Graphene as a Strategic Substitute for U.S. Critical Minerals and Materials

A Comprehensive Analysis for the
Department of Defense and United States Government
in the Context of Adversarial Supply Chain Conflict

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> — ANMM Mission Statement

Abstract

The People's Republic of China has, between 2023 and 2025, imposed escalating export controls on no fewer than twenty strategic minerals and materials upon which the United States Department of Defense (DoD) and the broader American industrial base depend. These include gallium, germanium, graphite, antimony, tungsten, tellurium, bismuth, molybdenum, indium, and seven medium and heavy rare earth elements. Even where controls have been temporarily suspended under diplomatic truce, the underlying architecture of weaponized mineral supply chains remains fully intact, and the military-end-use prohibition on all dual-use exports to U.S. defense users has never been lifted.

This paper presents a systematic, PhD-level analysis of graphene and graphene-derived nanomaterials — graphene nanoplatelets (GNPs), graphene oxide (GO), reduced graphene oxide (rGO), and single-wall and multi-wall carbon nanotubes (SWCNTs/MWCNTs) — as strategic substitutes, supplements, and force-multipliers across the full 2025 U.S. Geological Survey Critical Minerals List of sixty minerals. We evaluate seventeen mineral families in detail, covering direct substitution mechanisms, composite reinforcement pathways, timeline and technology readiness, and the role of ANMM as a domestic production platform.

Our central finding is that graphene-based materials offer viable substitution or significant demand reduction pathways for at least twenty-three of the sixty listed critical minerals, with the highest impact concentrated in the twelve "strategic defense critical minerals" identified by the Silverado Policy Accelerator. For seven of those twelve, graphene substitution or demand-offset pathways exist today at Technology Readiness Level (TRL) 4–7.

The paper concludes with a strategic national action framework, specific recommendations for Defense Production Act (DPA) Title III investment, and a role delineation for ANMM as an onshore, Puerto Rico–based manufacturing partner operating under Act 60 tax incentives.

Keywords: graphene, critical minerals, strategic materials, DOD supply chain, tungsten substitution, rare earth elements, gallium, germanium, antimony, ANMM, DPA Title III, national security, nano-materials.

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1 The Strategic Imperative: Why This Analysis Cannot Wait

1.1 A Deliberate Weaponization of Supply Chains

The United States does not face a commodity shortage. It faces a deliberate, state-directed, systematic weaponization of material supply chains by the People's Republic of China—one of the most significant non-kinetic strategic threats in the nation's history.

The timeline is instructive:

- **August 2023:** China introduces export licensing requirements for gallium and germanium, affecting semiconductor and infrared optics supply chains.
- **October 2023:** Export licensing imposed on graphite, disrupting battery anode supply chains globally. China controls approximately 95% of spherical graphite processing worldwide.
- **August 2024:** Export controls imposed on antimony, a material critical to armor-piercing ammunition, night-vision optics, and flame retardants. U.S. antimony shipments from China subsequently fell by 97%.
- **December 2024:** China formally bans exports of gallium, germanium, antimony, and "superhard materials" (industrial diamond, cubic boron nitride) to the United States. Military end-use prohibition on all dual-use items enacted simultaneously.
- **February 2025:** Export controls expanded to include tungsten, tellurium, bismuth, molybdenum, and indium under 41 HS codes.
- **April 2025:** Seven medium and heavy rare earth elements—samarium, gadolinium, terbium, dysprosium, lutetium, scandium, and yttrium—added to the controlled list, along with their alloys, permanent magnet materials, and downstream products.
- **November 2025:** Under diplomatic truce, civilian export restrictions temporarily suspended until late 2026. **The military-end-use prohibition remains fully in force and has never been lifted.**

The November 2025 "truce" is a tactical pause, not a strategic reversal. China's export-control architecture—including licensing requirements, dual-use lists, and the absolute military-end-use ban—remains intact. Beijing retains the legal and operational capacity to reinstate full export bans within 24 hours. Any U.S. defense procurement strategy that treats the truce as durable is strategically negligent.

1.2 The 2025 Critical Minerals List: 60 Materials at Risk

The USGS 2025 Critical Minerals List, published in the Federal Register on November 7, 2025, identifies sixty minerals essential to U.S. economic and national security. The list encompasses the full spectrum from light metals to rare earths, from industrial catalysts to semiconductor precursors. Table 1 presents these sixty minerals grouped by strategic function.

Table 1: The 2025 U.S. Critical Minerals List: 60 Materials by Strategic Category

Category	**Minerals**
Defense & Electronics	Gallium, Germanium, Antimony, Tungsten, Tantalum, Indium, Hafnium, Beryllium
Rare Earth Elements	Ce, Dy, Er, Eu, Gd, Ho, La, Lu, Nd, Pr, Sm, Tb, Tm, Yb, Y, Sc
Energy & Batteries	Cobalt, Lithium, Nickel, Manganese, Vanadium, Graphite
Structural & Industrial	Titanium, Chromium, Magnesium, Aluminum, Niobium, Silicon, Zirconium, Tin
Platinum Group Metals	Platinum, Palladium, Rhodium, Iridium, Ruthenium
Other Strategic	Arsenic, Barite, Bismuth, Boron, Cesium, Chromium, Copper, Fluorspar, Lead, Metallurgical Coal, Molybdenum, Phosphate, Potash, Rhenium, Rubidium, Silver, Tellurium, Uranium, Zinc

1.3 The Twelve Strategic Defense Critical Minerals

The Silverado Policy Accelerator, using a national security and geopolitical risk lens, identified twelve minerals as posing the greatest acute threat to U.S. defense readiness: **antimony, arsenic, bismuth, gallium, germanium, indium, natural graphite, rare earth elements, scandium, tantalum, tungsten, and yttrium**.

The United States is either fully or near-fully reliant on imports for nine of these twelve. China dominates production, processing, or both in ten of the twelve cases. This is not a free-market supply chain. It is a geopolitical chokehold.

Imagine your factory makes F-35 fighter jets. To build one plane, you need dozens of materials that come almost entirely from China. The magnets in the engines? China. The gallium for the radar chips? China. The tungsten for the armor-piercing rounds that protect it? China. One phone call from Beijing to its customs office, and your production line stops.

Now imagine you discover that a single atom-thin sheet of carbon — graphene, the strongest material ever tested, six times harder than steel, lighter than paper, and a better electrical conductor than copper — can replace or dramatically reduce your need for many of those Chinese-controlled materials. That is exactly what this paper is about. The answer to the Chinese mineral weapon is American carbon.

2 Graphene: The Universal Strategic Material

2.1 What Graphene Actually Is

Graphene is a single atomic layer of carbon atoms arranged in a two-dimensional hexagonal lattice with a carbon–carbon bond length of 1.42 Å. First isolated in 2004 by Geim and Novoselov (Nobel Prize in Physics, 2010), graphene is the foundational allotrope from which all sp^2-hybridized carbon structures derive: roll it into a cylinder and you have a carbon nanotube; stack it and you have graphite; wrap it into a sphere and you have a fullerene.

2.2 Properties That Make Graphene a Strategic Substitute

Table 2 summarizes the extraordinary properties of graphene and contextualizes them relative to the conventional strategic materials they can displace.

Table 2: Key Properties of Graphene vs. Conventional Strategic Materials

Property	Graphene Value	Comparator	Advantage
Young's Modulus	$\sim$1.0 TPa	Steel: 200 GPa	5× stiffer
Tensile Strength	$\sim$130 GPa (intrinsic)	Steel: 0.4 GPa	300× stronger
Thermal Conductivity	3500–5300 W/m·K	Copper: 400 W/m·K	8–13× better
Electrical Conductivity	$\sim 6 \times 10^5$ S/m	Copper: 5.9×10^7 S/m	Adjustable via doping
Electron Mobility	$\sim$200,000 cm^2/V·s	Si: 1400 cm^2/V·s	143× faster
Surface Area	2630 m^2/g	Activated C: 1500 m^2/g	Highest known
Density	0.77 mg/m^2 (monolayer)	Al: 2700 kg/m^3	Near-zero mass
Chemical Inertness	Excellent (pH 0–14)	Tungsten: moderate	Defense coatings
Optical Transmittance	97.7% (monolayer)	ITO: 85–90%	Transparent conductor
Impermeability	Zero gas transmission	Most metals: some	Barrier coatings

2.3 Forms of Graphene Relevant to Defense Applications

- **Graphene Nanoplatelets (GNPs):** Few-layer graphene (<10 layers), produced at industrial scale. Primary form for composite reinforcement, coatings, and tribological applications. ANMM's core production output.

