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Rocket's Red Glare: Modernizing America's Energetics Enterprise

BY NADIA SCHADLOW, BRADY HELWIG, BRYAN CLARK, TIMOTHY A. WALTON

A REPORT OF THE HAMILTON COMMISSION ON SECURING AMERICA'S NATIONAL SECURITY INDUSTRIAL BASE COCHAIRED BY DR. ARTHUR HERMAN AND DR. NADIA SCHADLOW

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Cover: A missile is fired during a joint training between the United States and South Korea on June 6, 2022, in East Coast, South Korea. (Photo by South Korean Defense Ministry/Dong-A Daily via Getty Images)

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ABOUT THE HAMILTON COMMISSION ON SECURING AMERICA'S NATIONAL SECURITY INDUSTRIAL BASE

In 1791, Alexander Hamilton, America's first secretary of the treasury, set out to make the United States "independent of foreign nations for military and other essential supplies." He also foresaw a critical role for government in encouraging "new inventions" in manufacturing through patent and trade policy, as well as through government support, since these innovations would be crucial to the new nation's security.

Today policymakers are once again considering how to reduce American vulnerabilities in strategic industries. Over the past two decades, the United States has grown dependent on other countries for supplies of key components. These vulnerabilities became apparent during the COVID-19 pandemic, which laid bare US dependence on global supply chains across a range of strategic industries. America's competitors view this dependence as a potent source of geopolitical leverage. China in particular has weaponized economic dependence in its drive for global preeminence. To reduce American vulnerabilities and boost innovation, the United States needs to bolster manufacturing capability and reshore supply chains in strategic industries.

Hudson Institute's Hamilton Commission on Securing America's National Security Innovation Base examines sectors critical to American national security and proposes policies to reduce dependence and advance US leadership in these industries. Members of the Commission include elected officials of both parties, national security experts, former government and military officials, scientists, engineers, and industry leaders. Supported by the latest Hudson Institute research, the Commission will identify the policy tools needed to reduce US vulnerabilities by building secure and resilient supply chains in strategic sectors.

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This report reflects the views of the authors, but views expressed herein may not fully represent the opinions of members of the Hamilton Commission. It does not reflect views of the respective employers of commission members. The authors take full responsibility for any factual mistakes or errors.

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EXECUTIVE SUMMARY

Energetic materials are critical chemicals that release huge amounts of energy in a very short amount of time. Energetics come in three main forms: explosives, which create the lethal effects in warheads; propellants, which produce thrust for missiles and rockets; and pyrotechnics, such as fireworks, which illuminate or mark targets for military and civilian applications. Nearly every weapon on the modern battlefield, from small arms to missiles to munitions, relies on some form of energetic materials. Improvements in energetics can offer significant benefits on the battlefield. In some cases, better compounds can boost the range of missiles by 40 percent or more—allowing the targeting of an adversary from a safer distance—while also improving lethality and decreasing munition size.

These advantages can help the US military realize many of its operational concepts, such as those developed to counter the People's Republic of China (PRC). China's armed forces, the People's Liberation Army (PLA), aims to prevent the US military from operating near its shores by fielding thousands of anti-ship missiles. This concept is often referred to as an anti-access/area-denial (A2/AD) strategy. If China's leaders act on their stated intention to invade the island of Taiwan, denying the PLA this objective would require large numbers of long-range, precision-guided munitions fired from outside the A2/AD "bubble," coupled with other platforms that could penetrate the PLA's defenses with powerful munitions. These types of US responses depend on energetics and the munitions that use these compounds.

Since the end of the Cold War, however, the industrial base for munitions has grown increasingly brittle as innovation and investments in energetics have stagnated. Although the United States developed key compounds like CL-20—one of the world's most powerful non-nuclear explosives—in the late 1980s, the US military still overwhelmingly uses the same energetic materials it deployed during World War II.[1] Moreover, recent assessments of the industrial base have found that the DoD imports roughly a third of its energetic materials from foreign sources, with a significant portion of these sourced from China or other countries.[2] For instance, one expert we spoke with stated that most trinitrotoluene (TNT) in the explosive fill of common US bombs comes from Poland and Ukraine.[3] Of course, the latter may struggle to fill these orders for the foreseeable future. Other challenges include an aging network of twentieth-century production facilities, a broken business model that discourages innovation and investment, a shrinking workforce, and stifling regulations.

Fixing the industrial base for munitions and energetic materials will require a national strategy that includes the following steps:

- **Provide clear lines of authority and responsibility within the DoD for the munitions and energetics enterprise.** Authority for the munitions industrial base is fragmented across dozens of entities within the Department of Defense. Policymakers should establish a central regulatory and investment authority in the DoD, and then rework safety and acquisition regulations to prioritize performance.
- **Invest in munitions, energetics, and precursor chemical production to send a clear demand signal to the private sector.** Today's industrial base contains hundreds of bottlenecks and single points of failure, and it lacks surge capacity in case of a crisis. The DoD also lacks a clear pathway to deploy advanced energetics, and an inconsistent demand signal for munitions makes private companies hesitant to commit more money.
- **Drive innovation in energetics testing and evaluation, discovery of materials and concepts, and manufacturing processes.** Adjacent technologies, including artificial intelligence and machine learning, plus advanced manufacturing techniques, have the potential to be game-changing for energetic materials. If paired with sufficient research and development funding and investment in integrated modeling and simulation, the DoD could advance energetic breakthroughs.

INTRODUCTION

For decades, the United States has underinvested in energetic materials—critical chemicals found in nearly every weapons system on the modern battlefield. Energetics are used most commonly as explosives and rocket fuel. Improved formulations can dramatically increase range, improve lethality, and decrease the size of munitions—including bombs, missiles, rockets, and artillery shells. If drawn into a war with the PRC, the US military may need tens of thousands of precision munitions to defend strategic locations like Taiwan.

But since the end of the Cold War, the US energetics enterprise, and the industrial base for munitions more broadly, have fallen into disrepair. For the major energetics materials RDX, HMX, nitrocellulose (NC), and nitroglycerin (NG) and the resulting munitions, the industrial base relies on a handful of aging production facilities and suffers from a lack of surge capacity. This means that if the United States had to fight a high-intensity conflict, the DoD risks running out of precision-guided munitions in a matter of weeks. A 2018 survey of the munitions industrial base found over 300 single points of failure in the supply chain.[4] Moreover, recent DoD assessments found that the military depends on other countries for a significant amount of its energetic materials.[5] And the US has fallen behind China and Russia in deploying advanced energetics like CL-20, one of the most powerful non-nuclear explosives in the world.[6]

Photo Caption: A Javelin missile fired by soldiers with the 2nd Stryker Brigade Combat Team heads toward a target during a live-fire training exercise on April 28, 2022, in Fort Carson, Colorado. (Photo by Michael Ciaglo/Getty Images)

To address these challenges, the US needs to reinvest in its munitions industrial base with a focus on energetics production. First steps should include the creation of a centralized hub within the DoD. This office should build on the DoD's recent energetics studies, especially the work of the Chemical Energetic Materials Working Group (CEMWG), to produce a National Strategy for Munitions and Energetic Materials. This strategy should develop a better business model for energetics, including a more consistent demand signal and a clear "on-ramp" to deploy advanced energetics on the battlefield. Next, the US should build a resilient munitions industrial base. This would start with investment in pilot plants for next-generation energetic materials and the expansion of production capacity to be both flexible and responsive to DoD requirements.

Allied capabilities will be an important part of creating a more resilient munitions industrial base. Germany and our soon-to-be NATO ally Sweden both retain substantial capabilities in all defense-specific energetics domains. The war in Ukraine may prove to be an impetus toward more cooperation and integration in these domains.

Finally, the United States should increase investments in research and development to ensure the US military benefits from the next energetics breakthrough.

ENERGETIC MATERIALS AND PRECISION-GUIDED MUNITIONS: AN UNDERRATED DUO

Defining Energetics

Energetic materials are a class of chemicals that can release huge amounts of energy in a short amount of time. These properties make them perfectly suited for use as explosives or fuel. Energetics are in a handful of commercial products, including mining equipment and some space technologies, but they are primarily in defense systems. For the purposes of this report, we will focus on their military applications.

Broadly speaking, energetics can be separated into those that *deflagrate* and those that *detonate*. Deflagration is a chemical reaction characterized by violent burning—think of the brilliant explosion of a firework. Detonation involves a combustion reaction that creates a shock wave.

