

Working Paper

Critical Minerals and Materials Geoeconomics: Lessons and Ideas from Past Wars and Strategic Competitions

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Gabriel Collins and Michelle Michot Foss

Executive Summary

"... you can't make bullets out of gold."

— President Dwight D. Eisenhower, 1957¹

While gold is not the material for physically manufacturing implements of war, economic power coupled with creative thinking is an essential precursor for victory in warfare regardless of whether it is industrial/economic in nature or kinetic conflict. Imaginative policy executed at scale has helped ensure US critical minerals security in past wars and strategic competitions. This brief report outlines ten goeconomic experiences and ideas that were either used by previous generations of American leaders or new concepts which likely are applicable today. Where possible, these approaches emphasize channeling market and technological forces to maximize returns on taxpayer dollars obligated.² Each of these experiences hold lessons for a new generation of American policymakers who once again face global competition with industrialized, highly capable adversaries.

Defense occupies a much-reduced share of total US materials demand than during the enormous World War 2 buildup. Indeed, the post-war ramp down of defense-related domestic material and mineral supply chains and manufacturing for much of the period between WW2 and the present time helped set the stage for contemporary concerns about security and readiness. The post-1991 "Peace Dividend" geopolitical window opened by the fall of the Soviet Union further removed policymakers' thinking from the reality that victory in a protracted industrial war requires a country to be able to sustain both military needs and a significant portion of pre-war civilian economic activity levels.

Yet unlike the 1991 to early 2000s window, the US now faces multiple industrially capable competitors in a loose axis headed by China and Russia. The return of Great Power competition matters because protracted war is the historical norm when industrial powers clash, a lesson being renewed and hammered home by the past three years of bloodshed in Ukraine.

Furthermore, killing technologies have in many instances evolved, as have their materials consumption profiles.

The humble and vitally important 155mm artillery shell has not changed much in terms of physical dimensions or materials requirements per unit during the intervening 80 years. But much else has altered on air, land, and sea battlefields. In the maritime domain, a modern DDG-51 destroyer consumes approximately as much fuel as a similarly sized World War 2 light cruiser under many operating regimes. Other machines have become far more fuel intensive. A P-51 Mustang takes off under full power at a fuel flow rate of 120 gallons per hour, while an F-16 Viper with an afterburner engaged for the same takeoff could burn approximately 130 gallons in a single minute.³ Land combat has also become an order of magnitude more supply-intensive. An American division engaged in active combat in the WW2 European theater could consume 600 to 700 tons/day of supplies.⁴ By the 2010s, mechanized US divisions could consume more than 6,000 tons per day of supplies.⁵

As the demand for mass in warfare reasserts itself, creating and sustaining today's combat mass requires many materials that our grandfathers' wars did not. The vast shifts in technologies, with more on the way, have placed a premium on new alloys and advanced materials for high performance gear and weapons systems. No World War 2 aircraft used meaningful amounts of titanium in their airframes and fabrication of even Vietnam-era fighters and strike aircraft typically only required hundreds of pounds of titanium ("buy weight").⁶ By the 1990s, each tactical aircraft produced necessitated the purchase of tens of tonnes of titanium — an order of magnitude increase.⁷

Likewise, aircraft ordnance in World War 2, Korea, and to a substantial extent, Vietnam, required steel, high explosives, lead, and some copper. Fast forward to the present and key munitions like standoff strike missiles still need lots of steel and explosives but also require a smorgasbord of other materials ranging from titanium to rare earths, to composites and complex additive manufactured materials, and exotic electronics inputs like gallium and indium. Warfare's newest mass addition, drones, face similar challenges. The materials inputs for ten million drones containing explosives but also composites, servo motors, semiconductor packages, and so forth is something WW2, Korea, Vietnam, and Gulf War 1 and 2 never featured.

Concurrently with rising materials intensity in key military hardware, technological lines have blurred in important ways. Computing, geopositioning, and telecommunications all reflect the reality that *materials and manufacturing supply chains that serve defense industries make a first stop at off-the-shelf consumer products*. This has critical implications for industrial war because securing direct military requirements alone will likely prove insufficient to prevail.

Semiconductors — where US Department of Defense, DoD, procurement constitutes perhaps 2-3% of the civilian market — offer an example. So does oil, where DoD use even during recent wars accounted for less than 3% of total US refined products consumption. Another example is cobalt, a strategic metal that is, among other things,

critical for the superalloys used in jet engines. Direct military uses likely account for less than 10% of total world demand, with the balance used in commercial, civilian products.⁸ Likewise, during Vietnam, the United States' second most ammunition-intensive conflict to date after WW2, military usage of copper (an important ammunition raw material) never exceeded 7% of total domestic copper demand. But a shortage of copper would nonetheless have seriously impeded war efforts by forcing tougher “guns versus butter” decisions on policymakers.

*More complicating is the dominant position China occupies in supply chains for key non-fuel minerals and the materials and manufactured components derived from them that are essential for defense – a unique circumstance.*⁹ By contrast, the US holds a position of strength in oil, natural gas, the petrochemicals sourced from hydrocarbons – including carbon fiber and plastics, resins, and advanced composites. Plastics and resins altogether are the fastest growing commodity group worldwide. Defense needs for these materials are the subject for a follow on working paper.

Supply Chain Challenges: Balancing the Legacy and the New

Traditional, legacy metals remain vital. On that front, however, the state of affairs for the global mining industry, in particular in the US and Europe, is precarious.¹⁰ Worldwide, mining and minerals processing and finishing assets are mature, with falling ore grades, rising operating costs, and sustainability metrics (including energy, water use, and emissions) that reflect that maturity. Mines and smelters are built to last, but lack of new capacity means that older facilities must run. Achieving new investment is burdened by diminishing quality of new opportunities; logistics hurdles and higher costs for higher quality but remote targets; the gamut of pressures aggregated in “ESG” (environment, social, governance) parameters; and rising political risks, not least “resource nationalism” expressed in myriad ways¹¹. All of these harsh realities, and more, contribute to longer cycle times and levels of risk/uncertainty that simply make mining projects unacceptable to capital markets.

There also is the aforementioned, sharp geopolitical angle: China occupies a position of dominance in materials supply chains and manufacturing that is orders of magnitude beyond what Axis powers commanded during WW2 and other conflicts. China's vast minerals production and processing, encouraged by Western nations in order to bring China into the club of industrial economies, creates comparative advantages not only in physical inventory and capacity but also in intellectual property. Where China faces weaknesses – for instance in supply of conventional petroleum fuels and natural gas for both civilian and defense uses – Beijing is constructing partner arrangements that constitute “a rival camp”, an axis equivalent, to many minds.¹²

Intensifying economic warfare between the US and People's Republic of China, PRC has crossed into the critical minerals realm. In 2010, China withheld supply of rare earth

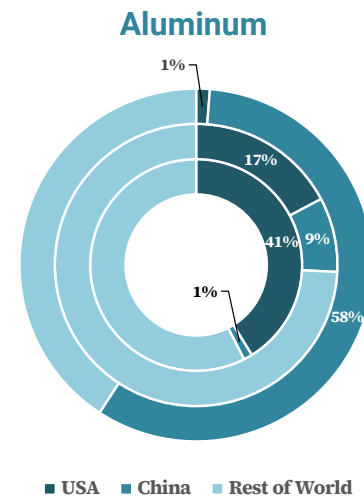
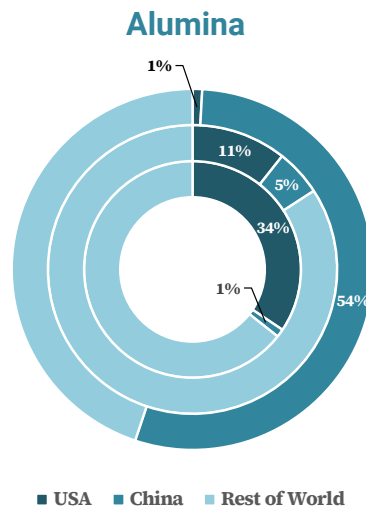
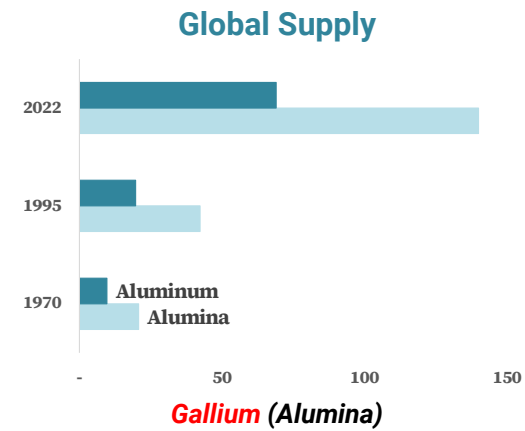
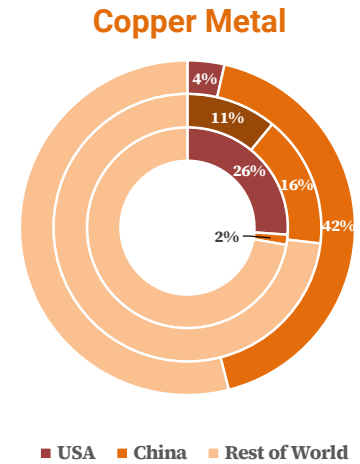
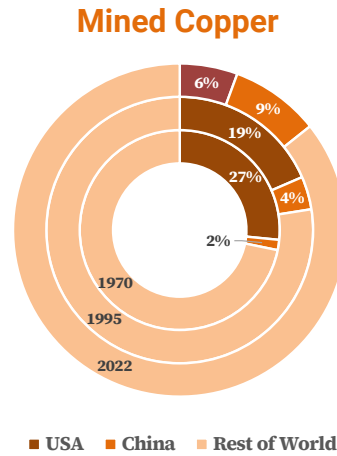
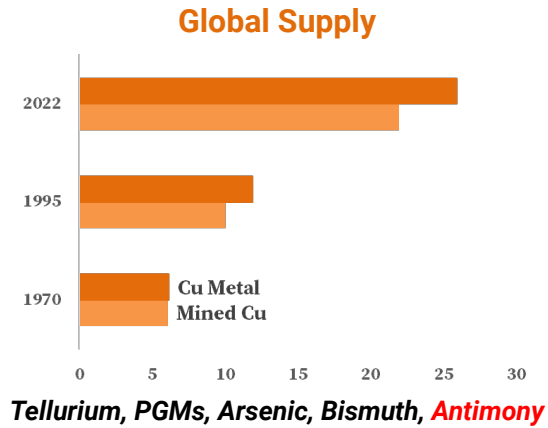
compounds, rocking Japan and Korea and sending an early signal on potential disruptions to come.¹³ In 2023, China began restricting exports of gallium, germanium, and graphite – ostensibly in response to US export controls on advanced semiconductors and associated technology to Chinese firms.¹⁴ In August 2024 China add antimony to the export restrictions list and it is possible that tungsten could be added next.¹⁵ In November 2024, China’s Commerce Ministry banned the export of gallium, germanium, antimony, and superhard materials to the US while also imposing additional restrictions on shipments of graphite.¹⁶ In February 2025, China imposed a raft of additional restrictions in response to US tariffs.¹⁷

