Light gas gun launch to orbit

1. System outline

The launcher is an 80 km horizontal light-gas gun of 2.5 m bore. It fires a 20 m projectile of average density 1000 kg/m³ and slenderness L/D = 12, carried in a discarding sabot, to a muzzle velocity of 8 km/s. The projectile mass is about 44 t and its areal density is m/A = 20,000 kg/m². The drive gas is hot hydrogen, injected through ports distributed along the barrel so that the base pressure is renewed as the projectile recedes. The projectile carries fixed lifting fins that curve its path upward through the atmosphere, and a small solid rocket motor that circularizes the orbit after the atmosphere is cleared. Over an 80 km barrel the launch acceleration is $a = v^2/2L = 400$ m/s², about 41 g, which is what makes a projectile of this length and mass survivable. The sections below treat, in turn, why a dense projectile is wanted, why the fins must be fixed, the density-versus-structure trade that sets the design, the heat protection of body and fins, the sabot clearance, and the way barrel length sets cost.

2. Areal density sets the atmospheric loss

Drag decelerates the projectile in proportion to the air it displaces per unit of its mass, so the loss is governed by the areal density σ = m/A and falls as the projectile is made denser and heavier. Figure 1 shows the velocity lost against σ for a ballistic shot at three gun elevations. The fall is steep at low σ and flattens into a knee. A light projectile at σ = 1000 kg/m² loses 4 to 7 km/s, most of the muzzle velocity; by σ = 20,000 kg/m², the design value, the loss is down to a few hundred m/s for an inclined shot. The two model curves bracket the drag: a first-principles aeroprediction (solid) sits about 10 to 15 percent above a simple empirical fit (dashed). The lesson is direct: mass is the cheapest defence against drag, and the projectile should be as dense as the rest of the design allows.

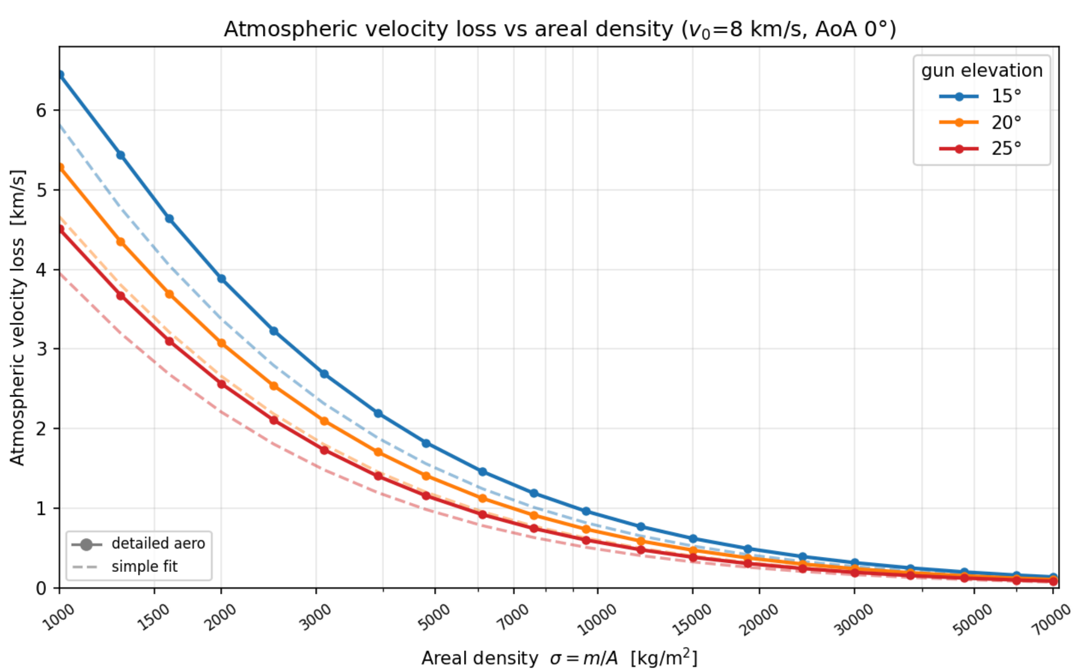

Figure 1. Atmospheric velocity loss against areal density, three gun elevations, detailed and simple drag models.