Energetics come in three main forms:

1. **Propellants** are energetic materials applied to react in a controlled manner to produce thrust. Examples of propellants include solid or liquid rocket fuel, as well as gunpowder in small arms and artillery.
2. **High explosives** detonate and are the main component of most explosive devices, from charges in hand grenades to the

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Photo Caption: A soldier shoots a Tube-Launched, Optically Tracked, Wireless-Guided (TOW) Missile from the Improved Target Acquisition System (ITAS) mounted on a High Mobility Multipurpose Wheeled Vehicle (HMV) at Fort Drum, New York, on March 2, 2022. (US Army photo by Spc. Pierre Osias)

Figure 1: Energetic Materials

ABBREVIATION	FULL NAME	APPLICATION	DATE INVENTED
NC	Nitrocellulose	Propellant	1832
NG	Nitroglycerine	Explosive/Propellant	1847
CN	Cesium Nitrate	Low Explosive/ Pyrotechnic	1860 (Naturally Occuring Cesium)
TNT	Trinitrotoluene	Explosive	1863
PETN	Pentaerythritol Tetranitrate	Explosive	1894
RDX	Hexogen/Cyclonite	Explosive	1898
AP	Ammonium Perchlorate	Oxidizer	Early Twentieth Century
HMX	Octogen	Explosive/Propellant	1949
CL-20	China Lake Compound #20	Explosive/Propellant	1980s

Notes: This table shows the application and years of discovery or invention of common energetic materials. Note the age of the RDX and HMX, two of the most widespread in the US inventory.

Source: Authors.

warheads on missiles. High explosives are triggered by a smaller, "primary" explosive that provides the *initiation for* a reaction.

3. **Pyrotechnics** are non-explosive devices that produce light, smoke, sound, and/or heat. Examples include flares, aircraft decoys, smoke grenades, and incendiary devices like thermite and some fireworks.

Energetic materials considered essential to the defense enterprise include ammonium perchlorate (AP), TNT, NC, NG, RDX, and HMX.[7]

Energetics and Precision-Guided Munitions

On the twenty-first-century battlefield, many of the bombs, missiles, and rockets that American forces can be classified as precision-guided munitions (PGMs). The Department of Defense defines a PGM as "a guided weapon intended to destroy a point target and minimize collateral damage."[8] Precision munitions rely on a guidance system—such as gyroscopes, signals from the global positioning system (GPS), radar, infrared or electro-optical seekers, or laser guidance—to carry a munition directly to its target. Even so-called dumb bombs like the Mark 82, which do not feature an internal guidance system, have been turned into "all-weather, precision weapons" thanks to guidance packages that mount directly to their tailfin.[9] Most modern PGMs are accurate to within about three meters, or ten feet.[10]

PGMs are made up of three parts: a guidance system, an explosive munition, and "an anti-jamming device to prevent adversaries from interfering with the guidance signals."[11] Energetic materials make up the explosive or propellant that powers these PGMs. The chemical makeup of a warhead helps determine the explosive power of a munition. Propellants and explosives also play a role in determining the size of a munition—a more powerful explosive, for example, can allow for a smaller munition. Ultimately, the characteristics of energetic materials determine the range, lethality, and size of precision-guided munitions.

The list of 14 critical technology areas published by the Office of the Under Secretary of Defense for Research and Engineering lacks a specific reference to energetics, but its hypersonics and space technology priority areas depend on energetics.[12] Moreover, other critical technology areas are enabling technologies for energetics, such as advanced materials science and advanced computing and software, which, through modeling, can enable lower-cost research and development. In addition, it identifies microelectronics as a key research area. Innovative manufacturing techniques and materials fuel advances in microelectronics, which in turn enable the development of smaller and more powerful devices like guidance systems and sensors for munitions.

Commercial Space Activity and Energetics

The commercial space industry is one of the major producers and consumers of energetic materials in the United States, having developed a largely separate supply chain from the DoD. Developments in this sector are increasingly critical to national security and are a boon to American prosperity and innovation.

The National Security Space Launch (NSSL) program, in which private companies work with the US government to send satellites into orbit, is now looking to replace the Russian RD-180 rocket engine—use of which is prohibited due to sanctions. Although the NSSL is phasing out the RD-180, it likely will not find replacements with similar performance before 2030.[13] The NSSL program is also at risk of sole or limited sourcing since only a limited number of companies receive contracts. This reduces the capital available for new entrants to develop products that satisfy DoD requirements.[14]

The private energetics enterprise is a critical part of reducing launch cost and increasing annual launch capacity.

Unfortunately, the small number of subcontractors that provide energetics and propulsion services face several challenges. Many of these firms are subject to International Traffic in Arms Regulations (ITAR), which include rocket, space launch vehicle, and missile power plants on the US Munitions List.[15] This means that companies producing engines or energetics are limited in terms of partnerships or potential customers that may offset the cost of research and development. The industry also has high barriers to entry, including fixed costs such as production facilities and the real estate required for these facilities, as well as stringent safety requirements associated with developing and producing explosives. In addition, thus far, capital flows have been less active in supporting the subcontractors that design and produce the rocket motors than in supporting the companies that ultimately launch them. Thus the US government should provide a more consistent and reliable demand signal to adequately maintain and support the energetics sector.

THE ROLE OF ENERGETICS AND MUNITIONS IN DEFENSE

Even in an era of high-tech warfare, no substitutes exist for energetics and precision-guided munitions. "There is no modern defense system or type of weaponry that does not rely on energetic materials," notes a 2004 study from the US National Academy of Sciences.[16] America's history of munitions shortages and low surge capacity, coupled with the potential for tensions with near-peer competitors to spiral into a protracted war, should raise red flags surrounding our ability to fight and win against near-peer adversaries like China's PLA. Advances in range, lethality, and size that advanced energetics provide can enable new operational concepts, including long-range precision fires and smaller, lighter platforms with an enhanced ability to operate in contested environments. These operational concepts are directly relevant to the types of scenarios that the US military could face in the western Pacific, as well as in the Persian Gulf or Europe.

The United States has made impressive gains in precision since the first guided weapons were fielded during World War II. However, advances in precision have plateaued (as noted above, modern PGMs are accurate to within about three meters of a target). As a result, future gains in precision are likely to offer only marginal benefits.[17] Future advances will likely involve the development of more powerful energetic materials that can improve the range and lethality of munitions while simultaneously reducing size, lowering unit costs, and preserving gains in safety and precision.

Photo Caption: Marines detonate a timber charge during a demolition and explosive training exercise at the ETA-7 engineer demolition training range on Marine Corps Base Camp Lejeune, North Carolina, on January 11, 2018. (US Marine Corps photo by Pfc. Ginnie Lee)

Advanced Energetics and Precision-Guided Munitions: A Brief History

With the onset of modern industrialized warfare in the late nineteenth and early twentieth centuries, the development and production of energetic materials became critical for national security. This era marked the beginning of cased ammunition with smokeless gunpowder, artillery with complex warheads, and rockets. Two of the most important compounds in current US use, RDX and HMX, were discovered in 1898 and 1930 respectively. The US military first employed both during World War II.

Around this time, new technology allowed scientists to develop rudimentary precision munitions. In 1897, American inventor Nikola Tesla developed a prototype of a remote-controlled "boat" designed to maneuver up to enemy ships and fire torpedoes at close range. Though not technically precise, Tesla's innovation laid the groundwork for later breakthroughs. By the 1940s, the US Navy and Air Force had developed a full slate of guided weapons and remotely controlled vehicles.[18] The first guided munition was used operationally in May 1943, when a Royal Air Force bomber dropped an acoustic homing torpedo that seriously damaged a German U-boat.[19] Though not particularly effective as a strategic weapon, the German V-2 rocket can also be classified as a precision munition since it featured an internal guidance system, and it is considered the world's first ballistic missile.[20]

Although the period between the turn of the twentieth century and the present has witnessed significant advances in the fields of chemistry, engineering, and industrial production—and a wide expansion of applications for energetics—for the most part, *the US military still relies on the same energetic materials it used during World War II*. HMX and RDX remain the most advanced energetic compounds in wide use in the US arsenal.

CL-20, a compound developed in the 1980s at Naval Air Weapons Station China Lake, showed significant performance improvements over previous compounds as both an explosive and a propellant. Notably, one expert explained that the integration of CL-20 allowed for a 20 to 40 percent improvement in the range of existing missile systems. Novel materials might yield further improvements. Nonetheless, CL-20 has yet to see significant use in US weapons due to challenges in developing a scalable manufacturing process and the need to comply with legislation and regulation. In contrast, China began producing CL-20 at scale in 2011, and Russia has added the compound to its arsenal.[21]

