A Minimum-Chemical Space Transportation Architecture: Coilgun Freight, Laser-Thermal Launch, and a Water-Based Orbital Logistics Network

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Abstract

We present a concept-stage architecture study of a launch portfolio that eliminates chemical propulsion except as a crew abort motor: (A) a coilgun freight line (4.9 km track, 1,000 g) delivering bulk mass to LEO at ~$150/kg; (B) a maglev + laser-thermal cargo system (6.8 km track at 30 g, 475 MW beam, Isp 900 hydrogen heat exchanger) delivering delicate cargo at $323–3,800/kg depending on flight rate; (C) a crewed variant (38 km track at 3 g, 3.8 GW beam) at $0.6–2.4M/seat at maturity; and (D) a LEO water depot with beamed-steam tugs extending the network to escape, the Moon, and Mars. First-cut split-step wave-optics simulation shows the vertical-beam-plus-relay-mirror geometry delivers 0.75 ± 0.02 of beam power through the full atmospheric degradation budget, while adaptive optics is shown to be structurally ineffective on slant paths — consistent with published moving-target power-beaming data. All cost figures are stated as bands under an explicit calibration doctrine (×2–3 first-of-a-kind bands; a 3× survivability test on every headline claim); the architecture retains its advantage over chemical incumbents at 3× cost growth everywhere the program bets, with the sole failing claim (crew capex) pre-declared and carrying its own kill criterion. A demonstration ladder from sub-$1k benchtop builds to the full system, a technology risk register with retirement costs, and a free published slug interface standard for demand generation complete the program design.

Keywords: beamed-energy propulsion · laser-thermal launch · coilgun · electromagnetic launch · Inductrack · propellant depot · space logistics · adaptive optics · thermal blooming

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Table of Contents

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1. Introduction

This study documents a three-system launch portfolio plus one orbital node, sharing magnetics-and-power DNA, with chemical rockets eliminated except as a crew abort motor:

1. **Coilgun freight line** — 4.9 km track at 1,000 g, bulk mass to LEO at ~$150/kg (direct-to-escape variant: 8.7 km, ~$190/kg)
2. **Maglev + laser-thermal cargo** — 6.8 km track (30 g) + 475 MW beam, delicate cargo to LEO, $323–3,800/kg depending on flight rate
3. **Maglev + laser-thermal crew** — 38 km track (3 g) + 3.8 GW beam, 6-seat vehicles, $0.6–2.4M/seat at maturity
4. **LEO dock + tug fleet** — slugs become ships; tugs add the final 3.2 km/s to escape

The total capital ladder runs $0.1B pilot → $4–12B cargo → $23–84B crew, with every phase generating revenue and de-risking the next. Marginal costs are electricity: $11/kg (beamed) and ~$3.6/kg (gun) in energy alone.

The study is presented as a *concept/architecture paper*: physics checks, subsystem sizing, cost models, and — deliberately foregrounded — the decision trail, including rejected branches, an adversarial self-review, and pre-declared kill criteria. Section 2 states the epistemic rules under which every claim in the document is made.

2. Epistemic Framework and Cost Calibration Doctrine

2.1 Claim tiers (owner standard, adopted Jul 20, 2026)

Claims in this study carry three tiers: **[E] established** (textbook physics, published data), **[I] inference** (first-cut analysis, scaling laws, our simulations — method-limited), **[S] speculation** (demand models, far-horizon concepts). Blanket assignments unless marked otherwise: Physics constraints (§3) = [E]. Simulation results = [I] (v0/v1 are first-cut: limited Monte Carlo, reduced-order blooming). All dollar figures = [I]-grade approximations from memory-sourced cost curves, not verified quotes — and they sit atop 5+ step inference chains (payload fraction × capex × rate × amortization) where errors compound; every $/kg is ±2× until work item 22 (citation and uncertainty pass, Appendix A) closes it. Demand/market claims = [S].

Governing equations for checkable math: rocket equation $\Delta v = v_e \ln(m_0/m_1)$ · jet power $P = T v_e/2$ · magnetic pressure $B^2/2\mu_0$ · Inductrack $L/D \approx v/w$ · Bradley–Herrmann N_D scaling · $F = BIL$ — implementations in `mmm_waveoptics_v0/v1.py` and the program's models.

2.2 Cost Calibration Doctrine (adopted Jul 20, 2026)

Motivation. The item-22 citation pass showed that memory-sourced cost errors are not uniformly directional and therefore cannot be fixed by a single "% of realism" dial: the chemical-launch comparison was stale in the *unfavorable* direction (published 2026 prices are lower than the strawman), the EM-launcher extrapolation ratio was ~5% high, and the black-carbon figure was fine at midpoint but banded too narrowly. Meanwhile the published record on first-of-a-kind megaprojects (pioneer-plant and aerospace overrun literature) puts early capital estimates at roughly **40–60% of final actuals** — 2–3× growth is the historical norm, not the exception. A program that publishes optimistic points is betting reviewers won't know this; they will.

The doctrine:

1. **Physics exact.** No calibration dial ever applies to [E]-tier claims.
2. **Costs are bands, not points.** The stated midpoint is the honest estimate — never a target, never a goal-seeded number. Default band ×2–3 for first-of-a-kind items until item 22 closes that figure with sources; quotes and bids narrow bands, opinions don't.
3. **The 3× survivability test.** Every headline $/kg or capex claim carries the question: *does the architecture keep its advantage over the incumbent at 3× the estimate?* Advantage retained at 3× = the claim is load-bearing; advantage inverted inside the band = the claim is decorative and must not carry an argument.
4. **Kill-criterion restatement.** A cost estimate "fails" when the *advantage inverts inside the band* — not when the midpoint moves. An estimate that doubles while keeping a 10× advantage is a pass and is reported as such.

The doctrine applied to this study's headline claims is presented as results in §13.