3. Fixed fins and a horizontal gun

The projectile must be turned from horizontal to a climbing path, and it is turned by lift on its fins. The loads rule out moving them. At the muzzle the dynamic pressure is $q = ½\rho v^2 = ½(1.225)(8000^2) = 39$ MPa, about 390 atmospheres. The lift needed to bend the trajectory upward at a few g is of order $m \cdot a \approx 44{,}000 \times 50 \approx 2$ MN, carried on fin areas of order a square metre, and the hinge moment to hold or move a surface under that load is of order 1 MN·m. No actuator holds a meganewton-metre against a 39 MPa stream at 41 g of axial load. The fins are therefore fixed at a constant cant, giving a constant trim angle of attack of about 5 degrees. This is sufficient rather than limiting: at fixed angle the lift is largest in the dense low air, where the turn is wanted, and falls off on its own as the vehicle climbs and the air thins.

Inclining the gun instead of lifting with fins is not an option at this length. An 80 km tube inclined even 20 degrees would rise $80 \cdot \sin 20° \approx 27$ km, taller than any landform; at a buildable few degrees it still climbs several kilometres. A tube this long can only lie flat. So the gun is horizontal and the fixed fins do the turning.

4. The density and structure trade-off

Density helps twice: it lowers the drag loss of Section 2, and by keeping more speed to the top of the arc it shrinks the circularization burn. It also hurts. A denser projectile at fixed average density is longer and more slender, and the casing must be thick enough not to buckle under the launch load, so structure mass rises with σ. The two pull against each other and produce a clear optimum in payload fraction, shown in Figure 2 for four barrel lengths. Each curve peaks where falling drag and rising structure balance; a longer barrel lowers the launch g, cheapens the structure, and pushes the optimum to higher density and higher payload. The 80 km gun peaks near 42 percent at high density; the 7 km gun, at 500 g, is crushed to about 4 percent. At the design point, $\sigma = 20{,}000$ kg/m² for the 20 m projectile, the 80 km curve gives a payload fraction of roughly 27 percent, on the rising flank below its optimum, the optimum itself being unreachable at 1000 kg/m³ without an impractically slender rod.

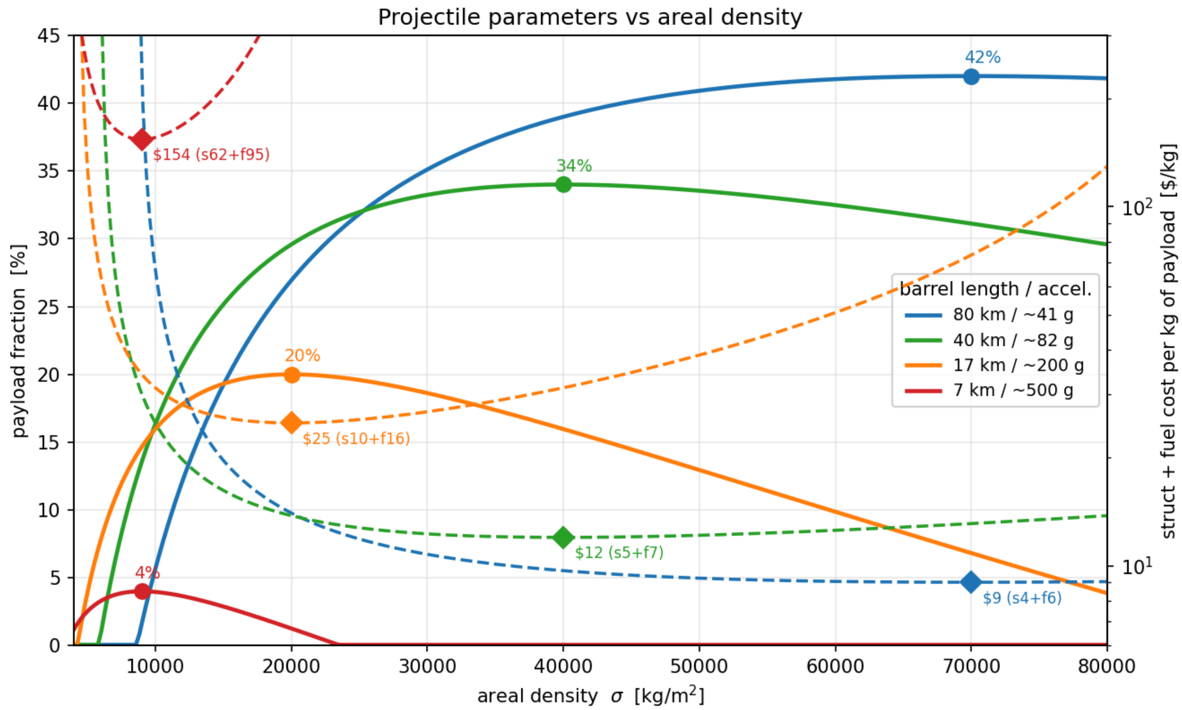

Figure 2. Payload fraction (solid) and cost per kilogram (dashed) against areal density, for four barrel lengths. Each length has an optimum density; longer barrels push it higher.

