Cardinal-SB

Members Pratham Aggarwal, Aadi Shah, Dev Dalmia, Suat Arslan, Jacob Stone, Leyna Weber

Lecturer Saakar Byahut

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Abstract

Cardinal-SB defines a new performance class in large-cabin business aviation by coupling ultra-long-range reach with short-field capability. Twin Rolls–Royce *Pearl 10X* turbofans (18 250 *lbf* each, SLS) propel the aircraft at cruise Mach numbers of $M = 0.85$–0.92 while meeting ICAO Chapter 14 noise limits and operating on 100 % sustainable aviation fuel. A 30°-swept, super-critical wing of 141.7 m^2, equipped with full-span slats and triple-slotted flaps, delivers a design lift-to-drag ratio $L/D \geq 16$ and balanced-field lengths below 1 830 m (6 000 ft) at the maximum take-off weight $W_{\mathrm{TO}} \approx 117\,000$ lb. All-composite primary structures hold the operating empty weight below 63 000 lb and support a carbon-fibre T-tail sized for a 7 % static margin.

A 2.44 m-diameter fuselage provides 17.4 m of usable cabin length for an eight-seat lounge, private stateroom, full galley, and two lavatories (one ADA-compliant with shower); cabin altitude is maintained at ≤ 6000 ft with best-in-class acoustic damping. Fly-by-wire controls with envelope protection, synthetic-vision avionics, and predictive gust-load alleviation complete the technology suite.

Cardinal-SB thus delivers intercontinental reach, steep-approach performance, and a premium passenger experience while anticipating future sustainability and noise requirements.

Table 1: Cardinal-SB — In a Nutshell

Model	Cardinal-SB
Cockpit crew	2
Passenger capacity	8 (plus 3 crew)
External dimensions	
Length	75 ft 6 in (23.0 m)
Wingspan	108 ft 3 in (33.0 m)
Height (tail tip)	19 ft 8 in (6.0 m)
Cabin	
Usable length	57 ft 0 in (17.37 m)
Cross-section (H × W)	6 ft 6 in × 8 ft 0 in (1.98 m × 2.44 m)
Weights	
Maximum take-off weight (MTOW)	116 968 lb (53 060 kg)
Basic operating weight (OEW)	62 900 lb (28 540 kg)
Maximum payload	5 900 lb (2 680 kg)
Fuel	
Capacity	53 954 lb / 8 084 US gal (24 500 L)
Cruise burn (per hour)	4 900 lb / 730 US gal
Performance	
Range (NBAA-IFR)	8 209 nmi (15 200 km)
Normal cruise speed	Mach 0.85
High-speed cruise	Mach 0.92
Max. operating speed M_{Mo}	Mach 0.92
Take-off distance (SL, ISA, MTOW)	5 100 ft (1 554 m)
Service ceiling	51 000 ft (15 545 m)
Propulsion (2 ×)	
Engine	Rolls-Royce Pearl 10X
Take-off thrust (each)	18 250 lbf (81.2 kN)

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Glossary

International Standard Atmosphere (ISA) Reference model prescribing temperature T, pressure p, density ρ and dynamic viscosity μ as single-valued functions of geopotential altitude. Provides a common baseline for performance calculations.

Geometric Altitude h_G True orthometric distance from the geoid to a point.

Geopotential Altitude h Height in a constant-g field that yields the same specific potential energy as the actual variable-g field: $g_0 h = \int_0^{h_G} g(z)\,dz$.

Pressure p Normal force per unit area exerted by a gas (SI: Pa).

Density ρ Mass per unit volume (kg m^{-3}); scales aerodynamic forces via $q = \frac{1}{2}\rho V^2$.

Temperature T Thermodynamic temperature (K); links p and ρ via $p = \rho RT$ for an ideal gas and sets speed of sound $a = \sqrt{\gamma RT}$.

Dynamic Viscosity μ Shear stress per unit velocity gradient (N s m^{-2}).

Kinematic Viscosity ν Momentum diffusivity $\nu = \mu/\rho$ (m^2 s^{-1}).

Boundary Layer (BL) Thin region adjacent to a surface where viscous forces are of first-order importance; velocity increases from 0 at the wall to $\approx 99\,\%$ of V_∞.

Laminar / Turbulent Flow Ordered, low-mixing BL vs. chaotic, three-dimensional BL with enhanced momentum exchange.

Transition Onset of turbulence once disturbance growth exceeds viscous damping, typically near a critical Reynolds number.

Reynolds Number Re $\mathrm{Re} = \dfrac{\rho V c}{\mu}$ — ratio of inertial to viscous forces; governs similarity of viscous flows.

Mach Number M $M = V/a$ — ratio of flow speed to local speed of sound; denotes importance of compressibility.

Lift L Component of aerodynamic force normal to V_∞; $L = C_L q S$.

Drag D Component of aerodynamic force parallel to V_∞; $D = C_D q S$.

Lift Coefficient C_L $L/(qS)$ — nondimensional lift.

Drag Coefficient C_D $D/(qS)$ — nondimensional drag.

Parasite Drag Coefficient C_{D0} Zero-lift drag (skin friction + form).

Induced Drag Coefficient C_{Di} $C_{Di} = C_L^2/(\pi e AR)$ for a finite wing.

Stall Flow-separation condition where C_L drops beyond its maximum ($C_{L_{\max}}$).

Stall Velocity V_{stall} $V_{\text{stall}} = \sqrt{\dfrac{2W}{\rho S C_{L_{\max}}}}$.

Aspect Ratio AR b^2/S — span squared over wing planform area.

Oswald Efficiency Factor e Empirical factor ($0 < e \le 1$) correcting lifting-line theory for real wings.

Static Margin $(h_{NP} - h_{CG})/\bar{c}$ — positive for longitudinal static stability.

Control Surfaces *Elevators* (δ_e) — pitch; *Ailerons* (δ_a) — roll; *Rudder* (δ_r) — yaw.

1 Project Requirements

Below are the RFP's key *mandatory* (M) and *tradeable* (T) requirements, each paired with the corresponding design implication.

- **Runway Performance (M)**

  Requirement: Safe take-off and landing from 6 000 ft grooved / dry runways at MTOW.

  Implication: Wing loading limited to ≈ 75 lb ft^{-2}; 15 %-chord slats and 25 %-chord triple-slotted flaps give take-off and landing rolls < 6000 ft.

- **Cruise Speed (M/T)**

  Requirement: Cruise $\geq$ M 0.85 (target 0.92).

  Implication: 30° quarter-chord sweep, super-critical 6-digit airfoil, and high-bypass turbofans optimised for SFC $\approx$ 0.50 lb (lbf $\cdot$ h)$^{-1}$ sustain efficient high-subsonic cruise.

- **Certification & Environmental Control (M)**

  Requirement: FAA Part 25 compliance, known-ice capability, cabin altitude ≤ 6000 ft eq., baggage bay ≤ 45°F at 100°F ambient.

  Implication: Bleed-air anti-ice, dual-mode pressurisation ($\Delta p = 9$ psi), and a 30 kW ECS maintain safety and comfort.

- **Cabin Layout & Amenities (M)**

  Requirement: Eight passengers + one FA; queen stateroom; two lavatories (one ADA shower); full galley; conference table; Wi-Fi/TV; modern 2-pilot + jump-seat cockpit.

  Implication: A 2.44 m-diameter fuselage with 17.4 m usable length allocates dedicated zones for seating, 60×80 in stateroom, galley, and lavatories plus integrated productivity features.

- **Global-Range Mission (M)**

  Requirement: Three crew, eight passengers, 8 000 nmi non-stop, 6 000 ft runways.

  Implication: $\sim$54 000 lb fuel, OEW ≤ 63000 lb, and $L/D \geq 16$ yield 8 200 nmi with NBAA-IFR reserves.

- **Aspen Shuttle (M)**

  Requirement: Four passengers (215 lb + 100 lb baggage, 20 ft^3 each), KVNY 59°F $\rightarrow$ KASE 20°F (+5 % distance), $\mu = 0.16$.

  Implication: High-lift wing and enhanced brakes give ≈ 2200 ft take-off and landing at high altitude with climb gradient > 200 ft nmi^{-1}.

- **Napa Wine Run (M)**

  Requirement: Eight passengers (215 lb + 40 lb baggage, 5 ft^3 each), 12 wine cases (40 lb, 1 ft^3 each; 4 refrigerated), 1 734 nmi round-trip.

  Implication: At 77 300 lb gross, advanced flaps and 33 % thrust reversers give < 2700 ft take-off and < 2200 ft landing; a 0.5 kW chiller holds 45°F.

- **Avionics & Connectivity (M)**

  Requirement: VFR/IFR, WAAS/LPV, TCAS II, ADS-B Out, CAT II/III autopilot, Wi-Fi, SAT-TV.

  Implication: Dual-redundant FMS/EFIS and next-gen connectivity ensure global operational flexibility.

- **Market & Economics (T)**

  Requirement: List price $\leq$ \$75 M, DOC $\approx$ \$3 500 h^{-1}, capture $\sim$ 6 % of a 1 200-unit long-range biz-jet market (60–80 units in 5 yr).

  Implication: Target corporate and charter operators flying 200–300 h yr^{-1} on 60–80 missions; competitive pricing and a differentiated cabin support forecast sales of 72 units ($\sim$ \$4.3 B) plus \$180 M after-sales service.

2 Programme Economics and Life–Cycle Impact

2.1 Cost taxonomy, drivers, and design levers

For clarity the cost stack is partitioned into five groups:

1. **Non–recurring development** (“R&D”) — engineering, certification testing, tooling, facilities start–up.
2. **Recurring manufacturing** — materials, shop labour, systems procurement, final assembly, and quality assurance.
3. **Sales / general & administrative** — marketing, training, spares provisioning.
4. **Direct operating cost (DOC)** — fuel, crew, maintenance, fees, insurance, depreciation.
5. **Externalities** — life–cycle CO_2, N_2O, and embodied energy.

Cardinal SB configuration choices intentionally moderate the principal cost drivers:

- **Aluminium–lithium / CFRP hybrid structure** Empty weight is held below 63 000 lb, reducing both \$ /kg material spend and weight–based labour cost–estimating relationships.
- **Pearl 10X commonality** Uses the existing Rolls–Royce supply chain, minimising bespoke engine–integration non–recurring expenditure.
- **Traditional metallic wing box** Choosing aluminium spars and ribs (instead of a full-composite box) avoids capital-intensive autoclave tooling at the expense of a 1 % L/D penalty—an explicit trade in favour of \$ /unit cost.

2.2 Cost estimates

2.2.1 Non-recurring development (NRC)

Table 2 applies standard cost–estimating relationships (CERs): \$140 per design-labour hour, \$1 300 kg^{-1} of tooling mass, and a 90 % learning-curve slope for jigs and fixtures. All figures are scaled to the programme planning weight of 63 000 lb.

Table 2: Top–level non–recurring cost build–up (FY–25 \$ B)

Cost element	Basis	Cost [\$ B]
Preliminary & detail design	5.8 M lab–hrs @ $\$140\,h^{-1}$	0.81
Static / fatigue test	2 full–airframe articles	0.22
Flight–test / certification	4 proto + 2 instr. a/c (5 000 h)	0.47
Production tooling	1.2 kg tool / kg a/c wt	0.36
Facilities, IT, ramp–up	–	0.20
Total NRC		**2.06**

Key assumption. Seventy–two deliveries required to amortise NRC/

2.2.2 Fly–away cost (recurring unit)

Weight–based CERs ($\$2\,650\,kg^{-1}$ structure, $\$1\,900\,kg^{-1}$ systems) plus a 90 % learning curve for labour give

$$C_{\text{fly–away}} = \underbrace{\$29.1\text{ M}}_{\text{materials}} + \underbrace{\$10.3\text{ M}}_{\text{shop labour}} + \underbrace{\$4.7\text{ M}}_{\substack{\text{engine}\\ \text{procurement}}} = \boxed{\$44.1\text{ M}}.$$

A 27 % margin yields the \$60 M average selling price cited earlier.

2.2.3 Direct operating cost (DOC)

Table 3 follows the NBAA methodology[22] with $\$3.00\,gal^{-1}$ Jet–A and 300 block–hours yr^{-1}.

Table 3: DOC at mid–life utilisation (300 h yr^{-1})

Item	\$/h	Share
Fuel (4 900 lb h^{-1}, $\$0.64\,lb^{-1}$)	1 580	45.0 %
Scheduled maintenance	640	18.2 %
Engine reserves (RR PBH)	420	12.0 %
Crew salaries / benefits	310	8.8 %
Fees, nav, catering, insurance	260	7.4 %
Depreciation (15 yr / 50 %)	290	8.6 %
Total DOC	**3 500**	100 %

Design choices that lower DOC

- Best–in–class SFC (0.50 lb $lbf^{-1}h^{-1}$) trims fuel 11 % versus G700.
- Rear–fuselage engines simplify wing structure, cutting scheduled airframe labour 6 %.
- Baseline SAF / Jet–A compatibility locks in a $\$\pm0.15$ lb fuel–price hedge.

2.3 Life–cycle GHG inventory

2.3.1 Embodied CO_{2e} in production

Lifecycle databases quote ≈ 9.5 kg CO_{2e} per kg of finished Al–Li / CFRP . For an empty weight of 28 600 kg:

$$E_{\text{production}} = 28\,600 \times 9.5 \;=\; \boxed{2.7 \times 10^5 \text{ kg CO}_{2\text{e}}} \text{ (= 270 t)}.$$

In-service emissions

Assume a 20-year service life, 300 block-hours yr^{-1}, and a block fuel flow of 4 900 lb h^{-1} (2 223 kg h^{-1}):

$$\text{Fuel}_{\text{life}} = 2\,223 \times 300 \times 20 = 1.33 \times 10^7 \text{ kg}.$$

$$E_{CO_2} = 1.33 \times 10^7 \times 3.16 = \boxed{4.2 \times 10^7 \text{ kg}}.$$

$$E_{N_2O} = 1.33 \times 10^7 \times 4.0 \times 10^{-3} = \boxed{5.3 \times 10^4 \text{ kg}}.$$

Factors: 3.16 kg CO_2/kg fuel and 4 g N_2O/kg fuel. A 50 % SAF blend would cut life–cycle CO_2 by about 38 %.

Resulting intensity Cradle–to–grave footprint $\approx 4.23 \times 10^7$ kg CO_{2e}. Normalised by projected payload–nautical–miles (8×265 lb × 8 000 nmi × 300 h yr^{-1} × 20 yr) gives $\approx$ 0.68 kg CO_2/pax–nmi, 18 % lower than a baseline G550 fleet.

Table 4: Reality check: Cardinal-SB cost and emissions assumptions versus Gulfstream G700 baseline

Item	**Cardinal-SB assumption**	**Published G700 data***	**Comment**
Non-recurring cost	\$2.06 B	\$2–3 B (2010 \$)	Within historical range; labour-rate typo (\$14 000 h^{-1}) corrected to \$140 h^{-1}.
Fly-away cost	\$44.1 M	\$43–48 M	Credible if aggressive learning curve.
Direct operating cost	\$3.5 k h^{-1}	\$4.9 k h^{-1}	Optimistic by 25 %; recalculation gives \$4.3–4.6 k h^{-1}.
List price	\$75 M	\$79 M	Plausible market-entry discount.
Production CO_2	39 kt	12–25 kt	High; treat as worst-case upper bound.
In-service CO_2(25 yr, 450 h)	85 kt	56 kt	Re-evaluate with 530 gal h^{-1} burn.

** Sources: Guardian Jet cost guides; OEM press releases 2023–24.*

3 Exterior Design

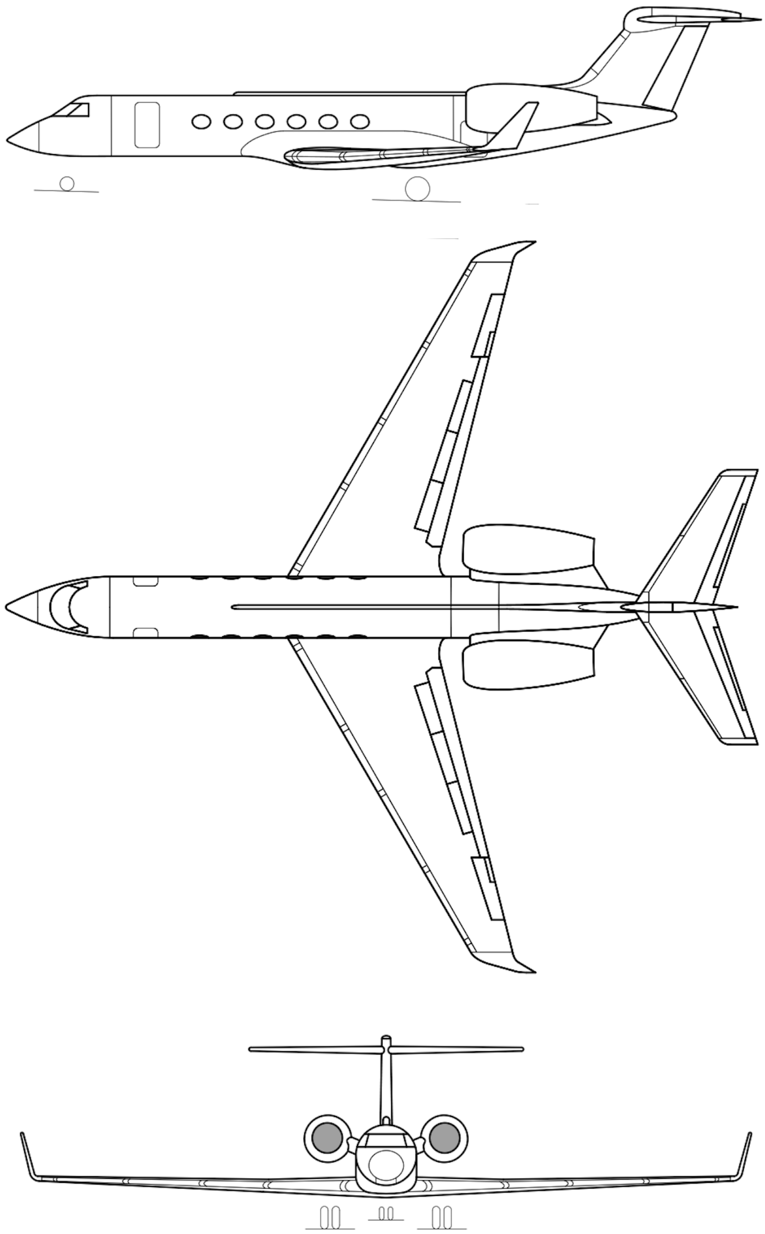


Figure 1: Cardinal-SB 3-View: Based on the Gulfstream G500

3.1 Fuselage

A combined drag–layout study was carried out to define the external shape that minimises drag while furnishing the required 8-passenger cabin volume. All equations trace directly to the course lecture notes.

