Universal Lunar Structural Alloys

A Dual-Alloy Framework for Geochemically Constrained Production and Cislunar Manufacturing

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We propose two potentially strategic alloy families derived directly from lunar mineral feedstocks to support electromagnetic projectile launch to cislunar space: an aluminum-based alloy (LA-1 or LA-1T) sourced from anorthositic highland regolith, and a titanium-based alloy (LT-1) sourced from ilmenite-bearing mare regolith. The extreme accelerations the projectile experiences during launch deterministically specify the minimum mechanical properties these alloys must achieve. Both alloys are producible via a FFC electrochemical reduction facility, with O_2 as a coproduct [1, 2].

Coilgun barrel length Tens of meters → *Causes* → **Peak acceleration** ~10,000 G → *Forces* → **Peak axial launch stress** $\sigma_c = \rho LF / m$ → *Requires* → **Req'd alloy yield strength $\sigma_{y,t}$** 385 - 400 MPa

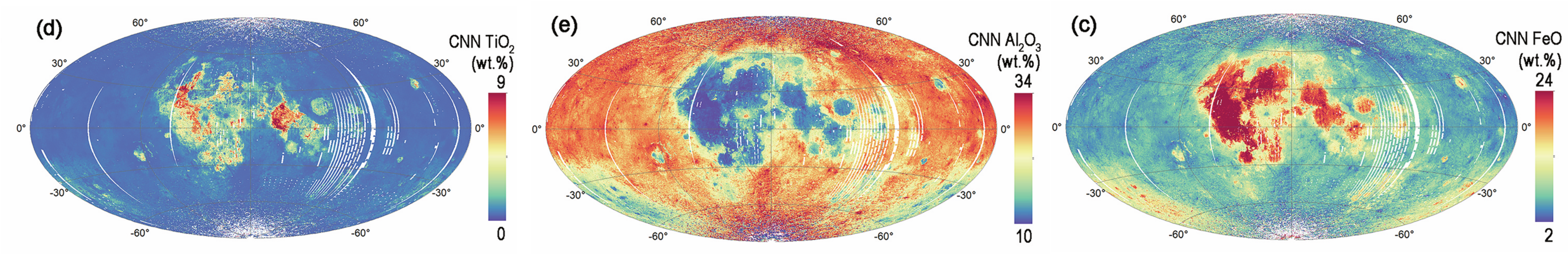
Peak inertial force (EM launched projectile): $F = ma = 100\ \text{kg} \times 98{,}100\ \text{m/s}^2 = 9.81\ \text{MN}$

Alloy Performance Summary

Alloy	Feedstock System	Target $\sigma_{y,tensile}$ (MPa)‡	SF* at L_{min}
LA-1	Al-Si-Mg-Fe (anorthositic highland)	200 ($AlSi_{10}Mg$-class)	0.52 ✗
LA-1T	Al-Si-Mg-Fe-Ti (highland + impact Ti)	385 - 400 (target)	~1.0+† ✓
LT-1	Ti-Al-Fe (ilmenite-bearing mare)	750+ (Ti-6Al-3Fe analog)§	1.96 ✓

* SF - Safety Factor. L_{min} refers to minimum feasible projectile length (estimated to be between 0.75 and 1.5 meters).
† LA-1T conditioned on confirmed TiO_2 in highland feedstock; yield strength is a design target pending experimental validation.
‡ $\sigma_{y,t}$ Denotes tensile yield strength, used as a conservative lower bound; compressive yield strength governs the launch stress state and is expected to be modestly higher.
§ LT-1 analog: Ti-6Al-3Fe, vanadium-free alpha-beta titanium system; Fe acts as beta stabilizer derivable directly from ilmenite FFC reduction [8].

Geochemical Basis ▼



Map 1 (Ti): High-TiO_2 concentrations confirmed at lunar poles (Qiu et al. 2025) and equatorial mare basins. Polar locations are strategically important because they co-locate with water ice for resource utilization.

Map 2 (Al): High-Al_2O_3 concentrations span the lunar highlands. Highland feedstock is the primary input for LA-1 (Al-Si-Mg-Fe) and LA-1T (with Ti microalloying).