Buckling works both ways. On launch, the base carries the full inertial load of everything ahead of it in compression, which sets the base wall thickness. But after the projectile leaves the muzzle it decelerates in the atmosphere, and that deceleration peaks near 10.5 g, compressing the column from the nose instead of the base. For the low-g 80 km gun, whose launch load is only 41 g, the reversed 10.5 g atmospheric load is a quarter of it, not negligible. The casing is therefore sized to resist buckling in both directions: thick at the base for the launch push, and stiff enough forward that the reversed deceleration does not crumple the lightly built nose.

5. Ablation and heat protection

The projectile is hottest at the muzzle, where it travels at 8 km/s in sea-level air; the nose stagnation flux there is about 25,000 W/cm². The pulse is brief, since the whole climb through dense air lasts under a minute, so it is the integrated heat, not the peak, that sizes the shield. Figure 3 shows the result along the body. The ablative coating is thickest at the nose, about 21 mm, and thins to about 9 mm at the base, following the flank heat flux (dashed, falling from roughly 2800 to 1450 W/cm² down the body). The structural wall runs the other way, from about 11 mm at the nose to 24 mm at the base, set by the buckling load of Section 4 in both directions. Where the wall is already thick, aft, it sinks the heat itself and little coating is needed; where the wall is thin, forward, the coating carries the insulation.

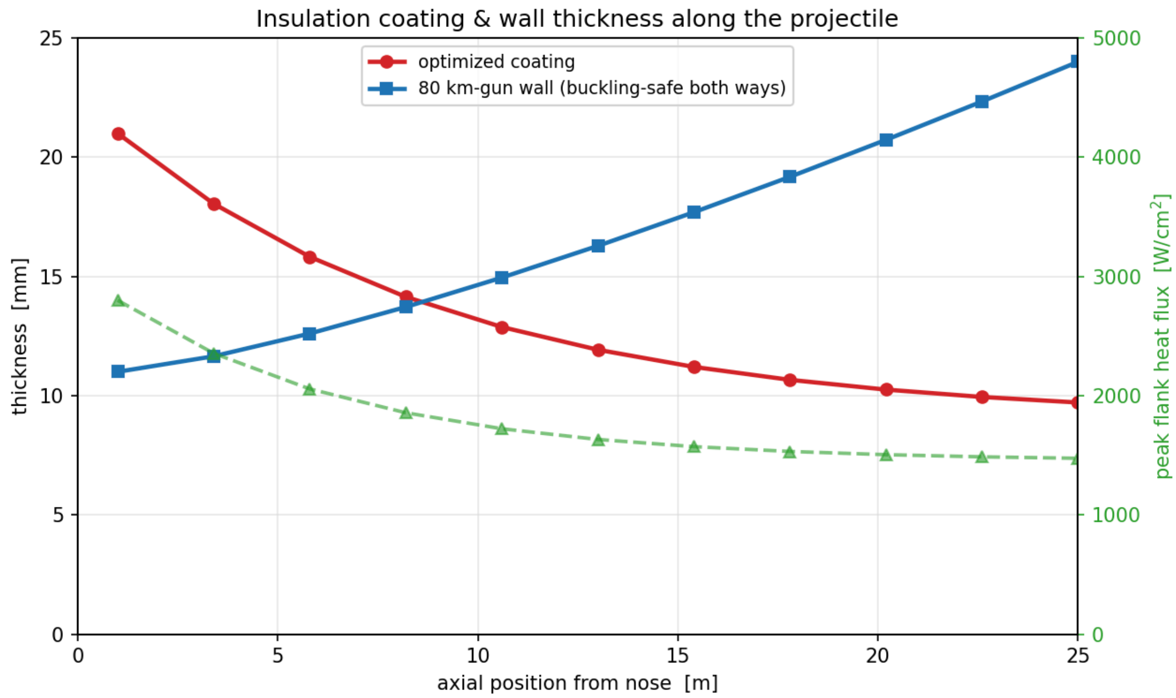

Figure 3. Ablative coating and structural wall thickness along the projectile, with the flank heat flux. Coating is front-loaded, wall is aft-loaded.

The fins see the worst heating on the vehicle. Their leading edges are near-sharp, and a small edge radius drives the stagnation flux up as one over its square root, so a fin leading edge at the muzzle sees of order 100,000 W/cm², several times the nose. The fins therefore carry the most protection per unit area. Figure 4 shows the cross-section: a blunt carbon-phenolic leading edge, the highest-grade ablator on the vehicle, faired into tapered silica-phenolic on the faces, over the structural spar. The leading edge takes the stagnation spike; the faces take the lower turbulent flux and taper to the trailing edge.