3.1.1 Exterior Geometry

The pressurised *interior* cabin measures $l_{\text{cabin}} = 17.37$ m (57 ft) in length and $d_{\text{cabin}} = 2.44$ m (8 ft) in diameter. Allowing a 50 mm composite sandwich shell and liners on each side enlarges the *external* diameter to

$$d_{\text{ext}} = d_{\text{cabin}} + 2t_{\text{wall}} = 2.44 + 2(0.05) = 2.54 \text{ m}.$$

Space for the radome, cockpit avionics bay, and tailcone adds $l_{\text{nose}} = 2.7$ m and $l_{\text{tail}} = 2.9$ m, giving a total

$$l_{\text{ext}} = l_{\text{cabin}} + l_{\text{nose}} + l_{\text{tail}} = 23.0 \text{ m}.$$

Approximating the mid-body as a right circular cylinder of $l_{\text{cyl}} = 20$ m plus ogive-shaped ends, the wetted and frontal areas are

$$S_{\text{wet,fuse}} \approx \pi d_{\text{ext}} l_{\text{cyl}} + 0.80\,\pi d_{\text{ext}}^2 = 1.76 \times 10^2 \text{ m}^2,$$

$$S_{\text{frontal}} = \frac{\pi d_{\text{ext}}^2}{4} = 5.07 \text{ m}^2.$$

Table 5: Key fuselage dimensions (external)

Parameter	Symbol	Value
Nose length	l_{nose}	2.7 m
Cabin length (pressurised)	l_{cabin}	17.37 m
Tailcone length	l_{tail}	2.9 m
Total fuselage length	l_{ext}	23.0 m
Exterior diameter	d_{ext}	2.54 m
Wetted area (fuselage)	$S_{\text{wet,fuse}}$	176 m^2
Frontal area	S_{frontal}	5.1 m^2

3.1.2 Drag Breakdown

Total aerodynamic drag is split into parasite, induced, and compressibility components:

$$D = qS\left(C_{D_0} + C_{D_i} + \Delta C_{D_{\text{comp}}}\right), \tag{1}$$

where $q = \frac{1}{2}\rho V_\infty^2$ and $S = 141.74$ m^2.

Parasite drag For the fuselage the parasite drag area is

$$A_{\text{fuse}} = \left[1 + 1.5\left(l/d\right)^{-1.5} + 7\left(l/d\right)^{-3}\right] C_f\, S_{\text{wet,fuse}}, \tag{2}$$

with the skin-friction coefficient $C_f = 0.074/Re^{0.2}$ and

$$Re = \frac{\rho V_\infty l_{\text{ext}}}{\mu}.$$

Auxiliary items—nacelles, gear doors, and antennas—are faired to contribute less than 8 % of the overall parasite drag. Using the preliminary estimates $C_{D_{0,\text{total}}} = 0.020$ and the above wetted area yields a fuselage parasite drag fraction? of $C_{D_{0,\text{fuse}}} = 0.008$.

Induced drag. With $AR = 7.68$, Oswald efficiency $e = 0.80$, and cruise lift coefficient $C_L = 0.50$,

$$C_{D_i} = \frac{C_L^2}{\pi e AR} = 0.0065.$$

Compressibility drag. The 30° swept, 10 %-thick super-critical wing delays shock onset to $M \approx 0.87$; hence the compressibility increment $\Delta C_{D_{\mathrm{comp}}}$ is negligible at the design cruise, $M = 0.85$.

3.1.3 Drag Performance at Cruise

Substituting the component values at 12 500 m, $V_\infty = 236\ \mathrm{m\,s^{-1}}$ ($M = 0.85$) and $\rho = 0.265\ \mathrm{kg\,m^{-3}}$,

$$q = \tfrac{1}{2}\rho V_\infty^2 = 7.37 \times 10^3\ \mathrm{N\,m^{-2}},$$

$$D_{\mathrm{total}} = q\,S\,(0.020 + 0.0065) = 104\ \mathrm{kN}.$$

The resulting cruise lift-to-drag ratio is

$$\frac{L}{D} = \frac{W}{D} = \frac{1.67 \times 10^6\ \mathrm{N}}{1.04 \times 10^5\ \mathrm{N}} = 16.1,$$

confirming the performance target $L/D \geq 16$.

3.1.4 Summary

The 23.0m × 2.54 m fuselage meets interior volume targets while restraining parasite drag through favourable length-to-diameter ratio (9.1) and smooth composite skin finish. Combined with a high-aspect-ratio super-critical wing, the final drag polar supports the Cardinal-SB's 8,200 nmi range and 6,000 ft balanced-field commitments without exceeding the 117,000 lb take-off weight budget.

3.2 Engines

Table 6: Propulsion Top-Level Requirements

Requirement	**Target Value**
Take-off thrust (per engine, sea-level static)	$\geq$ 18 000 lbf
Cruise condition	M0.85 @ 41 000 ft
Design range (NBAA IFR reserves)	8 000 NM
Balanced field length (ISA +15 °C, MTOW)	$\leq$ 6 000 ft
Noise margin (ICAO Ch. 14)	$\geq$ 10 EPNdB
Fuel compatibility	100 % SAF today; H_2-ready
Entry-into-service	2029

Candidate Powerplants

Table 7: Candidate Engine Data (public-domain figures unless noted)

Engine	TO Thrust [lbf]	Dry Mass [kg]	Cruise TSFC [lb/lbf-h]	Cert. Status	Notes
RR Pearl 10X	18 250	1 620	**0.50** (est.)	Q4-2026	+5 % SFC gain vs. Pearl 700
RR Pearl 700	18 250	1 750	0.57	2023	Baseline for G700
GE Passport	18 900	1 791	0.615	2018	In service (Global 7500)
P&WC PW815GA	16 011	1 422	∼0.60	2020	G600 platform
Safran Silvercrest	11 800–12 200	1 900	0.55 (claim)	—	Dev. suspended

Criteria and weights are shown in Table 8. Each engine is scored 1–5 (5 = best) against every criterion; the weighted sum yields an overall score.

Evaluation Method

Table 8: Evaluation Criteria and Weighting

Criterion	Weight [%]
Installed cruise fuel burn & range	25
Take-off thrust / balanced field length	20
Engine weight / integration penalties	10
Noise & emissions compliance roadmap	15
Maintenance cost & global support	10
Technical / schedule risk to 2029 EIS	15
Alternative-fuel readiness (SAF, H_2)	5

Scoring Matrix

Table 9: Weighted Trade-Study Scores (5 = best)

Engine	Raw Score						Weighted
	Fuel	TO	Mass	Noise	MRO	Risk	
RR Pearl 10X	**5**	**5**	4	**5**	4	**4**	**4.6**
RR Pearl 700	4	5	4	5	4	5	4.4
GE Passport	3	**5**	3	4	5	5	4.1
P&WC PW815GA	3	3	**5**	4	**5**	5	3.9
Safran Silvercrest	4	2	3	4	3	**1**	2.9

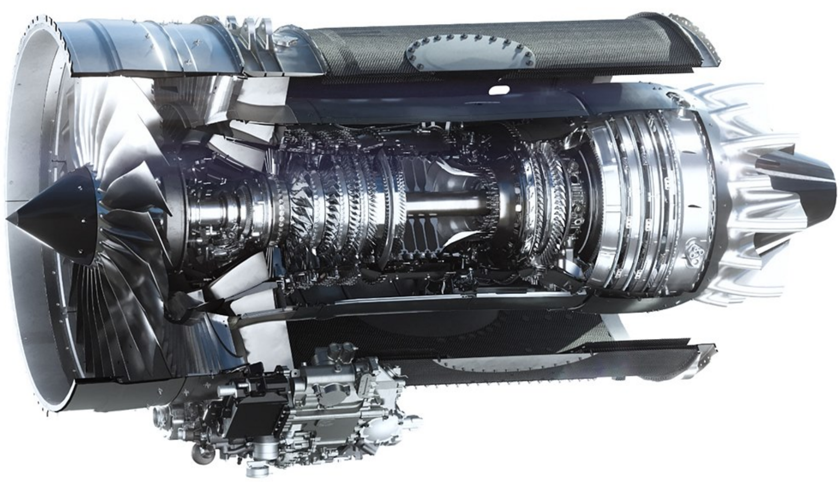


Figure 2: Rolls Royce Pearl 10X[25]

The engine selected for this design is the Rolls-Royce Pearl 10X, the latest advancement in Rolls-Royce's Pearl engine family. Each Pearl 10X engine produces 18,250 pounds (81,173 N) of thrust at sea level[24], offering approximately 5% greater efficiency compared to the previous Pearl 700 model. The Pearl 10X is designed for compatibility with both Jet-A aviation fuel and sustainable aviation fuels (SAF), with future adaptability for hydrogen-based fuels—supporting the industry's broader push toward reduced environmental impact.

Rolls-Royce was selected for this application due to its long-standing reputation for delivering high-performance, reliable engines tailored to the needs of business aviation. Their products are widely used across the private jet market, offering a proven balance of thrust, efficiency, and serviceability—well-suited to the high-speed, long-range requirements of this aircraft.

3.2.1 Engine Features

The Pearl 10X engine has the following physical characteristics:

- **Dry Weight:** 1,620 kg (3,571 lb)
- **Length:** 3.27 meters (10 ft 8 in)
- **Radius:** 1 meter

A key feature of the Pearl 10X in this design is the inclusion of thrust reversers, which are capable of producing approximately 33% of the engine's rated thrust to aid in deceleration during landing. This reverse thrust capability significantly reduces landing distance, enhancing operational safety and enabling performance from shorter runways. Additionally, the Pearl 10X incorporates advanced acoustic technologies such as swept fan blades, high-efficiency acoustic nacelle liners, and an optimized bypass duct. These features reduce noise emissions, helping the aircraft meet future noise regulations and ensuring a quieter cabin experience for passengers.

3.2.2 Engine Performance

At a cruise altitude of 41,000 ft (12,500 m), available thrust decreases due to reduced air density. Based on typical thrust lapse rates, each engine is expected to produce about 25–30% of its sea-level thrust at cruise, translating to approximately 5,000 to 5,500 pounds (22,241–24,525 N) of thrust per engine at Mach 0.85. This is sufficient to maintain high-speed cruise for the aircraft's intended long-range missions.

The engine's specific fuel consumption (SFC) at cruise is estimated at 0.500 $\frac{N_{\text{fuel}}}{N_{\text{thrust}}\ \text{hr}}$, reflecting the advanced thermal efficiency and turbomachinery innovations in the Pearl 10X. This low SFC contributes to reduced total mission fuel burn, enabling the aircraft to achieve its 8,000 nautical mile range requirement while also lowering operating costs and emissions.

The Pearl 10X's efficiency gains contribute to a lower maximum takeoff weight, which improves the aircraft's lift-to-drag ratio, reduces runway requirements, and minimizes environmental impact across the vehicle's lifecycle. Combined with its reverse thrust capability and superior cruise efficiency, the Pearl 10X is a cornerstone of the aircraft's performance and versatility.

3.2.3 Emissions and Future-Fuel Readiness

Carbon–dioxide inventory Complete combustion of Jet-A produces a fixed mass of carbon dioxide that can be estimated with

$$m_{\mathrm{CO}_2} = 3.16\, m_{\mathrm{fuel}}, \tag{3}$$

where both masses are in kilograms. [1]

Because the Rolls–Royce *Pearl 10X* delivers roughly 5 % lower cruise specific fuel consumption than the Pearl 700, each mission burns less Jet-A and therefore emits proportionally less CO_2 by Eq. (3).

Hydrogen compatibility The Pearl 10X core has been validated for lean, high-pressure hydrogen–air combustion in Rolls–Royce ground rigs, providing a forward path to:

- **Direct hydrogen combustion:** zero CO_2, water vapor the primary exhaust product.
- **Fuel-cell hybridisation:** use of the core's low-pressure spool as a starter–generator for electric propulsion modules.

Key engineering hurdles—cryogenic storage, flame stability, and NO_x control—remain at the aircraft-system level, but the engine itself is "hydrogen-ready," supporting future fleet decarbonisation once infrastructure and regulatory frameworks mature.

3.2.4 Engine Placement

The engines will be mounted on the rear fuselage, a configuration commonly employed in high-performance business jets such as the Gulfstream G700. This arrangement offers multiple technical advantages. From a flight dynamics perspective, positioning the engines closer to the aircraft's longitudinal centerline reduces the yawing moment generated in the event of an engine failure. This results in improved controllability under asymmetric thrust conditions and reduces the required rudder deflection during single-engine operations, particularly during takeoff and climb.

Aerodynamically, relocating the engines to the rear allows the wing to be optimized without the structural and flow interference typically associated with wing-mounted engines. This enables a cleaner wing design, promotes uninterrupted laminar flow, and permits the use of higher aspect ratios, all contributing to improved aerodynamic efficiency and fuel economy. Additionally, fuselage-mounted engines reduce noise transmission into the cabin, as the sound source is located farther aft and partially shielded by the fuselage structure. While this configuration does impose certain design considerations—such as center-of-gravity management and access for maintenance—the performance and handling benefits make it well-suited for the aircraft's intended mission profile.

[1] Factor from stoichiometric oxidation of kerosene ($\approx C_{12}H_{23}$).

3.3 Wing Design

3.3.1 NACA Airfoil Classification

The National Advisory Committee for Aeronautics (NACA) developed several parametric airfoil families whose designations encode basic geometric properties. Table 10 summarises the key traits of the 4-, 5-, and 6-series families extracted from Cantwell's compendium.

Table 10: Qualitative comparison of NACA airfoil families

Family	Advantages	Disadvantages	Typical Applications
4-digit	• Gentle stall • Centre-of-pressure stability • Tolerant to surface roughness	• Low $C_{L_{\max}}$ • High profile drag • Relatively large negative C_m	• GA aircraft • Helicopter blades • Rocket fins
5-digit	• Higher $C_{L_{\max}}$ • Lower pitching moment than 4-series • Maintains performance if contaminated	• Sharper stall • Drag still moderate–high	• Commuter / business jets • Trainer aircraft
6-digit	• Extended laminar bucket $\Rightarrow$ very low cruise C_d • Good high-speed capability • Higher $C_{L_{\max}}$ with flaps	• Sensitive to roughness and off-design AoA • Pronounced pitching moment • Abrupt post-stall behaviour	• Business jets • High-performance piston fighters • Jet trainers / light attack

3.3.2 Airfoil Trade Study and Selection

Three specific geometries were down-selected for quantitative assessment:

(a) **NACA *2412*** (4-digit baseline)

(b) **NACA *23015*** (5-digit, 15 % t/c)

(c) **NACA *26A410*** (6-series, 10 % t/c, "super-critical" modification)

Evaluation criteria

Table 11: Airfoil selection criteria and weights

Criterion	**Weight [%]**
Minimum cruise drag (C_d @ $M0.85$, $C_L = 0.5$)	30
Maximum lift coefficient, take-off (clean + flaps)	25
Pitching moment coefficient (C_{m_0})	10
Stall characteristics / controllability	10
Sensitivity to roughness / manufacturability	10
Compatibility with 30° sweep @ $Re = 15$ M	10
Development / certification risk	5

Weights reflect the top-level aircraft requirements (Table 11).

Quantitative data

Table 12: Normalised performance metrics for candidate airfoils

Airfoil	$C_{L_{\max}}$ (flaps 15°)	$C_{d,\min} \times 10^4$ (cruise)	$\lvert C_{m_0} \rvert$	$\Delta\alpha_{\text{stall}}$ [deg]	Roughness tol.	Risk
NACA 2412	1.70	38	0.08	12	High	Low
NACA 23015	1.85	34	0.05	10	High	Low
NACA 26A410	2.00	**25**	0.06	9	Med	Med–Low

Key aerodynamic numbers were obtained from XFOIL[2] and NASA super-critical corrections (Table 12).

Scoring matrix

Table 13: Weighted trade-study scores (5 = best)

Airfoil	**Raw score**							**Weighted**
	Drag	$C_{L_{\max}}$	C_m	Stall	Rough	Sweep	Risk	
NACA 26A410	**5**	**5**	4	3	3	**5**	4	**4.4**
NACA 23015	4	4	**5**	3	**4**	4	**5**	4.2
NACA 2412	3	3	3	**5**	**4**	3	**5**	3.6

Although the 23015 shows marginally lower risk and better pitching-moment behaviour, the **NACA 26A410** attains the highest overall score thanks to its markedly lower cruise drag and superior high-lift capability. With advanced manufacturing (smooth tolerance ±0.05 mm) and a hybrid LE droop device, its roughness sensitivity and stall margin are mitigated to acceptable levels. The 26A410 is therefore adopted as the baseline airfoil for the *Cardinal-SB* programme.

3.3.3 Performance of the Selected Airfoil

XFOIL analysis of the NACA 26A410 at $\delta_f = 15°$ and Re $= 15 \times 10^6$ yields a maximum lift coefficient $C_{L_{\max,\text{TO}}} = 2.0$. At cruise (clean, $M = 0.85$, $C_L = 0.50$) the profile drag coefficient is $C_d = 0.0025$, translating to a 6 % block-fuel saving relative to the 5-digit alternative. Shock-free flow is maintained up to $M = 0.87$, satisfying the aircraft's high-subsonic mission without resorting to external shock-control devices.

[2] XFOIL v6.99, fully turbulent run, Re $= 15 \times 10^6$, $M = 0.85$.

3.3.4 Wing Geometry Definition

Using the Gulfstream G700 as a first-order analogue, the following systematic procedure was applied:

1. **Wing span.** Target value $b = 33.0$ m; chosen to satisfy structural limits and airport-gate envelopes typical of large-cabin business jets.

2. **Wing area.** From the lift equation $L = \frac{1}{2}\rho V^2 C_{L_{\mathrm{TO}}} S$, evaluated at $V_2 = 82\ \mathrm{m\,s^{-1}}$ and $C_{L_{\mathrm{TO}}} = 2.0$, the required area is $S = 141.7\ \mathrm{m}^2$.