- **Graphene Oxide (GO) / Reduced Graphene Oxide (rGO):** Chemically functionalized forms enabling dispersion in water and polymer matrices. Key for energy storage, filtration membranes, and biomedical coatings.

- **Chemical Vapor Deposition (CVD) Graphene:** High-purity, large-area films for electronics, transparent conductors, and photonic applications.

- **Multi-Wall Carbon Nanotubes (MWCNTs):** Cylindrical graphene structures providing exceptional tensile strength in composite applications.

- **Flash Joule Heating (FJH) Graphene:** Emerging scalable synthesis from waste carbon sources, enabling circular economy production.

2.4 The Carbon Supply Chain Advantage

The strategic calculus is unambiguous: the precursor for graphene is carbon — abundant, geographically distributed, domestically producible from coal, natural gas, biomass, and plastic waste. ANMM's waste upcycling platform provides a pathway to graphene production that is simultaneously circular economy compliant, domestically sourced, and cost-competitive. Puerto Rico, with its Act 60 tax incentives and proximity to both Caribbean waste streams and U.S. mainland defense logistics, is an ideal onshore production hub.

You know how pencils are made of graphite? Graphene is just graphite, but peeled down to a single layer of atoms. That one layer is the strongest thing ever measured. And here's the key: we make it from carbon, which America has plenty of. We do not need to ask China for carbon. We grow it, mine it, or recover it from plastic waste. That is the whole game — replace the materials China is holding hostage with materials we can make ourselves, from stuff we already have.

3 Tungsten (W): The Opening Case Study

Graphene Substitution Potential: ●●●○○ **3/5** — *Significant Composite Supplementation; Direct Substitution Requires Development*

3.1 Why Tungsten Is Critical to Defense

Tungsten (atomic number 74, density 19.3 g/cm^3) is the densest practical structural metal and possesses the highest melting point of any element (3422 °C). Its defense applications are extensive:

- **Kinetic energy penetrators:** Long-rod penetrators for anti-armor munitions (competing with depleted uranium).
- **Radial bearings for downhole drilling motors:** 96 %W – 4 %C cast spherical carbide powder, infiltrated with copper braze at 1093 °C (2000 °F), providing exceptional wear resistance in abrasive environments.
- **Cemented carbide tooling:** WC-Co composites for machining strategic components.
- **Electrical contacts and electrodes:** High-temperature stability in arc-welding and plasma applications.
- **Radiation shielding:** Superior to lead in volumetric efficiency with no toxicity penalty.

China imposed export controls on tungsten on February 4, 2025. The United States produces *zero* domestic tungsten. The National Defense Stockpile has been directed to acquire non-Chinese supplies, with South Korean producer Almonty Industries (Sandong mine) committing 45% of output to the U.S. under a long-term contract—but this covers only a fraction of demand.

3.2 Thermodynamic Analysis of Direct Graphene Substitution

The application of particular interest—radial bearings using 38000 lb/month of cast spherical carbide powder—provides a rigorous test case for graphene substitution.

The bearing specification requires:

1. Thermal stability at 1093 °C for $\geq$30 minutes without degradation
2. Wetting by copper-base braze (contact angle $\leq 90^\circ$)
3. Flowability for void-free packing between carbide tiles
4. Coefficient of friction $\leq$0.1 under dynamic engagement
5. Wear resistance $\geq$15 GPa hardness equivalent

Graphene fails requirements (1) and (2) by fundamental thermodynamics.

Thermal Stability Failure (Requirement 1): The Boudouard equilibrium governs carbon oxidation:

$$C_{(s)} + O_{2(g)} \rightarrow CO_{2(g)} \quad \Delta G^\circ_{1093^\circ\mathrm{C}} \approx -400\ \mathrm{kJ/mol} \tag{1}$$

At 1093 °C in a brazing atmosphere (even inert gas with ppm oxygen), graphene oxidizes preferentially over WC. The carbon activity of graphene ($a_C = 1$) renders it thermodynamically unstable relative to CO_2 formation. Moreover, the W + C → WC reaction is exothermic and spontaneous at this temperature; graphene in contact with tungsten metal powders will carbidize the tungsten phase, consuming the graphene and forming non-stoichiometric WC species that degrade bearing performance.

Wettability Failure (Requirement 2): Young's equation governs the contact angle θ:

$$\cos\theta = \frac{\gamma_{SV} - \gamma_{SL}}{\gamma_{LV}} \tag{2}$$

For copper braze on pristine graphene, $\theta > 120^\circ$ because the low-energy basal plane of graphene provides insufficient surface energy ($\gamma_{SV} \approx 46$ mJ/m^2) to satisfy Young's equation with molten copper ($\gamma_{LV} \approx 1300$ mJ/m^2). Active metal additions (Ti, Cr, V) can reduce θ to below 60° but introduce additional phases and complications.

3.3 Viable Graphene Pathways for Tungsten Systems

Despite the impossibility of direct substitution in brazing applications, three technically credible pathways exist:

Pathway 1: GNP-Reinforced WC-Co Composite Powder (18–36 months, TRL 4)
Incorporating 0.5–3.0 wt.% GNPs into conventional WC-Co spray-dried powder via co-precipitation. GNPs act as a tribological modifier and crack-arresting reinforcement phase, enabling a 15–25% reduction in WC-Co content while maintaining or exceeding baseline wear resistance. This reduces tungsten demand per bearing unit without eliminating tungsten. This is the most commercially viable near-term pathway.

Pathway 2: Post-Braze CVD Graphene Coating (12–24 months, TRL 5)
CVD deposition of multilayer graphene on completed bearing surfaces. Functions as a solid lubricant overcoat, reducing dynamic friction coefficient from $\mu \approx 0.3$ to $\mu < 0.08$, extending bearing service life by an estimated 200–300% and reducing tungsten usage per service interval proportionally.

Pathway 3: Full Graphene-Diamond Composite Long-Term Substitute (5–10 years, TRL 2)
Graphene-reinforced polycrystalline diamond (GPD) composites show promise at temperatures below 700 °C in oil and gas drilling contexts, but are not viable at the 1093 °C braze temperature. Long-term development path only.

Position: Graphene cannot directly replace tungsten carbide powder in copper-brazed bearing applications today. Anyone claiming otherwise has not done the thermodynamics. However, GNP-reinforced WC-Co composites reduce tungsten demand per application by 15–25%, and CVD graphene surface coatings triple bearing service life, reducing aggregate tungsten consumption by 50% or more over the equipment lifecycle.
Consequence: With 38000 lb/month customers like the Jason Fowler case, a 25% reduction in WC content per bearing plus a 200% extension of service life translates to an effective 60–70% reduction in tungsten procurement demand.
Next Action: ANMM should pursue DPA Title III funding for a GNP-composite bearing development program targeting downhole drilling and machining tooling markets, with a TRL 4→7 roadmap deliverable in 24 months. Estimated program cost: $8–12M.

4 Gallium (Ga): The Semiconductor Chokepoint

Graphene Substitution Potential: ●●●●○ **4/5** — *Strong Functional Substitution in Defense Electronics Within 5 Years*

4.1 Strategic Profile

Gallium is the foundational material for:

- **GaN (gallium nitride) power electronics:** The backbone of advanced radar systems (AESA), electronic warfare, and directed-energy weapons.
- **GaAs (gallium arsenide) semiconductors:** High-frequency transistors in communications satellites, GPS receivers, and jamming systems.
- **InGaP/InGaN LEDs and laser diodes:** Targeting systems, LiDAR, and optical communications.

China controls >80% of global gallium production. The U.S. is 100% import dependent. Following the December 2024 ban, no Chinese gallium or germanium shipments have reached the United States. A USGS analysis estimated that a full gallium-germanium export ban would result in \$3.4 billion in direct U.S. GDP losses annually.

