Universal Lunar Structural Alloys: A Dual-Alloy Framework for Geochemically Constrained Production and Cislunar Manufacturing. A. Daga,[1] [1]Department of Space Resources, Colorado School of Mines, Golden, CO 80401. Andrew_daga@mines.edu.

Introduction: This work is part of a larger research effort at the Colorado School of Mines to develop a lunar electromagnetic mass driver for exporting bulk structural materials from the lunar surface to cislunar manufacturing facilities. The concept involves a superconducting coilgun designed to accelerate a 100 kg metallic projectile to nearly 2.4 km/s, a speed sufficient to reach the Earth-Moon L1 or L2 Lagrange points without additional propulsion. Because the acceleration occurs over a barrel of practical length (tens of meters), the projectile experiences peak accelerations potentially reaching 10,000 times Earth's gravity, creating stresses much higher than those in typical aerospace structures. This paper explores the core materials science question stemming from this challenge: which metallic alloy compositions can be directly derived from documented lunar regolith feedstocks, withstand the launch environment of an electromagnetic coilgun, and serve as useful structural materials for orbital and surface manufacturing? One response to this constraint may be a dual-alloy framework consisting of two complementary universal structural alloys, designated LA-1 and LT-1, each geochemically aligned with one of the Moon's two main geological regions.

Geochemical Basis for a Dual-Alloy Approach: The Moon's surface is divided broadly between the anorthositic polar highlands and the ilmenite-bearing equatorial mare basalts, provinces that differ fundamentally in their oxide mineralogy and therefore in the metallic streams that ISRU extraction processes will naturally produce. Highland regolith, dominated by plagioclase feldspar (anorthite, $CaAl_2Si_2O_8$), yields aluminum–silicon–magnesium oxide mixtures amenable to aluminum alloy production. Mare regolith, rich in ilmenite ($FeTiO_3$) and pyroxene, yields titanium–iron–aluminum streams that favor titanium alloy systems. A single universal alloy is difficult to derive from both feedstocks without either extensive beneficiation or significant compositional compromise. The dual-alloy approach embraces this geochemical partitioning as a design feature: LA-1 is the highland alloy, LT-1 is the mare alloy, and together they constitute a versatile structural materials palette for cislunar industry.

Alloy Specifications: LA-1 belongs to the aluminum–silicon–magnesium family, directly analogous to the terrestrial $AlSi_{10}Mg$ system, the standard alloy for laser powder-bed and wire-arc additive manufacturing. Its composition is constrained to elements derivable from anorthositic feedstock and is engineered to tolerate elevated residual iron. Target density is approximately 2,680 kg/m³. LT-1 belongs to the titanium–aluminum–iron family, analogous to near-alpha and alpha-beta titanium aerospace alloys, exploiting the ilmenite reduction product stream directly with iron and aluminum retained as deliberate alloying constituents. Target density is approximately 4,500 kg/m³. Both alloys are proposed to be produced through a single unified electrochemical reduction process based on the FFC Cambridge method and its commercial derivatives, most notably the Metalysis platform under active investigation by the European Space Agency for lunar ISRU applications [1, 2]. In this process, a blended oxide feedstock serves as the cathode in a molten calcium chloride electrolyte at 800–1,000°C; oxygen ions migrate to the anode and are evolved as molecular oxygen, a coproduct of direct value for life support and propellant production. Alloy composition is controlled by the input oxide blend, yielding an oxide-in, alloy-out manufacturing paradigm that eliminates the multi-stage separation and remelting steps of conventional extractive metallurgy. Importantly, the same production pathway is used for both alloys, potentially permitting a single electrolytic facility to serve the full dual-alloy output stream by switching feedstock blends.

Materials Performance and Terrestrial Analogs: Figure 1 presents an Ashby-style plot of specific tensile yield strength ($\sigma y, t/\rho$) versus fracture toughness K_{1c} for LA-1 and LT-1 relative to their terrestrial analogs and standard structural reference materials [3-6]. Target property envelopes are derived by analogy to terrestrial alloy families of equivalent composition class, adjusted conservatively for residual iron from electrochemical reduction and the absence of optimized

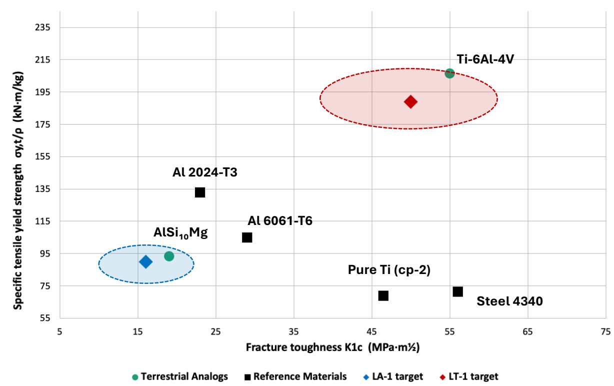

Fig. 1. Specific tensile yield strength ($\sigma y, t/\rho$) vs. fracture toughness $K_{1}c$ for LA-1 and LT-1 (dashed envelopes) relative to terrestrial analog alloys and structural reference materials. Note that the Y axis is density-normalized yield strength; high-density materials such as steel plot lower than their absolute strength would suggest. Target envelopes are conservative analogical estimates pending experimental validation; data from [3–6].

thermomechanical post-processing; they represent design targets pending experimental validation. Tensile values are used as the conservative basis; compressive yield strength is expected to be modestly higher for both alloy families, which is significant given that axial compression governs the launch stress state.