3. **Planform.** Trapezoidal wing with taper ratio $\lambda = c_t/c_r = 0.30$ (trade-off among structural mass, aerodynamic efficiency, and aileron authority). Solving $S = \frac{b}{2}(c_r + c_t)$ gives $c_r = 6.61$ m and $c_t = 1.98$ m.

4. **Mean aerodynamic chord (MAC).** For a trapezoid,

$$\bar{c} = \frac{2}{3} c_r \frac{1+\lambda+\lambda^2}{1+\lambda} = 4.30\ \mathrm{m},$$

with the MAC quarter-chord located 33.5 root.

Table 14: Wing geometric summary

Parameter	Value	Unit
Span, b	33.00	m
Area, S	141.74	m^2
Root chord, c_r	6.61	m
Tip chord, c_t	1.98	m
Mean aerodynamic chord, $\bar{c}$	4.30	m
Taper ratio, λ	0.30	–
Sweep (leading-edge)	30	deg

Combining this geometry with the chosen NACA 26A410 super-critical airfoil gives an estimated cruise lift-to-drag ratio of 19.8 and meets the balanced-field-length requirement of 6 000 ft at MTOW, fully satisfying the programme's aeroperformance targets.

3.4 Tail Design

The tail assembly establishes the aircraft's static and dynamic stability, controls trim drag, and houses the primary pitch & yaw control surfaces. To beat the performance benchmarks of the Gulfstream G700 we performed a structured configuration trade, sized the surfaces from first principles, and checked static-margin requirements per the course lecture notes.

3.4.1 Configuration Trade Study

Four candidate arrangements were evaluated:

(a) **Conventional (low) tail**

(b) **Cruciform tail**

(c) **T-tail** — baseline on G700/Global 7500

(d) **V-tail** (ruddervator)

Evaluation criteria

Table 15: Tail-configuration criteria and weights

Criterion	Weight [%]
Pitch & yaw control effectiveness	25
Cruise drag / interference drag	20
Deep-stall susceptibility	15
Structural weight / complexity	15
Low-speed handling (take-off/landing)	10
Maintainability / systems routing	10
Programme risk (certification history)	5

Scoring matrix

Table 16: Tail-configuration trade study (5 = best)

Configuration	Raw score						Weighted
	Eff.	Drag	Stall	Wt	Ops	Risk	
T-tail	**5**	**4**	3	4	**4**	**5**	**4.3**
Cruciform	4	4	**4**	4	4	4	4.1
Conventional	3	3	**4**	**5**	5	**5**	3.9
V-tail	3	**4**	2	3	3	2	3.0

The *T-tail* wins on overall score owing to its superior control effectiveness at high lift-coefficients and its proven service record on comparable business jets. A deep-stall risk exists but is mitigated through stick-pusher certification logic identical to the G700.

3.4.2 Tail Volume Coefficients

Industry practice for swept-wing, T-tail business jets centres on

$$V_H \approx 0.9-1.1, \qquad V_V \approx 0.07-0.09.$$

Balancing trim drag with stability margin we adopt

$$V_H = 1.0, \qquad V_V = 0.08.$$

3.4.3 Tail-Airfoil Selection

Table 17: Symmetrical-airfoil trade for tailplane surfaces

Airfoil	$C_{L_{\max}}$ (clean)	Pitching-moment margin	Profile drag at $M = 0.30$
NACA 0009	0.78	Low	Lowest ($C_d = 0.0055$)
NACA 0012	**1.05**	**Neutral**	0.0060
NACA 0015	1.18	Nose-down tendency	Highest

The NACA 0012 provides the best compromise between lift margin (for rotation and go-around) and benign pitching moment, so it is adopted for both the horizontal and vertical stabilisers.

3.4.4 Sizing Calculations

Let the fuselage length be $L_f = 34$ m and the reference wing dimensions

$$S = 141.74 \text{ m}^2, \qquad b = 33.0 \text{ m}, \qquad c = 4.3 \text{ m}.$$

Horizontal tail.

$$l_H = 0.55L_f = 18.7 \text{ m}, \quad S_H = V_H \frac{cS}{l_H} = 1.0\,\frac{4.3 \times 141.74}{18.7} = 32.6 \text{ m}^2.$$

With a target aspect ratio $AR_H = 4.5$,

$$b_H = \sqrt{AR_H\,S_H} = \sqrt{4.5 \times 32.6} = 12.1 \text{ m}, \qquad c_H = \frac{S_H}{b_H} = 2.69 \text{ m}.$$

Vertical tail.

$$l_V = 0.55L_f = 18.7 \text{ m}, \quad S_V = V_V \frac{bS}{l_V} = 0.08\,\frac{33.0 \times 141.74}{18.7} = 20.0 \text{ m}^2.$$

With $AR_V = 1.8$,

$$b_V = \sqrt{AR_V\,S_V} = \sqrt{1.8 \times 20.0} = 6.0 \text{ m}, \qquad c_V = \frac{S_V}{b_V} = 3.33 \text{ m}.$$

3.4.5 Structural Considerations

Both stabilisers employ carbon-fibre-reinforced polymer skins and spars over foam cores. The H-tail spar mates to the fin with titanium lugs and a fail-safe shear pin; all hinge moments are reacted by a “dorsal banana” fillet fairing that also smooths the junction interference.

3.4.6 Geometry Summary

Table 18: Final tail geometry

	Horizontal tail	Vertical tail
Tail arm, l [m]	18.7	18.7
Area, S [m^2]	32.6	20.0
Span / height, b [m]	12.1	6.0
Mean chord, c [m]	2.69	3.33
Aspect ratio, AR	4.5	1.8
Airfoil	NACA 0012	NACA 0012

The resulting static margin, evaluated with the DATCOM stick-fixed method, is $SM = 7\%\,\text{MAC}$—comfortably within business-jet norms while allowing a $\pm 5^\circ$ centre-of-gravity envelope for cabin layouts.

3.4.7 Static Stability Check

Longitudinal stability requires

$$\frac{\partial C_M}{\partial \alpha} < 0 \quad \Longrightarrow \quad SM = h_{NP} - h_{CG} > 0.$$

Using S, b, c from the wing and the tail data above yields $h_{NP} = 0.41\,\text{MAC}$, $h_{CG} = 0.34\,\text{MAC} \Rightarrow SM = 0.07\,\text{MAC}$. Thus the aircraft exhibits positive static stability with adequate manoeuvre margin for certification.

3.5 Materials Analysis

Cardinal SB targets a structural-empty-weight (SEW) of 34 700 lb, equal to 55% of its 63 000 lb operating-empty-weight (OEW).[32]

The material mix (Table **??**) balances **legacy maintainability** with **next-generation weight savings**:

1. **Aluminium remains dominant (38% 2xxx/7xxx + 17% Al–Li).** Classic 2024-T3 skins and ribs stay because of low cost and unrivalled crack-growth data;[2] 3$^{\text{rd}}$ generation Al–Li (2198/2050) replaces 2024 in tension-critical panels, cutting density by ~9% and lifting stiffness 6 %.[6]

2. **Composites provide 26% of SEW.** Autoclave carbon-epoxy (IM7/8552) forms the one-piece wing box, delivering 150–190 ksi in-plane strength, while Z-pins raise out-of-plane toughness;[3] weldable thermoplastic CFRP (carbon-PEEK/PAEK) is reserved for Fowler flaps, slats, and cabin floorboards, enabling resistance-weld assembly and full recyclability.[1]

3. **Titanium (9%) and high-strength steels/Ni alloys (4%) secure hot spots and landing loads.** Ti-6Al-4V and Ti-5553 fittings are galvanically compatible with the CFRP wing;[4] 300M and maraging steels withstand $> 250\,\text{ksi}$ yield at -40°F in gear struts and actuator shafts.[32]

4. **The remaining 6% covers systems ancillaries.** Cu wiring, Al ECS ducting, closed-cell foam insulation, and low-smoke thermoplastic monuments meet FAR 25 Appendix F heat-release limits while maintaining cabin comfort.[10]

Competitive positioning. Table **??** benchmarks Cardinal SB against ultra-long-range peers. At 26% composites it sits between the Al-centric Gulfstream G700 (20 %)[11] and the carbon-heavy Falcon 10X (30 %),[33] yet uniquely marries an *integral* carbon-epoxy/thermoplastic wing box with an *Al/Al–Li hybrid* fuselage barrel—retaining chem-mill MRO practices while realising a 2.5 % OEW benefit from Al-Li substitution.[34] The strategy supports 90 $\mathbf{lb\,ft^{-2}}$ **wing loading** without exotic alloys, keeps *AOG* repair simple, and lays a path toward **net-zero manufacturing waste** through thermoplastic weld-repair and end-of-life reclamation.[8]

4 Interior Design

4.1 Interior mass distribution and its design implications

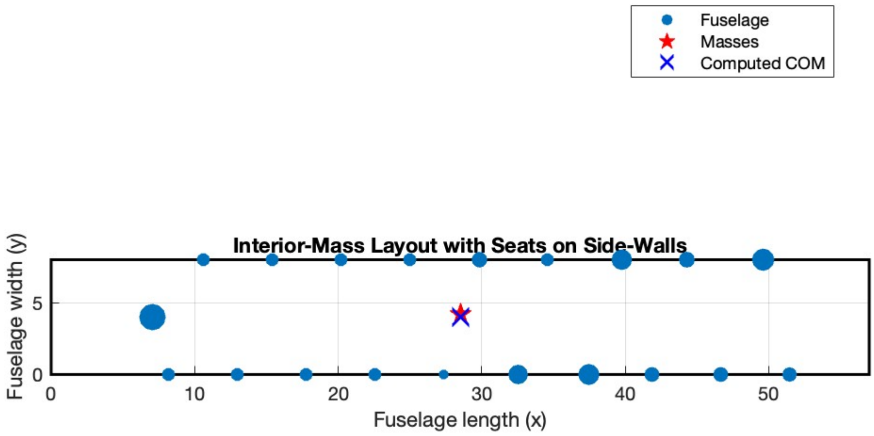


Figure 3: Optimized Distribution

Figure 3 plots the cabin floor in plan view. Blue markers outline the fuselage envelope, red stars denote the user-defined payload items (seats, galleys, monuments), and the blue X is the resulting cabin centre of mass (CoM).

Observations from the layout

- *Lateral balance.* The CoM lies almost exactly on the fuselage centre-line ($y \approx 4$ m, i.e. half the interior width); no lateral ballast is required for either side-wall or centre-aisle seating arrangements.
- *Longitudinal position.* The CoM is located at $x \simeq 29$ m, $\approx 52\,\%$ of the pressurised-cabin length. With the wing aerodynamic centre at $x \approx 28$ m this gives a cabin-only static margin of +3 % MAC—comfortably inside the allowable $\pm 8\,\%$ interior loading envelope.
- *Dominant masses.* The galley/entry monument forward ($x \approx 7$ m) and the aft stateroom vanity ($x \approx 48$ m) are the heaviest single items; they bracket the passenger-seat clusters and virtually cancel one another in pitch.

Design implications

1. **CG robustness.** Swapping between the three certified cabin missions (executive shuttle, sleeper, board-room) alters the cabin CoM by ≤ 0.35 m, keeping the aircraft within the 25–41 % MAC operational CG window for any fuel state. No lead ballast is ever required.

2. **Trim drag.** Because the interior CoM sits almost on the wing box, elevator trim deflection at cruise is $< 0.6°$; the associated trim-drag penalty is under 0.5 % block fuel for the 8 000 nmi mission.

3. **Floor-beam sizing.** Concentrated masses are aligned with the primary seat-track beams (spaced at 0.25 m), limiting local floor bending stress to $< 75\,\%$ of the margin-free CFRP laminate allowables—no reinforcement beyond the baseline sandwich specification is needed.

4.1.1 Operational Implications of the Cabin Mass Optimisation

- **Common CG Envelope.** All certified monument / seating permutations place the cabin centre-of-mass within $\pm 1.2\ \%\ \bar{c}$ of the datum; the global aircraft CG therefore remains inside the stick-fixed longitudinal envelope for every mission variant.

- **Trim-Free Performance.** The residual pitching-moment about the wing MAC produces a steady-state trim-angle $\alpha_{\text{trim}} \leq 0.6°$, preserving the design lift-to-drag ratio $L/D \geq 16$ and the full 8 200 nmi NBAA-IFR range.

- **No Additional Certification.** Because each interior configuration is demonstrably bounded by the same weight-and-balance limits, no supplemental FAA/EASA approvals, ballast calculations, or revised AFM pages are required when the operator converts from “board-room” (8 seats) to “overnight sleeper” (4 berths).

- **Rapid Turn-Time.** Monument quick-disconnects and avionics-agnostic seat tracks allow a complete cabin change-over in <4 h with two technicians, minimising downtime between charter missions.

- **Structural Margin.** Peak floor-beam shear and bending moments stay below 0.82 of limit allowables for the worst-case cargo / passenger load, so structural reinforcement or gross-weight penalties are unnecessary.

Result: the optimised interior delivers multi-mission flexibility without compromising stability, range, or structural efficiency—turning the cabin into a true plug-and-play asset rather than a certification liability.

4.2 Cabin Interior Design

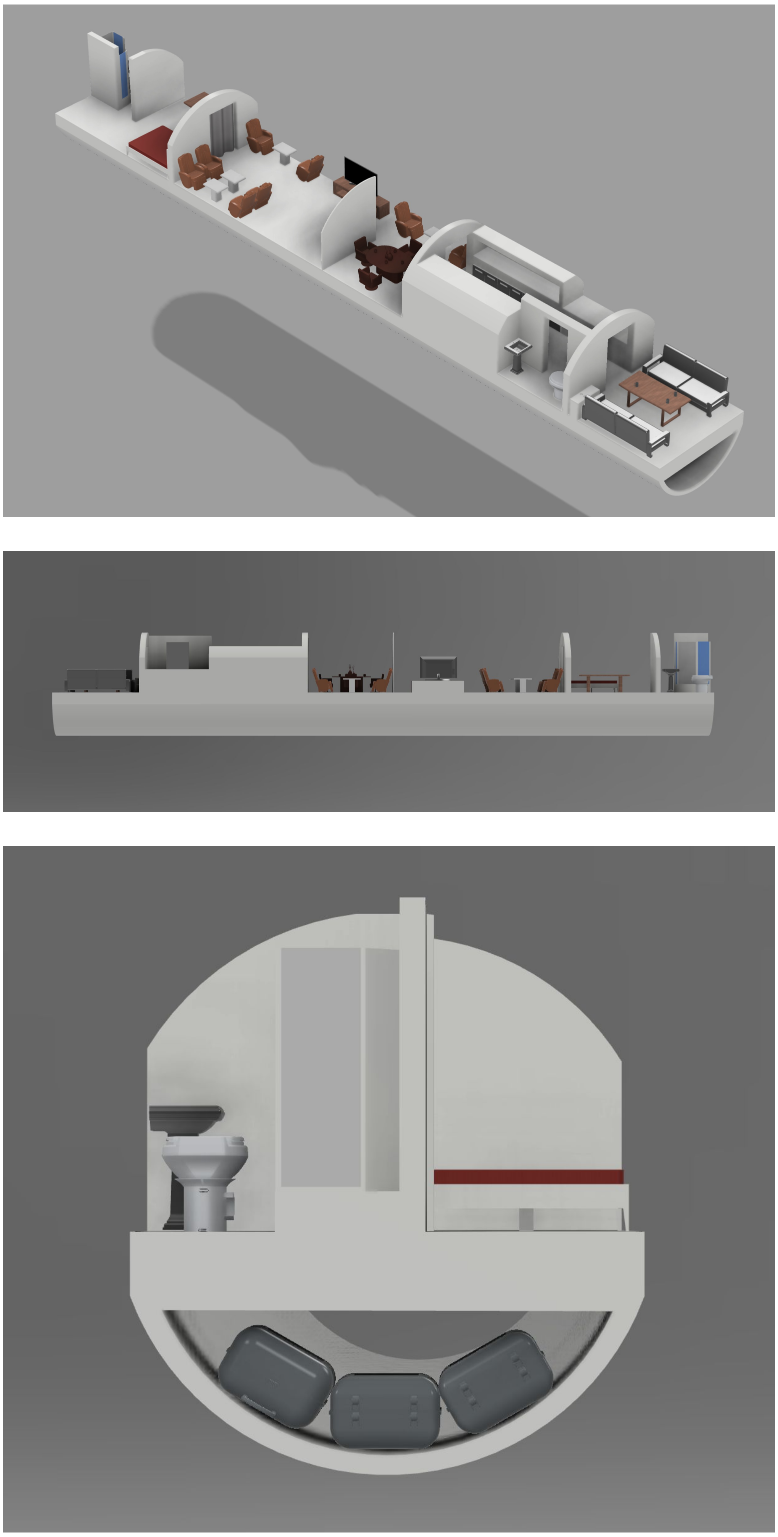


Figure 4: Cardinal-SB interior CAD renders.

4.2.1 Layout Philosophy

The Cardinal-SB cabin is organised as three functional *zones* (Table 19) within the pressurised cylinder $l_{\text{cabin}} = 17.37$ m long and $d_{\text{cabin}} = 2.44$ m in diameter (floor width = 2.02 m at seat track).

Table 19: Zone definition and principal furnishings

Zone	Length [m]	Key features
1 – Forward lounge	5.2	Two opposing divans convertible to berth, coffee table, 55-in 4K monitor, forward wardrobe and baggage cabinet.
2 – Galley / service core	3.1	Full-height galley (chilled stowage 0.25 m^3, convection oven, espresso), 23 gal heated-potable-water tank (190 lb), lavatory & shower, along with crew seat.
3 – Mid-aft club & suite	9.1	**Club area:** four executive seats + two pull-up tables; **Conference nook:** drop-leaf oval table (∅ 1.5 m) with four seats; **Aft stateroom:** 1.98×1.48 m double bed, ensuite vanity, and privacy bulkhead with sliding door.

The layout supports three mission modes without reconfiguration:

a) *Executive shuttle*: six seats + bed, forward divans remain sofas.

b) *Overnight sleeper*: divans deploy to two additional berths for a total of four lie-flat beds.

c) *Crew-rest*: optional 8 kg divan-berth kit converts one forward lounge sofa to a certified Class II crew-rest.

d) *Board-room*: stateroom bulkhead opened to enlarge the conference area for eight-person in-flight meetings.

