel energetic materials may require significant investments, but the cost of scaling these materials' production should be weighed against the cost of acquiring and maintaining larger stockpiles of advanced weapons. Again using the U.S. military's experience in the Red Sea as an example, the former secretary of the Navy stated that as early as April 2024, the U.S. Navy alone had expended nearly \$1 billion worth of weapons in the campaign against the Houthis.¹¹¹ If munitions with higher performing energetics could reduce these expenditures by just 5 percent, the Navy might save \$50 million worth of munitions in a similar future contingency. These savings would more than compensate for the cost of new explosives and go a long way toward recouping the development and infrastructure costs of improved energetics or purchasing the large numbers of weapons the military may need to fight a more taxing conflict against a great power adversary.

By improving the effects of each weapon, smaller but more powerful munitions and reduced expenditures may decrease the number of sorties required to conduct a single strike or mission.¹¹² Reduced sorties would ease congestion at crowded air bases and, more importantly, increase the tempo of strike operations by minimizing the number of times platforms

109 The USS *Dwight D. Eisenhower* carrier strike group fired 155 Standard Missiles and 135 Tomahawks during its nine-month deployment in the Middle East. Joseph Trevithick, "770 Weapons Expended by Eisenhower Carrier Strike Group on Historic Red Sea Deployment," *The War Zone*, July 15, 2024, <https://www.twz.com/news-features/770-weapons-expended-by-eisenhower-carrier-strike-group-on-historic-red-sea-deployment>.

110 Hacker, *Beyond Precision*.

111 Lauren C. Williams, "Mideast Missile Duels Have Cost U.S. Navy Nearly \$1B, Secretary Says," *DefenseOne*, April 16, 2024, <https://www.defenseone.com/threats/2024/04/mideast-missile-duels-have-cost-us-navy-nearly-1b-secretary-says/395791/>.

112 Although "sortie" often refers to the flight of a single aircraft, the term is used here to refer to the number of times any delivery platform must deploy from a base and then return to rearm.

must return to base to reload. Increased tempo would allow a large target set to be struck in a shorter amount of time, a key feature of many campaigns to support a denial strategy in the Taiwan Strait.¹¹³ A reduction in the total sortie quantity might also reduce platform attrition over the course of a protracted campaign by reducing the number of times U.S. forces would need to contest and penetrate an adversary’s defenses. With the U.S. military’s force structure centered on exquisite platforms and advanced systems that have limited production rates and long production timelines, even slight reductions in attrition could prove beneficial in a prolonged campaign in which force preservation is a strategic priority.

Reductions in expenditure and sortie rates also have logistical implications because they reduce the amount of weapons, fuel, and other commodities that must be transported into and around the theater. Given the scale of the Indo-Pacific, America’s vulnerabilities in sealift, and the potential for China to contest U.S. military logistics from the continental United States to the First Island Chain, any reduction in logistical requirements is desirable. Reducing lift requirements by improving the capability of individual weapons and platforms is one way to alleviate the U.S. military’s contested logistics problems despite issues associated with domestic shipbuilding. Moreover, China’s anti-access / area denial (A2/AD) strategy revolves around preventing the United States from building up the “iron mountain” of forces, munitions, and supplies necessary for traditional power projection in the Indo-Pacific. Improvements that reduce the total size of this build-up also reduce the U.S. military’s vulnerability to PLA attacks and alter the assumptions underpinning their A2/AD strategy.

For these reasons, integrating improved energetics into U.S. weapons should not be viewed as increasing the effectiveness of munitions alone but as increasing the total offensive and defensive combat power of the U.S. formations that employ them. British and American leaders in World War II justified investments in RDX as necessary to maximize the striking power of their bomber and anti-submarine forces; reduce the number of bombers and pilots lost during repeated raids; and decrease the quantity of bombs, gasoline, and other resource-intensive supplies needed to execute the war’s campaigns. As the United States once again confronts the possibility of a great power war that could stretch the nation’s total industrial capacity, maximizing the military value of material, fiscal, and manpower expenditures becomes paramount.

This analysis calls for viewing the costs associated with the development and production of advanced energetics from a different perspective. The high cost of improved energetic materials and the infrastructure necessary to produce them at scale are often cited as the primary obstacles to their adoption. This view, however, fails to weigh these costs against the military advantages and potential fiscal savings promised by improving the performance of America’s munitions. Policymakers must consider the opportunity costs of failing to

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113 See, for example, Elbridge A. Colby, *The Strategy of Denial: American Defense in an Age of Great Power Conflict* (New Haven, CT: Yale University Press, 2021).

invest in technologies that maximize the effectiveness of current and future weapons: more weapons, more sorties, more platforms, more supplies, and more personnel. Put simply, investments that sharpen the tip of America's power projection spear could have outsized impacts on the performance and efficiency of the entire spear compared to those that build out the spear's shaft alone.

