ERODIUS

EXECUTIVE SUMMARY

43RD ANNUAL VFS STUDENT DESIGN COMPETITION

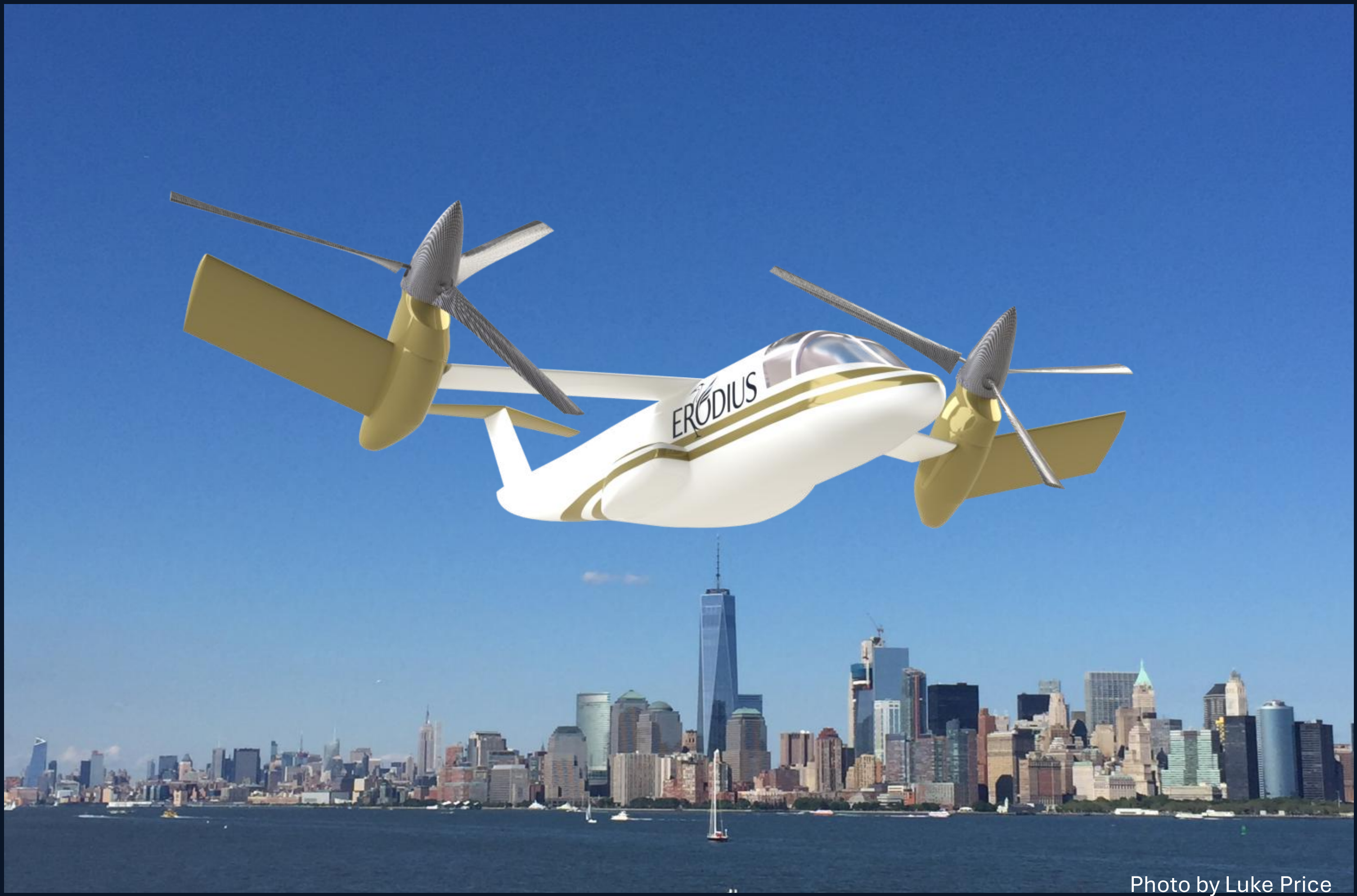
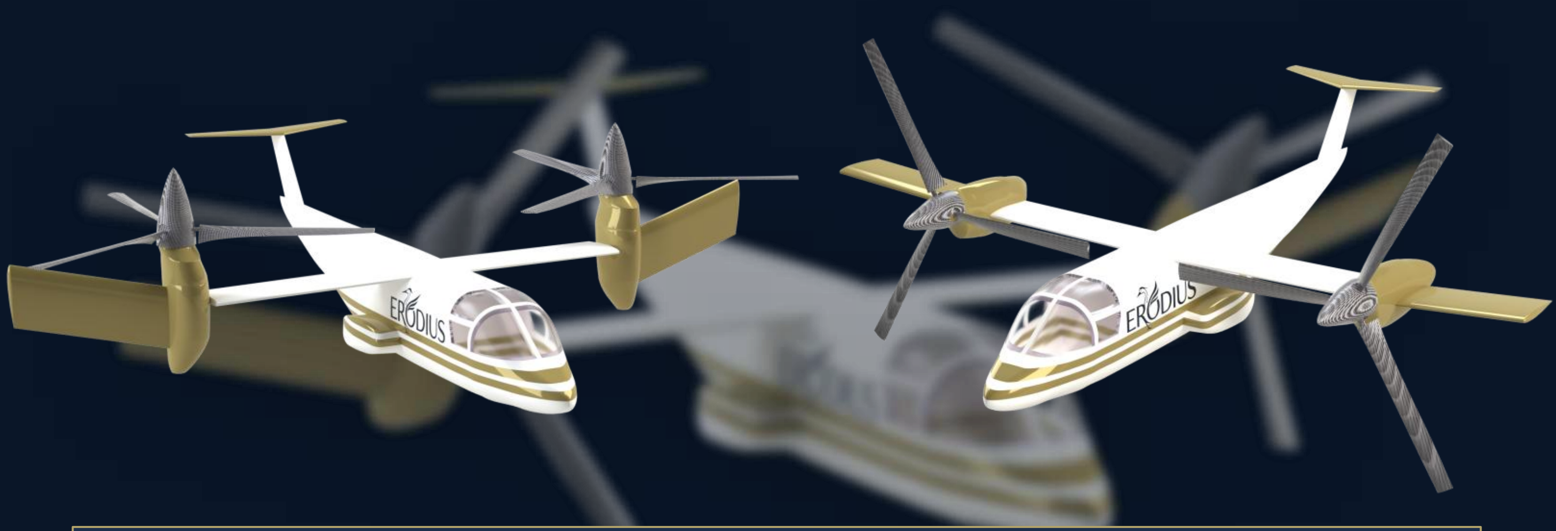


Photo by Luke Price

HYBRID-ELECTRIC TILTROTOR

Introduction

To address the Request for Proposal for the 43rd Annual Vertical Flight Society Student Design Competition sponsored by Leonardo, Georgia Tech presents *Erodius*. *Erodius* draws its name from the Greek word for “heron”, and the mythological figure who was transformed into one. Much like the heron, which is known for its efficient gliding flight, this program focuses on redesigning the XV-15 to achieve highly efficient forward flight via electric-fuel hybridization.



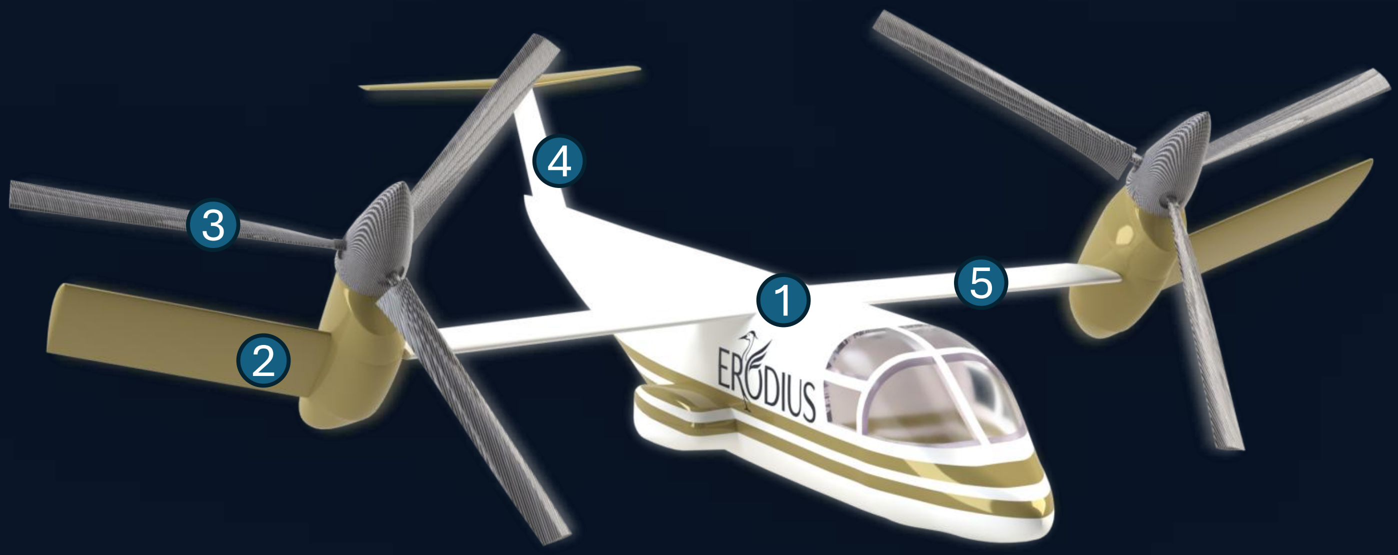
Vehicle Design

Erodius is a hybridized VTOL tiltrotor designed to achieve a 306 nm mission range with a cruise speed of 260 KCAS while carrying a 1,600 lb payload consisting of 6 passengers and 2 crew members. To accomplish this, the vehicle relies on an advanced turbo-electric and battery hybrid powerplant system. In Phase I, *Erodius* maintains the traditional XV-15 architecture and integrates a battery, generators, and electric motors with minimal structural changes to evaluate the direct impact of hybridization. In Phase II, the vehicle leverages modern carbon fiber composite materials, full fly-by-wire controls, and a novel, optional lifting nacelle extension.