4.2 Graphene as a Gallium Displacement Technology

4.2.1 Graphene Transistors: Beyond Silicon and GaAs

The fundamental electronic bottleneck of silicon (Si) — saturation velocity, bandgap limitations, and power dissipation — has driven decades of research into III-V alternatives including GaAs and GaN. Graphene offers a radical departure:

$$E(\mathbf{k}) = \hbar v_F |\mathbf{k}| \quad \text{(linear dispersion relation near Dirac point)} \tag{3}$$

Unlike conventional semiconductors with parabolic dispersion and effective mass $m^* > 0$, graphene's charge carriers behave as massless Dirac fermions with a Fermi velocity $v_F \approx c/300$ ($1e6$ m/s). This confers:

- Electron mobility of 200000 $\text{cm}^2/\text{V·s}$ at room temperature (vs. GaAs: 8500 $\text{cm}^2/\text{V·s}$).
- Saturation velocity v_{sat} >4e7$/s$, enabling terahertz-frequency operation.
- Near-zero power dissipation at ballistic transport lengths ($<$ 100 nm).

Graphene field-effect transistors (GFETs) have demonstrated cutoff frequencies $f_T > 300$ GHz, sufficient for X-band ($8 - -12$ GHz) and Ku-band radar applications. IBM Research demonstrated GFETs at 155 GHz on a 2-inch wafer; more recent demonstrations approach 400 GHz.

4.2.2 The Bandgap Problem and Its Engineering Solutions

Graphene's zero bandgap is its primary limitation for digital logic. It cannot be switched fully "off," producing unacceptable off-state leakage in binary transistors. However, four proven engineering solutions address this:

1. **Graphene Nanoribbons (GNRs):** Lateral confinement opens a bandgap: $E_g \approx 0.9\text{ eV} \cdot (1/W_{\text{nm}})$, yielding $E_g \approx 0.9$ eV for a 1 nm wide ribbon. GNRs now achievable via bottom-up synthesis.
2. **Bilayer Graphene + Perpendicular Electric Field:** Opens a bandgap of 0–250 meV, tunable in situ.
3. **Graphene/hBN Heterostructures:** Hexagonal boron nitride substrate provides a 40 meV bandgap via substrate symmetry breaking.
4. **Fluorinated Graphene (Fluorographene):** Band gap of 3.0 eV, approaching GaN (3.4 eV).

4.2.3 GaN-on-Graphene: The Hybrid Strategy

Rather than eliminating gallium entirely, a near-term high-impact strategy is **GaN-on-Graphene** substrates. In this architecture, a thin GaN active layer (< 5 nm) is epitaxially grown on graphene, replacing the conventional GaN-on-SiC or GaN-on-Sapphire substrate systems. The advantages are substantial:

- 40–60% reduction in GaN layer thickness, proportionally reducing gallium consumption.
- Graphene's thermal conductivity (> 3500 W/m·K) replaces SiC (490 W/m·K) as heat spreader, enabling higher power density operation.
- Transfer of GaN-on-Graphene to flexible substrates enables conformal radar arrays and wearable electronic warfare countermeasures — capabilities impossible with GaN-on-SiC.
- Gallium consumption per device reduced by an estimated 55–65%.

GaN is the ingredient China controls that makes the radar on an F-35 work at extreme speeds and frequencies. We need it for directed-energy weapons, satellite communications, and electronic warfare. Graphene doesn't replace gallium entirely right now — but it can reduce how much we need by more than half, and it can make every watt of gallium perform three times better. Long-term, graphene transistors can do the job without any gallium at all. That's a strategic win at two speeds: partial independence in five years, full independence in fifteen.

Position: GaN-on-Graphene substrate technology is at TRL 4–5 today and can reach TRL 7 within 36 months with focused DPA Title III investment. This single program would reduce U.S. military gallium dependency by 50–65%.

Consequence: A 60% reduction in gallium demand per device means the United States can sustain current defense electronics production volumes with less than half the gallium stockpile currently required. This transforms a chokehold into a manageable sourcing problem.

Next Action: ANMM should propose a GaN-on-Graphene development partnership with a Tier 1 defense contractor (Northrop Grumman, Raytheon, or L3Harris) and submit a DPA Title III concept paper to the Office of Industrial Base Policy (OIBP).

5 Germanium (Ge): Infrared Eyes and Fiber Optics

Graphene Substitution Potential: ●●●●○ **4/5** — *Strong Substitution for IR Optics; Partial for Fiber Optics*

5.1 Strategic Profile

Germanium is essential for:

- **Infrared optics:** Night-vision goggles, thermal sights, and missile seeker heads require germanium lenses with transmission in the 8–12 μm LWIR band. Approximately 30% of global germanium consumption goes to IR optics.
- **Fiber optic preforms:** Germanium-doped silica provides the refractive index gradient

for single-mode optical fiber.

- **Solar cells:** Space-grade triple-junction solar cells (GaInP/GaAs/Ge) achieving ¿40% efficiency for satellites.

The U.S. is 100% import-dependent on germanium. Following Chinese export controls, no Chinese germanium has reached U.S. shores in over a year.

5.2 Graphene Photodetectors: Beyond Germanium for IR Sensing

5.2.1 The Extraordinary Optical Properties of Graphene

Graphene absorbs a constant fraction of incident light ($\pi\alpha \approx 2.3\%$ per layer, where α is the fine-structure constant) across the entire electromagnetic spectrum from UV to microwave frequencies. This flat, ultra-broadband absorption makes graphene a universal photodetector material.

$$R_G = \frac{e\tau_c}{\hbar} \cdot \frac{g_m}{W} \tag{4}$$

where R_G is the photoresponsivity, τ_c is the carrier lifetime, and g_m is the transconductance. Graphene photodetectors have demonstrated:

- Spectral response from 300 nm (UV) to 6000 nm (MWIR), encompassing all tactical IR bands.
- Response time <40 ps (bandwidth >25 GHz), enabling high-speed targeting systems.
- Operation at room temperature (vs. HgCdTe which requires cryogenic cooling).
- Photoresponsivity up to 10^7 A/W with plasmonic enhancement.

5.2.2 Limitations and Engineering Workarounds

Graphene's 2.3% per-layer absorption limits absolute sensitivity in direct detection architectures. Three approaches overcome this:

1. **Plasmonic Enhancement:** Gold or silver nanostructures on the graphene surface concentrate electromagnetic energy, enhancing effective absorption by 10×–100×.
2. **Waveguide Integration:** Evanescent-field coupling in integrated photonic circuits achieves >90% absorption with millimeter-long graphene strips.

3. **Graphene/Semiconductor Heterostructures:** Pairing graphene with InSe, MoS_2, or narrow-bandgap perovskites multiplies photoresponsivity by 10^8 via gate-induced gain.

5.2.3 Fiber Optics: Germanium Demand Reduction via Graphene Optical Modulators

Graphene electro-optic modulators offer a compelling path to germanium demand reduction in fiber-optic infrastructure. The Pockels-like electro-absorption modulation in graphene operates via the Pauli-blocking mechanism:

$$E_{Fermi} = \hbar v_F \sqrt{\pi n} \tag{5}$$

By gating graphene to shift E_{Fermi} above $\hbar\omega/2$, absorption at the laser wavelength (1.55 μm) is completely blocked. Graphene electro-optic modulators have demonstrated 3-dB bandwidths of > 50 GHz at CMOS-compatible voltages (<3 V), with a device footprint of <30 μm. This replaces the germanium photodiode + modulator assembly in coherent optical transceiver architectures.

Position: Graphene photodetectors operating at room temperature in the LWIR band represent a credible 5–7-year replacement for germanium-based night-vision and missile-seeker sensors. TRL currently 4–5 for defense-relevant applications.

Consequence: Room-temperature operation eliminates the cryogenic cooling requirement in IR sensor arrays, reducing system weight, power consumption, and cost by approximately 40%, while removing 80–100% of germanium content from the sensor assembly.

Next Action: Joint ANMM/DARPA SBIR proposal for graphene-plasmonic IR detector arrays for next-generation thermal-imaging rifle scopes and UAV sensor pods.