Map 3 (Fe): Fe positively correlates with Ti in mare regions (supporting LT-1 Ti-Al-Fe composition) and inversely correlates with Al in highland regions (ensuring appropriate Fe content in LA-1 alloy without excess).

Lunar regolith partitions into two geochemically distinct provinces: anorthositic highland regolith and ilmenite-bearing mare regolith. Recent CNN-based reanalysis of Chang'e-6 orbital spectra by Qiu et al. (2025) [5], with supporting quantitative analysis from Shi et al. (2026) [6], confirms higher TiO_2 at the lunar poles than previously indicated by Apollo-era mapping, suggesting contamination or transport from mare regions.

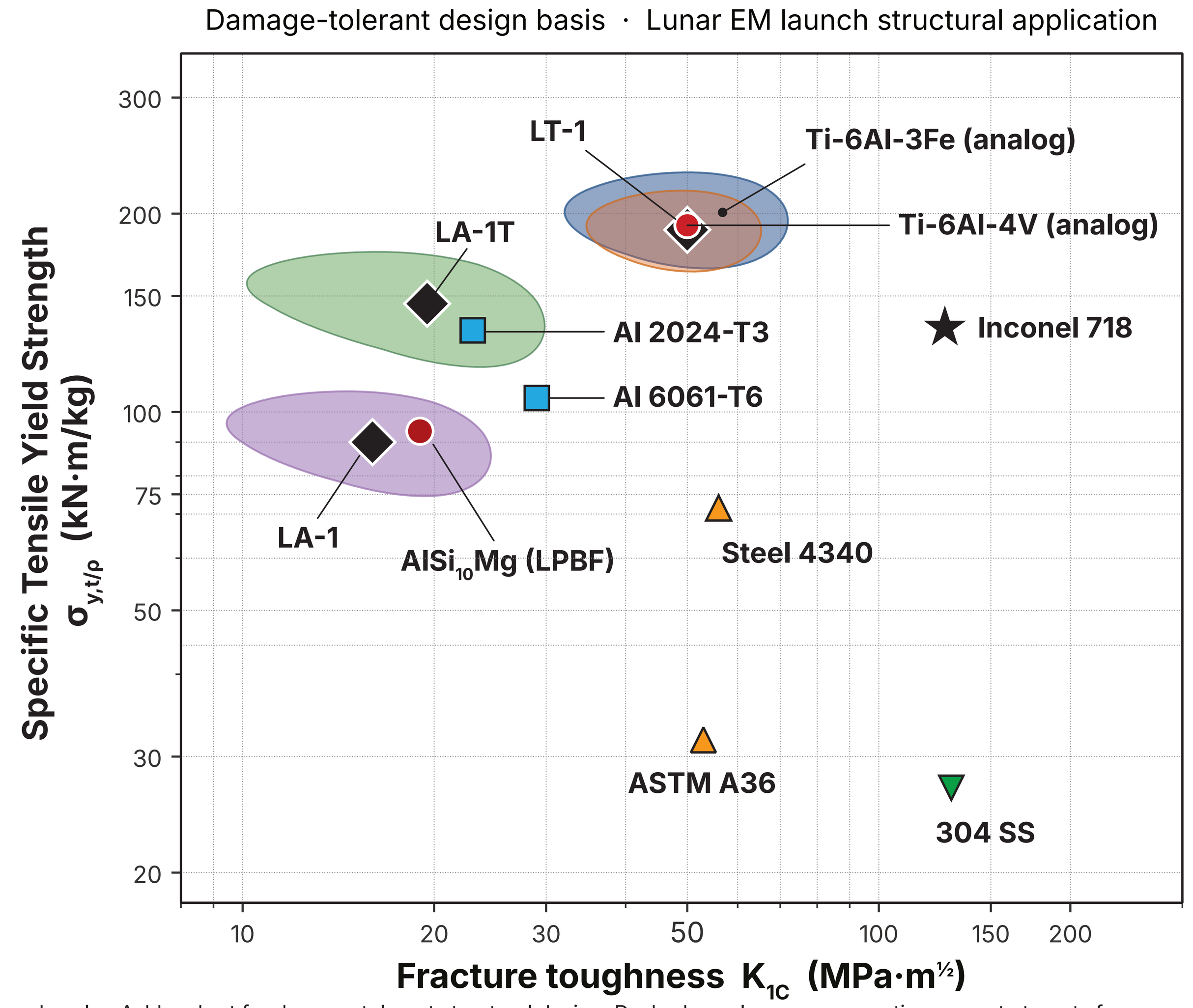
The dual-alloy strategy directly mirrors this geochemical partition: LA-1 and LA-1T derive from highland feedstock (high Al, low Fe), while LT-1 derives from mare feedstock (high Ti, with Fe naturally co-occurring through ilmenite $FeTiO_3$). The Fe map further confirms that LA-1 will receive appropriate (low) Fe content from highland processing, and LT-1 will receive the Fe it needs as beta-stabilizer from mare processing. Lunar geochemistry naturally prescribes the dual-alloy strategy rather than merely permitting it.