3. Governing Physical Constraints

Space is fast, not high. Three destinations, three price tags: touch 100 km and fall back — 1.4 km/s; stay in LEO — 7.8 km/s; leave Earth (escape) — 11.2 km/s (= √2 × orbital). Altitude to 100 km is 1 MJ/kg; orbital kinetic energy is 30 MJ/kg. Any altitude-first scheme (balloons, towers) attacks 3% of the problem.

The atmosphere is a 17% tax. Gravity + drag + steering losses ≈ 1.6 of the 9.4 km/s LEO budget. Worth harvesting (evacuated tube, mountain exit, thrust above the dense air) — never worth building an architecture around.

The rocket equation lives at the top of the velocity budget. Shaving the first 2 km/s saves ~8% of propellant; raising exhaust velocity attacks the exponent. Ground-assist helps; changing the engine (Isp 350 → 900) transforms (payload fraction 2% → 21%).

Every technology is regime-locked. Electric thrusters, power beaming, and Earth's magnetic field are all useless during ascent and excellent after orbit. Chemical wins ascent by *power density*, not efficiency — the propellant is the power plant. To launch without chemistry, either leave the power plant on the ground (beam) or deliver all velocity on the ground (track/gun).

G-force sorts the passengers permanently. Humans (≤3 g) can never take their velocity from the ground: direct-to-escape would need a 2,655 km track. Crew requires sustained thrust over minutes. Hardened cargo at 1,000 g needs 4.9–8.7 km. This is a law, not an engineering gap.

Ballistic coefficient is destiny in the atmosphere. A dense, slender 1,000 kg slug from a 4 km exit loses 516 m/s and ~1 kg of ablator crossing the whole atmosphere at 13 km/s. A flat plate (the Pascal-B manhole cover) becomes a reverse meteor.

4. Trade Space: Design Filters and Rejected Architectures

4.1 Design filters

1. **No step-function infrastructure.** Anything that must be 100% complete before delivering 1% of value will consume the program. Prefer systems that scale continuously and earn on every phase.
2. **Put complexity where the wrenches are.** Vehicle dumb and cheap; intelligence, power, and maintenance on the ground.
3. **Space assets must be thin, passive, and optional.** A dead relay mirror is a degraded day; a cut tether is a dead program.
4. **Non-contact magnetic force wherever surfaces meet at speed.** Inductrack levitation, coilgun (not railgun) launch, magnetic tug docking aids.

4.2 Rejected branches (and the numbers that killed them)

Concept	Fatal number	Verdict
Momentum-exchange tether	15–25 t infrastructure per t payload; catch = hypersonic rendezvous, meter tolerance, seconds; single structure in the debris belt	Step-function megastructure; bootstrap paradox
Fully electric launch	T/W > 1 needs ~100 MW-class jet power per tonne; power plant 10–500× vehicle mass; scale-invariant	Specific-power wall (~10–100× beyond batteries/reactors)
EAD as launch stage	Thrust density 2–20 N/m² → 2,551 m² of electrode for a 1 t vehicle; no air above ~50 km; thrust decays with airspeed	Regime-locked to atmospheric flight (per Gomez Vega framing)
Harnessing Earth’s magnetic field	50 μT field = 1 mPa magnetic pressure; dipole levitation of 1 t needs 4×10^{14} A·m²; static field carries no energy	Cannot amplify a field you didn’t generate; no reaction partner. **Exception:** electrodynamic tethers in orbit (3 N from 10 km/10 A → 1,555 m/s per month, propellant-free)
100 km “zipper tower”	Altitude = 3% of the job; NdFeB self-support height 1.1 km; erection mass	Compression + mass + hinging. Salvage: the instinct (magnetic structure held by fields) is the launch loop / space

	50,000+ t; magnetic joints have no bending stiffness	fountain family — dynamic support via momentum flux — itself rejected on filter #1
Space-based power generation	950 MW platform = 3,200 t solar + 2,400 t radiators (waste heat has no pond in space); burst variant still ~1,500 t (ISS = 420 t)	Bootstrap paradox, heavier than the tether
Ground-only slant beaming (full burn)	Isoplanatic patch ~16 μrad vs vehicle crossing 8,571 μrad/s; thermal blooming N_D = 270 at end-of-burn slant	Adaptive optics structurally cannot track the target; works only for first ~⅓ of burn
Microwave (28 GHz) instead of laser	Published system estimate: ~80 MW beam + 90–175 m antenna for an 8 kg payload ≈ 10,000 MW/t — ~100× our laser figure (95 MW/t) — because 10,000× longer wavelength wrecks diffraction; pulsed air-plasma thrusters also self-shield (residual plasma absorbs the next pulse)	Cheap watts (fusion-industry gyrotrons), impossible optics; CW solid-HX laser avoids plasma timing entirely. Their tracking data imported in §7

5. Selected Architecture

Systems are lettered in build order — A is built first, and each system's flight heritage is the entry condition for the next.

5.1 System A — Coilgun Freight (build first, with the pilot)

- **Staged-to-LEO (primary):** 9.8 km/s muzzle, 4.9 km track, 1,000 g, 48 GJ/shot (36 GW pulse). Slug: 180 kg shell + 190 kg circularization kick → **~630 kg to LEO, ~$150/kg**
- **Direct-to-escape (variant):** 13.05 km/s muzzle, 8.7 km track, 85 GJ (64 GW pulse); 670 kg cargo to escape at **$190/kg** (5,000 shots/yr) — vs published chemical pricing: ~$3–7k/kg to LEO (2026 Falcon-class list/rideshare), $5–10k/kg escape-class [sourced, item-22 pass]
- **Atmosphere transit (4 km mountain exit):** 516 m/s toll, peak 109 kW/cm² for <1 s, ~1 kg ablated (carbon-phenolic, 3× margin carried)
- **Gating tech: pulsed power.** 36–64 GW for ~1.3 s = flywheel motor-generator / compensated pulsed-alternator farms (batteries and capacitors both disqualify). ~1,500–2,700× (variant-dependent) the largest EM launcher built (Navy/GA ~33 MJ class) — the biggest extrapolation in the portfolio
- **Coilgun, not railgun:** no contact at 10–13 km/s. 25 MW feed → 20+ shots/day. Cargo: water, cryogens, metals, propellant, artillery-grade electronics (15,000 g proven)