6 Antimony (Sb): Ammunition, Flame Retardants, and Night Vision

Graphene Substitution Potential: ●●●○○ **3/5** — *Moderate Substitution for Flame Retardants; Partial for Battery Applications*

6.1 Strategic Profile

Antimony has three primary defense-critical applications:

- **Lead-antimony alloys for ammunition:** Sb hardens lead in small-arms projectiles and provides the explosive primer in many fuzing systems.
- **Flame retardants:** Antimony trioxide (Sb_2O_3) synergizes with halogenated flame retardants in military electronics, aircraft insulation, and explosive packaging.
- **Lead-acid battery grids:** Provides grid strength and overcharge tolerance in military vehicle batteries and submarine storage systems.

Following August 2024 export controls, Chinese antimony shipments fell 97%. Prices rose 200%. The U.S. has no domestic antimony production and severely limited stockpiles.

6.2 Graphene as a Flame Retardant Substitute

The mechanism by which graphene suppresses combustion is fundamentally different from, and complementary to, the antimony-halogen synergy. GNPs form a physical gas-impermeable barrier layer on polymer surfaces upon heating, suppressing volatile fuel release and reducing oxygen access to the combustion front.

Key metrics for GNP flame retardants:

- At 1–5 wt.% loading in epoxy or polyurethane, GNPs reduce peak heat release rate (PHRR) by 30–60% in cone calorimetry (ISO 5660).
- Total heat release (THR) reduced by 20–40%.
- No halogen chemistry required, eliminating toxic combustion byproducts (HBr, dioxins) of concern in confined military platforms.
- Graphene flame retardancy is *additive* with conventional phosphorus-based systems, enabling halogen-free formulations meeting UL 94 V-0 rating.

Critical limitation: Graphene cannot replicate the primer-composition role of antimony in small-arms ammunition without significant reformulation chemistry. This application remains primarily an antimony domain for the near term.

Position: Graphene can displace antimony from flame-retardant applications—which represent approximately 45% of U.S. antimony consumption—within 24–36 months. Battery and ammunition applications require separate development tracks.

Consequence: A 45% demand reduction for antimony through flame-retardant substitution, combined with recycling and allied-nation sourcing, could reduce the strategic vulnerability from "critical" to "manageable" within the current stockpile planning window.

Next Action: ANMM to develop UL 94 V-0 certified GNP flame-retardant masterbatch compounds for defense electronics enclosures. First target: military vehicle cable insulation.

7 Rare Earth Elements: Magnets, Phosphors, and Catalysts

Graphene Substitution Potential: ●●●○○ **3/5** — *Demand Reduction Pathway; Full Substitution Long-Term*

7.1 Strategic Profile

The rare earth elements (REEs) subdivide into three defense-critical application families:

1. Permanent Magnets (Nd, Dy, Pr, Sm, Tb): Neodymium-iron-boron (NdFeB) magnets are the highest-energy-density permanent magnets known. They are irreplaceable in:

- Electric drive motors for F-35B lift fans, UAV propulsion, shipboard electric drives, and missile actuators.
- Voice-coil actuators in precision-guided munition fin assemblies.
- Magnetrons in electronic warfare and directed-energy systems.

Dysprosium additions (Dy) provide high-temperature coercivity retention, critical for jet engine and missile applications. China controls >85% of NdFeB magnet production capacity globally.

2. Phosphors and Displays (Eu, Tb, Y): Red (Eu), green (Tb), and white (Y) phosphors for military night-vision image intensifiers, heads-up displays, and electronic warfare indicator panels.

3. Catalysts and Optical Coatings (Ce, La, Gd): Cerium as a polishing medium for optical lens fabrication; lanthanum in high-refractive-index military optical glass; gadolinium in MRI contrast agents for battlefield trauma care.

7.2 Graphene Strategies Across the REE Spectrum

7.2.1 Reducing Magnet REE Content: GNP-Enhanced NdFeB Composites

Direct substitution of REE-based permanent magnets by graphene is not yet feasible for high-coercivity applications. However, GNP incorporation into NdFeB at 0.1–0.5 wt.% produces measurable performance improvements via two mechanisms:

1. **Grain-Boundary Diffusion Enhancement:** GNPs at grain boundaries facilitate Dy diffusion into the NdFeB lattice, enabling a 20–30% reduction in bulk Dy content while maintaining equivalent coercivity at operating temperature.
2. **Microstructural Refinement:** GNPs pin grain growth during sintering, reducing average grain size from ∼5 μm to ∼3 μm, increasing coercivity by 8–15% without additional REE content.

7.2.2 Graphene-Based Motor Architectures: The Long Game

The most impactful long-term substitution pathway lies not in replacing REE in existing magnet designs but in replacing permanent-magnet motors with superior graphene-based electromechanical architectures.

Carbon-based supercapacitors combined with graphene armature windings can in principle eliminate the permanent magnet entirely from certain motor topologies:

- **Switched Reluctance Motors + Graphene Windings:** Zero rare earth content; graphene copper-composite windings (30–40% conductivity improvement over pure Cu) compensate for the lower power density of SRM topology.
- **High-Temperature Superconductor-Graphene Hybrids:** At TRL 3 for aerospace applications; potential for 5× power density improvement over NdFeB motors with zero rare earth content.

7.2.3 REE Phosphor Substitution: Quantum Dot Graphene Emitters

Graphene quantum dots (GQDs)—zero-dimensional graphene fragments 2–10 nm in diameter—exhibit size-tunable photoluminescence covering the entire visible spectrum. By controlling

GQD size, the emission wavelength is tuned from 400 nm (blue) to 700 nm (red) through quantum confinement.

$$E_{emission} \approx E_g + \frac{\hbar^2 \pi^2}{2m^* r^2} \tag{6}$$

GQD luminescent efficiency currently reaches 40–60% quantum yield, approaching but not matching the 80–95% yield of REE phosphors. For non-critical luminescent applications (indicator panels, non-image-intensifying displays), GQDs represent a viable near-term substitute with zero rare-earth content.

The rare earth problem is about the magnets in our missiles, drones, and ships. Right now, the best magnets use neodymium and dysprosium — and China makes essentially all of them.

Graphene can't outperform these magnets yet in a head-to-head competition, but it can stretch the rare earths we do have 20–30% further, and it can ultimately replace the entire motor design so that the magnet is no longer needed at all. It's like discovering that if you redesign the engine, you don't need the specific fuel China controls.

Position: GNP-enhanced NdFeB composites reduce Dy consumption by 20–30% within 24 months at TRL 5–6. Magnet-free graphene motor architectures are a 10–15-year transition.

Consequence: A 25% reduction in Dy content per magnet, applied across the U.S. defense procurement base, translates to equivalent capability with 25% fewer restricted exports from China. Given that China completely blocks military-end-use exports of Dy today, any reduction is strategically significant.

Next Action: ANMM to partner with a domestic magnet manufacturer (e.g., Arnold Magnetic Technologies or Electron Energy Corp) on GNP-NdFeB grain-boundary engineering under a DoD MANTECH program.

8 Cobalt (Co): The Battery Supply Chain Vulnerability

Graphene Substitution Potential: ●●●●● **5/5** — *Near-Full Substitution in Battery Applications Within 3–5 Years*

8.1 Strategic Profile

Cobalt is the cathode material in lithium-ion batteries that provides:

- Thermal stability (preventing thermal runaway)
- High specific energy density
- Cycle life >1000 cycles at 80% depth of discharge

The Democratic Republic of Congo (DRC) supplies ∼70% of global cobalt; China controls ∼80% of cobalt refining. This represents the most concentrated supply chain vulnerability on the entire critical minerals list.

8.2 Graphene Anode Technology: The Cobalt Eliminator

The most strategically impactful application of graphene to cobalt supply chains is in battery architecture. The standard lithium-ion battery uses a graphite anode and a cobalt-containing cathode ($LiCoO_2$, NMC, or NCA chemistry).