Vehicle Overview

1 An efficient generator-battery hybrid system keeps weight down while providing benefits of electrification for both Phase I and Phase II designs

2 In Phase II, an *optional* lifting nacelle extension allows for an improved flight envelope and cruise efficiency at high payload



3 A team-built BEMT code was used to validate the rotor in Phase I then optimize the rotor in Phase II with modernized structure

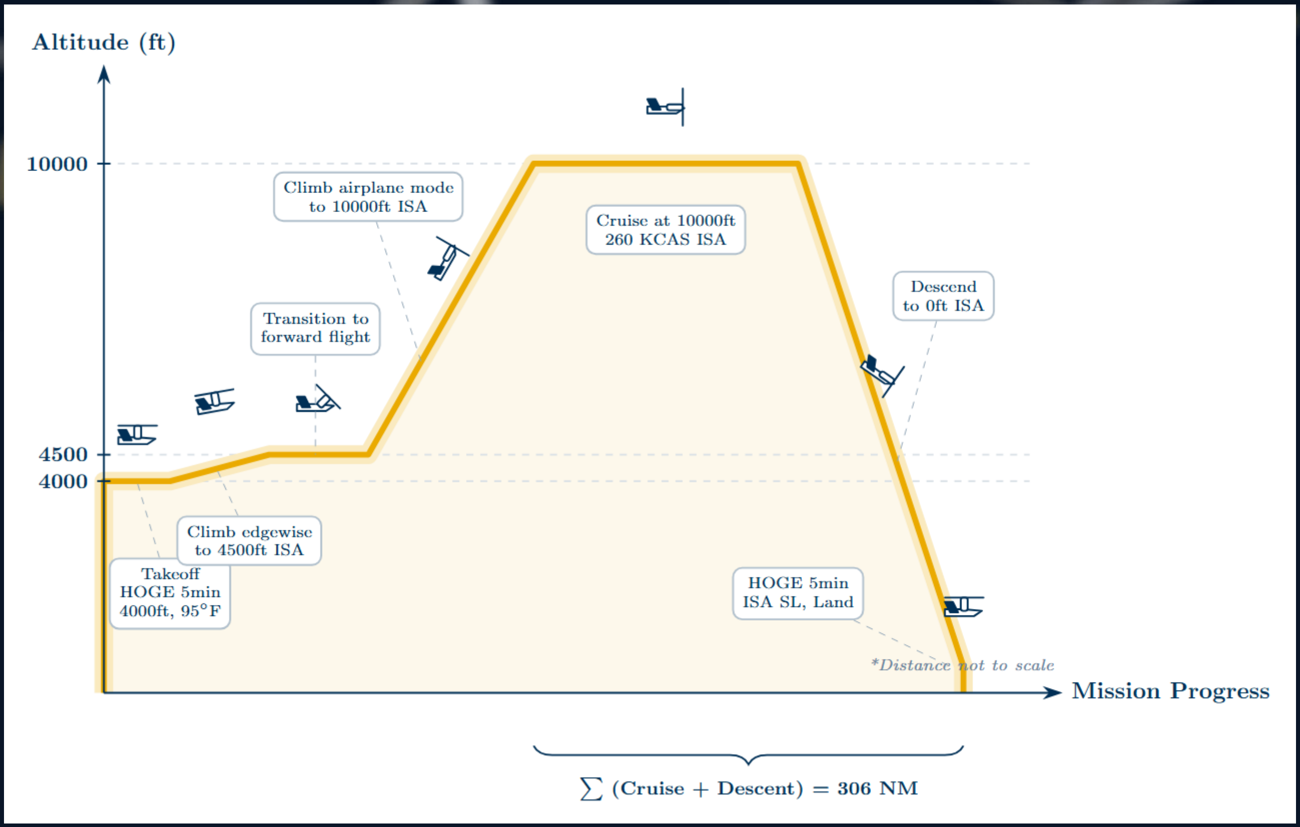
4 Tail design trade study was run to select a T-tail configuration for reduced weight and moving the surface out of the rotor wash in forward flight

5 While wing was the same as the XV-15 in Phase I, in Phase II its structure, airfoils, sweep, and dihedral was redesigned for maximized efficiency and minimal drag

Mission Operations

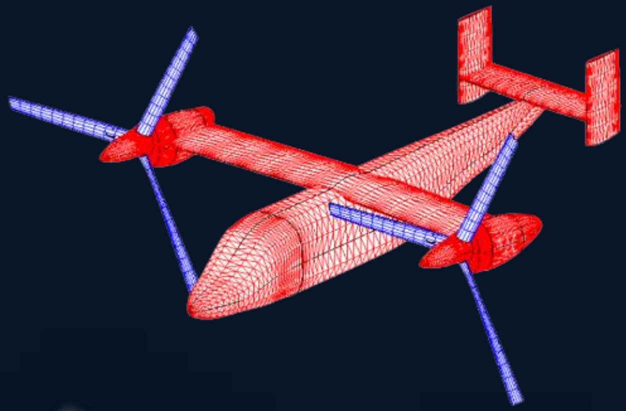
1. Cruise occurring at 260 ktas (equivalent to 115 m/s (223 kcas)), instead of 134 m/s (260 kcas).

2. Meet the 3048 m (10,000 ft) altitude requirement, then descend and fly at a new altitude for cruise where the original XV-15 was able to maintain 134 m/s (260 kcas) due to power limitations. This descent at forward speed of 134 m/s (260kcas) to 2134 m (7000 ft), completing the cruise segment at that altitude, then descending. Thereby, maintaining the 134 m/s (260 kcas) cruise and descending and landing for a total distance of 566,712 m (306 nm).

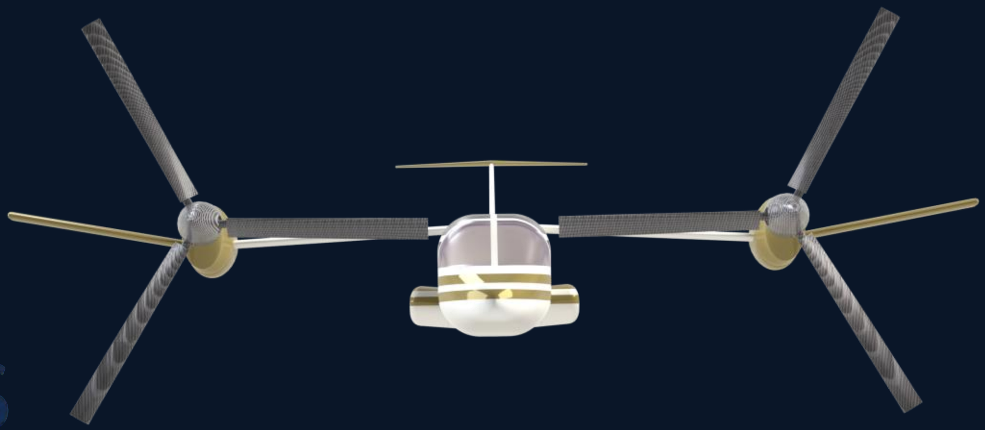


These two profiles allow Phase I and Phase II results to be directly compared to XV-15 performance while meeting all RFP requirements. T**he Phase II design is capable of performing the mission at 3048 m (10,000 ft), 134 m/s (260 kcas) .**

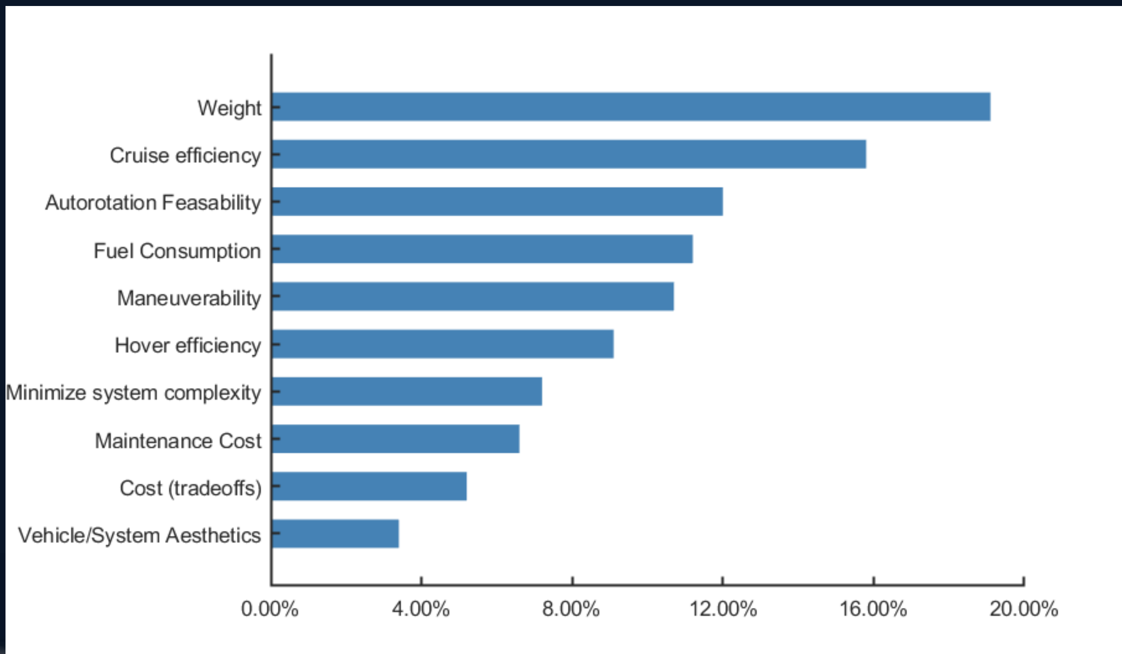
Performance metrics
(Iteratively Determined)