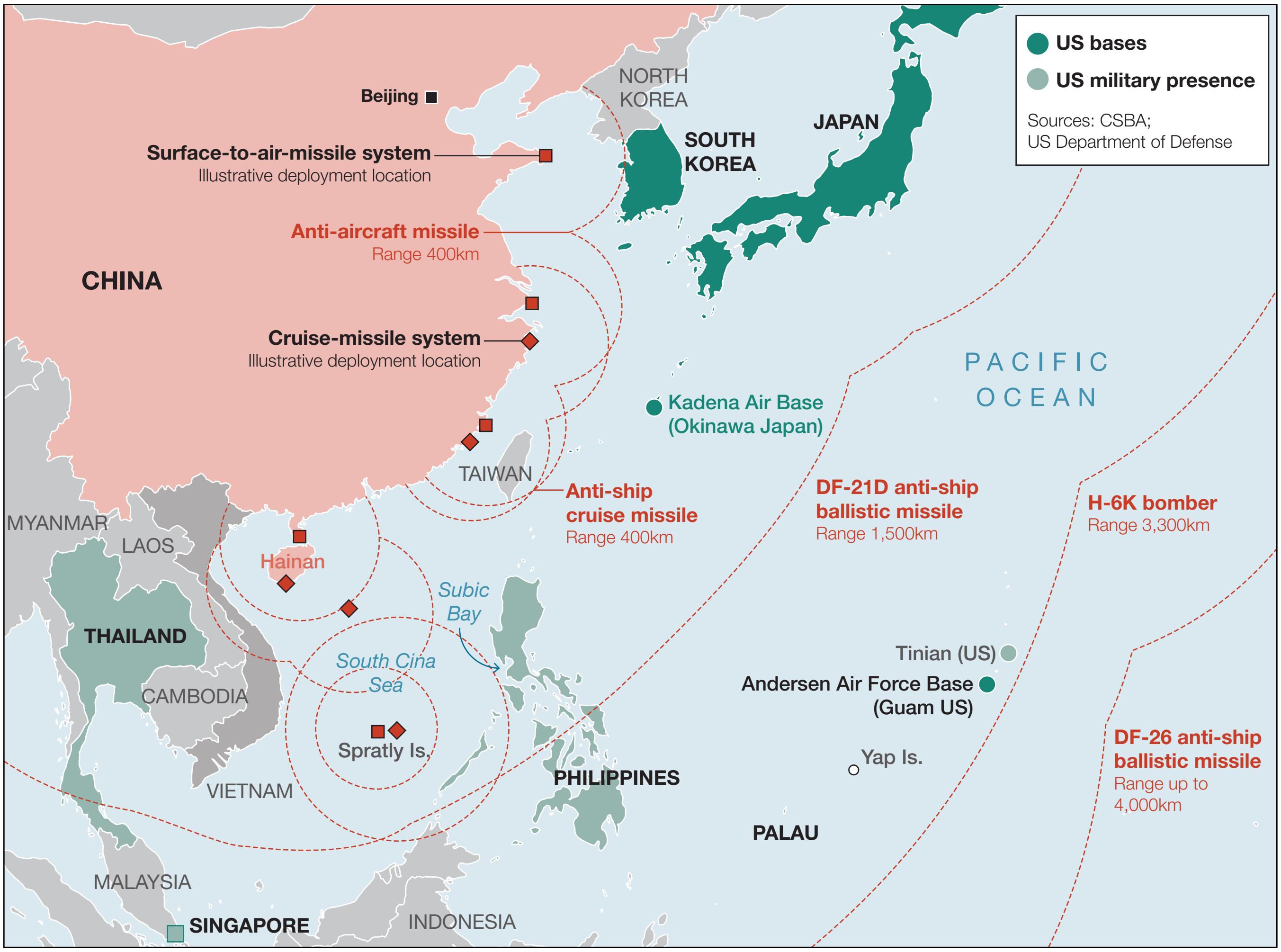
Several factors have contributed to Washington's reluctance to pursue innovation in energetics. One factor has been the DoD's push to develop a precision-strike regime. This has been a double-edged sword. By placing a premium on sensor and guidance systems, the DoD's emphasis on precision has improved the economy of a single weapon and increased lethality: more accurate weapons hit their mark. But this effort also tended to play down the importance of energetic properties that contribute to range and explosive power. As a result, innovation in the field of energetics began to stagnate.

Regulations pertaining to insensitive munitions also limited US advances in energetic materials. Insensitivity refers to the need to safely produce, transport, and store munitions across the logistics chain with a low risk of accidental detonation. However, a trade-off exists between safety on the one hand and operational effectiveness and innovation on the other. Enhanced safety is certainly a worthy goal, but ever-increasing regulations have stifled innovation in energetics, keeping more volatile compounds that may offer enhanced performance on the shelf.

Energetics, US-China Competition, and Taiwan

The rise of competitors like China has highlighted the importance of range and lethality, which will be key factors in the outcome of a conflict in the western Pacific. According to the DoD's *2021 China Military Power Report*, the PRC's national strategy seeks to achieve "the great rejuvenation of the Chinese nation" by 2049. In pursuing this goal, the PLA has undertaken a vast military modernization program over the last two decades,

Figure 2: Range of PRC Missiles



Notes: This map shows the range of ground-launched missiles in the PRC's inventory. Ballistic missiles such as the DF-21D and DF-26 are powered by solid-fuel rocket motors. Long-range munitions enabled by improved energetics are an important part of addressing the A2/AD challenge.

Source: "America's Top Brass Responds to the Threat of China in the Pacific," *The Economist,* March 11, 2021, https://www.economist.com/asia/2021/03/11/americas-top-brass-responds-to-the-threat-of-china-in-the-pacific.

much of it designed to deter the United States and constrain US military options. DoD officials have made clear that China could have the potential to invade Taiwan within five years.[22] The Pentagon has also identified the PRC as the primary military "pacing threat" that must guide future force development.[23]

Today, the PLA poses a number of threats to US air, land, and sea assets in the western Pacific. These threats combine to create an A2/AD challenge: the PLA can threaten to deny the ability of US forces to maneuver in the South and East China Seas, while also threatening US and partner forces throughout the western Pacific. The PLA can do this through the employment of long-range weapons with the ability to target ships, aircraft, and ground forces.

One former US official assesses the PRC's arsenal as follows:

> [The PLA] possesses a huge arsenal of missiles—numbering at least a thousand—that are capable of precision strikes at various ranges, and that now include both a dual-capable (nuclear or conventional) DF-26 missile capable of conducting precision land-attack and anti-ship strikes in the Western Pacific, the Indian Ocean, and the South China Sea from mainland China, as well as the new DF-17 hypersonic glide vehicle (HGV) launched atop a medium-range ballistic missile (MRBM). Even leaving aside ship-based systems and counting only land-based missiles, the PLA is able to extend its anti-air missile coverage all the way across the Taiwan Strait and over much of the island itself, and is capable of anti-surface missile attacks far beyond Taiwan's eastern coastline.[24]

PRC ballistic and cruise missiles pose a significant threat to US and allied bases. For instance, Kadena Air Base sits about 400 miles from mainland China, while Anderson Air Base sits some 1,800 miles away. "In the event of a major salvo of enemy guided conventional munitions," defense expert Andrew Krepinevich explains, "these bases run a high risk of being put out of action early in a war, especially if the enemy strikes first without warning."[25] Defending these bases will be crucial to US and allied efforts.

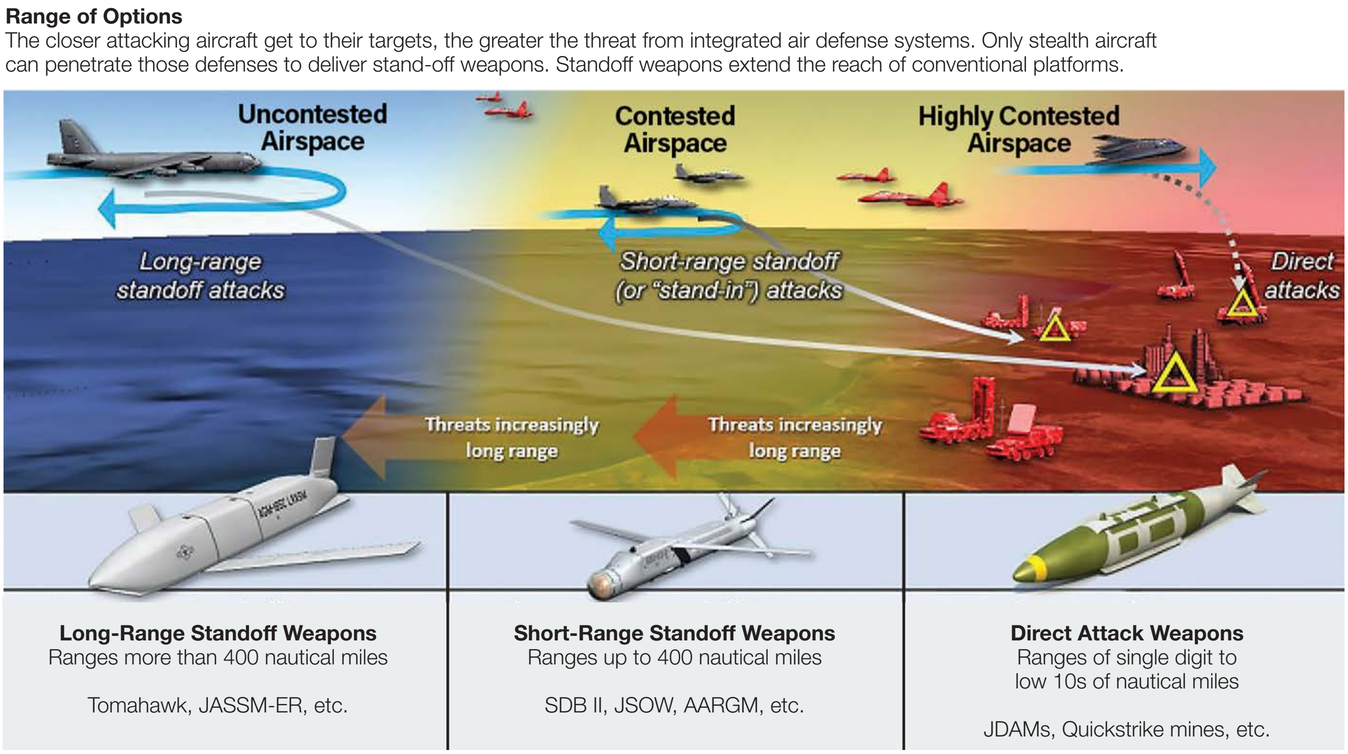
The composition of the PLA's missile forces also poses a problem for the US military. Until its 2019 withdrawal from the Intermediate Nuclear Forces (INF) Treaty, the United States was barred from developing or possessing intermediate-range missiles (defined as any missile with a range between 500 and 5,500 kilometers, or between 310 and 3,420 miles), as was the Soviet Union. The PRC, however, was never a party to this treaty. According to the International Institute for Strategic Studies, roughly 95 percent of the PLA's ballistic and cruise missile arsenal falls within this category.[26] Now that the INF Treaty limitations are no longer in force, the US is free to develop a range of weapons in this class.