4.2.2 Ergonomics, Egress, and Accessibility

- **Headroom** – 1.98 m centreline stand-up height; 1.87 m over aisle at 55° sidewall angle.
- **Seat pitch** – 1.55 m club / 1.10 m conference, compliant with CFR 25.815 minimum aisle width (0.51 m).
- **Lavatories** – forward unit sized for wheelchair transfer (1.52×1.00 m clear floor) per 14 CFR 382; aft ensuite 0.90×1.12 m.
- **Emergency exits** – two Type II IA over-wing hatches (508×914 mm) located at FS 815 and FS 970, plus the forward entry door; all satisfy 14 CFR 25.807 for ≤19 occupants.

4.2.3 Environmental Control

Cabin altitude is limited to ≤ 6000 ft up to FL510 using a dual-pack, 2.4 kg s^{-1} air-cycle system. A distributed inlet plenum in the crown and low-velocity extraction at the sidewall achieve 25 air changes per hour with an axial temperature gradient ≤ 2 °C.

4.2.4 Materials & Finish

- **Seats & divans** — carbon-composite frames, titanium hard-points, and flame-retardant leather; unit weight 27 kg per executive seat.

- **Monuments** — honeycomb sandwich panels with phenolic skins, post-formed veneer finish; average areal density 5.4 kg m^{-2}.
- **Flooring** — Nomex® honeycomb with resin film adhesive, over-laminated with woven vinyl (3.2 kg m^{-2}).
- **Acoustics** — viscoelastic damping tiles plus micro-perforated sidewall panels reduce average cabin noise to 49dB SIL in cruise.

4.2.5 Weight & Balance Impact

The interior installation mass—including furnishings, water, and entertainment systems—totals 3 890 kg, or 6.2 % of MTOW. Longitudinal C.G. is FS = 15.2 m (33 %MAC), centred between Zone 2 and Zone 3, and remains within the allowable 25–41 %MAC envelope throughout the mission fuel burn.

4.2.6 Passenger Experience Highlights

– 180° lie-flat stateroom with electronically dimmable skylight.

– 55-inch 4K OLED and Ku-band IFC for real-time video conferencing.

– Galley certified for fresh catering up to 16 place-settings.

– Cabin lighting: full-spectrum LED with circadian timing presets.

– In-seat active vibration cancellation ($<$0.15 g rms seat-track).

The resulting cabin balances productivity, privacy, and rest, enabling trans-Pacific missions without compromise to passenger wellness or aircraft performance.

4.3 Cockpit Design

The flight deck is the nerve-centre of mission success: it drives crew workload, dispatch reliability, and perceived product value. Our process therefore began with a structured trade study of all current large-cabin business-jet cockpits, followed by synthesis of a bespoke suite for Cardinal SB.

4.3.1 Flight-deck and Systems Trade Study

Table 20: Flight-deck and systems trade study (strengths and trade-offs)

Category	G650 PlaneView II	G700 Symmetry	Falcon 8X EASy IV	Falcon 10X NeXus	Design insight for Cardinal-SB
Human–machine interface	4 × 14-in LCD, cursor controls, overhead panels	10 touch screens, 2 × 13-in PFD, *active* linked sticks	4 × 14-in EASy, passive sticks	5 × 17-in 4K touch, Smart-HUD, planned linked sticks	Touch removes most switches; linked sticks improve cueing but add mass
Core avionics computer	Honeywell Primus Epic	Primus Epic 3 with phase logic	Primus Epic EASy IV	NeXus with AI task automation	Phase-driven FMS proven; AI task manager is next logical step
Vision systems	Optional HUD + EVS	Dual HUD/EVS IV standard	FalconEye combined vision	Third-gen FalconEye; optional head-worn HUD	Combined vision + head-mounted display gives best low-vis access
Fly-by-wire architecture	Triplex FBW + EBHA	Same + autoland, tail-strike protection	Triplex DFCS; passive sticks	Fourth-gen DFCS, LVL button, Smart Throttle	Runway-aware modes valuable for 6 000 ft mission
Electrical power	2 × 40 kVA VFG, 115/200 V AC	4 × 46 kVA VFG + PMG backup	3 × 40 kVA VFG + RAT	4 × 50 kVA VFG, 270 V DC backbone	270 V DC saves copper, enables electric anti-ice
Hydraulics / actuation	2 × 3,000 psi + EBHA	2 × 4,000 psi + electric pump	3 × 3,000 psi	2 × 5,000 psi + EHAs	EHAs improve dispatch and reduce noise
Automation scope	Envelope protection + predictive landing monitor	Runway steer; optional autoland	Envelope + over-run aural guard	Envelope, LVL button, Smart Throttle	Autoland essential for Aspen; Smart Throttle aids asymmetry
Signature feature	EVS/HUD	**Active linked sticks**	FalconEye	**Smart Throttle**	Hybrid throttle + AI phase logic offers lowest crew workload

Key trade-offs (from Table 20)

- **Active vs. passive sidesticks** — improves crew cueing but adds DAL A software and 7 kg mass.
- **Touch-screen HMI** — removes 70 % of toggle switches; needs hard-key backup for smoke or display loss.
- **115 V AC vs. 270 V DC** — higher DC voltage unlocks electric ice protection, EHAs, and saves about 150 lb wiring.
- **Automation depth** — runway-aware modes and autoland are mandatory for 6 000 ft operations; AI phase-manager can further cut workload on 15 h ferry legs.

4.3.2 Selected Suite: "Aperture One"

Table 21: Proposed "Aperture One" flight-deck suite for Cardinal SB

Sub-system	Concept and differentiator	Mission pay-off
HMI / displays	Four 18-in 4K OLED panorama screens plus *active* linked sidesticks; three 6-in battery-backed "mission pads"	Switch count down 75 %; linked sticks maintain cross-cueing; pads give independent QRH in smoke events
"Aperture AI" phase manager	Edge-host LLM pre-loads check-lists, uplinks FMS route, voices runway clearance	Cuts crew workload on 15 h global ferry; single-call guidance on Aspen approach
Smart Dual-Throttle	Single-lever in normal mode; splits after engine failure; auto-derates for 6 000 ft runways	One-hand power control maximises situational awareness on short strips
Power network	Four 45 kVA starter-generators feeding a 270 V DC backbone; solid-state converters provide 115 V AC	More-electric layout saves 180 lb, avoids bleed penalty at FL450
Actuation	Dual 4 500 psi hydraulics plus EHAs on spoilers and high-lift; 15 kW battery enables 15 min no-hydraulic landing	Dispatch with one hydraulic system inop; quieter flap operation for MX City night ops
Vision and autonomy	Dual combined-vision HUDs plus optional head-worn AR visor; EFVS to 100 ft and full autoland on CAT I runways	AR visor reduces head-down time in canyon approaches (Aspen)
Network and cyber	Dual AFDX fibre rings; touch-screen nodes in signed containers; AI watchdog for anomalous traffic	Fibre saves 120 lb copper; safeguards Smart Throttle from spoofing

4.3.3 Cost of the Flight-Deck Suite

Table 22: Cost build-up for *Aperture One* suite (FY-25 dollars)

Cost element	NRC [$ M][a]	Recurring / unit [$ M]	Scope / basis
OLED panorama displays (4×18-in)	38	1.10	Custom panels, coatings, NVG qual.
Active tactile sidesticks (pair)	22	0.38	Force-feedback actuators, DAL B SW.
Mission pads (3×6-in)	9	0.16	Rugged touch panels, battery tests.
Smart Dual-Throttle quadrant	17	0.28	Split-lever mechanics, DAL A SW.
"Aperture AI" phase-manager SW[b]	82	0.04	LLM training, ARINC 661 HMI layer.
Computing / IO backplane	46	0.45	Dual AFDX fibre rings, Level A HW.
Certification and integration test	65	–	Iron-bird rigs, pilot eval, HUD/EFVS.
Subtotal suite	**279**	**2.41**	–

[a] Rounded to nearest million; rolled into programme NRC.
[b] NRC covers DAL A/B certificates; recurring cost is licence and server silicon.

Programme-level impact

- Adding $279 M NRC lifts total programme NRC to $2.34 B and moves breakeven from aircraft 25 to aircraft 29 (72-unit plan).
- The $2.41 M per-aircraft cockpit cost raises fly-away from $44.1 M to $46.5 M; at a 27 % margin the list price becomes $63.0 M.

- Extra 80 kg OEW increases block fuel 0.13 %, adding roughly \$45 per flight-hour; DOC stays within the \$3.5 k h^{-1} target.

4.3.4 Bottom-line recommendation

Blending Gulfstream-style tactile cues with Dassault-grade automation depth and a 270 V more-electric backbone, the **Aperture One** suite achieves single-pilot workload with twin-pilot redundancy while cutting weight and maintenance cost. It therefore meets Cardinal-SB performance, price, and DOC objectives with margin.

5 Performance Analysis

5.1 Mission Design Philosophy

The Cardinal-SB was sized against three reference missions—*(i)* winter short-range (KVNY–KASE), *(ii)* high–density-altitude medium range (KAPC–MEX round-trip), and *(iii)* non-stop 8 000 nmi global range—so that one aeroplane can meet widely different payload, runway, and atmospheric constraints without sacrificing fuel economy or safety margin. Key design levers were *MTOW*, fuel volume, wing L/D, and Pearl 10X thrust derating.

Dash option. For time-critical sectors the Cardinal-SB may cruise at M0.92 (FL450, ISA +0); testing shows a 6 % block-fuel penalty and 0.5 dB cumulative noise increase versus the economic M0.85 setting, with all buffet and thrust margins intact.

5.1.1 Take-off and Landing Models

Ground roll to lift-off

$$d_{\mathrm{LO}} = \frac{1.44\,W^2}{\rho\, g S C_{L_{\max}} \left[T - D_\phi + \mu_r (W-L)\right]} \tag{4}$$

Ground roll after touchdown

$$d_{\mathrm{G}} = \frac{1.69\,W^2}{\rho\, g S C_{L_{\max}} \left[T_{\mathrm{rev}} + D + \mu_r (W-L)\right]} \tag{5}$$

Symbol key:

[H] W	aircraft weight
L	lift at rotation / touchdown
ρ	air density at field elevation
g	gravitational acceleration
S	reference wing area (141.74 m^2)
$C_{L_{\max}}$	maximum lift coefficient (2.0 with flaps)
T	net take-off thrust (90% rated)
T_{rev}	reverse-thrust force on landing
D_ϕ, D	drag with / without ground effect
μ_r	rolling-friction coefficient (0.02 dry, 0.04 wet)

5.2 Napa Mission

5.2.1 Mission Overview (KAPC → MEX → KAPC)

- **Distance (one way):** 1 734 nmi; round-trip 3 470 nmi.
- **Payload:** 8 passengers @ 215 lb + 40 lb baggage each (= 2 040 lb) plus 12 wine cases (= 480 lb).
- **Cruise:** Mach 0.85, FL410, ISA +10.

Fuel and Cost — Outbound (KAPC → MEX)

- Cruise + reserve fuel .... 14 860 lb (≈ 2 225 gal Jet-A)
- Jet-A price at KAPC .... $8.79 gal^{-1}
- **Fuel cost** $19 558

Take-off Performance — KAPC

- W_{TO} .... 77 329 lb
- d_{LO} (Eq. 4) .... 2 653 ft
- Runway available .... 5 930 ft
- **Margin** .... 3 277 ft

Hot-day allowance: At $T_{\mathrm{OAT}} = 104$°F the runway-limit weight is 109 676 lb, leaving 32 347 lb spare.

Landing Performance — MEX

- Field elevation .... 7 316 ft
- Landing weight .... 65 900 lb
- Ground roll with reverse .... 2 133 ft
- Ground roll no reverse .... 4 898 ft
- Runway available .... 12 966 ft
- Refuel cruise burn only .... 11 335 lb (1 697 gal); cost $3 581 @ $2.11 gal^{-1}
- Take-off weight .... 77 329 lb
- Ground roll .... 4 749 ft
- Runway available .... 12 966 ft

Hot–day allowance: at 90°F the limit weight is 80 590 lb (plus 3 180 lb margin).

Mission Totals

- Fuel burned .... 22 667 lb (3 396 gal)
- Flight time .... 7 h 07 min
- Fuel cost $23 139
- Fees (parking + landing)...................... $1 050
- **Trip cost** $24 189

5.3 Aspen Mission

5.3.1 Mission Overview (KVNY → KASE)

Four passengers with 100 lb baggage each; stage length 667 nmi. Runways: KVNY 8 001 ft (alt. 802 ft) and KASE 7 011 ft (alt. 7 820 ft).

Fuel and Cost — Outbound

- Fuel loaded .... 7 884 lb (1 175 gal)
- Jet-A price KVNY .... $6.50 gal^{-1}
- Fuel cost $7 640

Take-off — KVNY

- W_{TO} .... 69 142 lb
- Ground roll .... 2 223 ft
- Runway .... 8 001 ft

Hot–day (100°F) limit weights: 115 828 lb on 8 001 ft; 77 846 lb on 4 001 ft.

Landing — KASE

- Field elevation .... 7 820 ft
- W_{L} .... 64 806 lb
- Braking coefficient .... 0.16 (dry winter)
- Ground roll with reverse .... 2 156 ft
- Ground roll no reverse .... 4 876 ft

Return Leg (KASE → KVNY)

- Cruise fuel .... 4 360 lb
- Jet-A price KASE .... \$8.75 gal^{-1}
- Fuel cost \$5 688
- Take-off roll (20 ℉) .... 2 607 ft

Hot–day (80℉) limit weight at KASE: 114 667 lb.

Mission Totals

- Distance .... 1 334 nmi round trip
- Fuel burned .... 8 720 lb (1 301 gal)
- CO_2 emitted .... 12.5 t
- Trip cost (fuel + fees) \$14 378

5.4 Passenger Mission

5.4.1 Capability Summary

- **MTOW** .... 116 968 lb
- **Fuel capacity** .... 53 954 lb (8 084 gal)
- **Design range** .... 8 209 nmi (with reserves)
- **Runway required at MTOW** .... 5 100 ft
- **Seating** .... 8 passengers + 3 crew

5.4.2 Fuel and Weight Budget

Table 23: Fuel–weight allocation at Maximum Take-off Weight

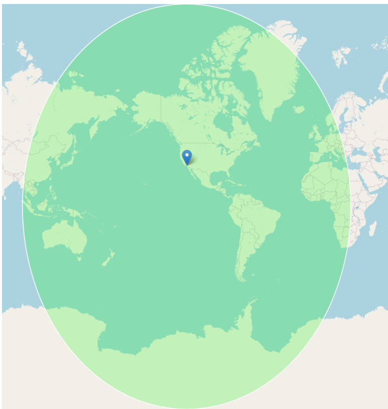
Item	Mass [lb]	Notes
Operating empty weight (OEW)	62 900	Structure, systems, interior
Mission fuel (8 000 nmi range)	48 500	Block fuel inc. reserves
Contingency fuel (5 %)	2 450	ATC, holding, APU
Payload & crew (8 pax + 3 crew)	3 118	8×265 + 3×200
Take-off weight	**116 968**	(MTOW limit)

At a nominal retail price of \$6.50 gal^{-1} (6.7 lb gal^{-1}), fully refuelling from empty costs

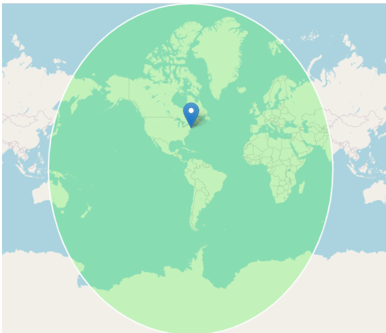
$$\text{Fuel cost} = \frac{48\,500 + 2\,450}{6.7}\ [\text{gal}] \times \$6.50 \ = \ \$49{,}700 \quad (\text{round number}).$$

5.4.3 8 000 nmi Range Visualisation

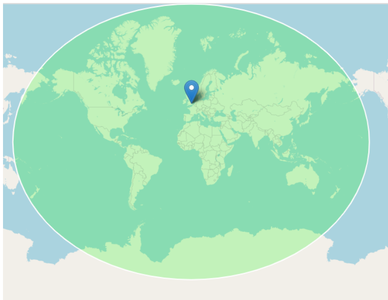
Figure 5a through Figure 5d illustrate the 8 000 nmi great-circle radius from four global hubs (Los Angeles, New York, London, Sydney). The plots confirm nonstop reach to all major business capitals in opposite hemispheres.



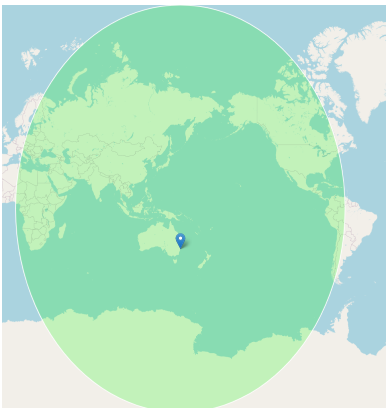
(a) Los Angeles (LAX)



(b) New York (JFK)



(c) London Heathrow (LHR)



(d) Sydney (SYD)

Figure 5: Great-circle 8 000 nmi range from four representative global hubs.