Performance Metric	XV-15	Erodius Phase I	Erodius Phase II
Percent Electric Energy (%)	0.00	54.88	80.08
Empty Weight, kg (lbs)	4614.0 (10172.1)	4678.6 (10314.5)	4481.6 (9880.1)
Payload Weight, kg (lbs)	725.5 (1599.5)	453.4 (999.6)	725.5 (1599.5)
Gross Takeoff Weight, kg (lbs)	6309.4 (13909.8)	6309.4 (13909.8)	5903.2 (13014.3)
Initial Fuel Capacity, kg (lbs)	771.4 (1700.6)	951.8 (2098.3)	450.0 (992.1)
Total Fuel Consumed, kg (lbs)	686.04 (1512.5)	778.36 (1716.0)	393.24 (866.9)
Max Hover Power, kW (hp)	1708.7 (2291.4)	1708.7 (2291.4)	1473.3 (1975.7)
Max Cruise Power, kW (hp)	1468.8 (1969.7)	1467.4 (1967.8)	1048.0 (1405.4)
Total Mission Time (min)	80.4	83.2	83.2
Lifting Nacelle Extension, m (ft)	0 (0)	0 (0)	3.06 (10.05)
Blade Chord, m (ft)	0.356 (1.17)	0.356 (1.17)	0.356 (1.17)
Battery Mass, kg (lbs)	0.0 (0.0)	100.0 (220.5)	300.0 (661.4)
Number of Electric Motors	0	2	3
Number of Generators	0	2	1
Generator Type	None	VerdeGo	Honeywell
Gas Engine Scale Factor	1.00	0.50	0.10



Conceptual Design for Phase II



The Requirements put forth by the RFP were consolidated to 10 Design Drivers that were then ranked in order of importance via the Analytical Hierarchy Process (AHP)

	Weight	Autorotation Feasibility	Cruise efficiency	Hover efficiency	Maneuverability	Fuel Consumption	Cost (tradeoffs)	Maintenance Cost	System Aesthetics	Minimize complexity
Weight	1.00	2.00	1.00	3.00	3.00	2.00	3.00	3.00	3.00	3.00
Autorotation Feasibility	0.50	1.00	0.50	2.00	2.00	2.00	2.00	2.00	3.00	1.00
Cruise efficiency	1.00	2.00	1.00	3.00	2.00	1.00	3.00	2.00	3.00	2.00
Hover efficiency	0.33	0.50	0.33	1.00	0.50	0.50	3.00	3.00	3.00	2.00
Maneuverability	0.33	0.50	0.50	2.00	1.00	2.00	3.00	2.00	3.00	1.00
Fuel Consumption	0.50	0.50	1.00	2.00	0.50	1.00	3.00	2.00	3.00	2.00
Cost (tradeoffs)	0.33	0.50	0.33	0.33	0.33	0.33	1.00	0.50	3.00	1.00
Maintenance Cost	0.33	0.50	0.50	0.33	0.50	0.50	2.00	1.00	3.00	1.00
System Aesthetics	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	1.00	0.33
Minimize complexity	0.33	1.00	0.50	0.50	1.00	0.50	1.00	1.00	3.00	1.00
SUM	4.98	8.83	5.99	14.49	11.16	10.16	21.33	16.83	28.00	14.33

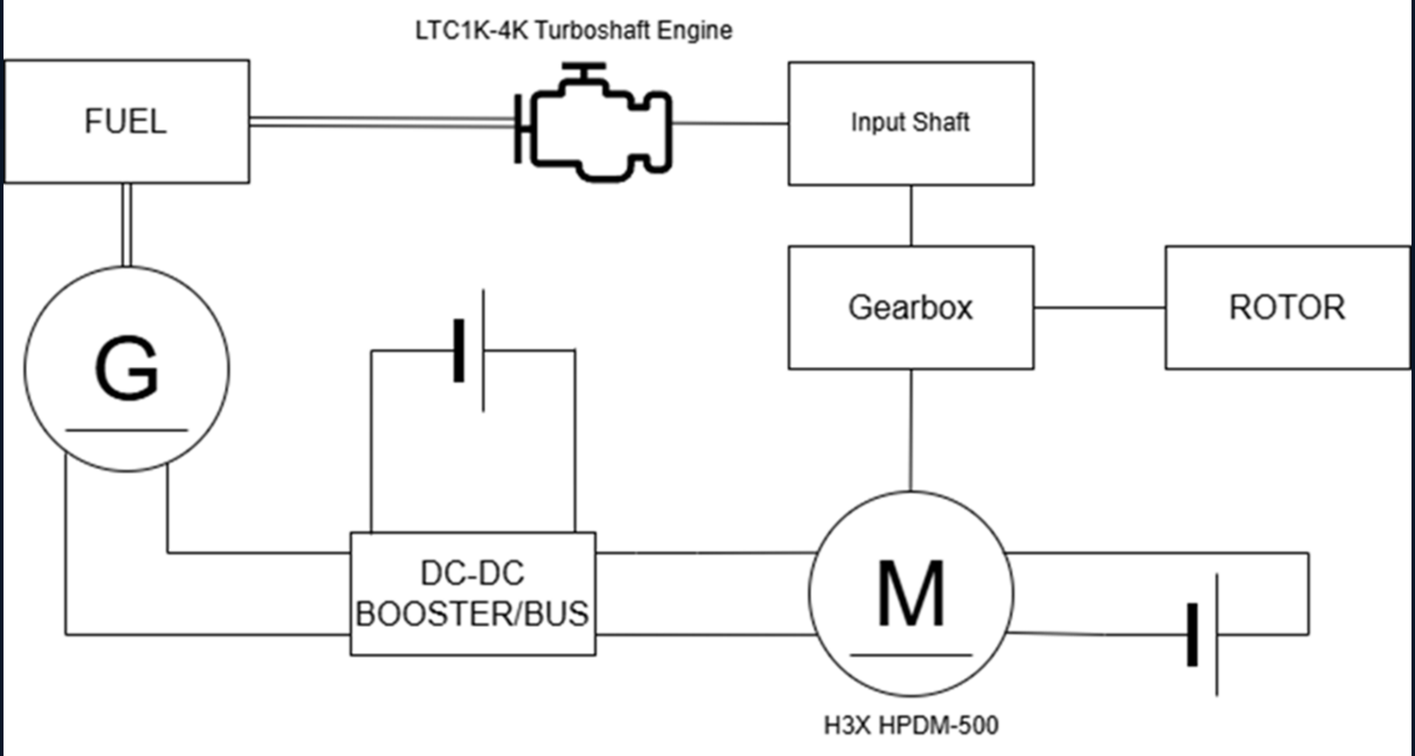
Hybrid-Electric Propulsion Design

There were four contestants for the hybrid propulsion system.

- Fully battery
- Battery hybrid
- Turbo-electric
- Turbo-electric and battery

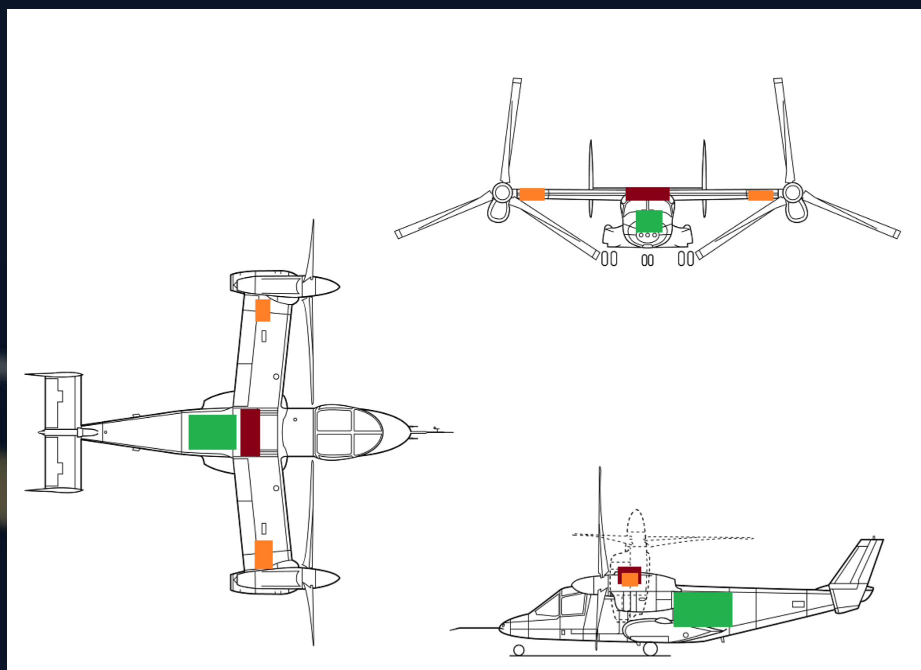
The sizing code automatically filter out fully battery and battery hybrid for not meeting the energy requirements.

The Turbo-electric and turbo-electric and battery produced similar outputs. In the end turbo-electric and battery was selected, because of the extra battery that can provide energy if there was a system failure, providing redundancy and safety.



Hybrid-Electric Propulsion Integration

The hybrid-electric propulsion uses fuel to power a generator which provides electricity for hybridization. Electric motor (red), new gearbox (orange), and turbogenerator (green).



The hybridization of the XV-15 contains two T-53 heat engines, HPDM-500 motors, and Honeywell 1MW/ Verdego-415 generator depending on which phase.

Gearing, Transmission, and Thermal Management

The hybrid propulsion system has the HPDM-500 electric motors attached on the interconnect driveshaft. To integrate the HPDM-500 motors, a 1:3 gearbox is included to match the motors 10,000 RPM to the existing herringbone gear stage, to preserve the original two planetary gearbox reduction to minimize airframe modifications.