Perhaps most dangerously, examining these opportunity costs assumes that the U.S. defense industry can produce weapons and platforms in the quantities required. As recent attempts to supply allies and partners and refill the U.S. military's own munition stockpiles have shown, however, the United States may struggle to rapidly expand the production of critical military equipment, from guided weapons to the aircraft that deliver them. Improving munitions with novel energetics is thus a crucial step toward ensuring the U.S. military has the firepower it needs to prevail in great power war, particularly in the near term. Military leaders and policymakers must think beyond the costs and even the potential tactical benefits of improved energetics to ask: "What are the risks of not integrating these materials and failing to maximize the effectiveness of every weapon, particularly if America's adversaries do?"

CHAPTER 5

The Way Forward

Given the advantages promised by improved energetics in today's strategic environment, how might DoD, Congress, and industry work to overcome the remaining barriers to innovation in the realm of explosives and propellants? Based on this report's analysis, the primary obstacles inhibiting the integration of materials like CL-20 into U.S. weapons can be distilled into three core issues:

- the lack of requirements for the improvements promised by new energetics,
- the added costs of new energetic materials and their production infrastructure, and
- the bureaucratic and safety risks of adopting new explosives and propellants.

This report concludes with several recommendations for how to move past these obstacles and encourage the adoption of improved energetics.

Lack of Requirements

Without a specific need for the additional range or explosive power of new energetics, the military services will struggle to justify the added costs and risks of integrating them into U.S. munitions. A requirement would provide the urgency needed to break through bureaucracy and transcend the barriers to energetics and munition innovation. This report has demonstrated how the strategic environment of previous decades failed to create a need for more powerful energetics and explored the numerous ways that improved energetics could help the U.S. military address many of its most serious operational challenges in the Indo-Pacific theater.

For a requirement for new energetics to emerge, their potential value must be applied to the correct military problems and the munitions that solve those problems. The previous chapter identified missions and operational challenges for which

improved explosives and propellants may offer a unique capability or advantage. These areas include:

- **Munitions in which no other explosive or propellant could produce the desired effects or characteristics, potentially due to stringent size and weight restrictions.** These weapons include reduced-size munitions and payloads, especially those intended for integration with small unmanned systems; submunitions; and special-purpose munitions such as torpedoes, bombs designed to strike hardened and deeply buried targets, and exquisite “silver bullet” weapons.
- **Weapons that provide U.S. forces with a clear advantage against Chinese and Russian forces in symmetric or asymmetric engagements.** This report has highlighted the role that improved energetics might play in fielding air-to-air missiles that would allow American fighter aircraft to outrange their opponents in BVR air combat.
- **Weapons for which additional range or power might significantly improve the survivability of their delivery platforms.** These munitions include ground-launched rockets and missiles and many air-launched weapons.
- **Weapons for which additional range or power might significantly increase the operational utility or flexibility of the munition or platform’s employment.** Figure 3 illustrated how additional range would allow U.S. fighter aircraft to employ the ARRW from additional bases in the Indo-Pacific. For other weapons, additional range or explosive power might allow them to reach or affect targets they otherwise could not. Additional range is especially advantageous for ground-launched weapons like the Army’s LRHW and PrSM.
- **Weapons for which the integration of improved energetics enables other modifications that enhance the munition’s unique capabilities or mitigate its vulnerabilities.** Reducing the size of a munition’s payload or propulsion using improved energetics could open up space and weight that might be used to improve a weapon’s lethality (e.g., additional sensors, computing power, larger payloads, or more range) or survivability (e.g., reduced size or radar signature, hardening, or additional countermeasures).

Munitions that fit into more than one of these categories are best suited to fully leverage the benefits of novel energetic materials.

Higher Costs

Scaled production will eventually reduce the cost of new energetics, but near-term investments are necessary to move compounds through the certification pipeline, develop improved manufacturing processes, and build the infrastructure necessary to produce them

in large quantities. Currently, the energetics space appears seized by the same chicken-and-egg problem that prevented U.S. investment in RDX in the 1920s. Demand for new materials like CL-20 is suppressed by its high cost, but only increased demand will drive the investments required to reduce costs over time. At present, neither the government nor industry appears willing to foot the bill and take the steps necessary to bring the cost of novel energetics more in line with existing materials.

Although willingness to accept the higher costs of weapons containing improved energetics will come from needing the range and power they provide, several approaches may reduce the focus on cost and foster the investments necessary for the widespread fielding of novel energetics:

DoD should focus on implementing improved energetics into pilot programs where their performance improvements are essential for giving U.S. forces a distinct advantage against adversary systems. The best way to justify added cost is by using novel energetics to provide an advantage that other materials or design modifications would struggle to replicate. Long-range air-to-air missiles, ground-launched weapons, and munitions to destroy hardened and deeply buried targets are three munition types for which the benefits of new energetics appear very promising.