Taiwan

Arguably the most concerning scenario for US defense planners is a PRC invasion and occupation of Taiwan, a policy known as "forceful reunification." China's leaders have repeatedly signaled their intent to invade and occupy the island as a matter of strategic and ideological importance. As recently as October 2021, President Xi Jinping reiterated that "the historical task of the complete reunification of the motherland must be fulfilled, and will definitely be fulfilled."[27] Ultimately, a successful amphibious invasion of Taiwan would likely hinge on a lightning operation that changes the status quo so quickly that it becomes nearly impossible to roll back at an acceptable cost.[28] Defeating this strategy would require the United States and its allies to execute a denial strategy to deter and, if necessary, prevent Beijing from executing a *rapid* takeover and occupation of Taiwan. This would require US and allied forces to "mount a strong defense against the enemy's initial strikes and to continue fighting beyond the conflict's initial phase."[29]

But defense experts have expressed concern that if a Taiwan scenario drags out for longer than a few days, the US military may quickly run out of its preferred munitions. Once a Taiwan contingency "begins to unfold," explain David Ochmanek and Michael O'Hanlon, "the United States needs the ability to sink or disable hundreds of Chinese ships quickly and deny Chinese forces the ability to operate with impunity in Taiwan's airspace."[30] Some experts have even questioned whether or not the US and its allies could survive the initial onslaught of Chinese munitions.[31]

Figure 3: Application of US Munitions at Varying Ranges.



Source: Mark Gunzinger, "Long-Range Strike: Resetting the Balance of Stand-in and Stand-off Forces," Mitchell Institute for Aerospace Studies, June 2020, https://mitchellaerospacepower.org/long-range-strike-resetting-the-balance-of-stand-in-and-stand-off-forces/.

Yet precedents suggest that the US military has tended to underestimate the number of munitions needed to prosecute a war.[32] According to the US Air Force, nearly 139,000 precision-guided weapons were used in the Middle East between 2014 and 2019.[33] Defeating a PLA invasion will be possible only if the DoD fields "deep munitions magazines" and builds stockpiles in the region, concludes Krepinevich.[34]

Innovative and mass-produced energetics are key to providing "lethality at scale," ensuring that the US will have a range of numerous options to deny China a successful invasion of Taiwan. Investments in energetics can help DoD field larger numbers of more powerful and longer-range weapons that can hold Chinese targets at risk and impose dilemmas on PLA planners.[35]

Energetic Materials and Battlefield Advantages

Advancements in energetics translate directly into advantages on the battlefield, enabling the US military to execute the operational concepts it has developed. Improved energetics are crucial for "outranging and overtaking enemy systems at great distances and delivering lethal effects against targets in every domain: on land, at sea, undersea, in the air, and in space."[36] Munitions powered by advanced energetics offer three main advantages: *increased range*, *increased lethality*, and *decreased size*.

Increased Range

On the tactical level, improved energetic materials can increase the range of a rocket, missile, or other munition. CL-20, for example, can increase range by up to 40 percent.[37] Such improved range allows for the targeting of an adversary from a safer distance, reducing danger to friendly forces. For example, when two opposing fighter aircraft converge, the aircraft that can launch its missile first may eliminate its target with less risk to itself.

Advanced energetics could also enable weapons such as air-breathing cruise missiles to achieve greater range while sustaining higher speeds.

From an operational standpoint, increased range is crucial to grant US forces the flexibility to fight from various distances and attack axes, rather than being forced to fight from close range. Longer range weaponry can thus impose challenges on PLA planners, which may increase their risk to force and decrease confidence in achieving campaign outcomes.

Increased Lethality

Lethality is the ability to destroy enemy systems and personnel as effectively as possible. The 2018 US National Defense Strategy "identifies lethality as the first out of three priority areas for the military to develop."[38] One way energetics boost lethality is by increasing explosive power. More lethal munitions increase the likelihood that a target will be disabled or destroyed on the first shot. CL-20, for example, offers an improved ability to destroy hardened targets like bunkers, missile batteries, or aircraft shelters. The Energetics Technology Center (ETC) states that, "compared to U.S. HMX-based explosives, CL-20 has a 40% increase in penetration depth, which is a significant increase in overall warhead lethality for specific applications."[39] In explosive submunitions such as those used in cluster weapons, more powerful explosives would allow each bomblet to have greater effects on its target. CL-20-based propellants also produce less smoke exhaust due to lower aluminum requirements in derivative formulations, allowing missiles to avoid visual and infrared detection and reduce the likelihood of interception.[40] These advantages—an improved ability to destroy hardened targets and missiles that are tougher to detect—help ensure that munitions achieve their desired effect.

US Army Long-Range Precision Fires

The Army's long-range precision fires (LRPF) program exemplifies the importance of energetics across the armed services and diverse warfighting domains. It consists of four subsidiary programs: the Precision Strike Missile (PrSM), Common Hypersonic Glide Body (C-HGB), Extended Range Cannon Artillery (ERCA), and a ground-launched Tomahawk and SM-6 modification program.[41] These systems are intended to redress the potential firepower disparity between forward-deployed forces and our adversaries by enabling the Army to "defend itself or strike deep into an adversary area of operations," in accordance with the Joint Warfighting Concept.[42]

The Army has taken the initiative to foster advanced energetics research and development in support of the LRPF program. Its Expeditionary Technology Search (xTechSearch) competition included over 350 companies seeking to design and produce an advanced solid propellant. Together, the LRPF program and the xTechSearch competition epitomize the central role that energetics innovation plays in future munitions.[43] However, as with all new concepts, transitioning into acquisition programs of record remains a challenge.

Decreased Size

Given the massive selection of potential targets in a conflict with China, the DoD may be hard-pressed to acquire enough precision munitions to target PLA assets. It needs a new approach to achieve what Mark Gunzinger has termed "affordable mass."[44] Improved energetic materials can preserve the lethality of munitions while helping them fit inside smaller forms. Advanced energetics can, for example, allow the DoD to build a 400-pound bomb with the same lethality as a current 1,000-pound bomb.[45] It can also allow air and missile defense interceptors to be smaller. As a result, US platforms could bring a greater number of weapons into the fight, carry deeper magazines, and spend less time restocking munitions—a time-consuming and potentially dangerous process that could leave systems vulnerable during a high-intensity conflict.[46] Additionally, smaller land, sea, and air assets could carry comparable firepower to larger systems and could be more survivable in a contested environment. As defense analyst T. X. Hammes notes, advanced energetics could also be a gamechanger for unmanned systems—for instance, by equipping small drones with weapons of comparable effect to their larger counterparts.[47]

Taken together, these advantages can help the DoD overcome existing operational weaknesses and instead impose dilemmas on the PLA. US longer-range munitions would allow ground forces, vessels, and aircraft to launch standoff strikes from safer ranges, while smaller, more lethal munitions would allow US forces to be more survivable and self-sufficient in contested environments. Consequently, the future of the energetics enterprise may be key to determining the success or failure of the US in a potential future conflict.