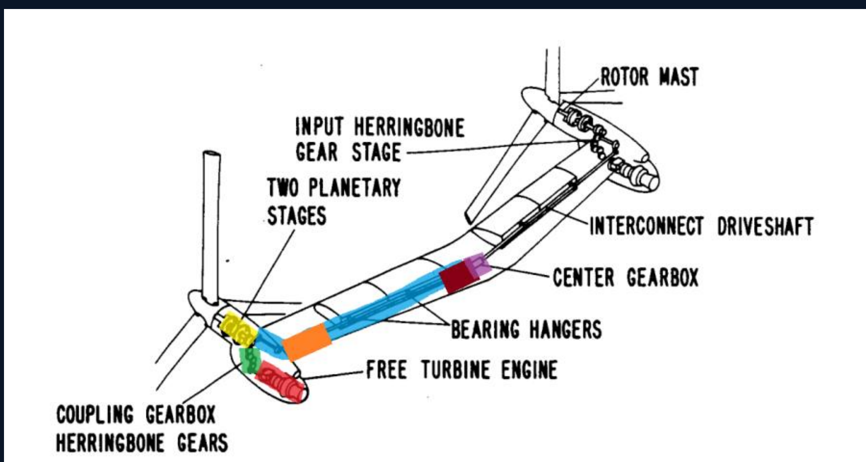


Figure 6.1.- Propulsion system.

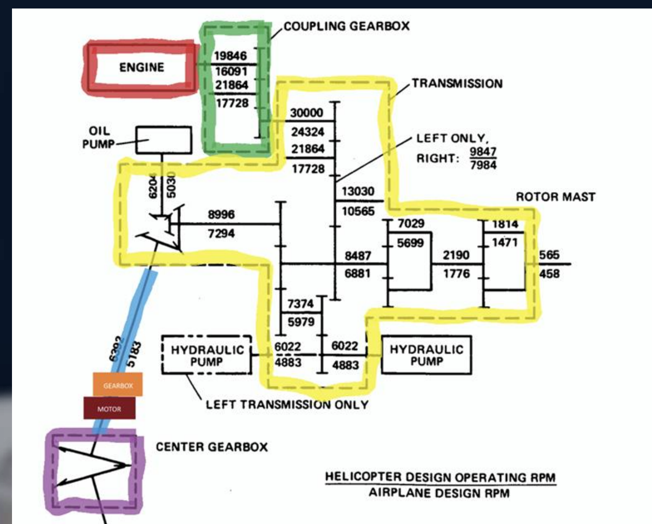


Figure 6.1.1.- Drive system schematic.

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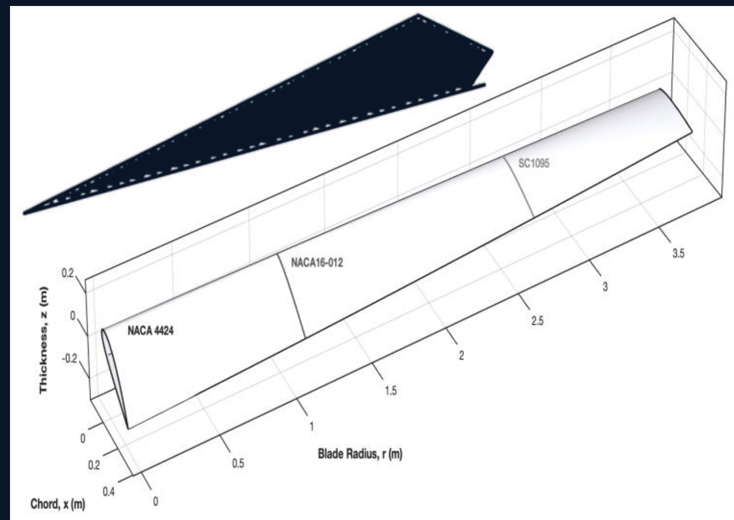
Component (Efficiency)	Waste Heat Generation at Emergency Scenario (kW)						
Port Nacelle	**14.6**	**27.3**	**23.65**	**23.65**	**25.84**	**22.92**	**22.92**
Gearbox (T-53)	14.6	7.3	3.65	3.65	5.84	2.92	2.92
Motor + Inverter (96%)	0	20	20	20	20	20	20
Starboard Nacelle	**7.16**	**23.58**	**23.58**	**23.58**	**42.86**	**42.86**	**42.86**
Gearbox (T-53)	7.16	3.58	3.58	3.58	2.86	2.86	2.86
Motor + Inverter (96%)	0	20	20	20	40	40	40
Transmission	**7.31**	**7.31**	**7.31**	**7.31**	**6.63**	**6.63**	**6.63**
Verdego Generator (830kW, 95%*)	0	41.5	41.5	41.5	0	0	0
Honeywell Generator (1MW, 97%)	0	0	0	0	30	30	30
Battery (Molicel INR-21700)	0	7.81	7.81	7.81	3.91	3.91	3.91
Total Heat Generation (kW)	**29.07**	**107.5**	**103.85**	**103.85**	**109.24**	**106.32**	**106.32**

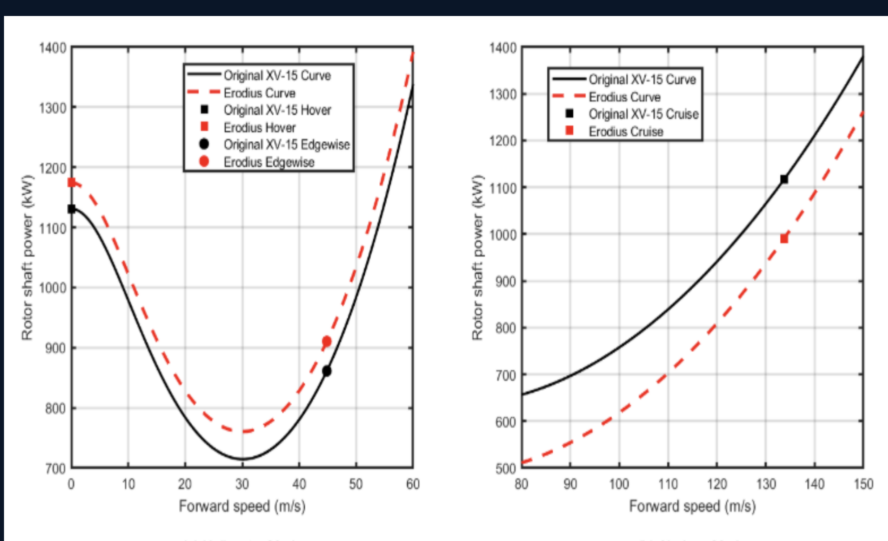
Assume inefficiency converted to heat
Assume max heat generation at OEI scenario
3 times more heat expected to generated due to hybridization
Larger radiator might be needed, water based thermal capacitor may help
Precise thermal dynamical analysis needed (further CFD investigation)

Rotor Design- Phase II

- The rotor redesign used trade studies and BEMT optimization to reduce vehicle weight, cost, and manufacturing complexity while improving performance for hybrid electric conversion.
- The rotors for *Erodius* are designed to prioritize forward flight performance while keeping hover performance strong.



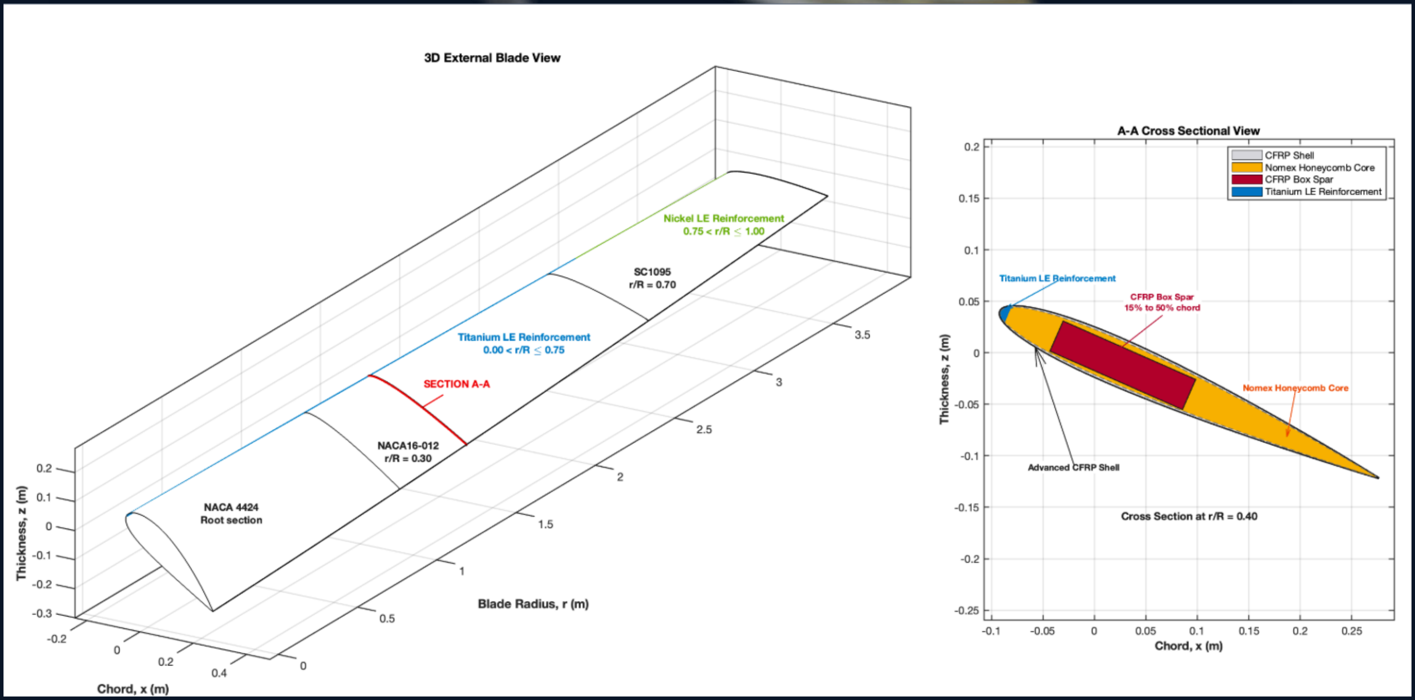
- A rotor blade BEMT optimization code was used to create an optimal blade and yielded the following results
- The MATLAB BEMT optimization that varied airfoil placement, twist, taper, chord, radial transitions, and rotor speed, using C-81 airfoil tables to evaluate lift, drag, pitching moment, stall margin, thrust, and power across the blade span.