In both systems, mineral-feedstock fractionation upstream of FFC reduction may be required to bring the as-reduced metallic ratios into the target alloy composition window.

Alloy Specifications ▼

Materials Selection: Specific Strength vs Fracture Toughness

Damage-tolerant design basis · Lunar EM launch structural application



Log-log Ashby chart for damage-tolerant structural design. Dashed envelopes: conservative property targets for lunar alloys, adjusted for residual Fe from FFC electrochemical reduction. Y-axis is density-normalized yield strength; high-density materials (steels, Inconel) plot lower than absolute strength suggests. Ti-6Al-3Fe envelope estimated from Liu et al. [8]. †LA-1T: design target, conditional on confirmed TiO_2 in highland feedstock.

The chart plots specific tensile yield strength ($\sigma_{y,t}/\rho$, normalized by density) against fracture toughness (K_{1c}) on logarithmic axes. Damage-tolerant design under impulsive loading favors the upper-right region of this space, where high strength-to-weight and high resistance to crack propagation coincide. LA-1 (anorthositic-highland Al-Si-Mg-Fe) anchors the lower-left region of feasibility, comparable to AlSi10Mg in laser powder bed fusion condition [7]. Titanium microalloying lifts the LA-1T target into a substantially stronger position, conditional on confirmed TiO_2 in highland feedstock. The LT-1 envelope (ilmenite-bearing mare Ti-Al-Fe) overlaps directly with the Ti-6Al-3Fe analog [8] and falls within the property region established by Ti-6Al-4V, indicating that a novel vanadium-free, iron-stabilized titanium alloy derivable from mare regolith occupies the same engineering property space as standard aerospace titanium.