5.2 System B — Maglev + Laser-Thermal Cargo (build second)

- **Vehicle:** 5 t gross; maglev exit 2.0 km/s (6.8 km evacuated track, 30 g); laser-thermal stage: 6.8 km/s at Isp 900 on 2,685 kg LH_2; **payload 1,065 kg (21% — vs 2% chemical for the same job)**
- **Ground power:** 475 MW beam / 950 MW wall-plug for 462 s. Energy 122 MWh/launch (~$12,200; **$11/kg marginal**). 25 MW grid feed → 5 h recharge. Battery buffer note: 7.8C draw exceeds LFP comfort — oversize to ~500 MWh, use LTO, or hybridize with flywheels
- **Laser array:** ~24,000 × 20 kW fiber modules; $2.4–9.5B at $5–20/W (the dominant capex; riding a falling cost curve)
- **Beam path:** direct slant for early burn only; **relay mirrors are load-bearing** for the back half — 4–8 m passive mirrors, 100–500 kg each, 2–3 for full-burn coverage. Ground beam exits vertically (blooming N_D 83 → 28 with 300 m array footprint; relay drift 83 μrad/s is trackable). Relay constraint: ≥99.99% dielectric coatings (bench-testable). Alternative: 2–3 extra full ground arrays downrange (~1000× more expensive)
- **Capex: $4–12B.** Per-kg: $36,600 @ 10 flights/yr; $3,800 @ 100 (Falcon 9 parity); **$870 @ 500; $323 @ 2,000**

5.3 System C — Crewed Variant (build last)

- 6 seats (~1 t/seat), 3 g limit → maglev only 1.5 km/s on a 38 km track; 40 t gross; **3.8 GW beam**
- Crew *status*, not crew count, drives cost (g-limits, human-rating margin, abort). 6-max saves little; larger cabins amortize better
- **Abort:** beam loss = engine loss → independent solid chemical abort motor. Chemical as parachute, not propulsion
- **Capex $23–84B.** Per seat: $45M @ 10 flights/yr (market parity) → $2.4M @ 200 → $0.6M @ 1,000. An airline: ruinous at low utilization, unbeatable at high

5.4 Node D — LEO Dock and Tug Fleet

Orbit is **92% of escape energy**; the tug adds only 3.2 km/s. Docking at ~0 m/s relative replaces hypersonic catching; slugs aggregate into assembled ships. Propellant is itself gun-delivered at ~$150/kg — the depot bootstrap.

Preliminary tug screening (superseded by the full accounting below; retained as the trade record):

Tug	Isp	Trip	Propellant kg per cargo kg
Chemical hydrolox	450	3 days	1.07
Beamed-thermal (perigee kicks from the existing array — Oberth optimal)	900	~1 week	0.44
Electric Hall (spiral penalty: 7.7 km/s dv, still frugal)	2,500	6–9 mo	0.37

Full-accounting trade result (Jul 15, 2026 revision — governing): water at $150/kg LEO, plant amortization, fleet sizing for 2,287 t/yr:

Tug	Water kg / cargo kg	Fleet needed	$/kg to escape
Beamed steam (Isp 400, perigee kicks) — SELECTED	1.38	8	**$225**
Hydrolox chemical (Isp 450)	1.36 (after 0.78 electrolysis yield)	4	$269
Electric water plasma (Isp 800, spiral)	1.67	133	$560

Key finding: steam and hydrolox consume essentially identical water per kg of cargo — electrolysis yield cancels the Isp advantage. The 192 t propellant plant (incl. 89 t of cryocoolers, the node's hardest development) buys nothing and is **deleted from baseline**. Node D reduces to: water storage tanks + docking ports + ~8 beamed-steam tugs. Hydrolox remains a fast-lane option (3-day vs 10-day trips) if a time-critical market appears; electric tugs lose on fleet capital (210-day trips), niche only.

Engineering delta: steam oxidizes carbon — tug HX uses oxide-coated or Ir-lined refractory instead of the C-C/TaC hydrogen stack. Same coupon test rig; add steam coupons to the campaign.

Staged vs direct escape: $216–320/kg staged vs $190 direct — direct gun wins for dumb bulk; staging wins for anything that must arrive as a functioning spacecraft.

Architecture-wide principle, confirmed at every node: ship the dumbest possible mass; add energy at the point of use. Gun throws water; beam superheats it; one laser array serves ascent and perigee departure; one HX technology family (two coating systems) powers both.

6. Beam Delivery: Wave-Optics Analysis

Work item 1; first-cut split-step simulation complete Jul 19, 2026 (scripts: `mmm_waveoptics_v0.py`, `mmm_waveoptics_v1.py`, MIT-licensed).

Method. Kolmogorov/von Karman phase screens (structure-function-calibrated) layered per the HV5/7 profile from the 2 km site; AO modeled physically as conjugation of the beacon-path column with 10 cm actuator-pitch fitting cutoff; point-ahead anisoplanatism implemented by laterally shifting each turbulence layer by θ_pa·h for the outgoing beam; vacuum far-field beyond the atmosphere; 8-draw Monte Carlo; metric = power fraction into the 2.5 m HX at range.

6.1 v0 results

Case	Zenith	Range	Point-ahead	AO	Delivered fraction
Vertical → relay mirror (baseline)	0°	600 km	2 μrad	on	**0.83 ± 0.01**

Slant mid-burn → vehicle	55°	350 km	20 μrad	on	0.64 ± 0.05
Vertical, no AO	0°	600 km	—	off	0.46 ± 0.09
Slant, no AO	55°	350 km	—	off	0.56 ± 0.09

(Diffraction-limited/no-atmosphere reference ≈ 0.99. Slant bucket angles are geometrically larger at closer range; comparison is against each case's own delivery requirement.)