Parameter	Metric (SI)	English (Imperial)
Rotor Radius (R)	3.81 m	12.50 ft
Root Chord (c_{root})	0.42 m	1.38 ft
Tip Chord (c_{tip})	0.38 m	1.25 ft
Hover Speed (Ω_H)	62 rad/s	592 RPM
Forward Flight Speed (Ω_C)	53 rad/s	506 RPM
Non-Dimensional & Shared Parameters		
Taper Ratio (λ)	0.90	
Blade Twist (θ_{tw})	-39°	
Airfoils (Root / Mid / Tip)	NACA 4424 / NACA 16-012 / SC 1095	
Airfoil Transitions (r/R)	30% / 70%	
Solidity (σ)	0.099	
Figure of Merit (FM)	0.75	

Rotor Structure and Manufacturing- Phase II

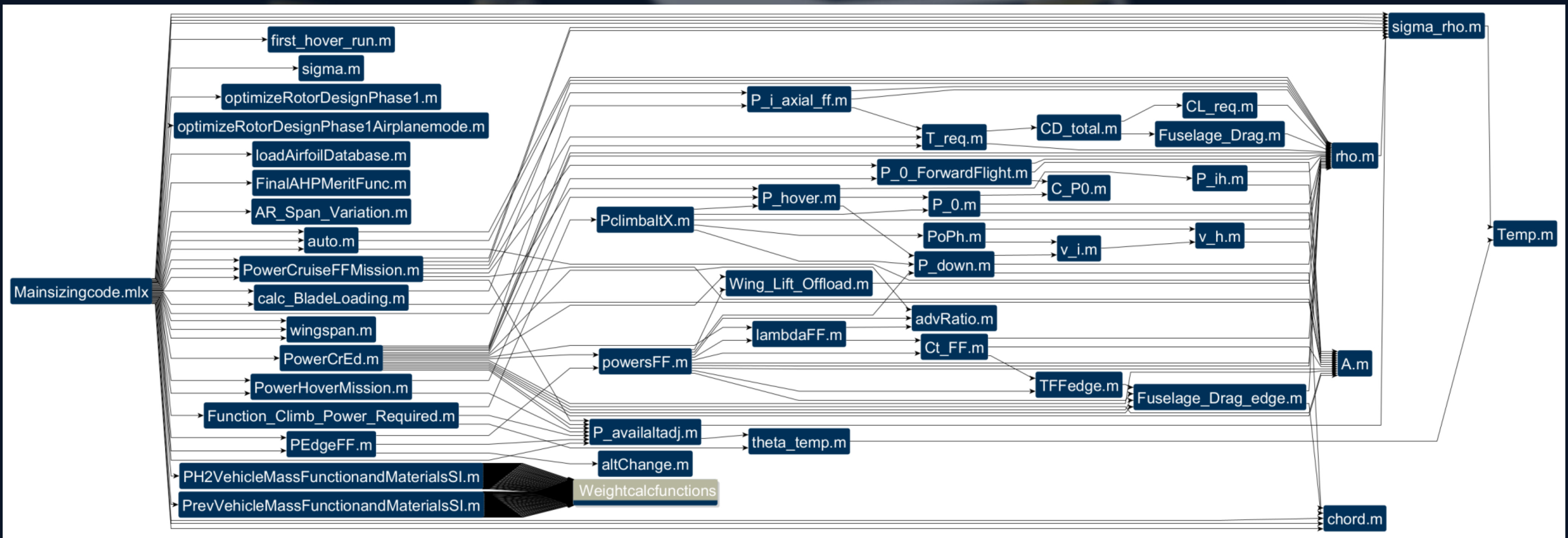
- The construction trade study selected a lightweight composite blade made from a CFRP outer shell, Nomex honeycomb core, and CFRP box spar, which balances low mass, stiffness, durability, and manufacturability.
- The box spar is modeled as a continuous root to tip structural member in the forward/mid chord region, with a 3 mm wall thickness and height equal to about 70% of local airfoil thickness.
- Because the blade operates at high tip Mach values, the design also includes leading edge reinforcement to reduce erosion and loading concerns.
- A titanium layer is applied from 0 - 75% span and a nickel layer from 75 - 100% span improving protection in the regions most affected by high velocity, erosion, and compressibility effects.



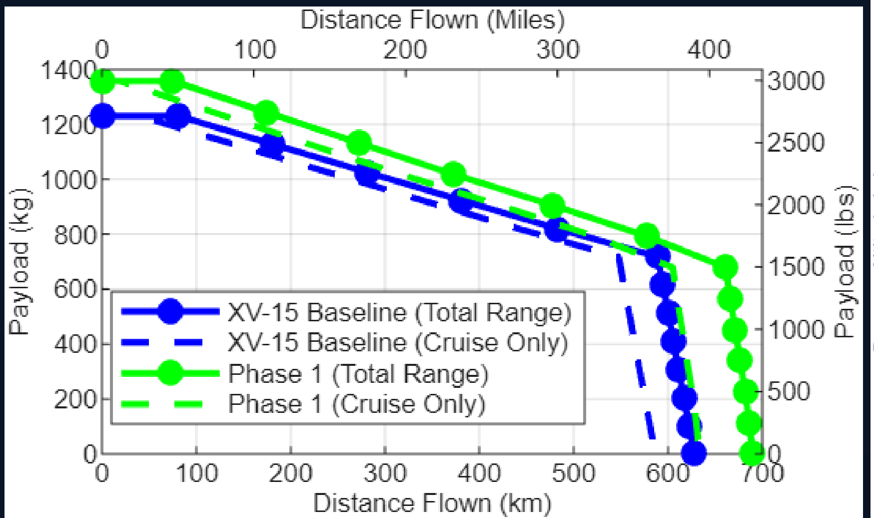
Sizing Code and Logic Map

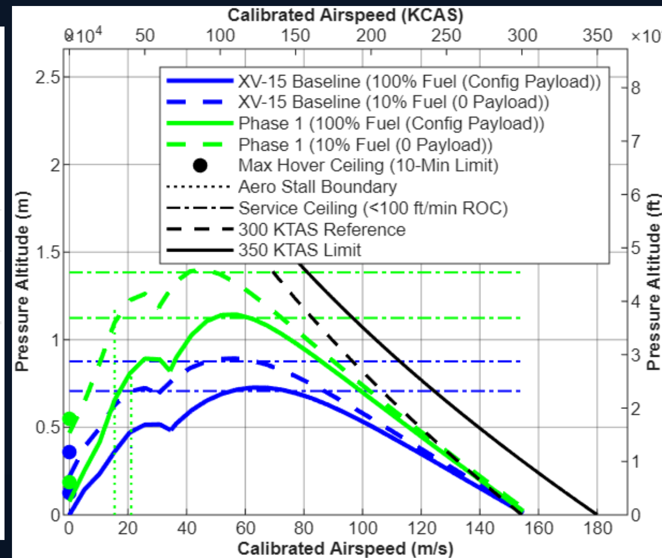
The team built a parallelized MATLAB sizing code to evaluate millions of vehicle configurations across all flight segments. Viable designs had to pass strict power limits, maintain a 10% energy reserve, and successfully complete the mission.

- Phase I optimized hybrid parameters (like battery mass and generators) while maintaining the baseline XV-15 weight.
- Phase II expanded the simulation to optimize aerodynamic geometries, such as wing chord and nacelle extensions, to identify the highest-performing aircraft via the scoring function.

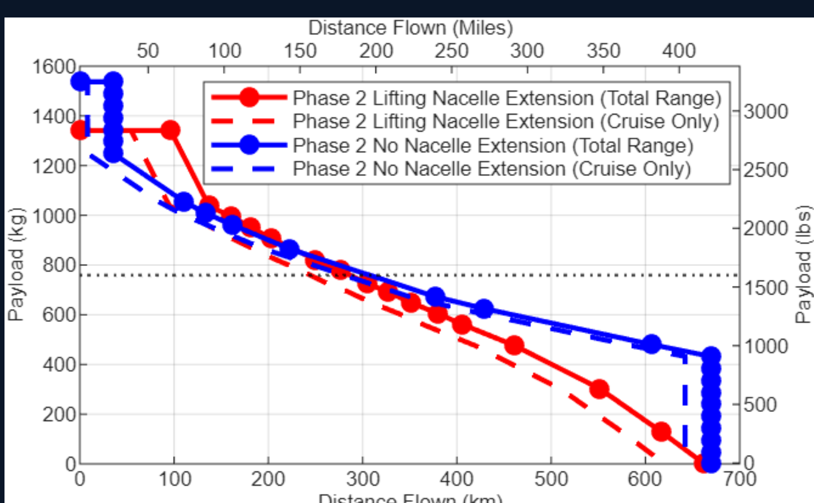


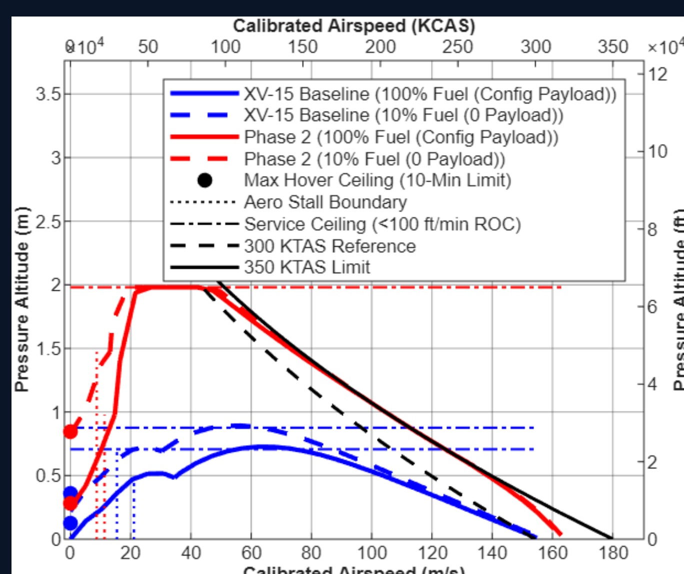
Vehicle Performance Envelope- Phase I and II