Beijing’s creeping restrictions at a basic level rhyme with the Soviet Union’s decision in 1948 to restrict exports of chromite ore and manganese that many Western countries had hitherto depended substantially upon.¹⁸ Moscow’s decision was likely predicated in part on US restrictions on goods exports to Eastern Europe imposed earlier in 1948 (just as China can claim its restrictions are in response to US semiconductor export controls).¹⁹

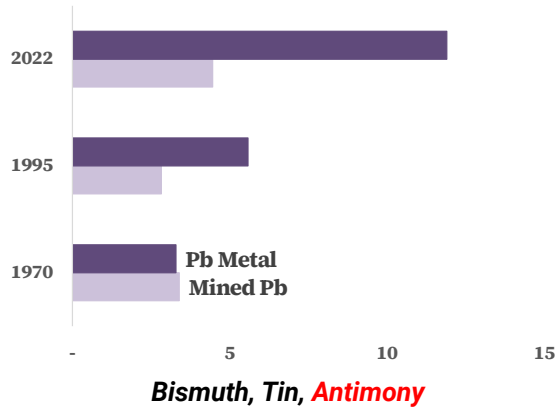
But unlike manganese, for which the US had developed alternative supplies during World War 2 after the German invasion of the USSR crimped exports, the materials and minerals that China is now mobilizing for geoeconomic leverage are not so easily obtained elsewhere. Furthermore, while the Soviet Union and Warsaw Pact controlled mineral resources within their own borders, they did not maintain a large presence in mining and processing assets abroad. China is the opposite, with Chinese firms ubiquitously present globally as owners/investors/operators throughout key mineral supply chains including cobalt, nickel, rare earths, and others.²⁰ As well, China has built domestically based processing capacity that enables them to control feedstocks of concentrates worldwide. Nearly every mine operator sends output to China for processing.

As a result, China’s shares of major finished metal output are massive – 42% with a possible doubling for copper, 52% of zinc, 44% of primary lead, 54% of alumina and 58% of aluminum – give it control of byproducts that drop out of refining and smelting such as the restricted elements gallium, germanium, and antimony (**Exhibit 1**). China also built and expanded capacity to extract essential elements that have grown in importance with high tech, such as rare earth elements, natural graphite, and manganese. Finally, China’s sheer ability to ramp up vast scale both at home and abroad has riled markets and undermined attempts by the US and other governments to gain or regain competitive footing. Nickel and cobalt are prime examples, with projects in the US, Australia and elsewhere rendered uneconomic by China’s large investments.²¹ China’s enormous scale economies facilitate not a small measure of influence in thinly traded metals markets. That influence has triggered increasing suspicions that China could, and has, put downward pressure on commodities prices to discourage competing investments elsewhere and maintain its market power.

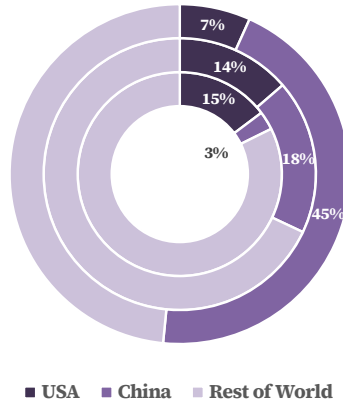
Exhibit 1 – Market Shares for 4 Key Metals Groups and Indicated Co-products



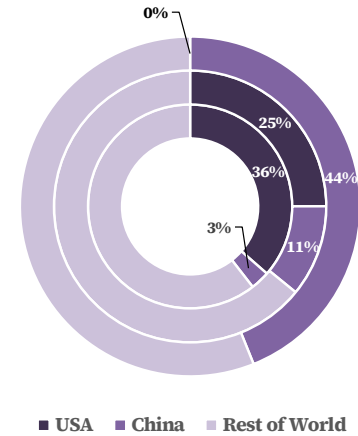
Global Supply



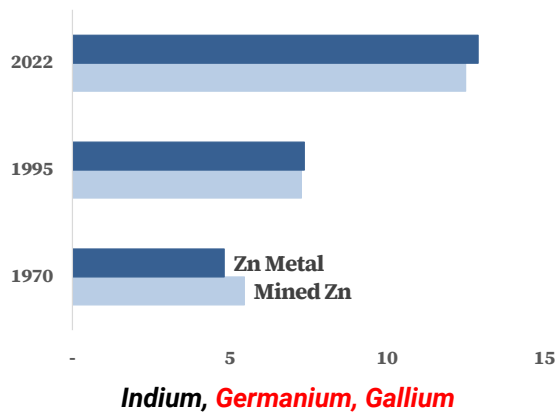
Mined Lead



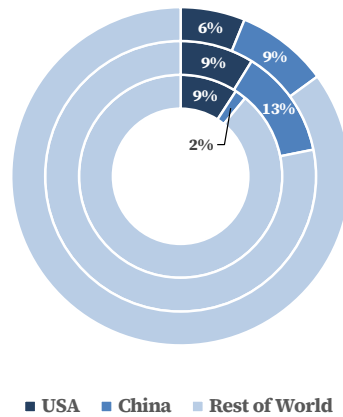
Lead Metal



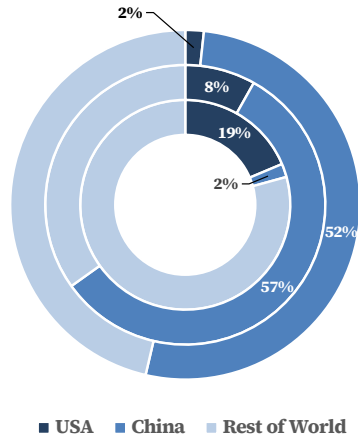
Global Supply



Mined Zinc



Zinc Metal



Source: Michot Foss, 2024²² after M.S. Moats. Global supply and market shares based on US Geological Survey, USGS data, all in millions of tonnes.

Note: Chinese export control actions.

For all of the worries about China, which generally coalesced as governments rolled out post-pandemic “new green deal” recovery plans²³ it was Russia’s invasion of Ukraine that hit home on materials supply chain weaknesses for defense. Minerals and materials security for national defense is now firmly intertwined with industrial policy, for better or worse, and in spite of persistent questions about priorities and tradeoffs. Moreover, new risks and considerations are shifting as China’s economic trajectory evolves and shifts onto a slower growth path.

Assembling the Modern Mineral and Material Geoeconomics Toolkit

Given context and where we stand today, dusting off old but useful minerals geoeconomics tools and responses and assessing how they might apply under modern fact patterns – and be updated when needed – is an essential exercise. Manufacturing and industrial prowess directly facilitate production of the physical mass needed to deter war and if deterrence fails, ensure sufficient regenerative capacity to prevail in what could readily become a 3-to-5 year or even longer term armed struggle for supremacy.²⁴ To that point, the potential approaches we describe in this report are in many instances tailored not to outright armed conflict, but rather to the economic shadow warfare that is already underway between the US and PRC and which will likely endure in various forms for many years and decades to come.

These options are arranged in the approximate order of deployment, with each successive response becoming more important as competition potentially intensifies into actual warfare. Options like preclusive purchasing and, especially, sabotage would most likely be employed in situations where kinetic conflict has already commenced or when competition and confrontation have intensified to the point where escalation to kinetic conflict is assumed to be the next logical evolution.

In Table 1 below we propose a basic taxonomy of the materials and minerals geoeconomics toolset.

Table 1 – Minerals and Materials Geoeconomics Taxonomy

Geoeconomic Tools	Unintended Consequences of Historical Experience	Go Forward Options
<ul style="list-style-type: none"> • Stockpiles • Production partnerships • Preclusive purchasing • Ownership displacement 	<ul style="list-style-type: none"> • Smuggling (black markets) • Sabotage of adversary assets 	<ul style="list-style-type: none"> • Brownfield locations for processing • Recycling • Infrastructure investments to facilitate supplies • Advanced materials development

Note: Most of these require meaningful degrees of US Government, USG, facilitation and/or funding including, when appropriate, aspects of “minerals diplomacy”.

Geoeconomic Tools

Geoeconomic tools entail overt strategic and tactical actions that USG entities can undertake to ensure and improve minerals and materials supply chain resilience.