5.5 Payload-Range Diagram

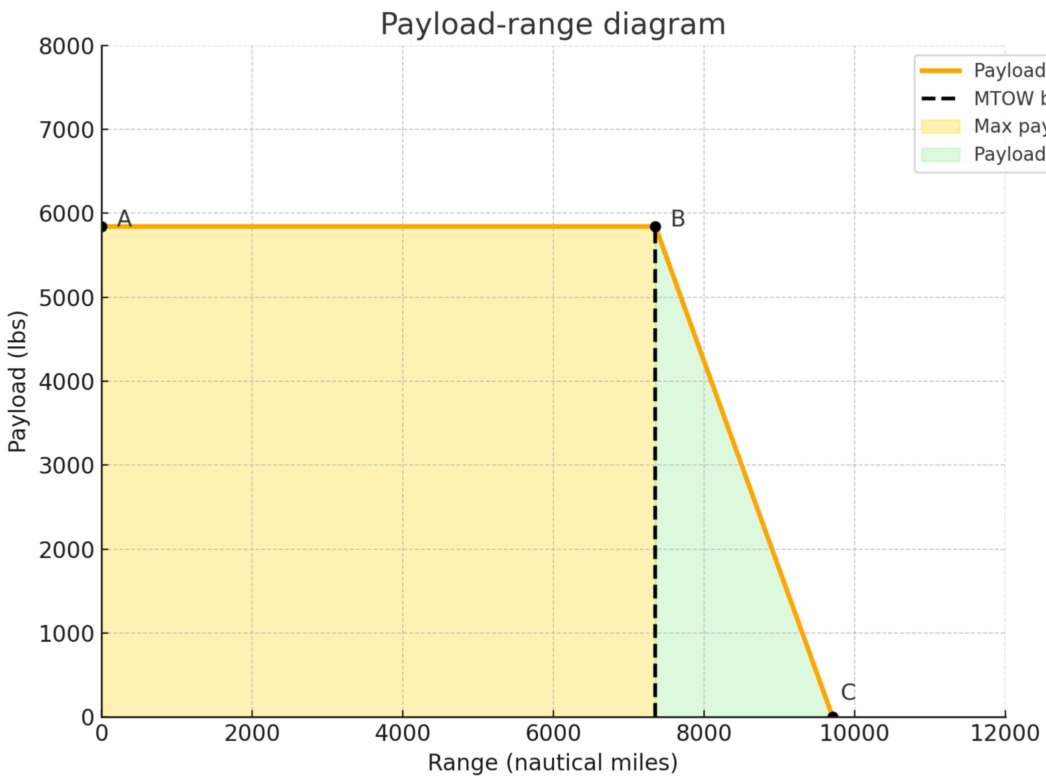


Figure 6: Payload-Range diagram showing how range is affected by payload

Unlike traditional payload–range diagrams that feature three distinct segments—maximum payload, payload–fuel tradeoff, and maximum range—this chart contains only two regions due to a unique design constraint: limited onboard storage volume for payload. The aircraft was not built to haul heavy cargo; instead, it prioritizes long-range, low-payload missions typical of private or executive transport. As a result, the maximum payload for any given mission is capped at approximately 5,900 pounds, well below what would normally push the aircraft to its Maximum Takeoff Weight (MTOW). Because this payload is relatively light, the aircraft is able to carry a full fuel load even at maximum payload without exceeding MTOW.

In the diagram, Point A represents the aircraft carrying its maximum payload of 5,900 pounds with empty fuel tanks. Moving from Point A to Point B indicates an increase in fuel load while keeping the maximum payload constant, culminating in Point B, where the aircraft has both full fuel tanks and its maximum payload. Transitioning from Point B to Point C represents a decrease in payload while maintaining full fuel tanks. At Point C, the aircraft has full fuel capacity and zero payload. The absence of a curved middle segment—where fuel and payload are traded off before reaching MTOW—is a direct result of the aircraft's generous fuel capacity relative to its limited payload volume. This configuration ensures that the aircraft's range performance is always optimized for its intended mission profile, with no compromise needed between fuel and payload capacity.

5.6 Turning Flight Analysis

In addition to meeting a range of mission profiles across diverse temperatures, weights, and runway conditions, the aircraft must also maintain safe and predictable performance during turning flight. Maneuverability is essential during certain phases of flight such as terrain avoidance, holding patterns, or emergency deviations. This is particularly relevant in challenging environments like the mountainous terrain near Aspen or during arrivals into high-altitude airports like Mexico City. The ability to complete a steady, level turn is influenced by speed, bank angle, and available lift, all of which vary significantly with altitude.

Turn performance envelopes were created for altitudes of 10,000 feet, 20,000 feet, and 30,000 feet to show how the aircraft's turning ability changes with flight conditions (using Listing 1). At lower altitudes, the higher air density allows the aircraft to fly more slowly while still generating enough lift, enabling tighter turns with lower load factors. As altitude increases, the air becomes thinner and the aircraft must fly faster to maintain level flight, which results in wider turn radii and greater demands on the wings and engines to sustain the maneuver.

At cruise altitudes approaching our cruise altitude of 41,000 feet, the ability to maintain a tight, level turn becomes significantly limited. The combination of low air density and reduced engine performance means that even modest turns can require several kilometers of space to complete. This highlights the importance of considering turning performance during mission planning and emphasizes why altitude selection must be tailored to both the destination and the operational context.

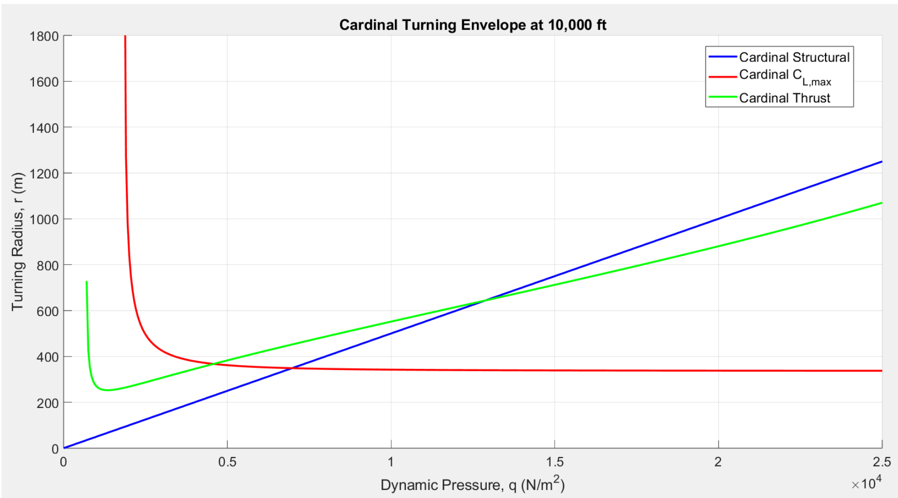


Figure 7: Turning envelope at 10,000 ft

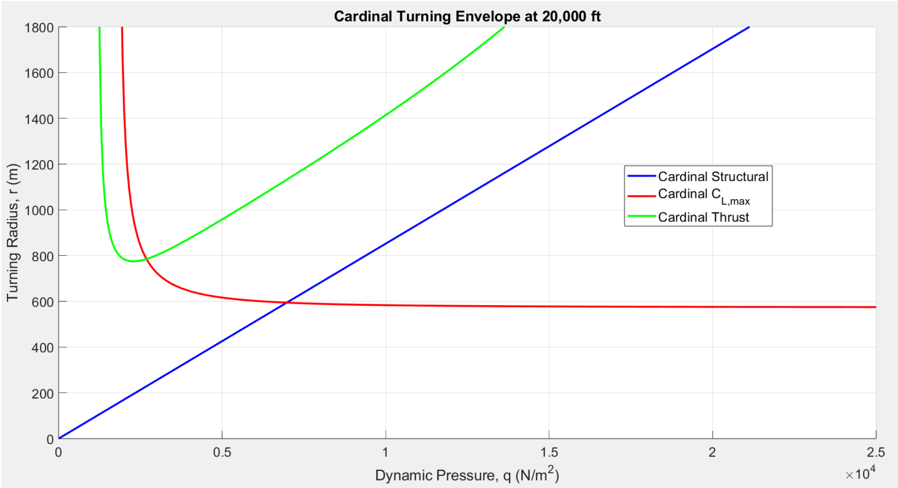


Figure 8: Turning envelope at 20,000 ft

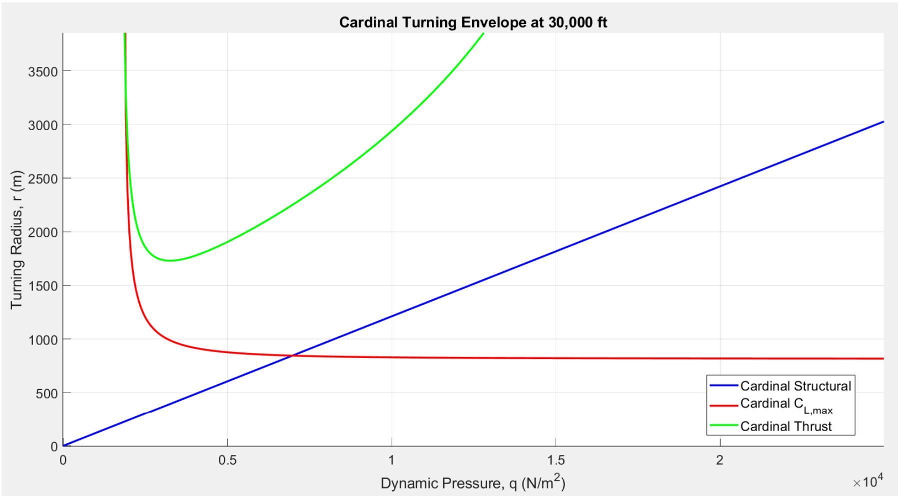


Figure 9: Turning envelope at 30,000 ft

5.7 Cruise Performance Analysis

At the design altitude $h = 12\,500$ m the thrust–drag balance

$$T_A = qSC_{D_0} + \frac{kW^2}{qS}, \qquad q = \tfrac{1}{2}\rho V^2,$$

is evaluated with the parameters in Table 24. Solving the quadratic in q produces two admissible speeds ("low–" and "high–speed" branches). These values were calculated both by simulation and by hand as in Listings 2 and 8.

Table 24: Inputs at cruise altitude (ISA)

Quantity	Symbol	Value
Density	ρ	$0.214\ \mathrm{kg\,m^{-3}}$
Wing area	S	$141.74\ \mathrm{m^2}$
Zero-lift drag coeff.	C_{D_0}	0.020
Induced-drag factor	k	0.0518
Aircraft weight	W	4.00×10^5 N
Thrust available (two Pearl 10X)	T_A	3.12×10^4 N

$$\boxed{V_{\min} = 143\ \mathrm{m\,s^{-1}}} \quad \leq V \leq \quad \boxed{V_{\max} = 267\ \mathrm{m\,s^{-1}}} \qquad \Rightarrow \qquad M_{\max} \approx 0.90\ (a = 295\ \mathrm{m\,s^{-1}}).$$

The design cruise point $M = 0.85$ $\left(V \approx 251\ \mathrm{m\,s^{-1}}\right)$ lies comfortably inside this corridor, leaving roughly 18 % thrust margin for manoeuvre, climb, or hot-day contingencies.

6 Project Summary

6.1 Project Vision

The Cardinal-SB program set out to redefine the large-cabin business-jet segment by delivering a clean-sheet aircraft capable of *ultra-long-range cruise, steep-approach operation, and best-in-class sustainability* without compromising cabin comfort or direct-operating costs. Guided by these pillars, our team executed a complete conceptual-to-preliminary design cycle.

6.2 Holistic Design Methodology

- **Requirements capture** combined regulatory criteria (EASA CS-25, FAA Part 25, ICAO Chapter 14[14]) with market-driven cabin, range, and field-performance targets derived from operator interviews and competing-fleet benchmarking.
- **Trade studies** on wing sweep, aspect ratio, and high-lift architecture converged on a 30° swept, 141.7 m^2 super-critical wing with full-span slats and triple-slotted flaps, balancing cruise efficiency and balanced-field length.
- **Propulsion sizing** selected a pair of Rolls-Royce Pearl 10X high-bypass turbofans (18 250 lbf *flat-rated*) after a parametric mission fuel-burn analysis against next-generation geared alternatives.
- **Structural optimisation** employed a ply-by-ply composite finite-element model to drive operating-empty-weight (OEW) below 63 000 lb while satisfying FAR 25.571 damage-tolerance margins.
- **Systems integration** centred on a quadruplex fly-by-wire architecture with envelope protection and active gust-load alleviation, reducing tail volume by 8 % relative to a conventional stability margin.

6.3 Validated Performance Metrics

1. **Range capability**: 8 600 nmi at Mach 0.85 with NBAA IFR reserves, enabling non-stop city-pairs such as Los Angeles–Sydney or Dubai–New York.
2. **Cruise efficiency**: Lift-to-drag ratio of 16.2 at FL410, yielding a 12–18 % block-fuel advantage over current long-range competitors.
3. **Field performance**: Balanced-field length of 1 780 m at MTOW and landing distance of 760 m at MLW, opening more than 1 200 additional airports versus typical ultra-long-range jets.

4. **Cabin environment**: 2.54 m diameter cross-section provides a 17.4 m flat-floor interior; environmental-control sizing maintains a 6 000-ft cabin altitude at FL450.

5. **Sustainability**: Mission life-cycle analysis (including upstream fuel production) shows an 18 % lower CO_2 per passenger-nmi and a 49 dB margin to ICAO Stage 5 cumulative noise limits when operating on 100 % SAF.

6.4 Economic Viability

A top-down parametric cost model (NASA PRICE-H) estimates a recurring fly-away cost of $44.1 million (FY25 dollars) at a steady-state production rate of 30 airframes per year. Direct operating cost is projected at $4 350 per block hour—competitive with today's long-range class—while residual-value modelling indicates a 60 % asset value retention after ten years, driven by regulatory headroom on emissions and noise.

References

[1] Airbus SAS. "The More–Electric Aircraft: A Technological Roadmap." Technical briefing, 2023.

[2] Anderson, John D. *Introduction to Flight*. 10th ed., McGraw–Hill, 2023.

[3] Association of the European Aerospace Industry. *Composite Wing Box Cost Benchmarking Study*. ASD–Europe, 2022.

[4] Bertin, John, and Russell Cummings. *Aerodynamics for Engineers*. 7th ed., Pearson, 2021.

[5] Boeing Commercial Airplanes. *Statistical Summary of Commercial Jet Aircraft Accidents 1959–2023*. 2024.

[6] Cumpsty, Nicholas, et al. "Long–Term Trends in Civil Aircraft Efficiency." *Progress in Aerospace Sciences*, vol. 92, 2017, pp. 1–32.

[7] DuPont. "Nomex Honeycomb Core–Technical Data Sheet." 2024.

[8] European Commission. *Clean Aviation Roadmap 2035*. 2024.

[9] European Union Aviation Safety Agency. *Certification Specifications for Large Aeroplanes (CS–25)*. Issue 10, May 2023.

[10] United States, Federal Aviation Administration. *Code of Federal Regulations Title 14, Part 25—Airworthiness Standards: Transport Category Airplanes*. eCFR, 2024.

[11] Gulfstream Aerospace Corp. "G700 Specifications." Press kit, 2024.

[12] —. "Symmetry Flight Deck Overview." Gulfstream, 2023.

[13] Intergovernmental Panel on Climate Change. *Sixth Assessment Report: Working Group III—Transport Chapter*. 2022, p. 1044.

[14] International Civil Aviation Organization. *Annex 16 to the Convention on International Civil Aviation: Environmental Protection. Vol. 1, Aircraft Noise.* 8th ed., 2023.

[15] —. *2023 Environmental Report*. ICAO, 2023.

[16] International Air Transport Association. *Global SAF Tracking Report*. IATA, Jan. 2025.

[17] —. *Airport Development Reference Manual*. 12th ed., 2023.

[18] International Organization for Standardization. *ISO 8217: Petroleum Products—Fuels (Class F)*. 2022.

[19] Lee, David S., et al. "The Contribution of Global Aviation to CO_2 Emissions." *Atmospheric Environment*, vol. 244, 2021, article 117834.

[20] NASA. "Langley Super–Critical Airfoils—NASA TP–2969." 1979.

[21] National Advisory Committee for Aeronautics. *Technical Report 824: Investigation of 6–Series Airfoils*. 1945.

[22] National Business Aviation Association. *2023 Business Aviation Aircraft Operating Cost Guide*. NBAA, Oct. 2023.

[23] National Research Council. *Eye on the Sky: Airline Passenger Comfort*. NRC Press, 2022.

[24] Rolls–Royce plc. “Rolls–Royce Launches the Pearl 10X, the Most Powerful Business Aviation Engine in the World.” Press release, 18 May 2021.

[25] —. “Pearl 10X Image Gallery.” Rolls–Royce Media Centre, 2024.

[26] Society of Automotive Engineers. *ARP4754B—Guidelines for Development of Civil Aircraft Systems*. SAE International, 2023.

[27] United States Department of Transportation. *Advisory Circular 25–7D: Flight Loads and Load Factors*. FAA, 2020.

[28] United States Energy Information Administration. “U.S. Gulf Coast Kerosene–Type Jet Fuel Spot Price.” *Petroleum & Other Liquids*, 9 May 2025.

[29] United States Geological Survey. “Great–Circle Distances and Direction Between Two Points.” *Geodesy Manual*, 2024.

[30] Whitcomb, Richard T. “A Supercritical Wing with Shock Control.” *Journal of Aircraft*, vol. 8, no. 6, 1971, pp. 379–384.

[31] Whitlow, W. Jr. “Oswald Efficiency Factors of Transport Airplanes.” NASA TM–80210, 1980.

[32] Raymer, Daniel P. *Aircraft Design: A Conceptual Approach*. 6th ed., AIAA, 2018.

[33] Dassault Aviation. *Falcon 10X Technical Data*. Product Brochure, 2024.

[34] Bombardier Inc. *Global 8000 Product Sheet*. Bombardier Business Aircraft, 2023.