8.2.1 Graphene-Enhanced Anodes: Silicon Stabilization

Silicon anodes offer 10× the theoretical capacity of graphite (4200 mAh/g vs. 372 mAh/g) but suffer from 300% volumetric expansion upon lithiation, causing pulverization and capacity fade. Graphene solves this:

- GNP-wrapped silicon nanoparticles (Si@G) buffer volumetric expansion through elastic deformation of the graphene shell.
- Cycle retention of Si@G: >85% after 500 cycles (vs. bare Si: <20%).
- Practical gravimetric energy: $800 - -1200$ mAh/g — 3× conventional graphite.

A battery achieving 3× the anode capacity requires 3× less cobalt in the cathode to achieve equivalent cell voltage and energy output. This is not indirect — it is a direct, calculable cobalt demand reduction.

8.2.2 Lithium-Sulfur with Graphene: The Cobalt-Free Architecture

Li-S batteries using graphene sulfur-host cathodes are completely cobalt-free and offer theoretical energy density of 2600 Wh/kg — 5× conventional Li-ion. The graphene cage traps polysulfide intermediates that previously caused rapid capacity fade, with recent demonstrations showing >1000 cycles at > 800 Wh/kg.

DoD applications: man-portable electronics, unmanned ground vehicles, directed-energy weapon power supplies, and submarine auxiliary power where energy density per kg is mission-critical.

Position: Graphene provides the clearest, most technically mature substitution pathway on the entire critical minerals list for cobalt. Si@G anodes are at TRL 6–7 for consumer applications and TRL 5 for military-grade cells.
Consequence: Full deployment of graphene silicon anode technology across DoD battery procurement would eliminate cobalt as a strategic vulnerability within 5–7 years.
Next Action: ANMM's TBM-100 aluminum-ion battery system (Patent No. 63/988,083) provides a complementary pathway using an entirely different electrochemistry. ANMM should pursue joint development with DoD battery prime contractors for military-specification graphene-Si cell qualification.

9 Indium (In): Transparent Conductors and the ITO Replacement

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Graphene Substitution Potential: ●●●●● **5/5** — *Near-Complete Substitution Available Now (TRL 6–7)*

9.1 Strategic Profile

Indium tin oxide (ITO) is the dominant transparent conducting material in:

- Touchscreen displays and heads-up display (HUD) assemblies
- Electroluminescent panels in cockpit instrumentation
- Liquid crystal display (LCD) electrodes across all military platforms

- Solar cell front contacts for space-rated photovoltaics

China controls >55% of global indium production. Export controls on indium were imposed in February 2025. ITO is intrinsically brittle, cannot be deposited on flexible substrates, and degrades under mechanical flexing.

9.2 Graphene Transparent Conductors: A Drop-In Replacement

CVD graphene transparent conducting films represent one of the most commercially mature graphene applications and the closest to a direct, drop-in substitution for ITO.

Table 3: CVD Graphene vs. ITO as Transparent Conductor

Property	**ITO**	**CVD Graphene (4-layer)**
Sheet Resistance	10–50 Ω/sq	30–125 Ω/sq
Optical Transmittance (550 nm)	85–92%	90.8%
Flexibility	Brittle (fractures >2% strain)	Flexible (>6% strain, no degradation)
Deposition Temperature	200–400°C	25°C (transfer method)
Strategic Material Content	Indium (critical)	Carbon (non-critical)
Chemical Stability	Good	Excellent (pH 0–14)
Cost (large area)	Low ($5–20/m^2)	$50–200/m^2 (improving rapidly)

The sheet resistance of 4-layer CVD graphene (30——125 Ω/sq) approaches ITO performance for most non-ultra-high-resolution display applications. For military HUDs, cockpit displays, and ruggedized touch interfaces, the flexibility advantage of graphene is operationally significant: ITO-coated glass cracks under battle-damage vibration; graphene-coated polymer does not.

Position: CVD graphene transparent conductors are commercially deployable today for military display applications. This is the single fastest critical-mineral substitution opportunity on this list.

Consequence: Full substitution of ITO with CVD graphene in DoD display procurement would eliminate indium as a supply chain vulnerability entirely within 24 months.

Next Action: ANMM to partner with a DoD display supplier for qualification testing of CVD graphene transparent electrodes under MIL-STD-810H environmental conditions.

10 Tantalum (Ta): Capacitors and the Electronic Heartbeat

Graphene Substitution Potential: ●●●●○ **4/5** — *Graphene Supercapacitors Provide Strong Supplementation and Eventual Substitution*

10.1 Strategic Profile

Tantalum electrolytic capacitors are in virtually every piece of military electronics. Their combination of high capacitance density, stability across temperature, and reliability is unmatched by ceramic or aluminum electrolytic alternatives in high-rel military applications. The Congo (DRC) and Rwanda supply ∼60% of global tantalum.

10.2 Graphene Supercapacitors as Tantalum Capacitor Replacements

Electrochemical double-layer capacitors (EDLCs) using graphene electrodes achieve:

$$C = \frac{\varepsilon_0 \varepsilon_r A}{d} \tag{7}$$

With the full double-layer $d \approx 5$ Å and graphene surface area $A = 2630$ m^2/g, the theoretical gravimetric capacitance is:

$$C_{theoretical} \approx 550 \text{ F/g} \quad \text{(experimental: 200–400 F/g in ionic liquid electrolytes)} \tag{8}$$

Compared to Ta capacitors' typical 100–560 , graphene supercapacitors in a matched footprint can provide 100–1000× higher capacitance, with:

- Charge/discharge time <1 ms (vs. Ta: typically > 10 ms)
- Cycle life $> 10^6$ (vs. Ta electrolytic: $\sim 10^4$–10^5 rated)
- Temperature range -40°C to $+85$°C (matching Ta mil-spec)
- No tantalum content

The key current limitation is energy density at low frequency: for bulk energy storage requiring time constants >1 second, Ta capacitors retain an advantage. For filtering, decoupling, and pulse-power applications (the majority of military capacitor use cases), graphene supercapacitors are technically superior.

Position: Graphene EDLCs at TRL 5–6 can displace tantalum capacitors in pulse-power and decoupling applications—approximately 60–70% of DoD tantalum demand—within 3–5 years.

Next Action: ANMM should develop a MIL-PRF-39003-equivalent graphene EDLC product line targeting EW system power management boards and radar transmitter modules.

11 Chromium (Cr): Corrosion Protection and Structural Coatings

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Graphene Substitution Potential: ●●●●○ **4/5** — *Graphene Barrier Coatings Strongly Competitive with Hexavalent Chromium*

11.1 Strategic Profile

Chromium has two distinct defense roles:

- **Stainless steel alloys:** > 10.5 %Cr provides passivation layer resistance to corrosion.
- **Hard chrome plating:** Hexavalent chromium (Cr^{6+}) electroplating for hydraulic actuators, aircraft landing gear, and gun barrels. HEXCHROME (Cr^{6+}) is a known carcinogen under REACH and is being phased out in EU and increasingly restricted in U.S. DoD applications.

11.2 Graphene Corrosion Barrier: A Dual Win

Graphene is thermodynamically and chemically the most impermeable material known. A single monolayer of CVD graphene on copper reduces the corrosion rate by a factor of >100 in NaCl solution, superior to conventional organic coatings of equivalent thickness.

The mechanism is simple and thermodynamically rigorous: graphene's zero porosity prevents all ionic and molecular transport, eliminating the electrochemical pathway for corrosion.

For DoD applications, graphene-epoxy nanocomposite coatings at 3–5 wt.% GNP loading:

- Reduce oxygen transmission rate by 40–60% compared to unfilled epoxy.

- Reduce water vapor transmission rate by 35–50%.
- Provide tribological protection (COF reduction from 0.4 to 0.08).
- Comply with REACH, TSCA, and DoD hazardous materials reduction mandates.
- Eliminate the need for hexavalent chromium pre-treatments on aluminum airframe components.

Position: Graphene-epoxy corrosion coatings are at TRL 6–7 and directly displace hexavalent chromium plating in non-bearing structural applications. This is a regulatory compliance win (Cr^{6+} phase-out) *and* a supply chain de-risking win simultaneously.

Next Action: ANMM to develop GraphMount (Patent No. 63/985,632) formulations certified to SSPC-SP 10 surface preparation and MIL-PRF-23377 primer equivalency for military aircraft maintenance depots.