Strategic Stockpiling

Strategic stockpiling gets considerable airtime as a solution not only for the US but allies. However, a range of questions permeate notions of expanding stockpiles. These include access for civilian, commercial use which, given the blurred lines between civilian and defense industries for many technologies and products, is a distinct issue. Commercial access would require amendments of enabling laws and regulation for defense stockpiles, creating potential conflicts of interest and the potential for market interference. Commercial access could serve as a source of internal tension if defense uses had to take priority and civilian manufacturing supply chains became overly dependent on defense stockpiles.

Another major quandary is what to stockpile. Many sensitive minerals and materials are used for civilian and defense products that the US no longer manufactures or for which we no longer have a manufacturing edge. Thus, many of the critical minerals of concern are imported in the form of manufactured components rather than as raw materials. A prominent example, addressed later, are magnets bearing the rare earth element neodymium. Notably, neodymium-iron-boron or NdFeB magnets resident in fighter jets and missiles also are used in wind turbine generators, illustrating the crossover between applications. Many manufactured components have limited shelf lives as technology continues advancing. Moreover, stockpiling gear – from LED screens to smart phones and drones – for defense is more expensive and highly subject to shelf-life deterioration, especially in software control systems.

Stockpiling entails acquisition, storage, and distribution – logistics that, for defense, are still in contention when it comes to US government control and authority. Rivalries have long existed between the mainline US Department of Defense and armed forces service branches as well as among the service branches. Past attempts to resolve inefficiencies and intra-agency conflicts have largely failed to quell differences of opinion.

Last, stockpiling means selecting locations that can support engagement outside of the US for both raw materials and defense materiel. Given that much of what DoD depends upon is manufactured abroad, key feedstocks would need to be located where vital manufacturing will continue to reside until that capacity is “reshored” to the US (if it ever is). When it comes to defense materiel, equipment, components, arms need to be accessible to locations of engagements. US DoD and service branches have robust supply chains for distribution in Europe. Sheer distances across potential nodes and flashpoints such as Northeast Asia and South China Sea shipping lanes make the “Indo-Pacific” region as demanding as it ever has been when it comes to strategic locations for defense stockpiles.²⁵

Stockpiling: Historical Lessons and Contemporary Ideas

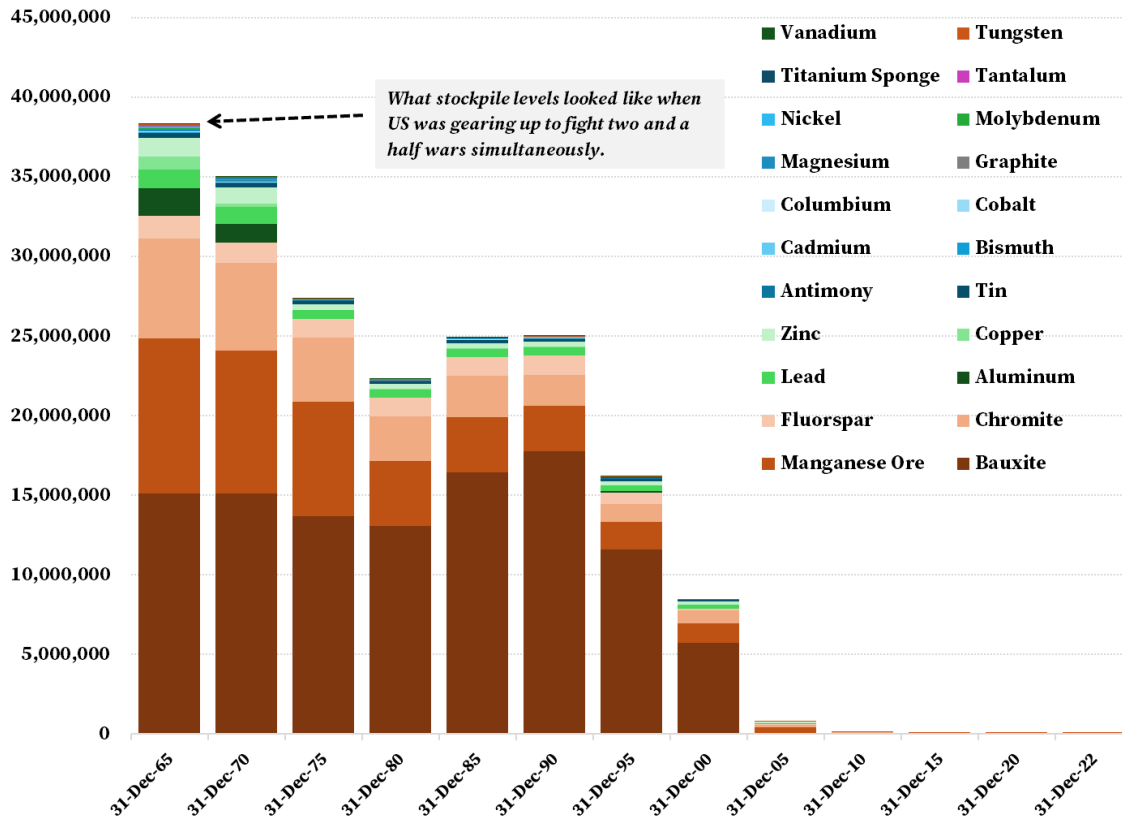
In theory, strategic stockpiling of critical commodities can create a cushion of operational space and time in which to prosecute the initial stages of a conflict. This should allow adaptation to the changed strategic circumstances and can facilitate developing alternative supplies through substitution or technological innovation. In 1939, the United States Congress passed the Strategic and Critical Materials Stockpiling Act, marking the inception of the National Defense Stockpile program and its mandate to “...maintain and manage strategic and critical materials for use during times of national emergency.”²⁶

Events dragged the US into World War 2 before the government was able to meaningfully stockpile critical mineral inputs such as chromium, manganese, nickel, rubber, and tin. Through a combination of actions including Hemisphere-wide commodity purchasing, preclusive buying of resources, establishment of sea lane control, and urgent expansion of domestic mining and processing, the US was able to successfully supply its Arsenal of Democracy. Victory notwithstanding, policymakers wanted to hedge against future exigencies with a significantly expanded national strategic commodity stockpile.

After the searing experiences of World War 2 and then the Korean War a scant five years later, US policymakers adopted stockpile estimates that were fundamentally predicated on ensuring “... the ability to respond to two and one-half conflicts at one time—that is, war with the Soviet Union in Europe, war with the Peoples Republic of China in Asia, and a “half-war” with another regional state, in this case Vietnam.”²⁷ This planning approach, which confronted a set of international security challenges reminiscent of the mid-2020s, led the US government to build substantial stockpiles of ores, metals, and other

materials covering anywhere from one to several years of peacetime demand (**Exhibit 2**).

Exhibit 2 – Quantities of Selected Key Commodities in US Government Stockpiles, Tonnes



Source: Collins, based on USGS historical reports, USGS Commodity Reports (1993-present).

Comparing the massive Cold War peak stockpiles with the precipitous post-Cold War drawdown and, at present, near lack of high-volume strategic stocks suggests the US is not postured for the threats we now face. Volume alone is not a full measure for an economy that uses millions of tonnes annually of base metals like aluminum but might require eight-to-nine thousand tonnes of cobalt or just tens or hundreds of tonnes of other items like germanium or indium.²⁸ But even stockpiles of these small volume, high-value “vitamins of the industrial world” have dwindled and in some cases been sold off entirely in the past 10-to-15 years.

Rebuilding stockpiles of critical minerals to cover at least 12-to-18 months of expected demand should be a critical near-term strategic priority. In some cases, this will require market purchases, which will likely need to be phased in over time to avoid inflating

prices and disturbing commercial activity while effectively trading against ourselves. In other cases, it may require government backing for offtake agreements that underpin mine development and that are primarily sold into the commercial market, but where the Defense Department could finance private firms' holding extra inventory of key metals/materials.

US officials also have the option of utilizing barter to obtain materials so long as doing so is "...authorized by law and is practical and in the best interest of the United States."²⁹ Titanium, a vital aerospace metal for which the US presently holds no national strategic inventory and whose supply chain vulnerability has been illustrated by the Russia-Ukraine war, presents one such potential case. Ukraine is one of the world's larger titanium sponge producers and badly needs artillery shells to defend itself against Russian aggression. If titanium sponge is worth \$6,000 per tonne and the US needs 35,000 tonnes for its national defense stockpile, that equals \$210 million of financial value. If the US government priced artillery shells at \$250 apiece (discount for an ally), 840,000 shells could be provided in exchange for a volume of titanium sponge sufficient to cover a year of US needs.³⁰

Public-Private Production Partnerships

For low-volume, high-value minerals, government funding for the construction of backbone infrastructure like processing plants able to support multiple private producers may be essential. The pervasive presence of state-supported Chinese entities along key mineral value chains such as rare earths and cobalt create a stark situation that Australian mining executive Angus Barker describes as follows: "*China can shift value anywhere in its vertically integrated supply chain to quash incipient competition.*"³¹