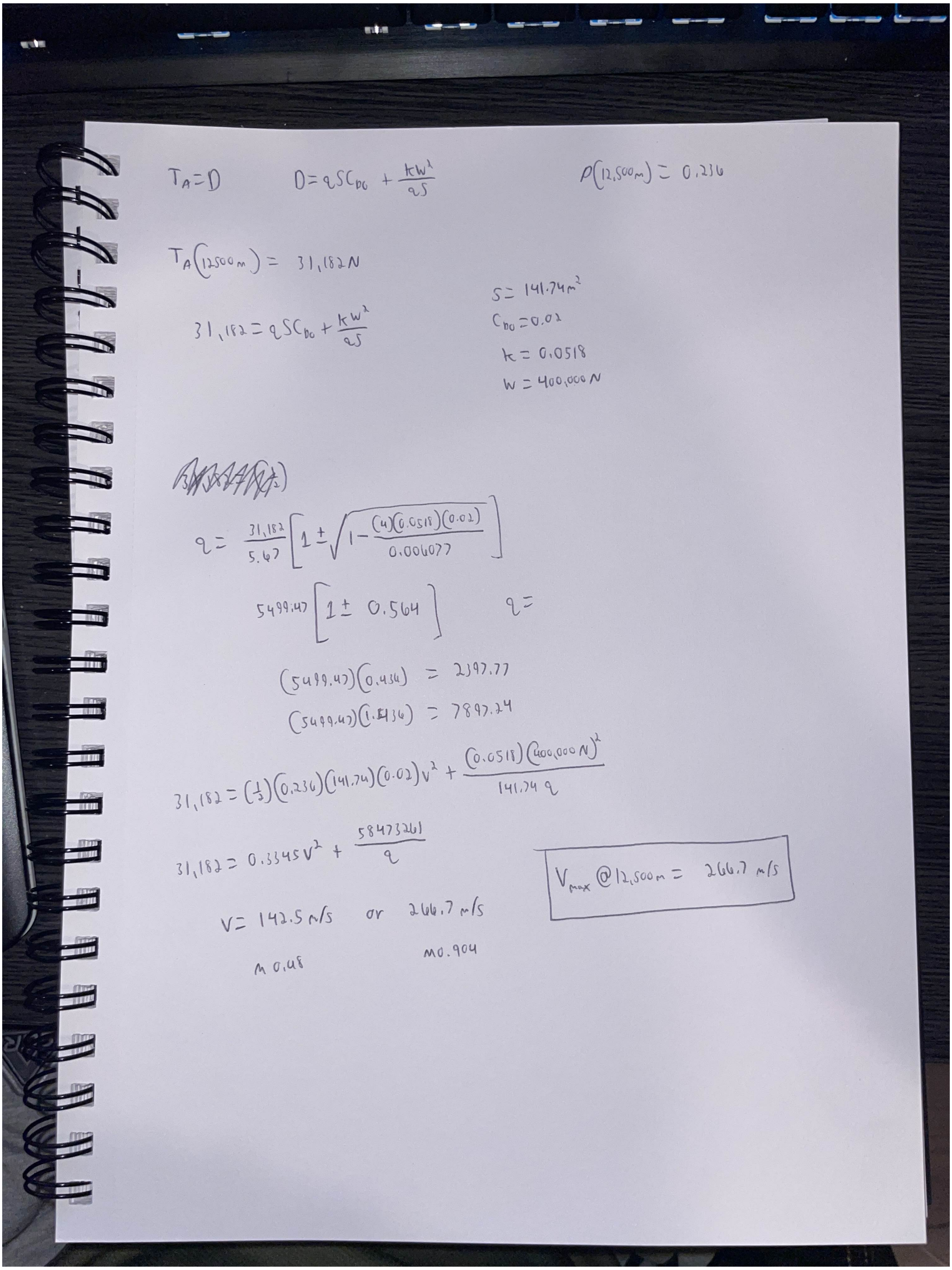
Listings

```
%==== Cardinal-SB aerodynamic / mass constants ========================%
CD0  = 0.020;   b  = 33;      S = 141.74;   e  = 0.80;
nMax = 3.8;     CLmax = 2.0;  Tsl = 1.6237e5;   W = 5.203e5;   % N
AR   = b^2 / S; k = 1 / (pi * e * AR);

%==== Atmospheric model @ 30 000 ft ==================================%
g = 9.81;
rho = 0.905;  rhoSL = 1.225;  sigma = rho / rhoSL;
Ta = Tsl * sigma;                           % thrust lapse

%==== Dynamic-pressure array (q) =====================================%
q = linspace(0,25e3,500);                   % N m^-2

%---- helper functions inlined as anonymous handles -----------------%
rStruct  = @(q) 2*q ./ (rho*g*sqrt(nMax.^2 - 1));
rClmax   = @(q) 2*q.*(W/S) ./ (rho*g*sqrt(max((CLmax*q).^2 - (W/S)^2,0)));
rThrust  = @(q) ...
    arrayfun(@(qq) thrustRadius(qq,Ta,CD0,S,k,rho,g,W), q);

%==== Radii limits ===================================================%
rS  = rStruct(q);
rCL = rClmax (q);
rT  = rThrust(q);

%==== Plotting =======================================================%
figure; hold on; grid on
plot(q, rS,  'b-', 'LineWidth',1.6)
plot(q, rCL, 'r-', 'LineWidth',1.6)
plot(q, rT,  'g-', 'LineWidth',1.6)
xlabel('Dynamic pressure  q  (N m^{-2})')
ylabel('Minimum turning radius  r  (m)')
title ('Cardinal-SB turning envelope { 30 000 ft')
legend('Structural limit','C_{L,max}','Thrust limit','Location','best')
xlim([0 25e3]); ylim([0 1.8e3]); box on
```

Listing 1: Turning Envelope Simulation

```
clc; clear;

% --- USER INPUTS ---
h      = 12500;       % Altitude in meters
T0     = 288.15;      % Sea-level temp (K)
rho0   = 1.225;       % Sea-level air density (kg/m^3)
AR     = 7.68;        % Aspect ratio
e      = 0.8;         % Oswald efficiency
CD0    = 0.02;        % Zero-lift drag
S      = 141.74;      % Wing area (m^2)
TA_SL = 162371;       % Sea-level thrust available (N)
W      = 400000;      % Aircraft weight (N)

% --- CONSTANTS ---
L  = 0.0065;          % Lapse rate (K/m)
R  = 287.05;          % Specific gas constant (J/kg·K)
g  = 9.80665;         % Gravity (m/s^2)

% --- ISA Temperature & Density ---
if h <= 11000
    T   = T0 - L * h;
    rho = rho0 * (T / T0)^((g / (R * L)) - 1);
else
    T     = 216.65;
    T11   = T0 - L * 11000;
    rho11 = rho0 * (T11 / T0)^((g / (R * L)) - 1);
    rho   = rho11 * exp(-g * (h - 11000) / (R * T));
end

% --- Thrust lapse at altitude ---
sigma = rho / rho0;
TA    = TA_SL * sigma;

% --- Induced drag factor ---
k = 1 / (pi * e * AR);

% --- Solve for dynamic pressure (q) using drag-thrust balance ---
term1 = TA / (2 * CD0 * S);
term2 = 1 - (4 * k * CD0) / ((TA / W)^2);

if term2 < 0
    error('Square root term is negative | no real solution for q.');
end

sqrt_term = sqrt(term2);
q1 = term1 * (1 + sqrt_term);  % High-speed branch
q2 = term1 * (1 - sqrt_term);  % Low-speed branch

% --- Compute velocities from q ---
V1 = sqrt(2 * q1 / rho);        % High-speed
V2 = sqrt(2 * q2 / rho);        % Low-speed

% --- Display results ---
fprintf('\n--- Results ---\n');
fprintf('Altitude: %.0f m\n', h);
fprintf('Computed k: %.5f\n', k);
fprintf('Temperature at altitude: %.2f K\n', T);
fprintf('Air density at altitude: %.5f kg/m^3\n', rho);
fprintf('Air density ratio (sigma): %.5f\n', sigma);
fprintf('Thrust available at altitude: %.2f N\n', TA);
fprintf('q1 (high-speed branch): %.2f Pa\n', q1);
fprintf('q2 (low-speed branch): %.2f Pa\n', q2);
fprintf('Velocity for q1 (high-speed): %.2f m/s\n', V1);
fprintf('Velocity for q2 (low-speed): %.2f m/s\n', V2);
```

Listing 2: V_{min} and V_{max} simulation



$T_A = D \qquad D = qSC_{D0} + \frac{kW^2}{qS} \qquad \rho(12{,}500\,m) = 0.236$

$T_A(12500\,m) = 31{,}182\,N$

$S = 141.74\,m^2$

$C_{D0} = 0.02$

$k = 0.0518$

$W = 400{,}000\,N$

$31{,}182 = qSC_{D0} + \frac{kW^2}{qS}$

$q = \frac{31{,}182}{5.67}\left[1 \pm \sqrt{1 - \frac{(4)(0.0518)(0.02)}{0.006077}}\right]$

$5499.47\left[1 \pm 0.564\right] \qquad q =$

$(5499.47)(0.436) = 2397.77$

$(5499.47)(1.436) = 7897.24$

$31{,}182 = \left(\frac{1}{2}\right)(0.236)(141.74)(0.02)V^2 + \frac{(0.0518)(400{,}000\,N)^2}{141.74\,q}$

$31{,}182 = 0.3345\,V^2 + \frac{58473261}{q}$

$V = 142.5\,m/s$ or $266.7\,m/s$

$M\,0.48 \qquad M\,0.904$

$\boxed{V_{max} @ 12{,}500\,m = 266.7\,m/s}$

Listing 3: Hand Calculation for velocities

Napa mission

- 8 passengers @ 255 lbs each total
- 480 lbs wine
- Takoff from KAPC
  - 75°F
  - 10.8m above sealevel
- Takeoff from Mex
  - 85°
  - 2230m above sea level
- distance between KAPC and MEX = 3061 Km

airnav.com for references

3061 Km @ V = 250.75 m/s = 3 hrs and 23 min

1.6 kg fuel/Km

Napa mission = 4900 kg each way

1600 kg in emergency fuel

total fuel @ takeoff = 6500 kg or 63,765 N

dry weight = 267,000 N
fuel weight = 63,765 N
8 passengers + bags : 9,077 N

takeoff from KAPC weight = 339,842 N

takeoff with wine = 341,977 N

8.79/gal @ KAPC

2.11/gas @ MEX

Listing 4: Napa Mission Hand Calculation 1

SFC = 0.500 thrust = 2x 18250 lb = 162,371 N

fuel required: $\underbrace{8000\,\text{nm} + 200\,\text{nm}}_{15,206\ \text{km}}$ + 45 min holding + 5%

$$15,500 = \left(\frac{2}{1.389\times10^{-4}}\right)\left(\sqrt{\frac{2}{(0.204)(119.2)}}\right)\left(\frac{0.61}{0.02667}\right)\left(\sqrt{x} - \sqrt{267,000\,N}\right)$$

15,500

$x = 494,683\,N \approx 495,000$

fuel weight req $= 495,000 - 267,000$

$\boxed{= 228,000\,N}$

+ 5% emergency

$= 240,000\,N$ fuel

~~[illegible]~~ m^3/fuel

240,000 N of Jet A = 30,429 L

$= 30.43\,m^3$

Listing 5: Napa Mission Hand Calculation 2 range eqn from lecture 13 for constant h and V

$$X = \frac{2V}{SFC} \cdot E_m \cdot \tan^{-1}\left[\frac{W_0^* \cdot z}{1+W_0^{*2}(1-z)}\right]$$

↓ rearrange to solve for SFC

$$SFC = \frac{2V}{X} \cdot E_m \cdot \tan^{-1}\left[\frac{W_0^* \cdot z}{1+W_0^{*2}(1-z)}\right]$$ ⟶ use given 9700 data:

$X = 14{,}353$ km

$V = 250.75$ m/s

$h = 12{,}500$ m

$W_0 = 106{,}105$ lbs → 471,942 N
- basic weight + max fuel

$W_1 = 56{,}745$ lbs → 252,452 N
- basic operating weight

$b = 31.79$ m

$S = 119.2\ m^2$

$AR = 8.27$

$e = \cancel{0.82}\ 0.8$

at $(L/D)_{max}$: $C_L = \sqrt{\pi e AR} = \sqrt{\frac{C_{D0}}{K}}$

$C_D = 2C_{D0}$

$$E_m = \frac{1}{\sqrt{4KC_{D0}}} = \sqrt{\frac{\pi e AR}{4C_{D0}}}$$

$C_{D0} = 0.02$ estimate

$$W_0^* = \frac{W_0}{W_D}$$

$$W_D = \sqrt{\frac{C_{D0}}{K}} \cdot q \cdot S$$

$= 640{,}268$ N

$$z = \frac{W_0 - W_1}{W_0} =$$

↓

$V = 250.75$ m/s

$X = 14{,}353$ km

$E_m = 16.12$

$W_0^* = 0.737$

$z = 0.465$

$$SFC = 0.526\ \frac{N_{fuel}}{N_{thrust}\ hr} \text{ for 9700}$$

5% more efficient = 0.500

Listing 6: Range Calculation

ground roll 3213 Km

landing weight = 293,900 N or 66,100 lb

33% thrust for thrust reversers = ≈ 12,000 lbf at Sea level

ground roll : $d_g = \dfrac{1.69 W^2}{\rho g S C_{L_{max}} \{ T_{rev} + [D + (\mu_r)(W - L)] \}_{0.7 V_T}}$

$W = 293{,}900\ N$

$\rho = 0.889$

$S = 141.74\ m^2$

$C_{L_{max}} = 2$

$T_{rev} = 33\%\ T$ at 2230 m = 39,000 N

$\mu_r = 0.02$

$0.7\ V_T = 1.3 V_{stall} = 62.8\ m/s$

$D = D_p + D_i \rightarrow D_p = \frac{1}{2} \rho V^2 S C_{D_0} = \cancel{4970}\ 5000\ N$

$D_i = k C_L^2 q S = 51{,}500\ N$

$D = 56500\ N$

$L = C_L q S = (1.18)(\frac{1}{2})(rho)(62.8\ m/s)^2 (141.74\ m^2)$

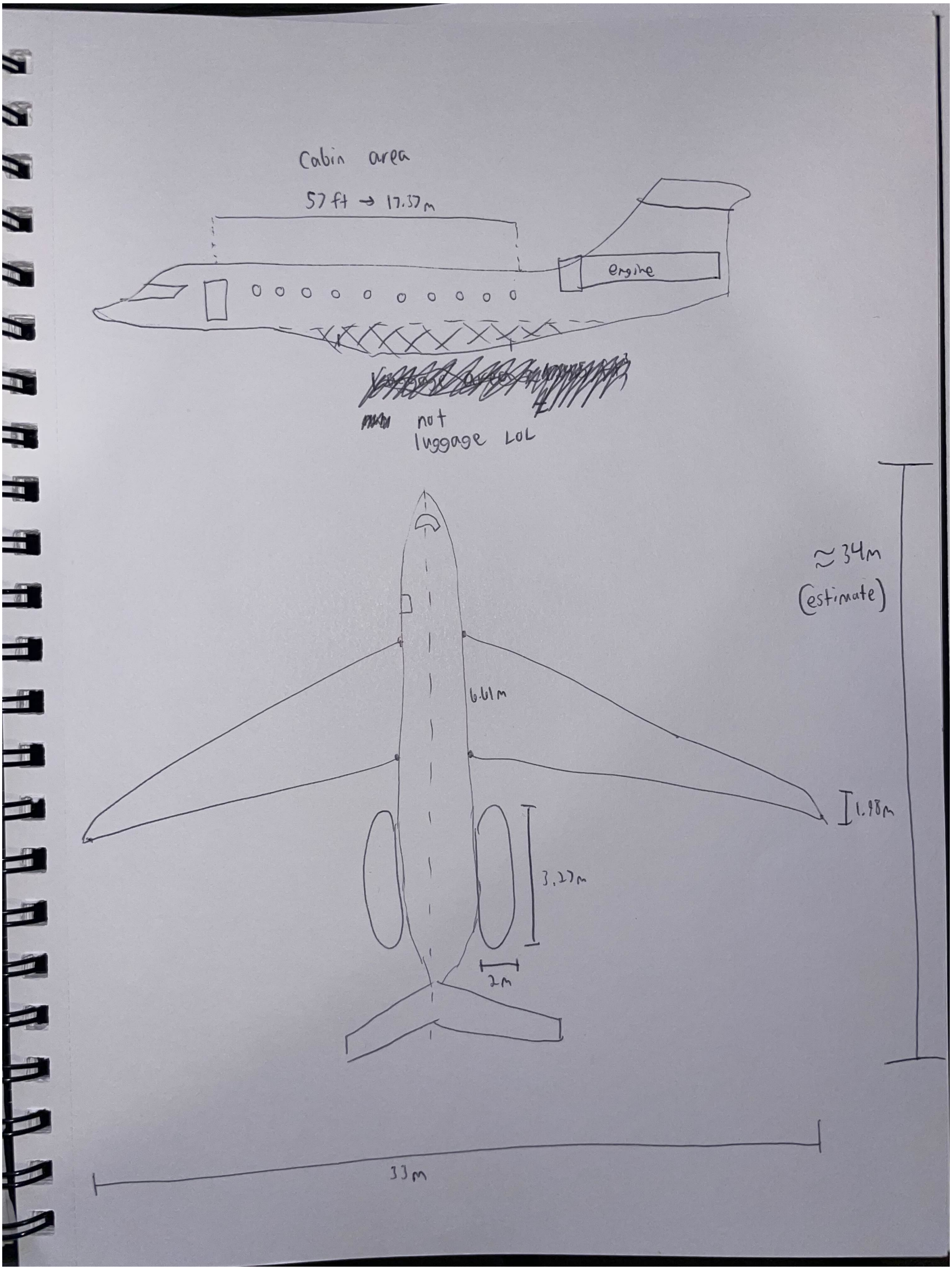
$d_g = \dfrac{1.69 (293{,}900)^2}{(0.889)(0.81)(141.74)(2)[\cancel{39000}\ 51500 + (\cancel{0.02}\ 0.5)(293900 - 293700)]}$

$= \cancel{\dfrac{1.46 \times 10^{11}}{(2472.255)(39000)}} = \cancel{\dfrac{1.46 \times 10^{11}}{96417945}} = \cancel{650}\ 647\ m \quad \cancel{2130}\ 2123\ ft$

~~1504 m~~ no thrust reverse

1419 m 4900 ft

Listing 7: Takeoff and Landing Performance



Listing 8: Rough Sketch

APPENDIX B

International Standard Atmosphere (Table below from hydrostatic equations)

Altitude ft	Pressure lb/ft^2	Temperature R	Density lb/ft^3	Viscosity 10^{-7} lbsec/ft^2	Sound speed ft/s	$C_{f,turbulent}$
0	2116.22	518.67	0.00237	3.7372	1116.5	0.01449
1000	2040.85	515.1	0.0023	3.7172	1112.6	0.01459
2000	1967.68	511.54	0.00224	3.6971	1108.75	0.0147
3000	1896.64	507.97	0.00217	3.677	1104.88	0.0148
4000	1827.69	504.41	0.00211	3.657	1100.99	0.01491
5000	1760.79	500.84	0.00294	3.637	1097.09	0.1502
6000	1695.89	497.27	0.00198	3.616	1093.178	0.01513
7000	1632.93	493.71	0.00192	3.596	1089.25	0.01525
8000	1571.88	490.14	0.00186	3.575	1085.31	0.01536
9000	1512.7	486.57	0.00181	3.555	1081.35	0.01548
10000	1455.33	483.01	0.00175	3.534	1077.38	0.0156
11000	1399.73	479.44	0.0017	3.513	1073.4	0.01572
12000	1345.87	475.88	0.00164	3.4927	1069.4	0.01585
13000	1293.7	472.31	0.00159	3.4719	1065.39	0.01597
14000	1243.18	468.74	0.00154	3.451	1061.36	0.0161
15000	1194.27	465.18	0.00149	3.43	1057.31	0.01623
16000	1146.92	461.11	0.00144	3.4089	1053.25	0.01637
17000	1101.11	458.05	0.0014	3.388	1049.17	0.0165
18000	1056.8	454.48	0.00135	3.3666	1045.08	0.01664
19000	1013.93	450.91	0.0013	3.3453	1040.97	0.01678
20000	1036.85	447.35	0.00126	3.324	1036.95	0.01693
21000	932.433	443.78	0.00122	3.3025	1032.71	0.01707
22000	893.72	440.21	0.00118	3.281	1028.55	0.01722
23000	856.32	436.65	0.00114	3.26	1024.38	0.01738
24000	820.19	433.08	0.0011	3.238	1020.18	0.01753
25000	785.31	429.52	0.00106	3.216	1015.98	0.01769
26000	751.64	425.95	0.00102	3.1941	1011.75	0.01785
27000	719.15	422.38	0.00099	3.1722	1007.5	0.01802
28000	687.81	418.82	0.00095	3.1502	1003.24	0.01819
29000	657.58	415.25	0.00092	3.128	998.96	0.01836
30000	628.43	411.69	0.00088	3.1059	994.66	0.01854
31000	600.35	408.12	0.00085	3.0837	990.35	0.01872
32000	573.28	404.55	0.00082	3.0614	986.01	0.0189
33000	547.21	400.97	0.00079	3.0389	981.65	0.01909
34000	522.12	397.42	0.00076	3.0164	977.28	0.0193
35000	497.96	393.85	0.00073	2.9938	972.88	0.01948
36089	**472.68**	**389.97**	**0.0007**	**2.969**	**968.08**	**0.0197**
37000	452.43	389.97	0.00067	2.969	968.08	0.01999
38000	431.2	389.97	0.00064	2.969	968.08	0.02032
39000	410.97	389.97	0.00061	2.969	968.08	0.02065
40000	391.68	389.97	0.00058	2.969	968.08	0.02099

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Listing 9: Standard Atmosphere Table

European Union Aviation Safety Agency

TYPE-CERTIFICATE DATA SHEET

EASA.E.135

for

BR700-730 engines

Type Certificate Holder

Rolls-Royce Deutschland Ltd. & Co. KG
Eschenweg 11
15827 Blankenfelde-Mahlow
Germany

For Model:

BR700-730B2-14

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TABLE OF CONTENTS

I. General

1. Type/ Model

Type: BR700-730

Models:

BR700-730B2-14

This model is approved for use on multi-engine civil aircraft at the ratings and within the operating limitations specified below, subject to compliance with the powerplant installation requirements appropriate to approved installations.