Photo Caption: Pallets holding munitions are transported off an aircraft cargo loader into a Boeing 747 at Travis Air Force Base, California, on April 26, 2022. (US Air Force photo by Senior Airman Jonathon Carnell)

SUPPLY CHAIN VULNERABILITIES

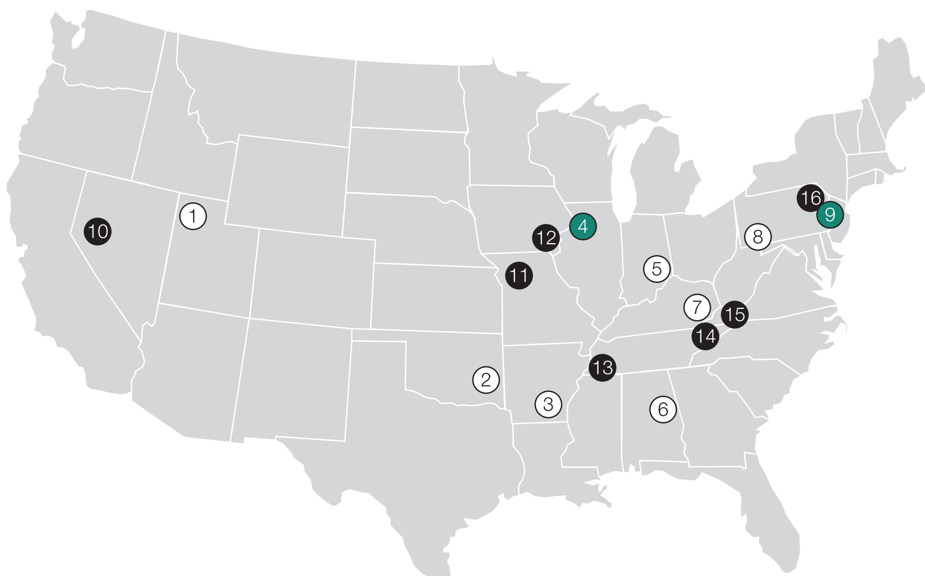
Vulnerabilities exist across every level of the supply chain for munitions and energetic materials. The missiles and munitions (M&M) industrial base, which includes the energetics supply chain, faces five major challenges: aging production facilities; intermittent production lines; dependence on foreign sources; a broken business model, which discourages investment and lacks a clear pathway to deploy advanced energetics; a shrinking workforce; and stifling regulation. A 2019 report by the DoD's Critical Energetics Materials Working Group (CEMWG) found that "the industrial base for chemicals was fragile, vulnerable to supply chain disruptions, dependent on foreign nations for a significant number of sole-source chemicals used in the majority of the DoD's munitions, reliant on obsolete specifications, and impacted by increasing environmental regulatory pressure within the U.S. and abroad."[48]

While some of these vulnerabilities have arisen due to market forces, including a limited private sector market for energetics, others have developed out of policy choices, the techno-economic strategies of our adversaries, and a lack of prioritization.

An Aging Industrial Base

On the production side, America's industrial base for munitions production is brittle, with serious potential bottlenecks. In 2018, a DoD task force on the munitions industrial base indicated more than 300 single points of failure.[49] A separate DoD analysis found that of 198 second- and third-tier suppliers in the M&M industrial base, 98 percent rely on a single or sole source.[50] These issues are especially pronounced in the supply chain for energetic materials. Unlike in other supply chains in critical industries, however, the US government is involved

Figure 4: Government-Owned US Facilities



Government Owned Government Operated (GOGO)

① **Tooele Army Depot**
- Supply depot operations
- Ammunition peculiar equip

② **McAlester AAP**
- 500, 1000 & 2000lb bombs
- Intelligent munitions
- Supply depot operations

Defensive Ammunition Center
- Explosive safety/engineering
- Demil R&D technology
- Training/career management

③ **Pine Bluff Arsenal**
- White/red phosphorus
- Smoke/obscurants
- Supply depot operations
- Chem defense equipment

④ **Rock Island Arsenal**
HQ Joint Munitions Command

⑤ **Crane Army Ammunition Activity**
- 5"/54 & 76mm load, assemble & pack
- Illum, pyro, flares
- Supply depot operations

⑥ **Anniston Munitions Ctr**
- Supply depot ops
- Missile storage
- Demi

⑦ **Blue Grass Army Depot**
- Supply depot operations
- Chemical defense equipment

⑧ **Letterkenny Munitions Ctr.**
- Tactical missiles
- Supply depot operations

⑨ **Picatinny Arsenal**
HQ Joint Munitions & Lethality LCMC Armament Research, Devel & Eng Center PEO ammunition

Government Owned Contractor Operated (GOCO)

⑩ **Hawthorne Army Depot**
- Western Area Demil Facility
- Supply depot operations

⑪ **Lake City AAP**
- Small caliber 5.56, 7.62, 20mm, .50 cal

⑫ **Iowa AAP**
- Missile warheads
- Load, assemble and pack 120mm tank, 105/155 artillery

⑬ **Milian AAP**
- Load, assemble and pack 40mm, mortars, demo blocks

⑭ **Holston AAP**
- Explosive RDX/HMX

⑮ **Redford AAP**
- Solventless propellant
- Nitrocellulose

⑯ **Scranton AAP**
- Projectile metal parts
- 155mm shells & 120mm mortar

AAP = Army ammunition plant
RDX = Rsch Dept Explosive
HMX = High Melt Explosive

Notes: The map identifies key facilities in the US energetics enterprise. Note that not all of these facilities produce the energetics themselves. Some—such as Hawthorne, Tooele, and Bluegrass—function as supply depots. Note also that two other important facilities—Indian Head Naval Surface Warfare Center and China Lake—are not part of this map because they are not part of Joint Munitions Command.

Source: "FY 2012 Annual Command History," The US Army Joint Munitions Command, 2012, https://www.jmc.army.mil/Docs/History/FY%202012%20JMC%20Executive%20Summary.pdf.

in all aspects of the energetics enterprise.[51] This includes "the science and technology (S&T) innovation of new molecules and formulations, the large-scale production of bulk quantities of energetic materials, and their applications in weapons and other systems."[52] On the one hand, this indicates that current vulnerabilities have arisen on the DoD's watch. On a more positive note, however, the department's outsized role in the supply chain offers it the opportunity to address these issues.

Beyond the operation of government-owned, contractor-operated (GOCO) facilities, the industrial base for energetics has limited private sector involvement. According to the ETC, the supply chain "is heavily dependent on a small number of GOCO facilities to produce, mix, load, and pack EM prior to delivery and installation into weapons systems."[53] This is partially due to extensive government regulation of the production cycle, including the rigorous program requirements and regulations concerning insensitivity of munitions (see "Stifling Regulations" below). Many DoD requirements mandate that energetics production occurs at a single specified government-owned, government-operated (GOGO) or GOCO facility. The most important of these is the Holston Army Ammunition Plant in Tennessee, which is the department's designated single-source producer of explosives RDX and HMX. In other words, some of the most widely used energetic materials are sourced from a single facility that was built in 1942.

Even without accounting for the reliance on foreign suppliers, this centralized production system introduces points of failure and reduces overall throughput, which exposes the United States to the risk of munitions shortages in the case of a plant accident, cyberattack, or natural disaster. Such risks have ample precedent. In 1996, for example, a fire broke out at a plant in Texas that happened to be the US military's sole source of CTPB, an energetic material used in solid rocket propellants. The contractor did not rebuild the plant, leaving several US missile programs without a major ingredient.[54] More recently, the McAlester AAP, which is the sole producer of general-purpose bombs for the DoD, is not operating because of an incident that occurred in November 2021. When placed in the context of the war in Ukraine and its effect on TNT supplies, this means that there is no plausible method of producing these munitions for the foreseeable future.

These facilities have also begun to show their age, with little investment beyond basic maintenance since the end of the Cold War. Not only has the lack of modernization increased the risk of failures that might cascade through the supply chain, but these facilities are also unable to capitalize on twenty-first-century manufacturing methods that might enable a shift to other products. *Lack of sufficient DoD funding has made contractors hesitant to invest in new production facilities since demand signals are weak*.[55] "Put plainly," the ETC assesses, "DoD has not provided sufficient funding to justify capital investments by contractors to replace existing Government-Owned Government-/Contractor-Operated (GOGO/GOCO) facilities or to construct more modern ones for the production of new [energetic materials]."[56] Most of the modernization investments have focused on the production of existing materials rather than on expanding the DoD's ability to produce novel energetics.

Across the missiles and munitions enterprise more broadly, many programs lack the surge capacity to ramp up production when a conflict breaks out. To take a recent example, the US military lacks a single operating production line for Stinger missiles, of which the US is currently sending thousands to Ukraine.[57] As one analysis by three active-duty officers noted, "At a simple level, munitions programs need both a steady state and a surge capability."[58] They added that "warfighter demands may change at a moment's notice, [while] production problems in the munitions and industrial base often take years to solve. The current system does not plan or budget for 'resiliency.'"[59] Likewise, Senator James Inhofe recently stated that "we don't have the capacity to produce enough munitions and ammo … this is a key challenge of both deterrence and protraction, warfighting scenarios."[60] Due to this lack of surge capacity, the DoD confronts a recurring problem in American history. [61] The US military entered World War II with only a handful of production facilities. Yet thanks to technical expertise retained from World War I, it constructed nearly 60 manufacturing plants over the course of the war.[62] In a war that may be decided in a matter of weeks or months, however, the US will not have time to rebuild the munitions industrial base.