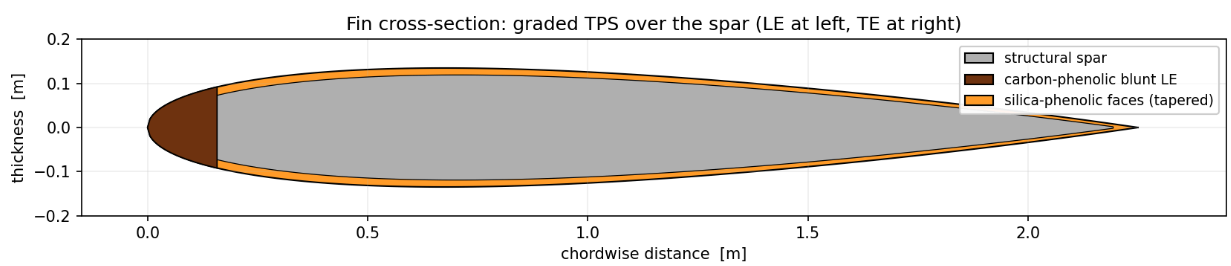

Figure 4. Fin cross-section: blunt carbon-phenolic leading edge, tapered silica-phenolic faces over the structural spar.

6. Stability and sabot clearance

A dart this slender, L/D = 12, cannot be spin-stabilized (spin stabilization fails above L/D of about 5 to 7), so it is fin-stabilized. The fixed fins hold the centre of pressure behind the centre of mass, and nose mass keeps the centre of mass forward, for a static margin of five to ten percent of the length; the dense aft motor and the ablating nose bracket the light payload and place the centre of mass naturally forward.

The projectile rides in a sabot that seals the bore. A small radial clearance is wanted, to keep the sabot from galling and welding itself to the wall at hypervelocity. The cost of that clearance is blow-by, driving gas escaping past the sabot, which both wastes hydrogen and lowers the base pressure. Figure 5 plots the velocity lost and the gas blown by against clearance, measured against the unrealistic ideal of a perfectly sealed, frictionless bore (zero loss). Even at a large 10 mm gap the velocity lost is only about 141 m/s, under two percent of the muzzle velocity, and the gas lost is about 0.6 percent of that injected; at a small 1 mm gap the loss is about 118 m/s. The difference between a tight and a loose gap is only some 20 m/s, so a small clearance costs almost nothing while removing the galling risk entirely. The plot shows plainly that a small air gap does not change much.