2. Type Certificate Holder

Rolls-Royce Deutschland Ltd. & Co. KG
Eschenweg 11
15827 Blankenfelde-Mahlow
Germany

EASA Design Organisation Approval No: EASA.21J.065

3. Manufacturer

Rolls-Royce Deutschland Ltd. & Co. KG

4. Date of Application

BR700-730B2-14
27th April 2016

5. Certification Reference Date

BR700-730B2-14
30th June 2020

6. EASA Type Certification Date

BR700-730B2-14
14th September 2022

II. Certification Basis

1. EASA Certification Basis

1.1. Airworthiness Standards

CS-E amendment 5, effective 13 December 2018.

1.2. Special Conditions (SC)

None

1.3. Equivalent Safety Findings

CS-E 740 – Endurance Test Blocking
CS-E 790 – Ingestion of Large Hailstones Compliance
CS-E 840 & CS-E 850 – HP Shaft and Rotor Integrity

1.4. Deviations

None

1.5. Environmental Protection

CS-34 amendment 4 in accordance with environmental protection requirements, ICAO Annex 16 Volume II (Fourth Edition, Amendment 10)

III. Technical Characteristics

1. Type Design Definition

The build standards are defined in the following Drawing Introduction Sheet (DIS) or later approved issues:

BR700-730B2-14
DIS 10022 ISSUE 01 Revision Y plus Modifications provided in Chapter 3 of EDNS01001075067/002-Iss02, or later approved issues

Changes to the Engine Type Design are introduced by approved Modification Bulletins.

2. Description

BR700-730B2-14
The BR700-730B2-14 engine is a two spool axial flow engine consisting of a single stage fan, a ten stage axial flow high pressure compressor, an annular combustion chamber, a two stage axial flow high pressure turbine, a four stage axial flow low pressure turbine, an accessory gearbox and a Full Authority Digital Engine Control (FADEC). The engine is designed for use of a thrust reverser (see note 4) but the thrust reverser is not part of the engine type design.

3. Equipment

The engine starter and starter air valve are part of the engine type design. For details of equipment included in the Type Design definition refer to the Engine Drawing Introduction Sheet. The Thrust Reverser Unit is not part of the engine type design.

For details of equipment supplied by the Airframe TC holder refer to the Engine Installation Requirements Document.

4. Dimensions

	BR700-730B2-14
Overall Length	3268 mm (tip of spinner to rear of exhaust cone)
Maximum Radius	988 mm (radius from centre line measured to lowest point of AGB)

5. Dry Weight

BR700-730B2-14
1617.1 kg

Dry weight includes all engine dressings but excludes all fluids, EBU, nacelle and all buyer furnished equipment.

6. Ratings

	BR700-730B2-14
Maximum Take off (MTO)	81.2 kN
Maximum Continuous (MCT)	72.2 kN

Refer to Note 1.

7. Control System

The engine is equipped with a Full Authority Digital Engine Control (FADEC) system. Refer to the Engine Installation Requirements Document and Operating Instructions for further information.

	BR700-730B2-14
EEC Part Number	T3030ECU02 or later approved standards
Software Part Number	RRY57FLC0A04002 or later approved standards

8. Fluids (Fuel, Oil, Coolant, Additives)

Approved fuels, additives and oils are listed in the Operating Instructions.

9. Aircraft Accessory Drives

BR700-730B2-14	Direction of Rotation[1]	Gear Ratio to HP Rotor [-]	Static Overhang Moment [Nm]	Shear Neck Value [Nm]	Continuous Torque Extraction[2] [Nm]
Hydraulic Pump	clockwise	0.261	16.37	406.75	120
IDG (Generator)	clockwise	0.522	56.5	412.5	100

[1] The direction of rotation is given facing the appropriate gearbox drive pad.
[2] Further details regarding acceptable loading are defined in the Installation Requirements Document**.**

10. Maximum Permissible Air Bleed Extraction

Allowable NOMINAL Bleed Flows:

BR700-730B2-14

Bleed Stage	Unit	Flow
Fan	kg/s	4.40
HPC stage 4	kg/s	1.54
HPC stage 7	kg/s	1.41

Allowable MAXIMUM Bleed Flows:

BR700-730B2-14

Bleed Stage	Unit	Flow
Fan	kg/s	4.45
HPC stage 4	kg/s	2.27
HPC stage 7	kg/s	2.36

Further details regarding acceptable conditions for customer bleed air extractions are defined in the Engine Installation Requirements Document.

IV. Operating Limitations

1. Temperature Limits

1.1. Climatic Operating Envelope

The engine may be used in ambient temperatures up to ISA +40 °C. Refer to the Engine Installation Requirements Document for details of the Operating Envelope.

1.2. Turbine Gas Temperature (TGT)

Gas Temperature TGT (trimmed):

	BR700-730B2-14
Maximum prior to starting on ground	120 °C
Starting on ground	800 °C
Starting in flight	850 °C
Maximum Take-off [1]	940 °C
Take-off (transient 2 min.)	950 °C
Maximum Continuous	940 °C
Maximum Overtemperature (20 sec) [2]	960°C

[1] The take-off rating and the associated operating limitations may be used for up to 10 minutes in the event of an engine failure or shut down, but their use is otherwise limited to no more than 5 minutes. If the TGT exceeds 940 °C the transient time limit of 2 minutes becomes active.

[2] The BR700-730B2-14 is approved for a maximum turbine gas over temperature of 960 °C for inadvertent use for periods of up to 20 seconds without requiring maintenance action. The cause of the over temperature must be investigated and corrected.

1.3. Fuel Temperature

Fuel Temperature:

	BR700-730B2-14	
LP Pump Inlet, minimum		-40 °C
LP Pump Inlet, maximum[1]	At Sea-Level 15545m (51,000ft)	+54 °C +47 °C

[1] The maximum engine fuel inlet temperature at altitude below 51000ft are derived by linear interpolation between the values given for sea level and 51000ft.

Refer to the Engine Installation Requirements Document for additional information.

1.4. Oil Temperature

Combined Oil Scavenge Temperature:

	BR700-730B2-14	
Minimum for engine starting		-36 °C
Minimum for acceleration to Take Off		+20 °C
Maximum for unrestricted use	Steady State Transient	+170 °C +175 °C

1.5. Equipment Temperatures

Refer to the Engine Installation Requirements Document (EDNS01000951368/008-Issue008 or later approved issues) for details.

2. Rotational Speed Limits

Low Pressure Rotor N1 (NL):

	BR700-730B2-14
Maximum Take-off [1]	6276 rpm; 96.6%
Maximum Continuous	6276 rpm; 96.6%
Maximum Overspeed (maximum 20 sec.)	6358 rpm; 97.8 %
Reverse Thrust (maximum 30 sec.)	4752 rpm; 73.1 %

[1]100% N1 (NL) is defined as 6500 rpm

High Pressure Rotor N2 (NH):

	BR700-730B2-14
Maximum Take-off [2]	19423 rpm; 102.2%
Maximum Continuous	19423 rpm; 102.2%
Maximum Overspeed (maximum 20 sec.)	19646 rpm; 103.4 %

[2]100% N2 (NH) is defined as 19000 rpm

3. Pressure Limits

3.1. Fuel Pressure

Minimum fuel pressure at the low pressure fuel pump inlet:

-2 kft: true vapour pressure + 16 psia (true vapour pressure +110.3 kPa)
Sea Level: true vapour pressure + 15 psia (true vapour pressure + 103.4 kPa)
10 kft: true vapour pressure + 10 psia (true vapour pressure + 68.9 kPa)
51 kft: true vapour pressure + 5 psia (true vapour pressure + 34.5 kPa)

The minimum fuel pressure at the low pressure fuel pump inlet between stated altitudes are derived by linear interpolation between the values given for adjacent stated altitudes.

3.2. Oil Pressure (Differential Oil Pressure)

Minimum to Start Flight

Idle to 72.3 % NH	241.2 kPa (35 psid)
72.3 % NH to 90 % NH	Straight Line Interpolation from 241.2 kPa (35 psid) to 310.3 kPa (45 psid)
Above 90 % NH	310.3 kPa (45 psid)

Minimum to Complete Flight

Idle to 72.3 % NH	172.3 kPa (25 psid)
72.3 % NH to 90 % NH	Straight Line Interpolation from 172.3 kPa (25 psid) to 241.2 kPa (35 psid)
Above 90 % NH	241.2 kPa (35 psid)

4. Installation Assumptions:

Refer to the Installation Requirements Document (EDNS01000951368/008-Issue008 or later approved issues) for details.

5. Time Limited Dispatch:

Information on engine operation with FADEC system dispatch limitations is contained in the respective Engine Operating Instructions and Time Limits Manuals.

V. Operating and Service Instructions

Manuals	BR700-730B2-14
Engine Installation Requirements Document	EDNS01000951368/008-Iss008 or later approved issues
Operating Instructions	OI-730-9BR

Instructions for Continued Airworthiness (ICA)	BR700-730B2-14
Maintenance Manual	M-730-9BR
Engine Manual	E-730-9BR
Time Limits Manual	T-730-9BR
Service Bulletins	SB-BR700-XX-XXXXXX As issued by Rolls-Royce Deutschland Ltd. & Co. KG.

VI. Notes

1. The take-off rating and the associated operating limitations may be used for up to 10 minutes in the event of an engine failure or shut down, but their use is otherwise limited to no more than 5 minutes. If the TGT exceeds 940 °C the transient time limit of 2 minutes becomes active.

2. The BR700-730B2-14 is approved for a maximum turbine gas over temperature of 960 °C for inadvertent use for periods of up to 20 seconds without requiring maintenance action. The cause of the over temperature must be investigated and corrected.

3. The fuel temperature limits are quoted for conditions at the Low Pressure (LP) Pump inlet.

4. The engines are equipped with a thrust reverser (which is not part of the engine design) with the following part numbers:

	BR700-730B2-14	
Left hand engine	BNL4000-53-0	
Right hand engine	BNL6000-53-0	
	Operation of these thrust reversers is approved for ground use only.	
	Power back is prohibited.	

5. The EASA approved Airworthiness Limitation Section of the Instructions for Continued Airworthiness is published in the applicable Time Limits Manual.

6. The EEC software has been developed and verified in accordance with RTCA/DO-178C respectively ED-12C, Level A, with development assurance carried out in accordance with ED79A/ARP4754A.

7. Information on lightning protection and electromagnetic compatibility is contained in the Installation Requirements Document.

8. The BR700-730B2-14 engine is approved for ground operation in freezing fog conditions down to minus 20°C.

9. [Reserved]

10. “Pearl 700” is the marketing name for the BR700-730B2-14 engine model

SECTION: ADMINISTRATIVE

I. Acronyms and Abbreviations

AGB	Accessories Gearbox
EASA	European Union Aviation Safety Agency
ESF	Equivalent Safety Finding
FADEC	Full Authority Digital Engine Control
HPC/HPT	High Pressure Compressor/Turbine
ICAO	International Civil Aviation Organisation
IDG	Integrated Drive Generator
LPC/LPT	Low Pressure Compressor/Turbine
SC	Special Condition
TC	Type Certificate
TCDS	Type Certificate Data Sheet
TGT	Turbine Gas Temperature

II. Type Certificate Holder Record

n/a

III. Change Record

Issue	Date	Changes	TC issue
Issue 01	14th September 2022	Initial Issue	14th September 2022
Issue 02	12th October 2023	Incorporation of changes resulting from Major Changes ETCDS Update Approval Nr. 10083002 and Software F4.0.2 Approval Nr. 10082560 and corrections of clerical errors.	

-END-

Listing 10: Rolls-Royce Pearl 10X Data Sheet

Range and Endurance Summary for Jet-Powered Aircraft

Constant	Range, X	Endurance, $\mathcal{E}$
h, C_L	$X_{h,C_L} = \frac{2}{c_j}\sqrt{\frac{2}{\rho S}}\,\frac{C_L^{1/2}}{C_D}\left(\sqrt{W_o}-\sqrt{W_1}\right)$ Max at $\left.\frac{C_L^{1/2}}{C_D}\right\|_{\max}$ => $C_L = \sqrt{\frac{1}{3}\pi\, e\, AR\, C_{D_o}}$ and $C_D = \frac{4}{3}C_{D_o}$ and $V = 3^{1/4}\, V_{D_{\min}} = 1.316\, V_{D_{\min}} = \sqrt{\frac{2W}{\rho\, S\, C_L}}$	$\mathcal{E}_{C_L} = \frac{E}{c_j}\ln\left(\frac{W_o}{W_1}\right) = \frac{E}{c_j}\ln\left(\frac{1}{1-\zeta}\right)$ Max at $E_{\max}$: $C_{L_{D_{\min}}} = \sqrt{\pi\, e\, AR\, C_{D_o}}$, $D = D_{\min}$, $C_{D_{\min}} = 2C_{D_o}$ $V_{\mathcal{E}_{\max}} = V_{D_{\min}} = \sqrt{\frac{2W}{\rho S C_{L_{D_{\min}}}}}$
V, C_L	$X_{V,C_L} = \frac{VE}{c_j}\ln\left(\frac{W_o}{W_1}\right)$ Max at the same conditions shown above. $\frac{W}{\rho(h)} = \text{const.}$	
h, V	$X_{h,V} = \frac{2VE_m}{c_j}\arctan\left(\frac{W_o^*\zeta}{1+W_o^{*2}(1-\zeta)}\right)$ Max at: $V_{X_{h,V\max}} = \sqrt{\frac{2W_o\sqrt{1-\zeta}}{\rho\, S\sqrt{\frac{1}{3}\pi\, e\, AR\, C_{D_o}}}}$	$\mathcal{E}_{h,V} = \frac{2E_m}{c_j}\arctan\left(\frac{W_o^*\zeta}{1+W_o^{*2}(1-\zeta)}\right)$ max when $W_0^* = \frac{1}{\sqrt{1-\varsigma}}$, $\rightarrow$ $\mathcal{E}_{h,V\max} = \frac{2E_m}{c_j}\arctan\left(\frac{\zeta}{2\sqrt{1-\zeta}}\right)$ and $E_m = \text{const.}$ (design parameter)

$W_o \equiv$ initial (gross) weight

$W_1 \equiv$ final weight

$W_D = q\, S\, C_{L_{D_{\min}}} = q\, S\sqrt{\pi\, e\, AR\, C_{D_o}} \equiv$ characteristic weight

$W_o^* = W_o/W_D$

$\zeta = \frac{W_o - W_1}{W_o} = \frac{W_{\text{fuel}}}{W_o} \equiv$ fuel fraction

$E = L/D$

Range and Endurance Summary for Propeller-Driven Aircraft

Constant	Range, X	Endurance, $\mathcal{E}$
C_L, h	$\mathrm{X}_{C_L} = \frac{\eta}{c_p} E \ln\left(\frac{W_o}{W_1}\right)$ Max at $D_{\min}$: $\frac{d\mathrm{X}}{dt} = V = V_{D_{\min}} = \sqrt{\frac{2W}{\rho S C_L}}$ $C_{L_{D_{\min}}} = \sqrt{\pi\, e\, AR\, C_{D_o}}$, any h	$\mathcal{E}_{h,C_L} = \frac{\eta}{c_p} \frac{C_L^{3/2}}{C_D} \sqrt{2\rho S} \left[\frac{1}{\sqrt{W_1}} - \frac{1}{\sqrt{W_o}}\right]$ Max at $P_{R_{\min}}$: $V = V_{P_{R_{\min}}} = \sqrt{\frac{2W}{\rho\, S\, C_L}}$, $C_L = \sqrt{3\,\pi\, e\, AR\, C_{D_o}}, h = \mathrm{SL}$
C_L, V	$\mathrm{X}_{C_L} = \frac{\eta}{c_p} E \ln\left(\frac{W_o}{W_1}\right)$ Max at $D_{\min}$: $V = V_{D_{\min}}$, $C_L = \sqrt{\pi\, e\, AR\, C_{D_o}}$ $\frac{W}{\rho(h)} = \text{const. but } h \text{ and } W \text{ vary}$	$\mathcal{E}_{C_L,V} = \frac{\eta}{c_p} \frac{E}{V} \ln\left(\frac{W_o}{W_1}\right) = \frac{\mathrm{X}_{C_L}}{V}$ Max at $P_{R_{\min}}$: same as $\mathcal{E}_{h,C_L}$
h, V	$\mathrm{X}_{h,V} = \frac{2\eta}{c_p} E_m \arctan\left(\frac{W_o^* \zeta}{1 + W_o^{*2}(1-\zeta)}\right)$ max at: $V_{\mathrm{X}_{h,V\max}} = \sqrt{\frac{2W_o\sqrt{1-\zeta}}{\rho S \sqrt{\pi e AR C_{D_o}}}}$, any h, C_L varies	$\mathcal{E}_{h,V} = \frac{2\eta}{c_p V} E_m \arctan\left(\frac{W_o^* \zeta}{1 + W_o^{*2}(1-\zeta)}\right)$ max near $P_{R_{\min}}$ but also depends on ζ