Dependence on Foreign Sources

Recent DoD reports on the defense industrial base show that the supply chain for energetic materials depends heavily on foreign sources, including China. Many foreign suppliers—if not located in the PRC —either interact with Chinese firms upstream in the supply chain or are in countries that border the PRC. According to the DoD's most recent annual report on the defense industrial base, "*A third of DoD's energetic material is produced overseas, and many materials have direct dependencies on China*" (emphasis added).[63] China is "the sole source or a primary supplier for a number of critical energetic materials used in munitions and missiles," concluded another interagency task force in 2018.[64]

As part of Beijing's broader techno-economic strategy, China has acquired companies around the world that produce raw materials or key inputs, like critical minerals and chemicals. The PRC has supported these industries to expand direct access to resources and gain strategic leverage. For instance, cesium nitrate—an important energetic chemical used in countermeasure flares—is sourced solely from a site in Canada, but a Chinese company purchased the production facility. As another example, butanetriol trinitrate (BTTN), a solid rocket fuel used to power AGM-114 Hellfire missiles, is produced using the chemical butanetriol (BT). But the last US producer of BT shuttered production in 2004, leaving the DoD dependent on a Chinese source.[65] This structure poses a variety of risks to the overall supply chain, and because the system has little flexibility and virtually no redundancy, problems at any level can halt production.

Most alarming is the DoD's current lack of situational awareness regarding key vulnerabilities in this supply chain. While weapons systems and munitions are produced in the United States, energetics and other components are frequently "too far down in the supply chain for DoD to have any visibility," notes a recent DoD report on industrial base capabilities.[66] Some of these disruptions have malicious intent. According to a 2019 DoD report, "competitor nations are aggressively attempting to acquire critical sub-tier suppliers, either directly or through the higher-level ownership chain of the company, with limited visibility from DoD."[67]

Even when more reliable sources of a critical material exist, either domestically or in friendly nations, the economics may drive manufacturers elsewhere. As the DoD has noted, "industry often chooses not to use domestic or allied sources of these chemicals even when available due to pricing."[68] Once companies depend on a foreign source, onerous safety and qualification regulations make switching to a substitute more difficult. "In many cases," notes the DoD's Office of Industrial Policy, "there is no other source or drop-in replacement material and even in cases where that option exists, the time and cost to test and qualify the new material can be prohibitive—especially for larger systems," which cost hundreds of millions of dollars each.[69] In addition, due to incentives related to cost, program managers are expected to manage double-digit internal cost growth over the multi-year life of a program and tend to opt for legal, lower-cost inputs—which become the most "rational" choice in the context of a program manager's decision constraints.

A Shrinking Workforce

One of the most pressing problems the DoD faces in the energetics domain is the attrition of its scientists and engineers. Limited numbers of commercial applications for energetics mean that the DoD already has a small talent pool from which to draw. Sparse opportunities for advancement, coupled with a lack of innovation in the field, often make replacing those who leave difficult if not impossible. ETC frames the problem as follows:

> STEM professionals are motivated by mission and a drive to solve hard problems. Consequently, they leave the defense enterprise if they lack the necessary skills, tools, and opportunities to solve problems in support of defense missions, and because investment in the EM field barely maintains current workforce capabilities, to say nothing of building new ones. Young scientists and engineers quickly identify outmoded facilities and an undermotivated and poorly incentivized workforce … scientists and engineers with competencies in fields like machine-learning and artificial intelligence can earn as much initially in the private sector as a senior manager with decades of experience in government. Perhaps most tragic is the loss of knowledge, experience, and institutional memory when retirements and workforce attrition does [*sic*] not involve the generational transmission of professional cultures and priorities.[70]

One start to solving these problems could be an increase in DoD investments in energetics.

Second, to develop a stronger pipeline for talent in this domain, the DoD should consider launching apprenticeship programs (with fast-tracking for needed security clearances), an approach that previously worked in shipbuilding and aircraft manufacturing. Such programs could include public-private partnerships and research agreements with contractors and academia.

The talent pipeline is lacking in both universities and secondary schools. There is a glaringly deficient number of US citizens in advanced university STEM programs, especially in PhD programs at elite universities.[71] It is also difficult to maintain STEM entrants. For example, nearly half of bachelor's degree students who began a STEM major between 2003 and 2009 left by 2009.[72] A lack of highly educated US citizens restricts the DoD's abilities to find talent that would advance its science and technology, research and development, and engineering programs. In American high schools, the academic performance of US students in STEM disciplines is increasingly disappointing. In 2016, only 35 percent of high school students took a mathematics course beyond Algebra 2, and less than three-fourths of students who take the Physics C: Mechanics, Physics C: Electricity and Magnetism, and Physics B College Board Advanced Placement (AP) exams pass them.[73] Although the United States' elementary and secondary science rank has improved by 13 points since 2006, and is now seventh out of 37 Organization for Economic Co-operation and Development (OECD) countries, its mathematics ranking of 25th out of 37 has seen little change.[74] DoD-based apprenticeship programs can help show students the necessity of STEM disciplines, prepare both university and secondary school students for careers in the DoD, and develop a stronger talent pipeline in the energetics enterprise.

A Broken Business Model

Due to a misaligned incentive structure and the lack of a clear pathway to deploy new materials, the business model for energetics production is broken. This has led to a reluctance among private sector players to invest in energetics, a lack of innovation, and declining levels of competition within the industrial base. Unlike other areas of the defense industrial base, as noted by the ETC, "the government bears the entirety of the risk for the development and operationalization of energetic materials, rather than developing a model wherein industry shoulders a greater share of the risk against a cost premium acceptable to the government."[75]

The first problem the DoD faces in the energetics enterprise is the lack of an organizational hub for munitions and energetics within the Pentagon. "EMs are not planned, programmed, and budgeted like every other Defense acquisition concern. They result from dozens of functions spread over different parts of the DoD, leading to a fractured, sub-optimized, and decidedly thin multiplicity of actors responsible for different segments of the value chain," notes the ETC.

Due to the lack of a dedicated planning and programming authority, the DoD tends to emit a highly inconsistent demand signal, increasing the risk for private sector players who may otherwise invest in munitions and energetics.[76] As the *FY2020 Industrial Capabilities Report* notes, "Conflict-driven procurements for missiles, munitions, and supporting energetic components make it difficult to maintain consistent and steady production demand."[77] This causes investors and businesses to shy away from the energetics and munitions enterprise. Giant swings in demand make it difficult for industries to optimize infrastructure and their workforce.[78] James Thomsen, the former principal deputy assistant secretary (research, development, and acquisition) for the Department of the Navy, notes that businesses invest in supply chains when there are "reasonably known demand signals." But the demand signal for new energetics "hardly exists" and is "underleveraged," making many businesses "unwilling to invest" in the multibillion-dollar industry.

The new wave of private-sector aerospace companies—such as SpaceX and Blue Origin, which currently partner with the US government through NASA—suggests that firms are willing to take risks in energetics-related sectors and other long-term enterprises. However, without the creation of future opportunities in energetics-related sectors, firms will lack incentives to invest in the facilities, tools, and human capital necessary to produce energetics.

Another challenge is the lack of a clear pathway to deploy advanced energetics on the battlefield. Energetic candidates are discovered via basic research, much of which academia does. Responsibility for moving materials forward via applied research then falls to defense science and technology (S&T) organizations, such as the Defense Advanced Research Projects Agency (DARPA) or any number of federally funded research and development centers. These organizations investigate novel materials and publish the results of scientific findings for the broader community.[79]

Candidate materials then face many layers of qualifications and testing. The ETC notes that qualifying an energetic material for inclusion in a weapons system could take several years and cost up to $2 million.[80] This red tape means that even if a novel and incredibly powerful energetic material was discovered by American scientists, it would take considerable time and money to integrate it into a weapons system.

As a result of these hurdles, programs are incentivized to choose an existing material on the basis of lowest cost and schedule risk. In addition, program managers and acquisition professionals have an incentivize to take the path of least resistance and use proven, off-the-shelf energetic materials that have already met lengthy safety and qualification testing requirements rather than taking a risk on an unproven material that might provide significant battlefield advantages. The DoD has entered a "valley of death" of its own making.

Ultimately, the DoD's inconsistent demand signal and the regulatory burdens in the energetics and munitions enterprise have led to a hollowing out of the industrial base. "The missiles and munitions (M&M) sector has trended toward consolidation," notes a recent DoD study, "with 30 prime contractors in this sector three decades ago, but only seven today."[81] For instance, two large companies, Orbital ATK and Aerojet Rocketdyne, dominate the market for solid rocket motors.[82] Following Northrop Grumman's acquisition of Orbital ATK in 2018, Aerojet Rocketdyne remains the last large independent supplier of missile propulsion systems.[83] A trend toward fewer large contractors risks decreasing innovation while introducing additional vulnerabilities into an already brittle supply chain.