12 Nickel (Ni) and Titanium (Ti): Structural Lightweighting

Graphene Substitution Potential: ●●●○○ **3/5** — *Composite Reinforcement Reduces Demand; No Direct Substitution*

12.1 Strategic Profile

Nickel: Superalloy base material (Inconel, Waspaloy) for turbine blades and compressor stages in jet engines; cathode material in NMC/NCA lithium-ion batteries.

Titanium: Lightweight structural material for airframe components, submarine pressure hulls, and implantable medical devices for combat casualty care. Russia controls ∼30% of global titanium sponge production; China processes ∼50% of global titanium for aerospace grade.

12.2 Graphene Composite Reinforcement: The Weight Reduction Equation

Graphene-reinforced aluminum (GRA) composites represent the highest-impact structural application:

- At 1–3 wt.% GNP loading in aluminum 6061 alloy, ultimate tensile strength increases from 310 MPa to 480 MPa (+55%).
- Elastic modulus increases from 69 GPa to 95 GPa (+38%).
- Density remains essentially unchanged (2700 kg/m^3).

The specific strength of GRA (178 kN·m/kg) approaches that of titanium alloy Ti-6Al-4V (213 kN·m/kg) while maintaining the cost and processability advantages of aluminum. In applications where titanium is specified for strength-to-weight rather than corrosion resistance, GRA offers a credible substitution pathway with a 60% cost reduction.

Similarly, graphene-reinforced nickel superalloys (GRN) at 0.5 wt.% GNP show creep resistance improvements of 20–30% at 900 °C, enabling thinner, lighter turbine blade cross-sections with equivalent service life—reducing nickel content per part by 15–25%.

Position: GRA composites can substitute for titanium in structural airframe applications (not corrosion-critical) at significant cost savings and with reduced supply chain exposure. GRN composites reduce nickel consumption per turbine engine by 15–25%.
Next Action: ANMM's SuperWall composite system (Patent No. 63/988,080) should be qualified for structural airframe secondary structure applications under MIL-HDBK-17 composite material allowables.

13 Platinum Group Metals (PGMs): Catalysts and Fuel Cells

Graphene Substitution Potential: ●●●●○ **4/5** — *Graphene Catalysts Reduce PGM Loading by 70–90% in Fuel Cell Applications*

13.1 Strategic Profile

Platinum (Pt) and palladium (Pd) are essential catalysts in:

- Proton exchange membrane (PEM) hydrogen fuel cells for military vehicles and silent-operation submarines.
- Catalytic converters for military vehicle fleet exhaust compliance.
- Chemical agent detection sensors (catalytic decomposition of VX, GB, HD).

South Africa produces ∼70% of global platinum; Russia produces ∼40% of global palladium. Both supply chains are geopolitically exposed.

13.2 Graphene as a Platinum Loading Reducer

The oxygen reduction reaction (ORR) at the PEM fuel cell cathode:

$$\mathrm{O_2 + 4H^+ + 4e^- \rightarrow 2H_2O} \qquad E^\circ = +1.23V \tag{9}$$

requires platinum as the catalyst to achieve practical reaction rates. Graphene provides a high-surface-area support platform with strong Pt-graphene interaction that:

- Disperses Pt nanoparticles to sub-2-nm diameter, maximizing active surface area.
- Prevents Pt agglomeration and dissolution over the fuel cell lifetime.
- Nitrogen-doped graphene (N-GNP) achieves intrinsic ORR activity approaching Pt/C reference catalysts.
- Pt/N-GNP composite catalysts achieve equivalent current density to Pt/C with 70–80% less platinum loading (from 0.4 mg/cm^2 to 0.08 mg/cm^2).

Position: Graphene catalyst supports reduce platinum demand in PEM fuel cells by 70–80% while maintaining or improving performance. This is one of the most technically mature critical mineral reduction applications, with commercial deployments by Toyota and GM already incorporating graphene-supported Pt catalysts.
Next Action: ANMM to develop N-doped GNP catalyst support material for DoD fuel cell vehicle programs and the Navy's submarine AIP (Air-Independent Propulsion) program.

14 Vanadium (V) and Manganese (Mn): Grid Storage and Steel

Graphene Substitution Potential: ●●●○○ **3/5** — *Graphene Flow Battery Electrodes Reduce V Demand; Mn-Graphene Cathodes Reduce NMC Content*

14.1 Vanadium Redox Flow Batteries

Vanadium redox flow batteries (VRFBs) provide grid-scale energy storage for military forward operating bases (FOBs) and resilient power nodes, but require substantial vanadium inventory as the electrolyte active species. Graphene modification of the carbon felt electrodes (currently the performance-limiting component) increases power density by 40–60%, reducing the electrolyte volume (and vanadium inventory) required per unit of stored energy by 30–45%.

14.2 Graphene-MnO_2 Composite Cathodes

MnO_2 is a cobalt-free, lithium-free cathode material with theoretical capacity of 308 mAh/g. Its practical limitation is poor electrical conductivity (< 0.01 S/m). GNP-wrapped MnO_2 (graphene-MnO_2 nanocomposite):

- Achieves 210 mAh/g practical capacity (vs. 70–100 for unmodified MnO_2).
- Eliminates cobalt and nickel from the cathode chemistry entirely.
- Manganese resources are geographically diverse (South Africa, Australia, Gabon); supply chain risk is significantly lower than for cobalt or nickel.

Position: Graphene-MnO_2 cathodes represent a path to cobalt-free, nickel-free, China-free battery chemistry. A Mn-graphene cell with a graphene-Si anode is potentially the most strategically sovereign battery chemistry achievable.
Next Action: ANMM to develop a full graphene-Si $\|$ G-MnO_2 prototype cell for DoD field battery qualification.

15 Lithium (Li): Electrolytes and Solid-State Pathways

Graphene Substitution Potential: ●●●○○ **3/5** — *Demand Reduction via Energy Density; Solid-State Enables Partial Substitution*

Lithium is unavoidable in current Li-ion battery chemistry, but graphene reduces the *amount* of lithium required per unit of stored energy through two mechanisms:

1. **Anode Capacity Increase:** Si@G anodes storing 3× more lithium per unit mass

mean a given battery capacity requires 3× less anode material, proportionally reducing overall cell mass and electrolyte volume (and hence lithium content) by 20–35%.

2. **Solid-State Electrolyte Enhancement:** Graphene-doped polymer solid electrolytes achieve Li^+ conductivity of $> 10^{-4}$ S/cm at room temperature while eliminating the liquid electrolyte phase—reducing lithium hexafluorophosphate ($LiPF_6$) salt content and enabling safer operation in combat environments.

> Graphene does not eliminate lithium from battery chemistry in the near term. It makes every gram of lithium work harder, extending the strategic value of domestic lithium reserves and allied-nation supply.

16 Silicon (Si) and Semiconductor Architectures Beyond China

Graphene Substitution Potential: ●●●●○ **4/5** — *Graphene Nanoelectronics Reduce Silicon Node Dependency on Foreign Fabrication*

Silicon itself is not a supply chain problem—the U.S. has abundant quartz resources. The strategic problem is *silicon semiconductor fabrication* concentrated in TSMC (Taiwan) and Samsung (Korea), with Chinese pressure on both. For the sub-5nm node critical for next-generation defense electronics, graphene-based computing offers an eventual path to domestic chip production at nodes where silicon physics fails.

Graphene nanoribbons (GNRs) with widths of 1–5 nm exhibit controlled bandgaps and can in principle be produced by bottom-up chemical synthesis on U.S. soil, without the extreme photolithographic facilities required for silicon sub-5nm processing.

> The most advanced chips in the world are made in Taiwan. China wants Taiwan. If China takes Taiwan, we lose the ability to make the chips in our most advanced weapons systems. Graphene offers a path to a different type of chip — one that doesn't need the $20 billion factory in Taipei to produce it. It's a fifteen-year transition, but the work needs to start today, because the geopolitical clock is running.

17 Bismuth (Bi), Tellurium (Te), and Molybdenum (Mo)

Graphene Substitution Potential: ●●●●● **2/5** — *Limited Graphene Substitution; Demand Reduction Pathways*

These three minerals, subject to Chinese export controls since February 2025, have more limited graphene substitution pathways:

Bismuth: Used in thermoelectric generators (Bi_2Te_3) and non-toxic lead ammunition projectiles. Graphene-doped Bi_2Te_3 improves thermoelectric figure of merit ZT by 15–25% through phonon scattering, reducing bismuth content per unit of thermoelectric output. Direct substitution is not feasible.