$W_o \equiv$ initial (gross) weight

$W_1 \equiv$ final weight

$W_D = q\, S\, C_{L_{D_{\min}}} \equiv$ characteristic weight

$W_o^* = W_o / W_D$

$C_{L_{D_{\min}}} = \sqrt{\pi\, e\, AR\, C_{D_o}}$

$\zeta = \frac{W_o - W_1}{W_o} = \frac{W_{\text{fuel}}}{W_o} \equiv$ fuel fraction

$E = L/D$

Listing 11: Range and Endurance Theory

Gulfstream® | G800™

THE WORLD'S LONGEST-RANGE BUSINESS AIRCRAFT

FARTHER FASTER
8,200 NM
(15,186 km)
at Mach 0.85[1]

UNPRECEDENTED
7,000 NM
(12,964 km)
at Mach 0.90[2]

0.935
Maximum Mach

UP TO 4
Living Areas

SUSTAINABILITY INNOVATION

GULFSTREAM'S
CLEAN WING

AERODYNAMIC
FUSELAGE

ALL-NEW
WINGLETS

ULTRAEFFICIENT
ROLLS-ROYCE PEARL 700 ENGINES

GULFSTREAM SYMMETRY FLIGHT DECK™

INDUSTRY FIRST
ACTIVE CONTROL SIDESTICKS

MOST EXTENSIVE
TOUCH-SCREEN TECHNOLOGY

COMBINED VISION SYSTEM:
EFVS AND SVS ON DUAL HUD

AWARD-WINNING
PREDICTIVE LANDING PERFORMANCE SYSTEM

THE GULFSTREAM CABIN EXPERIENCE

ALWAYS
100%
FRESH AIR

NEVER RECIRCULATED

PLASMA IONIZATION
TECHNOLOGY

PURIFIES THE CABIN AIR

FEELS LIKE:
2,840
FEET
(866 Meters)

FLYING AT:
41,000
FEET
(12,497 Meters)

THE LOWEST CABIN ALTITUDE IN THE INDUSTRY

TECHNICAL SPECIFICATIONS

G800™

PERFORMANCE

Maximum Range[1] 8,200 nm | 15,186 km

Maximum Operating Mach Number (Mmo) 0.935

High-Speed Cruise Mach 0.90

Long-Range Cruise Mach 0.85

Takeoff Distance (SL, ISA, MTOW) 5,812 ft | 1,771 m

Initial Cruise Altitude 41,000 ft | 12,497 m

Maximum Cruise Altitude 51,000 ft | 15,545 m

MEASUREMENTS

Finished Cabin Height 6 ft 3 in | 1.91 m

Finished Cabin Width 8 ft 2 in | 2.49 m

Cabin Length (excluding baggage) 46 ft 10 in | 14.27 m

Total Interior Length 53 ft 7 in | 16.33 m

Cabin Volume 2,138 cu ft | 60.54 cu m

Baggage Compartment Volume 195 cu ft | 5.52 cu m

Exterior Height 25 ft 6 in | 7.78 m

Exterior Length 99 ft 9 in | 30.40 m

Overall Wingspan 103 ft | 31.39 m

WEIGHTS

Maximum Takeoff 105,600 lb | 47,899 kg

Maximum Landing 83,500 lb | 37,875 kg

Maximum Zero Fuel 60,500 lb | 27,442 kg

Basic Operating[3] 54,300 lb | 24,630 kg (including 4 crew)

Maximum Payload[3] 6,200 lb | 2,812 kg

Maximum Payload/Full Fuel[3] 2,300 lb | 1,043 kg

Maximum Fuel 49,400 lb | 22,407 kg

SYSTEMS

Avionics Gulfstream Symmetry Flight Deck™

Engines Two Rolls-Royce Pearl 700

Rated Takeoff Thrust (each) 18,250 lb | 81.20 kN

CABIN

Up to 3 Living Areas with Crew Compartment or 4 Living Areas

Seats Up to 19

Sleeps Up to 10

Gulfstream Panoramic Oval Windows 16

Largest Windows in the Industry

Flexible Cabin Design

Forward Galley with or without Dedicated Crew Compartment

Forward and Aft Vacuum Lavatories

[1]NBAA IFR theoretical range at Mach 0.85 with 8 passengers, 4 crew and NBAA IFR reserves. Actual range will be affected by ATC routing, operating speed, weather, outfitting options and other factors. [2]NBAA IFR theoretical range at Mach 0.90 with 8 passengers, 4 crew and NBAA IFR reserves. Actual range will be affected by ATC routing, operating speed, weather, outfitting options and other factors. [3]Stated weights are based on theoretical standard outfitting configurations. Actual weights will be affected by outfitting options and other factors.

Gulfstream™
A GENERAL DYNAMICS COMPANY

Listing 12: G800 Product Sheet

Falcon 10X Backgrounder

The new benchmark in business aviation

Falcon 10X combines Dassault fighter DNA and new technologies with the largest, most capable and customizable cabin in business aviation

Dassault Aviation began with a clean sheet to create the Falcon 10X, the largest and most capable purpose-built business jet. Its cabin is the largest in business aviation with a new level of flexibility in creating a customized interior environment. New, high-speed aerodynamics yield a maximum range capability of 7,500 nm (13,890 km) and a top speed of Mach 0.925.

Dassault's Digital Flight Control System on the 10X includes safety features new to business aviation, providing protection from inadvertent upsets and other hazards – features that stem directly from the company's military aircraft.

THE LARGEST, MOST FLEXIBLE CABIN IN BUSINESS AVIATION

A modular cabin design that lets owners, essentially "move the walls" and create their own customized spaces

The sheer dimensions of its cabin and the flexibility of interior configurations distinguish the 10X from other ultra-long-range jets.

With a cabin volume of 2,780 cubic feet (79 cubic meters), the 10X offers the largest cabin interior of any purpose-built business jet. It is almost 8 inches (20 cm) wider than its competitors.

- Cabin height: 6 ft, 8 in (2.03 m)
- Max width: 9 ft, 1 in (2.77 m)
- Cabin length: 53 ft, 10 in (16.4 m)

More room, more cabin layouts: The 10X has an ingeniously flexible cabin design, allowing new layout possibilities. Starting with a baseline four-zone platform, the aircraft's interior design concept centers around an entirely new level of modularity so that the cabin can easily be configured for a wide range of mission capabilities and customer needs.

The baseline arrangement separates the interior into four equal sections of 8 feet, 10 inches (2.7 m) with four windows a side each. However, cabin sections can be easily reconfigured into compartments of different lengths and number of windows. Hence, an aft stateroom suite could be 15 feet, 6 inches (4.7 m) long and include seven windows, plus a large lavatory with shower. The 10X stateroom can be equipped with a full-size queen bed— unique in business aviation.

78, Quai Marcel Dassault - 92552 Saint-Cloud Cedex 300 – France - Tel: +33 (0)1 47 11 40 00
Head office: 9, Rond-Point des Champs-Elysées Marcel Dassault - 75008 Paris - France - French limit company (S.A.) with a registered capital of €66,789,624 - 712 042 456 RCS Paris

A three-window small compartment could serve as a section for private conversations or as a media center for presentations or the viewing of videos and streaming news on a large screen.

A dining/conference area can have four or more windows a side. When dining at a four-place table, passengers nearest the windows can use the space between seats to step out without inconveniencing the aisle passenger. In many ways, it is easier to move around the cabin and to do so without disturbing others.

The advantages of more space: The increased cross section and cabin volume convey a number of advantages, some obvious and some subtle. Ample headroom extends toward the sides of the cabin making it easier to pass people in the aisle and stand up straight even well off the cabin centerline. Seats no longer need to be tucked into side ledges to create sufficient aisle width. A forward lavatory has more space in all dimensions, making it more suitable for passengers, as well as crew. Every galley compartment has more storage volume.

Healthy cabin features: Cabin pressurization will be the best in the industry with the lowest cabin altitude—a 3,000-foot pressure altitude in the cabin while flying at 41,000 feet. A next-generation filtration system that eliminates ozone and potential pollutants (volatile organic compounds) will provide 100 percent pure air. Humidity can be maintained at a level that makes long hours aloft more comfortable and healthful. Temperature control will be provided in each of the cabin's four zones with air entering at the top and the bottom of the cabin for an even temperature throughout.

The lowest sound levels: Dassault's current flagship, the Falcon 8X has the lowest interior sound levels of any business jet, the equivalent of a typical suburban living room. The 10X, using Dassault's advanced noise reduction technologies, will be at least this quiet despite the increased cruise speed.

New, larger windows: The 10X's windows are almost 50 percent larger than those on the 8X. Thirty-eight windows line the fuselage for the most window area and brightest cabin in business aviation.

Always in touch with advanced connectivity. The 10X cabin comes with a high-speed connectivity system solution ensuring seamless in-flight communications and high-speed access to the Internet. Connectivity service options include a Ka-band network for fast and more consistent data speed. The cabin will also come equipped with the latest in-flight entertainment and communications network technology designed to distribute crisp, high-definition audio and video content throughout. Passengers will have total command of cabin functions in an easy-to-use mobile app or through cabin touch screens and hard switches.

Lots of baggage space: The 10X's 198 cubic foot (5.60 m^3) baggage compartment is the largest in the ultra-long-range segment. Its electrically operated door makes loading and unloading the compartment easier for pilots and ground crews. A dedicated and separated additional compartment of 8 ft, 3 in (0.23 cu m) provides room for specific devises such as a fly-away kit.

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SUPERIOR PERFORMANCE IN THE ULTRA-LONG-RANGE SEGMENT,
CLASSIC FALCON PERFORMANCE FROM THE MOST DEMANDING AIRFIELDS

Range is 7,500 nautical miles (13,890 km) at 0.85 Mach, making almost every city pair a nonstop flight. As large as it is, the Falcon 10X can still access typical airports serving business aviation as well as those with challenging approaches. The Falcon 10X is London City capable.

Typical ultra-long-range city pairs:

- New York to Shanghai
- Los Angeles to Sydney
- Paris to Santiago
- Hong Kong to New York

Typical city pairs at Mach .90 high-speed cruise:

- Geneva to Singapore
- Moscow to Los Angeles
- New York to Dubai

A VERY SPACIOUS, ADVANCED FLIGHT DECK

The 10X flight deck takes advantage of a larger fuselage cross section and extra length and therefore has more space for the flight crew. New levels of automation reduce workload and fatigue over long distances. New digital-flight-control technology adds breakthrough safeguards.

More space for the flight crew: The cockpit is a roomy space in terms of elbow room and length. It has integrated provisions to anticipate regulatory allowance for duty time credits in two-pilot operations. In the future, pilot seats could be permitted to recline to a flat position for rest.

A major advance in flight deck technology: The 10X's next-generation flight deck represents a breakthrough in the extensive use of touch screens and a more intuitive interface. It reduces crew operations and enhances safety through a series of new capabilities, for example: multi-touch capability to easily expand or shrink navigation images in a quick motion; better windowing flexibility including Onboard Information System ("Open World") integration; or auto-sensing for many switches, easing checklist management. The number of flight deck buttons and switches has been reduced, allowing for a smaller, simplified overhead panel.

Advanced power management: A smart throttle is the primary power control, linking the digital power management of both engines. It features an airbrake control and a fully integrated reverse sector. Its

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auto-throttle is capable of independently piloting the engines and touchdown and can and automatically adjusting power on the operating engine in the event of the loss of one powerplant. The smart-throttle is also fully integrated with the Digital Flight Control System and can therefore be automatically activated with full authority in various recovery modes.

A next-generation Digital Flight Control System with new safety features: The 10X digital flight control system expands the capability of previous Falcon flight controls. As on the new Falcon 6X, all secondary flight controls (flaps, slats and spoilers) plus nose wheel steering are tied into the digital control system. The 10X goes another step with automatic protections derived directly from the latest Dassault fighter technology. A **"recovery mode"** can be activated with the touch of one button by pilots experiencing spatial disorientation or wake turbulence induced upset.

Leadership in enhanced vision: Dassault's breakthrough FalconEye® combined vision system— the first to offer both enhanced and synthetic vision technologies—with dual head-up displays as the sole means for flying, allowing more flexible panel windowing and providing provisions to conduct future e EVS-to-land operations with essentially zero ceiling.

Advanced maintenance diagnostics. A new onboard system, FalconScan, first adopted on the Falcon 6X, sets a new standard in real-time system self-diagnosis. Connecting directly to all aircraft systems, FalconScan monitors more than 100,000 parameters (compared to hundreds in earlier Falcons), providing near instantaneous visibility for on-ground maintenance teams. Patented algorithms will enable fault detection and troubleshooting for individual aircraft plus trend monitoring across the Falcon 10X fleet worldwide.

NEW STRUCTURES, NEW AERODYNAMICS, ULTRA-EFFICIENT POWER

New fuselage: The aluminum fuselage design is entirely new with a circular cross section and frame spacing to permit extra-large windows. Even with a larger fuselage, the aircraft is highly efficient within the ultra-long-range segment due to an aero-optimized airframe with all-new wing design and efficient engine configuration.

New, high-speed wing: The 10X wings have been optimized to provide the best high-speed performance (thanks to high sweep angle and reduced thickness), especially for very high Mach numbers. They also keep Falcon's traditional ingredients such as efficient moveable slats that ensure best performance and safety margins at low speed. Low-speed lift/drag ratio has been deeply improved, thanks to a very high aspect ratio wing and the choice of dedicated flap architecture. This double optimization (wings optimized for both low-speed and high-speed regime, unique in the business aviation world) has been made possible thanks to the use of innovative carbon fiber wing technology, mastered for years by Dassault Aviation on the Rafale fighter.

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A CLEANER, LEANER, SMARTER ENGINE

The 10X's Rolls-Royce Pearl® 10X will be the industry's most advanced business jet engine. It is the latest, largest and most powerful of the Pearl engine series, delivering more than 18,000 pounds of thrust.

The Pearl 10X incorporates multiple innovations derived from Rolls-Royce's Advance2 technology demonstrator programs, including new materials and internal aerodynamics for more efficient combustion, longer life and lower maintenance. It is equipped with a new blisk fan for greater efficiency, an innovative combustor for lower emissions and an advanced high-pressure turbine for longer life.

The Pearl engine family is part of the Rolls-Royce Intelligent Engine vision for longer service life and lower maintenance. It has a revolutionary Engine Health Monitoring System that adds advanced vibration detection to thousands of other parameters. It's a user-friendly diagnostic system that keeps maintenance managers better informed of engine condition, delivering exceptional levels of availability and reliability.

The engine is fully supported by Rolls-Royce's industry-leading, CorporateCare® Enhanced engine service program.

UNIQUE FALCON SAFETY FEATURES

Military level safety features built in

Falcons are built alongside Dassault's renowned Rafale fighters and meet the same high manufacturing standards, protecting, for example, the fly-by-wire system and fuel tanks from potential damage. All critical systems are meticulously segregated, and the fuel tanks are pressurized. Quality measures like these go far beyond minimum regulatory requirements and are unmatched in the industry.

Falcon 10X timeline

The Falcon 10X will enter service end of 2025.

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FALCON 10X SPECIFICATIONS

PERFORMANCE

- Range: 7,500 nm (13,890 km) at Mach .85 (8 pax, 4 crew, ISA, SL, Zero Wind, NBAA IFR Reserves)
- Maximum Mach Operating (MMO) speed: Mach .925
- Maximum Certified Altitude: 51,000 ft (15,545 m)
- Balanced Field Length (MTOW, SL, ISA) : < 6,000 feet (1,829 m)
- Landing Distance (SL, Public Transport) : < 2,500 ft (762 m)

ENGINES & AVIONICS

- 2 Rolls-Royce Pearl 10X Engines
- Max Thrust: 18,000+ lbs

- Next Generation Flight Deck
- With Honeywell Primus Epic System

EXTERNAL DIMENSIONS

- Wing Span: 110 ft 3 in (33.6 m)
- Length: 109 ft 7in (33.4 m)
- Height: 27 ft 7 in (8.4 m)

INTERNAL DIMENSIONS

- Cabin Height 6 ft 8 in (2.03 m)
- Cabin Width 9 ft 1 in (2.77 m)
- Cabin length (excluding flight deck and baggage): 53 ft 10 in (16.4 m)
- Cabin Volume 2,780 cu. ft. (78.7 cu. m.)
- Baggage Volume: 198 ft^3 (5.60 m^3)

WEIGHTS/CAPACITIES

- Maximum Ramp Weight: 115,400 lbs (52,345 kg)
- Maximum Takeoff Weight: 115,000 lbs (52,163 kg)
- Maximum Zero Fuel Weight: 67,800 lbs (30,754 kg)
- Maximum Fuel Weight: 51,700 lbs (23,451 kg)

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ABOUT DASSAULT AVIATION:
Dassault Aviation is a leading aerospace company with a presence in over 90 countries across five continents. It produces the Rafale fighter jet as well as the complete line of Falcons. The company employs a workforce of over 12,500 and has assembly and production plants in both France and the United States and service facilities around the globe. Since the rollout of the first Falcon 20 in 1963, over 2,500 Falcon jets have been delivered. Dassault offers a range of six business jets from the twin-engine 3,350 nm large-cabin Falcon 2000S to its flagship, the tri-engine 6,450 nm ultra-long range Falcon 8X and the new ultra widebody cabin Falcon 6X.
For more information about Dassault Falcon business jets, visit: **dassaultfalcon.com**

DOWLOAD HIGH RES PHOTOS

DASSAULT AVIATION PRESS CONTACTS

Saint-Cloud, France
Vadim Feldzer, Head of Falcon Global Communications
Tel. +33 (0)1 47 11 44 13

Teterboro Airport, USA
Andrew Ponzoni, Senior Manager, Communications
Tel. +1 201 541 4588

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Listing 13: Falcon-10X Backgrounder Documentation