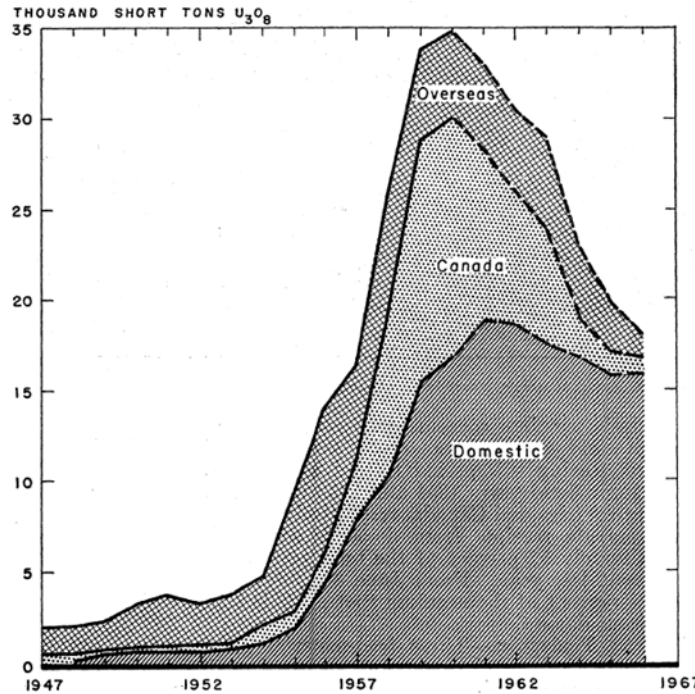
Chinese producers' behavior in the lithium market has attracted US government attention as a case in point. Jose Fernandez, former undersecretary for economic growth, energy and the environment in the US Department of State, noted in an October 2024 press briefing that the US government believes China is overproducing lithium in order to "...lower the price until competition disappears" with the intent to undermine supply diversity initiatives, and ultimately, competitively erode the \$369 billion US Inflation Reduction Act.³² Faced with such credible threats, private sector capital sponsors hesitate to fund mines, processing, and in the case of rare earths, magnet manufacturing plants. The fear is that a price assault that is intentional (authorized by Beijing) or not (in industries known for lumpy capacity additions that destroy price and value) will destroy the value of a newly acquired or built asset.

One successful example of targeted government intervention to minimize the impacts of price volatility and unlock private capital participation in both mining and processing comes from the Atomic Energy Commission's ("AEC") actions in the early Cold War to boost domestic uranium production and processing capacity. Between 1947 and 1970,

the AEC sponsored road construction to allow prospectors to access new areas of the American West for uranium exploration (especially on the Colorado Plateau), purchased uranium ore, and purchased uranium concentrate from mills at guaranteed minimum prices to de-risk projects and encourage private firms' participation.³³

AEC sponsorship initially aimed to ensure a domestic supply base for the United States' rapidly expanding nuclear weapons complex. The program ended up being sufficiently successful that the agency had to redefine its approach to allow uranium sales to private customers (i.e. electric utilities) and prevent further expansion of production based on what had previously been an "essentially unlimited purchase commitment."³⁴ For a sense of the scale-up velocity, consider that in 1950 the AEC purchased only about 650,000 pounds of uranium oxide from mills—about enough in volumetric terms to fill a single 20-foot shipping container.³⁵ By 1959, this volume had grown 46-fold and helped diversify US uranium supplies that previously had been largely obtained outside of North America and which had caused substantial strategic anxiety (**Exhibit 3**).³⁶

Exhibit 3 – Domestic and Foreign U3O8 Procurement, 1947-1966

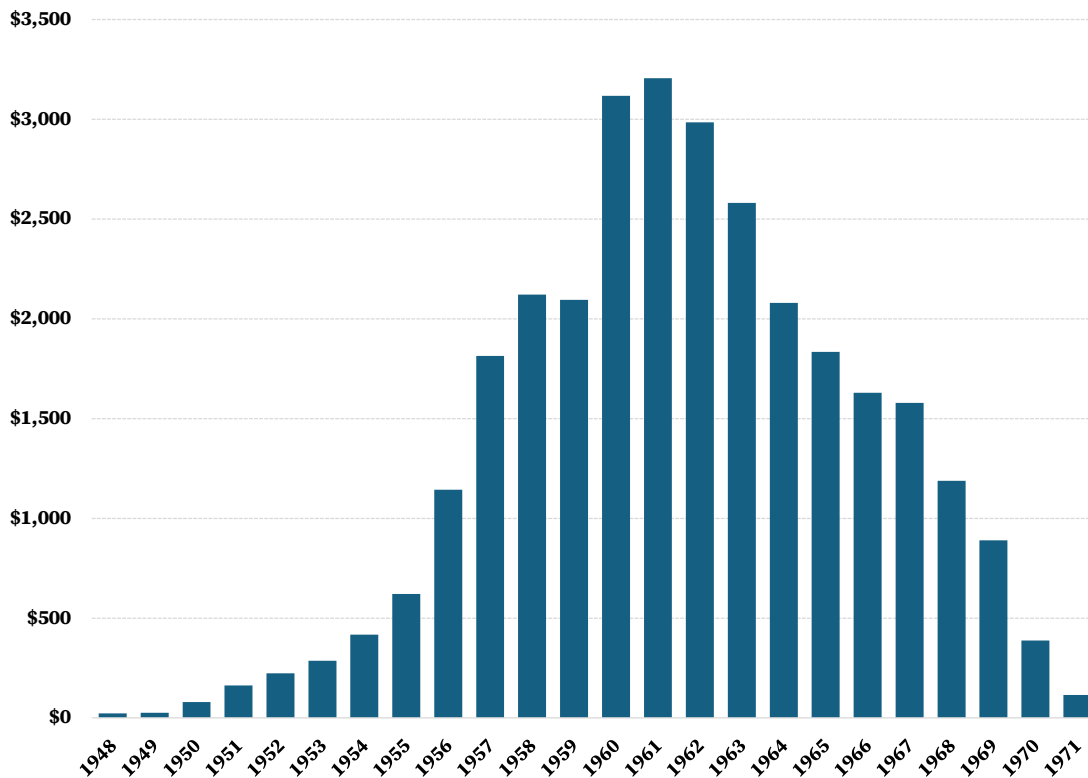


Source: USGS, 1960.³⁷

Over its lifetime, the AEC's uranium purchase program spent more than \$30 billion (inflation-adjusted to January 2025 dollars) to procure uranium oxide (**Exhibit 4**). We point this number out to provide perspective given that a rare earth magnet plant likely costs between \$50 and \$100 million. Indeed, in 2024 MP Materials received a Section 48C Advanced Energy Project tax credit worth \$58.5 million to initiate construction of its

NdFeB magnet plant in Fort Worth, Texas.³⁸ It is likely that the US can make targeted official interventions to incentivize construction of key mineral and material supply chain facilities and protect them from predatory PRC practices for amounts that are substantially less than what we spent to ensure supplies of a single critical mineral during the Cold War.

Exhibit 4 – AEC Annual Expenditures on U3O8 Purchases, Million USD³⁹



Source: Collins based on Albrethsen and McGinley, 1982.⁴⁰

Note: Reported figures adjusted to January 2025 levels using CPI from January of each fiscal year.

Preclusive Purchasing

Preclusive purchasing emphasizes two core objectives. First, it aims to deny adversaries physical access to necessary raw materials. Second, and related, by absorbing supplies it seeks to drive up commodity prices and impose additional costs on adversary economies.

Preclusive purchasing is in many ways a form of economic attrition warfare. The US government acknowledged as much in describing the United States Commercial

Company, which was created in 1942 to “...compete in neutral countries, such as Spain, Türkiye, and Argentina, with enemy powers for the purchase of any material that might be of use to the Axis Nations... This company will sustain proportionately heavy losses.”⁴¹

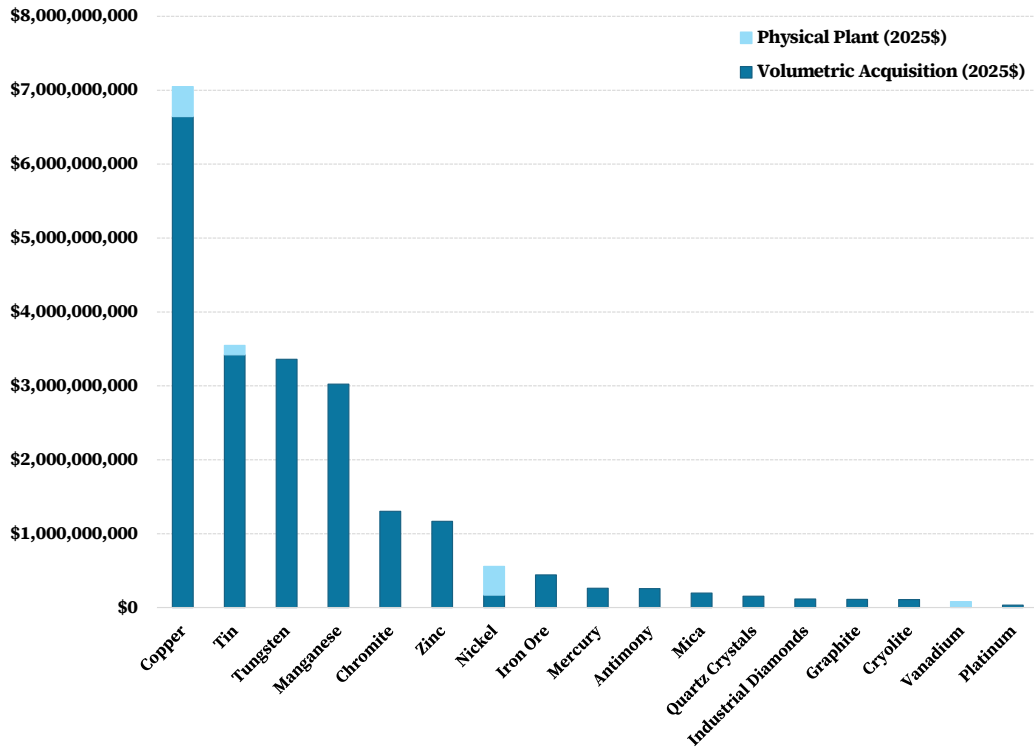
World War 2 offers the richest historical examples of preclusive purchasing. The approach became important as the US-led allies mobilized their massive combined economic base against an Axis system whose “blitzkrieg economy” was suited for resourcing a short, sharp war but not a protracted industrial one.⁴² In this section we briefly assess four World War 2 preclusive purchasing case studies covering multiple Latin American countries; China, Portugal and Spain; and Türkiye.