Findings. (1) The **relay-vertical baseline closes**: 83% delivery through the full atmosphere with modest AO, tight variance — before array-scale refinements, which only help. (2) **AO is structurally ineffective on the slant path** (0.56 → 0.64): with the correction measured through air offset from the beam's path by the point-ahead angle, conjugation decorrelates — now confirmed by wave propagation, independently of the earlier isoplanatic-patch scaling argument and the published 60.1%→0.43% moving-target collapse (§7). Shown slant numbers *flatter* reality: end-of-burn (72°, 700 km) is worse on every term and carries blooming N_D = 270 (excluded from this model; vertical N_D = 28 with 300 m footprint).

6.2 v1 gauntlet (blooming + AO temporal lag)

Blooming coupled into propagation (similarity-scaled steady-state upwind-integral model, iterated to convergence) plus AO temporal lag (1 ms latency against Bufton frozen-flow winds). Results: **vertical relay baseline 0.75 ± 0.02 with the full degradation budget** (blooming-off reference 0.80); slant progression 0.78 (early, 30°) → 0.22 (mid, 55°) → **0.03 (end-of-burn, 72°, N_D 270)** — quantitatively reproducing the "direct works early, relays carry the back half" design claim from an independent method. Residual caveat on the baseline: phase-compensation instability not modeled (threatens high-N_D slant far more than N_D 28 vertical; explicit check assigned to Phase 1 completion).

6.3 Array configuration

Vertical phased-array configuration confirmed as baseline. The simulated 1 m director is a single subaperture of the distributed array; array synthesis (many subapertures over a 100–300 m footprint) is deferred to the full Phase 1 sim — with the standing correction that **thermal absorption requires no optical coherence**: incoherent tiled addition suffices, so each subaperture needs only its own AO and pointing, and array-wide phase-locking is deleted from the requirements entirely. Tiling distributes per-aperture flux and *reduces* blooming — the first-cut result is therefore conservative for the baseline and optimistic only for the already-rejected slant case.

Remaining Phase 1 sim scope (work item 10): time-dependent thermal blooming coupled into propagation (the one term that could still move the vertical verdict); end-of-burn geometry sweep; Greenwood/temporal AO bandwidth error; distributed-array aperture synthesis; ≥100-draw Monte Carlo; radiometric absorption ledger.

7. External Validation and Design Imports

Source: the Japanese 28 GHz microwave beamed-propulsion program (Shimamura et al. — J. Spacecraft & Rockets drone power-beaming test; Sci. Rep. 2025 tractor-beam and vortex-plate studies; Phys. Plasmas rectenna monitoring). The nearest running hardware program to this architecture's Phase 1; four items adopted (Jul 17, 2026):

1. **Tracking-collapse validation (risk register: beam combining + propagation).** Their measured end-to-end efficiency fell from 60.1% (fixed receiver) to 0.43% (free-flying drone) — a ~140× collapse purely from target motion. First published hardware confirmation of the tracking argument that makes relay mirrors load-bearing in this architecture. Cite in the propagation white paper.
2. **Beam shaping as thermal-control actuator (risk register: heat exchanger, hot spots).** Their vortex-phase-plate result showed beam *shape* determines where energy deposits and whether force helps or opposes the vehicle. Adopted implication: our phased array actively flattens the flux profile across the HX panel — the hot-spot problem (AO residual 1.5–2× local flux) gains an active mitigation path in addition to passive HX margin. Adds a requirement to Phase 2–3 array control software; adds a flux-profile command interface to the SIS-adjacent vehicle spec.
3. **Transmitter-as-sensor (risk register: HX; Build Sheet 002).** Their rectenna standing-wave monitor watched the plasma front without cameras. Adopted: backscatter monitoring of the HX panel from the ground array (per-subaperture return power = panel health map); at Phase 0, a photodiode watching droplet scatter.
4. **Beam-riding misalignment data (Build Sheet 002 §7).** Their offset-vs-thrust studies are the gyrotron-scale version of the droplet limit-cycle; the deliberate-offset protocol run added to Build Sheet 002 reproduces the measurement at bench scale.

Their unresolved problem we structurally avoid: pulsed air-plasma thrusters self-shield (residual plasma absorbs subsequent pulses), forcing front-fed "tractor" geometries. The CW solid-HX vehicle has no plasma and no pulse timing — a design rationale line for the white paper.

8. Technology Risk Register and Retirement Path

Risk	Why it gates	Retirement path	Cost to retire
Hydrogen heat exchanger	Wall temp caps gas temp caps Isp caps payload. 48 MW/m² absorbed (3× fusion divertor); 2,900 K hydrogen; walls sub-mm (microchannels mandatory); hot-H2 corrosion (NERVA's killer — fixed with ZrC/NbC; modern stack: TaC/HfC on	Coupon (10 kW laser, $10k) → tile (100 kW) → panel (1 MW pilot). Flux, not power, is what material sees — bench results transfer to 475 MW. Watch: Ledinegg flow instability (orifice the channels), 300→3,000 K cycle fatigue, hot spots at 1.5–	$10k–$5M

	carbon-carbon, whose 44 MPa thermal stress beats W-Re 16×)	2× design flux from AO residual	
Design margin	Isp 900 sits at the solid-HX ceiling; laser-sustained plasma (gas hotter than walls) offers Isp 1,100–1,400 as block upgrade	De-rate check: Isp 850 → payload 21%→19%. Architecture robust	—
Beam combining + propagation	24k fibers into one phased aperture; thermal blooming self-defocus	Split-step wave-optics simulation (§6), then subscale field tests. Relay-vertical geometry buys ~10× margin	~$0 → $10M
Relay mirror coatings	475 MW × 0.01% absorption = 48 kW radiative-only rejection	≥99.99% dielectric coating coupons, ground vacuum test	$1–10M
Pulsed power (gun)	36–64 GW / 1.3 s; nothing built within 1,000×	Flywheel/pulsed-alternator farm; subscale gun (Navy-railgun-class energies) first	$50–500M
Slug terminal ops	Kick stage must survive 1,000 g (guided-artillery heritage); deep-space catch unpriced for direct-escape variant	Staged-to-LEO architecture sidesteps it (tug docks, doesn't catch)	design choice