Tellurium: Used in CdTe solar cells (space power) and Bi_2Te_3. Graphene-perovskite tandem solar cells offer potential CdTe-free space solar power, but are at TRL 2–3 for space-qualified applications.

Molybdenum (Mo): Alloying element in high-strength steel and lubricant (MoS_2 in extreme pressure gear oils). Graphene's superlubricity in vacuum ($\mu < 0.001$) is relevant to space mechanism lubrication as an MoS_2 supplement, but terrestrial Mo alloyed steel has no near-term graphene substitute.

18 Beryllium (Be) and Hafnium (Hf): The Precision Defense Materials

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Graphene Substitution Potential: ●●●●● **2/5** — *Limited; Specific Application Partial Substitution Only*

Beryllium: The lightest structural metal (1850 kg/m^3), used in:

- X-ray windows for battlefield radiology
- Neutron reflectors in nuclear weapon primaries
- Precision optical mounts (gyroscopes, inertial navigation)

Graphene-reinforced aluminum can approach Be's specific stiffness (44 MPa) in optical mount applications where beryllium is used primarily for its low density and high modulus rather than nuclear properties. For nuclear applications, there is no graphene substitute.

Hafnium: Used as a control rod material in naval nuclear reactors and as a gate dielectric in advanced semiconductor nodes. No graphene substitution pathway exists for nuclear control rod applications.

19 The Consolidated Substitution Matrix

Table 4 presents the complete graphene substitution assessment across all seventeen mineral families analyzed, ordered by strategic priority.

Table 4: Graphene Substitution Potential Matrix for U.S. Critical Defense Minerals

Mineral	Primary Defense Application	Rating (1–5)	TRL Today	Timeline
Indium	ITO Transparent Conductors	5	6–7	1–2 yrs
Cobalt	Li-Ion Battery Cathodes	5	5–6	3–5 yrs
Gallium	GaN Radar / EW Electronics	4	4–5	5–7 yrs
Germanium	IR Optics / Night Vision	4	4–5	5–7 yrs
PGMs (Pt, Pd)	Fuel Cell Catalysts	4	6	2–4 yrs
Tantalum	Military Capacitors	4	5–6	3–5 yrs
Chromium	Corrosion Protection Coatings	4	6–7	1–3 yrs
REEs (Nd, Dy)	Permanent Magnets	3	4–5	5–10 yrs
Tungsten	WC Bearings / Penetrators	3	3–5	2–4 yrs (demand reduction)
Antimony	Flame Retardants	3	5–6	2–3 yrs
Nickel	Superalloys / Battery Cathodes	3	4–5	5–7 yrs
Titanium	Structural Airframe	3	5–6	3–5 yrs
Vanadium	Flow Battery Electrodes	3	4–5	3–5 yrs
Manganese	Li-Ion Cathode Chemistry	3	4–5	3–5 yrs
Lithium	Battery Electrolyte Demand	3	5–6	2–4 yrs
Silicon	Next-Gen Semiconductors	4	2–3	10–15 yrs
Bismuth	Thermoelectrics	2	3–4	5–8 yrs
Beryllium	Optical Mounts	2	4–5	5–8 yrs
Tellurium	Space Solar Cells	2	2–3	10–15 yrs
Hafnium	Nuclear Control Rods	1	N/A	Not feasible
Molybdenum	Steel Alloying	1	N/A	Not feasible (near-term)

Rating: 1=Minimal, 2=Limited, 3=Moderate Demand Reduction, 4=Strong, 5=Near-Full Substitution

20 ANMM as the Defense Industrial Base Platform

20.1 Why Puerto Rico and Why Now

Advanced Nano-Materials Manufacturing LLC (ANMM) occupies a unique strategic position:

- **Domestic but competitive:** Puerto Rico is a U.S. territory, fully subject to defense procurement rules and ITAR, yet operates under Act 60 tax incentives (0–4% effective corporate tax rate) that provide cost competitiveness with foreign producers.
- **Circular economy input:** The Plastex Corporation acquisition in Isabela, PR, provides a waste plastic feedstock for graphene production via flash Joule heating and related pyrolytic processes, creating a circular supply chain entirely within U.S. jurisdiction.
- **Caribbean and Pacific rim logistics:** La Parguera facility and San Juan offices provide access to both U.S. mainland distribution and Caribbean/LATAM markets.
- **Established government relationships:** ANMM's founder has served as DPA Title III Advisor at Pearl Harbor (2024), providing direct working relationships within the DoD industrial base policy apparatus.
- **IP portfolio:** Six provisional patents filed February 2026 covering GraphMount-Epoxy (63/985,632), GraphCool-Roof (63/985,650), GraphPlast asphalt modifier (63/985,825), EMPCrete (63/986,486), SuperWall (63/988,080), and TBM-100 aluminum-ion battery (63/988,083).

20.2 DPA Title III: The Right Funding Instrument

Defense Production Act Title III authorizes the President to take actions to create, maintain, protect, expand, or restore domestic industrial base capabilities essential to national defense. ANMM's graphene production platform is precisely the type of capability for which Title III was designed:

- No commercial market currently provides sufficient production scale.
- The capability directly addresses identified supply chain vulnerabilities in the National Defense Authorization Act.

- The technology is at TRL 4–6, in the "valley of death" between laboratory and commercial scale — precisely where government capital is most needed.

Recommended Title III program request: \$45–65M over 3 years for a Puerto Rico graphene production facility capable of 50 MT/year of defense-grade GNP, CVD graphene on flexible substrate, and GNP-composite masterbatch materials.

> The Defense Production Act was written so the government can fund factories that the private sector won't build fast enough on its own — especially when those factories are critical to winning a war. ANMM is building the American graphene factory. We're not asking for a handout; we're asking the government to do exactly what the DPA was written to do: pay to build something that protects the country. The factory happens to be in Puerto Rico, where U.S. citizens live, where taxes are competitive, and where we can take waste plastic from the Caribbean and turn it into the material that protects American soldiers. That's the story. It's a good one.

21 The National Action Framework

21.1 A Three-Speed Strategy

Given the diversity of TRL levels and substitution potentials across the critical minerals list, a three-speed implementation framework is proposed:

21.1.1 Speed 1: Deploy Now (0–24 Months)

Applications at TRL 6–7 ready for defense procurement qualification:

- CVD graphene replacing ITO in military HUDs and cockpit displays.
- GNP-epoxy corrosion coatings replacing hexavalent chromium on aluminum airframes.
- GNP flame-retardant masterbatch in military electronics enclosures.
- Graphene-Pt/N-GNP catalyst supports for DoD fuel cell programs.

21.1.2 Speed 2: Develop and Deploy (2–7 Years)

Applications at TRL 4–6 requiring targeted development investment:

- GaN-on-Graphene substrates for AESA radar and electronic warfare.
- Graphene-Si battery anodes for man-portable and vehicle battery systems.
- GNP-WC composite bearings for defense industrial tooling.
- Graphene EDLC capacitors for EW power management.
- GNP-NdFeB composite magnets with reduced dysprosium content.

21.1.3 Speed 3: Invest and Seed (7–15 Years)

Applications at TRL 2–4 requiring fundamental technology investment:

- Graphene nanoribbon transistors for post-silicon semiconductors.
- Graphene-quantum-dot phosphors for REE-free displays.
- Graphene-high-temperature-superconductor hybrid motor architectures.

21.2 Recommended Government Actions

1. **DPA Title III Industrial Base Investment:** Fund domestic graphene production capacity at 100–500 MT/year to underpin Speed 1 and Speed 2 applications. Priority sites: Puerto Rico (ANMM), Texas, and Ohio.

2. **DARPA/DoD SBIR Programs:** Launch targeted BAA solicitations for GaN-on-Graphene radar substrates, graphene-Si battery cells, and graphene EDLC capacitors, with TRL 7 milestones and a clear path to MIL-SPEC qualification.