Latin America

As war loomed, American diplomats began frenetically working to lock up critical minerals supplies in the Western Hemisphere, lest they find their way into the Axis Powers’ war machine. Over an approximately two-year period, the Metals Reserve Company (a subsidiary of the government’s Reconstruction Finance Corporation), committed to purchase about \$3.2 billion in minerals, the bulk of which lay in Latin America.⁴³

These commitments, worth nearly \$60 billion in today’s dollars, imposed destination restrictions on where minerals could be shipped (**Exhibit 5**). In exchange, Latin American producers received stable, multi-year purchases of the metals and minerals they mined as well as promises, in some instances, that if the Metals Reserve Company signed more favorable agreements with subsequent sellers they too would be granted improved terms.⁴⁴ These MRC agreements helped anchor supplies of antimony, chromite, copper, cryolite, industrial diamonds, lead, manganese, nickel, tin, and zinc, while denying same to the Axis.

Exhibit 5 – US Preclusive Purchasing of Minerals During WW2



Source: Collins, based on USGS 1942 Minerals Yearbook.⁴⁵

Tungsten in China, Portugal, and Spain

With Imperial Japanese forces penetrating deeper into China in 1941 and 1942, US officials sought to deny the Axis Powers access to tungsten, a critical war mineral for which China was the world’s single largest producer. Accordingly, in 1942, the US moved to procure 8,000 of the 12,000 total tons of tungsten that Chinese producers were anticipated to mine that year.⁴⁶ The metal was of such importance that the US government elected to fly tungsten ore (alongside silk) out of China, over the Himalayas, and into India to load it on ships for transport onwards to the US.⁴⁷

Another tungsten-rich part of the world traded the logistical challenges of “The Himalayan Hump” for the diplomatic challenges of a nominally “neutral” Iberian Peninsula. Spain and Portugal were both important sources of tungsten ore for German industry. By 1943, the US government had authorized up to \$82 million (\$1.5 billion in 2024\$) for the preclusive purchasing of tungsten ore from Spanish mines, as well as \$2 million (\$37 million in 2024\$) for purchasing and leasing tungsten mines and tungsten-bearing properties in order to deny German entities access to them.⁴⁸

These operations helped absorb volumes of tungsten ore that Germany could have purchased to build stockpiles, but they were not sufficient to deny Germany its minimum basic war needs, a pressing concern as the Allies prepared for the D-Day invasion. Wanting to deprive Germany of tungsten that it feared would end up in armor-piercing shells fired at American tanks within months, the US sought to impose an oil embargo on Spain until Madrid ceased all shipments of “wolfram” [an alternative name for tungsten] to Germany (as well as acceded to several other Allied priorities).⁴⁹

This development launched the so-called “crisis de wolframio.” During a roughly 5-month period, the US (driven by military concerns), the British (driven by concerns about smuggling, loss of access to iron ore and potash from Spain, and impairment of investments), and Spanish (concerned about commercial opportunities and diplomatic humiliation) all maneuvered amidst one another.⁵⁰ In May 1944, the parties reached a compromise in which Spain was able to resume de minimus wolfram shipments of 20-to-40 tons monthly to Germany. US oil supplies were restored. By August 1944, Allied forces’ advances in Europe effectively severed Germany’s prior wolfram lifeline to the Iberian Peninsula and mooted the issue.⁵¹

Türkiye Chromite

Türkiye was a core source of chromite ore for Germany, which needed the chromium it contained for the manufacture of many types of armaments. In response, the Allies sought to pre-emptively buy up as much of Türkiye’s chromite production as possible. First, Britain and France agreed in January 1940 to purchase all Turkish chromite output for the next two years.⁵² When that agreement expired in 1942, Germany pressured Türkiye into commencing supplies and thereafter, chromite went in part to Germany and in part to British and American preclusive purchasers.⁵³ The Allied preclusive buyers ultimately spent \$33 million (approximately \$600 million in 2024\$) to acquire more than 725,000 tonnes of chromium from Türkiye.⁵⁴

Key Challenges for Preclusive Buying in Today’s World

Preclusive buying probably is a viable option only during wartime. Political divisions would make it extremely hard to obtain the necessary funding absent a true national emergency. Furthermore, commercial firms concerned with market-distorting impacts would lobby against such a scheme. Finally, China is a far larger consumer of most key metals and minerals than the US is. China-linked firms’ dominant positions on many global mining and processing value chains also positions the PRC very differently than Nazi Germany, which had a robust domestic industrial base but little external mining presence. All of that said, could preclusive purchasing assist in current and future situations, for instance post-conflict minerals arrangements in Ukraine?⁵⁵ Stay tuned.

Ownership Displacement

A key example of this tool comes from US actions in Latin America during World War 2. They may not be as easily replicable in the contemporary environment but are nonetheless worth recounting.⁵⁶

During the run up to US direct involvement in World War 2, Washington sought to extirpate German and Italian ownership of airlines in Latin America. Multiple geoeconomic tools were brought to bear on the problem. In the case of Bolivia, US authorities worked over a period of approximately nine months in 1941 to:

- (1) help the Bolivian government nationalize the German-founded L.A.B. airline with a stock buyout at fair market price to eliminate German equity ownership⁵⁷,
- (2) replace German management,
- (3) have Panagra [a Pan-American Airlines subsidiary] take over routes, and
- (4) provide financing for Bolivia to purchase additional aircraft and expand ground facilities.⁵⁸

The US took broadly similar steps in Argentina, Brazil, and Colombia – where a delicate dance was required given that Pan Am Airlines secretly held a controlling interest in *Sociedad Colombo-Alemana de Transportes Aéreos* (SCADTA).⁵⁹

Ownership displacement or replacement actions aimed at PRC-linked enterprises may not be a viable option at the present time. That said, continued deterioration of relations or emergence of a more acute crisis – such as serious conflict over Taiwan or in the Philippines' maritime littoral, or broader and deeper export restrictions on key China-origin metals and materials – could shift the political Overton Window⁶⁰ and open the door for such measures.

To give a sense of what such an operation for a key asset might cost, consider the Tenke Fungurume Mine in the DRC, which is 80% owned by China Molybdenum. In 2016, US-based miner Freeport McMoran sold its 56% interest in the mine to China Moly for \$2.65 billion. A few months later, Lundin Mining sold Chinese-backed interests its 24% interest for \$1.14 billion (the remaining 20% was and remains held by DRC state mining firm Gecamines).⁶¹ The mine's value has likely appreciated substantially in the intervening eight years but the example suggests that the basic table stakes for ownership displacement involving a critical global metals asset could plausibly fall in the range of \$5-to-\$10 billion.

Unintended Consequences of Historical Experience

Neither smuggling nor sabotage are solutions we would recommend. However, human history is replete with incidents of both as actors seek to remediate or take advantage of exigent situations.

Hidden Hand Purchasing or Smuggling

During exigent times, purchases through front companies or outright smuggling offer ways to obtain low-tonnage, high-value commodities such as rare earth metals. An embargo on supplies of rare earth elements or other critical minerals to US by China (perhaps the highest impact scenario) would likely raise prices for the affected commodities, which would give Chinese suppliers strong economic incentives to smuggle REEs into the market.⁶² Even if the materials were not sold “directly” to American customers, simply by making their way into the market at a premium price they would help ensure that necessary supplies are available. As well, the premium price would likely not be overly burdensome to manufacturers or the final consumers of REE-containing products.

Whereas a motor vehicle literally contains hundreds of kilograms of steel and is thus very exposed to changes in steel commodity prices and physical availability, REE are more like “vitamins of chemistry.” In other words, a product often cannot function without them, but a given phone, computer, etc., only needs very small quantities to achieve its functional goals. An iPhone, for instance, may contain as little as one-fourth of a gram of rare earths. This means that for neodymium, one of the densest rare earths, a piece of metal the size of an easily smuggled Coca-Cola can would be sufficient to produce at least 10,000 iPhones. Thus, for many applications, the effects of even significant price increases would be diluted by the rare earths’ small share of overall production materials input. This dynamic ultimately helps underpin market adaptability in the face of politically motivated supply restrictions.

Sabotage

Sabotage can play an important role during conflicts by denying adversaries access to mineral resources. In its “lighter” forms, sabotage can involve physical diversion of shipments or adulterating supplies. During World War 2, Allied agents in at least one instance caused hundreds of railcars’ worth of Turkish chromite ore bound for Germany to disappear en route while in another instance, they mixed the chromite with low-grade materials to effectively shrink the shipment.⁶³

In more severe cases, sabotage can involve damage or destruction of physical infrastructure in the mineral supply chain. During World War 2, the United States was concerned about sabotage of key industrial and mining assets in both Latin America

and Africa. The Federal Bureau of Investigation, FBI, was tasked with the counter-sabotage mission in Latin America.⁶⁴ Africa also received high level attention. As noted above, uranium from the Shinkolobwe mine located in the (then) Belgian Congo supplied a substantial portion of the Manhattan Project's needs.⁶⁵ Shinkolobwe's strategic importance helped underpin the deployment of 93 agents from the Office of Strategic Services ("OSS"), the Central Intelligence Agency's, CIA's, predecessor, throughout Africa.⁶⁶ In a contemporary global Great Power conflict between China and the US, it would be reasonable to expect a similar pattern of competition and intrigue across continents wherever strategic mineral sources are located.

Go Forward Options

Finally, we point to a set of strategic and tactical alternatives for securing key minerals and materials supply chains that can largely be controlled, and executed, within US borders. However, in some cases options may extend to foreign geographies. In those situations, international partnerships will be key for R&D and commercialization. Importantly, international arrangements almost always induce some form of USG involvement and/or support. We mentioned "minerals diplomacy" in **Table 1**. Whether for energy or minerals, USG entities often are active participants in international arrangements to secure supply chains. The historical record is replete with well-documented examples.