Stifling Regulations

Beyond the research and acquisition process, companies that seek to produce energetics and munitions face a tangled web of environmental and safety regulations. When new facilities are planned, environmental reviews often drag on for years, creating uncertainty and compounding the risk that investors will cut their losses. These regulations act as barriers to entry for start-ups or even established companies that seek to enter the market. As a 2022 DoD report, *State of Competition within the Industrial Base*, explains:

> The costs to enter the M&M market are higher than other sectors due to the nature of weapon systems—particularly as safety requirements add additional layers to the design of equipment and/or facilities. For example, any company storing or using energetic materials requires larger property investments, due to quantity-distance limitations and explosion-proofing of equipment and buildings. These additional costs, while necessary and appropriate, can heavily burden any entrant into the market.[84]

Our team spoke with a number of start-ups in the energetics space, and each indicated that regulation serves as a huge barrier to entry. While safety regulations are necessary in this space, the sheer scale of red tape has prevented the deployment of advanced energetics and threatens to reduce competition, erode production capacity, and stifle innovation in next-generation materials.

Next-Generation Energetics: Challenges and Opportunities

Since the development of RDX and HMX prior to World War II, the field of energetic materials has made only a handful of major breakthroughs. But advancements in adjacent fields, such as biochemistry and bioengineering, may offer opportunities for further breakthroughs. Discovery techniques include the use of artificial intelligence and machine learning tools to develop new compounds—an approach that has already sent shock waves through the pharmaceutical industry.[85] Advanced manufacturing techniques—including additive manufacturing, bioengineering, and biomanufacturing—could play a role in revolutionizing energetics production.[86]

The next breakthrough in munitions may come via nano-energetics—a field some have speculated could provide a two-times, five-times, or even ten-times increase in explosive power.[87] Such a breakthrough could open new possibilities for the US military, well beyond a further increase in the range and lethality of missiles. Strategist T. X. Hammes envisions a future battlefield characterized by swarms of thousands of miniature autonomous drones, each embedded with a powerful, yet tiny warhead made possible by nano-energetics.[88] Even less visionary breakthroughs, though, such as a cleaner and more cost-effective way of producing advanced energetics in bulk, could be potential game-changers for the United States.

But a lack of US investment in energetics means the next breakthrough could happen elsewhere. Between the fall of the Berlin Wall in 1989 and the 9/11 terrorist attacks in 2001, US investment in advanced munitions research, development, testing, and evaluation dropped by an alarming 45 percent.[89] Nearly two decades ago, Army scientist William Mattson warned that "energetics technology is an area where we have been surprised by foreign achievements in the past." He argued that, given investments by foreign nations, the United States would be "highly vulnerable in the field in the future."[90] In the two decades since, Mattson's warning has come to pass. China and Russia won the race to produce CL-20 and are deploying it in their weapons systems—despite the fact that the compound was developed in the United States. China in particular has produced CL-20 for over a decade.[91]

China maintains a dedicated energetics enterprise and provides significant state support for basic research. Beijing may be positioning itself to lead in the energetics of the future. As the ETC explains, the PRC has "governmental, semi-government, and commercial entities devoted to producing EM and heavily supports four top academic institutions to perform energetics research and develop their workforce."[92]

PRC support for its energetics sector is also evident in a review of the technical literature. According to data from the George-

Types of Rocket Engines

The different types of rocket engines can be divided into three main categories based on propellant type and function.

Solid

Fuel, oxidizers, and other additives are combined into bricks known as "grain." When ignited, the formulation deflagrates according to predetermined performance characteristics. This provides thrust until the material is exhausted. The bricks are highly reliable and provide rapid thrust. Their simple design also lends itself to large-scale production and long-term storability.

Further, engineers can arrange solid rocket motors in stages providing additional range, increased speed, or the initial thrust before the activation of another subsequent engine. But once a rocket is in flight, it is difficult to throttle or modulate the motors' thrust since the reaction cannot be easily stopped and restarted. These motors are the most widely used design, particularly in defense, propelling everything from Hydra rockets to Hellfire missiles and providing the thrust to boost weapons from vertical launch cells.

Liquid

Liquid propellant and oxidizers are stored in separate pressurized chambers. While in operation, the propellant is aerosolized before being combined with the oxidizer in the combustion chamber. The combustion chamber then ignites this mixture to produce thrust. While this system is more complex, the feeding system can be regulated, making it possible to terminate and restart the engine, enabling total control of the engine's performance throughout use. Engineers tend to use liquid propellant rockets in larger systems, such as the Space Shuttle's main engine or some Russian ICBMs. These systems have the inherent disadvantages of having to maintain the liquids, which increases cost and makes storage and operations more complex.

Hybrid

A hybrid design incorporates features of both solid and liquid propellant rockets, usually in the form of a solid fuel grain and liquid oxidizer. While designs have traditionally suffered from unstable combustion characteristics, some companies have demonstrated models that reduce these drawbacks through novel grain manufacturing techniques and other innovations.[93] So far, most examples of hybrid rockets have been in demonstration platforms and sounding rockets. However, Scaled Composites' SpaceShip One and SpaceShip Two have successfully made use of the design.[94]

town Center for Strategic and Emerging Technology, Chinese scientists have published almost seven times as many papers on energetics and related fields over the last five years than their American counterparts. Of the nine "clusters" of academic work our team analyzed, Chinese authors had written roughly 75 percent of the total papers. Where funding information was available, institutions affiliated with the Chinese government resourced the vast majority of these papers.[95] And Chinese scientists have begun to use advanced research techniques, including artificial intelligence and bioengineering, to pursue next-generation energetics. A team of Chinese researchers experienced in explosive and propellant design and safety will edit an upcoming special issue of the journal *Crystals* calling for submissions related to "Advanced Energetic Materials: Testing and

Modeling."[96] The United States has clearly fallen behind China and Russia in advanced energetics. To regain the initiative, the US needs a national strategy that prioritizes innovation in energetics and boosts production capacity across the industrial base. The US military cannot afford to cede the next energetics breakthrough to the PRC.

POLICY RECOMMENDATIONS

To bolster the munitions industrial base, and the energetics supply chain in particular, policymakers need to develop a national strategy across three lines of effort. The following measures should be key elements.

I. Provide clear lines of authority and responsibility within the DoD for the munitions and energetics enterprise.

- *Defense Department leadership should reestablish the Office of Munitions in the Office of the Secretary of Defense*. Currently, responsibility for the US munitions enterprise is fragmented across well over a dozen entities throughout the Department of Defense. The first step toward reforming the DoD's approach to energetics is to establish a coordinating body responsible for the munitions enterprise, including programming authority. Therefore, the DoD should reestablish the Office of Munitions.
- *The Office of the Secretary of Defense should commission a National Road Map for Munitions and Energetic Materials.* The first assignment for a newly reestablished Office of Munitions should be the creation of a national strategy to guide the development of munitions programs and energetics innovation and production. Such a strategy should "prioritize the development, transition, and integration of new EM into systems" and address aging supply chains and infrastructure.[97]
- *The White House and the Defense Department should detail several munitions and energetics experts to the Office of Science and Technology Policy (OSTP).* Staffers from the DoD's newly established munitions hub should be detailed

Photo Caption: EA-18G Growlers simultaneously fire two AGM-88 High Speed Anti-Radiation Missiles (HARM) durinaag a training exercise near Guam. (US Navy photo by Cmdr. Peter Scheu) to OSTP to directly inform key decision-makers of major developments regarding the industrial base for munitions and energetics. This arrangement would enhance coordination between the DoD and the White House on interagency programs that involve munitions, such as the use of the Defense Production Act.

- *The DoD should reassess the effectiveness and goals of insensitive munitions regulations.* Safety is critical, but extensive safety regulations have stifled innovation and the deployment of novel energetic compounds. The DoD needs to reduce regulations: it should conduct a Mil-Standard/Mil-Spec Review to update munitions regulations to be more specific and measurable and to reduce or eliminate unnecessary standards.[98] Performance should be balanced with safety.
- *DoD leadership should prioritize range, lethality, and capacity improvements in new and updated weapons systems.* At present, "no senior defense leader, product leader, or operational advocate is driving requirements for greater performance such as range, speed, effect, and size."[99] Existing weapons programs emphasize other factors, including safety, while others use "lowest price, technically acceptable" standards that do not allow for differentiation. A prioritization of improvements in the technical performance of munitions should also be coupled with continued developments in operational concepts and tactics.
- *The White House should issue an executive order directing federal agencies to assess the regulatory burden on producers of goods critical to national security, including energetics.* From semiconductors to batteries, lengthy environmental and safety reviews stifle American innovation and competitiveness in critical sectors. The energetics enterprise is no different: start-ups our team spoke with noted that environmental and safety regulations impose a significant barrier to entry. The White House should direct executive agencies to conduct an assessment of the regulatory burden on strategic industries and report within 120 days.

II. Invest in munitions, energetics, and precursor chemical production to send a clear demand signal to the private sector.