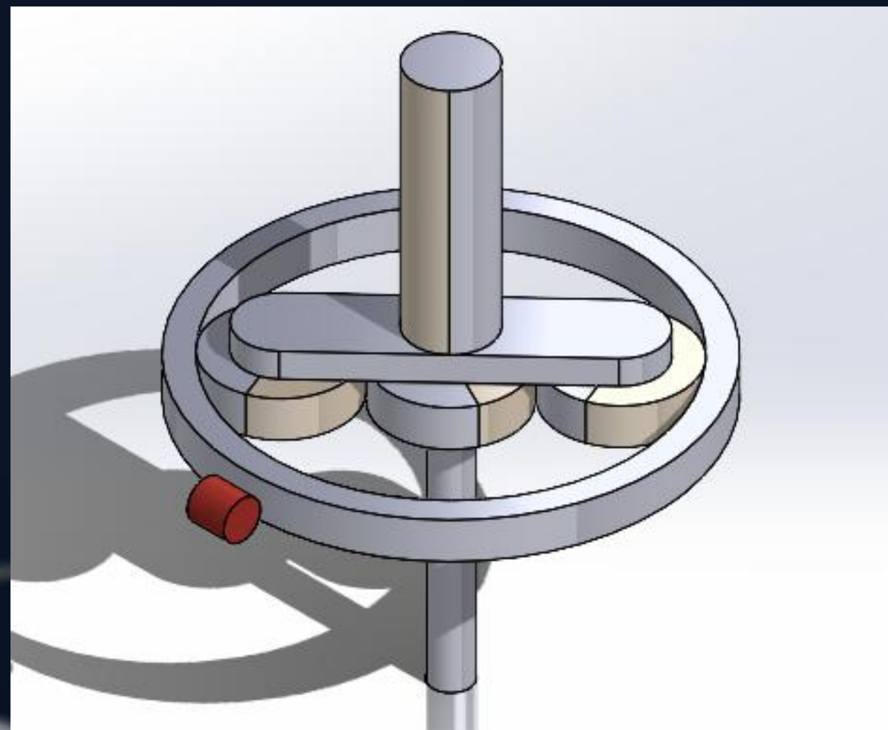
The flight envelope was mapped across various fuel and payload conditions. Phase I demonstrates an improved flight ceiling over the baseline XV-15 because its electric propulsion resists altitude-based power decay , though it still requires a lower 7,000 ft cruise to maintain 260 KCAS. Phase II drastically expands this envelope. By pairing weight reductions with a lifting nacelle extension, Phase II lowers the stall speed, enables earlier airplane-mode conversion, and comfortably achieves the 260 KCAS at 10,000 ft target with only a 5.5% empty weight penalty compared to a non nacelle extension configuration.

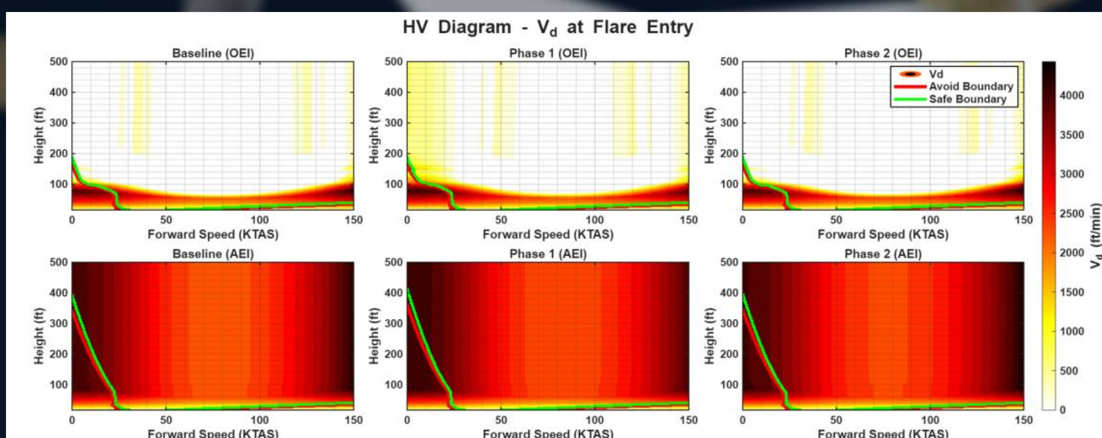




RPM System and Autorotation

A ‘**Planetary Assist System**’ is added to the last ring to induce RPM control. To optimize energy efficiency, the last planetary gears were modified to spin at cruise RPM when engines are running at maximum efficiency. The new gear tooth for sun, planet 1, planet 2, and ring, are as the following respectfully, 20, 55, 49, 124.



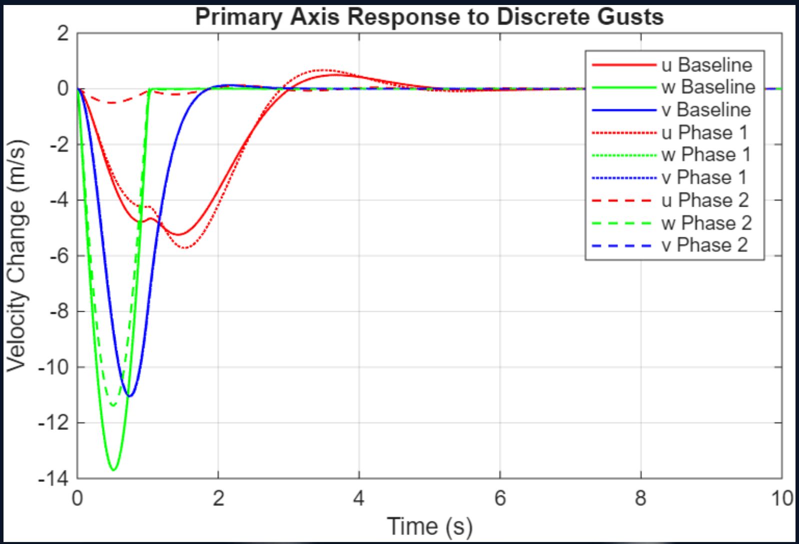


The table provides the mean hover AI values where $h \in [0,500]\ ft$. There is an improvement in the autorotative performance of Phase 1 with its weight change. However, Phase 2 AI is lowered equivalent to the XV-15 AI attributed to lighter rotor blades hence reduced rotor inertia I_R. The three configurations can enter into autorotation and safely land per the RFP requirement at any flight segment given adequate elevation and airspeed.

Configuration	AI (Mean)	
	OEI	AEI
Baseline	11.36	6.99
Phase 1	12.73	7.72
Phase 2	11.39	6.84

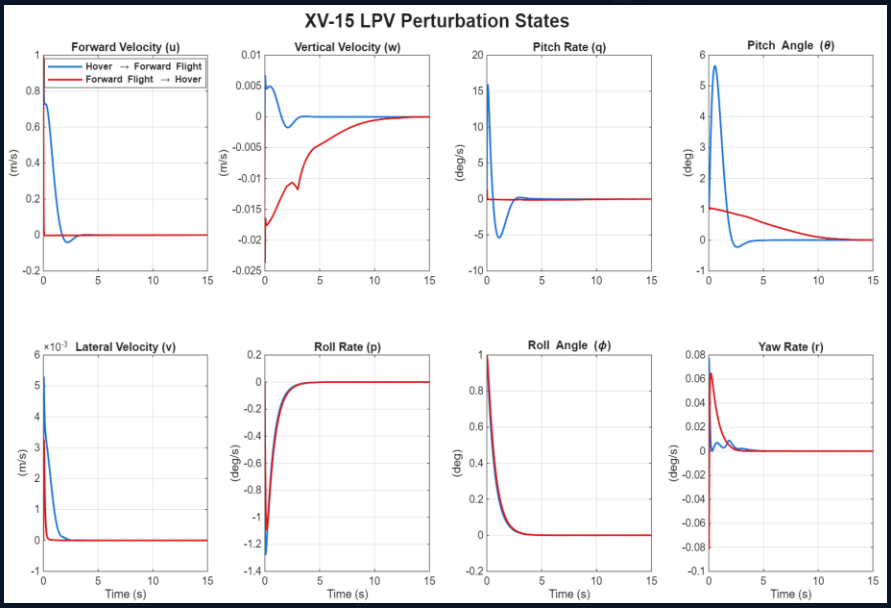
Vehicle Stability- Phase II

The Closed Loop System is augmented with LQR control gains; hence, the vehicle is **stable for all flight conditions & configurations.** Moreover, it **recovers** from 9.144 m/s (30 ft/s) **discrete gusts within 5 seconds.**



Configuration	PSD	Load (g)	
	V_{RMS} (m/s (ft/s))	Vertical	Lateral
Baseline	1.706 (5.599)	2.367	1.910
Phase 1	1.693 (5.556)	2.392	1.913
Phase 2	1.781 (5.843)	2.232	1.746

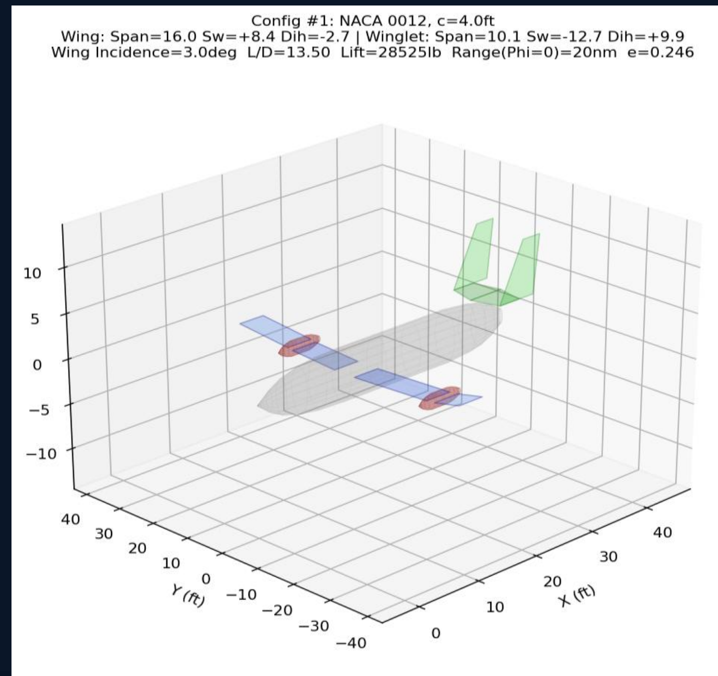
It can as well withstand moderate turbulent intensity ($I = 10^{-3}$) of the Von Karman Model. Phase II has a **superior gust alleviation,** experiencing the least peak loads, vertically and laterally.