Developing Expedited Brownfield Processing Locations

The most useful geoeconomic tools for accelerating new and advanced materials will come from purchase commitments for defense and de-risking funding through US government agencies as illustrated earlier with loan and tax credit incentives.

One of China's most important points of supply chain presence is processing. Just like crude oil, mineral ores are functionally useless without the capability to refine them into usable products. Smelting and processing is a key weak link in existing domestic critical minerals initiatives. Certain domestic geographies would make particular sense as priority zones for locating new or expanded critical mineral processing operations activities that can benefit US supply chains. Potential areas include those near California's Mountain Pass rare earth mine and processing facility where MP Materials produces neodymium praseodymium concentrates for magnets. Other locations are those with mining-focused economies and ample available land (e.g., in Nevada, Utah, or New Mexico), or at or near the Y-12 National Security Complex near Oak Ridge, Tennessee.⁶⁷

Brownfield locations that have already hosted nuclear activities would make particularly suitable locations. Building a smelter in a greenfield location is likely to be viewed as "high risk" and face considerable public opposition. In contrast, locating a smelter where

plutonium and enriched uranium were previously handled may actually amount to a lowering of asset risk. The Department of Energy could be a lead agency here with its ongoing (or historical) operations at places like Los Alamos, Rocky Flats, Pantex, Hanford, and Y-12. An added benefit is that these locations already possess high-capacity transportation and power supply infrastructure, as well as local workforces and vendors experienced in working with challenging materials.

A consideration for brownfield locations are laws and rules intended to protect public interests when it comes to hazardous materials and exposure risk. The Toxic Substances Control Act, TSCA, Resource Conservation and Recovery Act, RCRA, and attendant requirements for remediating designated Superfund sites can pose severe constraints to use of brownfield sites. Streamlining and accelerating review and approval of remediated sites will be essential if investors are to achieve reasonable cycle times for financing. The same considerations apply to federal locations, including artillery ranges that could host mineral processing operations.

It would make sense to create a USG entity with centralized responsibility for administering critical mineral processing location development. Such an entity – call it the Federal Critical Minerals Real Estate Administration – could from its inception seek to forge the strongest possible bonds with commercial minerals processors and traders. Congress could even appropriate between \$1 and \$5 billion to support the entity's first year of operations so that it can credibly facilitate site rehabilitation and whatever infrastructure improvements may be needed to attract commercial tenants to the locations. Finally, Congress should set a sunset on the entity (perhaps in the 2040-2050 timeframe) so that taxpayers can be assured that no perpetual bureaucracy is being created.

Recycling: The Urban Mine

Some key materials already enjoy phenomenally effective recycling supply chains. Approximately 99% of lead-acid batteries discarded in the US have their lead recycled. More than two-thirds of steel production is fed by recycled material. For aluminum and copper, roughly 35% of US consumption is supplied by recycling scrap.⁶⁸

Newer recycling opportunities are also emerging. As one example, consider the burgeoning interest in recycling electric vehicle, EV, and other rechargeable batteries. Sector leader Redwood Materials has commenced industrial scale operations and is seeking by 2025 to provide enough battery materials to make approximately one million EV batteries per year.⁶⁹ Battery recyclers demonstrate the potential for a closed loop system that, once a critical mass is reached, makes the original sourcing of key metals and materials potentially less important. This critical mass depends however on widespread EV adoption within the US, which presently only has about five million passenger EVs in an overall vehicle fleet of close to 300 million units.⁷⁰

Unlike oil, battery materials are not consumed, and the recovered materials can, theoretically, be reprocessed and used over and over. As a blunt, but pertinent example, the battery that entered the US five years ago might have been made in China from cobalt and manganese smelted by Chinese processors but once it is here, it can theoretically be recycled *ad infinitum* within US borders. However, recycling *used* batteries poses physical and chemical challenges as compared to using waste metal from *new* battery manufacturing – generally, a higher quality resource.

Recycling is hard. Just like any other type of resource extraction, there are challenges posed by collection, “ore” quality (in this case the discards and items to be recycled), extraction processes, hazardous material issues, and other factors. At a basic level, recycling faces a similar, but amplified version of the economic challenge that dogs critical mineral diversification efforts in general: It is welcome during crisis and war when price tolerance is high but then withers when commodity prices are low.

Consider ongoing commercial electronics recycling efforts focused on recovering copper. Glencore, one of the largest global metals and materials traders, operates a facility in Quebec while Wieland has built a \$100 million recycling facility in Kentucky that it seeks to enlarge and Aurubis has built an \$800 million recycling facility in Georgia that aims to produce first metal in 2025.⁷¹ Whether such facilities can survive commercially in the open market will be a major test. In Japan, JX Advanced Metals has launched its own electronic waste (e-waste) aggregation efforts to recover copper to help meet the company’s supply commitments. Stated targets are for recovered and recycled copper to reach upwards of 50% of JX’s supply. While their effort is cast in terms of sustainability metrics it is a direct reflection of the company’s views on prospects for mined copper output going forward.⁷²

Variable input material quality influences recycling efforts. And recyclers in many cases also grapple with safety issues. Unlike relatively inert primary ore or scrap base metal piles, the recyclable goods (like old batteries, especially lithium ion chemistries) that contain a wealth of potentially recoverable minerals and materials can prove quite hazardous. As one example, Interco Trading suffered two major fires at battery recycling facilities in Illinois during 2020 and 2022 (**Figure 6**).⁷³ The fires’ sociopolitical impacts helped prompt the Illinois General Assembly to pass Public Act 103-1006 during the 2024 session. In a relevant part, the new law requires facilities that store five metric tons or more worth of used EV batteries to register the site with the Illinois Environmental Protection Agency and maintain detailed records of what is stored and in what quantities.⁷⁴

Figure 6 – Battery Recycling Facility Fire in Madison County, IL (2022)



Source: Madison County, Illinois Emergency Management Agency.⁷⁵

Magnets are another area where the commodity is of sufficient value and extractability to potentially justify recycling. One approach would leverage additional government funding to incorporate recycling capabilities alongside primary magnet production capacity now being built. For example, consider the recent award of a \$58.5 million Section 48C Advanced Energy Project tax credit allocation to MP Materials for the rare earth magnet plant it is building at its Independence facility in Fort Worth, Texas. The facility will help reduce US industry and national defense suppliers' extreme present reliance on neodymium-iron-boron, NdFeB, magnets from China.⁷⁶ At such a facility, it could be possible to consider bolting on recovery of materials from decommissioned magnets, such as those used in wind turbine nacelles.

US industrial and national security policymakers also need to think creatively about potential unorthodox minerals sourcing options in the event of a supply embargo. Consider the following example: A 3 megawatt, MW, wind turbine with a permanent magnet synchronous generator can contain 540 kg of neodymium, Nd.⁷⁷ If we assume that NdFeB magnets are approximately 30% Nd by mass, this would suggest 180 kilograms, kg (400 pounds) of Nd is available per 3MW turbine.⁷⁸ This suggests that depending upon weapons system, pulling down a single large wind turbine and recycling its permanent magnets could potentially provide the necessary inputs for producing

hundreds of munitions. Emerging approaches for making permanent magnets with fewer rare earth inputs could stretch urban mine (and other) inputs that much further.⁷⁹

The Urban Mine concept has limitations. Perhaps foremost among them from a strategic perspective is that war materials are not well positioned for circular use because they are often destructively expended far from the home market. Missiles and artillery shells are not recoverable once fired, nor are downed aircraft or drones or sunken ships. This dynamic would be especially relevant in an Asian war fought thousands of miles from the US, often over ocean or physically and politically inaccessible terrain.

Ultimately, recycling can potentially provide a useful slice in a much larger supply pie. In the least, recycling can assuage domestic, civilian needs during times of stress. America's last total industrial war, World War 2, saw recycling efforts but the highest-impact contributions came from new materials production. We caution, however, that too often perceptions are that recycling and the urban mine can replace virgin material altogether. This is a wholly unrealistic stance and often bears the effect of suppressing public support for mining and minerals processing.

Infrastructure Investments to Facilitate Supplies

During World War 2, the US government did not only seek to contractually lock up key mineral supplies. Through the Defense Plant Corporation ("DPC"), 1940-1945, it also invested in strategic minerals production and processing infrastructure both within the US and abroad. For instance, the DPC constructed a tin smelter in Texas City, Texas as well as multiple smelters in Latin America, perhaps most prominently, the Nicaro nickel facility in Cuba.⁸⁰ By the time Fidel Castro's regime nationalized the Nicaro facility in 1960, the US government had cumulatively invested \$100 million (1960\$) and counted the facility as one of the United States' most important global nickel supply sources.⁸¹

After a long hiatus, intensifying strategic competition and a sense of minerals and materials insecurity is driving the US government to apply the Defense Production Act to bolster minerals production and processing infrastructure. Thus far, these investments center on domestic resources within the United States – such as graphite deposits in Alabama and Alaska and associated processing facilities.⁸² The Department of Energy through its Fossil Energy and Carbon Management Office is also investing in critical minerals development, including funding of up to \$150 million to support "Critical Material Innovation, Efficiency, and Alternatives."⁸³