9. Development Program

9.1 Demonstration ladder

Phase	Beam / hardware	Delivers	Cost	Milestone
0	Benchtop	—	<$1k	Inductrack drum + Halbach cart (Appendix C); watt-class lightcraft
1	10 kW laser	100 g craft	~$100k	Lightcraft-class climb (Myrabo flew

				this in 2000: 50 g to 71 m)
1.5	100 kW (owned OR **rented** — industrial fiber / HELSTF beam time via SBIR customer)	1 kg free-flight hop	$0.5–3M	Suborbital-class demo at SBIR scale; closes the 100 g → 10 kg gap
2	1 MW array	10 kg suborbital	$10–50M	**HX qualification at full flux**; AO field data. Buy the array only when flight cadence justifies capex — beam time rents before it owns
3	10 MW array	22 kg near-orbital	$50–200M	Venture-scale pilot; first revenue (microsats)
4	475 MW + 6.8 km track	1,065 kg LEO	$4–12B	System B operational; coilgun (System A) built in parallel
5	3.8 GW + 38 km track	6 crew	$23–84B	System C, on System B's flight heritage

9.2 Test infrastructure and range plan (Jul 19, 2026)

Height-ladder finding: test altitude requirements are bimodal — bench height, then ~30 ft, then open sky. Intermediate tall-ceiling facilities (100–400 ft class) buy nothing: beam-riding control qualifies on **guide-wire tethered hops at 20–30 ft** (Myrabo lightcraft method), and free flight wants kilometers, not rafters. No 400 ft facility exists to rent, and none is needed.

The ladder (all within ~3 h of Rio Rancho — New Mexico is the one state where the full test infrastructure is a day trip):

Tier	Venue	Phase	What runs there	Access route
Bench	Home shop	0–1	Builds 001/002, torsion stand, low-power droplet	owned
	Light-industrial rental, ABQ/Rio Rancho			

Laser lab	(~1–2k sq ft, 3-phase 240 V, interlocked blackout laser room, ventilation + exterior gas storage for hydrogen coupons; 14 ft ceiling suffices)	2	1–10 kW HX coupon campaign, steam microthruster, coilgun stage bench	~$1–2k/mo lease at Phase 2 funding
Tethered hop	Same lab or 26–32 ft warehouse	2–3	Beam-riding control on guide wire	lease
Gun range	**EMRTC (NM Tech, Socorro)**	2–3	Subscale coilgun projectiles beyond lab backstop	commercial range rental
Free flight	**Spaceport America**	3+	10 kg vehicle flights; restricted-airspace umbrella eases outdoor-laser clearance	negotiated campaign contract
National labs	**Sandia via NMSBA**	1+	Pulsed power, magnetics, HX consultation at no cost to NM small businesses; CRADA path for facilities	apply after LLC formation
MW-class laser	White Sands / HELSTF	3+	Megawatt beam heritage (lightcraft flew here)	SBIR-customer partnership, not rental

Regulatory (file mentally now, act at Phase 2/3): outdoor beams require FAA coordination (AC 70-1) and DoD **Laser Clearinghouse** deconfliction for sky-directed propagation — the decisive argument for testing under Spaceport America's restricted airspace rather than private land.

9.3 Cadence doctrine (gate plan amended Jul 19, 2026)

Economics live at 100+ flights/yr and 1,000–5,000 shots/yr; gates must therefore prove **cycling, not just capability**. Cadence risk is cycle-count-invariant — switch lifetime, coil thermal fatigue, flywheel cycling, HX cycle life all retire at benchtop scale. Adopted: Phase 2 cadence endurance rig (item 20: 5,000 automated subscale cycles, ~$10–30k); HX coupon protocol extended to ≥1,000 cycles; Phase 3 gate adds sustained flights/week; Phase 4 adds dummy-payload cadence campaigns at marginal (energy-only) cost. **Low-demand operating mode is designed, not feared:** 50 bookings + 450 water-slug dummy shots ≈ a 500-shot year for ~$6k of additional electricity — the cycle ledger accumulated on unsold capacity is itself the sales instrument. No chemical system can afford to prove cadence on empty manifests; this one barely notices the cost.

10. Environmental Assessment

Thesis-relevant: constraint as moat (Jul 19, 2026).

Operational emissions are electricity: 115 MWh/t (beamed) and 21 MWh/t (gun) — near-zero carbon from NM solar; exhaust is steam; no soot, alumina, perchlorates, hypergolics, or deluge contamination anywhere in the stack. Chemical launch, by contrast, carries ~25–30 t CO_2/t payload plus ~0.3–3 t black carbon per launch (engine/cycle-dependent) injected at stratospheric altitude (≈500× surface warming potency — Ryan et al. 2022, sourced) — a compounding regulatory exposure that grows with exactly the industry-wide cadence this program bets on. Tightening launch regulation is a tailwind for this architecture.

Honest residuals, ranked: (1) sonic booms — the dominant real externality at 20+ shots/day; priced into WSMR-adjacent siting; (2) ~24 t H_2O per beamed launch partly above the tropopause — monitor-and-report item, owned in the white paper preemptively; (3) ~1 kg ablated carbon per gun shot (≈5 t/yr at full cadence — negligible vs. aviation); (4) beam-path wildlife/aviation safety — radar-triggered beam interrupt, Phase 3 requirement.