- *Congress should require the DoD to increase the size of the US military's preferred munitions stockpile.* American experiences in recent conflicts, such as Operation Inherent Resolve in Syria, have demonstrated higher-than-anticipated demand for PGMs. In a high-intensity conflict, the US could exhaust its inventories in a matter of weeks. An expansion of munitions inventories would also provide a clear demand signal to suppliers, helping jump-start energetics production.
- *Congress should provide funding to the DoD to increase supplies of energetic materials in the National Defense Stockpile*. Until additional production facilities for energetics come online, stockpiling is the best way to mitigate vulnerabilities in the supply chain. The Defense Department's 2023 budget request currently includes $253 million to procure critical materials via the National Defense Stockpile. The DoD should direct a portion of this funding toward energetic materials and the munitions enterprise.[100]
- *Congress should create an investment vehicle to boost production in energetics and other critical sectors.* The US needs to invest in capital-intensive production facilities for technologies relevant to national security. One proposal, the Industrial Development Finance Corporation Act, would create an investment vehicle to "[assist] U.S. manufacturers needing capital scale expanded operations, invest in upgraded plant and capital equipment, pursue R&D and innovation efforts, and strengthen domestically sourced supply chains."[101] As lawmakers consider various pieces of legislation related to supply chain resiliency, they could include programs to boost production capacity for munitions and energetics.
- *The DoD should work to divest government operations in the production stage for munitions and energetics, instead pursuing a public-private partnership model.* The DoD has successfully developed a variety of alternative acquisition

pathways for critical technologies, but few, if any, of these programs address energetic materials. Partnering with start-ups in the space, aerospace, and defense industries—as well as deepening collaboration with NASA and the national lab network—would allow the DoD to harness private sector and academic innovation in energetics, including in solid and hybrid rocket motors, and develop needed surge capacity.

- *The DoD should construct several pilot-scale plants to address critical vulnerabilities in the energetics supply chain.* The United States desperately needs to bring its industrial base for energetic materials into the twenty-first century. Building pilot facilities, with flexibility to produce different materials as the need arises and eventually to pivot toward next-generation energetics, is the first step toward system-wide modernization and expansion. According to a 2020 defense industrial base assessment, these plants would "provide the capacity to address multiple critical obsolescent energetic materials within the organic industrial base, guaranteeing availability of these legacy materials as needed. These Pilot-Scale Plants would also provide a stable pipeline for rapid scale-up of next generational energetic materials."[102]
- *AUKUS should create a trilateral line of effort centered around munitions and energetic materials*. AUKUS is a trilateral defense agreement that includes Australia, the United Kingdom, and the United States. The White House has announced that the pact will include eight lines of effort related to advanced defense-related technologies.[103] Given that Australia announced a $1 billion investment last year to create a domestic precision-guided munitions enterprise,[104] the White House should deepen collaboration by creating an additional line of effort centered around joint stockpiling and production for PGMs as well as advanced energetics research.
- *The State Department and Commerce Department should loosen export controls for munitions, energetics, and related components and software on the US Munitions List.* US producers of munitions and energetics are subject to extensive export controls, including the International Traffic in Arms Regulations' (ITAR) US Munitions List. By loosening controls to include trusted allies, the US could enhance the defense capability of allies while creating new markets for energetics producers. Policymakers should consider loosening these controls and granting additional export licenses to trusted allies. Officials attempted to loosen these controls in 2018 by expanding the National Technology Industrial Base (NTIB)—a grouping of trusted US allies—but progress has stalled. AUKUS could provide a forum to discuss export controls and further reform of the NTIB.[105]

III. Drive innovation in energetics testing and evaluation, discovery of materials and concepts, and manufacturing processes.

- *The DoD should boost R&D funding for advanced energetics.* Weapons system program offices should directly manage some funding, which would grant them additional leeway to take risks in developing new compounds that could boost performance. The Office of Munitions should manage most funding to drive energetics experimentation and prototyping.[106]
- *The White House and DoD should announce multi-year purchase agreements to encourage private investment in munitions and energetics production.* Purchase agreements are commitments that the US government will buy a certain number of products over a set amount of time. This would provide the clear demand signal that the munitions and energetics enterprise lacks, reducing risks for start-ups and other small and medium-sized firms and helping to funnel capital toward production. Such agreements and related actions should incorporate risk-appropriate pricing and other terms that would encourage private investment. Title III of the Defense Production Act grants the White House and DoD authority to enact purchase agreements.
- *Assign a portion of Small Business Innovation Research (SBIR) funding specifically to fund energetics discovery in-*

novation and new manufacturing approaches. The Small Business Administration provides SBIR and Small Business Technology Transfer (STTR) grants to plug start-ups into the US R&D ecosystem. In the energetics realm, restrictions on export and transfer force start-ups to sell to the DoD as a single customer, making SBIR crucial to their survival as a company. Apportioning a certain percentage of annual SBIR funding to energetics—ETC recommends $50 million over five years—would provide more stability for small firms and help them scale their businesses.[107]

- *The DoD should create an Energetics Workforce Development Plan to produce and acquire experts in the field*. This plan would focus on both short- and long-term developments to maximize readiness and stability. One aspect may be supporting academic institutions in expanding relevant degree programs and subsidizing research into new energetic compounds for future defense applications.[108] Further, incentivizing top intellectual talent with improved compensation and reduced hiring barriers could attract new talent and support retention efforts.[109]
- *In collaboration with NASA, the Department of Energy, and the National Labs, the DoD should create a public-private partnership focused on energetics innovation*. Such a program would enhance collaboration between the energetics programs scattered across the executive branch, bringing together scientists and researchers from diverse disciplines with top scientists and engineers from start-ups and defense primes, allowing the DoD to harness private sector and academic innovation in energetics—including in solid and hybrid rocket motors. It could build on the work of the National Armaments Consortium (NAC) program, a network of more than 900 engineers, researchers, and technologists focused on driving innovation in munitions and energetics.[110]
- *The DoD should conduct additional simulations to determine how shortages of key energetic materials would affect munitions production*. Over the past few years, the DoD has gleaned insights into vulnerabilities in the munitions industrial base by conducting "war room" simulations. Because these exercises require huge amounts of data and labor, they have been limited thus far "to only the highest risk items."[111] Congress and the DoD should fund additional war room exercises that simulate a loss of access to critical energetics.
- *DARPA should commission a program that uses adjacent technologies, such as artificial intelligence and machine learning, to discover and synthesize novel energetic compounds.* The use of AI and ML to discover new biochemical and other compounds is a rapidly emerging field that is generating considerable interest.[112]
- *The DoD should integrate energetics modeling and simulation with the test and evaluation environment*. Energetics must undergo a rigorous qualification and testing process before deployment in weapons systems. This process generates data that would be immensely valuable to researchers. Integrating these processes with modeling and simulation would allow energetics researchers to more fully leverage data sets that have already been created.

CONCLUSION

Energetic materials are found in almost every weapons system on the modern battlefield, and their role as explosives and propellants makes them critical for munitions. US military planners have pointed out that, in a potential conflict between the United States and China, the DoD would require huge amounts of precision munitions to deny the aims of Chinese aggression and achieve US objectives at moderate levels of risk. Improved energetics provide enhanced range, increased lethality, and decreased munition size—all key advantages that could help the DoD's operational concepts become realities.

Yet the munitions industrial base, and the supply chain for energetics in particular, have grown dangerously brittle. This has been made apparent by the war in Ukraine, where US provision of munitions to the country has led to shortfalls in the US arsenal.[113] Likewise, US TNT imports are threatened due to the loss of a major supplier based in Ukraine.[114] A lack of surge capacity means that the DoD will face serious key munitions shortages if a conflict becomes protracted. Compounding the issue, the department is not currently organized to invest in munitions and energetics production and generate a consistent demand signal. A broken business model and the lack of a clear pathway to deploy advanced energetics on the battlefield discourage private investment, while the talent pool continues to shrink. And extensive safety and environmental regulations create huge barriers to entry for innovative new players.

Photo Caption: The guided-missile destroyer USS *Mustin* (DDG 89) fires a Standard Missile 2 missile from the ship's forward and aft missile decks during a missile exercise on September 20, 2012, in the Pacific Ocean. (US Navy photo by Mass Communication Specialist 2nd Class Devon Dow)

Addressing these issues will require an ambitious strategy with three lines of effort, as outlined in this report. First, the DoD needs to create a central authority with responsibility for the entire energetics enterprise, and then alter munitions regulations to incentivize performance improvements. Second, policymakers should make investments and create incentives that encourage investment in the munitions and energetics enterprise. Third, Congress and the DoD should provide additional funding for next-generation energetics R&D, modeling and simulation, and pilot programs for advanced manufacturing techniques.

Without investments in energetic materials and munitions, the US military could face shortages during a protracted conflict, and it will continue to fall further behind the PRC in energetics innovation. Ensuring the US has the resources it needs to fight and win begins with shoring up the defense industrial base. Munitions and energetics are a vital part of this effort.

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