Weapon designers should integrate advanced energetics into exquisite silver bullet weapons with already high unit costs. Expensive munitions are ripe for leveraging advanced energetics because the higher cost of new compounds is more easily absorbed into their high unit costs. More importantly, with each silver bullet expenditure already costing multiple millions, every kilometer of additional range or ounce of explosive power has outsized value. For example, many hypersonic weapons are expected to cost more than \$5 million each, with some currently costing in the tens of millions. At this price per shot, maximizing range and explosive power are especially beneficial. Additionally, hypersonic weapons are a DoD research and development priority, which may increase funding opportunities for energetic testing and integration.

When comparing the costs of improved energetics to existing materials, DoD must go beyond the tactical benefits and consider the second- and third-order operational, strategic, and economic advantages that new compounds might provide. Looking past immediate costs and risks to focus on the longer-term benefits of more powerful explosives was key to the adoption of RDX in World War II. Today, DoD should not compare the costs of new energetics or the capital investments necessary to produce them in isolation. Rather, policymakers and program managers should consider how improving the performance of individual munitions could have effects that ripple up military kill chains to reduce munition expenditures, decrease sortie requirements, decrease platform and personnel attrition, and impact the logistical requirements for

potential Indo-Pacific campaigns.¹¹⁴ In thinking about the cost of new energetics, DoD must also consider the opportunity costs of forgoing better materials while U.S. adversaries press forward with their testing and implementation of compounds like CL-20.

Finally, improved manufacturing methods will be key to reducing the cost of novel energetics and producing them at scale. During World War II, commercial researchers and chemical firms were essential for developing the processes and equipment that enabled Holston to produce RDX in quantity and at costs comparable to TNT. With compounds like CL-20 remaining expensive to produce in small batches, similar private sector research and innovation may be crucial to reducing the cost of modern materials.

Added Risks

Energetics are inherently hazardous, and their explosive nature inhibits a “move fast and break things” attitude that may transcend barriers and speed innovation in other military technologies. That said, all military operations center on managing and mitigating risks, and the purpose of DoD’s acquisition bureaucracy is to leverage the benefits of novel weapons while reducing their danger. DoD leaders have encouraged the department to take on more risk in favor of improved performance, but it remains to be seen how these directives manifest in the organization’s behavior.¹¹⁵

DoD should begin by implementing novel energetics in roles that mitigate the risks presented by more powerful or more sensitive energetics. During World War II, RDX was initially used in underwater weapons such as torpedoes to limit the potential for enemy shells and shrapnel to detonate warheads before they were launched. A similar approach could be used today. New energetics may not be initially suited for certain roles, such as weapons carried aboard aircraft carriers or exposed to repeated thermal cycling. Other applications, however, may be ripe for experimentation with new energetics. Today, unmanned or attritable systems could employ more powerful weapons while reducing the risk to military personnel or exquisite platforms. The services could also explore different employment tactics and techniques or alter the designs of future platforms and weapons to reduce the safety risks associated with novel energetics.

114 The Center for Strategic and Budgetary Assessments has noted the merits of assessing the cost and performance of U.S. weapons not in isolation but as force packages that accurately reflect how the systems are employed in combat. Travis Sharp and Tyler Hacker, *Evaluate Like We Operate: Why DoD Should Evaluate Weapons Systems as Networked Force Packages, Not Individual Platforms* (Washington, DC: Center for Strategic and Budgetary Assessments, 2023), <https://csbaonline.org/research/publications/evaluate-like-we-operate-why-dod-should-evaluate-weapons-systems-as-networked-force-packages-not-individual-platforms>.

115 For example, Riley Ceder, “Navy Must Take Risks, Act Like the U.S. Is at War, Says Phelan,” *Military Times*, January 14, 2026, <https://www.militarytimes.com/news/your-navy/2026/01/14/navy-must-take-risks-act-like-the-us-is-at-war-says-phelan/>.