The RPM strategy for conversion is governed by LPV control. The conversion is performed in **12 seconds** showing stable response with a steady RPM rate, meeting the XV-15 conversion corridor.

Wing Design-Phase II

Prior to the March RFP update, the design included a uniform-chord 4 ft / 16 ft semi-span main panel with a 10 ft **optional nacelle extension** (+9.86° dihedral).
The vehicle assessment was performed **with and without the nacelle extension – the vehicle meets or exceed RFP requirements.**



At the 260 KCAS / 10 k ft design point, the configuration delivers L/D = 13.50 and C_L = 0.60 at α = 9.5°. Lift = 12,939 kg (28,525 lb) provides a substantial maneuver-margin over the 5,905 kg (13,019 lb) MTOW. P_{req} is below the rated 1,864 kW (2,500 shp) installed power.

Geometry		Performance	
Airfoil	NACA 0012	L/D at cruise	13.50
Chord (uniform)	1.22 m (4.00 ft)	C_L at best α	0.600
Wing semi-span	4.88 m (16.0 ft)	Best α	9.5°
Nacelle ext. semi-span	3.06 m (10.05 ft)	C_{D_0} (parasite)	0.0159
Total tip-to-tip span	18.62 m (61.1 ft)	C_{D_i} (induced)	0.0259
Reference area	19.30 m^2 (207.8 ft^2)	C_d (viscous, XFOIL)	0.0026
Aspect ratio (ref)	17.99	C_D (total)	0.0444
Aspect ratio (aero)	15.33	Lift	126,886 N (28,525 lb)
Wing sweep	+8.42°	Drag	9,399 N (2,113 lb)
Nacelle extension sweep	−12.74°	P_{req}	1,828 kW (2,452 shp)
Wing dihedral	−2.66°	Oswald e (closed-gap)	0.899
Nacelle ext. dihedral	+9.86°	Wing loading	3.34 kPa (69.7 psf)
Wing incidence to body	+3.0°		

The 17.99 reference / 15.33 aero aspect ratio drives a 2.7× reduction in induced drag at any given CL relative to the XV-15 baseline (AR = 6.12). Combined with the closed-gap Oswald correction (e = 0.899), this is the dominant source of the 76% L/D improvement over the Phase I baseline (L/D = 7.65 → 13.50).

The geometry was selected from a **Latin-Hypercube sweep** over six design variables (chord, airfoil, wing sweep & dihedral, winglet sweep & dihedral) at constraint MTOW = 13 k lb, wing-loading 40–120 psf. Of **1.6M possible combinations**, 663 converged and were further considered.

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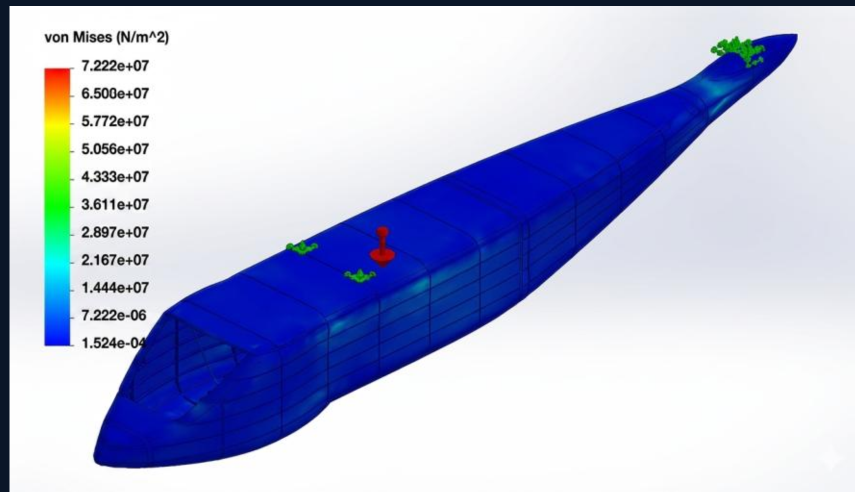
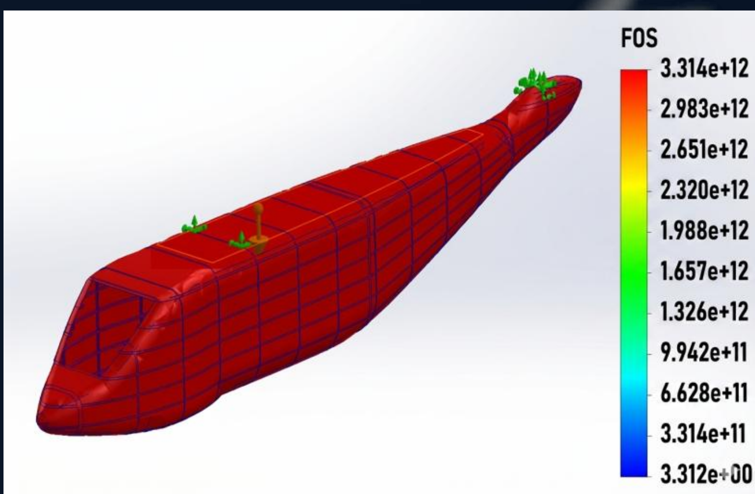
Internal Structure Design and Layout

FE analysis was used to confirm the structure based on published XV-15 weight to provide baseline for new design

Evaluation within 2% of the XV-15 reference with verification that estimated structure met flight requirements





The validated structure shows max von Mises = 72.22 MPa and max displacement = 37.01 mm under the 5.25 g ultimate static case (MoS ≈ +5.7 against 7075-T6 / 2024-T3 allowable).

Parameter	Phase I (Al)	Phase II (CFRP)
Skin gauge	1.25 in (32 mm)	~1 mm
Fuselage skin mass	364.39 lb	131.94 lb
Max von Mises	72.22 MPa	—
Min FoS	—	3.11
Result	within 2% of XV-15 ref	-63.8% skin mass

Phase II replaced aluminum skin with a Hexcel IM7/8552 CFRP sandwich (4–8 plies per side, 0.131 mm/ply, ~1 mm total face sheet, Nomex HRH-10 3.0 lb/ft^3 core).

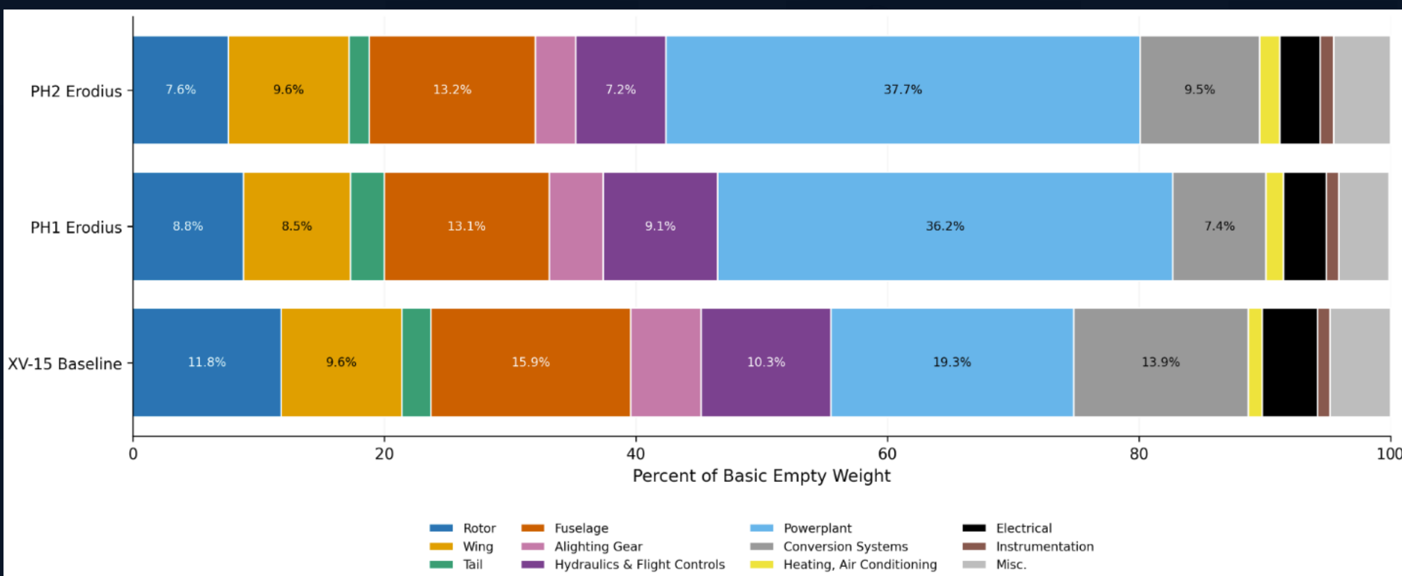
FoS = 3.11, more than 2× the FAR 25.303 floor of 1.5.