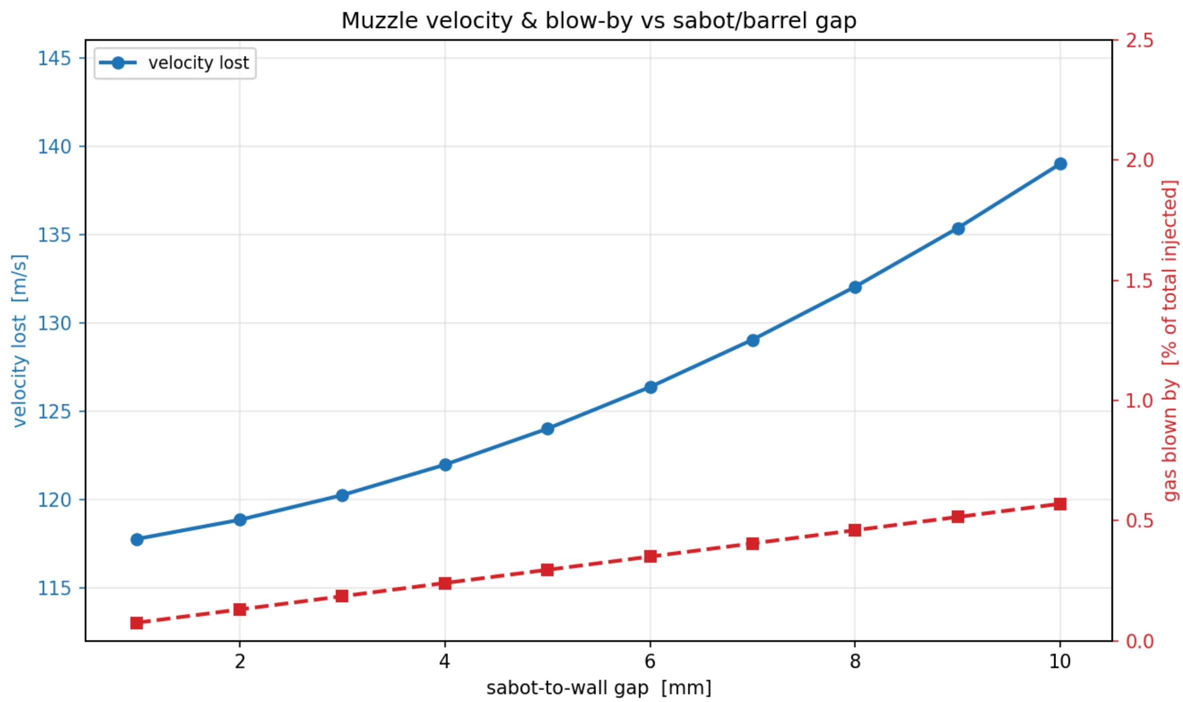

Figure 5. Velocity lost and gas blown by against sabot-to-wall clearance, relative to a frictionless sealed bore. A <1cm clearance costs little..

7. Barrel sizing and where the capital goes

The barrel is a pressure vessel, and its wall thickness is proportional to the working pressure, so its steel mass goes as p*L (pressure times length). The work done on the projectile is the mean base pressure times the bore area times the length, and that equals the muzzle kinetic energy, so p*L h is fixed by the end velocity and the projectile mass. A short high-pressure barrel and a long low-pressure barrel that reach the same muzzle velocity contain the same tonnage of steel and cost the same in raw material. Length by itself is not what makes the barrel expensive!

A longer barrel allows for smaller pressure, hence thinner walls. Thin walls are far easier to roll, forge, and weld than thick ones. Hence, for systems with the same end velocity and steel tonnage, but different lengths, the longer barrel will have a lower manufacturing cost. At 80 km the mean base pressure needed to drive the launch package at 400 m/s^2 is only about 1,200 psi. That is the operating pressure of mass-produced oil and gas transmission pipes. A barrel at that pressure can be built from welded line pipe rather than forged and autofrettaged like high-toughness gun steel. It also drives the storage tank (storing at higher pressures than the barrel will experience) rating below 10,000 psi - the code boundary above which pressure vessels must be forged and inspected by fracture mechanics.

One cost moves the other direction. Honing of a 2.5 m tube is the operation that scales with bore length, so a longer tube costs more to finish. But finishing grows only linearly with length, while the pressure-driven penalties, forging, autofrettage, code class, and premium steel, fall away steeply as the pressure drops (linearly with length increase).

8. Methods

Fig. 1. 3-DOF point-mass trajectory in the vertical plane (v, γ, h), marched explicitly at 20 ms steps under gravity, an Earth-curvature term, and drag; density from the US Standard Atmosphere. Ballistic launch at the stated elevation, zero AoA; loss is $\int(D/m)\,dt$ to 100 km or apogee. Drag deceleration is $q \cdot C_d/\sigma$, so the curve is a function of σ only. Two Cd laws: the empirical $C_d = 0.04 + 0.30/M$, and a Taylor-Maccoll (wave drag) plus van Driest II (turbulent skin friction) aeroprediction; the pair brackets the loss at about ±12 %.

Fig. 2. For each σ the Fig. 1 loss fixes the post-atmosphere state. Structure fraction is set by the buckling wall below, rising with σ (longer, more slender rod) and with launch g (shorter barrel), calibrated to 0.25 at 200 g and 0.53 at 2000 g.

Fig. 3. Heating along the Fig. 1 trajectory. Used methods are nose: Sutton-Graves, $q \propto \sqrt{(\rho/R_n)} \cdot V^3$, flanks: reference-enthalpy turbulent flat plate, $C_f = 0.0592 \cdot Re^{*\,-0.2}$, net of σT_w^4 reradiation. The system is solved for insulation holding the aluminium back-face under 450 K using 1-D transient conduction solver (explicit FD).

Fig. 4. Fin LE as a swept stagnation line; at $R_{LE} \approx 1$ cm the S-G flux is ~10^5 W/cm², several times the 0.15 m nose. Faces take the local turbulent flux. TPS graded to flux: a carbon-phenolic LE cap sized for the stagnation spike and its recession, silica-phenolic tapering aft over the spar. Section drawn as a 12 % airfoil, coating offset inward to the structural boundary.

Fig. 5. Annular sabot leak as a choked orifice, $\dot{m} \propto (\pi D \cdot gap) \cdot P_{base} \cdot \sqrt{(\gamma/R_s T)}$; the escaped gas is credited to neither base pressure nor thrust. The velocity deficit is referenced to a frictionless, perfectly sealed bore, an idealization used only as the zero. The galling and interference penalty that would dominate at zero or negative clearance is not modeled.