11. Network Extensions: Mars Pipeline and Destination Ranking

11.1 The Mars pipeline (Jul 15, 2026)

Principle: interplanetary space cannot hold a track — everything placed there is itself in solar orbit. The road (Kepler coasting) is free; all cost lives at the ramps. Infrastructure therefore replaces per-trip propellant only at the endpoints.

On-ramp: already built. The escape gun's 12.53 km/s atmospheric-exit velocity gives v∞ = 5.65 km/s — Mars Hohmann needs only 2.95 (ground requirement 11.57 km/s). Margin buys 4–5 month fast transits and stretches each launch window to ~4–6 months. Departure propellant: zero.

Coast: 259 days (Hohmann) / ~130–150 (fast), propellant zero. Windows every 780 days (synodic). At 5,000 shots/yr, one window ships ~1,300 t Marsward; between windows the gun serves LEO/lunar traffic.

Off-ramp: aerocapture (baseline). Entry speeds 5.7 km/s (Hohmann) to 7.1 km/s (fast) — below MSL's 5.8 for freight, well below Earth-return capsule heritage (12.5). Slug carries 12–15% ablative heatshield (1,000 g-compatible carbon nose, same family as launch ablator). Aerocapture pass → Mars orbit → 50–100 m/s periapsis-raise (steam puff). Arrival propellant: ~zero. Toll per kg ≈ heatshield mass fraction.

Mars-orbit port (the ownable asset). Tug fleet's one-time emplacement job, then Earth tugs retire from the route: station + water stock, nav/comm beacons, small local steam tugs (watered by incoming slugs) for orbit consolidation. Nobody owns the transfer orbit; the port sets the price of mass at Mars.

Phase-2 upgrade: Phobos momentum bank. Tether/rotating catcher anchored to Phobos (1.07×10^{16} kg): inbound freight deposits momentum into Phobos's orbit; outbound Earthward cargo withdraws it — inbound traffic funds outbound flings. 2,000 t/yr of 3 km/s catches perturbs Phobos by ~micrometers/s per year (planetary flywheel, effectively infinite bank). Passes the step-function filter as an *optional* upgrade: aerocapture runs the route without it. Softer than the Earth tether (no debris belt, lower closing speeds, free anchor mass); still inherits the catch-precision problem — phase it after the route is proven.

Steady state. Gun throws water and freight → Kepler carries → Mars atmosphere brakes → port aggregates. Per-trip consumables: one carbon nose and a puff of steam. The tug's role, as specified: build the off-ramp once, then stand down.

11.2 Destination ranking (Jul 15, 2026)

Law: the gun and the Kepler coast are destination-agnostic; only the off-ramp changes. Destinations rank by their brakes: atmospheres are free off-ramps; airless bodies charge a steam toll — but airless + low-g bodies are where the coilgun re-roots and turns importers into exporters.

Destination	Ground req (km/s)	Gun margin	Transit	Window	Off-ramp
Moon	10.95	huge	3 d	**daily**	propulsive (steam)
Venus	11.46	+1.07	146 d	584 d	thick atmo — generous aerocapture corridor (entry 10.7 km/s)
Mars	11.57	+0.96	259 d	780 d	thin atmo — narrow corridor (work item 13)
Jupiter+	14.23	−1.70 (out of direct reach)	997 d+	399 d	—

Sequence:

1. **Moon first — the debug destination.** Daily windows delete the gun's idle-capacity problem; 3-day feedback loop iterates operations ~250× faster than Mars; nearest-term freight market. Phase-2: lunar surface coilgun (escape 2.38 km/s → **290 m track at 1,000 g**; vacuum, low-g, no weather = ideal site) plus lunavator drive the off-ramp toll to zero and flip the Moon to exporter (polar water, regolith, metals). Earth launcher tech exports at 1/30 scale.
2. **Mars — the anchor tenant.** Full pipeline per §11.1; Phobos

momentum bank as phase-2.
3. **Venus — the switch-yard.** Best transport physics (frequent windows, short transit, forgiving aerocapture), thinnest market (no reachable surface, no moon for momentum banking). Small port justified as gravity-assist junction to Mercury and outer-system routing, not as a terminus.
4. **Beyond the belt:** the gun's direct horizon ends near Jupiter's requirements; outer-system freight stages through tug perigee kicks (Oberth) or planetary assists.

12. Demand Generation and the Slug Interface Standard

Extension of Jul 16, 2026.

Premise: every cost model in this study clears its break-even only at high flight rates; demand is therefore the binding constraint, ahead of any single technology. History shows demand in space has been created by *documents*, not consortia: a free interface standard (CubeSat spec, 1999 → the smallsat industry), a published price (rideshare price sheets → manifested smallsat demand), and an anchor-tenant purchase promise (CLPS → seven lander companies). Coordination through paper scales; coordination through meetings doesn't. The pipeline adopts the same instrument set.

12.1 Slug Interface Standard (SIS) — Draft A scope

A free, published specification letting any mission designer, CubeSat program, servicing startup, or depot operator design against the pipeline before it exists:

- **Mass classes & envelopes:** S-630 (baseline LEO slug, 630 kg net), S-670 (direct-escape, 670 kg), sub-classes for rideshare partitions within one slug
- **Environment rating:** 1,000 g axial design / 1,500 g proof; vibration & thermal transit envelopes (launch heat pulse, coast cold-soak)
- **Berthing interface:** standard grapple/berthing feature for tug capture at ~0 m/s relative; alignment, capture-envelope, and load-path definitions
- **Water payload spec:** purity classes (propellant-grade vs. life-support-grade), freeze state, tank venting standard
- **Kick-stage envelope:** volume/mass allocation, minimum reliability floor and disposal requirement (debris control at 1,000+ shots/yr is a licensing precondition)
- **Nav & transponder minimums:** tracking, arrival-corridor trim authority, abort-to-disposal logic
- **Heatshield classes:** L (none — LEO), M (Mars aerocapture, ~13%), V (Venus, ~14%)

12.2 Companion instruments

- **Published price sheet:** the $/kg curves from this study, stated as offered service prices at declared flight rates — designers write proposals against numbers, not visions
- **Demand registry:** non-binding letters of intent ("would purchase N kg water at L1/LLO/Mars orbit at $X/kg") — the traction instrument that converts latent demand into evidence for funders
- **Circulation venues:** CONFERS (on-orbit servicing/assembly standards body), SmallSat conference, standards submission once Draft B stabilizes

12.3 Phase placement

SIS Draft A is a Phase 1–2 deliverable (cost ≈ $0; authored alongside the wave-optics work). The registry opens with Draft A publication. Draft B incorporates feedback before any Phase 3 hardware commitment, so the 10 MW pilot flies payloads already designed to the standard.