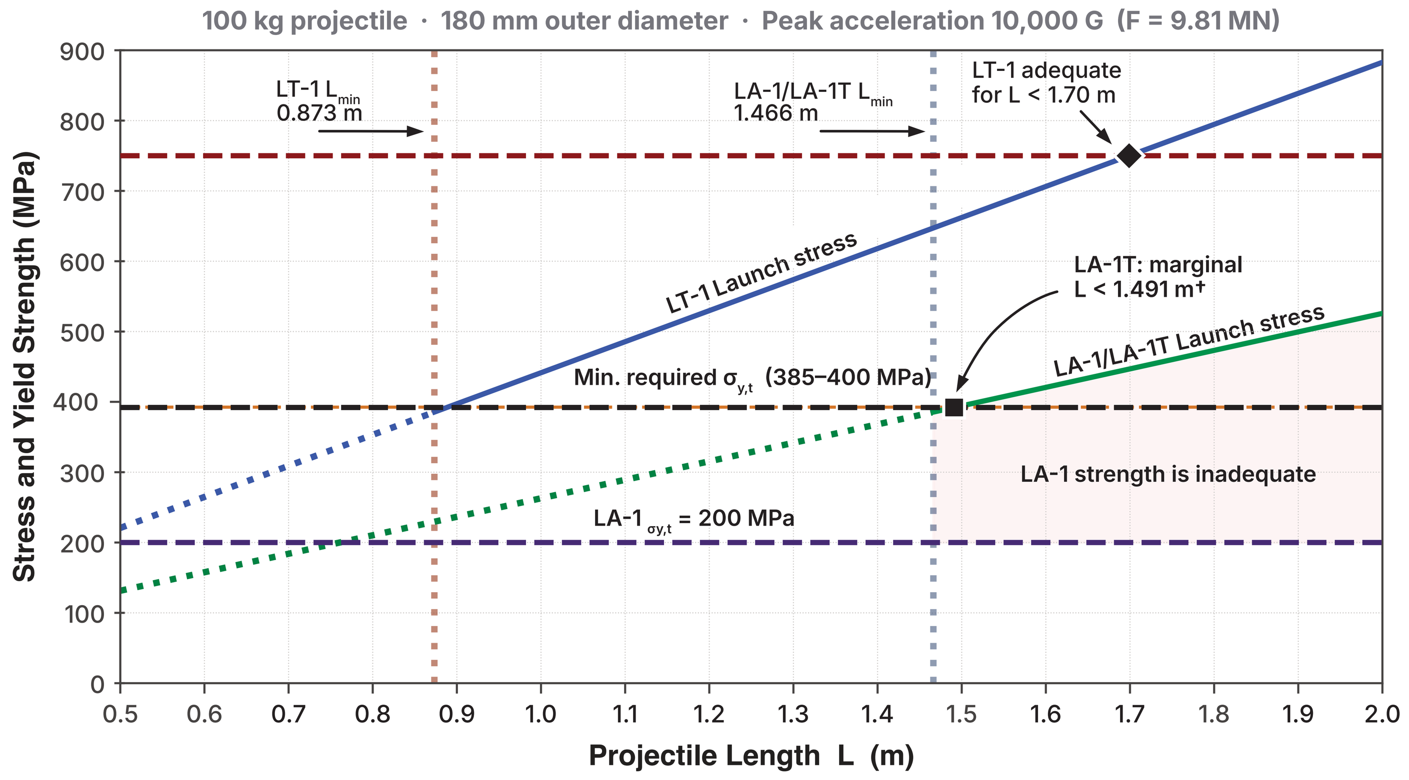
Structural steels (ASTM A36, 304 SS) sit far below all three lunar targets in specific strength, demonstrating why steel is not a competitive option for mass-efficient lunar structure despite the abundance of iron in mare regolith. Inconel 718 and 304 SS shown as terrestrial references only. Ni and Cr, both required at percent-level concentrations in these alloys, are essentially absent from lunar regolith (Ni occurs only as a minor siderophile contribution from meteoritic Fe-Ni metal, typically below 0.1 wt%).

- LA-1 target envelope (highland Al–Si–Mg–Fe)
- LA-1T target envelope (highland Al–Si–Mg–Fe–Ti†)
- LT-1 target envelope (mare Ti–Al–Fe)
- Ti-6Al-3Fe (Fe→V analog)
- Lunar alloy target points
- Close terrestrial analogs
- Standard Aluminum alloys [7,10]
- Standard Structural steels [10]
- Standard 304 stainless steel [10]
- Standard Inconel 718 (Ni superalloy) [10]

Structural Analysis ▼

Launch Stress and Alloy Yield Strength vs Projectile Length

100 kg projectile · 180 mm outer diameter · Peak acceleration 10,000 G (F = 9.81 MN)