After applying AC 20-107B BVID and hot-wet knockdowns (~30% on F_cu), effective FoS ≈ 2.2

Weight Breakdown

Phase I *Erodius* introduced a significant increase in propulsion weight due to hybrid-electric integration

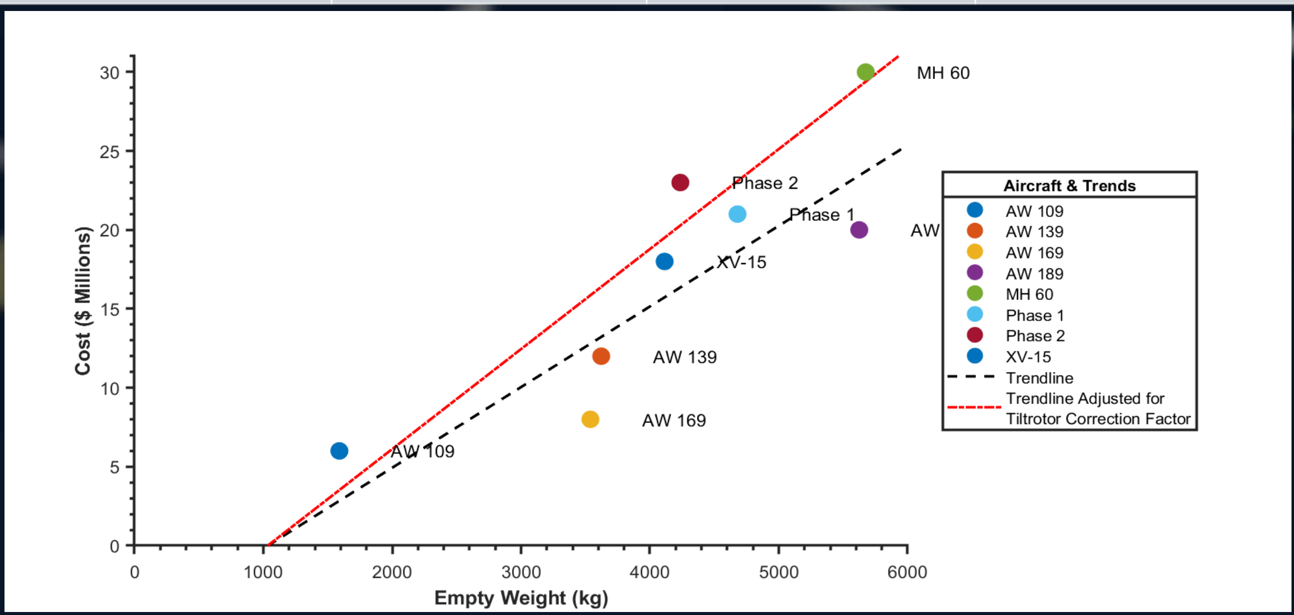
Phase II *Erodius* recovered much of this penalty through structural optimization, nacelle downsizing, fly-by-wire implementation, and subsystem weight reductions, ultimately reducing research mission empty weight below the original XV-15 baseline.



Parameter	Baseline XV-15 kg (lb)	Validation Code kg (lb)	% Error from Baseline	Erodius PHI kg (lb)	% Difference from Baseline	Erodius PHII kg (lb)	% Difference from Baseline
Rotor	485.3 (1,070.0)	472.2 (1,041.0)	-2.71%	472.2 (1,041.0)	-2.71%	318.1 (701.2)	-34.47%
Wing	396.0 (873.0)	399.6 (880.9)	0.90%	399.6 (880.9)	0.90%	402.1 (886.6)	1.56%
Tail	94.8 (209.0)	103.0 (227.0)	8.61%	103.0 (227.0)	8.61%	68.0 (150.0)	-28.23%
Fuselage	654.1 (1,442.0)	660.9 (1,457.0)	1.04%	657.7 (1,450.2)	0.57%	553.4 (1,220.1)	-15.39%
Alighting Gear	230.4 (508.0)	228.2 (503.0)	-0.98%	213.2 (470.0)	-7.48%	132.3 (291.7)	-42.58%
Hydraulics & Flight Controls	423.7 (934.0)	424.6 (936.0)	0.21%	424.6 (936.0)	0.21%	298.7 (658.6)	-29.49%
Powerplant	795.6 (1,754.0)	796.4 (1,755.7)	0.10%	1,684.2 (3,713.5)	111.72%	1,575.4 (3,473.4)	98.03%
Transmission/Conversion Systems	572.9 (1,263.0)	592.8 (1,307.0)	3.48%	384.5 (847.7)	-32.88%	384.5 (847.7)	-32.88%
Heating, Air Conditioning	45.4 (100.0)	47.2 (104.0)	4.00%	47.2 (104.0)	4.00%	64.9 (143.0)	43.00%
Electrical	179.6 (396.0)	168.7 (372.0)	-6.06%	168.9 (372.3)	-5.98%	134.1 (295.6)	-25.35%
Instrumentation	41.3 (91.0)	41.5 (91.6)	0.66%	41.5 (91.6)	0.66%	43.6 (96.1)	5.60%
Miscellaneous (Furnishings, Equipment)	197.8 (436.0)	185.5 (409.0)	-6.19%	188.1 (414.7)	-4.89%	188.1 (414.7)	-4.89%
Basic Empty Weight	**4,116.8 (9,076.0)**	**4,120.5 (9,084.2)**	**0.09%**	**4,784.6 (10,548.9)**	**16.22%**	**4,175.7 (9,205.7)**	**1.43%**
Oxygen System	27.2 (60.0)	27.2 (60.0)	0.00%	27.2 (60.0)	0.00%	27.2 (60.0)	0.00%
Fixed Research Instrumentation	136.1 (300.0)	136.1 (300.0)	0.00%	136.1 (300.0)	0.00%	136.1 (300.0)	0.00%
Portable Research Instrumentation	203.7 (449.0)	203.7 (449.0)	0.00%	162.8 (359.0)	-20.04%	24.3 (53.5)	-88.09%
Avionics & Navigation	65.3 (144.0)	65.3 (144.0)	0.00%	65.3 (144.0)	0.00%	65.3 (144.0)	0.00%
Environmental Control Package	12.2 (27.0)	12.2 (27.0)	0.00%	12.2 (27.0)	0.00%	12.2 (27.0)	0.00%
Shaker	7.7 (17.0)	7.7 (17.0)	0.00%	7.7 (17.0)	0.00%	–	–
Research Mission Empty Weight	**4,568.8 (10,073.0)**	**4,572.5 (10,081.2)**	**0.08%**	**5,196.3 (11,455.9)**	**13.73%**	**4,481.8 (9,880.2)**	**-1.91%**

Cost and TRL

	Phase I design	Phase II design	XV-15
Unit flyaway cost Production 30 units/year *2026 US Dollars, millions*	**$20.75 ±0.92**	**$22.77 ±2.94**	**$17.72 ±0.53**
Program cost, total 2 Prototype Aircraft 5 years of 30 unit/year production *2026 US Dollars, millions*	**$508** *$254/ unit* **$3,100** *$20.8/ unit*	**$577** *$289/ unit* **$3,400** *$22.8/ unit*	**$461 ($305*)** *$232 ($153)/ unit* **$2,700** *$17.7/ unit* **inflation adjusted NASA 1973 program cost*
Maintenance Cost Total Operating Cost *2026 US Dollars*	**$1,200/ flight hour** $2.3 Million/ year at 1 daily RFP flight	**$1,000/ flight hour** $3.1 Million/ year at 1 daily RFP flight	**$1,100/ flight hour** $2.0 Million/ year at 1 daily RFP flight



Component Family	Phase I	Phase I Notes	Phase II	Phase II Notes
Wing	9	Standard XV-15	9	Carbon Fiber composite construction
Hub and Blades	9	Standard XV-15	7	Composite rotor assembly
Fuselage	9	Standard XV-15	9	Composite skin with 7076-T3 aluminum alloy bulkheads
Empennage	9	Standard XV-15	7	Carbon Fiber Reinforced Polymer V-Stab and Aluminum H-Stab
Turbine Installation	9	Standard XV-15	9	Standard XV-15
Landing Gear	9	Standard XV-15	8	Safran-style composite landing gear assembly
Controls / Fly-by-Wire	9	Standard XV-15	9	Full Fly-by-Wire system integration
Hybrid System	6	Established architecture with newly tested components	6	Established architecture with newly tested components

Summary

- In response to the 43rd Annual VFS Student Design Competition sponsored by Leonardo , the Georgia Institute of Technology proudly presents the *Erodius*, a highly efficient hybrid-electric tiltrotor design with innovative hybridization architecture.
- With its exceptional hybrid-electric design and modern design improvements, the *Erodius* can execute demanding flight profiles with ease. The *Erodius's* high payload capacity at hot and high altitude (4,000 ft/95°F) in conjunction with its expanded flight ceiling and 260 KCAS cruise speed expands on current vehicle capabilities. This allows for extended range operations and passenger transport in challenging conditions while maintaining strict energy reserves and a hybrid architecture. These capabilities are certain to solidify the *Erodius* as an indispensable asset for commercial travel routes and reduced-cost operations for a minimally adjusted XV-15, and modernized vehicle redesign effort.

- Combining the efficient gliding flight with the VTOL capabilities of its predecessor, we are confident that the *Erodius Phase II* will revolutionize modern tiltrotor operations. By providing unmatched forward flight efficiency through its unique lifting nacelle extension, the *Erodius* will contribute to the success and advancement of next-generation hybrid-electric aviation, and inform the sizing and development of new electric architecture implementation.