3. **National Defense Stockpile Augmentation:** While developing graphene substitutes, the NDS should immediately accelerate procurement of tungsten, antimony, and gallium from non-Chinese allied sources (Australia, Canada, South Korea) using the $2B appropriation from the One Big Beautiful Act.

4. **ITAR and EAR Exclusion Clarification:** ANMM recommends that DoD and the Department of Commerce issue clarifying guidance on the export control treatment of graphene nanomaterials to prevent allied-nation supply chain friction while maintaining China/FEOC restrictions.

5. **Act 60 Expansion for Advanced Materials Manufacturers:** Puerto Rico's industrial policy authority should recognize graphene production as a qualifying Act 60

export service activity, providing maximum tax incentive alignment with defense industrial base priorities.

22 Risk Analysis and Intellectual Honesty

This analysis has been deliberately critical of overstatements regarding graphene substitution potential. Key risk factors that could delay or limit the pathways described:

1. **Production Scale Gap:** Current global graphene production (all forms) is estimated at ∼1,000 MT/year. Defense applications described in this paper would require 5,000–50,000 MT/year at full deployment. The investment required to close this gap is substantial and will not occur without government catalysis.

2. **Qualification Timeline:** Military qualification (MIL-SPEC, MIL-PRF, QPL listing) for new materials typically requires 3–7 years even after TRL 7 demonstration. Speed 1 applications assume this timeline is compressed through proactive engagement with military qualification authorities.

3. **Supply Chain Depth:** Domestic graphene production requires carbon precursors, high-purity gases (Ar, H_2, CH_4), and specialized furnace equipment. Some of these inputs have their own supply chain vulnerabilities. A full supply chain analysis for ANMM's production facility is recommended prior to Title III application.

4. **Adversarial IP Acquisition:** China is the world's largest publisher of graphene research and holds significant graphene-related patent portfolios. U.S. defense applications should build on domestically-held IP (including ANMM's provisional patent portfolio) and should incorporate export control clauses preventing technology transfer.

5. **Cost Competitiveness:** Several graphene substitutions (CVD graphene for ITO, GNP-composite bearings) currently carry a cost premium of 2–5× over the incumbent material. This premium will decrease with scale but must be accounted for in defense procurement cost modeling.

23 The 1000-Year Test

ANMM's foundational philosophy asks a deceptively demanding question: *Will someone look at this in 100 or 1000 years and say that was the right thing to do?*

Applied to this analysis, the answer is affirmative — not because the technology is perfect, but because the direction is correct.

The long arc of materials strategy in American history runs from wooden warships to steel battleships, from steel to aluminum, from aluminum to carbon fiber. Each transition required a national industrial bet at a moment when the need was not yet fully apparent.

The Chinese export control regime has made the need fully apparent.

Carbon is not a Chinese resource. Carbon is everywhere. It is in the air, in the ground, in the plastic waste choking Caribbean beaches, in the coal seams of Appalachia. A civilization that learns to work with carbon at the atomic level does not need to beg Beijing for germanium or gallium or rare earths. It grows its own electronics, builds its own magnets, and protects its own warships with materials derived from its own soil.

That is a 1000-year bet worth making. And it starts with a factory in Puerto Rico.

At dinner, someone asks: "Why should we spend billions on graphene when we could just mine more tungsten or buy more gallium from our allies?"
Here's the honest answer: You should do both. Mine the tungsten, buy the gallium — and build the graphene factory at the same time. Because thirty years from now, when carbon nanotube transistors are running your grandchildren's military hardware and graphene batteries are powering the fleet, you'll look back at 2026 and say:
"That was the year America decided to stop being held hostage by a periodic table someone else controlled."
That is worth the investment.

24 Conclusions

This analysis establishes the following central conclusions:

1. **China's mineral weapon is real and is not being fully disarmed.** The November

2025 diplomatic truce is a tactical pause. The military-end-use prohibition on all dual-use mineral exports to U.S. defense users remains in effect and has never been suspended. Any defense procurement plan dependent on Chinese mineral supply for military-end-use applications is operating on borrowed time.

2. **Graphene provides viable substitution pathways for at least 21 of the 60 critical minerals on the 2025 USGS list.** Substitution ratings of 3 or above apply to 17 mineral families, covering the majority of the 12 strategic defense critical minerals identified by the Silverado Policy Accelerator.

3. **The most impactful near-term applications are:** ITO replacement (indium), hexavalent chromium coating replacement (chromium), fuel cell catalyst loading reduction (platinum group metals), and flame retardant replacement (antimony). These applications are at TRL 6–7 and require procurement policy change, not further research investment.

4. **The highest-impact medium-term applications are:** GaN-on-Graphene radar substrates (gallium), graphene-Si battery anodes (cobalt), and GNP-WC composite bearings (tungsten). These require $50–200M in focused development investment to reach TRL 7 within 3–5 years.

5. **ANMM is positioned to serve as the Defense Industrial Base platform** for domestic graphene production, leveraging Act 60 tax incentives in Puerto Rico, a circular economy feedstock from Caribbean plastic waste, and an established relationship with the DoD industrial base policy apparatus.

6. **The appropriate government instrument is DPA Title III,** supplemented by DARPA SBIR programs for Speed 2 applications and ONR/ARO basic research funding for Speed 3 technologies.

Final So What

The strategic question is not whether graphene can replace every Chinese-controlled mineral today. It cannot.

The question is whether the United States will make the 5, 10, and 15-year investments now to ensure that by 2030, 2035, and 2040, it is progressively less hostage to Beijing's mineral export control architecture.

Graphene is not a silver bullet. It is a systematic, technically credible, domestically producible material platform that addresses, to varying degrees, the majority of the nation's most acute mineral supply chain vulnerabilities.

The answer is yes: invest in ANMM, fund DPA Title III, qualify the applications, and build the American graphene industrial base — before the truce ends.

A Summary of ANMM Patent Portfolio (February 2026)

Table 5: ANMM Provisional Patent Portfolio Filed February 2026

USPTO App. No.	Title	Filing Date
63/985,632	GraphMount-Epoxy: Graphene-Enhanced Structural Adhesive	2/18/2026
63/985,650	GraphCool-Roof: Graphene Thermal Management Coating	2/18/2026
63/985,825	GraphPlast: Graphene-Modified Asphalt Composite	2/18/2026
63/986,486	EMPCrete: EMP-Hardened Graphene Concrete Composite	∼2/21/2026
63/988,080	SuperWall: Graphene Structural Panel System	2/22/2026
63/988,083	TBM-100: Aluminum-Ion Battery with Graphene Electrodes	2/22/2026

Inventor: Dr. Gregory S. Carmichael. Non-provisional filings due February 2027.

B Glossary of Technical Terms

AESA

Active Electronically Scanned Array — next-generation radar architecture using thousands of individual transceiver modules.

COF Coefficient of Friction.

CVD

Chemical Vapor Deposition — high-purity thin-film deposition technique for large-area graphene production.

DPA Title III
Defense Production Act Title III — statutory authority for government investment in domestic industrial base capabilities.

EDLC
Electrochemical Double-Layer Capacitor (supercapacitor).

FEOC
Foreign Entity of Concern — designation applied to Chinese, Russian, North Korean, and Iranian state-affiliated companies under NDAA provisions.

GFETs
Graphene Field-Effect Transistors.

GNP
Graphene Nanoplatelet — few-layer graphene produced in scalable processes.

GQD
Graphene Quantum Dot — sub-10nm graphene fragment with tunable photoluminescence.

ITO Indium Tin Oxide — incumbent transparent conductor material.

NdFeB
Neodymium-Iron-Boron — highest energy density permanent magnet material.

NDS National Defense Stockpile.

ORR
Oxygen Reduction Reaction — the kinetically limiting reaction in hydrogen fuel cells.

rGO Reduced Graphene Oxide — partially restored graphene produced via chemical or thermal reduction of graphene oxide.

TRL Technology Readiness Level (1–9 scale per NASA/DoD definitions).

C Contact Information

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"To strengthen American economic sovereignty by building the next generation of resilient financial infrastructure, advanced nano-materials manufacturing, and sustainable resource upcycling — creating dual-use technologies from Puerto Rico that serve investors, defense partners, and global markets alike."