Legend

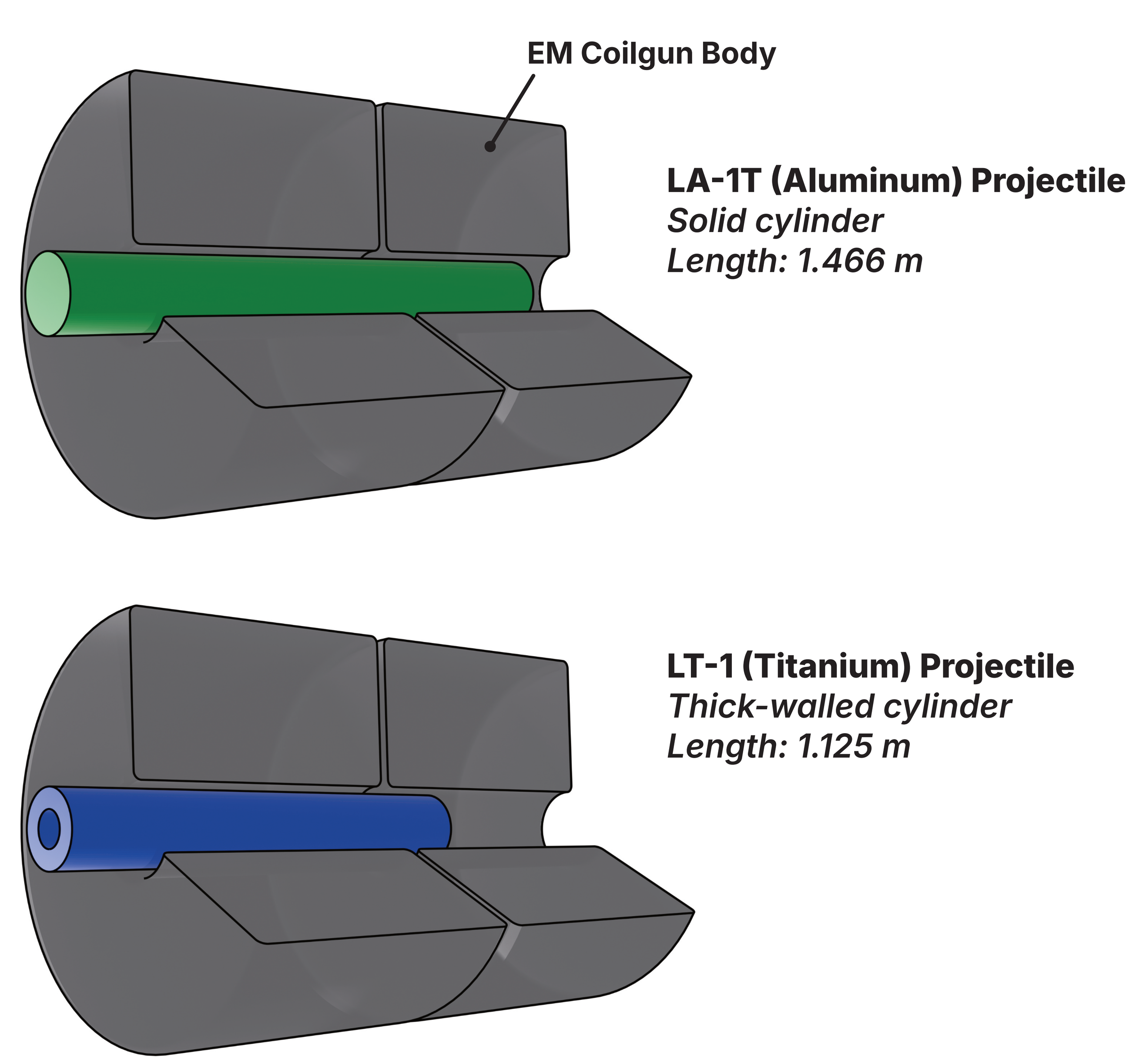
- LT-1 launch stress ($\sigma_c = \rho LF/m$, $\rho = 4{,}500\ \text{kg/m}^3$)
- LA-1 / LA-1T launch stress ($\sigma_c = \rho LF/m$, $\rho = 2{,}680\ \text{kg/m}^3$)
- LT-1 yield strength ($\sigma_{y,t} = 750$ MPa, Ti-6Al-3Fe analog)
- LA-1T yield strength† ($\sigma_{y,t} = 392$ MPa, design target)
- LA-1 yield strength ($\sigma_{y,t} = 200$ MPa, AlSi10Mg-class)

Notes:

1. Stress increases with increasing projectile length because wall thickness decreases (mass fixed at 100 kg, outer diameter fixed at 180 mm).
2. Diagonal lines: launch stress demand $\sigma_c = \rho LF/m$ (increases with length).
3. Horizontal dashed lines: alloy yield strength capability $\sigma_{y,t}$ (material property, independent of length).
4. Adequacy requires $\sigma_{y,t} > \sigma_c$
5. Net alloy cross-section $A = m/(\rho L)$ is implicit in σ_c; internal annulus diameter varies with L and ρ, providing a design variable for EM optimization.
6. Dotted lines: geometrically infeasible range (solid-cylinder lower bound).
7. Tensile $\sigma_{y,t}$ used as conservative lower bound for compressive yield [10].
8. †LA-1T: design target (385–400 MPa), conditional on confirmed TiO_2 in highland feedstock. Ti-6Al-3Fe analog [8,9].