13. Cost Survivability of Headline Claims

The doctrine of §2.2 applied to this study's current headline claims:

Claim	Midpoint	At 3×	Advantage at 3×?
Gun freight $/kg to LEO	$150	$450	**Yes** — vs $3–7k/kg published chemical; ~10× margin survives
Beamed cargo $/kg (500–2,000 flights/yr)	$323–870	~$1,000–2,600	**Yes at rate** — still at/below Falcon parity; but break-even flight rate ≈3× higher → item 9 (demand model) is the binding analysis, not the capex digit
Marginal energy cost	$11/kg	$33/kg	**Trivially** — remains noise against any incumbent
Phase 0–2 program cost	$270–$500k	scales	Absorbable at self/SBIR funding tiers by design
Crew capex (System C)	$23–84B	$69–252B	**No** — not robust at 3×; consistent with the already-accepted end state (gate plan Phase 6 kill: chemical crew taxis remain the permanent answer)

Reading: the architecture survives the realistic number everywhere the program actually bets. The one claim that fails the 3× test (crew) already carries its own kill criterion and an acceptable end state — which is the correct shape for a failing cost claim: pre-declared, gated, and non-load-bearing. This table, maintained as estimates are re-sourced under item 22, is itself the anti-fragility exhibit for reviewers and funders: the program does not need its optimistic numbers to be right.

14. Limitations and Adversarial Review

Red-team register, Jul 19, 2026 — adversarial self-review ahead of any public submission.

Hidden advantages banked: (1) thermal propulsion needs incoherent tiled power, not a phased beam — array-wide coherence deleted from requirements (correction applied, §6.3); (2) unburned slugs are suborbital by default — orbit requires an affirmative kick, so the gun's failure mode is disposal, not debris; (3) the 500 MWh battery farm is a merchant grid-storage asset between launches; (4) gun (all-weather) and beam (clear-sky) hedge each other's availability; (5) engineless vehicles make marginal airframe cost trivial.

Hidden liabilities opened as work items: beamed-line weather/clearance availability unquantified (item 21 — first cut now published: ~200 flyable days/yr); tube exit aperture and km-scale expansion unaddressed (23); relay µrad pointing under load likely 2–3× mass growth, and cargo beam-loss impact footprints undrafted (24); dual-use/ITAR posture for a steerable near-GW array to be decided deliberately, before external framing decides it for us.

Peer-review posture: the study survives review as a *concept/architecture paper* (Acta Astronautica / JBIS / AIAA class) contingent on item 22 — citations on every cost figure, uncertainty bands on every result, claims scoped to evidence. It is not, and does not claim to be, a validated engineering study; the gate/kill-criteria apparatus is the submission's differentiating strength and is foregrounded accordingly (§2, §13).

15. Open Work and Future Directions

The program's open work is maintained as a live status ledger (Appendix A), ordered easiest → hardest across three tiers: desk-and-paper items at the current phase (wave-optics completion, benchtop builds, the SIS and demand instruments, HX coupon specs, the citation and availability passes); engineering analyses for Phases 1–3 (flux-profile control, relay constellation geometry, aerocapture corridors, pulsed-power point design); and far-horizon concept work gated behind earlier data (lunar surface coilgun, Mars port, Phobos catcher). The gate item for the beam-delivery verdict is time-dependent thermal blooming coupled into propagation (item 10); the precondition for journal submission is the full citation and uncertainty pass (item 22).

Appendix A — Work Item Status Ledger

Maintained live; items close when completed, without prompting. Conventions: the ledger is ordered easiest → hardest, and IDs match that order 1–19. IDs were renumbered once to complexity order by owner decision, Jul 19, 2026, with all cross-references updated in the same edit; they are frozen henceforth. CLOSED items are immutable records. Last updated Jul 20, 2026.

Tier 1 — Desk & paper, current phase (0–1): items 1–10, hours to weeks each, ~$0

#	Item	Status
1	Split-step wave-optics propagation sim	**CLOSED** — v0 + v1 gauntlet complete (0.75 vertical baseline; slant 0.78/0.22/0.03); remainder transferred to 10
	Benchtop builds	OPEN — build sheets released;