Improved energetics should be employed in small-scale pilot programs to prove their operational utility and safety. The successful employment of RDX by the British military in World War II paved the way for its adoption by the United States. Both RDX and more recent insensitive energetics were first used in limited applications before their widespread integration and fielding. DoD must provide novel energetics an opportunity to demonstrate their advantages (and safety) in reality. If the U.S. military remains unwilling to leverage improved materials, then it should help willing allies and partners experiment first.¹¹⁶

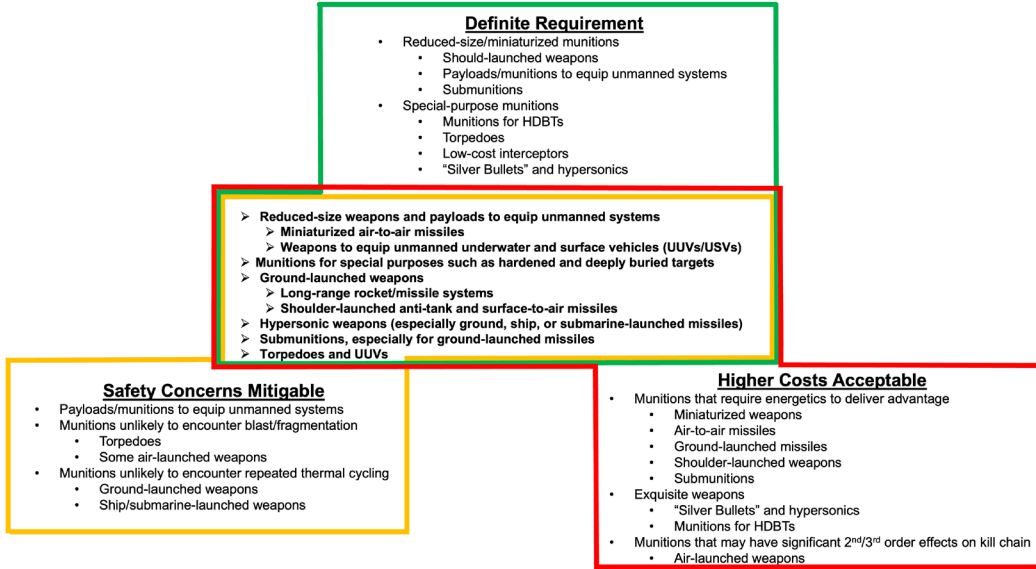
Last, DoD must consider the long-term operational and strategic risks of not adopting novel energetics alongside the near-term fiscal, safety, and tactical risks of increasing their use. Over time, continued reliance on existing materials may put the U.S. military at a disadvantage relative to its great power adversaries. Unlike RDX during World War II, the United States should not wait until more powerful energetics are an urgent operational need to explore their production and fielding. Conducting small-scale pilot programs for specific applications now is likely a safer approach to adopting new explosives than an expedited testing and integration process driven by the urgent needs of a future conflict.

Putting it All Together

The above recommendations mention several military applications for which the advantages of new energetics might encourage their adoption regardless of additional cost or risk. To summarize these recommendations, Figure 10 displays a Venn diagram of the munition types that present the most overlap between this report's recommendations. These munition categories are most suited to integrating and experimenting with novel explosives and propellants.

¹¹⁶ For example, the Ukrainian military has demonstrated the safe use of CL-20 in the Switchblade 300 loitering munition.

FIGURE 10: VENN DIAGRAM OF MUNITION CATEGORIES SUITED FOR NOVEL ENERGETICS INTEGRATION



Note: Figure created by CSBA.

Energetics are the boom behind every weapon in the U.S. military’s arsenal. Their performance affects military operations and effectiveness from the smallest tactical engagement—a mortar shell fired to suppress an enemy fortification—to the operational and strategic balance, where energetics play a role in determining the striking power and range of the military’s most advanced missiles.

New energetic materials such as CL-20 will not resolve all of the U.S. military’s challenges in the Indo-Pacific, and a weapon’s range and power have more determinants than its propellant or explosive compound. By continuing to ignore the potential benefits of improved energetics, however, DoD may be actively choosing less bang for its buck.

LIST OF ACRONYMS

A2/AD	anti-access / area denial
AARGM-ER	Advanced Anti-Radiation Guided Missile Extended Range
AGM	air-to-ground missile
AIM	air intercept missile
AMRAAM	Advanced Medium Range Air-to-Air Missile
ARRW	Air-Launched Rapid Response Weapon
BRAC	Base Realignment and Closure Act
BVR	beyond visual range
CSBA	Center for Strategic and Budgetary Assessments
EMS	energetic materials system
FYDP	Future Years Defense Program
GBU	guided bomb unit
GMLRS-ER	Guided Multiple Launch Rocket System Extended Range
GOCO	government-owned, contractor-operated
HIMARS	High Mobility Artillery Rocket System
ISR	intelligence, surveillance, and reconnaissance
LRHW	Long-Range Hypersonic Weapon
MOP	Massive Ordnance Penetrator
PGM	precision-guided munition
PLA	People's Liberation Army
PrSM	Precision Strike Missile
RAF	Royal Air Force
RDX	Research Department Explosive
SiAW	Stand-in Attack Weapon
SM-6	Standard Missile 6



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