Projectile Concept ▼

Electromagnetic Projectile Design Establishes the Material Requirements



Findings ▼

The EM launch environment serves as an extraordinary test of structural capabilities. Although derived from the structural requirements of electromagnetic launch, LT-1 and LA-1T represent a broader set of universal lunar structural alloy families producible from two distinct lunar provinces. Any alloy capable of surviving 10,000 G launch acceleration is likely structurally qualified for the most demanding lunar surface and cislunar manufacturing applications, including habitat construction, pressure vessels, and additive manufacturing.

Finding 1. Two distinct lunar provinces yield complementary alloy families. Anorthositic highland regolith provides aluminum, silicon, magnesium, and iron in the proportions needed for an AlSi10Mg-class structural alloy (LA-1). Ilmenite-bearing mare regolith provides titanium, iron, and aluminum in the proportions needed for a Ti-6Al-3Fe-class alloy (LT-1) [3,4,11]. The two alloys are not alternatives but companions, sourced from geochemically distinct provinces and serving different structural roles.

Finding 2. The FFC electrochemical reduction pathway is common to both alloys, with oxygen as a coproduct. The same processing facility can produce LA-1 from highland feedstock or LT-1 from mare feedstock, with the choice of regolith input determining the alloy output.

Finding 3. Titanium microalloying lifts LA-1 into the LA-1T envelope, conditional on confirmed highland TiO_2. Recent CNN-based reanalysis of orbital spectra calibrated against Chang'e-6 samples by Qiu et al. (2025) [5] suggests higher polar highland TiO_2 than Apollo-era mapping indicated. If confirmed, the highland feedstock can deliver enough titanium to reach the LA-1T target envelope of 385 to 400 MPa yield strength.

Finding 4. Under 10,000 G launch acceleration, LT-1 provides comfortable structural margin while LA-1T sits at the geometric and structural limit. LT-1 operates at SF ≈ 1.5 across a broad length window from 0.873 to 1.700 m, while LA-1T as a solid cylinder admits only one feasible configuration at SF ≈ 1.0. LA-1, lacking titanium microalloying, is not launch-rated at 10,000 G but remains adequate for habitat construction, pressure vessels, and other cislunar structural applications not subject to extreme acceleration loads.

Finding 5. Available mineral feedstocks (which determine alloy composition) constrain the length of the electromagnetic launcher. This is illustrated by the marginal structural adequacy of LA-1T at 10,000 G. Because peak acceleration scales inversely with coilgun length for a given exit velocity, any mission requiring aluminum-class projectiles imposes a lower bound on launcher geometry. LT-1, with a structural margin of approximately 50% at 10,000 G, enables more compact coilgun designs. The alloy selection therefore propagates upward into launcher sizing, illustrating how lunar geochemistry constrains not only materials but also system architecture.

References: [1] Chen G.Z., Fray D.J. and Farthing T.W. (2000) *Nature* 407, 361–364; [2] Lomax B.A. et al. (2020) *Planet. Space Sci.* 180, 104748; [3] Korotev R.L. (1997) *Meteorit. Planet. Sci.* 32, 447–478; [4] Korotev R.L. (2005) *Chem. Erde* 65, 297–346; [5] Qiu D. et al. (2025) *Commun. Earth Environ.* 6, 940; [6] Shi X. et al. (2026) *Nat. Sensors* 1, 232–240; [7] Aboulkhair N.T. et al. (2019) *Prog. Mater. Sci.* 106, 100578; [8] Liu Y. et al. (2020) *Metals* 10, 854; [9] Guo C. et al. (2026) "Fe modification of Ti-6Al-xV-yFe alloys," *J. Alloys Compd.* [online: https://www.sciencedirect.com/science/article/pii/S0925838826008522]; [10] ASM International (1990) *ASM Handbook* Vol. 1, Materials Park, OH; [11] Heiken G., Vaniman D. and French B.M., eds. (1991) *Lunar Sourcebook*, Cambridge Univ. Press, Ch. 7.

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