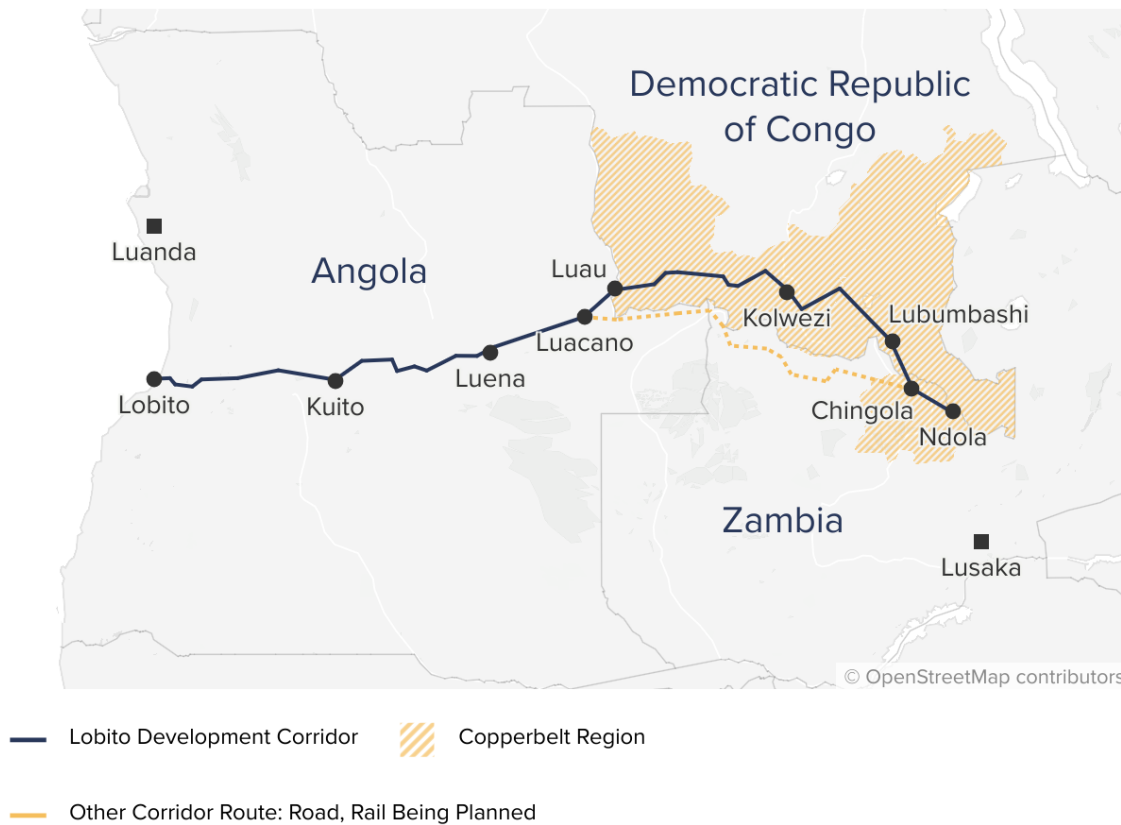
During WW2, the DPC invested in facilities both domestically and abroad. USG minerals and materials production and processing investments in the current era of competition have thus far focused more on domestic assets. Foreign mines can be more challenging – requiring dedicated, complicated minerals diplomacy often backed by

presence of US defense commands. A current example is Syrah Resources' graphite mine in Mozambique, once of the world's few current non-Chinese supply sources. Syrah had to declare force majeure in December 2024 due to protests that impeded mine operations.⁸⁴ The US Development Finance Corporation had agreed to a \$150 million loan in 2024 to help provide working and sustainment capital but the force majeure declaration, which came roughly a month after the DFC disbursed \$53 million to Syrah, means that future disbursements cannot occur until the mine resumes operations.⁸⁵ Moreover, in 2022 Syrah had obtained a \$102 million Department of Energy loan to support a processing plant for Mozambique graphite in Vidalia, Louisiana.⁸⁶ In 2023, the company requested an additional \$300 million in federal support for the Vidalia facility.⁸⁷ In early 2025, Syrah was awarded a \$165 million tax credit for potential expansion in Vidalia.⁸⁸ US lending for Syrah's projects was predicated on Chinese limits of graphite and rising prices. Syrah and other producers filed a petition in late 2024 to the US Department of Commerce and International Trade Commission (ITC) claiming Chinese dumping of graphite is creating uncompetitive conditions.⁸⁹

The Syrah experience offers a cautionary tale but is not necessarily a reason to shy away from such investments. What it does highlight is that policymakers need to be transparent with voters and make a compelling case as to the value of placing taxpayer funds at risk abroad in order to help secure mineral supplies whose core role is to maintain American prosperity and security. "Just trust us" will not work in the political climate but a forthright approach that explains to voters why a few dollars per year per American taxpayer helps underwrite national economic security can present a more compelling case.

Policymakers also need to be clear with voters that mineral and material security investments will, by necessity, involve multiple steps of the value chain from mine to transportation, to processing. Transportation is an especially important dimension. For American policymakers, the evolving Lobito Corridor Project may be the most apropos contemporary example.⁹⁰ The project aims to begin construction in earnest by 2026.⁹¹ Participants intend to build 800 kilometers, km, of new rail line; upgrade existing rail lines and port terminals; and add rolling stock and locomotives to link mines and refineries for cobalt, copper, and other minerals in the Democratic Republic of the Congo, Zambia, and Angola to world markets through the project's geographical namesake, the Angolan port of Lobito (**Figure 7**).⁹²

Figure 7 – The Lobito Development Corridor



Map: Center for European Policy Analysis • Source: Africa Intelligence

Source: Castellet Nogués, 2024.⁹³

China is building a competing rail line from the Zambian Copper Belt to the Tanzanian port of Dar es Salaam.⁹⁴ Competition will be stiff and debate is vigorous within the new Trump Administration about whether US-led efforts need to be continued and possibly accelerated in order to lock in logistics and ideally, box out the PRC-backed route.⁹⁵ Major US-facilitated mineral offtake deals coupled with provision of security assistance – potentially including force deployments – could offer a unique set of incentives for Congolese leadership that China has thus far been unable to provide.⁹⁶

History shows that during times of heightened competition, multidimensional approaches to mineral sourcing must often include hard security guarantees. Absent the ability to physically assure flows, equity stakes in upstream mining and supply activities may not be able to secure resource needs during a conflict. During World War 1, German firms owned one-third of Chile’s nitrate production – a vital precursor for making explosives – and yet could not physically obtain supplies they would otherwise have been entitled to because the powerful British Royal Navy severed sea lanes.⁹⁷

Germany ultimately solved its problem through industrial scale deployment of the Haber process to fix nitrogen directly from the atmosphere.⁹⁸ Had it not been able to do so, its ability to sustain industrial war would have been severely compromised. A converse example comes from World War 2, where bringing the German U-Boat threat under control during the Battle of the Atlantic and using high-speed merchant vessels helped permit successful maritime shipments of uranium ore from the Shinkolobwe mine in the Belgian Congo.⁹⁹ This ability to ensure maritime communications underpinned raw materials supply for the Manhattan Project and the atomic bombs that helped the US end the war in the Pacific.¹⁰⁰

The relationship between hard power to ensure resource flows and host nation sovereignty is likely to be a perpetual concern. Warm relations at the time deals are signed and infrastructure built can cool – as happened with the Cuban Revolution. They can also face complications if host governments choose unstable, value-destructive policy paths – as China has arguably recently experienced in Venezuela.¹⁰¹

When investor nations with significant power projection capabilities face threats to vital mineral or energy flows attributed to host country actions, intervention is a real possibility. President Carter’s National Security Advisor Dr. Zbigniew Brzezinski bluntly alluded to this possibility during 1977 testimony to Congress over a treaty designed to restore Panamanian control over the Panama Canal. When a member of Congress asked Brzezinski what would happen after 2000 if the Panamanian government suddenly announced that it was closing down the canal for “repairs,” he acerbically responded: *“In that case, according to the Neutrality Treaty, we will move in and close down the Panamanian Government for repairs.”*¹⁰²

New, Advanced Materials

Of all geoeconomic tools and prescriptives, those that can speed and optimize the development cycle – from invention to testing to commercialization and deployment – of new and advanced materials should win high priority status.

Necessity is the mother of invention and war (and to some extent, tensions and disruptions leading up to wars), are among the most pressing forms of necessity in human existence. Materials science often advances faster as we fight. Over the past 120 years, two examples of war-driven materials breakthroughs changed the world.

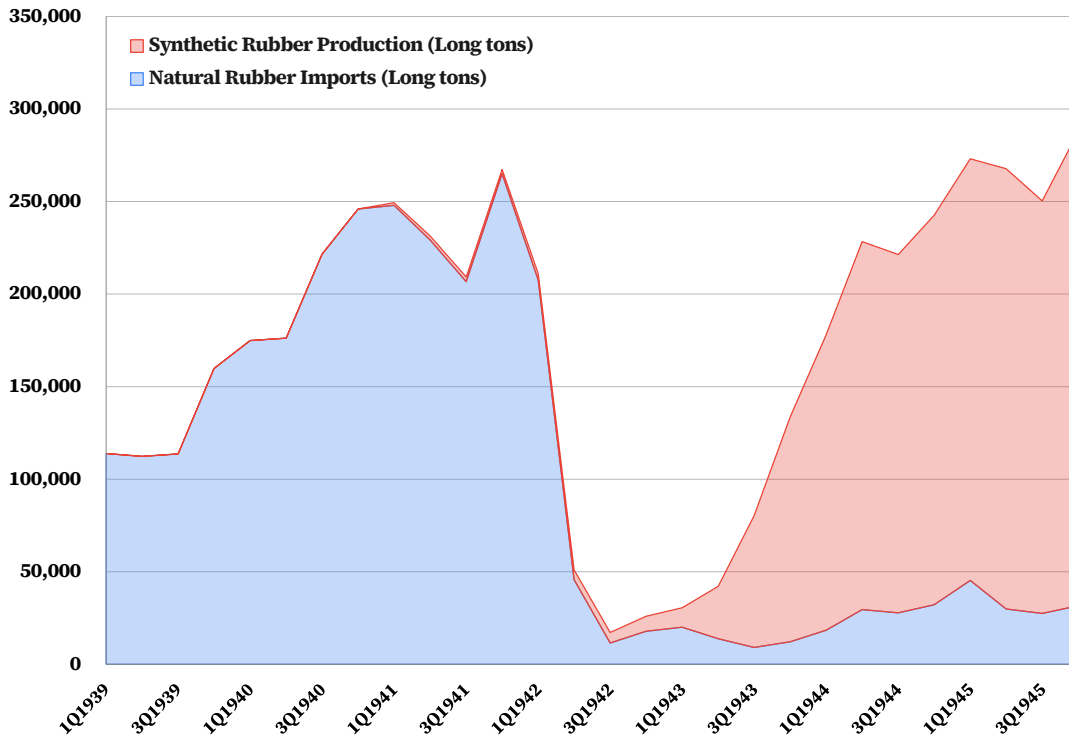
As noted above, in the first case when Germany was cut off from its Chilean nitrate resources by the Royal Navy during World War I it deployed the Haber Process at scale, enabling it to produce explosives from synthetic rather than mined inputs. In the second example, the Japanese conquest of what is now Indonesia and Malaysia in 1941-1942 curtailed critical natural rubber supplies to the United States. The US overcame