Fracture toughness K_{IC} is paired with specific strength because under impulsive loading, critical flaw size scales as $(K_{IC}/\sigma)^2$, making toughness as design-critical as yield strength for powder-processed compacts.

Electromagnetically Derived Alloy Requirements: Structural alloy requirements for lunar applications are typically framed around surface operations, habitat loading, or transfer vehicle structures, where gravitational and inertial loads fall within ranges addressed by established aerospace alloy systems. The electromagnetic launch environment considered here operates in a fundamentally different regime: peak accelerations approaching 10,000 G's impose inertial loads that deterministically specify minimum alloy properties from first principles, inverting the conventional direction of materials selection logic.

For a notional projectile of 100 kg mass and 180 mm outer diameter, the peak axial inertial force at 10,000 G's is F = ma = 100 kg × 98,100 m/s² = 9.81 MN. The net load-bearing cross-sectional area of the alloy core is $A_{net} = m/(\rho L)$, where ρ is alloy density and L is projectile length. This immediately reveals a critical geometric constraint: because the bore area is fixed at $\pi(0.090)^2 = 254.5\ cm^2$, the minimum physically feasible projectile length (i.e., the length at which the alloy exactly fills the bore with no void) is $L_{min} = m/(\rho A_{bore})$. For LA-1 ($\rho$ = 2,680 kg/m³), L_{min} = 1.466 m; for LT-1 (ρ = 4,500 kg/m³), L_{min} = 0.873 m. The peak compressive stress at any feasible geometry is $\sigma c = F/Anet = \rho LF/m$.

At L = 1.466 m, LA-1 yields $\sigma c \approx$ 386 MPa against a conservative lower-bound yield strength of 200 MPa for an $AlSi_{10}Mg$-class alloy [3], giving a safety factor of approximately 0.52; this is inadequate by nearly a factor of two. This is not a marginal shortfall; it establishes quantitatively and deterministically that a conventional aluminum alloy analog cannot serve as the projectile material in this geometry. The launch constraint thus specifies a minimum tensile yield strength of approximately 385 – 400 MPa for any viable highland alloy. This falls well above the envelope of standard aluminum alloy systems and raises the question of whether geochemically available alloying elements can close the gap.

The answer may lie in the titanium content of real highland regolith. While pristine ferroan anorthosite carries negligible TiO_2, documented Apollo 16 bulk highland soils carry 0.5 – 1.5 wt% TiO_2 from impact-mixed mare basalt ejecta [7]. Aluminum alloys microalloyed with titanium, particularly Al–Si–Mg–Ti systems, can achieve yield strengths approaching 400 – 500 MPa through grain refinement and precipitation hardening, substantially closer to the launch-derived requirement. LA-1 is therefore specified conservatively as a baseline; a higher-strength variant, designated LA-1T, conditioned on confirmed titanium availability in the extraction feedstock, represents a well-motivated near-term refinement. This illustrates the broader principle: electromagnetic launch cadence and geometry deterministically constrain alloy composition, reversing the conventional direction of materials selection logic in which a structure's loading environment is known and alloys are chosen to meet it. Here, the alloy does not yet exist, and the loading environment specifies what it must become. LT-1 at 1.0 m length achieves $\sigma c \approx$ 441 MPa against a conservative yield bound of 750 MPa [4], giving SF ≈ 1.70, confirming that the mare titanium alloy is structurally adequate across a practical range of projectile lengths without compositional modification.

Conclusions and Future Work: The LA-1 and LT-1 dual-alloy framework offers a geochemically supported, unified process specification for lunar structural metals production. It addresses both the mechanical demands of electromagnetic launch and the feedstock requirements of cislunar additive manufacturing. The structural analysis demonstrates that the launch acceleration environment is not just a test for candidate alloys but a deterministic design parameter: for a given bore diameter, projectile mass, and peak acceleration, the minimum yield strength requirements directly depend on alloy density and projectile length. LT-1 satisfies these requirements across practical geometries, while LA-1, in its baseline aluminum analog form, does not, prompting development of the LA-1T variant conditioned on the availability of highland titanium. Future research will focus on projectile fabrication, with powder metallurgy press-forming and hot isostatic pressing identified as promising methods capable of achieving the dimensional tolerances necessary for spin-stabilized ballistic flight.

References: [1] Fray D. J. et al. (2000) *Nature, 407,* 361–364. [2] Lomax B. A. et al. (2020) *Planet. Space Sci., 180,* 104748. [3] Aboulkhair N. T. et al. (2019) *Prog. Mater. Sci., 106,* 100578. [4] Boyer R. et al., eds. (1994) *Materials Properties Handbook: Titanium Alloys.* ASM Intl. [5] ASM Aerospace Specification Metals (2023) *Al alloy datasheets: 6061-T6, 2024-T3.* [6] MIL-HDBK-5J (2003) *Metallic Materials for Aerospace Structures.* DoD. [7] Korotev R. L. (2005) *Chemie der Erde, 65,* 297–346.