2	(Inductrack drum; droplet rig)	hardware ordering underway
3	NMSBA application	OPEN — triggers immediately on LLC formation
4	Phase 2 laser-lab requirements sheet; Spaceport America first contact at Phase 3 planning	OPEN
5	SIS Draft A authoring	OPEN — skeleton published; full document is a Phase 1–2 deliverable
6	Demand registry instrument (LOI template, tiers)	OPEN — pairs with 5
7	Standards-body engagement plan (CONFERS, SmallSat)	OPEN — follows 5
8	HX coupon test spec (hydrogen + steam coupon sets)	OPEN — Phase 1; gates Phase 2 hardware; spec extended to ≥1,000-cycle automated endurance
9	Market/utilization model (flight-rate demand curves)	OPEN
10	Phase 1 sim completion (inherits from item 1): PCI stability check, distributed-array synthesis, ≥100-draw Monte Carlo, radiometric ledger	OPEN — blooming coupling and end-of-burn sweep already delivered by v1; scope reduced
20	Cadence endurance rig spec: automated subscale coilgun, 5,000-cycle campaign, condition monitoring + cost-per-shot ledger (~$10–30k, Phase 2)	OPEN — new under cadence doctrine
21	Beamed-line availability analysis: NM cloud/wind statistics × Laser Clearinghouse windows → flyable-days model feeding the cadence economics	OPEN — **first cut v0 published Jul 20** (mmm_item21_flyable_days_v0, this directory): ~200 flyable days/yr (150–250); LCH quantified from published observatory data; availability binds at the 2,000-flights/yr tier; v1 refinement scope listed therein
22	Citation & uncertainty pass: source every cost figure, band every result, apply [E]/[I]/[S] labels line-by-line per the Epistemic Convention — precondition for	OPEN — **kickoff published Jul 20** (mmm_item22_citation_pass_v0, this directory): 11 headline rows sourced; corrections applied to this document in the same commit; full inference-chain pass remains

	journal submission AND now mandated by owner's accuracy standard	
23	Tube exit-aperture concept: fast shutter vs. plasma window vs. per-shot membrane; km-scale thermal expansion joints	**CLOSED Jul 21, 2026** — concept selected (mmm_item23_exit_aperture_v0, this directory): two-stage muzzle vestibule — slow outer gate valve + per-shot burst membrane; phase-locked rotary shutter documented as alternate; expansion clause disposed to standard bellows practice (LIGO-class existence proof). Verification folds into item 20 (cycle life) and Phase 2 track design
24	Beam-loss range-safety footprint analysis + relay pointing-stability budget under thermal load	OPEN — red-team finding; Tier 2
25	Trademark application: "Magnetic Matter Movers" word mark via USPTO TEAS — base fee $350/class (+$200/class surcharge if using custom goods/services description instead of the ID Manual); file after LLC formation so the LLC is owner; likely classes: research/publication services + catalog hardware (one class suffices to start). Not deadline-bound: common-law rights accrue from use, and the dated public repo establishes first use	OPEN — new Jul 20, 2026

Tier 2 — Engineering analyses, Phases 1–3: items 11–16, weeks to months each, still simulation/paper

#	Item	Status
11	Flux-profile control requirement (beam-shape modes + backscatter loop)	OPEN
12	Relay constellation geometry (orbits, count, 462 s handoff)	OPEN
	Aerocapture corridor	

13	vs. gun dispersion + kick-stage trim budget	OPEN — first data-free Monte Carlo candidate
14	Venus corridor memo (quantifies thin/thick gap for 13)	OPEN — pairs with 13
15	Lunar off-ramp point design (steam brake vs. semi-hard bulk; polar water bootstrap)	OPEN
16	Pulsed-power farm point design + subscale demonstrator spec	OPEN — hardest Tier 2 item; feeds System A; now carries 5,000-cycle switch/coil/flywheel life requirement

Tier 3 — Far-horizon concept work, Phases 3+: items 17–19, meaningful only after earlier tiers return data

#	Item	Status
17	Lunar surface coilgun concept (290 m track; catch-mass economy)	OPEN
18	Mars port point design (station mass, tug count, emplacement manifest)	OPEN
19	Phobos catcher feasibility memo	OPEN — deliberately last: gated behind a proven Mars route

Appendix B — Key Reference Numbers

- Delta-v to LEO: 9.4 km/s (7.8 orbital + ~1.6 losses) · Escape from surface: 11.2 · Escape from LEO: +3.2
- Isp 900 laser-thermal hydrogen: $T_{gas} \approx 2{,}900$ K; propellant fraction for 6.8 km/s = 54% (vs 86% chemical)
- Beam requirement: ~95 MW per tonne of vehicle gross (T/W 1.5, 50% coupling)
- Halbach near-field: 1 T at 1 cm gap ≈ 30 t/m² lift — 10^8 × Earth-field pressure
- Inductrack L/D ≈ v/w; drag *power* constant with speed (magnetic lift gets cheaper as you go faster; aero drag grows as v^3)
- Earth's field: 1 mPa pressure, 1 mJ/m³ — an orbital reboost resource only (ED tether: 1,555 m/s per month on 5 t)

Appendix C — Benchtop Inductrack Build

Magnetic Matter Movers catalog piece / scale model of the launch sled (demonstration ladder Phase 0):

8× ½" N42 cubes in Halbach (λ = 51 mm, $B_0 \approx 0.93$ T), 3D-printed carrier (N-red/S-blue pole language), 30 cm aluminum drum ≥3 mm wall, 50 W motor. Lift-off at ~54 RPM; ~1 cm hover gap at 1,000–1,500 RPM; constant ~28 W drag at any speed (the launch-relevant signature). Gotchas: Halbach assembly needs a clamping jig (adjacent magnets fight the pattern); add guide rails or V-groove drum for lateral stability; cap at 1,500 RPM for rim safety. BOM ~$80–120.

Appendix D — Document History

Date (2026)	Event
Jul 15	Original compilation: core architecture, physics ground rules, rejected branches, Systems A–C, Node D + water-depot revision, Mars pipeline, destination ranking
Jul 16	Extension: demand generation & Slug Interface Standard
Jul 17	Extension: external validation & design imports (28 GHz program)
Jul 19	Extensions: wave-optics first-cut results (v0 + v1 gauntlet); test infrastructure & range plan; environmental ledger & cadence doctrine; red-team register. Ledger renumbered to complexity order (frozen)
Jul 20	Epistemic Convention adopted; Cost Calibration Doctrine adopted; item-21 and item-22 first cuts published; corrections applied; items 20–25 added. Public repository and site live (prior-art date)
Jul 21	Restructuring for journal layout — content preserved; structure, TOC, and section numbering added. Item 23 closed same date (exit-aperture concept note, this directory); ledger row updated. Changes go forward in dated commits

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