industrial and political challenges to scale up production of petroleum and alcohol-derived synthetic rubber, filling a materials gap that otherwise could have cost it the war. This section will briefly delve into that history and attempt to extract lessons that may be applicable today as the US once again must urgently prepare for the prospect of industrial warfare.

As America reeled from the attack on Pearl Harbor in late 1941 and early 1942, Japanese forces were consolidating their control over the Dutch East Indies, which supplied nearly all of the US supply of natural rubber. Massive strategic stakes flowed from the loss of rubber supplies given its importance to modern mechanized warfare, with a half-ton of rubber needed per Sherman tank, one ton for a heavy bomber, and about 80 tons for a battleship.¹⁰³ Indeed, the 1942 Rubber Survey Report chaired by Bernard Baruch minced no words about rubber's strategic importance, noting that: *"Of all critical and strategic materials, rubber is the one which presents the greatest threat to the safety of our nation and the success of the Allied cause...if we fail to secure quickly a large new rubber supply our war effort and our domestic economy both will collapse."*¹⁰⁴

In response, the US spooled up a synthetic rubber production effort that ultimately cost about one-third that of the Manhattan Project (making it one of the war's biggest industrial efforts). Rubber production exceeded one million tons annually by 1945.¹⁰⁵ But the ultimate success conceals a deeper story of serious lack of focus and internal political squabbles and poor managerial decisions that introduced significant delays that impaired the American war effort and even helped delay the D-Day invasion.¹⁰⁶

Figure 8 – Quarterly US Natural Rubber Imports and Synthetic Rubber Production, 1Q1939-to-4Q1945 (long tons)



Source: Collins, based on the War Production Board.

This story of delay also illustrates the importance of using multiple geoeconomic tools. The US roughly quadrupled its natural rubber stockpiles between 1939, when national security hawks began urging the implementation of a synthetic rubber manufacturing expansion, and the end of 1941. Yet even that major buildup was not nearly enough to sustain industrial warfare and had the synthetic rubber expansion failed, *"...the rubber shortage, in terms of civilian transportation breakdown and rubber-starved military machine, may have defeated the United States."*¹⁰⁷

The rubber saga also illustrates a brighter prospect for the United States in its evolving competition with China – for key bulk commodities such as oil, gas, grains, and so on the US is flush. For others, it can access fungible global commodity markets. And for the key minerals and materials of which China dominates supply and processing such as rare earths, graphite, and tungsten, a few billion taxpayer dollars invested judiciously can yield strategic dividends.

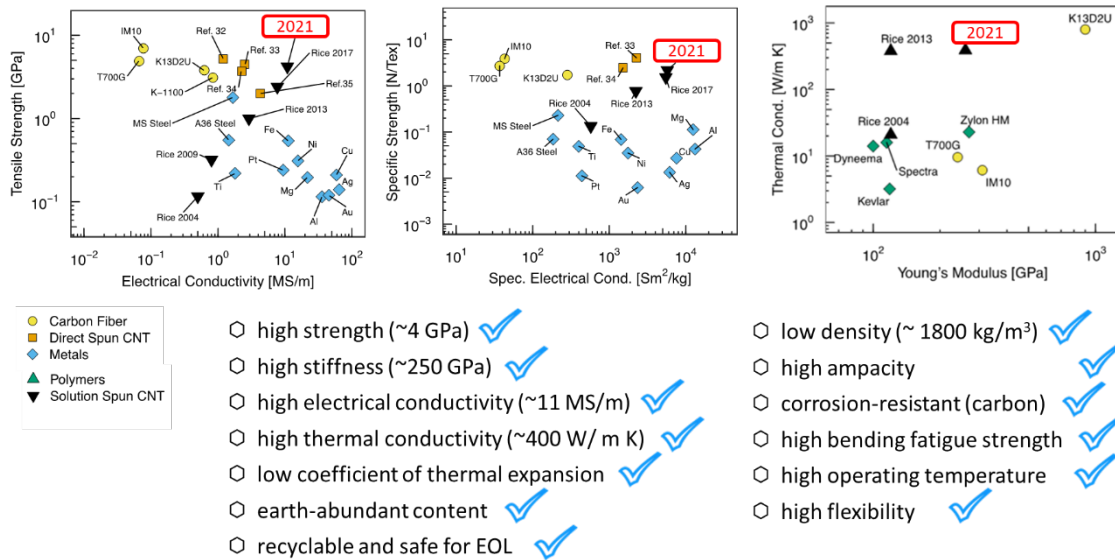
In short, the most pressing problems in the basic commodity space are either

- (1) less expensive to resolve than was the case in WW2 or else
- (2) the US has latitude to structure partnerships in places like Congo, Ukraine, and multiple parts of Latin America that allow construction of supply chains that are “mostly” commercial and thus could help resolve supply vulnerabilities with government dollars serving as anchors that then unlock a multiple in private capital support.

At the core of US competence, materials science and engineering are supported through large networks of public and private funding domains. Shifts in warfare and weapons systems require advanced and new materials. National laboratories that serve both energy and defense service branches and headquarters are crucial links to corporate and university centers of invention and innovation. As we have pointed out overall, materials supply chains and associated geoeconomic considerations necessarily entail close linkages between civilian and defense spheres when it comes to research, development, and deployment.

New alloys and composites have been and are being developed for performance in weapons systems and field operations, including improvements in protection of military personnel. A long, historical trajectory exists of plastics and resins displacing metals. Displacement of metals with plastics has been key for lightweighting vehicles to achieve improved fuel efficiencies. The introduction of carbon fibers provided additional options for fabrication that sustained strength while reducing the weight of materials for aircraft and ground vehicles as well as other products. A push to commercialize carbon nanotube fibers (CNTF) to displace metals and legacy carbon fiber to enhance composites is altering the strategic game. CNTF materials surpass steel in tensile strength while providing electrical and thermal conductivity at mere fractions of metals' weight.

Figure 9 – Displacement of Metals and Carbon Fibers with CNTF



Source: Pasquali, 2023.¹⁰⁸

Note: Symbols designated “Rice” represent progression in CNT research at Rice University. The boxes marked “2021” indicate performance status as of those publication release dates.

CNTF can be blended with titanium in epoxies, deployed in next generation textiles that go beyond Kevlar fibers, deployed for conductive wiring harnesses and cables to displace copper and aluminum. CNTF is being incorporated into batteries and can be fabricated into building materials. Most appealing about carbon nanomaterials and their advances is that they are rooted in existing hydrocarbon industrial footprints. Carbon material can be sourced through existing downstream, refining and petrochemical operations. As we note at the outset of this paper, hydrocarbons and derivative materials remain a distinct comparative advantage for the US. Solid carbon also can be sourced through any number of low carbon energy strategies under active development, such as methane pyrolysis to yield solid carbon and hydrogen or even separation of carbon from carbon dioxide captured from industrial facilities.

Beyond carbon nanomaterials, a crucial arena of both civilian and defense attention is cyber risk. Advanced applications of ferroelectrics can aid in development of anti-hacking by helping to turn “dumb” materials into “smart” devices for anti-tampering.

In all, the distinct burden is cycle time from bench science to testing and ultimate deployment in civilian and defense applications. An example of efforts to address the R&D to commercialization cycle across materials landscapes is the multi-organization Materials Genome Initiative report on autonomous experimentation.¹⁰⁹ Creative notions are converging for how best to use machine learning and artificial intelligence to speed

adoption of new advanced materials that could ensure US materials security and resilience.¹¹⁰

Conclusion

While gold cannot be made into physical bullets, effective economic statecraft makes financial power a force multiplier that increases competitiveness—and when necessary, warfighting capacity—across domains. It does so positively through ensuring that our industrial base is appropriately provisioned and negatively through denying the same to adversaries.

The United States now faces an unprecedented challenge because all previous conflicts and situations of sharp competition (Cold War 1.0) involved adversaries who were vulnerable to combined American financial and industrial mass. While the US remains the world's largest economy and premier financial power, the industrial mass disparity between China and the US roughly mirrors that which existed between Germany and the US at the outset of World War 2. But this time we are the ones with less capacity. Bearing that stark reality in mind, this analysis aims to help US and Allied policy makers compete now while buying time to forge a more unified and larger industrial base through a range of policies and actions to expand our factory floor capabilities. Manufacturing is now war by other means and critical materials, metals, and minerals play a central role.

Notes

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